ASBESTOS PCM FIBER COUNTING PERFORMANCE IN THE PROFICIENCY ANALYTICAL TESTING PROGRAM

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ABSTRACT

The Proficiency Analytical Testing (PAT) Program is a U.S. based proficiency testing program operated by the American Industrial Hygiene Association (AIHA) in cooperation with the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC), under a Cooperative Research and Development Agreement. Currently 1,200 laboratories in the Program report annually 24,000 Phase Contrast Microscope (PCM) analyses for asbestos fibers.

An earlier evaluation (1986) of the performance of laboratories enrolled in the PAT Program found that total variability for chrysotile asbestos fibers had improved by approximately one-third from the mid 1970's to the early 1980's, but deteriorated as large numbers of new asbestos counters were hired by laboratories. Evidence for the deterioration of the performance of chrysotile asbestos fiber counting included a high variability for fiber counting found among laboratories with little proficiency test experience and among PAT Program laboratories from late 1973 through 1978, when the program underwent rapid growth in participation.

The evaluation of asbestos fiber counting reported here covers 20 years of the PAT Program (1972 to 1992). Estimates are obtained for total variability, intracounter variability, and intercounter variability. The total variability of counting chrysotile asbestos fibers improved by approximately 35 percent in recent years when compared to the variability

found during the period 1975 to 1977, at the lowest filter fiber densities used in the PAT Program. The greatest improvement in total and intercounter variability occurred in the second half of 1978. The intracounter variability for counting chrysotile asbestos fibers at the lowest filter fiber densities used in the PAT Program was consistently 1/3 to 1/2 lower than estimates obtained during the period 1975 to 1977.

Total, intercounter, and intracounter variability for counting amosite and chrysotile asbestos fibers also were compared over a six year period starting in 1986. PAT Program laboratories achieved about one-quarter lower intracounter variability and about one-third lower total and intercounter variability when counting amosite fibers versus chrysotile fibers. In addition, amosite intercounter variability improved by about one-third with large improvements occurring in the first year that amosite was included in the program.

Factors affecting performance changes such as changes in PCM fiber counting methods, PAT participation, AIHA Laboratory Accreditation Program, and PAT sample production are studied and discussed as possible factors affecting variability over the twenty year period.

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INTRODUCTION

The Proficiency Analytical Testing (PAT) and the Asbestos Analyst Registry (AAR) Programs are U.S. based proficiency test programs which evaluate the quality of Phase Contrast Microscope (PCM) asbestos fiber counting. Since 1972, the PAT Program has measured laboratory performance in several analytical areas, including PCM asbestos fiber counting, and participants currently number over 1200 laboratories that analyze for asbestos, including over 350 laboratories which have obtained American Industrial Hygiene Association (AIHA) Laboratory Accreditation. A related program, the Asbestos Analyst Registry (AAR) Program, was started in 1986 to measure the performance of individual fiber counters. The AAR Program has over 1800 PCM asbestos counters in 250 organizations participating. The AAR Program is designed to provide quality audit samples to counters that perform asbestos fiber counts at remote or mobile sites such as at abatement sites or on board ship tenders. A similar study of the AAR data will be the topic of a subsequent paper.

The main goal of this study is the identification of trends in precision over time. The procedures used to estimate precision are described in the section, "Precision Estimates." The grouping of data into time periods based upon factors that have changed over the years that might affect performance is described in the section, "Selection of Time Periods." General time trends are discussed in the section, "Changes in Variability." The modeling used to describe these trends is discussed in

"Models for RSDs over Time," and the trends identified by the modeling are discussed in "Changes in Total Variability," "Changes in Intracounter Variability," and "Changes in Intercounter Variability." Analysis of the most recent data comparing variability of chrysotile counting with that of amosite counting is in the section, "Comparison of Amosite and Chrysotile Performance." An "Appendix" provides details on the statistical methods used.

PAT PROGRAM OPERATION

The PAT Program evaluates laboratories that perform Phase Contrast Microscope (PCM) asbestos fiber counting. No fiber identification is involved. The PAT Program uses quality audit samples which are prepared by filtering sonicated suspensions of chrysotile or amosite fibers and aluminum oxide through cellulose ester membrane filters. PAT samples have been generated using chrysotile since 1972, but beginning in 1988 amosite asbestos samples have been generated on alternate rounds.[1] The homogeneity of PAT Program quality audit samples is verified before shipment to participants. Manual PCM fiber counting and visual inspection by a single microscopist are used to evaluate filters for excessive fiber fineness or fiber clumping on at least 13 filters from each fiber loading level produced.

The PAT Program rates and tracks overall laboratory performance. The program provides a set of samples four times a year with each set consisting of four asbestos fiber loading levels. The PAT Program also provides a blank filter. In the PAT Program the set of samples is rotated from round to round among all the counters within the laboratory with one counter officially analyzing all asbestos samples on a round. Only counts from one counter are officially reported on a round although laboratories are encouraged to fully utilize PAT Program samples by using permanent filter mounts and additional filter wedges of PAT Program samples to evaluate all counters within the laboratory and to repeat the evaluation of counters.

When participating laboratories fail to meet PAT Program performance criteria, they can request extra samples to help in correcting the problem. However, these are not officially reported or used to change performance ratings. Whenever possible, the same counter who had outliers should be selected to perform the counts on PAT Program samples on the subsequent round. In addition, laboratories applying for or having AIHA Laboratory Accreditation who have repeated poor PAT Program performance will be required to explain what actions are being taken to correct the problem. If this does not resolve the performance problem or if the Laboratory Accreditation Committee considers laboratory actions to be inadequate, AIHA has the authority to schedule additional laboratory site visits at the laboratory's expense and/or begin a process to revoke accreditation.

The Proficiency Analytical Testing (PAT) Program uses a laboratory rating scheme whereby all participating laboratories are evaluated against the performance of 70 to 80 reference laboratories. Reference laboratories are selected from all participating laboratories. Reference laboratories must have been previously rated in all analytical areas covered by the PAT Program (metals, silica, asbestos, and organics) as proficient; and if the laboratory is in the United States, the laboratory must be accredited by AIHA. Then a test is performed on reference laboratory data to exclude outliers, and performance limits are based upon the mean ± 3 standard deviations on the square root scale. These performance limits are then used to identify if the results reported by each participating laboratory are acceptable. Analysis is done on the square root scale because distributional tests on PAT Program asbestos fiber count data have indicated that a square root transformation usually yields an approximately normal distribution.[2]

PRECISION ESTIMATES

This study uses similar procedures to those used in a 1986 PAT Program study to estimate the precision of PCM asbestos fiber counting.[3] Table I contains a list of the various sources of variability for the PAT Program asbestos counts. Although four variance components are listed, plus total variance, it is only possible to estimate two of the components. Since only one counter from each laboratory counts during a round, the variability between counters within a laboratory is confounded (mixed up with) variability between laboratories. Since only one determination is made on each filter, filter to filter variability cannot be separated from within counter variability (the variability resulting from differences in determinations were a person to recount the sample). The term "intercounter variance" will denote the sum of between laboratory variance and counter to counter variance. The term "intracounter variance" will refer to the sum of the within counter variance and filter to filter variance. (In the 1986 study this component was called intralaboratory variance.) There is quality control data for rounds 46 and later, from which an estimate of between filters variability can be obtained. However, unless indicated otherwise, "intracounter variability" will include variability between filters. The total variance is, then, the sum of the intercounter and intracounter variances. (In the 1986 study the total variance was called "interlaboratory variance.") By estimating two of these three components, the third can be obtained. All three variances are expressed as relative variances or as the squares of the relative standard deviations (the standard deviation as a fraction of the mean).

The symbol RSD will denote relative standard deviation. As shown in Table I, RSD_{BC} will denote intercounter RSD, and RSD_{WF} will denote intracounter RSD. When it is clear which RSD is referred to, subscripts will be omitted from the symbol RSD.

Estimates of intercounter variability can be easily obtained as follows. Treat each of the four samples within each round individually, and compute sample standard deviations and means for each of the four. The estimated RSDs are obtained by taking the ratios of the estimated standard deviations to the means. Thus, for each round, four estimated RSDs are obtained. To obtain confidence limits for true RSDs, some normality distributional assumptions are required. Also, the normality of the estimated RSDs is assumed in models to be considered later. The data are assumed to follow a normal distribution after square root transformation. Normal probability plots of the samples in each round indicate that the square root transformation is usually appropriate to obtain approximate normality of the data. This approach differs from that used in the 1986 PAT Program asbestos study, in which the square root was used for all data except for 8 PAT rounds, generally rounds with very high intercounter variability (0.47 to 1.20 RSD). In that study several samples were considered together for selection of a transformation.[3] In the present study, the samples within each round are used separately to estimate the relative standard deviations, and the square root is usually no worse than and often better than the log transformation or cube root transformations previously used. As was demonstrated in the earlier PAT asbestos study, the estimates of precision (RSD) on the original scale are approximately twice those produced on the square root scale for normally distributed data. The exact relationship between results on the square root and the original scales is given in the Appendix section, "Conversion of Estimated RSDs from Square Root to Original Scale." For approximately normally distributed data, for large samples, the RSD_T estimator described above is approximately normally distributed. Except for the very early rounds, the number of laboratories involved should assure approximate normality of RSD_T estimates.

The PAT Program does not use duplicate samples. However, estimates of intracounter variability can be obtained by selecting pairs of PAT Program samples that are near the same filter fiber density (within 100 fibers/mm^2) using the procedures similar to those described in the 1986 study. This results in about one-third of PAT Program data being used to estimate intracounter variability, since only some PAT Program rounds have sample pairs with approximately the same filter fiber density.

The intracounter standard deviation of the PAT data must be estimated differently from the total variability. The approach used in the previous study[3] selected rounds with paired samples, in which the means of these paired samples differed by no more than 100 fibers/mm^2. The present analyses use the same criterion, except that medians are used instead of means. The estimates are obtained from the residual mean square of an analysis of variance, in which square roots of the individual measurements for the paired samples in each selected round are used as the dependent variable. The explanatory factors in the analysis of variance are the sample number and the laboratory identifier. The residual mean square is used as an estimate of the intracounter variance. Taking the square root of this estimate and dividing by the mean and converting the estimate to the original scale (since the data are on the square root scale) yields an estimate of the intracounter RSD (see Table IV). The estimates can be converted from square root scale to the original scale by using the relationship given in the Appendix.

As is indicated in Table I, after estimates for the RSD_T and RSD_{WF} are obtained, estimates for RSD_{BC} can be obtained for those rounds where the pairing was carried out. Thus, if $S1_T$ and $S2_T$ are unbiased estimates of RSD_T^2 for the two paired samples of round r, and if W1 is the estimate of RSD_{WF}^2 obtained, as described above, from the analysis of variance, then $((S1_T$ and $S2_T)/2 - W1)$ is an unbiased estimate of RSD_{BC}^2. Again, the estimated RSD_{BC} must be transformed from the square root scale to the original scale.

For rounds 46 and later, RSD_F can be estimated from filters counted by the producer. For any given round 46 and afterward, a counter employed by the producer makes all counts on that given round -- but only a small number of filters are counted. Dividing sample standard deviation by sample mean yields an estimate of RSD_F.

Subtracting estimated RSD_F^2 from estimated RSD_T^2 yields an estimate of the total variance associated with counters and laboratories.

SELECTION OF TIME PERIODS

The aim of this study is to evaluate changes in performance over time as measured by changes in precision. To do this, the data are divided into time periods. These time periods are based upon the changes that have occurred in PCM asbestos fiber counting and the PAT Program (see Table II). These include changes in fiber counting methods, laboratory participation, the type of asbestos fiber used in sample generation, changes in PAT Program sample producers, and changes in the AIHA Laboratory Accreditation Program. The time periods are similar to the ones used in the 1986 PAT asbestos study, but periodization presented here includes changes in the PCM asbestos fiber counting methods, and PAT Program asbestos fiber sample production.[3]

Three principal methods of PCM asbestos fiber counting have been used in the United States since the start of the PAT Program in 1972. Table III summarizes some of the many significant changes in PCM fiber counting that occurred in terms of: counting rules, counter training, microscope standardization, graticules, microscope resolution tests, and quality control.[4-6] Although NIOSH P&CAM 239 method was officially published in 1979, draft versions of the method were distributed to PAT laboratories and counters attending NIOSH PCM asbestos fiber counting courses starting in 1975. Thus, its use by many participating laboratories pre-dates its official publication.

The type of asbestos laboratory participating in the PAT Program also went through several changes: almost exclusively government laboratories prior to 1974; predominately full service industrial hygiene laboratories from 1974 to the mid 1980's; predominately laboratories involved exclusively with asbestos abatement in later years.

The study of trends in PAT Program PCM asbestos fiber counting performance is more extensive for chrysotile samples since amosite samples were only introduced in the PAT Program in 1986.

CHANGES IN VARIABILITY

One way to study the data is to plot total variability estimates over time (see Table IV). The column in Table III indicating the number of laboratories is the total number of laboratories that participated in the asbestos fiber counts in each round. (Asbestos fiber counting was introduced into the PAT Program in round 3. Round 67 data are not included in this study because of problems with the data.) The actual estimates shown in the table are computed after removal of laboratory measurements that fail the Grubbs outlier test at the 1% significance level (two-sided test).[7] Before round 60, no round has more than one lab with measurements removed by this procedure. For rounds 60 and later, between 1 and 5 labs had measurements deleted, but this is only a very small fraction of the total number of measurements from each round.

Table IV shows the RSD_T estimates for chrysotile fiber counting. Figure 1 is a plot of the estimated RSD_T corresponding to filters with the highest fiber densities in each PAT round (highest loading (H)), while Figure 2 is the corresponding plot for the lowest fiber density filter on each PAT round (lowest loading(L)). The confidence limits (CL) are computed from the following formula,[8] in which "Est." before a parameter denotes an estimate of the parameter:

$$CL = \text{Est. RSD} + 1.96 * \text{Est. Std. Err (RSD)},$$

$$\text{where: Est. Std. Err.(RSD)} \quad \frac{\text{Est. RSD}}{(2 \text{ X D.F.})^{.5}} \text{ X } (1 \quad 2 \text{ X } (\text{Est. RSD})^2)^{.5}$$

(D.F. is the degrees of freedom of the standard deviation used in the computation of the estimated RSD.)

These plots indicate:

1. The confidence limits in the later periods are much narrower than those in the earlier periods. This is largely due to the large increase in the number of labs doing the analyses in later years, and also to factors that lowered the RSD estimates themselves.

2. Both the highest and lowest loading plots suggest that the RSD_T estimates are lower and more constant since early in period 5, but

this observation is confounded by the fact that the earlier rounds generally had much bigger spreads from their lowest to their highest loadings.

3. Comparison of the lowest and highest loading plots indicates that within each period, highest loadings have somewhat lower estimated RSD_T than do lowest loadings, and the difference is bigger for the earlier periods. However, trends in Figures 1 and 2 can be affected by differences in fiber loadings from round to round and sample to sample.

The intracounter estimates are shown in Table IV and confidence limits, computed as for total RSD estimates, are plotted in Figure 3:

1. Confidence limits for intracounter RSD are much narrower in the later periods than in the earlier periods. This is a result of the increased number of laboratories participating in later periods.
2. As with the total RSDs, the estimates from the early part of period 5 onward are more constant and lower than in the earlier periods.

3. Examination of Table IV indicates that the loadings for matched samples are much more variable in rounds before 1976 than after 1976. Also, the data indicate that RSD_{WF} estimates tend to decrease with increasing loading.

Intercounter estimates are also given in Table IV. These indicate:

1. Confidence limits are narrower in later periods than in earlier periods, due to the increased number of labs in later periods.

2. For round 50 and later there is little difference between the RSD_{BC} estimates -- all estimates are less than 0.46. In period 4, rounds 33 to 45, all estimates exceed 0.46.

3. Plots of the ratio of estimated RSD_{BC}^2 to estimated RSD_T^2 indicate that this ratio follows no clear time trends, and, except for a few low values in period 1, falls mostly between 0.5 and 0.8. This is not dependent on loading.

Plots of the estimated filter-to-filter variability indicate that, regardless of the loading, this variability drops considerably after rounds 46 to 60. At 300 fibers/mm^2, many RSD_F estimates exceed 0.12 during round 46-60. Afterward, most are less than 0.12. The lowest estimates are in the later rounds of period 5, before it was necessary to use more than one batch per round in preparing the required number of samples. As more batches are required, estimated RSD_F increases.

After the total RSDs for periods 5,6, and 7 are corrected for the estimated between filters variabilities, there is very little difference among total variance estimates for these periods.

MODELS FOR RSDS OVER TIME

Some of the differences across period and by loading can be quantified by making statistical models for the total RSD estimates which take into account differences in loading from round to round. Several different kinds of models have been constructed. These are discussed in the Appendix. The results presented here model the total RSD estimates in each round as a quadratic function of the sample median. These models are then used to obtain values for the total variability corresponding to 300, 500, and 700 fibers/mm^2. For each of the three loadings, regression models are fitted over the seven time periods. The natural log of the predicted value of RSD is regressed on the period and round within period with weights inversely proportional to the estimated variance of the predicted value. The model allows for differences among periods and changes within each of the periods, by including linear and quadratic components for change by round within period. Since the fullest model allows for many parameters, Mallow's C_p is used to select models with a reduced number of parameters.[9] This statistic allows the user to find models that explain as much as possible of the variability in the data, but without including so many explanatory variables as to inflate the variance of the model predictions. For each of the models (at 300, 500, and 700 fibers/mm^2) simultaneous 96.7% confidence limits are constructed for each period's predicted total RSDs, under the models. Overall, the confidence intervals hold at the 90% confidence level. Two periods are said to differ if the confidence intervals do not overlap. This is a somewhat conservative procedure, and is discussed more fully in the first section of the Appendix.

The amount of intracounter data is limited, because no more than one sample pair resulting in a single predicted value is available for each round. Therefore, matched samples are not separated by loading. Regression models are constructed, in which the intracounter RSD is expressed as a function of the period, the average of the medians for the matched samples, and the round within period. Also, terms representing products of these various factors are included. As with the intercounter variability, the natural logs of the intracounter RSDs are used in the analysis. For this model, weights are inversely proportional to the degrees of freedom associated with the RSD estimates. Since the fullest model involves many factors, Mallow's C_p procedure, as for total variability models, is used to choose a group of acceptable models, from which one model is chosen to make comparisons among periods.[8]

Examination of Table V indicates that the loading range for the paired samples does change somewhat from period to period. In periods 6 and 7, there are few loadings in excess of 700 fibers/mm^2. If we restrict our interest to two loadings, 300 and 500 fibers/mm^2, we can obtain results on those loadings from a single model, which models RSD_{WF} as a function of round within period and loading. As for the intercounter RSDs, two periods will be "statistically different" if the lower confidence limits on one period's RSDs exceed the upper confidence limits on the other period's RSDs. Simultaneous 90% confidence limits are obtained, so that over both levels, differences indicated by the period-to-period comparisons are significant at the 10% level. As for total variability, this is a somewhat conservative procedure and is discussed more fully in the section of the Appendix, "Models for Changes in Intracounter and Intercounter RSDs Between Periods."

Models for intercounter variability based on the differences of estimated intracounter RSD are determined by procedures analogous to intracounter models, and are obtained at 300 and 500 fibers/mm^2. The weight used on each round is inversely proportional to the degrees of freedom associated with the intracounter estimate for that round. The intracounter and total RSD estimates have approximately equal degrees of freedom, and as indicated in the previous section, the between counters (and within counters) RSD appears to be relatively constant fractions of the total RSD, for most of the rounds. Thus, we think that the degrees of freedom associated with the RSD_{BC} estimates should be approximately proportional to the degrees of freedom of the intracounter (or total) RSD estimates.

CHANGES IN TOTAL VARIABILITY

The comparisons of periods are not always consistent across the three loadings: 300, 500, and 700 fibers/mm^2. All statements of statistically significant differences control the Type I error at the 10% level simultaneously, over all three levels and all comparisons of periods. The plots (total RSD by round) show that data from some periods are modeled by horizontal lines and from other periods by straight lines with nonzero slope (indicating change within period) or even by quadratics (also indicating change within period). The choices of which forms to fit by loading and period are based on use of Mallow's C_p statistic. The models chosen were not the only reasonable models that might have been chosen, but the alternative choices would have yielded similar conclusions. Further discussion of the models is given in the first section of the Appendix.

1. At 300 fibers/mm^2, the lowest filter fiber density modeled, the fitted model indicates that both periods 6 and 7 intercounter RSDs are lower than the total RSDs of period 4. In other words, intercounter variability after 1984 is consistently lower than the intercounter variability found between 1975 to 1977. According to the preferred models indicated by the C_p statistic, there is no trend (changes in intercounter RSD) within period for periods 4, 6, and 7. Thus, the fitted values and the associated confidence limits are all horizontal lines (see Figure 4). The lower confidence limits for period 4 are higher than the upper confidence limits for the periods 6 and 7 model-based predictions, indicating that the differences in intercounter RSDs are statistically significant for all rounds within these time periods.

(It is not clear why rounds in some periods differ. It is certainly easiest to draw conclusions when the differences between periods are consistent over all rounds within periods, as shown by horizontal lines.)

2. At 300 fibers/mm^2, periods 1 and 5 show changes in intercounter variability that occur within these time periods. The early rounds of period 5 from (early 1978) are indistinguishable from period 4 (1975 to 1977). However, by the fourth round of period 4 (round 49), mid 1978, period 5 intercounter variability is lower than that in period 4. Thus, we can say that the 1975 to 1977 intercounter variability exceeds later intercounter variability, with the exception of counting conducted in early 1978 (Figure 4).

3. Also, periods 5 (after the fourth round), 6, and 7 RSDs are not distinguishable from each other. There appears to have been little improvement in intercounter variability since round 46 (1978) at the 300 fibers/mm^2 level.

4. Comparisons can also be made with the earlier periods, namely period 1. (Periods 2 and 3 have only three rounds each.) However, few laboratories participated in early PAT rounds, resulting in wide confidence intervals for period 1. Period 1 results are therefore not significantly different from the later periods.

Thus, the main observation is that the period 4 RSDs are statistically higher than those of later periods at the lowest filter fiber density modeled (300 fibers/mm^2 loading). This is of special interest because the performance of the method at low loadings is important for fiber counting near the present standards.

5. The results for higher filter fiber densities, 500 and 700 fibers/mm^2, are not as clear, since the period 4 data are modeled as lines with negative slopes at these loadings (see Figure 5). Thus, the period 4 RSDs are higher than the periods 6 and 7 RSDs (which themselves are indistinguishable) for rounds early in period 4 (rounds 33 to 39, 1975 to 1976) but not for the later rounds (rounds 40 to 45, late 1976 through 1977) (Figure 5). As with the 300 fiber/mm^2 density models, models at 500 and 700 fibers/mm^2 showed that the later periods (5, 6, and 7) do not differ from each other, and period 1 does not differ from any of the later periods.

CHANGES IN INTRACOUNTER VARIABILITY

The results of the intracounter model are displayed in Figure 6.

1. At both 300 and 500 fiber/mm^2 level, all estimates for intracounter variability from period 7 are lower than all estimates for intracounter variability from period 4, 1975 to 1977. Except for the first few rounds of period 4, period 4 RSDs are larger than period 7, in tests done at the 10% significant level. Because the

estimates for the first few rounds of period 4 correspond to loadings in excess of 600 fibers/mm^2, the predictions at 300 and 500 fibers/mm^2 for those early rounds seem uncertain. (See the next section for further discussion.) Thus, we think it is reasonable to call the difference between periods 4 and 7 RSDs statistically significant; period 7 RSDs are over 40% less, on average.

2. All other comparisons of intracounter variability among time periods and loading levels were not conclusive since confidence intervals overlap considerably.

CHANGES IN INTERCOUNTER VARIABILITY

The results of the intercounter RSD model at 300 fibers/mm^2 are shown in Figure 7. The models fitted to the intercounter variability data at 300 and 500 fibers/mm^2 indicate that the differences between the periods 4 and 6 RSDs and between the periods 4 and 7 RSDs are significant at the 10% level at both loadings - except for comparisons involving the first few rounds of period 6 and the first few rounds of period 7, which do not yield RSD_{BC}s statistically distinguishable from the first few rounds of period 4. On average, the period 7 RSD_{BC}s are about .63 of the period 4 RSD^s_{BC}. One reason to minimize the importance of the comparisons involving the first few rounds of periods 4 and 7, is that for those rounds (see Table IV, rounds 33, 36, 87, and 89), the available data correspond to loadings higher than 600 fibers/mm^2. Therefore, the quality of the predictions for those early rounds is uncertain.

The reduction in the intercounter RSDs can be related to the changes observed in the total RSDs. As was indicated in the section on "Precision Estimates," the ratio of estimated RSD_{BC} to RSD_T does not change in a systematic way over time periods. When the ratio is modeled, there is no statistically significant difference between the ratio for period 4 compared to that for period 7, although the ratio does vary slightly by loading -- about 0.84 at 300 fibers/mm^2, and a little higher as the loading increases.

These estimated values can be used to obtain the following result, at 300 fibers/mm^2:

RSD_T (period 7) ~ (1/0.84) RSD_B (period 7) ~ (1/0.84) (0.63) RSD_{BC} (period 4)

~ (1/0.84) (0.63) (0.84) RSD_T (period 4)

~ 0.63 RSD_T (period 4), where "~" means "approximately."

Thus,

RSD_T (period 7) ~ 0.63 RSD_T (period 4).

This approximation only makes sense, because RSD_{BC} is a much larger part of RSD_T than RSD_{WF}.

A similar result holds for 500 fibers/mm^2.

From the model for RSD_T at 300 fibers/mm^2 whose predicted values are shown in Figure 4, the ratio of the period 7 to period 4 RSD_Ts is 0.64. The results here indicate that a main reason for the improvement in total variability at 300 fibers/mm^2 is that intercounter variability has improved. Similar results hold at 500 fibers/mm^2.

COMPARISON OF AMOSITE AND CHRYSOTILE PERFORMANCE

Since 1986, amosite samples have been produced in the PAT Program on even rounds, chrysotile samples on odd rounds. Total RSD estimates for amosite are given in Table VI. Plots of period 7 RSDs, by lowest loadings, are given in Figure 8. Figures 8 shows a downward trend in both amosite and chrysotile intercounter RSDs with considerable improvement in amosite occurring on the first three rounds after amosite was introduced into the program. As a result, amosite total RSDs were consistently lower than chrysotile total RSDs.

As in the study of chrysotile over all rounds, the comparison of chrysotile and amosite total RSDs was carried out over three loadings -- 300, 500, and 700 fibers/mm^2. At 300 fibers/mm^2, the size of the difference between the RSDs varies over time, although the amosite RSDs are lower, except for round 86. Since the amosite RSDs are almost always lower, it makes sense to compute an average total RSD over all rounds.

The simultaneous 90% confidence limits on the ratio of the amosite total RSD to the chrysotile RSD are:

300 fibers/mm^2: (0.534, 0.823)

500 fibers/mm^2: (0.590, 0.707)

700 fibers/mm^2: (0.562, 0.803)

As with the comparison of total RSDs for chrysotile, the RSDs for amosite are modeled by a quadratic in each round. The predicted values at the three concentrations are produced from these fitted models. These predicted values are then used in the comparison of the logs of the RSDs, done on the weighted scale, with weights inversely proportional to the variance of the predicted values from the regression models.

From these fitted models, the following observations can be made. The data at 300 fibers/mm^2 indicate that whereas the amosite RSDs consistently decline from round 86 to 104, the chrysotile RSDs increase slightly from round 87 to 95, and then decrease to round 105. Also, as is clear from Table VI, amosite RSD_T estimates at 300 fibers/mm^2 in round 90 are one-third to one-half lower than in the first amosite round, round 86. The time trends at 500 and 700 fibers/mm^2 are not statistically significant at the 5% significance level.

The analysis of the intracounter RSDs (see Table VII) indicates that the difference between the amosite and chrysotile RSDs does vary with the loading, but the amosite RSD estimates tend to be lower. We note that the matching criterion used in preparing these estimates was that the sample medians differ by no more than 150 fibers/mm^2. Use of the 100 fibers/mm^2 matching rule that was used earlier would not have yielded enough matches for the amosite rounds. The estimated 90% confidence limits on the ratio of amosite intracounter RSD to chrysotile intracounter RSD are (0.616,0.939). In other words, intracounter variability is significantly lower for amosite.

The intercounter RSDs (Table VII) estimates also were based on the 150 fibers/mm^2 matching criterion. The estimated 90% confidence limits on the ratio of amosite intercounter RSDs to chrysotile intercounter RSDs varied by loading -- 300 or 500 fibers/mm^2.

300 fibers/mm^2: (0.471, 0.847)

500 fibers/mm^2: (0.612, 1.002)

DISCUSSION

Total Variability

In recent years (see Table IX), laboratories have demonstrated total precision of 0.33 to 0.54 for chrysotile and 0.24 to 0.59 for amosite in the PAT Program. Models based upon these estimates which take into account the dependence of total variability on fiber loading yield simultaneous 90% confidence limits for chrysotile intercounter variability of 0.44 to 0.47 at 300 fibers/mm^2, and somewhat lower variability at higher loading levels -- at 500 fibers/mm^2, and 700 fibers/mm^2 for recent PAT Program rounds.

Initially when amosite was introduced to the PAT Program in 1986, amosite total variability was similar to chrysotile intercounter variability, but after one year, two amosite PAT Program rounds, amosite total RSD estimates improved by one-third to one-half (Table V). Chrysotile PAT samples generally contain curved long fibers, fibers which are longer than the 5 μ length rule for fiber counting. Although one expects amosite samples to be easier to count than chrysotile fibers since amosite fibers are straight, the process of producing homogeneous amosite fibers results in a large number of amosite fibers that fall near the 5 μ cut-off for fiber length. Therefore PAT amosite samples are a much better challenge than either chrysotile fibers or typical field samples of amosite to measure a counter's ability to accurately estimate if fibers are longer than 5 μ.

Comparisons across time periods of individual total RSD estimates and total variability model predictions demonstrate that total variability has improved since the mid 1970's at the lowest fiber density level modeled (300 fibers/mm^2) by approximately 35 percent and that improvement is statistically significant at the 90% confidence level. Improvements at higher fiber densities such as the 500 fibers/mm^2 level also may have occurred, but comparisons were not found to be statistically significant for all PAT Program rounds within the time periods. The most important component of this improvement at 300 fibers/mm^2 appears to be reduction in variability between laboratories and between counters within laboratories.

Of special interest is the performance of PAT laboratories in 1978, since most of the improvement in total variability at 300 fibers/mm^2 appears to have taken place in the second half of 1978.

The PAT Program contains one of the two largest databases on PCM asbestos fiber counting in the United States, but has the limitation that details on individual laboratory operations are not available and may be the result of factors that could not be studied, or some mix of contributing factors. Of the factors that are identified to describe time periods, analytical methods, type of participating laboratory, changes in PAT Program sample production, and changes in AIHA laboratory accreditation requirements, three of these factors could have changed in 1978: (1) the widespread adoption of NIOSH P&CAM 239 or its predecessor draft methods by participating laboratories; (2) the effect on laboratories of the AIHA Laboratory Accreditation Program, which began the process of re-accrediting laboratories; and (3) the changes in the production of PAT Program asbestos samples resulting in improved sample-to-sample homogeneity.

The changes in NIOSH P&CAM 239 PCM fiber counting method over the U.S. Public Health Service method of 1968 are significant. These include: an emphasis on training counters, the identification of bias problems among different microscopes, more specific fiber counting rules, precautions concerning fiber migration over time with the dimethyl phthalate mounting technique, and an emphasis on frequent recounting of slides.[5]

Drafts of NIOSH P&CAM 239 were distributed to counters in NIOSH training courses and to PAT Program laboratories starting in 1975, although the method was not officially published until 1979, 4 years later. Unfortunately, it is not possible from PAT Program rounds to ascertain when during this 4 year period most participating laboratories adopted the various improvements recommended by the NIOSH method. It is possible that the improvement in PAT Program total variability is a result of adoption of P&CAM 239 improvements, if the majority of laboratories adopted P&CAM 239 in 1978, just prior to its official publication.

1978 is also a time period in which the first large scale reaccreditation of laboratories was undertaken by AIHA. As a result, considerable changes were made in the accreditation program to ensure timely implementation of corrective actions and a system to quickly follow up on PAT Program performance.

Although the procedures used to generate PAT Program asbestos samples have remained essentially unchanged, the samples have been produced and quality controlled for sample-to-sample homogeneity by different groups over the years. Sample-to-sample homogeneity is a component of variation of both the intracounter and total variabilities in this study, but not of interlaboratory variability. Examination of Figures 6 and 7 indicate that the improvement in total variability at 300 fibers/mm^2 in 1978 is related to the improvement in intercounter variability, not to intracounter variability.

Also, it is doubtful that the improvement in 1978 of total variability is due to changes in PAT Program sample production for two reasons. First, the change in PAT's sample producer occurred between 1977 and 1978 and the improvement in intercounter variability occurs six months later, starting in mid 1978. Second, sample-to-sample variability was determined by the PAT Program sample producer, SRI International, using the one counter for all of 1978 and verified by the NIOSH Chemical Reference Laboratory using a second counter. Homogeneity tests conducted by SRI International and NIOSH researchers prior to sample shipment on each sample show no significant change from early 1978 to late 1978.

Since 1978, PAT Program intercounter variability is fairly stable. This means that a noticeable improvement in intercounter variability with the introduction of NIOSH 7400 could not be demonstrated. This is somewhat surprising given the heavy emphasis of NIOSH 7400 on counter training, microscope standardization, standardization to the Walton-Beckett graticule, introduction of the HSE/NPL microscope resolution test, standardization of counting rules, the adoption of the acetone/triacetin mounting technique, and extensive quality control required by the method. These included daily use of reference slides, 10% blind recounts, and exchange of field samples among laboratories -- all elements designed to improve intercounter variability.

Nevertheless, PAT Program performance is unchanged in the 1980s and 1990s, when many laboratories outside the AIHA Laboratory Accreditation Program began participating in the PAT Program. Perhaps some other factor such as the introduction of NIOSH Method 7400 in 1984 or the start of the AIHA Asbestos Analyst Registry in 1987 helped to maintain laboratory-to-laboratory agreement.

Perhaps, the number of laboratories outside a laboratory accreditation program in the 1980s and 1990s and the fact that much of the asbestos fiber counting being conducted today is conducted outside laboratories in the field at abatement sites may be significant confounding factors in this study.

As with the 1986 study, very little could be concluded about asbestos fiber counting prior to 1975 because few laboratories participated in PAT and there were significant program changes in 1974 and early 1975.

Intracounter Variability

In recent years (Table IV), laboratories have demonstrated an intracounter RSD of 0.18 (round 105) to 0.33 (round 101) for chrysotile and 0.15 (round 94) to 0.24 (round 99) for amosite in the PAT Program. Models based upon these estimates predict a 90% intracounter RSD for chrysotile in recent rounds of 0.16 to 0.24 and do not change very much by fiber loading. Comparisons among time periods indicate that except for the early rounds in period 4, the period 7 RSDs are lower than period 4, for tests at the 10% significance level, at both 300 and 500 fibers/mm^2.

The largest consistent difference in intracounter variability occurred between time period 4, 1975 to 1977, and the later time periods. A large reduction in intracounter variability of over 40% was found.

As with amosite intercounter variability, some improvement in amosite intralaboratory variability occurred with the first year that amosite was introduced into the program.

Intercounter Variability

In recent years (Table IX), the estimated intercounter RSDs have been between 0.333 and 0.439 for chrysotile, and between 0.208 and 0.552 for amosite. For chrysotile, models based upon these estimates predict a 90% confidence interval for the intercounter RSD of 0.31 to 0.40 at 300 fibers/mm^2, and slightly lower limits at 500 fibers/mm^2. Comparisons across time periods indicate that except for early in period 4, the period 7 RSDs are lower than period 4, both for 300 and 500 fibers/mm^2. The reduction in variability is about 37% for chrysotile.

CONCLUSIONS

This study has used data from almost 20 years of the Proficiency Analytical Testing (PAT) Program to evaluate the performance of participating laboratories and the changes in asbestos fiber counting that have occurred.

Chrysotile total variability and intercounter variability in the PAT Program improved by approximately 35% since 1978. Statistically significant improvement in total variability occurred at the lowest fiber loading levels studied--300 f/mm^2. Much of the improvement occurred during the latter half of 1978. Two factors may have contributed to this performance improvement: (1) fiber counting methods such as NIOSH P&CAM 239 improved the standardization of counting rules and microscopes, recommended counter training and internal quality control involving frequent re-counting; (2) AIHA's industrial hygiene laboratory accreditation program began its first large scale re-accreditation involving site visits of laboratories. Much of the improvement in total variability in 1978 was related to a reduction in intercounter variability, a possible consequence of these two factors.

A similar improvement in chrysotile intercounter performance could not be demonstrated when NIOSH 7400 was published in 1984. NIOSH 7400 incorporated improvements in fiber counting rules, counter training requirements, microscope and graticule standardization, mounting techniques, working conditions for counters, and extensive internal quality control including the exchange of field samples. However other factors such as an increase in the number of PAT Program participating laboratories not participating in a laboratory accreditation program, an increase in the amount of fiber counting being conducted in the field at abatement sites, and the rapid growth in counters may be significant confounding factors -- masking improvements in analytical methods. The 1986 PAT study expressed concern that future performance might deteriorate since laboratories with little PAT Program experience were found to have poorer intercounter precision. There were many laboratories in the late 1980s with little asbestos fiber counting experience, due to the rapid growth in asbestos fiber-counting related to asbestos removal in public buildings. Fortunately, there is no evidence that performance deteriorated in the 1980s.

Amosite total RSD estimates at the 300 fibers/mm^2 loading improved by one-third to one-half within one year, two amosite PAT Program rounds after amosite was introduced into the program in 1986. This is consistent with the finding of the 1986 PAT Program study that laboratories improve chrysotile performance as they gain chrysotile proficiency test experience and suggests that it is useful to challenge laboratories with a variety of fiber types in proficiency testing to both obtain a good estimate of a laboratory's ability to count a variety of fiber types and to improve performance. For 300, 500, and 700 fibers/mm^2, amosite RSD_T^S are about one-third lower than chrysotile.

A reduction in recent rounds in chrysotile intracounter RSDs of 1/3 to 1/2 was found at both 300 and 500 fibers/mm^2, relative to RSDs in 1978. Amosite RSD_{WT}s are about 20% lower than chrysotile.

A reduction in recent rounds in chrysotile intercounter RSDs of about 35% was found at both 300 and 500 fibers/mm^2, relative to RSDs in 1978. Amosite RSD_{BC}s are between 20% and 30% less than chrysotile.

APPENDIX

MODELS FOR CHANGES IN RSDS BETWEEN PERIODS

Some of the differences across period and by loading can be quantified by making statistical models for the total RSD estimates. Several different kinds of models have been constructed. Plots indicate the dependence of RSD estimates on loading. Thus, the models need to adjust for loading. One way to do this, is to pick the highest median concentration sample from each round, and construct regression models using the selected samples. Explanatory factors to be included in these regression models are the median determinations for the selected rounds, the period, and the round within each period. The hope is that by choosing maximum samples, the spread in loading is less, and, therefore, the rounds would be more comparable. A similar approach can be used for the lowest loadings. One problem here is that there is considerable spread in both the lowest and highest loadings. The accompanying Table VIII demonstrates this.

Another approach is to model the total RSD estimates in each round as a function of sample median. Thereby, the relationship between RSD and loading can be used to obtain predicted values of total RSD for various loadings in each round. Examination of the frequency distribution of the medians from all rounds indicates that 300, 500, and 700 fibers/mm^2 are good choices for loadings, since most rounds have minimum sample medians less than 300 and most have maximum sample medians greater than 700 fibers/mm^2. In fact, about 40% of rounds have minimum loadings less than

300 fibers/mm^2. The corresponding point for maximum loadings is about 800, but only two rounds from period 7 would qualify. Thus, 700 is used as the highest loading.

In this approach, a quadratic model in sample median is used to describe the four total RSD estimates in each round. Predicted values and standard errors of these predicted values are obtained at each of the three loadings mentioned above. Although for all rounds it is possible to make predictions at the three mentioned loadings, it makes no sense to do this for any specified loading for rounds in which the four sample medians are all lower or all higher than the specified loading. Thus, for each of the three loadings, only those rounds are included in the subsequent analysis for that loading if the round's lowest loading is no more than a little higher than the specified loading, and if the round's highest loading is no less than a little lower than the specified loading. By a "little higher," we mean that the minimum median should not exceed the specific target amount (300, 500, or 700) by more than 10 fibers/mm^2. By a "little lower," we mean that the maximum median of the given round should not be more than 10 fibers/mm^2 lower than the target amount.

For each of the three loadings, regression models are fitted over the seven periods, in which the natural log of the predicted value of the RSD is regressed on period and round within period. Since in the fullest model the round and round*round factors are allowed to differ from period to period, there are many factors to include in the fullest model. Thus, for instance, if data for six of the seven periods have appropriate ranges for the particular loading, then since each period is allowed an intercept and linear and quadratic trends within period, there are 6 X 3, or 18 parameters in the full model. Therefore, a selection procedure called Mallow's C_p is used to select a group of acceptable models before a decision is made about a final model for determination of period differences.[9]

The within round quadratic models require that the predicted values produced by the quadratic models be weighted to reflect the variability associated with these predictions. The weights used are the reciprocal of the squared estimated standard errors of the predictions. The weights are larger for those predicted RSD_Ts that come from models which describe a higher proportion of the variability in the RSD data for the round, and also take into account whether the medians in the round's data are close to or far from the particular loading value at which the prediction is made.

The actual method of comparison of periods requires that the RSDs associated with two periods will be called statistically different if the lower confidence limits of one period exceed the upper confidence limits of the other period. The aim is to make all comparisons of the periods over all three loadings, and to have 90% confidence for all comparisons. Since separate comparisons are made at all three loadings, the confidence bands used are 96.7% confidence bands(given below), which hold simultaneously for all comparisons of periods at any given loading. Over all three loadings, the error rates add -- so that the error rate for the simultaneous comparisons is 3*3.333%, or 10%. Thus, the confidence in all comparisons is (1 - .10) X 100%, or 90%, as desired.

As an example of the confidence bands, consider the model for 300 fibers/ mm^2, predicted values from which are displayed in Figure 4. The fitted model has seven parameters -- two parameters for the straight line fitted to period 1 data, one parameter for the horizontal line fitted to period 4 data, three parameters for the curve fitted to period 5 data, and one parameter for the single horizontal line fitted to periods 6 and 7 data. The 96.7% simultaneous confidence limits for all rounds over all periods are given by:[10]

(Est. RSD) +- SQRT(7*$F^{.9667}$ (7,49)) * standard error(Est. RSD),

where Est. RSD denotes the fitted value, under the model, at a particular round, 49 denotes the number of degrees of freedom of the residual mean square from the analysis of variance, $F^{.9667}(7,49)$ is the upper 96.7% point of the F distribution with 7 and 49 degrees of freedom.

Rather than use overlapping confidence intervals as the criterion for significant differences between time periods, we could evaluate the differences between the predicted values of rounds in period 4 versus rounds in other periods. Thus, in place of Est. RSD in the above formula, we might use Est. RSD (period 4, round i) -Est. RSD (period 7, round j) for all rounds i and j. However, there seems to be little difference in conclusions, when this model is used.

The results given in the main part of the paper indicate that at 300 fibers/ mm^2, period 4 total RSDs exceed those of periods 6 and 7. Since the period 4 data used in the comparison consist of only eight rounds, it seems wise to ask how sensitive the results are to weights used in fitting the models, and to possible outliers.

The weighting scheme was described above. As a modification of it, an iterative weighting scheme was used to smooth the weights. It was a version of a biweight weighting scheme.(11) The results are similar to those obtained without iterating the weights, at each of the loadings studied.

Another concern is the possible presence of outliers in the data. As indicated in the text, few measurements were removed. Variances are very sensitive to data far away from the bulk of the data, and there is no question that inclusion of some of the removed points would inflate the variance estimates. It is expected that for rounds where there are fewer laboratories, the effect of including these excluded points would be bigger than for rounds with many laboratories. Thus, it is expected that if all measurements were included, period 4 would differ more from periods 6 and 7 than when some measurements are excluded.

Another approach to the effect of outliers was to use a different estimate of relative variability - the ratio of the sample median of absolute values of (lab determination - sample median) to sample median. Since the median is not sensitive to far away measurements, this measure would not be sensitive to such points.

The analyses based on this measure lead to similar results to those using the RSD estimates. At 300 fibers/mm^2, the period 6 ratios are statistically distinguishable from period 4 at the 10% significance level, but period 4 (modeled by a horizontal line) and the middle rounds of period 7 (modeled by a quadratic) are not statistically distinguishable.

MODELS FOR CHANGES IN INTRACOUNTER AND INTERCOUNTER RSDS BETWEEN PERIODS

The intracounter and intercounter standard deviations of the PAT data must be estimated differently from the total variability. The approach used in the previous paper[3] selected rounds with paired samples, in which the means of these paired samples differed by no more than 100 fibers/mm^2, or 150 fibers/mm^2 in the comparison of amosite and chrysotile. The present analyses use the same criterion, except that medians are used instead of means. The estimates are obtained from the residual mean squares of analyses of variance, in which square roots of the individual measurements for the paired samples in each selected round are used as the response values. The explanatory factors in the analyses of variance are the sample number and the laboratory identifier. Table IV indicates which rounds have such paired samples. These are not always the same pairings obtained in the earlier paper, since some rounds had several possible pairings meeting the matching criterion, and only one such pairing is used here.

The intention in using the matching scheme is that if loadings are similar, then the counters should yield consistent counts for the two samples. If this is not true, then the variance estimate is inflated by interaction.

A further problem is that we do not know how the variance changes with increased loading. An earlier paper[10] on the PAT silica data studied the dependence of the intracounter estimate of variability on the absolute value of the difference between sample medians of the matched samples. The smaller the absolute value of this difference, the smaller the estimated intracounter RSD, based on the residual from the analysis of variance. It seems sensible, then, to use a matching rule, since, ideally, an estimate of within laboratory variability would be based on samples at the same loading, which would have zero difference between their median loadings.

The form of the confidence bands for both intracounter and intercounter RSDs is similar to that given for total RSDs in the previous section. The difference is that because of the nature of the matching scheme, at most one intracounter and one intercounter RSD estimate is obtained per round, and each round's estimates are at different loadings. Thus, the full models for both intracounter and intercounter RSDs include terms for changes across round within period, and also factors for median loading and interaction of median loading with round within period. Again, Mallow's C_p is used to choose a satisfactory model from the terms included in the full model. One model is selected for all loadings for intracounter RSD, and one model is selected for all loadings for intercounter RSD. For example, the chosen model for intracounter RSD (model results displayed for 300 fibers/mm^2 in Figure 6) includes an intercept, which estimates the RSD for periods 1,5, and 6; a term for linear trend across rounds in period 4; separate intercept, linear trend, and quadratic trend terms for period 7; and a term for linear trend in loading. These are six parameters. Confidence limits for any loading are given by:

$$(\text{Est. RSD}) \pm (6 * F^{.90}(6,50))^{.5} * \text{standard error (Est. RSD)},$$

where Est. RSD denotes the fitted value, under the model, 50 denotes the degrees of freedom of the residual mean square in the analysis of variance, $F^{.90}(6,50)$ is the upper 90% point of the F distribution with 6 and 50 degrees of freedom. Fifty-six rounds of data, each contributing one intracounter RSD estimate, were used in fitting the model. The same model was used to make predictions for any loading, which is why the 90% point is used to obtain confidence limits that hold simultaneously for all estimates and all comparisons at the 90% confidence level. As was done for total RSDs, confidence limits on differences of predicted values may also be obtained from the above formula. An analogous procedure is used for the intercounter RSD model.

For both intracounter and intercounter RSDs, a variety of models were fitted, based on the C_p statistic, and the results of the comparisons were similar to those of the models presented in Figures 6 and 7.

CONVERSION OF ESTIMATED RSDS FROM SQUARE ROOT TO ORIGINAL SCALE

It can be shown that for data that are normally distributed on the square root scale, the true RSD on the original scale (RSDO) is approximately twice the true RSD on the square root scale. This approximation works best for small values of the RSD. An exact formula can be derived as follows: if X is normally distributed on the square root scale, with mean μ and variances σ^2, then the mean of X^2 is $\mu^2 + \sigma^2$, and the variance of X^2 is $2\sigma^2 (2\mu^2 + \sigma^2)$.

Thus:

$$\mathrm{RSDO} \quad \frac{2\ \sigma\ \ 2\mu^2\ \ \sigma^2}{\mu^2\ \ \sigma^2} \quad \frac{2\ \mathrm{RSD}\ \ 2\ \ \mathrm{RSD}^2}{1\ \ \mathrm{RSD}^2}$$

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TABLE I

PAT Asbestos Fiber Counting -- Variance Components

Variance Components	Confounding Pattern	Terminology - Relative Variance
1. Laboratory to Laboratory, or Between Laboratories. $RSD^2 = RSD^2_B$	1. and 2.	Intercounter Variability $RSD^2 = RSD^2_{BC} = RSD^2_B + RSD^2_C$
2. Counter to Counter, Within a Laboratory. $RSD^2 = RSD^2_C$		
3. Within Counter. $RSD^2 = RSD^2_W$	3. and 4.	Intracounter Variability $RSD^2 = RSD^2_{WF} = RSD^2_W + RSD^2_F$
4. Filter to Filter* $RSD^2 = RSD^2_F$		
5. Total $RSD^2 = RSD^2_T$		Total Variability $RSD^2_T = RSD^2_{BC} + RSD^2_{WF}$

* Can be estimated from PAT Program sample producer quality control of PAT asbestos sample homogeneity for PAT rounds 46 and later.

Unless otherwise indicated, the intracounter RSD^2 component will include both within counter and filter-to-filter variability.

Total variability, RSD^2_T, is the sum of all four components above, but because of confounding:

$$RSD^2_T = RSD^2_{WF} + RSD^2_{BC}.$$

Also, if $S1_T$ and $S2_T$ are unbiased estimates of RSD^2_T, and W1 is an unbiased estimator of RSD^2_{WF}, then:

$$\text{Mean}\left(\frac{S1_T \quad S2_T}{2} \quad W1\right) \quad RSD^2_{BC}.$$

Thus, an obtain unbiased estimator of RSD^2_{BC} can be obtained when there are unbiased estimators of the other components.

TABLE II

Changes in the Proficiency Analytical Testing Program
Asbestos

Per	Round	Date	Sampling and Analytical Method	Labs	Sample	Producer	Accred
01	01-26	05/72-01/74	USPHS68	g	chry.	NIOSH	None
02	27-29	02/74-06/74	USPHS68	g&p	chry.	NIOSH	Accred.
03	30-32	08/74-02/75	USPHS68	g&p	chry.	CAP	Accred.
04	33-45	03/75-11/77	PCAM239	g&p	chry.	CAP	Accred.
05	46-75	01/78-10/83	PCAM239	g&p	chry.	SRI	Reacc.
06	76-85	01/84-04/86	NIOSH7400	g&p*	chry.	SRI	Reacc.
07	86-END	07/86-END	NIOSH7400	g&p*	+amosite	SRI	Reacc.

Legend

Methods
USPHS68 Method = 1968 US Public Health Service method[4]
PCAM239 Method = NIOSH P&CAM 239 method published in 1979 but distributed to PAT participants starting in 1975.[5]
NIOSH7400 = NIOSH 7400 method and subsequent revisions.[6]

Labs
g Labs = government labs
g&p Labs = government & private labs
g&p* Labs = growth in participation of many labs that perform asbestos but no other industrial hygiene analyses.

Sample
chry. = PAT sample are chrysotile
+amosite = PAT samples rotated each round among amosite and chrysotile. Starting with round 88 even rounds are amosite.

Producer
NIOSH = NIOSH producer of PAT samples
CAP = College of American Pathology's subcontractor, Hyland Labs, producer of PAT samples.
SRI = SRI International producer of PAT samples.

AIHA Accreditation Program Site Visits
Accred. = AIHA accreditation program in operation, and initial site visits of laboratories being performed.
Reaccred. = AIHA accreditation program in operation and re-site visit and evaluation of laboratory operations being performed.

TABLE III

Phase Contrast Microscope Asbestos Fiber Methods

Method	USPHS 68[4]	PCAM 239[5]	NIOSH 7400[6]
Counting Rules	Vague	More Specific - Field Boundary - Fiber Bundles	Specific - Examples - No Hybrid Rules
Training	None	Recommended 1 Counter/Lab	Required Each Counter
Microscope Standardization	Little	Scope Differences Cited	Required Resolution Test
Graticule	Porton/Other	Porton/Other	Walton-Beckett
Mounting	Dimethyl phthalate 2-30 days	Dimethyl phthalate 2 days	Acetone/Triacetin Hot Block/Video Almost Permanent
Working Conditions	Not Specified	Not Specified	Specified - Room lighting - Breaks - Ergonomics
Quality Control	Not Specified	Recommended - 10% Recounts - Workshops - Recommended Differences	Required - Field Blanks - Reference Slides - 10% Blind Recounts - Proficiency Testing - Sample Exchanges

TABLE IV

Chrysotile Total Variability Estimates

Round*	#Labs**	Sample 1 Median f/mm^2	Sample 1 RSD	Sample 2 Median f/mm^2	Sample 2 RSD	Sample 3 Median f/mm^2	Sample 3 RSD	Sample 4 Median f/mm^2	Sample 4 RSD
3	5	L 148	0.776	270	0.661	350	0.507	H 530	0.462
5	9	268	0.717	L 260	0.688	404	0.693	H 580	0.445
7	11	304	0.664	H 356	0.697	L 170	0.854	260	0.644
8	9	363	0.236	H 638	0.528	392	0.531	L 321	0.532
9	7	L 686	0.439	980	0.308	980	0.627	H 1257	0.526
11	10	L 444	0.412	989	0.529	H 1564	0.497	1462	0.539
12	11	H 2225	0.573	966	0.386	L 383	0.526	1337	0.668
13	11	H 1132	0.575	L 535	0.469	1086	0.467	975	0.535
14	11	H 1157	0.582	L 760	0.520	1066	0.563	787	0.800
15	14	L 550	0.522	H 1357	0.515	1229	0.641	746	0.471
16	19	344	0.717	L 158	0.675	556	0.663	H 713	0.635
17	20	842	0.488	L 320	0.494	375	0.496	H 873	0.516
18	20	H 1062	0.393	436	0.507	1013	0.425	L 300	0.476
19	18	526	0.379	H 887	0.400	440	0.425	L 87	0.779
20	19	700	0.438	L 391	0.390	H 858	0.434	488	0.525
21	19	H 1233	0.406	1128	0.430	429	0.449	L 323	0.391
22	23	L 75	0.883	98	0.805	H 320	0.648	104	0.613
23	23	H 400	0.601	L 137	0.337	184	0.611	257	0.456
24	25	L 23	0.902	416	0.608	1060	0.399	H 1675	0.417
25	31	1100	0.587	H 2053	0.552	490	0.530	L 186	0.489
26	27	760	0.440	H 1161	0.456	938	0.442	L 253	0.515
27	49	H 1198	0.624	383	0.619	L 336	0.805	825	0.657
28	53	291	0.599	H 1875	0.511	L 119	0.729	501	0.856
29	57	L 194	0.733	1035	0.638	425	0.718	H 1490	0.572
30	57	L 340	0.584	679	0.600	H 806	0.621	567	0.562
31	61	H 2332	0.581	1029	0.754	L 319	0.648	1998	0.596
32	69	L 1510	0.493	1643	0.492	2090	0.482	H 2343	0.403
33	70	1335	0.542	H 1994	0.549	929	0.517	1323	0.553
34	72	L 100	0.745	322	0.817	H 2419	0.591	1495	0.655
35	76	L 284	0.699	673	0.694	1141	0.675	H 2446	0.559
36	84	L 900	0.589	1680	0.586	929	0.571	H 2668	0.513
37	83	2388	0.482	L 1026	0.481	H 2556	0.457	1224	0.544
38	87	L 561	0.504	H 2347	0.514	1770	0.586	1089	0.528
39	87	H 2490	0.500	680	0.517	844	0.489	L 232	0.658
40	96	L 99	0.973	233	0.770	189	0.797	H 547	0.644
41	93	203	0.791	707	0.648	L 116	0.790	H 1287	0.627

* Round 67 data are not included in this study because of a problem with the data.

** Although the column contains the total number of laboratories in each round, the sample estimates are often based on slightly fewer estimates because measurements are removed as a result of an outlier test.

TABLE IV (continued)

Chrysotile Total Variability Estimates

Round	#Labs		Sample 1 Median f/mm²	Sample 1 RSD		Sample 2 Median f/mm²	Sample 2 RSD		Sample 3 Median f/mm²	Sample 3 RSD		Sample 4 Median f/mm²	Sample 4 RSD
42	102		1193	0.541		262	0.725	L	50	0.900	H	1250	0.590
43	106		333	0.651	L	257	0.804		286	0.706	H	349	0.742
44	110		160	0.674		98	0.718	H	1025	0.552	L	33	0.822
45	116		614	0.560	H	1380	0.568	L	84	0.784		866	0.592
46	123	L	154	0.623		328	0.755	H	441	0.712		236	0.679
47	121		394	0.638		359	0.657	H	431	0.710	L	303	0.675
48	119		255	0.643		332	0.679	H	467	0.706	L	129	0.671
49	127	H	678	0.618		395	0.534	L	265	0.521		383	0.619
50	128		468	0.509	L	160	0.572	H	685	0.503		199	0.557
51	133	H	331	0.452		265	0.479	L	196	0.461		317	0.441
52	137	L	153	0.384		468	0.380	H	560	0.380		294	0.387
53	149		473	0.429	H	661	0.408	L	394	0.414		683	0.402
54	151		562	0.460	L	376	0.434	H	709	0.461		392	0.457
55	148	L	237	0.420		576	0.394	H	784	0.395		377	0.399
56	160		309	0.460	L	101	0.552	H	678	0.459		468	0.451
57	165		322	0.485		271	0.607	L	146	0.496	H	693	0.472
58	168	L	185	0.492		515	0.443	H	632	0.395		318	0.436
59	173		900	0.412	L	283	0.507	H	974	0.452		473	0.454
60	182	H	1065	0.391	L	537	0.457		982	0.395		745	0.437
61	185	H	1235	0.358		682	0.368	L	369	0.403		603	0.409
62	190		748	0.340		971	0.366	L	320	0.376	H	1214	0.359
63	190		602	0.348		970	0.305	H	1430	0.343	L	314	0.459
64	196		929	0.330		696	0.368	L	320	0.390	H	968	0.344
65	205		547	0.370	H	913	0.308		736	0.379	L	463	0.404
66	203	H	1142	0.394		995	0.387	L	679	0.409		1086	0.400
68	218		770	0.336	H	1062	0.316	L	686	0.353		841	0.411
69	237	H	1167	0.325		866	0.316	L	549	0.327		670	0.338
70	247	L	585	0.340		932	0.335		750	0.326	H	1084	0.315
71	249		858	0.322	H	1279	0.324	L	528	0.379		850	0.351
72	252	H	868	0.392		423	0.382		774	0.393	L	305	0.444
73	257	L	343	0.398	H	672	0.368		368	0.409		534	0.403
74	268	L	217	0.547		560	0.371		786	0.402	H	823	0.346
75	291	H	810	0.414		713	0.402	L	280	0.498		454	0.434
76	294	L	320	0.450		532	0.422	H	640	0.422		464	0.426
77	324	H	709	0.432		568	0.399	L	180	0.468		441	0.422
78	332		432	0.411		631	0.390	H	633	0.479	L	310	0.429
79	336	L	180	0.506	H	529	0.408		267	0.458		521	0.427
80	363	H	838	0.376	L	197	0.451		660	0.402		375	0.394
81	377		562	0.399	L	173	0.480		622	0.377	H	868	0.409
82	382		488	0.384	H	763	0.403		645	0.394	L	133	0.480
83	401	L	234	0.488		720	0.415	H	914	0.392		344	0.440
84	401	L	252	0.414		623	0.425	H	839	0.376		341	0.444
85	458		764	0.369	H	905	0.342	L	167	0.478		776	0.366

TABLE IV (continued)

Chrysotile Total Variability Estimates

Round	#Labs	Sample 1 Median f/mm^2	Sample 1 RSD	Sample 2 Median f/mm^2	Sample 2 RSD	Sample 3 Median f/mm^2	Sample 3 RSD	Sample 4 Median f/mm^2	Sample 4 RSD
87	528	L 185	0.499	604	0.442	H 626	0.427	356	0.438
89	564	369	0.434	635	0.434	L 242	0.497	H 645	0.427
91	679	488	0.407	278	0.417	H 572	0.382	L 165	0.452
93	755	415	0.406	673	0.382	H 903	0.400	L 273	0.450
95	919	287	0.529	451	0.517	H 664	0.457	L 160	0.536
97	883	L 283	0.505	688	0.372	543	0.362	H 808	0.353
99	1145	L 135	0.446	370	0.432	H 700	0.371	215	0.395
101	1208	203	0.484	L 176	0.456	283	0.451	H 435	0.398
103	1237	L 166	0.409	369	0.383	495	0.407	H 556	0.387
105	1213	H 694	0.342	564	0.330	L 216	0.379	299	0.369

H = Estimate used in Figure 1 plot of highest loadings.
L = Estimate used in Figure 2 plot of lowest loadings.

TABLE V

Chrysotile Intracounter and Intercounter Variability Estimates

Period	Round	Matched Samples	Degrees of Freedom*	Loading f/mm²	RSD_{WF}	RSD_{BC}
1	3	(2,3)	4	310	0.143	0.579
1	5	(1,2)	8	264	0.428	0.597
1	7	(3,4)	10	215	0.377	0.701
1	8	(1,3)	7	377	0.274	0.323
1	9	(2,3)	6	980	0.299	0.419
1	13	(1,3)	10	1109	0.617	< 0
1	14	(2,4)	10	773	0.691	< 0
1	17	(2,3)	19	348	0.230	0.448
1	18	(1,3)	19	1037	0.239	0.339
1	19	(1,3)	17	483	0.340	0.225
1	20	(2,4)	18	439	0.257	0.397
1	22	(1,4)	21	90	0.366	0.716
1	23	(3,4)	22	220	0.377	0.410
2	27	(2,3)	48	359	0.460	0.606
4	33	(1,4)	69	1329	0.237	0.504
4	36	(1,3)	83	915	0.261	0.531
4	40	(1,3)	94	144	0.581	0.778
4	41	(1,3)	91	160	0.473	0.689
4	42	(1,4)	101	1221	0.241	0.524
4	43	(2,4)	104	308	0.485	0.660
4	44	(1,2)	108	129	0.435	0.584
5	46	(1,4)	120	195	0.476	0.487
5	47	(2,3)	120	395	0.359	0.611
5	48	(1,2)	118	293	0.274	0.619
5	49	(2,4)	125	390	0.374	0.466
5	50	(2,4)	128	180	0.363	0.455
5	51	(2,4)	131	291	0.280	0.377
5	52	(2,3)	135	514	0.212	0.321
5	53	(2,4)	148	672	0.177	0.368
5	54	(2,4)	149	384	0.206	0.401
5	57	(1,2)	163	296	0.385	0.418
5	59	(1,3)	172	937	0.245	0.364

* The degrees of freedom is the degrees of freedom corresponding to the residual from the analysis of variance, which adjusts the square roots of laboratory determinations in the matched samples for different loadings of those samples, and for differences between laboratories. If there were L laboratories, the residual would have L-1 degrees of freedom. Because of removal of possible outliers, the degrees of freedom is often less than L-1. (Compare with Table III.)

TABLE V (continued)

Chrysotile Intracounter Variability Estimates

Period	Round	Matched Samples	Degrees of Freedom	Loading f/mm^2	RSD_W	RSD_B
5	60	(1,3)	181	1024	0.189	0.349
5	61	(2,4)	182	635	0.253	0.303
5	64	(1,4)	194	948	0.185	0.286
5	65	(1,4)	204	505	0.210	0.331
5	66	(2,4)	202	1041	0.198	0.345
5	68	(1,4)	214	805	0.220	0.311
5	71	(1,4)	246	852	0.204	0.272
5	72	(1,3)	250	854	0.236	0.320
5	73	(1,3)	255	356	0.245	0.328
5	74	(3,4)	266	805	0.189	0.329
5	75	(1,2)	290	761	0.220	0.350
6	76	(2,4)	292	498	0.241	0.356
6	78	(2,3)	331	632	0.280	0.346
6	79	(1,3)	333	224	0.278	0.407
6	81	(1,3)	375	593	0.280	0.277
6	84	(1,4)	397	297	0.305	0.315
6	85	(1,4)	454	770	0.218	0.301
7	87	(2,3)	526	616	0.201	0.391
7	89	(2,4)	563	640	0.218	0.380
7	91	(1,3)	677	531	0.208	0.341
7	99	(1,4)	1139	175	0.241	0.354
7	101	(1,3)	1207	243	0.299	0.372
7	103	(3,4)	1234	525	0.212	0.341
7	105	(3,4)	1210	258	0.177	0.333

TABLE VI

Amosite Total Variability Estimates

Round	#Labs		Sample 1 Median f/mm²	Sample 1 RSD		Sample 2 Median f/mm²	Sample 2 RSD		Sample 3 Median f/mm²	Sample 3 RSD		Sample 4 Median f/mm²	Sample 4 RSD
86	479	L	258	0.585	H	393	0.558		387	0.571		318	0.588
88	557		696	0.407		364	0.409	L	115	0.487	H	702	0.421
90	622	L	326	0.341		528	0.301	H	1046	0.298		747	0.300
92	720	L	250	0.322		874	0.285		383	0.320	H	996	0.297
94	848	H	948	0.289		840	0.259	L	376	0.317		465	0.284
96	862		478	0.277		726	0.271	L	316	0.274	H	958	0.279
98	970		817	0.262	H	1175	0.251		623	0.273	L	367	0.282
100	1178	H	720	0.261		520	0.259	L	157	0.315		391	0.279
102	1245		372	0.244		506	0.287	H	771	0.255	L	269	0.282
104	1167	L	240	0.275		581	0.247	H	812	0.239		396	0.254

H = Highest loading sample in each round.

L = Lowest loading sample in each round.

TABLE VII

Intracounter and Intercounter Precision

Amosite and Chrysotile (Period 7 (After January 1986)

Matching Based on 150 Fibers/mm^2

Round	Asbestos Type	Matched Samples	Degrees of Freedom*	Median	RSD_{WF}	RSD_{BC}
86	Amosite	(1,4)	475	288	0.226	0.552
87	Chrysotile	(2,3)	526	616	0.201	0.391
88	Amosite	(1,4)	555	699	.235	0.349
89	Chrysotile	(2,4)	563	640	.218	0.380
91	Chrysotile	(1,3)	677	530	.208	0.341
92	Amosite	(1,3)	715	316	.181	0.269
93	Chrysotile	(1,4)	752	344	.245	0.359
94	Amosite	(3,4)	844	421	.148	0.264
95	Chrysotile	(1,4)	916	224	.325	0.439
97	Chrysotile	(2,4)	880	748	.175	0.321
99	Chrysotile	(1,4)	1139	175	.241	0.354
100	Amosite	(2,4)	1172	455	.158	0.220
101	Chrysotile	(1,3)	1207	243	.299	0.372
102	Amosite	(1,4)	1232	320	.165	0.208
103	Chrysotile	(3,4)	1234	525	.212	0.341
105	Chrysotile	(3,4)	1210	257	.177	0.333

* See remark in Table V about degrees of freedom.

TABLE VIII

Minimum and Maximum Medians -- Cumulative Frequency Distributions

Minimum Medians fibers/mm^2	Cumulative % < Minimum Median	Maximum Medians fibers/mm^2	Cumulative % Maximum Median
23	1%	320	1%
115	10%	467	10%
154	20%	632	20%
176	30%	685	30%
217	40%	771	40%
258	50%	868	50%
303	60%	968	60%
321	70%	1142	70%
376	80%	1257	80%
550	90%	1994	90%
1510	100%	2668	100%

TABLE IX

PAT Program Summary Statistics. 1986-92

Total Variability

Chrysotile	Finding
0.33 - 0.54 RSD Estimates	
0.44-0.47 RSD Model - 300 f/mm^{2*}	About 36% reduction
0.41-0.43 RSD Model - 500 f/mm^{2*}	from period 4
0.37-0.39 RSD Model - 700f/mm^{2*}	
Amosite	
0.24 - 0.59 RSD Estimates	
0.534 - 0.823 ratio - 300 f/mm^{2**}	About 35% smaller
0.590 - 0.707 ratio - 500 f/mm^{2**}	RSDs for amosite
	than chrysotile

Intracounter Variability

Chrysotile	
0.18-0.33 RSD Estimates	
0.16-0.24 RSD Model - 300 f/mm^{2*}	About 42% reduction
0.14-0.22 RSD Model - 300 f/mm^{2*}	from period 4
Amosite	
0.15-0.24 RSD Estimates	
0.616-0.939 ratio - 300 and 500 f/mm^{2**}	About 22% smaller RSDs
	for amosite than chrysotile

TABLE IX (Continued)
PAT Program Summary Statistics. 1986-92
Intracounter Variability - Continued

Intercounter Variability

Chrysotile	
0.333-0.439 RSD estimates	
0.31-0.40 RSD Model - 300 f/mm^{2*}	About 37% reduction,
0.30-0.39 RSD Model - 500 f/mm^{2*}	compared to period 4
Amosite	
0.208-0.552 RSD Estimates	
0.471-0.847 Ratio- 300 f/mm^{2**}	At 300 f/mm2 amosite RSDs
0.612-1.002 Ratio- 500 f/mm^{2**}	about 34% less than chrysotile

* Simultaneous 90% Confidence Limits

** Simultaneous 90% Confidence Limits on ratio of amosite to chrysotile RSD.

CAPTION LISTING

Figure 1 -- RSD_T estimates and 95% confidence limits for highest loadings -- chrysotile.

Figure 2 -- RSD_T estimates and 95% confidence limits for lowest loadings -- chrysotile.

Figure 3 -- RSD_{WF} estimates and 95% confidence limits for paired loadings -- chrysotile.

Figure 4 -- RSD_T model -- 300 fibers/mm^2 -- chrysotile.
90% confidence limits for all comparisons.

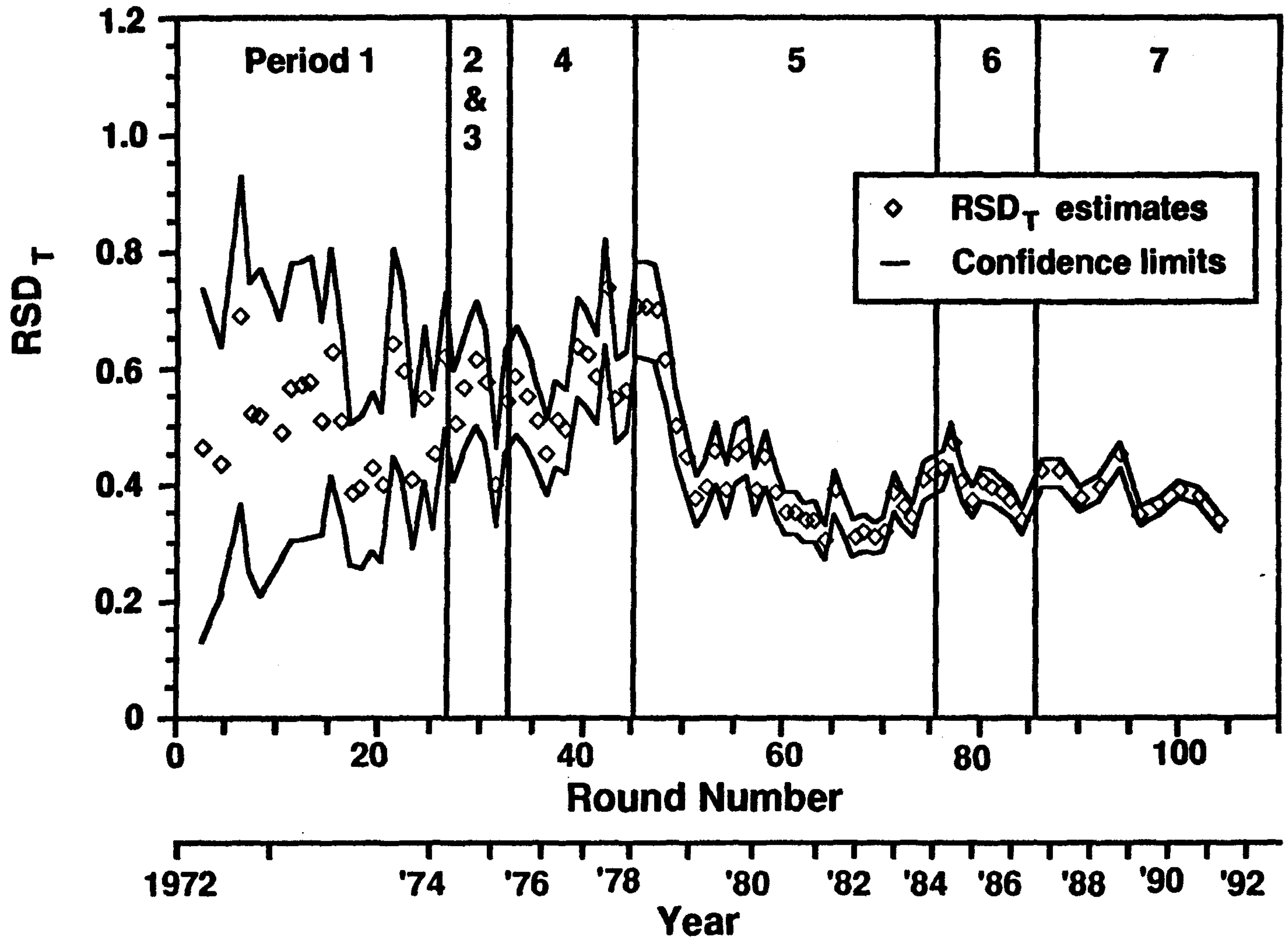
Figure 5 -- RSD_T model -- 500 fibers/mm^2 -- chrysotile.
90% confidence limits for all comparisons.

Figure 6 -- RSD_{WF} model -- 300 fibers/mm^2 -- chrysotile.
90% confidence limits for all comparisons.

Figure 7 -- RSD_{BC} model -- 300 fibers/mm^2 -- chyrsotile.
90% confidence limits for all comparisons.

Figure 8 -- RSD_T estimates and 95% confidence limits for lowest loadings -- period 7 -- chrysotile and amosite.

Figure 9 -- RSD_{WF} estimates and 95% confidence limits -- period 7 -- amosite and chrysotile.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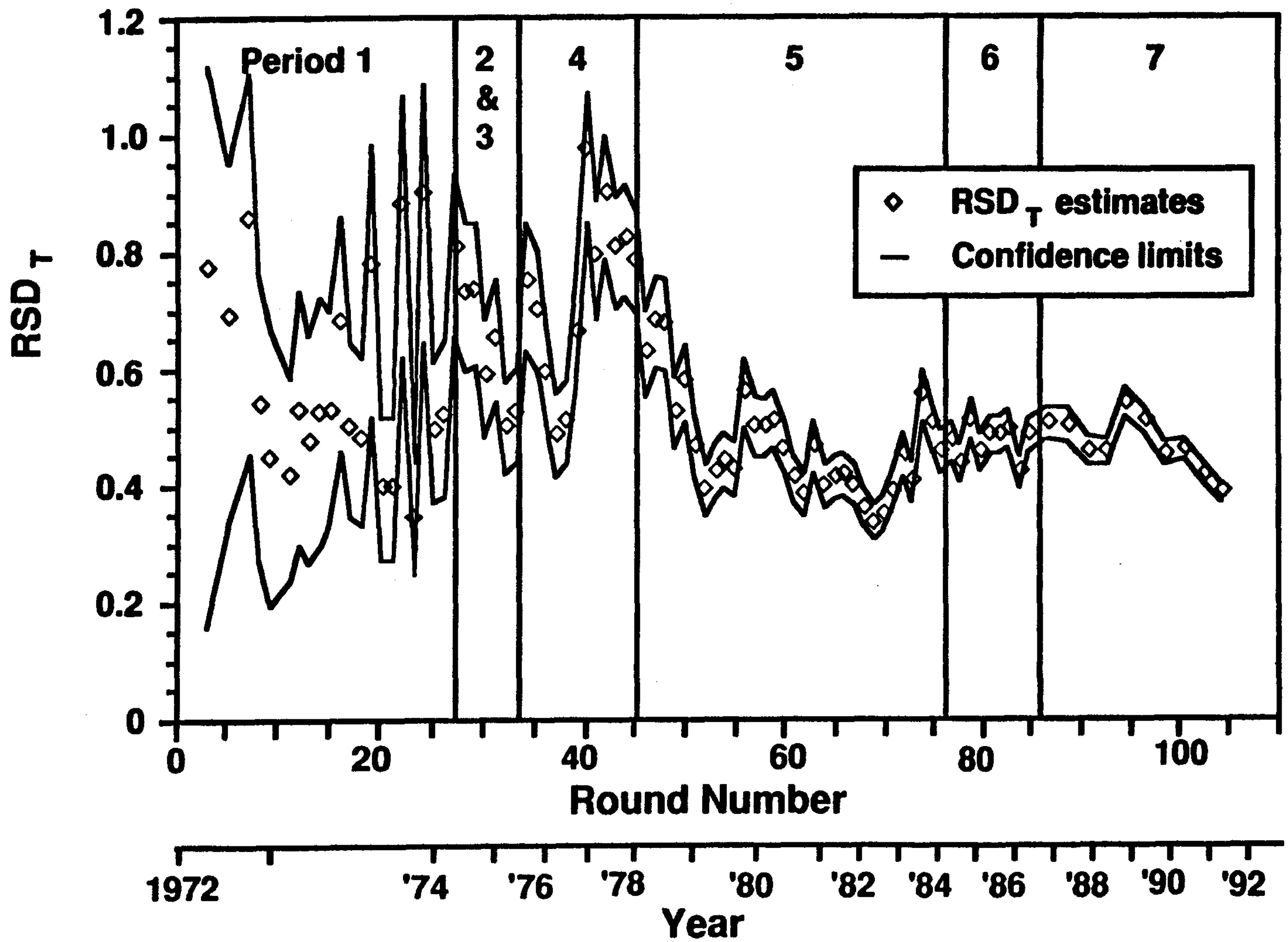
0.8
0.6
0.4
0.2
0
Period 1
2
&
3
4
5
6
7
RSD T estimates
Confidence limits
0
20
40
60
80
100
Round Number
1972
'74
'76
'78
'80
'82
'84
'86
'88
'90
'92
Year



RSD T
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1.0
0.8
0.6
0.4
0.2
0
Period 1
2 & 3
4
5
6
7
RSD T estimates
Confidence limits
0
20
40
60
80
100
Round Number
1972
'74
'76
'78
'80
'82
'84
'86
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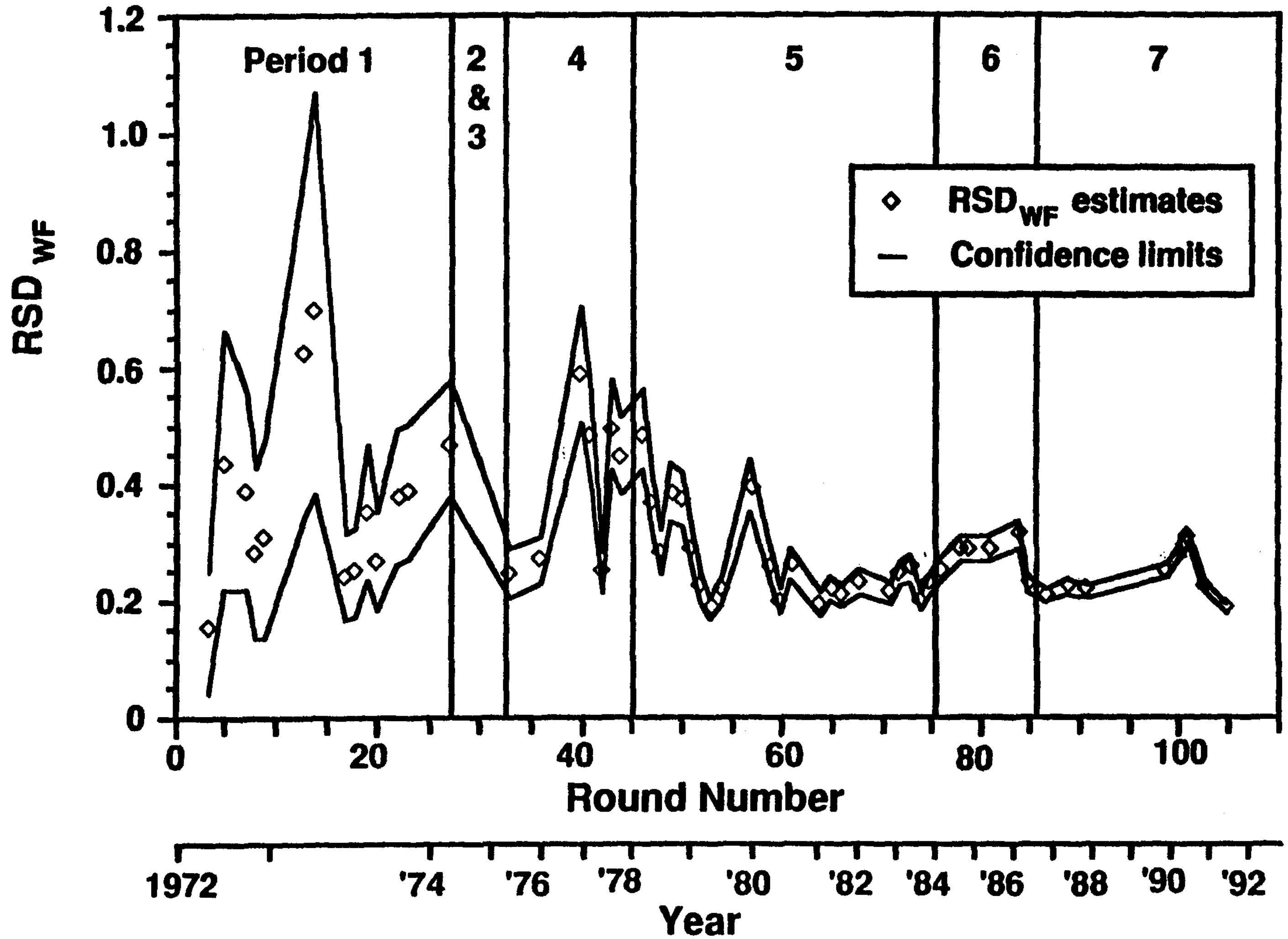
'90
'92
Year



Period 1
2 & 3
4
5
6
7
RSD WF estimates
Confidence limits
RSD WF
1.2
1.0
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
Round Number
1972
'74
'76
'78
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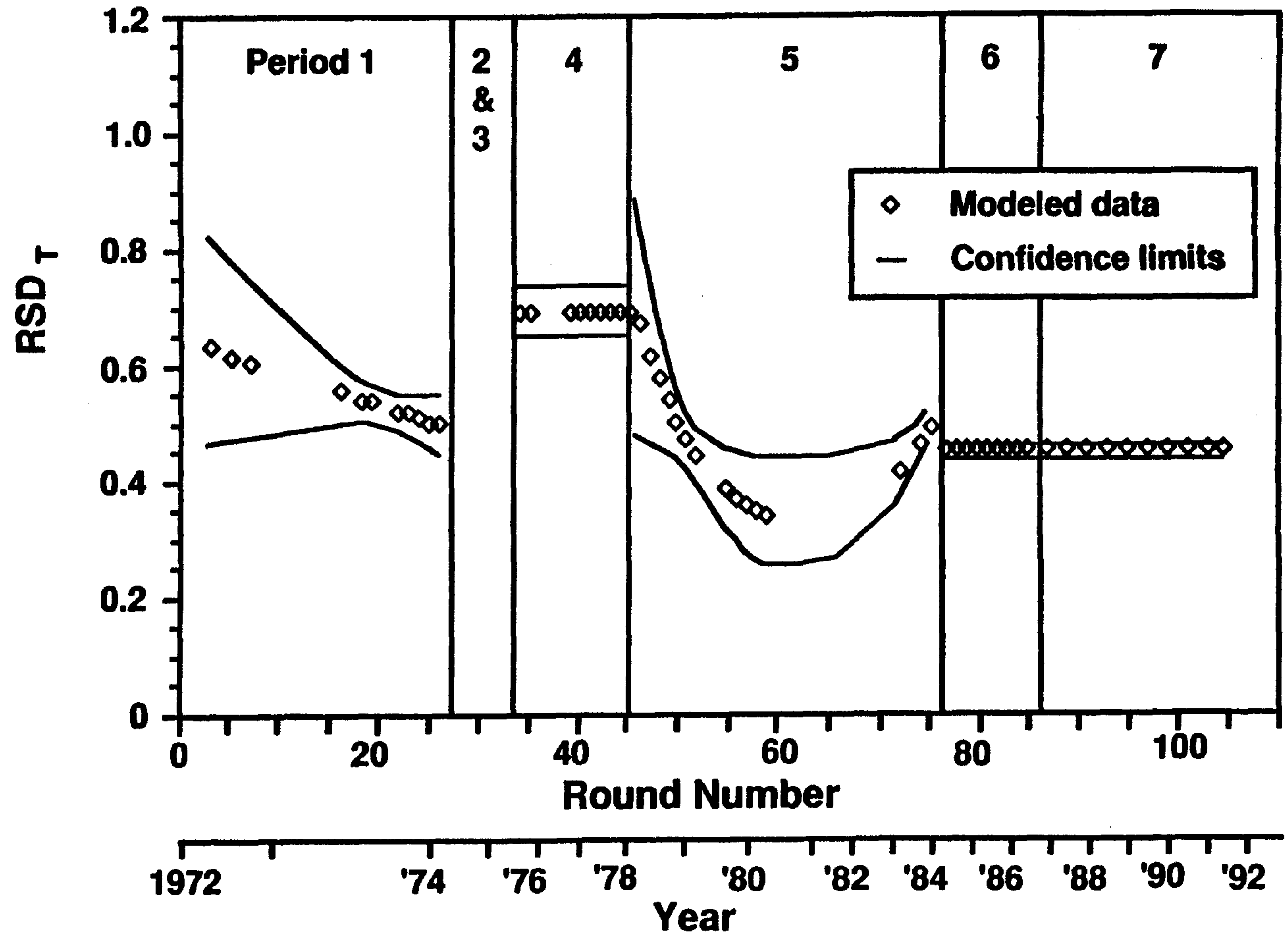
'88
'90
'92
Year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1.0
0.8
0.6
0.4
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Period 1
2 & 3
4
5
6
7
Modeled data
Confidence limits
0
20
40
60
80
100
Round Number
1972
'74
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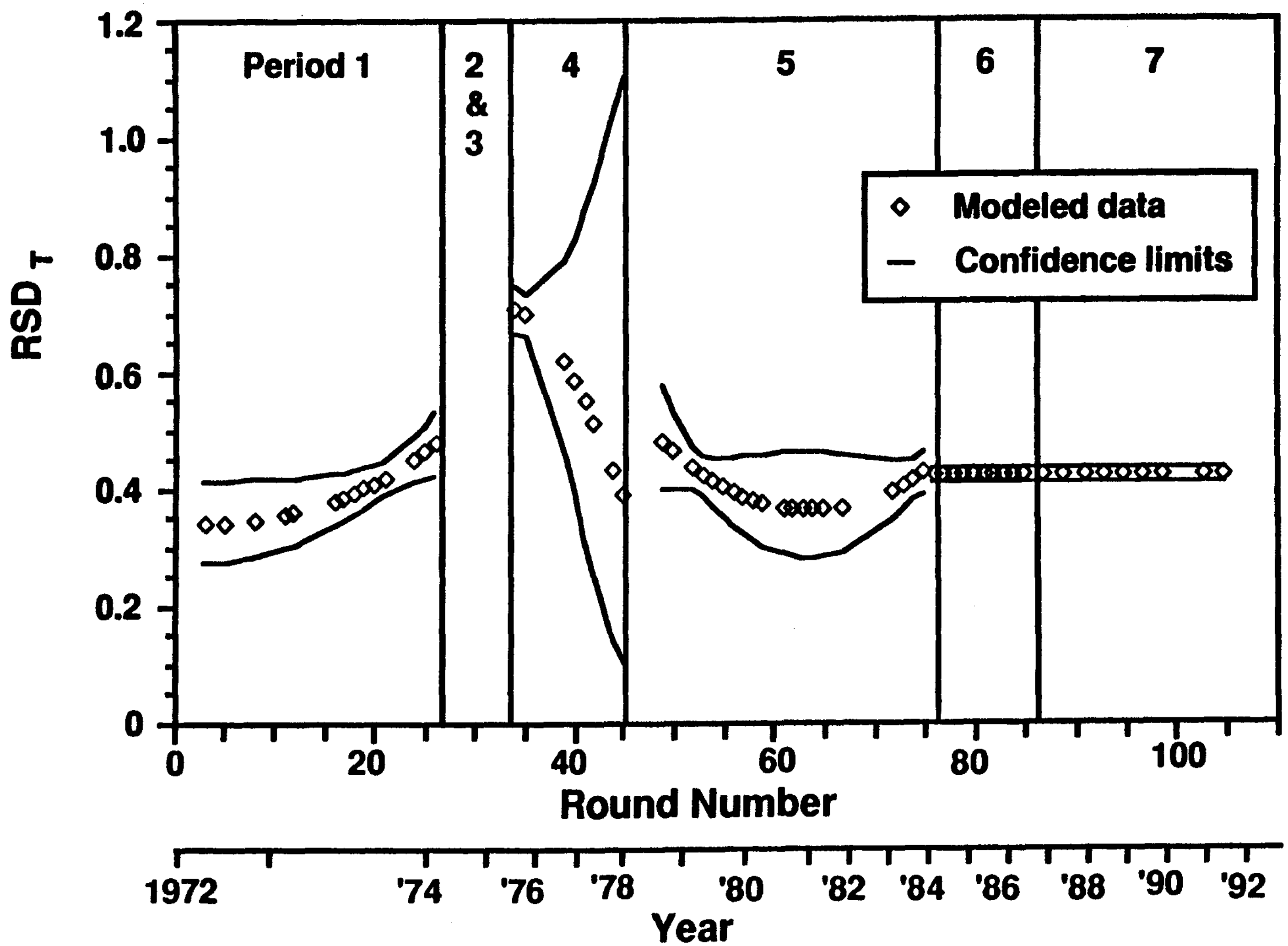
'88
'90
'92
Year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2 & 3
4
5
6
7
Modeled data
Confidence limits
RSD T
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0.6
0.4
0.2
0
20
40
60
80
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Round Number
1972
'74
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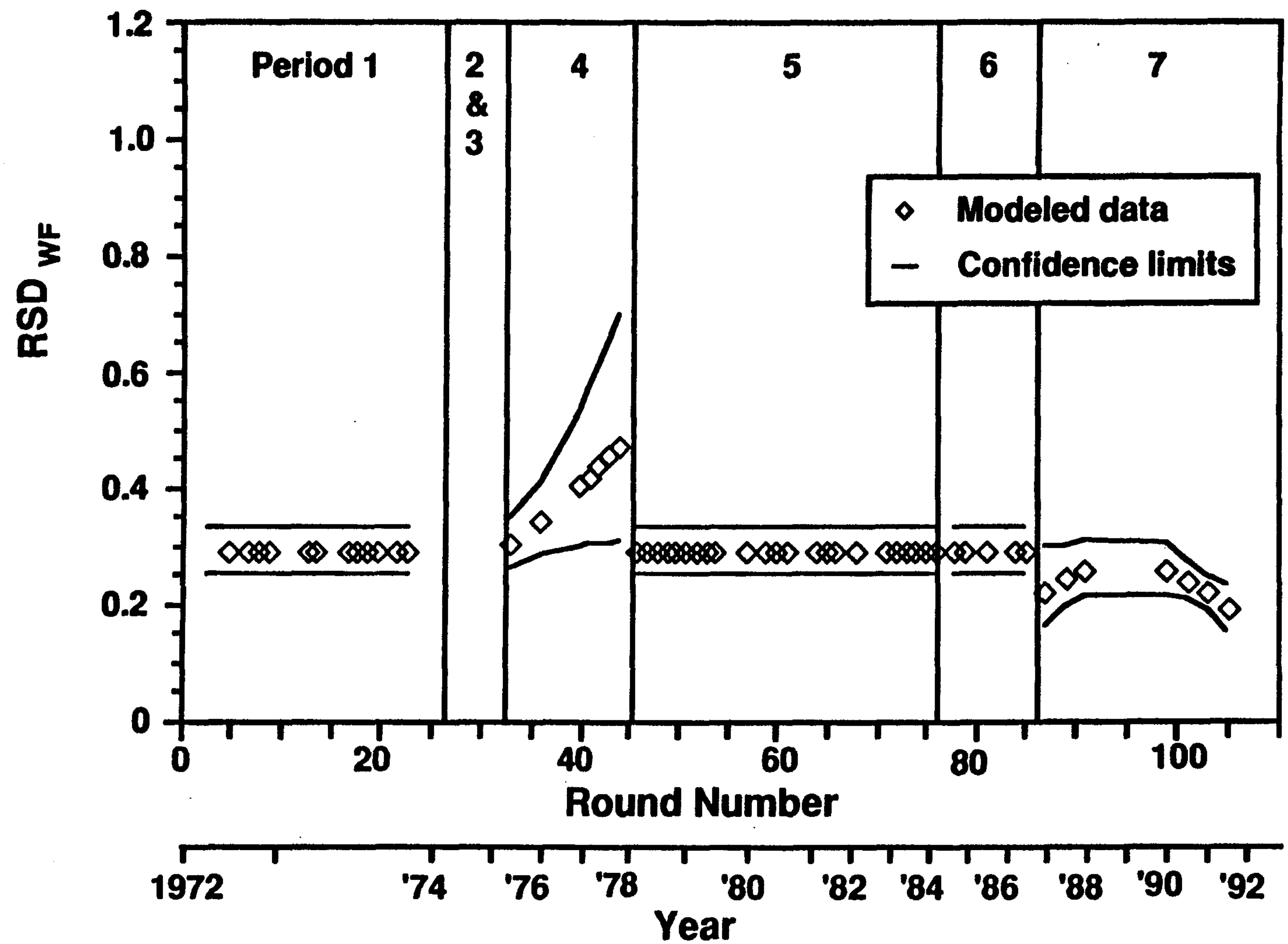
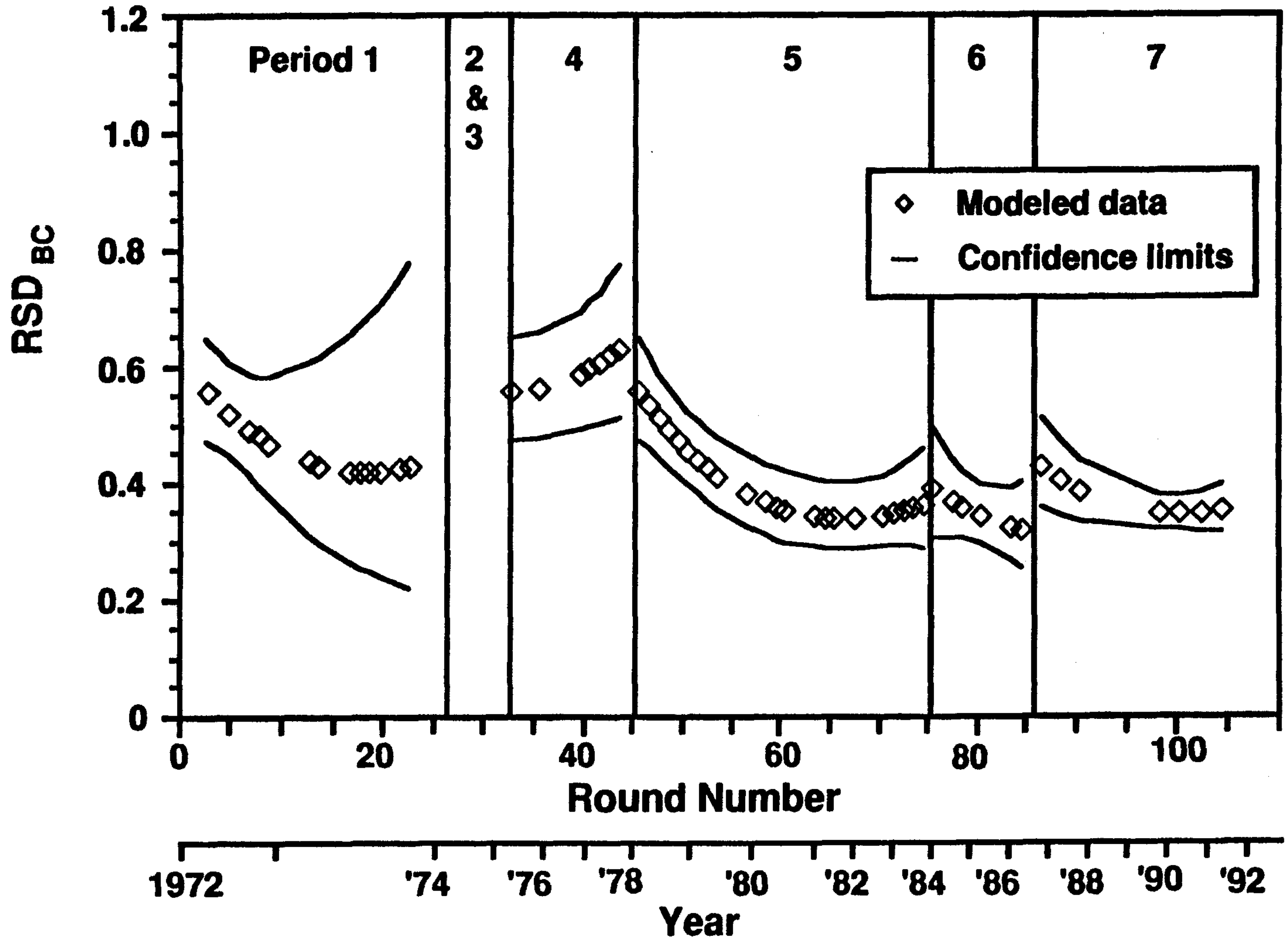
'84
'86
'88
'90
'92
Year



Period 1
2 & 3
4
5
6
7
Modeled data
Confidence limits
RSD WF
1.2
1.0
0.8
0.6
0.4
0.2
0
20
40
60
80
100
Round Number
1972
'74
'76
'78
'80
'82
'84
'86
'88
'90
'92
Year



Period 1
2 & 3
4
5
6
7
Modeled data
Confidence limits
RSD BC
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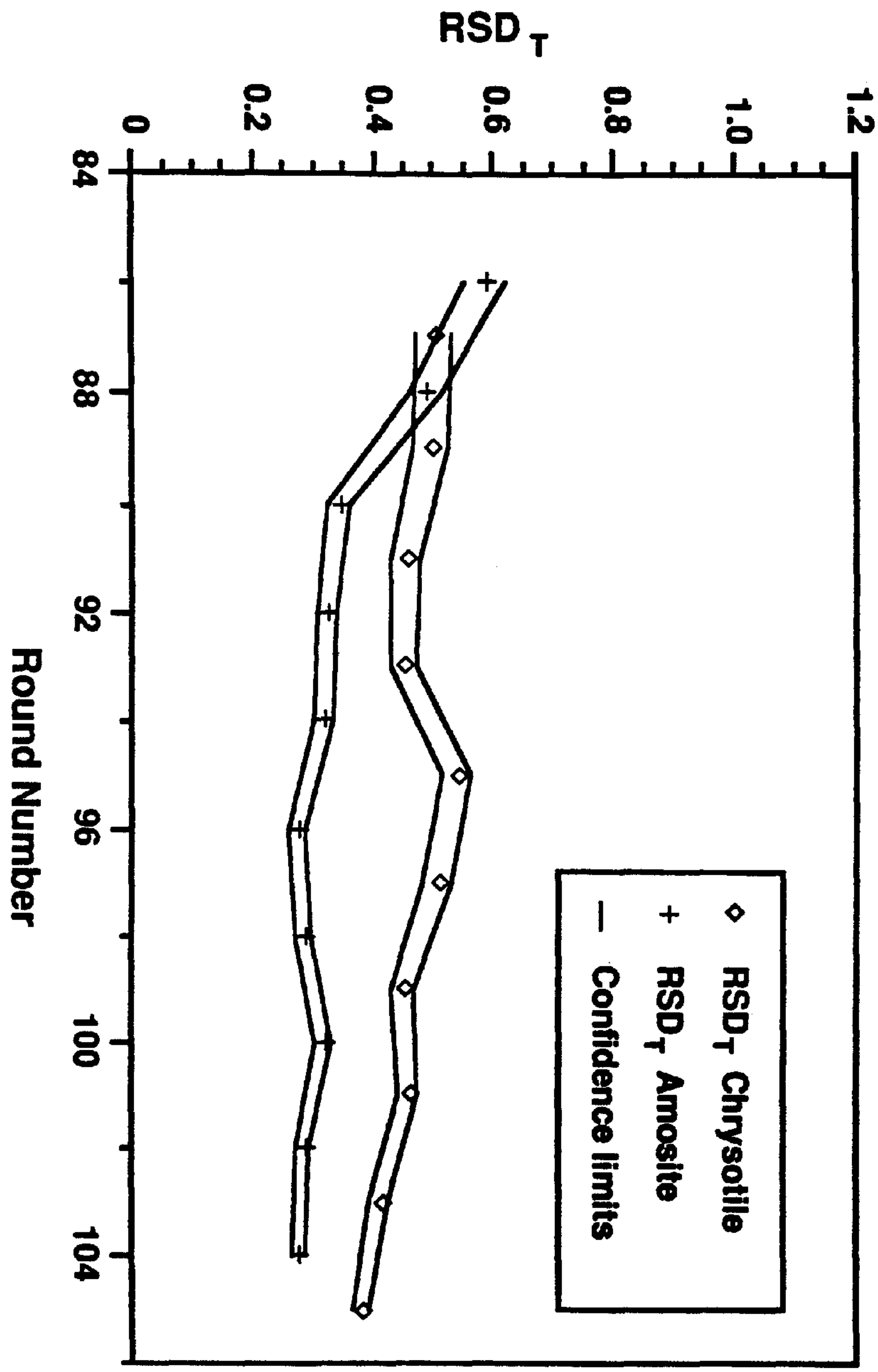
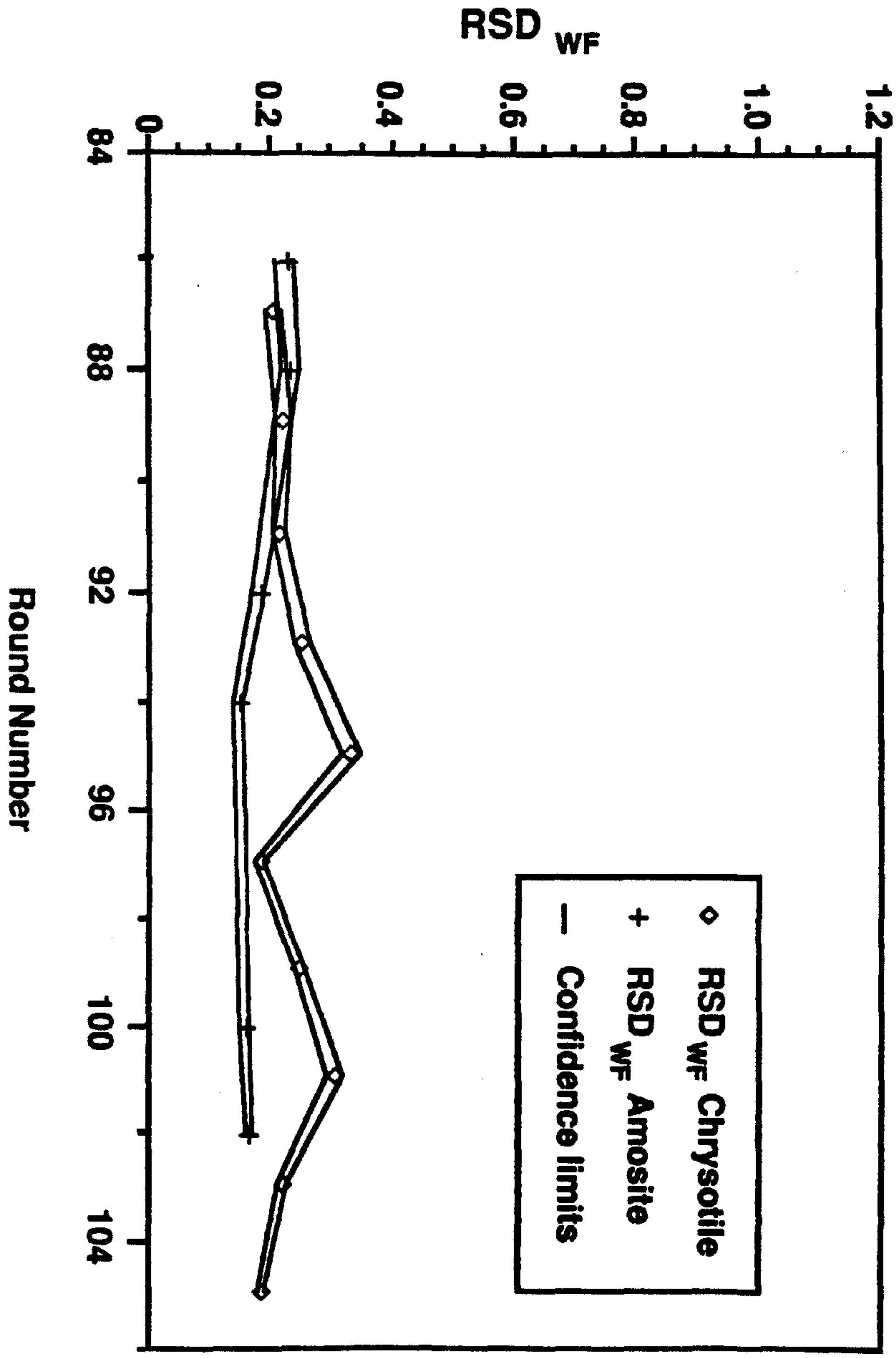
1.0
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
Round Number
1972
'74
'76
'78
'80
'82
'84
'86
'88
'90
'92
Year



RSD T
0
0.2
0.4
0.6
0.8
1.0
1.2
84
88
92
96
100
104
Round Number
RSDT Chrysotile
RSDT Amosite
Confidence limits



RSD WF
0
0.2
0.4
0.6
0.8
1.0
1.2
84
88
92
96
100
104
Round Number
RSD WF Chrysotile
RSD WF Amosite
Confidence limits