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Statistical Analysis of Truncated-Data Methods to Shorten Thermal-Aging Tests of Electrical Insulation

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13. ABSTRACT

The standard tests of insulation materials (motorette tests and magnet-wire twist tests) call for aging ten specimens until failure at each of three or four temperatures to obtain a life-versus-temperature curve. Valuable time could be saved if an estimate of the life at each temperature is valid from data truncated at fewer than all ten failures. Therefore a statistical analysis was made, using 50 previous thermal evaluations, of the validity of three truncated-data estimates of the life at each temperature: the log average of the times for the fifth and sixth failures (method A), an estimate from a probability-plot fit to the first five failure times (method B), and simply the fifth failure time (method C). The estimates were found valid, with method A being the most accurate and method B the least accurate. All results with method A fell within the 95% confidence limits for the complete-data method, and 90% of the results from the other two methods fell within these limits. Method A would have saved over 7 weeks, and method B or C would have saved over 10 weeks. Thus a choice between using the log average of the fifth and sixth failure times at each temperature or simply using the fifth failure time would depend on the relative importance of the accuracy and the time saved in a given situation.

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STATISTICAL ANALYSIS OF TRUNCATED-DATA METHODS TO SHORTEN THERMAL-AGING TESTS OF ELECTRICAL INSULATION

INTRODUCTION

The Navy has a serious interest in the thermal stability of the electrical insulation materials and insulation systems it buys, since this stability affects the reliability of its vessels. Functional methods of measuring the thermal stability of insulating materials and insulation systems for electrical equipment allow the Navy to select the best, as well as design new systems.

In 1953 the Navy began exploring the environmental factors that govern the thermal stability of magnet-wire systems (1). Following this study the Navy helped develop twist tests of the thermal stability of magnet wire (2,3). In addition the Navy helped improve the design and the procedures for test of the small assemblies of wire windings called motorettes which typify motors (4). Over the years industry and the Navy converged on standard life-predicting procedures for magnet wire and motorettes, permitting the development of thermal index ratings of materials and classification ratings for insulation systems.

However, even before a consensus on these procedures, it became evident that the Navy was paying a heavy price for the thermal-aging information. This price involved time as well as money. The conventional practice in obtaining data for a life-versus-temperature curve is to age until failure ten specimens at each of three or four temperature points. Often the Navy had to decide on comparative life of insulation systems without waiting for complete results of the testing. At a given temperature, when the percent of the ten specimens in the failed category is plotted against the failure times on probability paper (which linearizes the Gaussian distribution curve), as few as five failures gave a prediction of the mean life within ± 5%. In most instances the prediction was later confirmed by the complete data analysis.

These successes created interest in saving the many extra hours required to run each test to completion. Goldenberg's (5) results on median analysis supported the Navy's experience that complete sets of failures were not necessary to obtain meaningful life predictions and hence encouraged a more thorough pursuit of truncated-data analysis. Thus an extensive analysis of the data gathered on many of the past tests was initiated to determine the most accurate method for obtaining thermal predictions in the least time.

APPROACH

In this analysis three possible methods for truncating thermal-aging data were studied for their value in shortening the testing time needed to obtain a three-temperature-point regression life curve. Method A is the *median* method, which employs the log average of the life values for the fifth and sixth failures as an estimate of the log average of all ten samples. Since even one aging cycle at the coolest of the three test temperatures can amount to several weeks of additional testing, two other truncating methods, which allow the test to be stopped after the fifth failure instead of the sixth failure, were studied. Method B uses a *probability* plot (Fig. 1) to graphically estimate the mean value. This method has the disadvantage that personal skill and judgment may bias the placing of the best-fit line to the accumulative percentage points, producing some variation in the results. Method C selected for evaluation is simple and precise; it uses the life value of the *fifth failure* as the estimated average life value for the ten samples under test.

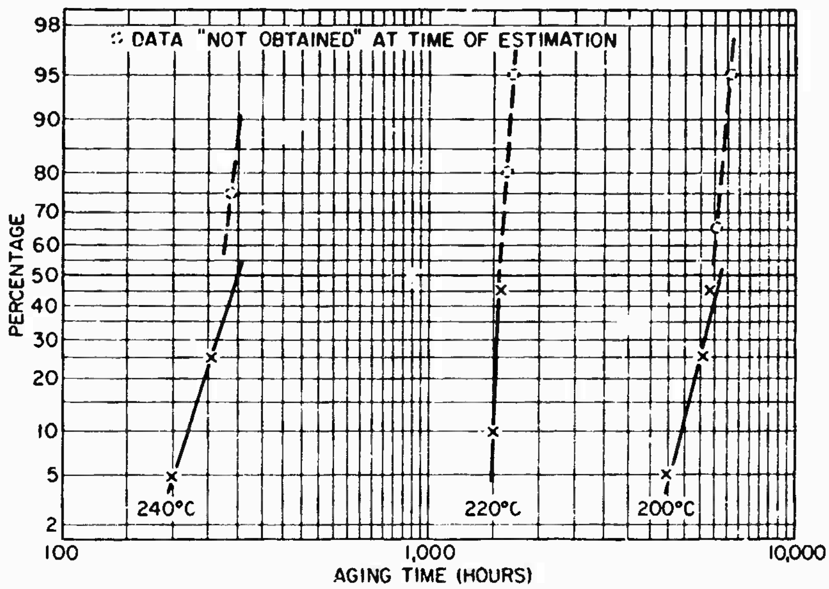

Fig. 1 — Typical probability plot for estimating the log average of partially obtained thermal aging data. The crosses at a given temperature are points derived by standard probability methods from the first five failures.

The regression analysis in IEEE 101 (formerly AIEE 1F) was used in the computer program to place the best-fit regression line to the three test-temperature points. The data used at each test temperature consisted of ten life values for the complete-data method, two life values for method A, and one life value for methods B and C. All three truncating methods were compared with the customary complete-data method (6) which uses one life value at each test temperature, namely, the log average life of all ten samples.

Fifty previously completed thermal evaluation experiments were used. Twenty-five of these are motorette tests of insulation systems, and 25 are twist tests of magnet wire (both varnished and unvarnished). Tests were selected randomly from a wide range of sources. Included were the twist-test data of the six laboratories participating in the round-robin program of the Electrical Research Association, Leatherhead, England (5). Also included were the test results of seven laboratories participating in the round robin on the IEEE 117 test procedure for motorettes (4). The remaining sets of data were taken from experiments performed at the Naval Research Laboratory and the Naval Ship Research and Development Center. The data represent a period of 15 years, starting with NRL motorette and twist experiments performed in 1954. When more than three temperature points were involved, the data from only the three coolest temperatures were considered. The 50 experiments studied cover a wide range of insulations including polyvinal formal, polyesters, overcoated polyesters, epoxys, film/polyester-fiber/fiberglass combination, and polyimides.

ANALYSIS OF DATA

Percent of Error in Estimations

Accuracy of the estimations evolving from methods A,B, and C were expressed as a percent of error:

$$\text{percent of error} = \frac{\text{complete-data value} - \text{estimated value}}{\text{complete-data value}} \times 100,$$

where the complete-data value is obtained from all failures of the ten specimens at each temperature.

Percent of Error Based on Time — Observations of the percent of error were made for the estimated regression-line life value in hours at the coolest of the three test temperatures (no extrapolation). Table 1 is a breakdown of the average values for 25 twist and 25 motorette tests. On the average, method A produced the least percent of error in the estimated life, method C a close next, and method B the greatest.

Table 1
Average error in using the regression line applying to the life at each of three temperatures for estimating the hours of life at the coolest of the three test temperatures for the magnet-wire twist test, the motorette insulation test, and both tests combined

Method for Obtaining the Life at Each Temperature	Error (%)		
	Twist Test	Motorette Test	Tests Combined
A: median of fifth and sixth failures	4.9	7.0	6.0
B: probability-plot estimate	7.5	8 5	8.0
C: fifth-failure value	6.1	6.1	6.1

Percent of Error Based on Temperature — The average percent of error for the estimated temperature value in degrees centigrade was calculated at an extrapolated reference life line of 20,000 hours, except that in the case of the IEEE 117 round-robin data the estimate was calculated at an extrapolation of 10,000 hours. This adjustment was made on the basis that the average life obtained at a given test temperature was approximately half that obtained from the twist tests and the remaining 18 Navy motorette tests. Unlike the Navy procedure, which employed a humidity condition with no visible condensation, the IEEE round-robin tests used the NRL-developed condensation chamber (7), which produces a more severe (but adequately controlled) condition with visible condensation. (The Navy is converting to this condensation chamber as adopted by the latest revision of the IEEE 117 Test Procedure.)

Table 2 is a breakdown of the average percent of error for these extrapolated temperature-value estimates. The twist and motorette tests combined show the same order of increasing percent of error (method A, C, and B) that was evident in Table 1 with the nonextrapolated life values. The most striking observation here is the increase in error by a factor of 2 or 3 for the motorette tests as compared to the twist tests. This may be considered an interesting and even valuable observation but not surprising when one considers the complexity of the motorette-system test compared with the magnet-wire twist test. Figure 2 is a histogram of the frequency distribution of percent of errors for the 150 temperature values estimated from extrapolated regression lines. A comparison is given for the three methods A, B, and C as well as a breakdown for twist and motorette data. The increase in spread for the motorette values is particularly evident here.

Table 2
Average percent of error in extrapolation of the regression line applying to the life at each of three temperatures for estimating the temperature corresponding to a life of 20,000 hours

Method	Error (%)		
	Twist Tests	Motorette Tests	Tests Combined
A: median	0.47	1.36	0.92
B: probability	0.57	1.46	1.02
C: fifth failure	0.64	1.23	0.94

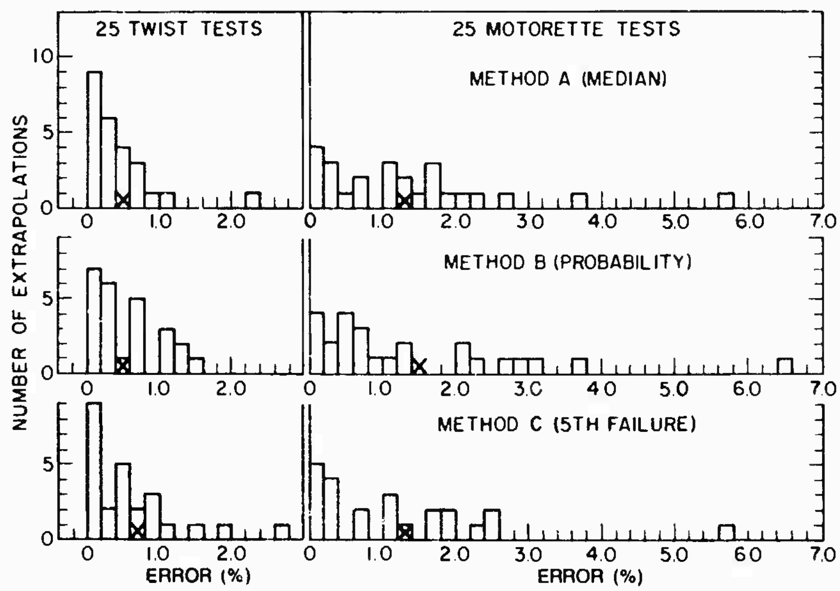

Fig. 2 — Frequency distribution of errors in extrapolations of the regression line applying to the life at each of three temperatures for estimating the temperature corresponding to a life of 20,000 hours using methods A (median of the values for the fifth and sixth failures), B (estimate from a probability plot), and C (value for the fifth failure). The symbol X along each abscissa is at the average value.

Comparison of Tables 1 and 2 shows that when the percent of error is calculated in terms of temperature at a given life rather than in terms of life at a given temperature, it drops by a considerable factor (about 10 to 1 for the twist tests, and about 5 to 1 for the motorette tests). This difference is not surprising, since a small change in temperature corresponds to a large change in life. One is ultimately concerned with a temperature value for a given time rather than a period of time for a given temperature (as set forth in the concept of a temperature index or a temperature rating); hence one is justified in putting confidence in the smaller error for the temperature comparisons.

Variation in Width of Complete-Data Confidence Limits

In considering the relative magnitude of error it was realized that this absolute value did not tell us all we need to know. The reproducibility of the original data as obtained by the complete-data method needs to be considered. This factor undoubtedly has a bearing on the failure pattern, which in turn affects the ability to make accurate estimations using partial data. (This fact becomes quite apparent in the case of the motorette test data.)

To compare the width of the confidence limits on a common basis, the time difference between the regression line and its confidence limit, at any given temperature point, is computed as a percent of variation:

$$\text{percent of variation} = \frac{\text{regression value} - \text{confidence limit value}}{\text{regression value}} \times 100.$$

This percent of variation for each set of confidence limits is plotted in Fig. 3. Immediately apparent is the considerably wider spread of confidence limits for the motorette data as compared with the twist data. The overall average percent of variation for the motorettes is about 1/3 greater than for the twists, which reflects the greater error for the motorette estimations.

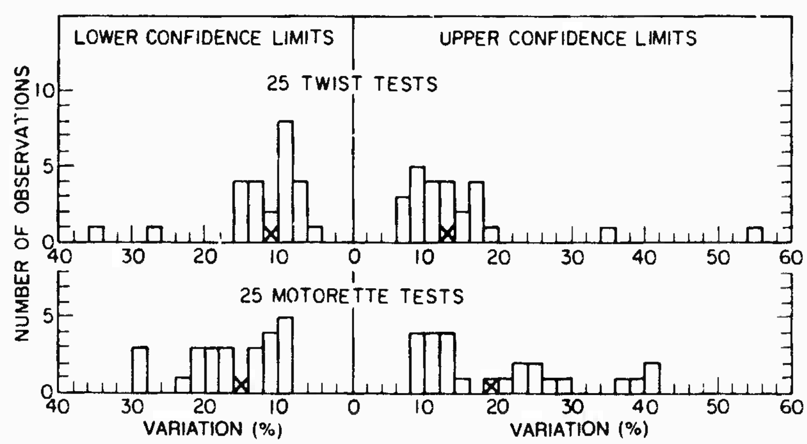

Fig. 3 — Variation of the 95% confidence limits from the regression line for 50 thermal aging tests using the complete-data method. The symbol X is at the average value

Percent of Acceptability for Estimations

The need for a meaningful gauge to measure the acceptability of the estimations on a common basis using the three methods thus became apparent. The 95% confidence limits of the regression curve obtained by the complete-data method was chosen as the most logical gauge for this purpose. On this basis a percent of acceptability was computed as follows:

$$\text{percent of acceptability} = \frac{\text{percent of variation} - \text{percent of error}}{\text{percent of variation}} \times 100.$$

This percent of acceptability reflects the location of the estimated regression line as a percent of the distance between the complete-data regression line and one of its confidence limits. (If the estimated line falls between the complete-data regression line and the confidence limit the percentage value is between 100 and 0; if the estimated line is outside the confidence limit, the value is less than 0.) On this basis, if the estimated regression line falls within the complete-data confidence limits, the estimation is considered valid.

The values of the percent of acceptability are plotted in Fig. 4 for the 50 experiments. When the data are compared in Figs. 5 and 6, in which the twist and motorette data are plotted separately, the increase in the absolute percent of error for motorette tests as compared with the error for twist tests (Fig. 2) has been adjusted out. The average values for the data plotted in Figs. 4, 5, and 6 are given in Table 3. The same order among the methods (method A, C, and B) can be observed here as was previously noted for the percentage-of-error values.

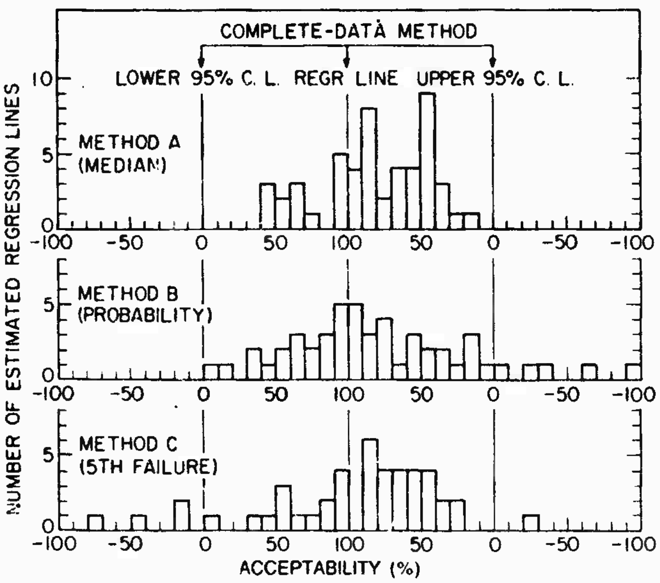

Fig. 4 — Location of estimated regression lines at the coolest test temperature for 50 thermal aging tests (motorettes and twists). The percent of acceptability is the percent of the distance of the estimated regression line between the 95% confidence limit for the complete-data regression line and the complete-data regression line itself.

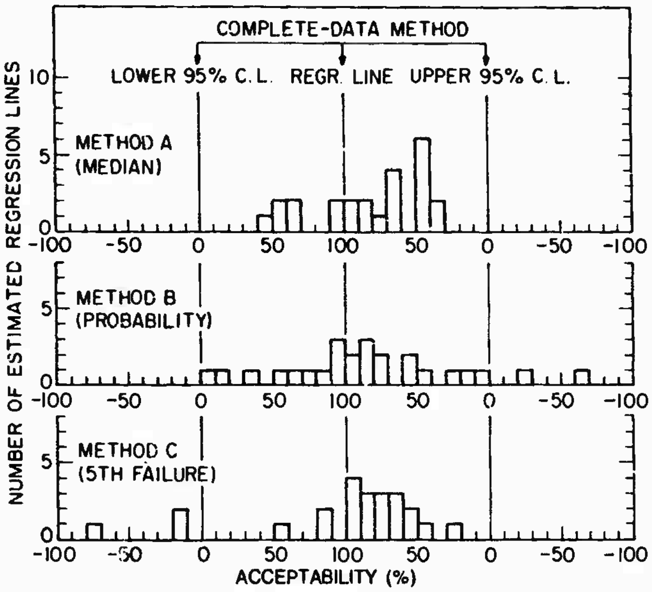

Fig. 5 — Location of estimated regression lines at the coolest test temperature for 25 twist thermal-aging tests

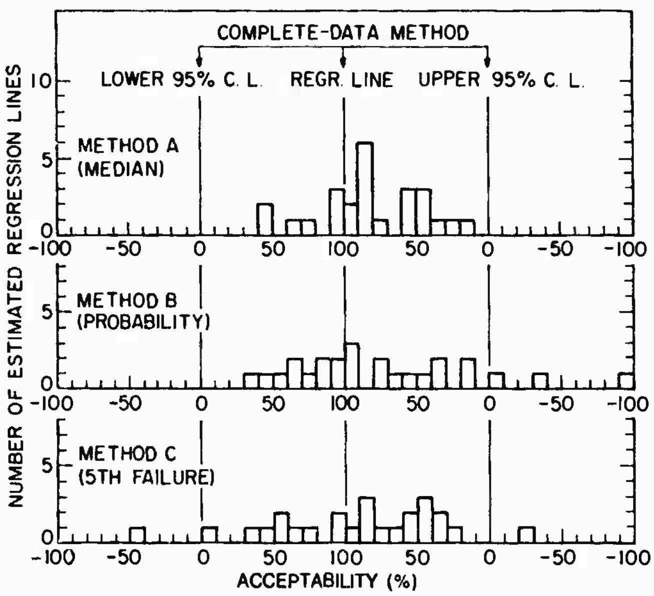

Fig. 6 — Location of estimated regression lines at the coolest test temperature for 25 motorette thermal-aging tests

Table 3
Average values for the percent of acceptability of the 25 twist thermal-aging tests and the 25 motorette thermal-aging tests

	Acceptability (%)		
Method	Twist Tests	Motorette Tests	Tests Combined
A	64.4	62.9	63.7
B	47.0	53.1	50.1
C	51.3	61.3	56.3

Table 4 lists the number of estimated regression lines, out of a possible 25 for each of the two kinds of test, falling outside the complete data confidence limits at the coolest test temperature. Method A rates a perfect score in the acceptability test, and methods B and C tie for second place, with each having five estimated regression lines falling outside the confidence limits.

Table 4
Number of estimated regression lines at the coolest test temperature which fall outside the 95% confidence limits for the complete-data regression line

	Number of Lines With Negative Percentages of Acceptability		
Method	Twist Tests (25)	Motorette Tests (25)	Tests Combined (50)
A	0	0	0
B	3	2	5
C	2	3	5

Testing-Time Saved Using Truncated Data

The remaining and final analysis to be made was to compare the three methods in terms of time saved in obtaining the coolest temperature point for each life-versus-temperature curve. The histograms in Fig. 7 compare method A with methods B and C in terms of both hours saved and percentage of total aging time saved. On the average method A saved 16.5% of total aging time or 1243 hours (7.4 weeks) as compared with 21.7% or 1691 hours (10.4 weeks) for methods B and C. Table 5 is a comparison of the average time saved when considering twist and motorette tests separately.

For all methods the time saved for the motorette tests is significantly greater than the time saved for the twist tests. Moreover each aging cycle eliminated in motorette testing also offers an additional savings of time due to the concurrent elimination of the humidification cycle (48 to 60 hours). When the humidification time is included, it increases the time saved from about 26% to approximately 30%.

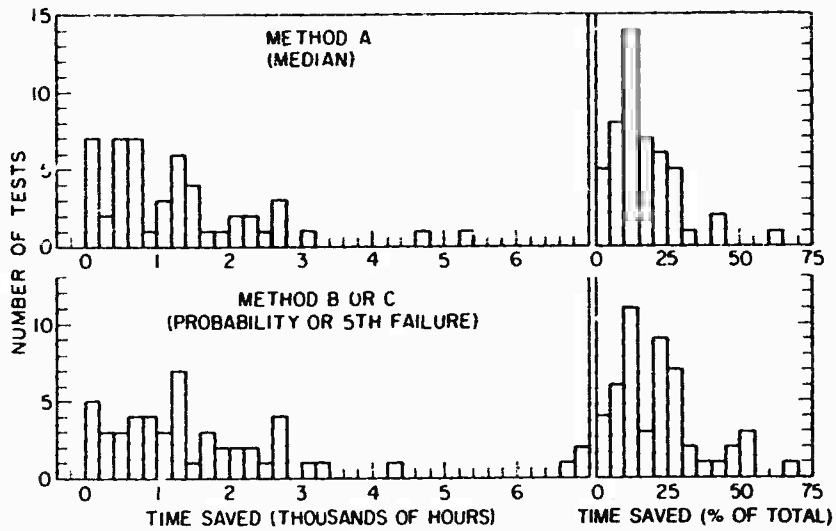

Fig. 7 — Frequency distribution of the time saved in 50 thermal-aging tests (motorette and twist tests) using methods A, B, or C

Table 5
Testing-time saved by using truncated-data methods

Method	Time Saved			
	Twist Tests (25)		Motorette Tests (25)	
	Hours	Percent	Hours	Percent
A	1069	12.5	1417	20.4
B or C	1492	17.5	1890	26.1

SUMMARY OF OBSERVATIONS

The observations resulting from this study can be summarized as follows:

- As applied to twist and motorette thermal-life estimations the median method (log average for the fifth and sixth failures out of ten specimens), on the average, proved most accurate, with the fifth-failure method second and the probability-plot method (using the first five failures) third.

- For 20,000-hour extrapolated temperature estimations the motorette tests in comparison with the twist tests exhibited an increase by a factor of 2 or 3 in the average percent of error.

- In terms of the truncated-data estimations falling within the 95% confidence limits for the complete-data values the median method rated first with a perfect score of 100% and the other two methods second with a score of 90% each.

- From analysis of the complete data the motorette-test confidence limits were about 1/3 wider than the twist-test confidence limits.

- The average overall time saved was 16.5% (7.4 weeks) for the median method and 21.7% (10.4 weeks) for either of the other two methods.

- The average percent of time saved using the median method was 12.5% for twist tests and 20.4% for motorette tests. For the other two methods it was 17.5% for twist tests and 26.1% (30% if considering humidification time) for motorette tests.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of this study of three truncated-data methods the conclusions and recommendations are the following:

- The estimation of thermal-life values for electrical insulation using truncated data has been proven valid, and a substantial aging time can be saved by its use, particularly when applied to motorette tests.

- The median method offers the greatest degree of accuracy and reliability.

- The probability-plot estimate using five failures and the fifth-failure method offer a significant increase in aging time saved but at a sacrifice of about 0.2% average accuracy and 10% reliability.

- In making a choice between the three methods, consideration should be given to such factors as cost limitations, time urgency, and reliability needed.

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