STATISTICAL ANALYSIS
OF A DETERMINATION
OF THE HALF LIFE OF KRYPTON-85

Battelle

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MASTER

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by

James W. Johnston

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STATISTICAL ANALYSIS OF A DETERMINATION
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SUMMARY

Data from 53 determinations of Kr^{85} to Ra^{226} ratios done over a 15-year long experiment to determine the half-life of Kr^{85} ($K_{1/2}$) were analyzed. A number of least squares regression models were fitted to the data. The best fitting model produced a $K_{1/2}$ of 10.715 years with a standard deviation of 0.008 years. An average half-life estimate, based on individual half-life estimates from 48 of the Kr/Ra ratios was also calculated to show the effect on the uncertainty of estimation. The average half-life method produced a $K_{1/2}$ estimate of 10.714 years with a propagated standard deviation of 0.0565 years.

The uncertainty associated with the regression estimate could have been reduced by greater care for consistency in the ionization chamber set-up. It was found that use of a glass sample holder for the earlier determinations and a plastic sample holder for 11 of the later determinations increased the uncertainty but apparently did not bias the results. The broad fluctuation of counting times from determination to determination, caused by use of capacitors with different capacitance, also contributed to the less than optimum precision.

It was also found that the temperature/pressure adjustment used had no significant effect on the results. That is, the ratios are not significantly different when calculated with or without the T/P correction. However, including the changes in the average T/P from determination to determination did produce a significant reduction in the uncertainty of estimation.

DATA BASE AND NOTATION

The study to experimentally determine the half-life of krypton 85 began on 2/13/58 and there were 53 "determinations" through 1/5/73, a period spanning about 1.5 nominal half-lives (10.76 years). For the purpose of this study a "determination" will be defined as the set of runs, done on a study day, used in the determination of a radium/krypton ratio. Each determination consisted of a variable number of runs in the $4\pi\gamma$ ionization chamber on each of the radium and krypton samples plus blank runs to determine background. Temperature and pressure were also recorded a variable number of times during the determination. The usual experimental procedure was to do a single background (B) run, 3 to 6 runs on the radium (R) standard, 4 to 10 runs on the krypton (K) sample, another 3 to 6 radium runs and a final background run, all using NBS's $4\pi\gamma$ ionization chamber. This B-R-K-R-B design accounted for 43 of the 53 determinations; the R-B-K-B-R design was used 5 times, the R-B-K-R-B design 2 times and the R-B-K-K-R-B, the R-K-R-B and B-R-B-K-B-R-B designs were each used once. At the end of the experiment there was a series of 11 determinations which used a plastic instead of a glass sample holder. The same radium and krypton samples were used. The first 6 of these determinations using the plastic holder had associated determinations using the glass holder on the same day or within 10 days.

The following notation will be used to describe the data and analysis and to discuss the results. The datum recorded for each run in the ionization chamber was the length of time required to charge a capacitor

(equivalent to the waiting time to the m^{th} count). Let x_{vijk} be the waiting time observed on the

k^{th} run, $k = 1, \dots, K_{vij}$, $K_{vij} \leq 10$, within the
 j^{th} set of runs, $j = 1, \dots, J_{vi}$, $J_{vi} \leq 2$, in the
 i^{th} determination, $i = 1, \dots, 53$ on the
 v^{th} sample, where $v = 1$ for a background run,
 $v = 2$ for a radium run,
 $v = 3$ for a krypton run.

Also, let

D_i be the number of days from the start of the study to the
day on which the i^{th} determination was done,

T_{vijk} and P_{vijk} be the k^{th} temperature and pressure
readings, respectively, recorded for the j^{th} set of runs
on day i ,

E_{vij} be the temperature/pressure ratio adjusted from degrees
centigrade to degrees Kelvin, $E_{vij} = (\bar{T}_{vij} + 273.16/\bar{P}_{vij})$,
where summation for the averages $\bar{T}_{vij}$ and $\bar{P}_{vij}$ is over
those k recorded during, or between, the ion chamber runs
for B, K or R, according as v is 1, 2 or 3,

c_{ij} be the correction factor for putting the background readings
on the same counting basis as the radium and krypton readings.

The capacitor and the background run setting for the ionization chamber
were changed from determination to determination so that the average
counting times vary widely over the study period. The background averages

($\bar{X}_{1i..}$) varied from about 2 to 13 minutes, the average times for the radium sample ($\bar{X}_{2i..}$) varied from 14 seconds to almost 3 minutes, the averages of the runs on the krypton sample ($\bar{X}_{3i..}$) varied from 20 seconds to 2.4 minutes.

A listing of the basic data is given in the Appendix.

RATIO CALCULATIONS AND HALF-LIFE ESTIMATION PROCEDURE

Given the above basic data, the following calculations were done for each determination.

$$\rho_{1i} = \frac{\bar{X}_{2i..}}{\bar{X}_{3i..}} = \frac{\text{Average elapsed time for the Ra runs}}{\text{Average elapsed time for the Kr runs}}$$

$$\rho_{2i} = [1/\bar{X}_{3i1.} - B_i] / [1/\bar{X}_{2i1.} - B_i]$$

$$= \frac{\text{Net Counting Rate for Kr}}{\text{Net Counting Rate for Ra}}$$

$$\rho_{3i} = \left[\frac{\bar{E}_{3i.}}{\bar{X}_{3i1.}} - BE_i \right] / \left[\frac{1}{2} \left(\frac{\bar{E}_{2i1.}}{\bar{X}_{2i1.}} + \frac{\bar{E}_{2i2.}}{\bar{X}_{2i2.}} \right) - BE_i \right]$$

$$= \frac{\text{Temperature \& Pressure Corrected Net Counting Rate for Kr}}{\text{Temperature \& Pressure Corrected Net Counting Rate for Ra}}$$

where

$$B_i = 1/2 \left[c_{i1} / \bar{X}_{1i1.} + c_{i2} / \bar{X}_{1i2.} \right],$$

$$BE_i = 1/2 \left[c_{i1} E_{1i1} / \bar{X}_{1i1.} + c_{i2} E_{1i2} / \bar{X}_{1i2.} \right].$$

The average temperature-pressure correction for the i^{th} determination was also calculated as

$$E_i = \sum_{vj} E_{vij} / \sum_v J_{vi}$$

The results of the above intermediate calculations were used to make both regression and average estimates of the half-life of K-85. The theory involved is as follows.⁽¹⁾

At determination i the essential data were:

- D_i , the time from the start of the experiment in days,
- $\bar{X}_{1i..}$, the adjusted average background time,
- $\bar{X}_{2i..}$, the average time to record m_i radium counts, and
- $\bar{X}_{3i..}$, the average time to record m_i krypton counts.

Given that there are N_{vi} atoms present at the start of counting on day D_i the disintegration rate is $\lambda_v N_{vi}$ per second (λ_v in seconds), and $\bar{X}_{vi..}$ is the waiting time to record the m_i^{th} count, m_i being the same for both the radium and krypton samples. Then, defining η_v as the counter efficiency factor,

$$m_i = (\eta_v \lambda_v N_{vi}) \bar{X}_{vi..} \text{ , or } \frac{m_i}{\bar{X}_{vi..}} = \eta_v \lambda_v N_{vi} ; v = 2,3 \text{ or R, K}$$

and assuming the counter efficiencies remain in constant ratio

$$r = \eta_3 / \eta_2$$

over the 15-year study span,

$$1 = \frac{\bar{X}_{3i..} \lambda_K N_{Ki}}{\bar{X}_{2i..} \lambda_R N_{Ki}} r$$

so that

1. A more detailed general exposition is available in: Stevenson, P.C., Processing of Counting Data, Nat'l Academy of Science - Nat'l Research Council, May 1966; (NAS-NS 3109), particularly pp. 3,4.

$$\frac{\lambda_K N_{Ki}}{\lambda_R N_{Ri}} r = \frac{1/\bar{X}_{3i}}{1/\bar{X}_{2i}} = \rho_i$$

Substituting the decay equations

$$N_{Ri} = N_{R0} \exp[-\lambda_R D_i]$$

and

$$N_{Ki} = N_{K0} \exp[-\lambda_K D_i]$$

we get

$$\begin{aligned} \rho_i &= r \frac{\lambda_K N_{K0} \exp[-\lambda_K D_i]}{\lambda_R N_{R0} \exp[-\lambda_R D_i]} \\ &= \frac{m_0/\bar{X}_{3i..}}{m_0/\bar{X}_{2i..}} \exp[-(\lambda_K - \lambda_R) D_i] \\ &= \rho_0 \exp[-(\lambda_K - \lambda_R) D_i] \end{aligned}$$

This relationship remains valid as long as the ratio of the counting efficiencies does not change. Then

$$\ln \rho_i = \ln \rho_0 - (\lambda_K - \lambda_R) D_i \quad (1)$$

The end products of each of the 53 determinations were the ratios ρ_i , adjusted for background and temperature/pressure. The relationship of Eq. (1) is linear so that fitting the line

$$y = \alpha + \beta D_i$$

with $y = \ln \rho_i$, will provide an estimate of β . Now

$$\beta = \lambda_R - \lambda_K$$

so that

$$\hat{\lambda}_K = \lambda_R - \hat{\beta} \quad (2)$$

[Note that a shift in the ratio, r , of efficiencies would only affect the intercept, through ρ_0 , and not the slope.]

Since λ_R is known ($1.17 \times 10^{-6}/\text{day}$), each ratio determination also provides an estimate of the half-life, as follows from Eq. (1),

$$\begin{aligned}\hat{\lambda}_{Ki} &= (\ln \rho_0 - \ln \rho_i + \lambda_R D_i)/D_i \\ &= (\ln \rho_0 - \ln \rho_i)/D_i + \lambda_R\end{aligned}$$

Then, for either the regression or individual determination methods,

$$K_{1/2} = \ln 2 / \hat{\lambda}_K \quad (3)$$

DATA EDITING

The first three determinations (done on 2/13/58, 5/15/59, and 3/1/60) were handled separately because the experimental setup was different (a voltmeter, rather than a capacitor, was used to control the counting time) and because the sequence of sets of runs was different for the first and second determinations.

The 28th determination, done on 2/12/65, had a large discrepancy between the averages for the two sets of radium runs, and resulted in a ratio that was larger than the previous ratio, done 67 days earlier, and a between radium set standard deviation of 5.408. The 39th determination, done on 9/5/68, had a smaller discrepancy between the sets of radium runs (sd = 1.457), but the ratio was smaller than the following ratio, done 77

days later. The next largest between radium set standard deviation was 0.318 and the between set standard deviation, pooled over the 48 remaining capacitor determinations, was 0.152. $\left[F_{(1, 48)} = \frac{(1.457)^2}{(0.152)^2} = 91.88 \right]$ has a probability of occurrence of less than 0.0001 under the assumption that the between radium sets averages for the 39th determination come from a normal population with the same variance as the other determinations (excluding the 28th).] The 28th and 39th determinations were initially removed from the analysis because of the reversals in the time ordering of the resultant ratios, a physical impossibility. The statistical improbability of the F-ratio indicates that at least one of the sets of radium runs in each case was most probably the cause of the discrepancy.

ESTIMATION MODELS

The NBS half-life estimation procedure was to calculate the ratio of the temperature and pressure corrected net counting rate for krypton to the rate for radium similarly adjusted. Each ratio was adjusted for radium decay and a straight line fitted to the points defined by the logarithm of the ratios and the number of days since the start of the study to the day on which the ratio was determined. (The data available to us did not have a finer time lapse measurement than days.) This calculational procedure corresponds, in most respects, to what will be designated as Model 3. In the above notation Model 3 is

$$\ln \rho_3 = \alpha + \beta_1 D.$$

(4)

The calculational formula for ρ_3 , as given above, is the same as used by NBS in their calculation of the ratios except that it does not include an adjustment for radium decay. Our procedure was to fit the line to the logarithm of the ratios and to adjust the resulting slope as in Eq. (2).

Other models were investigated. Model 1 used the ratios defined by ρ_1 in a multiple linear regression fit of

$$\ln \rho_1 = \alpha + \beta_1 D + \beta_2 B + \beta_3 E \quad (5)$$

The rationale for attempting to fit this model was that the ratio, ρ_1 , is the ratio of the unadjusted counting times and the regression model provides a means of estimating the variability associated with the successive fitting of the regression parameters β_1 , β_2 , and β_3 . However, Model 1 implies that the background correction is multiplicative. As is evident from the equations for ρ_2 and ρ_3 , background is additive and so cannot be mathematically separated in the logarithmic transformation of the ratios. The coefficient matrix proved to be singular for this model, and so no solution was obtained. Model 1 will not be discussed further.

Model 2 used the background corrected counting rates in the calculation of the ratios, ρ_2 but the temperature/pressure correction (a multiplicative factor) was used as a regression variable. Model 2 is:

$$\ln \rho_2 = \alpha + \beta_1 D + \beta_2 E \quad (6)$$

As for Model 3, the estimate of the decay parameter (λ_K) was the regression parameter (β_1) adjusted for radium decay (λ_R).

Models 2 and 3 were applied to the entire data set (52 determinations, DET 39 being excluded), the subset characterized by use of the glass sample holder, and the subset using the plastic holder. The models were also run with the addition of a second "intercept" parameter for the glass subset. The effect on the fit of removing determinations suspected of being anomalous was also investigated.

The average of the half-lives calculated for 48 of the determinations was also used as an estimate of the half-life. Equation 3 and the equation preceeding it show that the decay parameter estimate is adjusted for radium decay. Each of the three ratio definitions was used to provide an average half-life estimation, but the first two ratios may be biased since they do not include temperature/pressure corrections and only the last two are background adjusted. For reasons discussed below, only the average half-life determination based on the second ratio (ρ_2) will be discussed in detail.

The statistical uncertainty associated with the estimate of the half-life is an important quantity for this study. When the decay constant obtained by a regression model was used to estimate the half-life, "propagation of errors"⁽²⁾ was used to estimate the associated variance. From Eq. (3),

$$V(K_{1/2}) = (\ln 2)^2 V(1/\hat{\lambda}_K) \doteq (\ln 2)^2 V(\hat{\lambda}_K)/\hat{\lambda}_K^4 ,$$

where $\doteq$ indicates an approximation through propagation of errors was used.

2. See H. H. Ku, "Notes on Propagation of Error Formulas", pp. 331-341 in Precision Measurement and Calibration, H. H. Ku, Ed., NBS Special Publication 300 - Vol. 1, Feb. 1969. U.S. Gov't. Printing Office, Washington, D.C.

From Eq. (2),

$$\hat{\lambda}_K = \hat{\lambda}_R - b \quad ,$$

and

$$V(\hat{\lambda}_K) = V(\lambda_R) + V(b)$$

where b is the regression coefficient ($\hat{\beta}_1$) associated with the mathematical variable D , i.e., days from start of study. The estimate of the half-life of Ra 226 used was 1620 yr. with a standard deviation of 2 years.⁽³⁾ This implies (through propagation of error formulas) that $V(\lambda_R) \approx 2.091560 \times 10^{-18}/(\text{day})^2$, and that $\lambda_R = 1.171440 \times 10^{-6}/\text{day}$. The $V(b)$ to be used is the variance of the estimate of β_1 calculated from the least squares fit of Model 2 or 3. Combining the above formulas and calculations,

$$V(K_{1/2}) = \left(\frac{\ln 2}{\hat{\lambda}_K^2} \right)^2 [V(b) + 2.091560 \times 10^{-18}] \quad ,$$

and

$$sd(K_{1/2}) = \frac{\ln 2}{\hat{\lambda}_K^2} sd(\hat{\lambda}_K) \quad .$$

RESULTS OF FITTING THE ESTIMATION MODELS

The main objective of fitting a number of models was to determine which model was best, in the sense that it resulted in minimum variance for the half-life estimate. The model which best satisfied this criterion was Model 2, run with determinations 1 and 39 removed. The resulting equation was:

$$\ln p_2 = 0.25229 - (1.75934 \times 10^{-4}) D + 0.011316 E \quad (7)$$

3. See the last section for a discussion of the impact on the analysis of various values for the half-life of radium-226.

The estimate of λ_k resulting from this model was 1.77106×10^{-4} , which produced a half-life estimate of 10.715 years with a standard deviation of 0.008 years. The 95 percent confidence limits on the estimate, based on the t distribution with 48 degrees of freedom, were 10.699 to 10.732 years.

Some preliminary analyses were required to arrive at Eq. (7). First, the data base had to be "firmed up". The problem of ratio reversals for determinations 28 and 39, referred to in the Data Editing Section was resolved by selecting the set of radium runs that removed the reversal and deleting the other set. For determination 28 the second set was used, and for 39 the first set was used. When Model 2 was run with all 53 determinations, the standard deviation of the estimated regression parameter, b_1 , for days, D, was 2.5996×10^{-7} . The residual for determination 39 was more than 2.5 times the next largest residual. When determination 39 was removed completely, the $sd(b_1)$ was reduced to 1.4817×10^{-7} , a 43 percent reduction. On this run the residual for the first determination was the maximum, at $-.00451$, and the next largest residual was $-.00268$. The largest positive residual was $.00240$. When DET1 was removed, the $sd(b_1)$ was reduced to 1.3447×10^{-7} , only a 9 percent reduction. This is not extremely persuasive evidence for removal of DET 1, but other evidence, discussed later, makes it suspect. When model 2 was modified to include a dummy variable for the subset of the data characterized by use of the glass sample holder, the estimate of the G vs. P parameter was not significantly different

from zero ($t = 1.08$ with 48 d.f.) when the 52 observations, including DET 1, were used. But when DET 1 was removed, the parameter for the dummy variable was significantly different from zero ($t = 1.92$ and $P(t_{47} > 1.92) \approx 0.03$). This procedure is equivalent to testing the null hypothesis: a single regression equation ($\ln \rho_3 = \alpha + \beta_1 D + \beta_2 E$) is adequate to represent the data. Rejection of this hypothesis requires an explanation of what causes the differences between the fits for the glass and plastic data.

First, the fact that the above hypothesis was not rejected with DET 1 in the data set and the high negative residual for DET 1 leads to the conclusion that DET 1 was biased low. DET 1 is the day zero determination. Reference to Eq. (1) indicates that the logarithm of the day zero ratio is the intercept for the simple linear regression model. When the theory is extended to the three-parameter model 2, the intercept is the line in three-space above the E axis where the regression plane intercepts the $(\ln \rho, E)$ plane. The estimate for $\ln \rho_{3,0}$ using the glass subset with DET 1 included was 0.36639 with a standard deviation of estimation of .0005730. The actually observed logarithm of the ratio for DET 1 was 0.36337 with a within determination standard deviation of 0.001049 (obtained via propagation of errors, and having approximately 4 d.f.). A test of the hypothesis that there is no statistical difference between the actually observed ρ_0 and the ρ_0 estimated from the model for the glass subset is available using the t-test. This test is highly significant ($|t| = 4.50$ with 43 d.f.) so that we can conclude that DET 1 produced a biased result.

These considerations do not answer the question regarding why the glass and plastic data require different model parameters, but they do remove the confusion which may have resulted from leaving the biased status of DET 1 indeterminate.

The explanation of the difference between the results produced by the plastic and glass data sets is dependent upon a number of statistical tests. These are summarized in Table 1. The upper block of Table 1 gives the regression parameters for the various data sets. Note that b_{0p} is about 70 percent of b_{0g} and that b_{2g} is about 57 percent of b_{2p} , whereas b_{1p} is 99.6 percent of b_{1g} . That is, there is little difference between the estimate of the regression parameter for days (D), but the plastic data produce an intercept which is 30 percent less than that for the glass data and the regression parameter for the temperature-pressure factor has a more extreme difference in the opposite direction. The statistical significance of these differences will be investigated below. The next block of statistics are the standard deviations associated with the estimates of the regression parameters. Note that the standard deviations of the parameters for the plastic data are 2.5 to 3.6 times those for the glass data despite the fact that the residual standard deviations are quite comparable. The next block of statistics provides estimates of the day zero ratios. These also appear quite comparable, the glass-plastic difference being 0.002 in the $\ln \rho_0$ units.

The summary statistics in the top part of Table 1 were used in the statistical tests summarized in the lower part of Table 1. The first test

TABLE 1. Statistics For Model 2

Statistic		GLASS G N = 40	PLASTIC P N = 11	ALL A N = 51	ALL A-I N = 51
Intercept	b_0	.263642	.185975	.252290	.251760
I_G	$10^3 \times b'_0$				- 1.004050
D	$10^4 \times b_1$	- 1.762214	- 1.755395	- 1.759343	- 1.761482
E	b_2	.0102378	.0178061	.0113160	.0115030
sd (b_0)		.0181043	.0446012	.0175791	.0171106
$10^4 \times \text{sd} (b'_0)$					5.235555
$10^7 \times \text{sd} (b_1)$		1.748069	6.295303	1.344667	1.719516
$10^3 \times \text{sd} (b_2)$		1.797103	4.497314	1.745034	1.701103
$10^3 \times \text{Resid. sd}$		1.136506	1.134516	1.195931	1.163906
$b_2 \bar{E}$		.102966	.178645	.113750	.115630
$\ln \hat{\rho}_0$		.366608	.364620	.366048	.365985
$\hat{\rho}_0$		1.442833	1.439967	1.442025	1.441933
$K_{1/2}$		10.6979	10.7392	10.7153	10.7023
sd ($K_{1/2}$)		.01054	.03826	.00814	.01038

TESTS OF HYPOTHESES

Null Hypothesis	Test Statistic	Probability
1. G and P have the same residual variance	$F = (1.1365)^2 / (1.1345)^2 = 1.004$	NS (.50)
2. Residuals for G & P are from the same distribution	$z_U = 1.580$	.1141
3. $\beta_{0G} = \beta_{0P}$	$t = .07766 / .02496 = 3.11$	<.005
4. $\beta_{1G} = \beta_{1P}$	$t = 6.819 \times 10^{-7} / 6.384 \times 10^{-7} = 1.07$	NS (.28)
5. $\beta_{2G} = \beta_{2P}$	$t = -.007568 / .004740 = -1.60$	.1168
6. $\ln \rho_{0G} = \ln \rho_{0P}$	$t = .00199 / .00168 = 1.18$	NS (.24)

compares the residual variances for Model 2 applied to the glass and plastic data separately. The F-ratio is near unity indicating that the underlying variance structure is the same for the two data sets once the variability due to days and T/P has been removed. This conclusion does not imply that a single fit of the combined data sets is appropriate. In fact, a Mann-Whitney U-Test done on the residuals from the fit of Model 2 to the combined data set (A, N = 51) approached significance. (The test statistic z_U is asymptotically normally distributed.) Acceptance of hypothesis 2 is questionable.

Since the fit of Model 2 is so good, accounting for almost 100 percent of the variability, the non-significant (NS) result of the test of hypothesis 1 implies that the residual standard deviation is a good characterization of the experimental variability; i.e., the uncertainty associated with the logarithm of a determination ratio. This test also eliminates heterogeneity between the glass and plastic experimental variances from consideration as a factor contributing to the significant difference between the results of the two data sets. The fact that the 11 residuals for the plastic data set are not uniformly distributed among the 40 residuals for the glass set, (3 were below and 8 above the median residual of the combined data set and the U-test approached significance) implies that combining the glass and plastic data sets without an adjustment for the difference could bias the half-life estimation. The predominantly positive residuals for plastic indicate that the combined fit underestimates the $\ln \rho_{2i}$ for the plastic holder data.

The third test indicates that the intercept (β_0) for glass is different from, i.e., significantly larger than, the intercept for the plastic data set. Thus, the intercept is definitely a contributing factor to difference between the results of the application of model 2 to the two data sets. The fourth test indicates that a single regression parameter for days, β_1 , can be used. This is encouraging since it is upon β_1 that the half-life estimate will be based. The test of the fifth hypothesis produced a two-tailed probability of 0.1168. (All tests are against the two-sided alternative of non-equality). Although 0.1168 is slightly greater than the 0.1 level usually used as the upper limit for rejecting hypothesis, it is close enough to make the acceptance of hypothesis 5 suspect. The difference between the parameters associated with the T/P factor is large enough to contribute to the significant difference observed in the application of model 2 to the G and P data sets.

The overall conclusion to be drawn from these tests is that the best estimate of the regression parameter for days will be obtained by combining the two data sets and using the resulting estimate of β_1 to estimate the half-life. Fortuitously, in a relative sense, the plastic data underestimate the intercept and overestimate the parameter for the T/P factor so that the estimates of $\ln \rho_0$ at the points for day zero and $\bar{E}_G$ or $\bar{E}_P$ are not significantly different. The results indicate that the lines for the two data sets, adjusted to the average T/P factor, have the same intercept and are parallel. The significant difference between the two data sets is real, but it has no real effect on the half-life estimation. Consequently, model 2 with determinations 1 and 39 removed provides the best estimate of β_1 .

The second best model was a modified model 3, namely

$$\ln \rho_3 = 0.25273 - (1.75943 \times 10^{-4})D + 0.011274E \quad (8)$$

This will be referred to as Model 3E. By this time the reader should be familiar enough with the order of magnitude of the variability being dealt with to recognize from Table 2 that the estimated parameters of Eq. 8 are within a standard deviation of those for Eq. 7 (model 2). In particular, $b_{12} - b_{13E} = 9.1 \times 10^{-9}$ and $sd(b_{12} - b_{13E}) = 1.936 \times 10^{-7}$, so that a t-test on the difference between the regression parameters for days for models 2 and model 3E would be less than unity and consequently be non-significant. The difference in half-life estimates is only 0.0006 years, well within a standard deviation. In fact, the differences between model 2 and model 3E are so minute that they are approximately what would be expected from rounding error, which could have an effect on the 5th or 6th decimal place of the ρ values. (The original data were recorded to six significant digits.)

Table 2 also includes a column for model 3, which was:

$$\ln \rho_3 = 0.366273 - (1.760256 \times 10^{-4})D \quad (9)$$

An F test of the null hypothesis that the addition of the T/P (E) variable does not improve the fit produced a value of 38.22. The probability of obtaining a value this large is less than 0.0001. This significant F test indicates that the addition of the T/P variable to model 3 produced a significant improvement in the fit of the data. This was not expected since the calculation of ρ_3 included a correction for T/P. Theoretically, if the correction for T/P in

Table 2

Model 2 Compared to Model 3E and Model 3

N = 51			
<u>Statistic</u>	<u>Model 2</u>	<u>Model 3E</u>	<u>Model 3</u>
b_0	.252290	.252731	.366273
$10^4 \times b_1$	-1.759343	-1.759434	-1.760256
b_2	.0113160	.0112738	_____
$sd(b_0)$	.0175791	.0183694	.000540
$10^7 \times sd(b_1)$	1.344667	1.405135	1.855573
$10^3 \times sd(b_2)$	1.745034	1.823507	
$10^3 \times sd(\text{Resid.})$	1.195931	1.249711	1.657764
$K_{1/2}$	10.7153	10.7147	10.7097
$sd(K_{1/2})$	.00814	.00850	.01215
b_2^E	.113685	.113261	_____
$\ln \hat{\rho}_0$	.365974	.365992	.366273
$\hat{\rho}_0$	1.441919	1.441943	1.442349
95% CL on $K_{1/2}$			
Lower	10.6990	10.6976	10.6853
Upper	10.7316	10.7318	10.7341

the calculation of ρ_3 were adequate, one would expect that the average T/P levels for the determinations would not be a significant variable in the linear regression fit. Apparently the T/P "correction" accounts only for within determination temperature and pressure differentials. The T/P variable used in Models 2 and 3E is the average ($\bar{E}_i$) of the T/P determinations (E_{vij}) within each determination. The fact that $\bar{E}_i$ is a significant regression variable indicates that the between determination differences in T/P have an effect that is not accounted for by the corrections for T/P which were made. Further, if the within determination correction for T/P had any effect at all, one would expect Model 2 to have a regression parameter different from those for Model 3E, since model 2 uses ρ_2 which has no correction for T/P. In fact, a t-test on the differences between the calculated ratios ($\rho_{2i} - \rho_{3i}$, $i = 2, \dots, 38, 40, \dots, 53$) resulted in the low value 0.151. This non-significant result indicates that the T/P "correction" used for ρ_3 makes no appreciable difference in the results.

The conclusion to be drawn from these comparisons of Models 2, 3E and 3 and the T/P ($\bar{E}_i$) factor is that the within determination T/P adjustment was not needed, but that a between determination correction is required. The regression parameter estimator $b_2 = .011316$ provides the weight to be given to the average temperature/pressure ratio ($\bar{E}_i$) for each determination.

In summary of the model fitting effort it was found that:

- The best precision of estimation was given by Model 2,

$$\ln \rho_2 = 0.25229 - (1.75934 \times 10^{-4})D + 0.011316E$$

- The estimate of the half-life of krypton-85 resulting from this model was 10.715 years.
- The standard deviation of the estimate was 0.008 years, equivalent to about 3 days or to a relative (to the estimate) standard deviation of 0.076 percent.
- Confidence limits on the estimated half-life at the 95 percent level were (10.699, 10.732).
- There is a significant difference between the results of applying Model 2 to the data set characterized by the use of the glass sample holder and the set using the plastic holder, but this difference affects only the intercept and T/P parameter, not the parameter associated with days upon which the half-life estimate was based.
- A between determination adjustment for T/P is more important than a within determination correction.

AVERAGE HALF-LIFE ESTIMATE

The basic objective of NBS's experiment was to determine the half-life of Kr-85, or, equivalently, the decay rate. The decay rate is the number of atoms which disintegrate to another nuclear form per unit time. As such, the decay rate can be estimated by the slope associated with the exponential decay equation. It is well known⁽⁴⁾ that the least squares estimate of the

4. See, e.g., F. A. Graybill, An Introduction to Linear Statistical Models, McGraw-Hill, 1961, p. 115, Theorem 6.2. It was assumed that the conditions of this theorem were not violated by the use of the random (as opposed to mathematical) variable $\bar{E}_i$.

slope is the minimum variance unbiased estimate of the slope when the measurement errors are statistically uncorrelated and have the same variance. Since these conditions appear to be met, one would not expect the estimate based on the average half-life to be better, in the sense of having a smaller variance. But it is informative to go through the calculation to dissuade others estimating half-lives who could use the regression method but expect to try the average method. (5)

The conclusions of the regression analysis included the fact that there was no statistically significant difference between the determination ratios whether calculated by the formula for ρ_2 or the formula for ρ_3 and that the T/P correction used had no significant effect on the results. These conclusions provide the basis for using the individual half-life determinations based on ρ_2 in the average half-life method of estimating the half-life. Also, the conclusion that the first ratio determination was biased low suggested that a better estimate of $K_{1/2}$ would be obtained if the Model 2 estimate of the day zero ratio, $\hat{\rho}_0$, were used.

The average half-life method of estimating the half-life of krypton-85 produced an average of 10.7142 based on the ρ_2 for 48 determinations, (determinations 1, 2 and 3, 28 and 39 were not included). The standard

-
5. e.g., R. K. Wanless and H. G. Thode in the Canadian Journal of Physics, Vol. 31, 1953, reported a standard deviation of 0.18 yr. on their estimate of $K_{1/2}$ of 10.27 years. They averaged the determinations from two different ratio determinations and took the average of the 7 resulting averages and calculated the sd based on the 7 averages. The averages for the two columns in their Table II of ratio determinations are statistically different, and so should not have been averaged together. The regression method could have been applied to their basic Kr^{85}/Kr^{84} and K^{85}/Kr^{86} ratios. The resulting uncertainty on their estimate would then have been more meaningful.

deviation of the 48 determinations was 0.0407 years, so that the standard deviation of the average of the determinations was 0.00587 (or 2.1 days).

This precision is 28% better than the best linear regression model.

However, this standard deviation of the average half-life does not reflect the total uncertainty due to random error which should be considered when characterizing the precision of the estimate. At each determination (i), $K_{1/2}$ was estimated by Eq. (3) which, with i and the calculation of $\hat{\lambda}_K$ explicit, is

$$K_{1/2i} = \ln 2 [(\ln \rho_i - \ln \rho_0)/D_i + \lambda_R]^{-1} .$$

This equation uses the quantities $\ln \rho_0$ and λ_R for each determination.

The "between determination" variability estimated by the standard deviation of the determinations does not include the variability due to the "corrections" for $\ln \rho_0$ and λ_R .

The propagation of errors required to obtain a realistic estimate of the uncertainty on the average half-life involves some straightforward algebra. The chain of equations relating the basic measured quantities which "carry" their associated variability, are as follows.

$$\bar{K}_{1/2} = \frac{1}{48} \sum_{i=1}^{48} K_{1/2,i} \quad (10)$$

$$K_{1/2,i} = - \ln 2 / \hat{\lambda}_{Ki} \quad (11)$$

$$\hat{\lambda}_{Ki} = (\ln \rho_{2,i} - \ln \rho_{2,0})/D_i - \lambda_R \quad (12)$$

The required propagation of error formulas are:

$$V(\bar{K}_{1/2}) = \frac{1}{48} \sum_{i=1}^{48} V(K_{1/2,i}) + \frac{1}{47(48)} \sum_{i \neq j} \text{cov}(K_{1/2,i}, K_{1/2,j}) \quad (13)$$

$$V(K_{1/2,i}) = \left(\frac{\ln 2}{\hat{\lambda}_{Ki}} \right)^2 V(\hat{\lambda}_{Ki}) \quad (14)$$

$$V(\hat{\lambda}_{Ki}) = \frac{1}{D_i^2} V(\ln \rho_{2,i}) + \frac{1}{D_i^2} V(\ln \rho_{2,0}) + V(\lambda_R) \quad (15)$$

The covariance (cov) terms in Eq. (13) are zero since each half-life determination is independent of the others. There may have existed some dependencies in the measurement errors from determination-to-determination, but they are included in the variance estimator used. The variances required are given by Eq. (15). $V(\ln \rho_{2,i})$ was estimated by the residual variance from the fit of Model 2 as $s_r^2 = 1.430250 \times 10^{-6}$. Model 2 also provided the $V(\ln \rho_{2,0})$.

$$V(\ln \hat{\rho}_0) = s_r^2 [1 + X_0^T C X_0] = 1.583355 \times 10^{-6}$$

where C is the inverse of the variance-covariance matrix for Model 2 and X_0^T is the vector (1, 0, $\bar{E}$) with $\bar{E} = 10.0521$, the overall average T/P adjustment. Finally,

$$V(\lambda_R) = \left(\frac{\ln 2}{(1620)^2} \right)^2 \left(\frac{4}{365.25} \right)^2 = 2.091577 \times 10^{-18} / (\text{day})^2 .$$

Then

$$V(\hat{\lambda}_{Ki}) = \frac{1}{D_i^2} (1.430250 \times 10^{-6} + 1.583355 \times 10^{-6}) + 2.092 \times 10^{-18} .$$

and

$$v(K_{1/2,i}) = \left(\frac{\ln 2}{(1.771237 \times 10^{-4})^2} \right)^2 v(\hat{\lambda}_{Ki}) ,$$

$$\begin{aligned} v(\bar{K}_{1/2}) &= (1.016957 \times 10^{13}) \left(\frac{3.013605 \times 10^{-6}}{71,842.69} + 2.092 \times 10^{-18} \right) \\ &= 426.586 \end{aligned}$$

and

$$sd(\bar{K}_{1/2}) = 20.65 \text{ days} = .0565 \text{ years.}$$

The conclusion is that the necessary inclusion of the within determination random variability of the $\ln \rho_{2,i}$ and accounting for the variability due to the repeated use of $\ln \rho_{2,0}$ raises the uncertainty on the average half-life estimate by about a factor of 10, from 5.87×10^{-3} to 5.65×10^{-2} years. The total standard deviation of the average half-life estimate is thus 6.7 times the standard deviation of the regression estimate (8.14×10^{-3} years).

NOTE ON CORRECTION FOR RADIUM DECAY

A summary of the results of determinations of the half-life of radium-226 is given in E. K. Hyde, I. Perlman, and G. T. Seaborg, The Nuclear Properties of the Heavy Elements: Vol. II, Detailed Radioactivity Properties, Prentice Hall, 1964; pp. 449-451. The value used in the present report, 1620 ± 2 years, was adequate for making the radium decay correction. When the higher value of 1622 ± 13 , accepted for use by Hyde et al, was used, the $K_{1/2}$ estimate was 10.71534 years, compared to 10.71526 for the 1620 year value, and $sd(K_{1/2})$ obtained with a standard deviation of 13 was 0.0082 compared to 0.0081. Reference to Kohman, Ames, and Sedlet's paper (Paper 22.60, "The Specific

Activity of Radium", in The Transuranium Elements, Part II, edited by G. T. Seaborg et al., McGraw-Hill, 1949) revealed that ± 13 referred to a "probable error" based on a standard deviation of weighted (somewhat subjectively) observations and weighted averages with a systematic error component of 0.5 percent combined into the $\pm$ value in an unreported manner. Thus, the ± 13 is not a simple standard deviation and so cannot be validly compared with the ± 2 , which reflects, to the nearest year, a relative standard deviation of 0.1 percent of 1620 years. So much has been done to arrive at the ± 13 figure that recovery and verification of the underlying standard deviation would require a reanalysis of the data given by Kohman et al.

The low value obtained by Martin and Tuck in 1959 after they "critically evaluated all published information" was, as reported by Hyde et al., 1602 years. Use of this value produced a $K_{1/2}$ of 10.71446 years, a reduction of less than 0.01 percent. The lowest value discussed by Hyde et al., 1577 years gave a $K_{1/2}$ of 10.71332 years, a reduction of less than 0.02 percent from the value of 10.71526 obtained with the 1620 year value. The conclusion is that any value in the broad range of usually used values for the half-life of radium-226 would give closely comparable results when used to correct for radium decay. The results of the present report were not adversely affected by use of 1620 ± 2 as the half-life of radium.

A pessimistic estimate of the uncertainty on the half-life of Ra-226 is available from Table 6.6 of Hyde et al. Excluding the two lowest specific alpha activity values (2.9 and 2.98), the calculated standard deviation relative to the average value of 3.575×10^{10} α -particle per second per gram was 4.4 percent. Such a relative standard deviation indicates that the standard deviation of the determinations to date is about 70 years. Even when the next three lowest determinations (3.15, 3.22 and 3.33) and the highest determination

(3.88) were removed the standard deviation (0.1044) was 2.9 percent of the average value, 3.600. Applying this to the half-life estimate of 1620, the standard deviation was 47 years which, propagated into the uncertainty on $K_{1/2}$ gave a value of 0.00839 years compared to the original value, based on ± 2 , of 0.00814. Even this extreme case has little effect on the final results.

APPENDIX

LISTING AND SUMMARIES OF DATA

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2	LISTING OF DATA SUMMARY FOR REGRESSION ANALYSIS
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DESCRIPTION OF TABLES

The Tables are largely self-explanatory but a few comments on coding and calculations will be given for each.

TABLE 1

This basic data for the experiment was key punched from copies of NBS's computation sheets. The first column, headed DET is the determination identification number. Copies of the data sheets for the first three determinations, which used a voltmeter rather than a capacitor in the 4 π chamber set up, are given separately below since the records did not conveniently fit the card format used for the rest of the data. The second column, headed E, gives the coded experimental run sequence. The background, radium and krypton runs were done in different orders for different determinations and coded as follows.

<u>Run Sequence</u>	<u>Code</u>	<u>Number of Instances</u>
B-R-K-R-B	1	41 (Also DET's 28 & 39)
R-B-K-B-R	2	5
R-B-K-K-R-B	3	1 (DET 1)
R-K-R-B	4	1 (DET 2)
R-B-K-R-B	5	2
B-R-B-K-B-R-B	6	1 (DET 44)

The E code was not used in the analysis. This is not the same as the E (for environment) used as the name of the T/P ratio.

The DAY column gives the days from the start of the study. The column headed V has 1 designating background, 2 for radium, and 3 for krypton

sample runs. The next column, J, gives the ID for the first (1) or second (2) set of runs on a B or R sample. For K runs ($V = 3$) J merely designates the first or second card of the single set of runs. [Only DET 1 had the K runs separated.] The four separate background runs for DET 44 were handled as two sets of duplicate runs.

The column headed C contains the codes for the background count adjustment factor used to put the background counting time on the same basis as the sample runs. The codes were as follows:

<u>Count Factor</u>	<u>Code</u>
.001	1
.002	2
.003	3
.004	4
.005	5
.01	6
.02	7
1/3	8
.1	9
.03	10
1/300	11
1/30	12

The columns headed K=1 thru K=6 give the observed counting times for each set of replicate runs on each sample. The last two columns give the average temperature and pressure observed during, or temporally nearest, the set of runs.

The determinations using the plastic sample holder have a P preceeding the DET ID. The last two determinations listed are the determinations with calculated ratios which were anomalous because they did not rank in temporal

order. They have the ID's used in the initial coding and so have duplicates in the sequence of ID's for the DETS used. The ratio reversal was corrected by removal of the first set of radium runs for DET 28 and the residual from the least squares fit was not unusually large so DET 28, with the single set of radium runs, was used in the final analysis. DET 1 was removed so that the final analysis was based on 51 determinations. [The last two lines are the result of a printer jam on a trailer card and do not reflect any dissatisfaction with the data.]

TABLE 2

A computer code was written to calculate and punch the summary variables listed in Table 2 from the basic data of Table 1. The calculational formulas for the variables are given in the text. [Add the subscript i and let $R = \rho$.] DETs 2 and 3 were hand calculated. The first DET 28, with OUT 28 at the end, is the determination based on the single usable set of radium runs.

TABLE 3

This table, and the next two, was generated by the same computer code as above. It was based on the data from 48 determinations, (DETs 1-3 and anomalous 28 and 39 were removed). The first 7 columns contain the punched data tabulated in Table 2. The last three columns contain the individual half-life estimates, in years, based on ρ_1 , ρ_2 and ρ_3 , respectively.

The last three rows are the summary statistics for the columns of data to which they are related by the angled lines. The column average, standard deviation and coefficient of variation as a percentage ($100 \text{ sd}/\text{AVE}$) are given.

TABLE 4

The title describes the contents of this table except for the fact that N is the number of replicate runs in each set of runs and that RUN 2 for the KRYPTON columns merely contains a copy of RUN 1.

TABLE 5

This table, in columns 3, 4 and 5, gives the averages, over all replicates and runs of the counting times for each sample determination. The TP FACTOR column was calculated according to the formula for E_i in the text. The R1-R2 SD column contains the between radium determination standard deviations. The DET WT column was not used in the analyses reported. The values were calculated by dividing the AVE KR counting time by the nominal half-life value of 10.72 years. The weighted regression done using these determination weights in an attempt to account for a potential differential effect due to the different counting time durations did not improve the fit. The last column contains the standard deviation of the 5 or 6 temperature/pressure ratios used to calculate the TP FACTOR (E_i). The last line of the table contains the pooled standard deviations and associated degrees of freedom for within and between determination radium runs, and within determination temperature/pressure.

COMPUTATION SHEETS
FOR
DETERMINATIONS 1, 2, 3

COMPUTATION SHEET 1-3

DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

TEST NO. II

Kr⁸⁵

DATE 2-12-59
44th day

A	B	C	D	E	F	G	H	I	J	K
RUN NUMBER	Time	V ₀	V ₁	V ₂	V ₃	V ₄	V ₅	V ₆	V ₇	V ₈
		41713				C = 96.0		Var = V ₀ × 127.667 × 10 ⁻¹		
RRS	1355	00283	147975	157692	195.24	0076477	0076243	002375	29985	25.9
	1406	00278	146775	146497	131.860	0076356				26.0
	1417	00268	135395	135127	177337	0076198			29985	26.2
	1423	00270	144338	144063	188716	0076346				26.2
By	1433	00280	00350	00270	71752	0000038	0000038	003004	30013	26.3
Kr	1447	00550	140345	139795	127521	0109625	0109647	0032917	30051	26.4
	1452	00273	139164	138995	126645	0109673				26.4
	1455	00271								
	1459	00266	140482	140217	127238	0109683			30019	26.5
	1502	00256	139903	139647	127419	0109597				26.6
	1506	00260	139923	139663	127366	0109655				26.6
Kr	1511	00260	130715	130455	136809	0095342	0095241	0033628	30021	26.6
	1515	00260	130715	130455	136772	0095381				26.6
	1521	00249	148805	148553	155317	0095340				26.6
	1525	00267	129555	129588	136011	0095275			30020	26.7
	1530	00258	147929	147671	154852	0095263				26.7
RRS	1535	00225	134055	133830	175595	0076215	0076169	0023246	30027	26.7
	1540	00252	134929	134677	176705	0076214				26.7
	1545	00266	134486	134222	176388	0076095				26.7
	1550	00260	134055	133798	175700	0076151				26.7
	1554	00254	116431	116677	155893	0076127				26.7
By	1600	00260	00952	00492	673495	000103	0000102	0000231	20028	
	By	0000091	Kr ⁸⁵	23917						
	RRS	00223								

COMPUTATION SHEET 2-4

DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

TEST NO. Kr 85 #1

DATE 5-15-59

A	B	C	D	E	F	G	H	I	J	K
RUN NUMBER			Xviii k Δt	Xvii k Δv	$\Delta v / \Delta t$	Xvi k / Xv k T/P	T_k/P	$\Delta v / \Delta t$	$\Delta v / \Delta t \cdot T_k/P$	
RRS 100	10330	122275	157601	121945	.0076377			.0076356	.077570	
	10334	122837	160526	122503	.0076316	$\frac{11.5}{27.500}$	10.159			
	10321	124795	162978	124474	.0076375					
Sc	10367	137756	135291	137389	.0101551	$\frac{10.505}{27.500}$	10.159	.0101619	.103240	
	00315	140198	137501	139883	.0101732					
	00309	133040	130514	132781	.0101737					
	00320	151791	146175	151471	.0101539					
	00352	135227	132541	134845	.0101738	$\frac{76.60}{27.500}$	10.160			
	00356	134020	131820	132664	.0101414					
RRS	10340	115569	151785	115229	.0076165			.0076165	.077406	
100	10328	135737	177746	135459	.0076209	$\frac{26.1}{27.500}$	10.162			
	10337	119866	157022	119529	.0076122					
12	10330	14121	133189	.00791	.000095	$\frac{26.5}{27.500}$	10.162	.000095	.000097	
	May 15 = 135 TH day									
	$\frac{N}{N_0} = e^{-\frac{E_0}{T}}$									
	91 365 456 amp									
BS	.000097									
RRS 100	.077488	.027391								
Kr 85	103245	103148	Ratio $\frac{Kr 85}{RRS 100} = 1.33282$ 1.33275							

COMPUTATION SHEET

DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

TEST NO.

3-1

DATE March 1, 1960

[illegible]

TABLE 1

LISTING OF KRYPTON HALF-LIFE DETERMINATION DATA

***** X(V,I,J,K) *****												
DET	F	DAY	VJ	C	K=1	K=2	K=3	K=4	K=5	K=6	TEMP	PRESS
4	1	958	11	5	323.140	.	.	.	.	.	28.580	29.700
4	1	958	12	5	340.462	.	.	.	.	.	28.195	29.695
4	1	958	21		176.054	176.155	175.829	.	.	.	28.539	29.699
4	1	958	22		175.758	176.016	175.763	.	.	.	28.300	29.695
4	1	959	31		141.813	141.780	141.832	141.763	141.777	141.781	28.470	29.695
5	1	942	11	5	414.150	.	.	.	.	.	23.810	29.100
5	1	942	12	5	335.198	.	.	.	.	.	23.934	29.119
5	1	942	21		88.564	88.916	89.007	.	.	.	23.835	29.100
5	1	942	22		88.875	89.916	89.505	.	.	.	23.904	29.117
5	1	942	31		72.805	72.811	72.781	72.681	72.647	72.647	23.855	29.102
6	1	1000	11	5	336.400	.	.	.	.	.	26.780	29.963
6	1	1000	12	5	378.000	.	.	.	.	.	26.580	29.955
6	1	1000	21		129.699	129.730	129.813	.	.	.	26.740	29.960
6	1	1000	22		129.601	129.738	129.629	.	.	.	26.620	29.955
6	1	1000	31		107.259	107.153	107.237	107.317	.	.	26.690	29.958
7	1	1055	11	5	220.384	.	.	.	.	.	23.960	29.868
7	1	1055	12	5	197.503	.	.	.	.	.	24.075	29.870
7	1	1055	21		89.740	89.604	89.642	.	.	.	23.980	29.870
7	1	1055	22		89.761	89.710	89.763	.	.	.	24.048	29.871
7	1	1055	31		75.002	74.955	74.855	74.953	75.007	75.080	24.005	29.872
8	1	1111	11	5	187.683	.	.	.	.	.	24.910	29.657
8	1	1111	12	5	188.867	.	.	.	.	.	24.980	29.684
8	1	1111	21		90.585	90.532	90.613	.	.	.	24.940	29.663
8	1	1111	22		90.559	90.603	90.638	.	.	.	24.985	29.678
8	1	1111	31		76.528	76.520	76.583	76.398	76.424	76.538	24.970	29.670
9	1	1174	11	5	607.400	.	.	.	.	.	23.760	29.451
9	1	1174	12	2	170.200	.	.	.	.	.	23.680	29.456
9	1	1174	21		135.466	135.617	135.485	.	.	.	23.740	29.453
9	1	1174	22		135.299	135.275	135.305	.	.	.	23.710	29.455
9	1	1174	31		115.335	115.252	115.314	115.329	.	.	23.720	29.454
10	1	1230	11	5	283.469	.	.	.	.	.	21.900	29.717
10	1	1230	12	5	236.460	.	.	.	.	.	21.995	29.714
10	1	1230	21		88.593	88.720	89.684	.	.	.	21.920	29.715
10	1	1230	22		88.721	88.811	88.668	.	.	.	21.983	29.715
10	1	1230	31		76.611	76.465	76.421	76.582	76.574	76.588	21.945	29.715

11	1	1287	11	5	142.201	.	.	.	.	.	20.750	29.793
11	1	1287	12	5	206.078	.	.	.	.	.	20.790	29.802
11	1	1287	21		87.518	87.457	87.486	.	.	.	20.755	29.795
11	1	1287	22		87.450	87.439	87.350	87.339	.	.	20.780	29.801
11	1	1287	31		76.141	76.073	76.136	76.095	76.149	.	20.765	29.799
12	1	1351	11	5	330.400	.	.	.	.	.	25.320	29.721
12	1	1351	12	5	408.600	.	.	.	.	.	25.180	29.730
12	1	1351	21		133.735	133.435	133.634	.	.	.	25.290	29.722
12	1	1351	22		133.523	133.355	133.398	.	.	.	25.210	29.728
12	1	1351	31		117.415	117.547	117.497	117.406	117.472	.	25.247	29.724
13	1	1407	11	3	323.543	.	.	.	.	.	24.790	29.716
13	1	1407	12	3	315.485	.	.	.	.	.	24.950	29.706
13	1	1407	21		134.345	134.542	134.275	.	.	.	24.820	29.716
13	1	1407	22		134.510	134.417	134.489	.	.	.	24.920	29.707
13	1	1407	31		119.382	119.529	119.410	119.379	119.475	.	24.870	29.714
14	1	1471	11	3	290.472	.	.	.	.	.	26.560	29.765
14	1	1471	12	3	294.775	.	.	.	.	.	26.775	29.785
14	1	1471	21		135.795	135.890	135.813	135.822	.	.	26.615	29.770
14	1	1471	22		135.714	135.634	135.725	.	.	.	26.723	29.783
14	1	1471	31		122.157	122.088	121.988	122.349	122.113	121.943	26.665	29.770
15	1	1527	11	2	321.360	.	.	.	.	.	25.930	29.620
15	1	1527	12	2	355.466	.	.	.	.	.	26.030	29.645
15	1	1527	21		135.936	135.156	136.059	136.118	136.057	.	25.980	29.625
15	1	1527	22		135.802	135.570	135.732	135.771	.	.	26.045	29.643
15	1	1527	31		123.409	123.344	123.271	123.301	123.442	123.231	26.030	29.635
16	1	1583	11	5	246.028	.	.	.	.	.	21.690	29.550
16	1	1583	12	5	271.243	.	.	.	.	.	21.865	29.545
16	1	1583	21		89.157	89.344	89.231	.	.	.	21.720	29.549
16	1	1583	22		89.366	89.276	89.313	.	.	.	21.830	29.545
16	1	1583	31		81.749	81.717	81.876	81.819	81.890	.	21.760	29.549
17	1	1646	11	4	175.220	.	.	.	.	.	22.610	29.492
17	1	1646	12	4	187.177	.	.	.	.	.	22.785	29.490
17	1	1646	21		88.996	88.993	89.229	89.079	.	.	22.635	29.492
17	1	1646	22		88.973	89.149	89.124	.	.	.	22.750	29.491
17	1	1646	31		82.463	82.515	82.488	82.533	82.436	82.579	22.675	29.492
18	1	1744	11	1	290.219	.	.	.	.	.	23.850	30.005
18	1	1744	12	3	206.640	.	.	.	.	.	24.575	29.955
18	1	1744	21		88.159	87.952	88.176	.	.	.	23.850	30.008
18	1	1744	22		88.146	88.362	88.378	.	.	.	23.888	30.003
18	1	1744	31		83.118	83.315	83.262	83.378	83.423	83.402	23.855	30.005
18	1	1744	32		83.487	.	.	.	.	.	23.855	30.005

19	1	1904	11	3	276.054	.	.	.	.	.	26.940	29.745
19	1	1904	12	5	554.153	.	.	.	.	.	26.995	29.738
19	1	1904	21		91.491	91.350	91.272	91.341	.	.	26.960	29.745
19	1	1904	22		91.082	91.163	91.327	.	.	.	26.980	29.740
19	1	1904	31		88.392	88.478	88.532	88.377	88.375	.	26.980	29.740
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20	5	1959	11	5	248.893	.	.	.	.	.	30.070	29.715
20	5	1959	12	5	269.674	.	.	.	.	.	30.210	29.708
20	5	1959	21		91.448	91.334	91.257	91.395	.	.	30.035	29.715
20	5	1959	22		91.378	91.272	91.434	91.423	.	.	30.165	29.709
20	5	1959	31		89.328	89.096	89.115	89.174	89.219	89.312	30.100	29.715
20	5	1959	32		89.304	.	.	.	.	.	30.100	29.715
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21	5	2045	11	5	195.395	.	.	.	.	.	25.830	29.525
21	5	2045	12	5	191.833	.	.	.	.	.	25.770	29.512
21	5	2045	21		89.923	89.927	89.916	.	.	.	25.850	29.525
21	5	2045	22		89.956	89.017	89.773	89.845	.	.	25.785	29.518
21	5	2045	31		89.370	89.574	89.350	89.291	89.341	.	25.810	29.523
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22	1	2119	11	5	281.456	.	.	.	.	.	26.120	29.430
22	1	2119	12	5	258.890	.	.	.	.	.	26.360	29.427
22	1	2119	21		91.024	91.032	91.007	.	.	.	26.147	29.444
22	1	2119	22		91.039	91.027	91.053	.	.	.	26.323	29.429
22	1	2119	31		91.500	91.536	91.572	91.441	91.550	91.574	26.233	29.440
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23	1	2241	11	5	243.311	.	.	.	.	.	28.170	29.390
23	1	2241	12	5	242.603	.	.	.	.	.	28.040	29.385
23	1	2241	21		92.003	92.741	92.716	92.764	.	.	28.170	29.390
23	1	2241	22		92.799	92.596	92.700	.	.	.	28.040	29.385
23	1	2241	31		95.265	95.423	95.257	95.067	95.290	95.264	28.090	29.385
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24	1	2308	11	4	155.446	.	.	.	.	.	25.640	29.552
24	1	2308	12	4	149.314	.	.	.	.	.	25.800	29.550
24	1	2308	21		90.681	90.756	90.629	.	.	.	25.660	29.552
24	1	2308	22		90.715	90.677	90.718	.	.	.	25.770	29.545
24	1	2308	31		94.324	94.374	94.425	.	.	.	25.715	29.548
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25	1	2366	11	2	106.011	.	.	.	.	.	26.740	29.717
25	1	2366	12	2	117.025	.	.	.	.	.	26.800	29.708
25	1	2366	21		90.312	90.265	90.244	.	.	.	26.750	29.715
25	1	2366	22		90.367	90.389	90.429	.	.	.	26.790	29.709
25	1	2366	31		94.827	94.702	94.688	94.668	.	.	26.770	29.715
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26	1	2423	11	3	187.894	.	.	.	.	.	27.960	29.585
26	1	2423	12	3	220.296	.	.	.	.	.	27.890	29.580
26	1	2423	21		90.852	90.680	90.738	.	.	.	27.960	29.585
26	1	2423	22		90.914	90.771	90.669	.	.	.	27.900	29.580
26	1	2423	31		96.389	96.370	96.505	96.376	96.439	.	27.930	29.580

27	1	2489	11	2	248.606	.	.	.	.	.	.	22.040	29.850
27	1	2489	12	3	211.295	.	.	.	.	.	.	22.860	29.840
27	1	2489	21		89.134	89.123	89.085	.	.	.	.	22.040	29.850
27	1	2489	22		89.208	89.213	89.055	89.139	.	.	.	22.860	29.840
27	1	2489	31		95.755	95.994	95.780	95.721	95.968	95.933	.	22.540	29.840
28	2	2647	11	7	730.236	.	.	.	.	.	.	24.940	29.725
28	2	2647	12	6	528.439	.	.	.	.	.	.	24.960	29.720
28	2	2647	21		67.878	67.667	67.959	68.076	.	.	.	24.920	29.735
28	2	2647	22		67.801	67.768	67.835	67.782	.	.	.	24.970	29.720
28	2	2647	31		75.167	74.819	74.819	74.765	75.227	74.849	.	24.950	29.723
29	1	2805	11	5	179.427	.	.	.	.	.	.	27.730	29.975
29	1	2805	12	5	181.432	.	.	.	.	.	.	27.750	29.960
29	1	2805	21		61.549	61.503	61.479	.	.	.	.	27.740	29.970
29	1	2805	22		61.723	61.700	61.525	.	.	.	.	27.750	29.960
29	1	2805	31		69.995	70.106	70.003	69.844	69.874	70.013	.	27.740	29.965
30	1	3121	11	5	212.234	.	.	.	.	.	.	26.430	29.595
30	1	3121	12	6	452.457	.	.	.	.	.	.	26.580	29.570
30	1	3121	21		69.698	69.660	69.805	69.711	.	.	.	26.450	29.590
30	1	3121	22		69.910	69.853	69.850	69.769	.	.	.	26.540	29.575
30	1	3121	31		83.412	83.476	83.668	83.669	83.695	83.688	.	26.550	29.580
31	2	3182	11	5	145.262	.	.	.	.	.	.	26.160	29.500
31	2	3182	12	5	199.253	.	.	.	.	.	.	26.200	29.490
31	2	3182	21		62.335	62.216	62.479	62.360	.	.	.	26.140	29.500
31	2	3182	22		62.604	62.489	62.590	62.597	.	.	.	26.230	29.485
31	2	3182	31		75.476	75.691	75.582	75.693	75.715	75.601	.	26.180	29.495
32	1	3295	11	8	751.804	.	.	.	.	.	.	23.650	29.410
32	1	3295	12	8	763.500	.	.	.	.	.	.	23.660	29.440
32	1	3295	21		21.299	21.191	21.208	21.287	21.211	.	.	23.660	29.420
32	1	3295	22		21.140	21.147	21.175	21.211	21.178	.	.	23.660	29.440
32	1	3295	31		26.250	26.211	26.285	26.242	26.261	26.180	.	23.660	29.440
32	1	3295	32		26.265	26.251	.	.	.	.	.	23.660	29.440
33	1	3366	11	6	231.729	.	.	.	.	.	.	23.040	29.790
33	1	3366	12	6	372.625	.	.	.	.	.	.	23.160	29.790
33	1	3366	21		49.019	48.995	49.021	49.014	49.922	.	.	23.060	29.790
33	1	3366	22		48.973	48.918	49.087	49.002	49.034	.	.	23.140	29.790
33	1	3366	31		61.344	61.371	61.320	61.485	61.423	61.359	.	23.110	29.790
33	1	3366	32		61.483	61.271	.	.	.	.	.	23.110	29.790
34	2	3464	11	6	306.174	.	.	.	.	.	.	23.580	29.470
34	2	3464	12	6	347.122	.	.	.	.	.	.	23.620	29.460
34	2	3464	21		49.509	49.600	49.530	49.558	49.526	.	.	23.560	29.475
34	2	3464	22		49.532	49.543	49.619	49.664	49.623	.	.	23.640	29.455

34	2	3464	31	63.336	63.368	63.252	63.433	63.353	63.401	23.620	29.460
34	2	3464	32	63.364	63.287	63.300	63.200	.	.	23.620	29.460
P	35	1	3464	11	6	326.073	.	.	.	26.650	29.450
P	35	1	3464	12	6	296.023	.	.	.	26.700	29.440
P	35	1	3464	21		49.546	49.498	49.577	49.562	49.513	26.655
P	35	1	3464	22		49.558	49.569	49.544	49.605	49.506	26.690
P	35	1	3464	31		63.060	62.973	63.026	63.026	62.994	63.042
P	35	1	3464	32		63.045	63.115	63.046	63.080	.	.
P	36	1	3585	11	10	327.713	.	.	.	.	23.420
P	36	1	3585	12	10	371.150	.	.	.	.	23.430
P	36	1	3585	21		16.695	16.688	16.678	16.699	16.683	23.420
P	36	1	3585	22		16.705	16.696	16.731	16.652	16.643	23.425
P	36	1	3585	31		21.730	21.728	21.709	21.801	21.729	21.715
P	36	1	3585	32		21.708	21.705	21.695	.	.	23.420
P	37	1	3595	11	6	342.744	.	.	.	.	23.460
P	37	1	3595	12	6	334.969	.	.	.	.	23.490
P	37	1	3595	21		50.275	50.148	50.208	50.241	50.224	23.460
P	37	1	3595	22		50.216	50.183	50.346	50.298	50.327	23.790
P	37	1	3595	31		65.679	65.657	65.647	65.655	65.642	65.753
P	37	1	3595	32		65.522	65.569	.	.	.	23.480
P	38	1	3687	11	9	338.696	603.397	457.115	601.927	.	23.455
P	38	1	3687	12	9	659.074	.	.	.	.	23.460
P	38	1	3687	21		20.440	20.465	20.482	20.450	20.451	23.460
P	38	1	3687	22		20.478	20.445	20.473	20.448	20.466	23.460
P	38	1	3687	31		27.148	27.187	27.143	27.140	27.175	27.255
P	38	1	3687	32		27.255	27.168	27.108	27.081	.	23.460
P	39	1	3688	11	9	531.640	.	.	.	.	23.040
P	39	1	3688	12	9	502.596	.	.	.	.	23.100
P	39	1	3688	21		20.623	20.644	20.615	20.528	20.588	23.070
P	39	1	3688	22		20.558	20.535	20.554	20.521	20.556	23.100
P	39	1	3688	31		27.327	27.362	27.291	27.305	27.328	27.394
P	39	1	3688	32		27.252	27.270	27.247	27.349	.	23.090
P	40	1	3800	11	6	670.172	.	.	.	.	23.310
P	40	1	3800	12	11	192.777	.	.	.	.	23.390
P	40	1	3800	21		39.547	39.606	39.541	39.624	39.658	23.330
P	40	1	3800	22		39.530	39.629	39.562	39.659	39.701	23.390
P	40	1	3800	31		53.579	53.623	53.653	53.690	53.556	53.704
P	40	1	3800	32		53.486	53.639	53.545	53.588	.	23.370
P	41	2	3857	11	9	413.456	.	.	.	.	23.530
P	41	2	3857	12	9	356.651	.	.	.	.	23.550
P	41	2	3857	21		20.469	20.515	20.532	20.467	20.518	23.520
P	41	2	3857	22		20.600	20.515	20.431	20.485	20.533	23.520

P 41	2	3857	31	28.000	28.050	28.000	27.966	27.964	28.065	23.540	29.765
P 41	2	3857	32	27.982	28.166	27.969	28.018	.	.	23.540	29.765
42	1	3934	1112	891.337	.	.	.	.	.	23.440	29.830
42	1	3934	1212	787.268	.	.	.	.	.	23.500	29.805
42	1	3934	21	20.613	20.614	20.597	20.552	20.637	.	23.460	29.825
42	1	3934	22	20.528	20.600	20.614	20.661	20.613	.	23.500	29.805
42	1	3934	31	28.716	28.586	28.548	28.603	28.657	28.633	23.480	29.825
42	1	3934	32	28.665	28.619	28.700	28.684	.	.	23.480	29.825
P 43	2	3934	1112	702.213	.	.	.	.	.	23.380	29.680
P 43	2	3934	1212	909.792	.	.	.	.	.	23.410	29.670
P 43	2	3934	21	20.698	20.700	20.635	20.700	20.688	.	23.360	29.680
P 43	2	3934	22	20.577	20.680	20.702	20.732	20.748	.	23.410	29.671
P 43	2	3934	31	28.596	28.716	28.616	28.618	28.583	28.665	23.390	29.675
P 43	2	3934	32	28.648	28.678	28.611	28.674	.	.	23.390	29.675
44	6	4036	11 9	419.275	355.461	.	.	.	.	23.590	29.518
44	6	4036	12 9	399.753	314.298	.	.	.	.	23.630	29.520
44	6	4036	21	20.833	20.848	20.880	20.885	20.835	.	23.600	29.520
44	6	4036	22	20.832	20.875	20.850	20.864	20.897	.	23.620	29.520
44	6	4036	31	29.413	29.433	29.433	29.445	29.434	29.450	23.610	29.520
44	6	4036	32	29.380	29.500	29.419	29.417	.	.	23.610	29.520
P 45	1	4151	11 6	406.282	.	.	.	.	.	23.370	29.800
P 45	1	4151	12 6	393.950	.	.	.	.	.	23.560	29.785
P 45	1	4151	21	40.748	40.786	40.852	40.799	40.834	.	23.435	29.795
P 45	1	4151	22	40.882	40.789	40.868	40.885	40.900	.	23.543	29.785
P 45	1	4151	31	58.663	58.850	58.703	58.777	58.761	58.752	23.530	29.785
P 45	1	4151	32	58.703	58.819	58.688	58.724	.	.	23.530	29.785
46	1	4152	1111	570.882	.	.	.	.	.	23.410	29.800
46	1	4152	1211	483.843	363.950	.	.	.	.	23.648	29.800
46	1	4152	21	13.879	13.866	13.919	13.893	13.836	.	23.450	29.800
46	1	4152	22	13.886	13.895	13.886	13.888	13.885	.	23.560	29.800
46	1	4152	31	19.991	20.034	19.938	19.990	19.982	19.983	23.515	29.800
46	1	4152	32	20.100	19.936	20.016	.	.	.	23.515	29.800
P 47	1	4256	11 9	212.542	.	.	.	.	.	23.340	29.870
P 47	1	4256	12 9	264.339	.	.	.	.	.	23.370	29.860
P 47	1	4256	21	20.445	20.577	20.464	20.516	20.455	.	23.345	29.866
P 47	1	4256	22	20.418	20.398	20.437	20.415	20.450	.	23.360	29.860
P 47	1	4256	31	30.054	29.949	29.967	29.949	30.030	29.949	23.350	29.865
P 47	1	4256	32	30.027	29.983	29.937	29.901	.	.	23.350	29.865
P 48	2	4312	11 9	468.190	.	.	.	.	.	23.500	29.460
P 48	2	4312	12 9	405.119	.	.	.	.	.	23.540	29.465
P 48	2	4312	21	20.683	20.685	20.663	20.705	20.660	.	23.500	29.450
P 48	2	4312	22	20.659	20.702	20.643	20.618	20.690	.	23.600	29.470

TABLE 2

LISTING OF DATA SUMMARY FOR REGRESSION ANALYSIS

GLASS SAMPLE HOLDER

DET	DAY	H	PF	E	R1	R2	R3	
2	744.			10.15984	1.332516	1.332930	1.332832	DET 2
2	747.			9.90907	1.262965	1.263414	1.263393	DET 3
4	858.	.150795E-04	.153119E-03	10.15512	1.240764	1.241404	1.241696KR	SET 1
5	942.	.125266E-04	.127821E-03	10.20447	1.222771	1.223019	1.223233KR	SET 1
6	1000.	.130827E-04	.130244E-03	10.00848	1.200435	1.200791	1.200811KR	SET 1
7	1055.	.240010E-04	.238205E-03	9.94893	1.196435	1.196659	1.196762KR	SET 1
8	1111.	.265572E-04	.266825E-03	10.04762	1.184184	1.184629	1.184678KR	SET 1
9	1174.	.999134E-05	.100705E-03	10.07958	1.174319	1.174556	1.174535KR	SET 1
10	1220.	.193910E-04	.192587E-03	9.93123	1.158862	1.159136	1.159110KR	SET 1
11	1287.	.257997E-04	.254496E-03	9.86402	1.148505	1.148840	1.148875KR	SET 1
12	1341.	.136320E-04	.137358E-03	10.03900	1.136686	1.136936	1.136962KR	SET 1
13	1407.	.928178E-05	.941038E-04	10.03070	1.125547	1.125705	1.125610KR	SET 1
14	1471.	.102524E-04	.103242E-03	10.06991	1.111903	1.112059	1.112206KR	SET 1
15	1527.	.154819E-05	.963804E-04	10.09540	1.101086	1.101218	1.101179KR	SET 1
16	1593.	.193783E-04	.193427E-03	9.98162	1.091221	1.091479	1.091349KR	SET 1
17	1646.	.220587E-04	.221695E-03	10.03177	1.079698	1.079855	1.079779KR	SET 1
18	1744.	.892184E-05	.892040E-04	9.90568	1.058252	1.058298	1.058265KR	SET 1
19	1804.	.992889E-05	.100192E-03	10.09129	1.032326	1.032355	1.032336KR	SET 1
20	1853.	.193149E-04	.197167E-03	10.20581	1.024058	1.024101	1.023997KR	SET 1
21	2044.	.258269E-04	.261571E-03	10.12747	1.005950	1.005864	1.005807KR	SET 1
22	2112.	.185290E-04	.188616E-03	10.17180	.994554	.994544	.994419KR	SET 1
23	2241.	.205709E-04	.210973E-03	10.25154	.973744	.973694	.973647KR	SET 1
24	2304.	.252608E-04	.265604E-03	10.11449	.961024	.960931	.960947KR	SET 1
25	2366.	.185218E-04	.186966E-03	10.09430	.953686	.953608	.953512KR	SET 1
26	2432.	.147922E-04	.150553E-03	10.17808	.941485	.941406	.941486KR	SET 1
27	2482.	.111215E-04	.110204E-03	9.90578	.929878	.929808	.930218KR	SET 1
28	2556.	.153220E-04	.195702E-03	10.29106	.923379	.923243	.923278	OUT 28
29	2647.	.231429E-04	.232112E-03	10.02900	.905155	.905006	.905158KR	SET 1
30	2805.	.277125E-04	.278208E-03	10.04145	.880058	.879853	.879837KR	SET 1
30	3121.	.228302E-04	.221261E-03	10.12015	.834700	.834436	.834659KR	SET 1
31	3182.	.178543E-04	.181194E-03	10.14925	.825903	.825708	.825622KR	SET 1
32	3225.	.439982E-03	.443819E-02	10.08500	.807971	.806163	.805884KR	SET 1
33	3366.	.348552E-04	.348009E-03	9.94506	.798255	.797909	.797936KR	SET 1
34	3464.	.311620E-04	.313848E-03	10.07241	.792739	.782403	.782580KR	SET 1
37	3700.	.255149E-04	.255706E-03	10.01559	.765492	.765133	.764242KR	SET 1
39	3680.	.193532E-03	.193212E-02	9.98483	.753216	.752229	.752368KR	SET 1
40	3800.	.161063E-04	.160949E-03	9.99337	.738821	.738655	.738742KR	SET 1
42	4034.	.398685E-04	.396635E-03	9.94785	.719712	.719481	.719220KR	SET 1
44	4034.	.269122E-03	.270563E-02	10.05330	.708739	.707095	.707095KR	SET 1
45	4152.	.685123E-05	.682149E-04	9.95558	.694281	.694252	.694275KR	SET 1

 PLASTIC SAMPLE HOLDER

 35 3464. .322246F-04 .228143F-03 10.18193 .785965 .785623 .785550KR SET 1
 36 3583. .781306F-04 .781307F-03 10.00655 .768121 .757610 .767786KR SET 1
 39 3637. .175807F-03 .175806F-02 9.95717 .753140 .752249 .752274KR SET 1
 41 3957. .261125F-03 .260295F-02 9.96758 .732061 .720519 .720720KR SET 1
 42 3954. .420537F-04 .420240F-03 9.98320 .722739 .722498 .722522KR SET 1
 45 4151. .249983F-04 .248858E-03 9.95848 .695099 .694788 .695000KR SET 1
 47 4254. .424399F-03 .421355E-02 9.92865 .682394 .679612 .679559KR SET 1
 49 4312. .230215F-03 .231820F-02 10.07066 .677271 .675728 .675660KR SET 1
 49 4534. .229630F-04 .231901F-03 10.09870 .650091 .649761 .649861KR SET 1
 50 4820. .209784E-04 .212441E-03 10.12766 .619400 .619071 .619098KR SET 1
 51 5440. .196767F-04 .201182F-03 10.07074 .555130 .554735 .554707KR SET 1

REMOVED DETERMINATIONS

1 0. 10.15852 1.436236 1.436452 1.438178 DET 1
 29 3657. .314262-03 .313333-02 9.97343 .722698 .720813 .720813 OUT 39

TABLE 3
INDIVIDUAL HALF-LIFE DETERMINATIONS WITH SUMMARY STATISTICS

DET	DAY	P1	P2	P3	H	HE	E	K(.5)1	K(.5)2	K(.5)3
4	850.	1.240764	1.241404	1.241596	.150795E-04	.153119E-03	10.15519	11.054	10.797	10.813
5	942.	1.222771	1.223019	1.223233	.125266E-04	.127821E-03	10.20447	11.034	10.781	10.791
6	1000.	1.209435	1.209791	1.209811	.130437E-04	.130946E-03	10.00868	10.967	10.736	10.736
7	1055.	1.196435	1.196859	1.196752	.240019E-04	.238305E-03	9.94883	10.886	10.674	10.668
8	1111.	1.184184	1.184629	1.184679	.265272E-04	.266825E-03	10.04762	10.853	10.653	10.655
9	1174.	1.174319	1.174556	1.174535	.999134E-05	.100705E-03	10.07958	10.991	10.788	10.786
10	1230.	1.158802	1.159136	1.159110	.193719E-04	.192587E-03	9.93123	10.805	10.620	10.618
11	1257.	1.149505	1.148840	1.148875	.257997E-04	.254496E-03	9.86402	10.852	10.675	10.676
12	1351.	1.136606	1.136936	1.136962	.136220E-04	.137358E-03	10.03900	10.887	10.715	10.715
13	1407.	1.125547	1.125705	1.125610	.938178E-05	.941088E-04	10.03070	10.880	10.711	10.707
14	1471.	1.111903	1.112059	1.112205	.102526E-04	.103242E-03	10.06991	10.834	10.673	10.678
15	1527.	1.101086	1.101218	1.101179	.954619E-05	.963304E-04	10.09540	10.832	10.677	10.675
16	1543.	1.091321	1.091479	1.091349	.193783E-04	.193427E-03	9.98162	10.865	10.715	10.710
17	1646.	1.079696	1.079855	1.079779	.220987E-04	.221695E-03	10.03177	10.874	10.729	10.726
18	1744.	1.058252	1.058293	1.058265	.898134E-05	.892040E-04	9.90568	10.765	10.623	10.626
19	1804.	1.032326	1.032355	1.032336	.992649E-05	.100192E-03	10.09129	10.869	10.740	10.739
20	1850.	1.024056	1.024101	1.023997	.193149E-04	.197167E-03	10.20681	10.917	10.791	10.787
21	2045.	1.005850	1.005864	1.005807	.258268E-04	.261571E-03	10.12747	10.823	10.703	10.701
22	2119.	.994554	.994544	.994419	.185390E-04	.183616E-03	10.17180	10.869	10.752	10.748
23	2241.	.973744	.973674	.973647	.205798E-04	.210973E-03	10.25154	10.870	10.758	10.756
24	2308.	.961024	.960931	.960947	.262008E-04	.265004E-03	10.11449	10.829	10.720	10.720
25	2356.	.953696	.953608	.953512	.185218E-04	.186966E-03	10.09430	10.892	10.785	10.782
26	2423.	.941405	.941406	.941406	.147922E-04	.150553E-03	10.17808	10.815	10.712	10.714
27	2459.	.929472	.929308	.930218	.111415E-04	.110204E-03	9.90578	10.793	10.693	10.703
28	2647.	.905105	.905006	.905158	.231429E-04	.232113E-03	10.02900	10.808	10.712	10.715
29	2805.	.889058	.879853	.879837	.277125E-04	.278258E-03	10.04145	10.796	10.704	10.703
30	3121.	.834706	.834436	.834059	.228302E-04	.231261E-03	10.13015	10.840	10.755	10.760
31	3182.	.825995	.825708	.825622	.178543E-04	.181194E-03	10.14925	10.841	10.759	10.756
32	3295.	.807971	.806163	.805884	.439782E-03	.443819E-02	10.08500	10.799	10.682	10.676
33	3366.	.795255	.797909	.797936	.349952E-04	.348009E-03	9.94506	10.803	10.722	10.723
34	3464.	.782739	.782403	.782509	.311920E-04	.313840E-03	10.07241	10.758	10.681	10.685
P 35	3464.	.785965	.785623	.785550	.322246E-04	.328143E-03	10.10193	10.831	10.752	10.751
P 36	3585.	.768121	.767818	.767786	.781306E-04	.781857E-03	10.00655	10.799	10.723	10.722
37	3595.	.765482	.765133	.764242	.295149E-04	.295706E-03	10.01559	10.770	10.694	10.674
P 38	3607.	.753140	.752249	.752274	.175607E-03	.175036E-02	9.95717	10.767	10.682	10.682
39	3648.	.753216	.752220	.752368	.193532E-03	.193212E-02	9.98483	10.772	10.684	10.687
40	3680.	.738621	.738655	.738742	.161063E-04	.160949E-03	9.99337	10.777	10.709	10.710
P 41	3857.	.732001	.730619	.730730	.261125E-03	.260295E-02	9.96758	10.789	10.695	10.697
42	3834.	.719712	.719481	.719239	.394688E-04	.396635E-03	9.94785	10.734	10.667	10.662
P 43	3934.	.722739	.722498	.722522	.420537E-04	.420249E-03	9.99320	10.799	10.731	10.732
44	4036.	.708739	.707095	.707095	.269122E-03	.270563E-02	10.05330	10.772	10.677	10.677
P 45	4151.	.695499	.694788	.695090	.249787E-04	.248898E-03	9.95848	10.782	10.717	10.721
46	4152.	.694201	.694202	.694275	.685120E-05	.682140E-04	9.95558	10.769	10.708	10.709
P 47	4256.	.682394	.679612	.679559	.424399E-03	.421355E-02	9.92865	10.781	10.666	10.665
P 48	4312.	.677271	.675728	.675660	.230215E-03	.231820E-02	10.07066	10.813	10.724	10.722
P 49	4536.	.650091	.649761	.649861	.229030E-04	.231901E-03	10.09870	10.787	10.727	10.728
P 50	4820.	.619400	.619071	.619098	.207784E-04	.212441E-03	10.12766	10.804	10.746	10.746
P 51	5440.	.555130	.554735	.554707	.199767E-04	.201162E-03	10.07074	10.788	10.735	10.734

AVE .9148504E+00 .9146026E+00 .9146003E+00 .6021273E-04 .6034257E-03 .1004791E+02 .1033402E+02 .1071417E+02 .1071390E+02

SD .1936440E+00 .1407877E+00 .1949966E+00 .1018272E-03 .1019250E-02 .9037908E-01 .6892393E-01 .4067414E-01 .4194626E-01

C-V .2116684E+02 .2122000E+02 .2122201E+02 .1691159E+03 .1689106E+03 .8994818E+00 .6361808E+00 .3796294E+00 .3915125E+00

TABLE 4
WITHIN RUN AVERAGES, STANDARD DEVIATIONS AND COEFFICIENTS OF VARIATION

DET NO.	RUN	BACKGROUND				RADIUM				KRYPTON			
		AVE	SD	CV-PCT	N	AVE	SD	CV-PCT	N	AVE	SD	CV-PCT	N
4	1	323.1400	0.0000	0.0000	1	176.0127	.1609	.0948	3	141.7910	.0259	.0183	6
4	2	340.4620	0.0000	0.0000	1	175.8457	.1475	.0839	3	141.7910	.0259	.0183	6
5	1	414.1500	0.0000	0.0000	1	88.9623	.0455	.0512	3	72.7287	.0787	.1082	6
5	2	385.1980	0.0000	0.0000	1	88.8437	.0212	.0239	3	72.7287	.0787	.1082	6
6	1	386.4000	0.0000	0.0000	1	129.7473	.0539	.0454	3	107.2415	.0680	.0634	4
6	2	378.0000	0.0000	0.0000	1	129.6560	.0724	.0558	3	107.2415	.0680	.0634	4
7	1	220.3440	0.0000	0.0000	1	89.6620	.0702	.0783	3	74.9755	.0750	.1000	6
7	2	197.5030	0.0000	0.0000	1	89.7447	.0390	.0335	3	74.9755	.0750	.1000	6
8	1	187.6030	0.0000	0.0000	1	90.5767	.0411	.0454	3	76.4985	.0717	.0937	6
8	2	186.8670	0.0000	0.0000	1	90.6000	.0396	.0437	3	76.4985	.0717	.0937	6
9	1	607.4000	0.0000	0.0000	1	135.5227	.0822	.0607	3	115.3075	.0380	.0330	4
9	2	170.2000	0.0000	0.0000	1	135.2930	.0159	.0117	3	115.3075	.0380	.0330	4
10	1	243.4600	0.0000	0.0000	1	88.6657	.0655	.0738	3	76.5402	.0775	.1013	6
10	2	236.4600	0.0000	0.0000	1	88.7333	.0723	.0815	3	76.5402	.0775	.1013	6
11	1	182.2010	0.0000	0.0000	1	87.4847	.0340	.0389	3	76.1288	.0463	.0609	5
11	2	206.9780	0.0000	0.0000	1	87.3965	.0609	.0696	4	76.1288	.0463	.0609	5
12	1	330.4000	0.0000	0.0000	1	133.6213	.1403	.1350	3	117.4674	.0586	.0499	5
12	2	468.8000	0.0000	0.0000	1	133.4257	.0869	.0651	3	117.4674	.0586	.0499	5
13	1	323.6430	0.0000	0.0000	1	134.3873	.1384	.1030	3	119.4350	.0652	.0546	5
13	2	315.9860	0.0000	0.0000	1	134.4720	.0488	.0363	3	119.4350	.0652	.0546	5
14	1	200.4720	0.0000	0.0000	1	135.8300	.0415	.0306	4	122.1063	.1432	.1173	6
14	2	224.7750	0.0000	0.0000	1	135.6910	.0497	.0366	3	122.1063	.1432	.1173	6
15	1	321.3600	0.0000	0.0000	1	135.8652	.4019	.2958	5	123.3328	.0811	.0658	6
15	2	155.3660	0.0000	0.0000	1	135.7138	.1032	.0761	4	123.3328	.0811	.0658	6
16	1	246.0240	0.0000	0.0000	1	89.2440	.0942	.1055	3	81.8102	.0762	.0931	5
16	2	271.2430	0.0000	0.0000	1	89.3133	.0452	.0506	3	81.8102	.0762	.0931	5
17	1	175.2240	0.0000	0.0000	1	89.0742	.1106	.1242	4	82.5023	.0512	.0621	6
17	2	187.1770	0.0000	0.0000	1	89.0820	.0952	.1069	3	82.5023	.0512	.0621	6
18	1	200.2190	0.0000	0.0000	1	88.0957	.1247	.1416	3	83.3407	.1223	.1468	7
18	2	200.6400	0.0000	0.0000	1	88.2953	.1296	.1468	3	83.3407	.1223	.1468	7
19	1	276.6540	0.0000	0.0000	1	91.3635	.0919	.1005	4	88.4308	.0707	.0799	5
19	2	350.1530	0.0000	0.0000	1	91.1907	.1243	.1369	3	88.4308	.0707	.0799	5
20	1	248.8030	0.0000	0.0000	1	91.3585	.0621	.0899	4	89.2211	.0963	.1080	7
20	2	269.6740	0.0000	0.0000	1	91.3767	.0739	.0809	4	89.2211	.0963	.1080	7
21	1	195.3950	0.0000	0.0000	1	89.9220	.0056	.0062	3	89.3852	.1095	.1225	5
21	2	191.8330	0.0000	0.0000	1	89.8977	.1095	.1218	4	89.3852	.1095	.1225	5
22	1	281.4560	0.0000	0.0000	1	91.0210	.0128	.0140	3	91.5288	.0509	.0556	6
22	2	258.0900	0.0000	0.0000	1	91.0397	.0130	.0143	3	91.5288	.0509	.0556	6
23	1	243.3110	0.0000	0.0000	1	92.8060	.1329	.1431	4	95.2610	.1138	.1195	6
23	2	242.0030	0.0000	0.0000	1	92.6983	.1015	.1095	3	95.2610	.1138	.1195	6

24	1	150.7460	0.0000	0.0000	1	90.6487	.0533	.0704	3	94.3743	.0505	.0535	3
24	2	149.3140	0.0000	0.0000	1	90.7033	.0225	.0252	3	94.3743	.0505	.0535	3
25	1	100.0110	0.0000	0.0000	1	90.2737	.0342	.0386	3	94.7212	.0719	.0759	4
25	2	110.0250	0.0000	0.0000	1	90.3950	.0314	.0348	3	94.7212	.0719	.0759	4
26	1	107.8940	0.0000	0.0000	1	90.7633	.0861	.0949	3	96.4158	.0568	.0589	5
26	2	220.2960	0.0000	0.0000	1	90.7847	.1231	.1356	3	96.4158	.0568	.0589	5
27	1	240.6060	0.0000	0.0000	1	84.1140	.0257	.0289	3	95.8585	.1197	.1249	6
27	2	211.2950	0.0000	0.0000	1	89.1537	.0740	.0830	4	95.8585	.1197	.1249	6
28	1	730.9360	0.0000	0.0000	1	67.3700	.1672	.2463	4	74.9410	.2010	.2683	6
28	2	528.4390	0.0000	0.0000	1	67.7965	.0290	.0428	4	74.9410	.2010	.2683	6
29	1	179.4270	0.0000	0.0000	1	61.5103	.0356	.0578	3	69.9725	.0971	.1387	6
29	2	181.4320	0.0000	0.0000	1	61.6493	.1083	.1157	3	69.9725	.0971	.1387	6
30	1	212.2340	0.0000	0.0000	1	69.7185	.0616	.0883	4	83.6013	.1240	.1483	6
30	2	452.4570	0.0000	0.0000	1	69.8455	.0580	.0830	4	83.6013	.1240	.1483	6
31	1	145.2620	0.0000	0.0000	1	62.3475	.1073	.1730	4	75.6263	.0913	.1207	6
31	2	199.2530	0.0000	0.0000	1	62.5725	.0493	.0788	4	75.6263	.0913	.1207	6
32	1	751.8040	0.0000	0.0000	1	21.2392	.0499	.2349	5	26.2444	.0336	.1282	8
32	2	763.5000	0.0000	0.0000	1	21.1702	.0283	.1336	5	26.2444	.0336	.1282	8
33	1	231.7290	0.0000	0.0000	1	48.9942	.0416	.0850	5	61.3820	.0763	.1243	8
33	2	372.6250	0.0000	0.0000	1	49.0028	.0635	.1296	5	61.3820	.0763	.1243	8
34	1	306.1740	0.0000	0.0000	1	49.5446	.0356	.0719	5	63.3294	.0704	.1111	10
34	2	337.1220	0.0000	0.0000	1	49.5962	.0565	.1140	5	63.3294	.0704	.1111	10
35	1	326.0730	0.0000	0.0000	1	49.5392	.0331	.0668	5	63.0407	.0404	.0641	10
35	2	226.0230	0.0000	0.0000	1	49.5564	.0361	.0729	5	63.0407	.0404	.0641	10
36	1	397.7130	0.0000	0.0000	1	16.6886	.0086	.0513	5	21.7244	.0312	.1434	9
36	2	371.1500	0.0000	0.0000	1	16.6954	.0370	.2220	5	21.7244	.0312	.1434	9
37	1	342.7440	0.0000	0.0000	1	50.2192	.0469	.0934	5	65.6405	.0695	.1059	8
37	2	334.9690	0.0000	0.0000	1	50.2740	.0711	.1414	5	65.6405	.0695	.1059	8
38	1	500.2833	127.7208	25.5297	4	20.4576	.0163	.0796	5	27.1660	.0563	.2071	10
38	2	659.0740	0.0000	0.0000	1	20.4620	.0148	.0724	5	27.1660	.0563	.2071	10
39	1	531.6400	0.0000	0.0000	1	20.5996	.0448	.2173	5	27.3125	.0485	.1775	10
39	2	502.5960	0.0000	0.0000	1	20.5448	.0162	.0787	5	27.3125	.0485	.1775	10
40	1	670.1720	0.0000	0.0000	1	39.5952	.0504	.1272	5	53.6066	.0677	.1262	10
40	2	192.7770	0.0000	0.0000	1	39.6162	.0699	.1765	5	53.6066	.0677	.1262	10
41	1	413.4560	0.0000	0.0000	1	20.5002	.0301	.1468	5	28.0120	.0478	.1707	10
41	2	356.6510	0.0000	0.0000	1	20.5128	.0622	.3033	5	28.0120	.0478	.1707	10
42	1	491.3370	0.0000	0.0000	1	20.6026	.0317	.1537	5	28.6405	.0530	.1851	10
42	2	797.2680	0.0000	0.0000	1	20.6232	.0233	.1132	5	28.6405	.0530	.1851	10
43	1	702.2130	0.0000	0.0000	1	20.6842	.0279	.1351	5	28.6355	.0403	.1409	10
43	2	909.7920	0.0000	0.0000	1	20.7078	.0315	.1519	5	28.6355	.0403	.1409	10
44	1	397.3645	45.1240	11.6489	2	20.8562	.0248	.1187	5	29.4324	.0309	.1049	10
44	2	357.0255	60.4254	16.9248	2	20.8636	.0246	.1181	5	29.4324	.0309	.1049	10
45	1	406.2820	0.0000	0.0000	1	40.8038	.0409	.1002	5	58.7460	.0625	.1063	10
45	2	393.9500	0.0000	0.0000	1	40.8648	.0439	.1074	5	58.7460	.0625	.1063	10

46	1	579.8920	0.0000	0.0000	1	13.8756	.0309	.2225	5	19.9967	.0501	.2503	9
46	2	423.8965	84.7772	19.9995	2	13.8980	.0041	.0292	5	19.9967	.0501	.2503	9
47	1	212.5420	0.0000	0.0000	1	20.4922	.0545	.2660	5	29.9796	.0480	.1601	10
47	2	264.3390	0.0000	0.0000	1	20.4236	.0202	.0991	5	29.9796	.0480	.1601	10
48	1	468.1900	0.0000	0.0000	1	20.6792	.0180	.0887	5	30.5207	.0470	.1539	10
48	2	405.1190	0.0000	0.0000	1	20.6624	.0342	.1657	5	30.5207	.0470	.1539	10
49	1	531.4235	73.2632	13.7749	2	40.9784	.0490	.1205	5	63.0218	.0390	.0619	10
49	2	368.8855	1.3675	.5062	2	40.9614	.0690	.2174	5	63.0218	.0390	.0619	10
50	1	484.2923	114.0008	23.5583	4	41.1834	.0493	.1197	5	66.4960	.1196	.1799	10
50	2	469.3043	143.6233	30.6034	3	41.1912	.0589	.1429	6	66.4960	.1196	.1799	10
51	1	512.5190	45.0202	8.7841	5	44.3274	.0469	.1057	5	79.8878	.0616	.0771	10
51	2	489.1912	27.2346	5.5673	5	44.3688	.0227	.0512	5	79.8878	.0616	.0771	10

TABLE 5

DETERMINATION AVERAGE COUNTING TIME, T/P FACTOR, BETWEEN RA RUN SD, WEIGHT, AND SD OF T/P FACTORS WITH POOLED STANDARD DEVIATIONS

DET	RAY	AVE PKGND	AVE RA	AVE KR	TP FACTOR	R1-R2 SD	DET WT	DET SD(E)
4	404	331.30100	175.02917	141.79100	10.12519	.20453	13.22677	.485920E-02
5	402	392.67400	83.23050	72.72867	10.20447	.07798	6.78439	.175490E-02
6	1000	382.20000	127.70167	107.24150	10.00800	.11186	10.00387	.166810E-02
7	1055	203.94350	89.70333	74.97550	9.94883	.10125	6.99398	.144239E-02
8	1111	183.27500	90.58833	76.49850	10.04762	.02858	7.13605	.274377E-02
9	1174	340.80000	135.40783	115.30750	10.07950	.28128	10.75630	.167881E-02
10	1230	257.25450	83.69950	76.54017	9.93123	.08287	7.13994	.167037E-02
11	1207	194.58950	87.43427	76.12880	9.66402	.11544	7.10157	.757161E-03
12	1351	309.60000	133.52350	117.46740	10.03900	.23964	10.95774	.321187E-02
13	1417	319.91450	134.42967	119.43500	10.03070	.10370	11.14132	.306026E-02
14	1471	292.62350	135.77043	122.10633	10.06991	.18199	11.39052	.908936E-03
15	1527	231.36300	135.80011	123.33283	10.09540	.21831	11.50493	.232137E-02
16	1583	254.63550	89.28117	81.81020	9.98162	.09104	7.63155	.327462E-02
17	1646	181.20300	89.07757	82.50233	10.03177	.01015	7.69611	.281400E-02
18	1744	246.42950	89.19550	83.34071	9.96500	.24454	7.77432	.165492E-01
19	1804	416.10350	91.28943	86.43080	10.09129	.22629	4.24914	.178092E-02
20	1859	259.25350	91.36762	89.22114	10.20601	.02581	8.32287	.324395E-02
21	2045	193.61400	89.90814	67.38520	10.12747	.03175	8.33817	.992062E-03
22	2119	270.17300	91.03033	91.52883	10.17180	.02286	8.53814	.545846E-02
23	2241	242.95700	92.75926	95.26100	10.25154	.14097	8.88629	.134947E-02
24	2304	152.38000	90.69600	94.37433	10.11449	.01796	8.80358	.308227E-02
25	2366	104.01400	90.33433	94.72125	10.04430	.14860	8.83594	.219906E-02
26	2423	204.09500	90.77400	96.41550	10.17800	.02613	8.99401	.449673E-03
27	2429	229.95050	89.13671	95.35650	9.90578	.05204	8.94202	.155382E-01
28	2547	629.68750	67.63325	74.94150	10.02900	.10394	6.99076	.271157E-02
29	2505	130.42950	61.57983	69.97250	10.04145	.17024	6.52729	.245429E-02
30	3121	332.34550	69.78200	83.60133	10.13015	.17961	7.79863	.573682E-02
31	3152	172.25750	62.45000	75.62633	10.14925	.31920	7.05470	.341007E-02
32	3295	757.45200	21.20470	26.24436	10.00500	.10910	2.44817	.444607E-02
33	3356	302.17700	42.99250	61.38200	9.94500	.01360	5.72593	.154073E-02
34	3454	321.64400	49.57040	63.32940	10.07241	.08159	5.90759	.359491E-02
35	3454	311.04300	49.54780	63.04070	10.18193	.02720	5.88066	.272041E-02
36	3505	394.43150	16.68700	21.72444	10.00655	.00506	2.02653	.644351E-03
37	3595	334.95650	50.24600	65.64050	10.01559	.08665	6.12318	.719454E-02
38	3687	532.04180	20.45590	27.16600	9.95717	.00696	2.53414	.175736E-02
39	3688	517.11800	20.57220	27.31250	9.98483	.08665	2.54781	.435184E-02
40	3800	431.47450	39.60370	53.60660	9.99337	.03320	5.00062	.194901E-02
41	3857	385.05350	20.50850	28.01200	9.96758	.01992	2.61306	.217850E-02
42	3934	839.30250	20.61290	28.64050	9.94785	.03257	2.67169	.440885E-02
43	3934	806.00250	20.69600	28.63550	9.99320	.03731	2.67122	.204787E-02
44	4035	372.19700	20.85990	29.43240	10.05330	.01170	2.74556	.349633E-03
45	4151	400.11600	49.03420	54.74600	9.95848	.09645	5.48004	.472329E-02
46	4152	472.39167	13.98330	19.99867	9.95558	.01486	1.66536	.280571E-02
47	4256	238.44050	29.45720	29.97960	9.92865	.10847	2.79660	.161899E-02
48	4312	436.65450	20.67030	30.52070	10.07060	.02656	2.84708	.137897E-02
49	4536	450.15450	40.96990	63.02180	10.09870	.02688	5.87890	.892640E-03
50	4820	477.86865	41.18764	66.49600	10.12700	.01283	6.20294	.139075E-02
51	5440	500.85510	44.34910	79.88780	10.07074	.06546	7.45222	.583469E-03

WITHIN RUN SD = .093245 DF = 291. BETWEEN RUN SD = .150025 DF = 48. WITHIN SD(E) = .439645E-02 DF = 214.

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