ornl

ORNL/TM-11172

OAK RIDGE
NATIONAL
LABORATORY

MARTIN MARIETTA

An Approach to Remedial Action Decisions on Sites which are Marginally Contaminated with Radium-226

L. R. Williams

OAK RIDGE NATIONAL LABORATORY
CENTRAL RESEARCH LIBRARY
CIRCULATION SECTION
4500N ROOM 175
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to see this report, send in name with report and the library will arrange a loan.

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615) 576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.
NTIS price codes—Printed Copy: A04 Microfiche A01

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/TM-11172

Health and Safety Research Division

An Approach to Remedial Action Decisions on Sites Which are Marginally Contaminated with Radium-226

L.R. Williams[1]

[1]Visiting Scientist
Indiana University at South Bend
Department of Mathematics and Computer Science
P.O. Box 7111
South Bend, IN. 46634

DATE PUBLISHED - June 1989

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES

3 4456 0313813 8

CONTENTS

	PAGE
ACKNOWLEDGEMENT	v
ABSTRACT	vii
INTRODUCTION	1
INCLUSION/EXCLUSION DECISIONS	4
VERIFICATION DECISIONS	9
DISCUSSION AND CONCLUSIONS	15
REFERENCES	17
APPENDIX	30

ACKNOWLEDGEMENT

This report would not have been completed without the help of R. W. Leggett who provided invaluable input on every aspect of this study.

AN APPROACH TO REMEDIAL ACTION DECISIONS ON SITES WHICH ARE MARGINALLY CONTAMINATED WITH RADIUM-226*

ABSTRACT

Current standards of the U. S. Environmental Protection Agency (EPA) for contamination of soil with uranium mill tailings include the requirement that the average Ra-226 concentration over a 100-m^2 area should not exceed 5 pCi/g above background in the top 15 cm of soil (40 CFR Part 192). The determination of compliance of a property with this portion of the EPA standard is often based on the Ra-226 concentration in one or two composite samples. When the decision is based on such a small sample size, the usual approach may falsely include or falsely exclude large numbers of properties for remedial action. This report illustrates how a preliminary determination of certain general statistical characteristics of the contamination may be most efficiently applied to reduce the number of erroneous decisions and associated costs concerning compliance with the EPA standard. Two points of decision are addressed: (1) whether a contaminated property should be included in a remedial action program and (2) whether a property that has undergone remedial action has been sufficiently decontaminated. The conclusions of this study apply generally (but perhaps not quantitatively) to determination of compliance with the EPA standard for Ra-226 in subsurface soil or that for radon daughters in air, for example, or with a great many regulatory limits for other contaminants.

*Research sponsored by the U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

I. INTRODUCTION

Current standards of the U.S. Environmental Protection Agency (EPA) for contamination of soil with uranium mill tailings include the requirement that the average Ra-226 concentration over a 100-m^2 area should not exceed 5 pCi/g above background in the top 15 cm of soil (40 CFR Part 192). There are thousands of properties in the U.S. that have been contaminated with Ra-226 from mill tailings, many to levels approaching this limit, which does not greatly exceed typical background Ra-226 levels in soil [normally 1-2 pCi/g (see Myrick et al., 1981)]. Determination of compliance of these properties with the EPA standard is an enormous task and presents particularly troublesome regulatory problems with regard to the large class of marginally contaminated sites, that is, those sites whose average Ra-226 concentration in surface soil is within 1 or 2 pCi/g of the standard.

The average amount of sampling per site that can be performed is severely limited by cost because of the large number of sites involved. For this reason, the decision to include or exclude a site may be based on the Ra-226 concentration in one or two composite samples collected from the site. When the sample size is small, a seemingly reasonable decision process for determining the appropriateness of remedial action may falsely include or falsely exclude a large number of marginally contaminated sites. An obvious approach is to include a property for remedial action provided the estimated mean Ra-226 concentration is above the guideline level. This approach has a high probability (nearly 0.5) of falsely excluding a property whose Ra-226 contamination is slightly above the EPA standard. An error probability of this magnitude is generally unacceptable to regulatory agencies. By using a decision-making approach based on statistical hypothesis testing, one can reduce the probability of falsely excluding marginally contaminated sites to a more acceptable level, say 0.05. Of course, for those properties whose average Ra-226 concentration is just below the EPA standard, the probability of a false inclusion will then be near 0.95, and considerable cost may be incurred in unnecessarily decontaminating sites that already meet the EPA standard.

This report addresses the problem of how to most efficiently apply statistical hypothesis testing and preliminary determination of certain general statistical characteristics of the contamination in order to reduce the number of erroneous decisions and associated costs concerning compliance with the EPA standard for Ra-226 in surface soil. Attention is restricted to this portion of the total EPA standards (see 40 CFR Part 192) because (1) it is generally the overriding criterion with regard to inclusion/exclusion decisions since it is the most readily tested and perhaps the most stringent condition of the total EPA standard, (2) there is a high probability of making a false inclusion/exclusion decision with regard to this portion of the standard, and (3) there is a relatively large amount of surface Ra-226 data for sites contaminated with uranium mill tailings on which to base the discussion. The conclusions apply generally (but perhaps not quantitatively) to determination of compliance with the EPA standard for Ra-226 in subsurface soil or that for radon daughters in air, for example, or with a great many regulatory limits for other contaminants. Two points of decision are addressed: (1) whether a contaminated property should be included in a remedial action program and (2) whether a property that has undergone remedial action has been sufficiently decontaminated. These two problems are similar in many respects but often differ with regard to philosophies regarding inclusion/exclusion decisions. In particular, with regard to initial inclusion in a remedial action program a conservative approach may be preferable -- a site is included for decontamination unless there is fairly strong evidence that it is in compliance with standards. The assumption here is that sites are not randomly selected for consideration, but rather there is some preliminary evidence which indicates possible site contamination. In verification surveys of sites that have already undergone remedial action, it is often assumed that a site has been cleaned sufficiently unless there is fairly strong evidence to the contrary. Another apparent difference that is important for the present analysis is that more is known (or can be reasonably assumed) concerning the distribution of the mean Ra-226 concentration in surface soil for sites that have already undergone an initial clean-up than for the more heterogeneous set of sites with their original contamination.

Two recent studies (Williams et al. 1989, Gilbert et al. 1987) were conducted to estimate the accuracy and precision that can be expected from composite soil samples. Williams et al. (1989) reported results of a study done on contaminated vicinity properties that had not yet received remedial action, whereas the study by Gilbert et al. (1987) was conducted on sites that had received an initial remedial action. Data collected in these two studies form the basis for much of the discussion in this report. Results reported for 10-composite samples (soil samples consisting of 10 portions of soil of approximately the same mass collected from 10 separate points on the site) by Williams et al. are used in discussions concerning inclusion and exclusion decisions and results reported for 21-composite samples (Gilbert et al.) are used in discussions related to verification of proper decontamination.

II. INCLUSION/EXCLUSION DECISIONS

An acceptable test procedure should have a low probability of falsely including properties whose surface Ra-226 concentration is near background. Unfortunately, the traditional hypothesis test based on a small number of composite samples may not have this property. If the area of the contaminated region is A m^2 and BG is the background Ra-226 concentration in pCi/g, then those sites whose average Ra-226 concentration exceeds the critical value,

$$C = 100(BG + 5)/A \ ,$$

will be above the guideline level. Here it is assumed that the area does not exceed 100-m^2; if A > 100 then replace A with 100 in the above equation for C. If the inclusion/exclusion decision is based on a statistical hypothesis test with significance level $\alpha = 0.05$ and null and alternative hypotheses,

$$H_0: \mu = C \qquad H_1: \mu < C \ ,$$

then the probability of falsely excluding a contaminated property will not exceed 0.05. In this approach, one would include a property for remedial action if the null hypothesis H_0 could not be rejected at the 0.05 significance level. This approach to decision making is conservative in that a site is assumed to be above the guideline value unless there is overwhelming evidence to the contrary. Assuming that the distribution of 10-composite values is normal with unknown standard deviation σ, one would reject the null hypothesis and exclude the property if the quantity $L_{.05}$,

$$L_{.05} = \bar{x}_n + s*t_{0.05}(n-1)/(n^{0.5}) \ ,$$

does not exceed the critical value C. Here n is the number of composite samples taken, $\bar{x}_n$ denotes the sample average, s denotes the sample standard deviation, and $t_{0.05}(n-1)$ is the 0.05 critical value of a student-t distribution with n-1 degrees of freedom (the probability is 0.05 that a student-t distribution will exceed the value $t_{0.05}$). This procedure is also discussed in Gilbert et al. (1987), where it is called the upper confidence limit rule.

The t test with unknown σ requires a minimum of two samples from each site, and for small values of n, can lead to high probabilities of false

inclusions for vicinity properties that are substantially below the guideline level. The data of Williams et al. (1989) indicates that there is a linear relationship between the mean and standard deviation of Ra-226 concentrations in 10-composite samples taken from the vicinity properties in their study. Specifically, the linear regression of standard deviation on the mean yielded the equation,

$$\sigma_{10} = 0.40 + 0.20\ \mu, \qquad \text{(Eq. 1)}$$

with $R^2 = 0.93$. This observed relationship between mean and standard deviation will be exploited to estimate the probability of falsely excluding a property whose average Ra-226 concentration is below the guideline value. Gilbert et al. (1987) observed a similar relationship although the correlation was not as strong. For 9-composite samples, Gilbert's regression yielded

$$\sigma_9 = 0.43 + 0.22\ \mu,$$

which is virtually identical to Equation 1 when adjusted for the different sample sizes. The close agreement is probably accidental; the two studies used different compositing techniques and were conducted on different ranges of soil Ra-226 concentrations. Gilbert observed the strongest correlation between composite mean and standard deviation for 21-composite samples,

$$\sigma_{21} = 0.10 + 0.23\ \mu, \qquad \text{(Eq. 2)}$$

with $R^2 = 0.76$. When adjusted for the difference in sample sizes (multiply by $(21/10)^{0.5}$), Equation 2 would suggest that the 10-composite standard deviation should be computed as $0.14 + 0.33\ \mu$. Although these coefficients are quite different from those in Equation 1, they do not yield significantly different estimates of the standard deviation in the low range of mean soil Ra-226 concentration considered by Gilbert et al. (1987).

Figures 1-2 give the fractions of properties at different levels of contamination which would be falsely included for remedial action using a t test based on 2, 3, 4, or 5 composite samples selected from sites with the area of the contaminated region equal to either 100-m^2 or 10-m^2. The curves were constructed from computer simulations by assuming that 10-composite soil samples have an approximately normal distribution whose mean and standard deviation satisfy Equation 1. The background level of Ra-226

concentration was taken to be 1.5 pCi/g. When the number of samples collected is small, properties that fall well below the guideline value may be falsely included for remedial action because of the large dispersion present in the student-t distribution for degrees of freedom that are near one.

If the number of samples collected is less than four, considerable improvement in the number of false inclusions can be obtained by using the observed relationship between the mean and standard deviation of the composite samples (Equation 1). If the standard deviation of a normal distribution with mean C is known to be 0.4 + 0.2 C, then a uniformly most powerful test of H_0 vs. H_1 is the Z test, where the standard normal distribution is used in place of the student-t and the known σ takes the place of the sample standard deviation s. Specifically using the Z test, one would reject the null hypothesis H_0 at the 0.05 significance level if the quantity $L'_{.05}$,

$$L'_{.05} = \bar{x}_n + 1.645(0.4 + 0.2C)/(n^{0.5}) ,$$

does not exceed the critical value C. Thus, using the Z test with known σ, one would include a property for remedial action if $L'_{.05}$ exceeds the critical value C. The statement that the Z test is uniformly most powerful means that no other test which has the same significance level, 0.05, will have a lower probability of making a false inclusion at any mean Ra-226 concentration below C. The test procedure that rejects H_0 when $L'_{.05}$ does not exceed C is a uniformly most powerful test even if Equation 1 is not satisfied, however the significance level of the test may not be 0.05. It isn't essential that the relationship between the mean and the standard deviation be linear in order for the test procedure described above to have an 0.05 significance level. If the standard deviation of the composite sample Ra-226 concentrations is an increasing function of the site mean Ra-226 concentration and if one can approximately predict the composite sample standard deviation on sites whose Ra-226 concentration is close to the EPA guideline level, then the uniformly most powerful test procedure will have a significance level that is approximately 0.05.

Comparisons between the t test (unknown σ) and the Z test (known σ) are made in Figs. 3-6 for $n \leq 3$ and sites with contaminated areas of 10 or 100-m^2. If the assumptions are satisfied, the Z test is clearly superior

to the t test even if one fewer 10-composite sample is taken for the Z test. For $n = 2$, the Z test with significance level $\alpha = 0.025$ (replace 1.645 with 1.96 in the computation of $L'_{.05}$) will generally have a lower probability than the t test with $\alpha = 0.05$ of making either type of error, inclusion or exclusion; for $n = 3$, only the probability of making an exclusion error is significantly reduced. Since the arguments are based on Equation 1, there is some uncertainty involved in estimating the actual significance level (the maximum probability of making a false exclusion) when using the Z test. If the standard deviation of the 10-composite values exceeds $0.4 + 0.2C$ on a site whose mean Ra-226 contamination is C, then the probability of making a false exclusion is greater than 0.05. For example, if the standard deviation is 25% greater than $0.4 + 0.2C$, the significance level is nearer 0.09, or if 50% greater, the error probability is 0.135. On the other hand, if the standard deviation is smaller than $0.4 + 0.2C$, then the probability of falsely excluding the site is less than 0.05. The overall significance level using the Z test would exceed 0.05 if Equation 1 consistently underestimates the standard deviation on marginally contaminated sites.

The actual number of sites that would be falsely included using the t test instead of the Z test at an equivalent sample size depends upon the actual distribution of the site means. If there aren't many sites with mean Ra-226 concentration below the guideline value, it doesn't matter a great deal which test procedure is used. On the other hand, if there is a large number of properties to be considered and a substantial proportion of them are expected to be at or below the guideline value, a significant cost savings in unwarranted remedial action could be realized by using the uniformly most powerful Z test. The early stages of a large scale remedial action program should include a study of the relationship between composite mean and composite standard deviation. The preliminary study should be conducted on a subset of the sites that is representative of the range of characteristics that exist in the total population, and the study should also investigate the relationship between composite standard deviation and the standard deviation of surface gamma measurements. Although surface gamma measurements were only made at selected locations on each site, Williams et al. (1989) observed a correlation between surface gamma

standard deviation and composite standard deviation that was similar to the one observed between composite mean and composite standard deviation. The linear regression yielded

$$\text{composite sigma (pCi/g)} = -0.7 + 1.4 \times \text{gamma sigma } (\mu\text{R/hr}),$$

with $R^2 = 0.92$. It is possible that the relationship between composite and gamma standard deviation is even stronger than the apparent relationship between site mean and composite standard deviation. Perhaps a conservative Z test would use the maximum estimate of σ (either 0.4 + 0.2C or -0.7 + $1.4\sigma_g$) in the computation of $L'_{.05}$. At small sample sizes, this conservative approach would still have a much lower probability of making false inclusions than the t test with the same sample size.

For values of n greater than 3, the decrease in probability of false inclusions may not be large enough to justify using the Z test instead of the t test because of the small uncertainty involved in assuming that the mean and standard deviation satisfy Equation 1. If it is determined that the routine selection of several composite samples from each site is cost-effective, then a preliminary study to determine the relationships between composite standard deviation and other variables may be unnecessary.

The above discussion is most relevant at the final step in the decision making process, and may not be particularly relevant in the early stages of site surveys. If the percentage of marginally contaminated properties is relatively small, a less expensive and more conservative approach may be more appropriate in the initial stages. For example, it may be cost-effective to take one or two individual samples at points showing highest gamma levels in order to make preliminary inclusion decisions; additional composite sampling could then be done on any site whose individual values indicated that the contamination could be above the guideline level. On many of the sites it may be possible to conclude on the basis of gamma measurements alone whether surface Ra-226 contamination on a site is above or below guideline levels. Of course, investigation of subsurface contamination may still be in order even if the top 15 cm of soil is below guideline levels. A preliminary study should also investigate the relationship that exists between site average surface gamma measurement and the average Ra-226 concentration in the top 15 cm of soil.

III. VERIFICATION DECISIONS

For sites that have already received some type of initial remedial action, it is possible to look more closely at different decision criteria by making some reasonable simplifying assumptions about the distribution of the site Ra-226 mean concentrations. Specifically, it is assumed that the average site Ra-226 concentration above background can be approximated by a lognormal distribution similar to the one shown in Figure 7. Such a lognormal distribution is completely identified by specifying the median m of the distribution and the fraction F of values that are more than 5 units above background. Six different possibilities are considered: m equal to 1 or 2, and F equal to 0.01, 0.05, or 0.10. With m=1 and F=0.05, for example, the claim would be that 50% of the remedial action properties have been cleaned to within 1 pCi/g of background but that 5% of the remedial action properties still have an average Ra-226 concentration that is more than 5 pCi/g above background. If Y denotes the Ra-226 concentration above background, then the natural logarithm of Y, log (Y), has a normal distribution with mean log (m) and standard deviation $[\log(5) - \log(m)]/z_F$, where the probability is F that a standard normal distribution exceeds the value z_F. The fraction of remedial action properties whose average Ra-226 concentration falls between any two values a and b can be computed in terms of the normally distributed log (Y). If the background concentration of Ra-226 is 1.5 pCi/g and Z denotes a standard normal, then

$$\begin{aligned} P(a \le X \le b) &= P(\log(a - 1.5) \le \log(Y) \le \log(b - 1.5)) \\ &= P(z_F[\log(a-1.5)-\log(m)]/[\log(5)-\log(m)] \le Z \le \\ &\qquad z_F[\log(b-1.5)-\log(m)]/[\log(5)-\log(m)]). \end{aligned}$$

The values for m and F considered were chosen to represent a range of what might be possible under the best circumstances, although they are certainly not the only values possible and they may not even be the most likely values. These values suggest the possibility that half of the sites requiring remedial action would be cleaned to within 1 or 2 pCi/g of background and that between 1 and 10 percent of the sites would not be cleaned to within 5 pCi/g of background. These ranges will provide

sufficient information to make meaningful comparisons among the different approaches.

The suggested hypothesis testing approach to remedial action decisions given in the previous section is conservative in the sense that a site is assumed to be above the guideline level unless the sample data taken from the site provide overwhelming evidence to the contrary. On sites that have already received an initial remedial action, this approach is probably too conservative. One might argue that these sites should be taken to be below the guideline level unless the sample data provide overwhelming evidence to the contrary. In this philosophy, one would switch the hypotheses H_0 and H_1 and then test at the 0.05 significance level, or equivalently, one could leave H_0 and H_1 alone and perform the test at the 0.95 significance level. The null hypothesis (further remedial action is needed) would be rejected at the 0.95 significance level if the quantity $L_{0.95}$ or $L'_{0.95}$,

$$L_{0.95} = \bar{x}_n - s * t_{0.05}(n-1)/(n^{0.5}) \qquad \text{(t test)}$$

or

$$L'_{0.95} = \bar{x}_n - \sigma_C * 1.645/(n^{0.5}) \ , \qquad \text{(Z test)}$$

does not exceed the critical value C. Here Equation 2 is used for 21-composite samples for the computation of $\sigma_C = 0.10 + 0.23\ \mu$.

A compromise between the 0.05 and 0.95 significance level tests is a 0.50 significance level test. With this test the null hypothesis would be rejected and no further remedial action performed if the sample average $\bar{x}_n$ does not exceed the critical value C. Of course, at the 0.50 significance level, the t test and the Z test are identical. [See Gilbert et al. (1987) for additional discussion of the three approaches.]

Tables 1 and 2 give the fractions of remedial action properties that would be falsely included for additional remedial action or falsely excluded with samples of size five or less for each of the six discussed lognormal distributions and each of the five possible test procedures. From Table 1, for example, it is evident that on sites of area 100-m^2 or more, if m = 1 and 5% of the sites need additional remedial action, then 7.8% would be falsely included and roughly 0.06% falsely excluded using a 0.05 significance level Z test based on two 21-composite samples, whereas 25% would be falsely included using the corresponding t test. At smaller

sample sizes, there is clearly an advantage to using the Z test instead of the t test at both the 0.05 and the 0.95 significance levels; if four or five samples are taken from each site, there are only minor differences in the error fractions derived for the Z and t tests.

Presumably, the ability of the remedial action contractor to decontaminate a site will be unrelated to the area of the site. Therefore, if the area of the contaminated region is significantly less than 100-m^2, then it is much less likely that the site will need additional remedial action because of the increase in the guideline level for such sites. As an illustration, Table 3 contains similar information to Table 1 for sites of area 50-m^2. Clearly, the impact of a particular verification test procedure will be most pronounced on sites which encompass a large area. For this reason, in the rest of this report attention is restricted to sites with area 100-m^2.

The values in Tables 1 and 2 appear to favor the 0.50 significance level test over the other two tests. Even in the best of circumstances, the 0.05 significance level test would lead to a substantial number of unnecessary decontaminations. The 0.50 significance level test would lead to a slight increase in the number of false exclusions when compared to the 0.05 significance level test, but the 0.50 test has substantially fewer false inclusions. The costs associated with collecting and analyzing samples could hardly be justified if one uses the 0.95 significance level test because a substantial fraction of the properties which need additional decontamination will be missed by this procedure. If it is known a priori that the number of sites needing additional remedial action is acceptably low, then there isn't much point to verification testing. When compared to a 0.95 significance level test, the 0.50 test provides a large reduction in the number of false exclusions. Although this reduction comes at the cost of a comparable increase in the number of false inclusions, this sort of tradeoff should be justified.

The cost of performing a remedial action and the cost of collecting and analyzing a composite sample could be useful in determining the number of samples to take from each site, and this information should be available by the time verification decisions need to be made. Experiences in the Grand Junction Area Remedial Action Program provide some probable lower-

bound estimates for these associated costs. The cost of collecting and analyzing one 21-composite sample is approximately $100, but the cost of collecting and analyzing additional samples from the same site is substantially lower, maybe as low as $15 or $20 per sample. The higher cost for the first sample is related to travel to the site, equipment setup, and site survey. The remedial action cost for a 100-m^2 site may be as low as $1000, but could be substantially higher. In Grand Junction, the soil is loaded onto a dump truck and then placed back on the original tailings pile. In other situations the contaminated soil may have to be sealed in drums and transported great distances at considerably greater cost.

For the remaining discussion, it is assumed that an 0.50 significance level test is to be performed for verification and that at least one composite sample is to be collected from each site. The following functions give the fraction of total properties that would be falsely included or falsely excluded for various values of F, m, and N.

Fraction falsely included =

$$\frac{(0.142)(F^{-0.052m-0.025m^2})[\log(1+F)]^{0.66}(m^{0.45-1.35F^2})(e^{0.77Fm-0.052m^2+0.017m^3})}{(1+F)^{6.2}(N^{0.70-2.6F+6.37F^2+0.019m})}$$

Fraction falsely excluded =

$$\frac{(0.129)(F^{0.015m+0.014m^2})[\log(1+F)]^{0.83}(m^{0.29+1.41F})(e^{0.12m^2-0.016m^3})}{(1+F)^{0.19-0.45m^2}(N^{0.39+1.62F-2.57F^2-0.080m})(e^{1.95Fm+5.46F^2})}$$

These functions apply to 21-composite samples provided that Equation 2 holds for the site mean concentrations and 21-composite standard deviations. They were derived as least squares fits to the logarithm of the error fraction for values of F ranging between 0.01 and 0.25 in increments of 0.01, values of m ranging between 0.5 and 4.0 in increments of 0.25, and integer values of N from 1 to 5. The maximum relative error

in the fit to the exclusion fraction is less than 7%. The fit to the inclusion fraction is good except in isolated pockets on the boundary of the region. The maximum relative error in the fit to the false inclusion fraction over the entire region is 16%; the maximum relative error is 7% if m and F are restricted to the intervals, $0.75 < m < 3.75$ and $0.03 < F < 0.25$. Most of the relative errors between function values and corresponding fractions are less than 1%.

From a statistical standpoint, it would be more desirable to base the estimates of the inclusion and exclusion fractions on the maximum likelihood estimators of the parameters of the lognormal distribution, or the parameters of the associated normal distribution. For a measured concentration X, let $Y = X - BG$ and $W = \log(Y)$, so that W is the logarithm of the above background concentration. F and m can be estimated from the mean $\bar{w}$ and standard deviation S_W of a random sample taken from the assumed normal distribution W as follows:

$$m = \exp(\bar{w})$$

and

$$F = P[Z > (\log(5) - \bar{w})/S_W],$$

where Z has a standard normal distribution.

In order to illustrate how the probabilities of false inclusion and false exclusion may be used, assume that the remedial action program involves 1000 properties, that costs associated with remedial action are $2000 per property, and that sampling costs are $100 for the first sample taken from the property and $20 for each additional sample. If at least one composite sample is to be taken from each property for purposes of remedial action verification, then a preliminary study involving one composite sample from 10% of the properties could be used to estimate $\bar{w}$ and S_W, or m and F, without incurring unnecessary costs. Tables 4 and 5 give cost analyses for two different combinations of F and m. If half of the sites are cleaned to within 2.5 pCi/g of background and 15% of the sites need additional remedial action, then the minimum total cost of sampling and unnecessary remedial action occurs when two samples are taken from each site; if $m = 3.0$ and $F = 0.10$, then the minimum cost occurs when $N = 3$. Of course, other variables such as the number of false inclusions or the

number of false exclusions should be taken into consideration in determining the number of samples to take from each property.

For an average Ra-226 concentration less than 10 pCi/g, Equation 1 predicts a greater standard deviation for 10-composite samples than the one predicted for 21-composite samples by Equation 2. As a result, the estimated fraction of false inclusions or false exclusions would be slightly larger if Equation 1 holds and 10-composite samples are used instead of 20-composite samples. For F and m in the ranges considered in this report, the increase in false inclusions is between 8.5% and 29% with a mean and median of 12%, and the increase in false exclusions does not exceed four percent. For any assumed lognormal distribution and linear relationship between composite standard deviation and site mean concentration, the probabilities of false inclusion and false exclusion can be computed using the BASIC program that is provided in the Appendix.

IV. DISCUSSION AND CONCLUSIONS

The average number of soil samples that can be taken per site will be severely limited by cost if there is a large number of properties to be tested for Ra-226 contamination in soil. When the sample size is small, the standard t test for determining the appropriateness of remedial action may falsely include a large number of marginally contaminated sites provided the test has an acceptably low probability of falsely excluding a site whose average Ra-226 concentration falls above the EPA guideline level. The total number of false inclusions can be substantially reduced without increasing the sample size if it is known that the standard deviation of composite sample Ra-226 concentration is approximately a linear function of the site mean Ra-226 concentration. A preliminary study to determine the relationship between composite standard deviation and site mean Ra-226 concentrations should be an important part of any large scale remedial action program. A study of the relationship between the standard deviations of the site composite Ra-226 concentrations and the site surface gamma measurements could also be used to decrease the number of false inclusions and false exclusions without substantially increasing cost. Also, an extensive study of the relationship between site average surface gamma measurement and site average Ra-226 concentration may lead to a substantial reduction in the total soil sampling cost. In many cases, one may be able to conclude with some confidence that the site should be included for remedial action (extremely high average gamma level) or that the site should be excluded (average gamma level near background) without taking any soil samples from the site.

Statistical test procedures which have a low probability of false exclusions are probably unnecessarily costly in terms of verification testing. On sites that have already received some type of remedial action, it appears that a reasonable test procedure is the one which includes a site for further remedial action only in the case that the sample average Ra-226 concentration is above the guideline value. For verification testing, it is plausible to assume that the average site Ra-226 concentrations follow a distribution that is approximately lognormal. A preliminary study of remedial action sites can be used to estimate the

parameters of the particular lognormal distribution. Data concerning costs associated with sampling and with remedial action would then enable the verification contractor to determine the effect of an alteration in the number of composite samples taken per site on the total sampling and remedial action costs and on the total number of sites which will be falsely excluded from additional remedial action. A comparison of costs and benefits can help determine the optimal number of composite samples to take per site.

REFERENCES

Gilbert, R. O., Baker, K. R., Nelson, R. A., Miller, R. H. and Miller, M. L.: 1987, "Sampling Errors Associated with Soil Composites used to Estimate Mean Ra-226 Concentrations at an UMTRA Remedial Action Site", Pacific Northwest Laboratory, **PNL-6262**.

Myrick, T. E., Berven, B. A., and Haywood, F. F.: 1981, "Determination of Concentrations of Selected Radionuclides in Surface Soil in the U.S.", *Health Physics* **45**, 631-642.

United States Environmental Protection Agency: 1983, "Standards for Remedial Actions at Inactive Uranium Processing Sites; Final Rule (40 CFR Part 192)", *Fed. Regist.* **48**, 590-604.

Williams, L. R., Leggett, R. W., Espegren, M. L., and Little, C. A.: 1989, "Optimization of Sampling for the Determination of Mean Radium-226 Concentration in Surface Soil", *Environ. Monit. Assess.*, to appear.

Table 1. Fractions of the number of remedial action sites for which an incorrect verification decision will be made under different test procedures and sample sizes. The area of each site is 100 m^2 and fifty percent of the sites have Ra-226 concentration less than 2.5 pCi/g (background Ra-226 concentration is taken to be 1.5 pCi/g).

Fraction exceeding 6.5 pCi/g		0.01		0.05		0.10	
Sample size	Test procedure	False incl.	False excl.	False incl.	False excl.	False incl.	False excl.
	0.05 Z	0.13	2.5E-4	0.16	8.8E-4	0.16	0.0013
1	0.50 Z	0.0085	0.0026	0.017	0.0098	0.020	0.015
	0.95 Z	2.4E-4	0.0073	5.7E-4	0.029	7.1E-4	0.045
	0.05 t	0.25	1.8E-4	0.25	6.4E-4	0.23	9.0E-4
	0.05 Z	0.050	1.8E-4	0.078	5.9E-4	0.085	8.4E-4
2	0.50 Z	0.0052	0.0021	0.011	0.0075	0.014	0.011
	0.95 Z	1.8E-4	0.0065	4.3E-4	0.024	5.4E-4	0.037
	0.95 t	4.0E-4	0.0087	8.8E-4	0.040	0.0011	0.075
	0.05 t	0.046	1.6E-4	0.073	4.9E-4	0.080	6.9E-4
	0.05 Z	0.031	1.5E-4	0.055	4.7E-4	0.063	6.6E-4
3	0.50 Z	0.0040	0.0019	0.0091	0.0063	0.011	0.0092
	0.95 Z	1.5E-4	0.0060	3.6E-4	0.021	4.6E-4	0.032
	0.95 t	2.7E-4	0.0078	6.2E-4	0.032	7.7E-4	0.053
	0.05 t	0.026	1.3E-4	0.048	4.0E-4	0.055	5.6E-4
	0.05 Z	0.023	1.3E-4	0.044	4.0E-4	0.051	5.6E-4
4	0.50 Z	0.0033	0.0017	0.0079	0.0056	0.0099	0.0081
	0.95 Z	1.3E-4	0.0056	3.2E-4	0.019	4.1E-4	0.028
	0.95 t	1.9E-4	0.0070	4.5E-4	0.027	5.7E-4	0.042
	0.05 t	0.019	1.0E-4	0.038	3.0E-4	0.045	4.2E-4
	0.05 Z	0.019	1.2E-4	0.038	3.6E-4	0.044	4.9E-4
5	0.50 Z	0.0029	0.0016	0.0070	0.0051	0.0089	0.0073
	0.95 Z	1.1E-4	0.0053	2.9E-4	0.018	3.7E-4	0.026
	0.95 t	1.7E-4	0.0064	4.1E-4	0.023	5.2E-4	0.035

Table 2. Fractions of the number of remedial action sites for which an incorrect verification decision will be made under different test procedures and sample sizes. The area of each site is 100 m^2 and fifty percent of the sites have Ra-226 concentration less than 3.5 pCi/g (background Ra-226 concentration is taken to be 1.5 pCi/g).

Fraction exceeding 6.5 pCi/g		0.01		0.05		0.10	
Sample size	Test procedure	False incl.	False excl.	False incl.	False excl.	False incl.	False excl.
	0.05 Z	0.37	3.2E-4	0.36	0.0012	0.32	0.0020
1	0.50 Z	0.023	0.0031	0.036	0.013	0.039	0.022
	0.95 Z	5.4E-4	0.0084	0.0011	0.037	0.0013	0.063
	0.05 t	0.48	2.5E-4	0.45	9.0E-4	0.40	0.0014
	0.05 Z	0.16	2.5E-4	0.18	8.9E-4	0.17	0.0013
2	0.50 Z	0.0013	0.0027	0.023	0.011	0.027	0.017
	0.95 Z	3.7E-4	0.0079	8.2E-4	0.033	0.0010	0.054
	0.95 t	9.7E-4	0.0091	0.0017	0.043	0.0020	0.083
	0.05 t	0.14	2.3E-4	0.17	7.7E-4	0.16	0.0011
	0.05 Z	0.094	2.1E-4	0.12	7.3E-4	0.13	0.0011
3	0.50 Z	0.0091	0.0025	0.0018	0.0094	0.021	0.014
	0.95 Z	3.0E-4	0.0075	6.8E-4	0.030	8.4E-4	0.048
	0.95 t	5.9E-4	0.0086	0.0012	0.039	0.0014	0.069
	0.05 t	0.076	1.8E-4	0.11	6.2E-4	0.11	9.1E-4
	0.05 Z	0.067	1.9E-4	0.096	6.4E-4	0.10	9.2E-4
4	0.50 Z	0.0073	0.0023	0.015	0.0084	0.018	0.013
	0.95 Z	2.6E-4	0.0072	5.9E-4	0.028	7.4E-4	0.044
	0.95 t	4.0E-4	0.0082	8.7E-4	0.035	0.0011	0.059
	0.05 t	0.053	1.5E-4	0.081	4.9E-4	0.088	7.0E-4
	0.05 Z	0.052	1.8E-4	0.080	5.8E-4	0.087	8.2E-4
5	0.50 Z	0.0062	0.0021	0.013	0.0077	0.016	0.012
	0.95 Z	2.3E-4	0.0070	5.4E-4	0.026	6.7E-4	0.041
	0.95 t	3.5E-4	0.0078	7.8E-4	0.032	9.6E-4	0.052

Table 3. Fractions of the number of remedial action sites for which an incorrect verification decision will be made under different test procedures and sample sizes. The area of each site is 50 m^2 and fifty percent of the sites have Ra-226 concentration less than 2.5 pCi/g (background Ra-226 concentration is taken to be 1.5 pCi/g).

Fraction exceeding 6.5 pCi/g		0.01		0.05		0.10	
Fraction needing additional remedial action		0.0002		0.0063		0.026	
Sample size	Test procedure	False incl.	False excl.	False incl.	False excl.	False incl.	False excl.
	0.05 Z	0.0059	5.6E-6	0.027	1.2E-4	0.047	3.7E-4
1	0.50 Z	2.5E-4	5.7E-5	0.0026	0.0013	0.0059	0.0042
	0.95 Z	7.6E-6	1.6E-4	9.6E-5	0.0038	2.3E-4	0.013
	0.05 t	0.020	3.6E-6	0.049	7.4E-5	0.071	2.2E-4
	0.05 Z	0.0017	4.2E-6	0.012	8.4E-5	0.025	2.4E-4
2	0.50 Z	1.5E-4	4.8E-5	0.0017	0.0010	0.0041	0.0031
	0.95 Z	5.8E-6	1.4E-4	7.6E-5	0.0033	1.9E-4	0.010
	0.95 t	1.1E-5	1.8E-4	1.2E-4	0.0052	2.8E-4	0.020
	0.05 t	0.0016	3.4E-6	0.012	6.5E-5	0.024	1.9E-4
	0.05 Z	0.0010	3.6E-6	0.0087	6.8E-5	0.019	2.0E-4
3	0.50 Z	1.1E-4	4.2E-5	0.0014	8.8E-4	0.0034	0.0026
	0.95 Z	5.0E-6	1.3E-4	6.7E-5	0.0029	1.7E-4	0.0089
	0.95 t	7.8E-6	1.6E-4	9.6E-5	0.0042	2.3E-4	0.014
	0.05 t	8.2E-4	2.6E-6	0.0075	4.9E-5	0.016	1.4E-4
	0.05 Z	7.2E-4	3.2E-6	0.0068	6.0E-5	0.015	1.7E-4
4	0.50 Z	8.9E-5	3.8E-5	0.0012	7.8E-4	0.0029	0.0023
	0.95 Z	4.6E-6	1.3E-4	6.2E-5	0.0027	1.5E-4	0.0080
	0.95 t	6.3E-6	1.5E-4	7.8E-5	0.0036	1.9E-4	0.012
	0.05 t	5.8E-4	1.8E-6	0.0058	3.4E-5	0.013	9.6E-5
	0.05 Z	5.7E-4	2.9E-6	0.0058	5.4E-5	0.013	1.5E-4
5	0.50 Z	7.7E-5	3.5E-5	0.0010	7.1E-4	0.0026	0.0021
	0.95 Z	4.3E-6	1.2E-4	5.8E-5	0.0025	1.5E-4	0.0074
	0.95 t	2.7E-6	1.4E-4	3.8E-5	0.0031	9.5E-5	0.0098

Table 4. Cost analysis for the remedial action verification procedure under the following assumptions: 1) there are 1000 properties involved; 2) half of the sites have been cleaned to within 2.5 pCi/g of background Ra-226 concentration; 3) fifteen percent of the sites need additional remedial action; 4) the cost of remedial action is $2000 per site; and 5) sampling costs are $100 for the first and $20 for each additional sample.

Sample size	Total number of: false incl.	false excl.	proper incl.	Total sampling cost(x1000)	Unnecessary remedial action cost(x1000)	Subtotal cost(x1000)
1	51	29	121	100	102	202
2	35	22	128	120	70	190
3	29	19	131	140	58	198
4	25	17	133	160	50	210
5	22	16	134	180	44	214

Table 5. Cost analysis for the remedial action verification procedure under the following assumptions: 1) there are 1000 properties involved; 2) half of the sites have been cleaned to within 3 pCi/g of background Ra-226 concentration; 3) ten percent of the sites need additional remedial action; 4) the cost of remedial action is $2000 per site; and 5) sampling costs are $100 for the first and $20 for each additional sample.

Sample size	Total number of: false incl.	false excl.	proper incl.	Total sampling cost(x1000)	Unnecessary remedial action cost(x1000)	Subtotal cost(x1000)
1	80	27	73	100	160	260
2	54	22	78	120	108	228
3	42	20	80	140	84	224
4	36	18	82	160	72	232
5	32	17	83	180	64	244

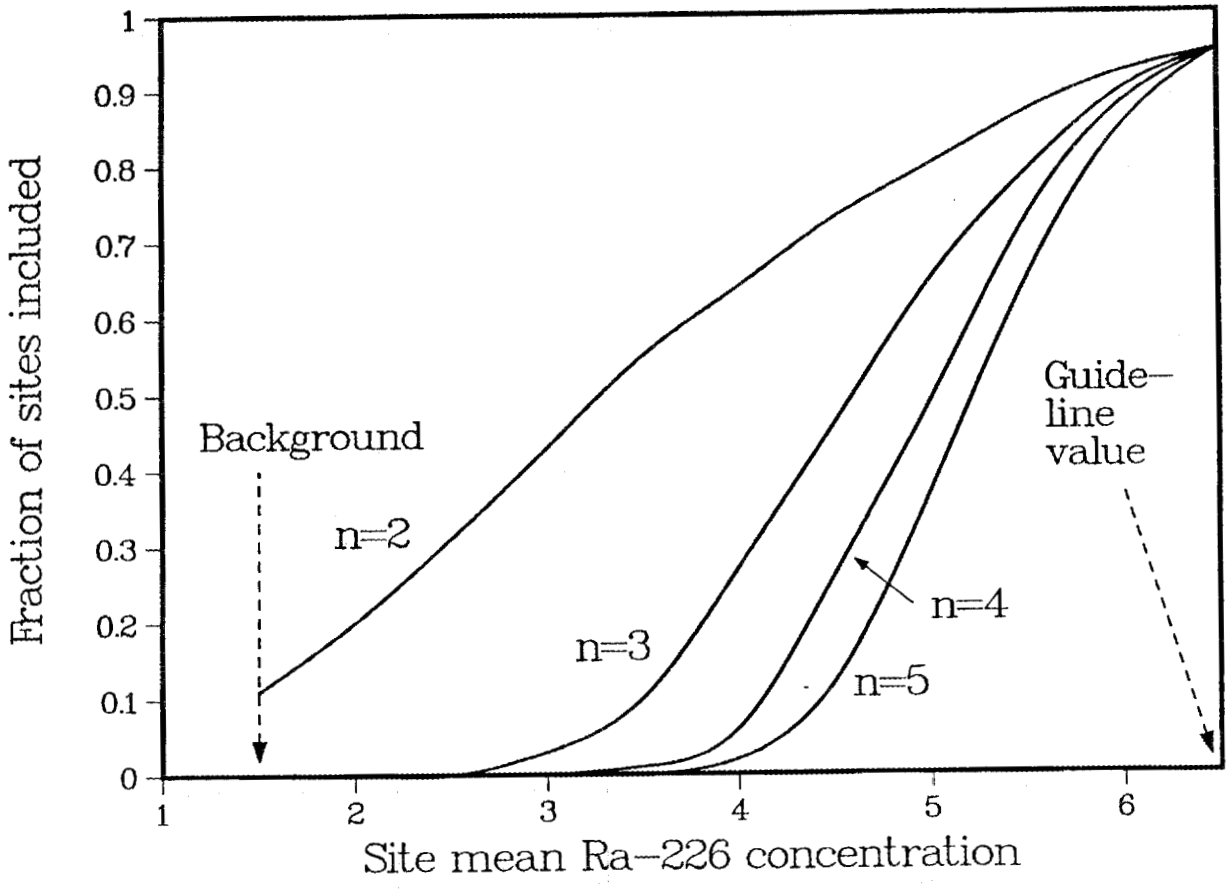

Figure 1. Fraction of 100-m^2 sites at a given Ra-226 concentration which would be falsely included for remedial action using an 0.05 significance level t test based on 2, 3, 4, or 5 composite samples. The Ra-226 concentration in composite samples is assumed to follow a normal distribution whose standard deviation is a linear function of the site mean concentration ($\sigma = 0.4 + 0.2\ \mu$).

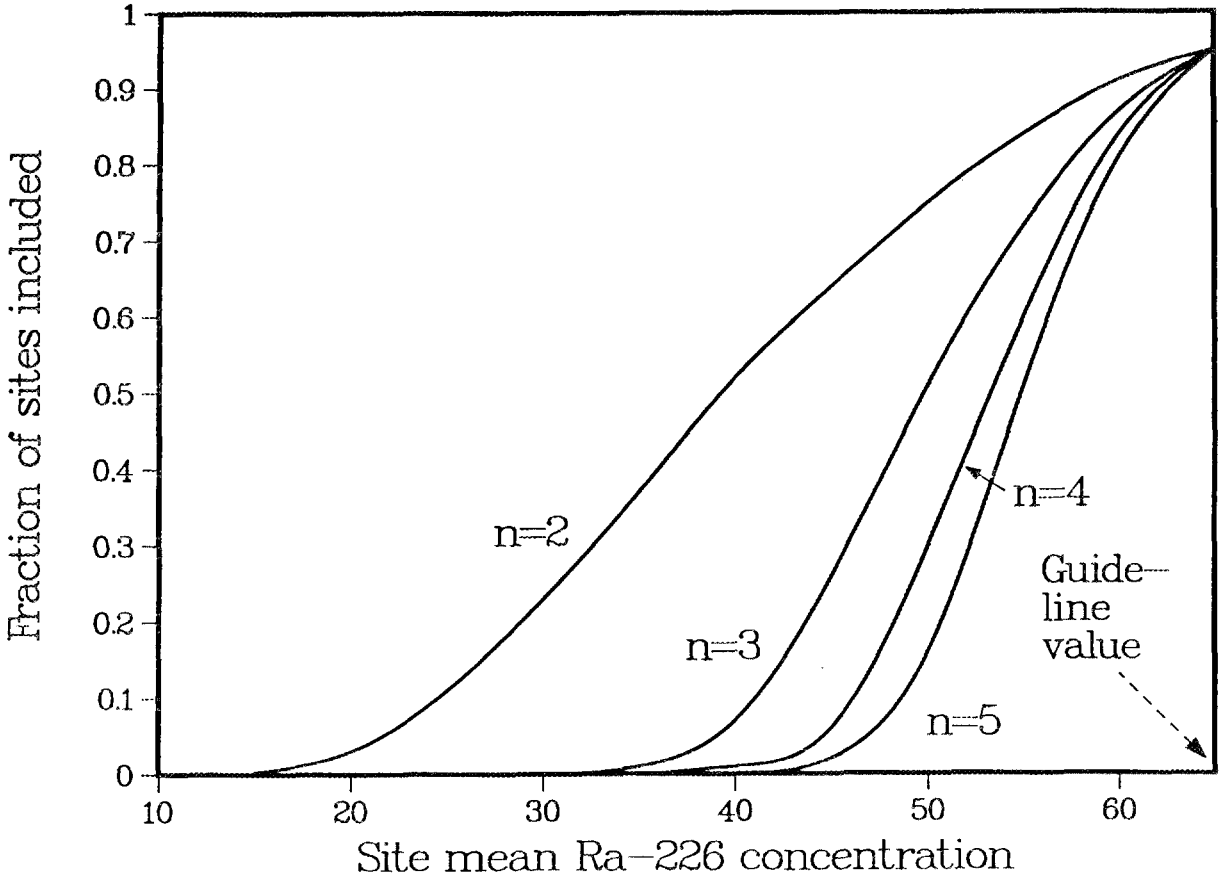

Figure 2. Fraction of 10-m^2 sites at a given Ra-226 concentration which would be falsely included for remedial action using an 0.05 significance level t test based on 2, 3, 4, or 5 composite samples. The Ra-226 concentration in composite samples is assumed to follow a normal distribution whose standard deviation is a linear function of the site mean concentration ($\sigma = 0.4 + 0.2\ \mu$).

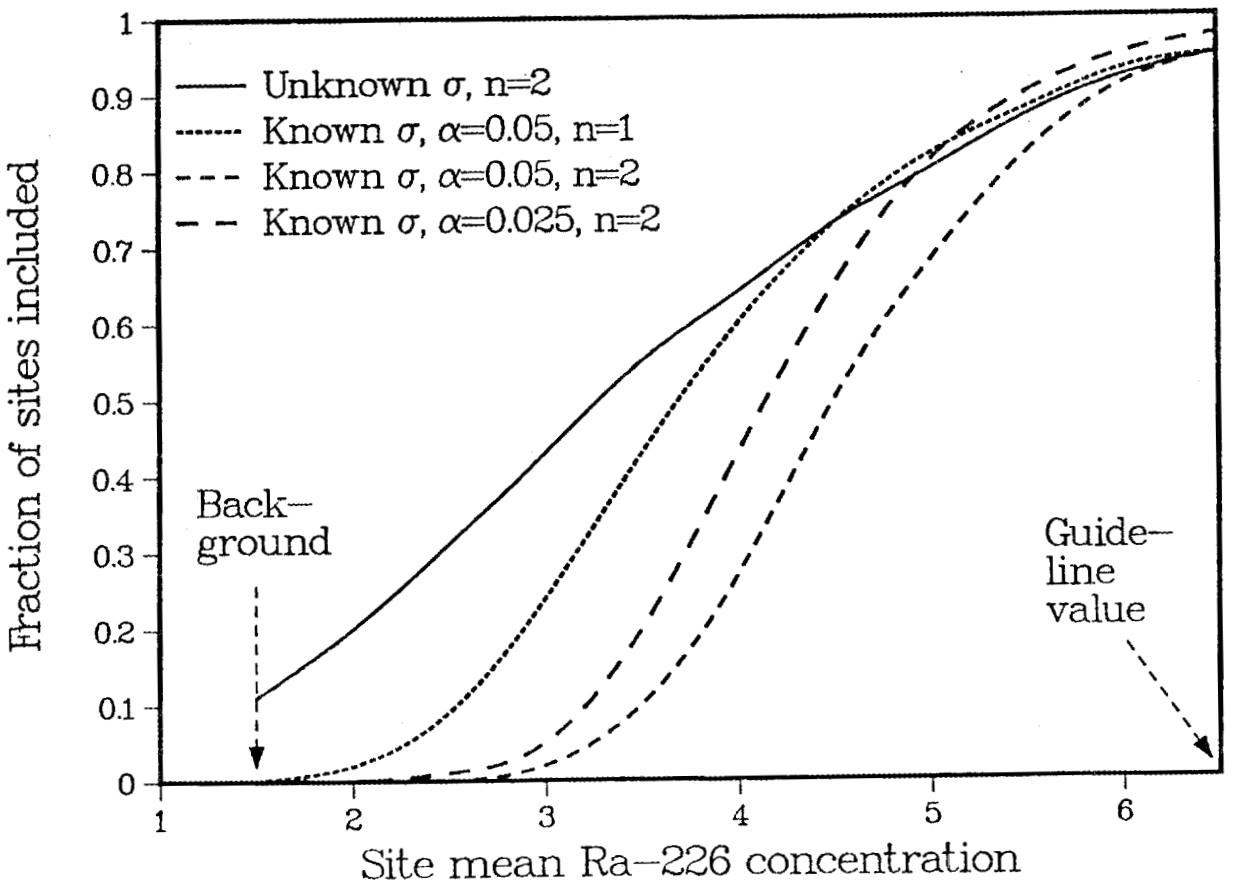

Figure 3. Fraction of 100-m^2 sites at a given Ra-226 concentration which would be falsely included for remedial action using an 0.05 significance level t test based on 2 composite samples compared to fractions of false inclusions using Z tests at specified significance levels and sample sizes. The Ra-226 concentration in composite samples is assumed to follow a normal distribution whose standard deviation is a linear function of the site mean concentration ($\sigma = 0.4 + 0.2\ \mu$).

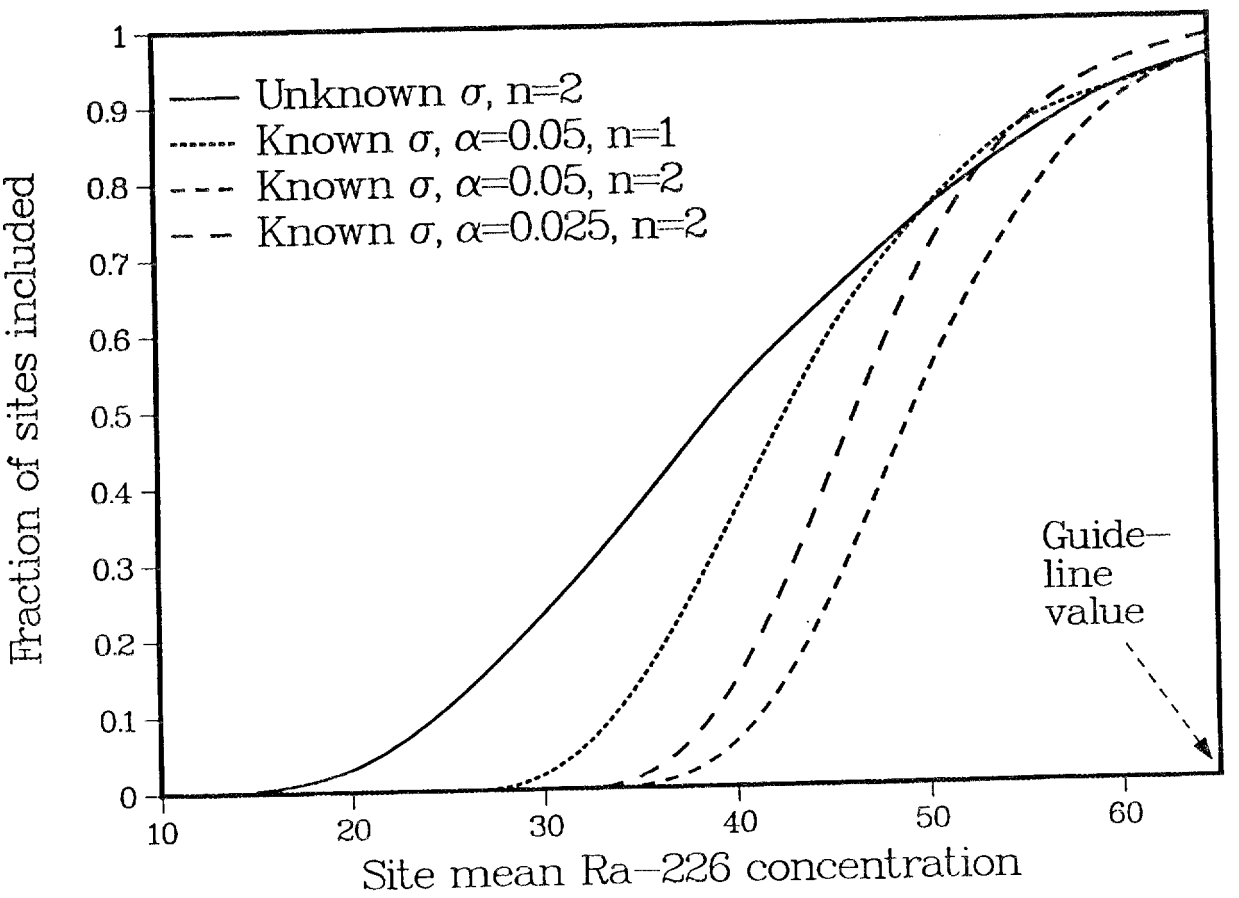

Figure 4. Fraction of 10-m^2 sites at a given Ra-226 concentration which would be falsely included for remedial action using an 0.05 significance level t test based on 2 composite samples compared to fractions of false inclusions using Z tests at specified significance levels and sample sizes. The Ra-226 concentration in composite samples is assumed to follow a normal distribution whose standard deviation is a linear function of the site mean concentration ($\sigma = 0.4 + 0.2\ \mu$).

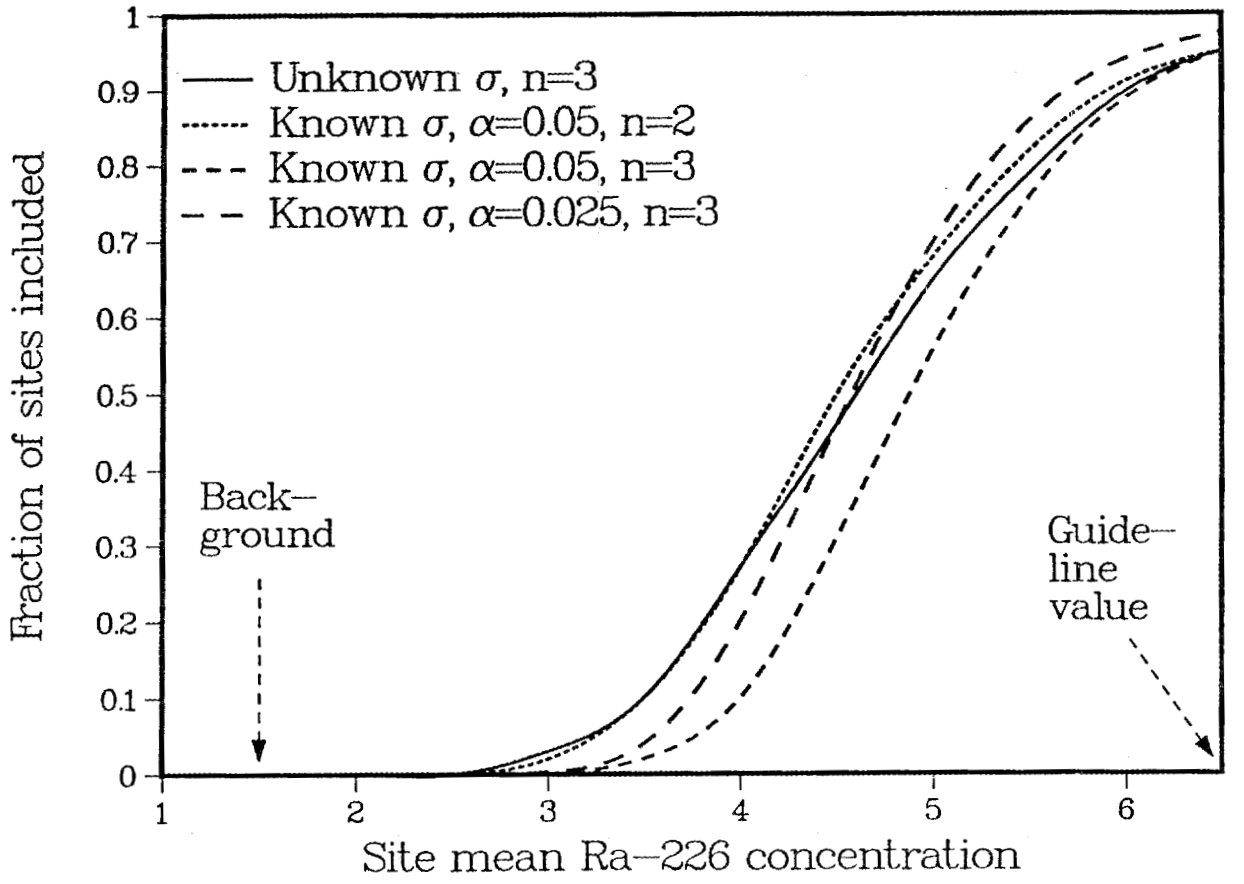

Figure 5. Fraction of 100-m^2 sites at a given Ra-226 concentration which would be falsely included for remedial action using an 0.05 significance level t test based on 3 composite samples compared to fractions of false inclusions using Z tests at specified significance levels and sample sizes. The Ra-226 concentration in composite samples is assumed to follow a normal distribution whose standard deviation is a linear function of the site mean concentration ($\sigma = 0.4 + 0.2\ \mu$).

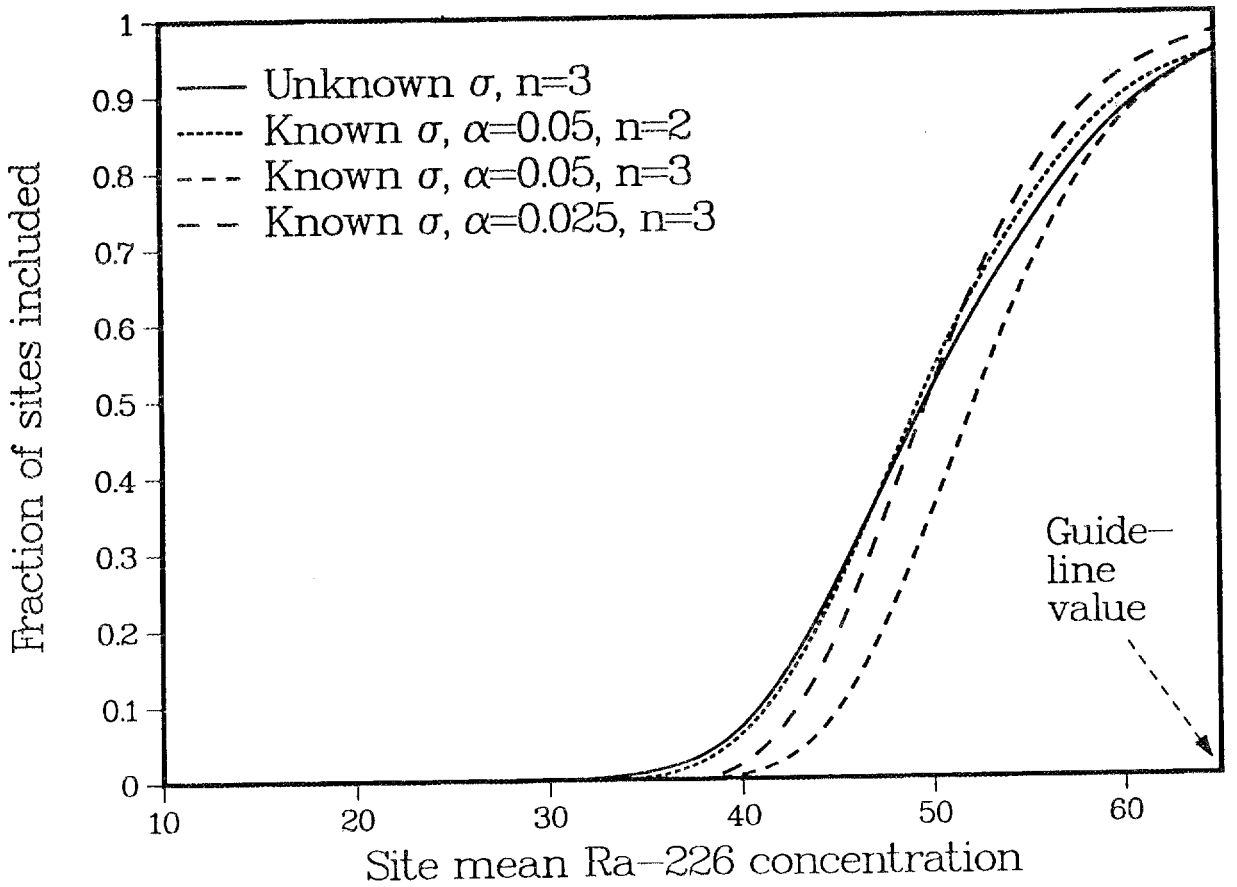

Figure 6. Fraction of 10-m^2 sites at a given Ra-226 concentration which would be falsely included for remedial action using an 0.05 significance level t test based on 3 composite samples compared to fractions of false inclusions using Z tests at specified significance levels and sample sizes. The Ra-226 concentration in composite samples is assumed to follow a normal distribution whose standard deviation is a linear function of the site mean concentration ($\sigma = 0.4 + 0.2\ \mu$).

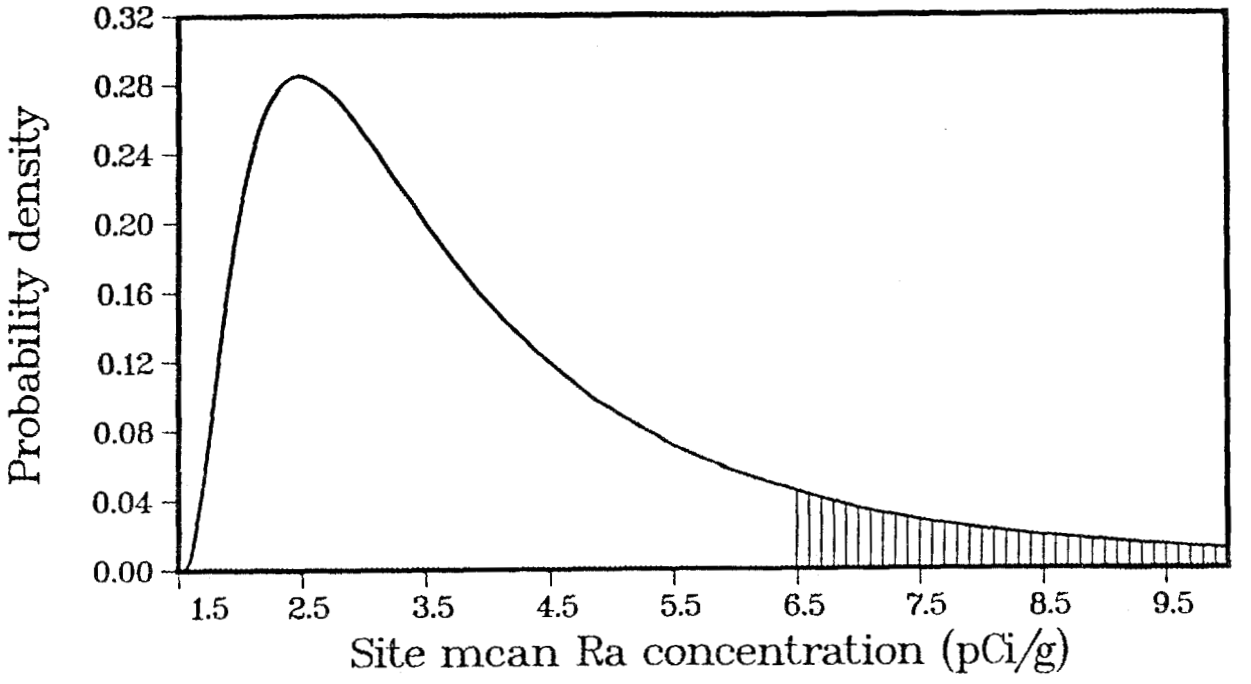

Figure 7. Possible lognormal distribution of site mean Ra-226 concentrations. The area of the shaded region represents the fraction of sites which are above the guideline level.

APPENDIX

```
100 PRINT "                    ***********************"
120 PRINT "                    *     WRITTEN BY      *"
130 PRINT "                    *   LYNN R. WILLIAMS  *"
140 PRINT "                    *   OCTOBER 2, 1987   *"
145 PRINT "                    ***********************"
146 PRINT
150 PRINT "  This program computes the fraction of properties that are
    expected to be"
160 PRINT "  falsely included for additional remedial action and the
    fraction that are"
170 PRINT "  expected to be falsely excluded under the following
    assumptions about"
180 PRINT "  a remedial action verification program.  1) The site mean
    concentration"
190 PRINT "  above background of the contaminant on the remedial action
    properties"
200 PRINT "  is assumed to follow a distribution that is approximately
    lognormal."
210 PRINT "  2) The decision to include a property for additional remedial
    action is"
220 PRINT "  based on the average concentration of the contaminant in a
    fixed"
230 PRINT "  number of composite samples, and the property is included if "
240 PRINT "  the sample average exceeds the guideline level.  3) It is
    assumed"
250 PRINT "  that the concentrations in composite samples selected from the
    same"
260 PRINT "  site follow a normal distribution whose standard deviation can
    be"
270 PRINT "  computed as a linear function of the average concentration on
    the site."
280 PRINT
```

```
290 PRINT "  WHEN ASKED TO ENTER INFORMATION FROM THE KEYBOARD, YOU MUST
    PRESS AND "
300 PRINT "  RELEASE THE RETURN KEY AFTER ENTERING THE INFORMATION."
310 PRINT : INPUT "     PRESS RETURN TO CONTINUE THE PROGRAM";Q$
480 DEFDBL A-G,M,P,X,Z,S,T
490 DIM ENDPOINT(250,2), FRACT.SITES(250), PROB.ENDPT(251)
500 PRINT :PRINT :PRINT
510 PRINT: PRINT
520 PRINT TAB(5);
530 INPUT "ENTER THE BACKGROUND CONCENTRATION ";BACKGROUND
540 IF BACKGROUND<0 THEN PRINT "BACKGROUND MUST BE NONNEGATIVE":GOTO 520
550 PRINT: PRINT
560 PRINT TAB(5);
570 INPUT "ENTER THE GUIDELINE LEVEL (amount above background) ";GUIDELINE
580 IF GUIDELINE<=0 THEN PRINT "THE GUIDELINE LEVEL MUST BE A POSITIVE
    NUMBER":GOTO 560
590 PRINT
600 PRINT :PRINT :PRINT :PRINT :PRINT
609 PRINT "              ******************************"
610 PRINT "              * STORING INTERVAL ENDPOINTS *"
611 PRINT "              *       PLEASE WAIT          *"
612 PRINT "              ******************************"
615 PRINT: PRINT
620 FOR J=1 TO 100
630 LET ENDPOINT(J,1)=BACKGROUND+(J-1)*GUIDELINE/100
640 LET ENDPOINT(J,2)=BACKGROUND+J*GUIDELINE/100
650 NEXT J
660 FOR J=1 TO 50
670 LET ENDPOINT(100+J,1)=BACKGROUND+GUIDELINE+(J-1)*GUIDELINE/50
680 LET ENDPOINT(100+J,2)=BACKGROUND+GUIDELINE+J*GUIDELINE/50
690 LET ENDPOINT(150+J,1)=BACKGROUND+2*GUIDELINE+2*(J-1)*GUIDELINE/50
700 LET ENDPOINT(150+J,2)=BACKGROUND+2*GUIDELINE+2*J*GUIDELINE/50
710 LET ENDPOINT(200+J,1)=BACKGROUND+4*GUIDELINE+4*(J-1)*GUIDELINE/50
720 LET ENDPOINT(200+J,2)=BACKGROUND+4*GUIDELINE+4*J*GUIDELINE/50
730 NEXT J
```

```
740 PRINT
745 PRINT:PRINT
750 PRINT TAB(5);"The site average concentration above background is
    assumed"
755 PRINT TAB(5);"to follow a lognormal distribution.  You can specify
    exactly"
760 PRINT TAB(5);"which lognormal distribution in either of two different
    ways."
765 PRINT TAB(5);"You can give the maximum likelihood estimates for the
    mean"
770 PRINT TAB(5);"and standard deviation of the associated normal
    distribution,"
775 PRINT TAB(5);"or you can specify the median above background
    concentration"
780 PRINT TAB(5);"and the fraction of sites requiring additional cleanup."
785 PRINT:PRINT TAB(5);"CHOOSE ONE OF THE FOLLOWING:"
790 PRINT:PRINT TAB(5);"1.  Enter mean and standard deviation of associated
    normal."
795 PRINT TAB(5);"2.  Enter median above background and fraction above
    guideline."
800 PRINT:PRINT TAB(5);
805 INPUT "CHOOSE 1 OR 2 ";C%
810 IF C%<>1 AND C%<>2 THEN GOTO 800
820 ON C% GOSUB 3000,3500
960 PRINT
970 PRINT :PRINT :PRINT :PRINT :PRINT
979 PRINT "      ***************************************************"
980 PRINT "      * COMPUTING THE FRACTION OF SITES IN EACH INTERVAL *"
990 PRINT "      *                  PLEASE WAIT                      *"
991 PRINT "      ***************************************************"
992 PRINT: PRINT
1000 LET PROB.ENDPT(1)=0
1010 LET PROB.ENDPT(251)=1
1020 FOR J=2 TO 250
1030 LET X=(LOG(ENDPOINT(J,2)-BACKGROUND)-MEAN.LOG)/STAN.LOG
```

```
1040 GOSUB 6000
1050 LET PROB.ENDPT(J)=1-P
1060 IF PROB.ENDPT(J-1)>PROB.ENDPT(J) THEN LET
     PROB.ENDPT(J)=PROB.ENDPT(J-1)
1070 IF PROB.ENDPT(J)>1 THEN LET PROB.ENDPT(J)=1
1080 NEXT J
1090 FOR J=1 TO 250
1100 LET FRACT.SITES(J)=PROB.ENDPT(J+1)-PROB.ENDPT(J)
1110 NEXT J
1200 PRINT: PRINT
1210 PRINT :PRINT :PRINT
1220 PRINT TAB(5);"The standard deviation of composite sample concentration
     is"
1230 PRINT TAB(5);"assumed to be a linear function of the site mean
     concentration."
1240 PRINT TAB(5);"The form of the assumed relationship is"
1250 PRINT
1260 PRINT TAB(5);"composite standard deviation = (intercept) +
     (slope)*(site mean)."
1265 PRINT : PRINT "     CHOOSE ONE OF THE FOLLOWING TWO EQUATIONS OR ENTER
     YOUR OWN"
1268 PRINT :PRINT "     1.  Gilbert's equation for 21-composite's:  sigma =
     0.1 + 0.23*Mean."
1270 PRINT "     2.  Williams' equation for 10-composite's:  sigma = 0.4 +
     0.2*Mean."
1272 PRINT "     3.  Select your own slope and intercept terms."
1275 PRINT : INPUT "     SELECT 1, 2, OR 3 ";C%
1276 IF C%<1 OR C%>3 THEN GOTO 1275
1277 IF C%=1 THEN LET INTERCEPT=.1:LET SLOPE=.23:GOTO 1320
1278 IF C%=2 THEN LET INTERCEPT=.4:LET SLOPE=.2:GOTO 1320
1280 PRINT :INPUT "     ENTER THE ESTIMATED INTERCEPT ";INTERCEPT
1290 PRINT
1300 INPUT "     ENTER THE ESTIMATED SLOPE ";SLOPE
```

```
1310 IF (ENDPOINT(1,1)*SLOPE+INTERCEPT)<=0 OR
     (ENDPOINT(250,2)*SLOPE+INTERCEPT)<=0 THEN PRINT "THESE VALUES ARE
     INCONSISTENT WITH THE REQUIREMENT THAT STANDARD":PRINT "DEVIATION MUST
     ALWAYS BE POSITIVE.  REENTER SLOPE AND INTERCEPT":GOTO 1270
1320 PRINT
1330 PRINT:PRINT :PRINT :PRINT :PRINT
1340 PRINT TAB(5);
1350 INPUT "ENTER THE NUMBER OF COMPOSITE SAMPLES TO BE SELECTED FROM EACH
     SITE ";NCS
1360 IF NCS<=0 OR NCS<>INT(NCS) THEN PRINT " THE NUMBER MUST BE A POSITIVE
     INTEGER!  TRY AGAIN.":GOTO 1340
1370 PRINT
1380 PRINT :PRINT :PRINT :PRINT :PRINT
1389 PRINT "             ***************************"
1390 PRINT "             * COMPUTING PROBABILITIES *"
1391 PRINT "             *     PLEASE WAIT         *"
1392 PRINT "             ***************************"
1393 PRINT: PRINT
1400 LET FALSE.INC=0
1410 LET FALSE.EXC=0
1420 FOR J=1 TO 100:REM THE FIRST 100 INTERVALS ARE BELOW GUIDELINE LEVEL
1430 LET MID=(ENDPOINT(J,1)+ENDPOINT(J,2))/2
1435 LET DENOM=SQR(NCS)
1440 LET SIGMA=(INTERCEPT+SLOPE*MID)/DENOM
1450 LET X=(BACKGROUND+GUIDELINE-MID)/SIGMA
1460 GOSUB 6000
1470 LET FALSE.INC=FALSE.INC+P*FRACT.SITES(J)
1480 NEXT J
1490 FOR J=101 TO 250
1500 LET MID=(ENDPOINT(J,1)+ENDPOINT(J,2))/2
1510 LET SIGMA=(INTERCEPT+SLOPE*MID)/SQR(NCS)
1520 LET X=(BACKGROUND+GUIDELINE-MID)/SIGMA
1530 GOSUB 6000
1540 LET FALSE.EXC=FALSE.EXC+(1-P)*FRACT.SITES(J)
1550 NEXT J
```

```
1560 PRINT
1600 PRINT:PRINT :PRINT
1605 IF FLAG$="yes" THEN GOTO 1700
1610 PRINT TAB(5);"OUTPUT WILL BE PRESENTED ASSUMING THAT THERE ARE 1000
     SITES."
1620 PRINT TAB(5);
1630 INPUT "DO YOU WISH TO CHANGE THE NUMBER OF SITES? (Y or N)";Q$
1640 IF LEFT$(Q$,1)<>"y" AND LEFT$(Q$,1)<>"Y" THEN LET NUMSITES=1000:GOTO
     1700
1650 PRINT: PRINT TAB(5);
1660 INPUT "ENTER THE TOTAL NUMBER OF REMEDIAL ACTION SITES ";NUMSITES
1670 IF NUMSITES<=0 OR NUMSITES<>INT(NUMSITES) THEN PRINT "THE NUMBER MUST
     BE A POSITIVE INTEGER!!":GOTO 1650
1700 PRINT
1710 PRINT:PRINT :PRINT :PRINT
1715 IF NCS=1 THEN E$="sample." ELSE E$="samples."
1716 PRINT USING "ASSUMPTIONS:  1. The verification decision is based on
     ###  composite \        \";NCS,E$
1717 PRINT USING "              2. There are ########   remedial action
     sites.";NUMSITES
1718 PRINT
1720 PRINT USING "     The estimated fraction of false inclusions =
     #.######      ";FALSE.INC
1730 PRINT
1740 PRINT USING "     The estimated fraction of false exclusions =
     #.######      ";FALSE.EXC
1745 PRINT
1750 PRINT USING "     The fraction requiring additional remedial action =
     #.######";FRACTION
1760 PRINT :PRINT
1770 PRINT "            E S T I M A T E D   N U M B E R   O F   S I T E S"
1775 PRINT "                    below guideline        above guideline
       total"
1780 PRINT
```

```
1785 PRINT USING "     included      [########.#   ]          ########.#
        ########.#";FALSE.INC*NUMSITES,(FRACTION-FALSE.EXC)*NUMSITES,
     (FALSE.INC+ FRACTION-FALSE.EXC)*NUMSITES
1786 PRINT
1790 PRINT USING "     excluded      ########.#             [########.#  ]
     ########.#";(1-FRACTION-FALSE.INC)*NUMSITES,FALSE.EXC*NUMSITES,
     (1-FRACTION- FALSE.INC+FALSE.EXC)*NUMSITES
1795 PRINT
1800 PRINT USING "     total         ########.#              ########.#
        ########.#";(1-FRACTION)*NUMSITES,FRACTION*NUMSITES,NUMSITES
1805 PRINT
1810 PRINT "The numbers inside  [   ]  represent incorrect decisions."
1815 PRINT :PRINT
1820 INPUT "     HIT RETURN TO CONTINUE"; Q$
1830 PRINT
1840 PRINT :PRINT :PRINT :PRINT
1850 PRINT TAB(5);"CHOOSE ONE OF THE FOLLOWING OPTIONS:"
1860 PRINT
1870 PRINT TAB(5);"1.  Change the number of composite samples to be
     collected."
1880 PRINT TAB(5);"2.  Change the slope and intercept terms."
1890 PRINT TAB(5);"3.  Change the parameters of the assumed lognormal
     distribution."
1900 PRINT TAB(5);"4.  Change the background and the guideline values."
1910 PRINT TAB(5);"5.  Stop program execution."
1920 PRINT:LET FLAG$="yes"
1930 INPUT "CHOOSE 1, 2, 3, 4, OR 5 "; C%
1940 IF C%<1 OR C%>5 THEN GOTO 1930
1950 ON C% GOTO 1320, 1200, 740, 500,2000
2000 END
3000 PRINT :PRINT
3010 PRINT TAB(5);"The maximum likelihood estimates of the mean and
     standard deviation"
3020 PRINT TAB(5);"of the normal distribution are the same as the sample
     mean and"
```

```
3030 PRINT TAB(5);"standard deviation of the natural logarithm of
     concentration minus"
3040 PRINT TAB(5);"background, log(concentration - background) ."
3050 PRINT :PRINT TAB(5);
3060 INPUT "ENTER THE SAMPLE MEAN OF THE LOG'S ";MEAN.LOG
3070 PRINT:PRINT TAB(5);
3080 INPUT "ENTER THE SAMPLE STANDARD DEVIATION OF THE LOG'S ";STAN.LOG
3090 IF STAN.LOG<=0 THEN PRINT "THE STANDARD DEVIATION MUST BE
     POSITIVE!!":GOTO 3070
3100 LET X=(LOG(GUIDELINE)-MEAN.LOG)/STAN.LOG
3110 GOSUB 6000
3120 LET FRACTION=P
3130 RETURN
3500 PRINT :PRINT
3510 PRINT :PRINT :PRINT :PRINT :PRINT
3520 PRINT TAB(5);"ENTER THE MEDIAN CONCENTRATION ABOVE BACKGROUND FOR THE"
3530 PRINT TAB(5);
3540 INPUT "REMEDIAL ACTION SITES ";MEDIAN
3550 IF MEDIAN<=0 OR MEDIAN>=GUIDELINE THEN PRINT "THE MEDIAN MUST BE A
     POSITIVE NUMBER LESS THAN THE GUIDELINE LEVEL":PRINT:GOTO 3520
3560 PRINT :PRINT
3570 PRINT TAB(5);"ENTER THE ESTIMATED FRACTION OF SITES REQUIRING
     ADDITIONAL"
3580 PRINT TAB(5);
3590 INPUT "REMEDIAL ACTION ";FRACTION
3600 IF FRACTION<=0 OR FRACTION>=.5 THEN PRINT "THE FRACTION MUST BE
     BETWEEN 0 AND 0.5":PRINT:GOTO 3570
3610 PRINT
3620 PRINT :PRINT :PRINT :PRINT :PRINT
3625 PRINT "            ********************************"
3630 PRINT "            *  COMPUTING STANDARD DEVIATION *"
3635 PRINT "            *          PLEASE WAIT          *"
3640 PRINT "            ********************************"
3645 PRINT:PRINT
3650 LET P=.5
```

```
3670 IF FRACTION<=.0014 THEN LET X=3:GOTO 3710
3675 IF FRACTION<=.0065 THEN LET X=2.5:GOTO 3710
3680 IF FRACTION<=.023 THEN LET X=2:GOTO 3710
3685 IF FRACTION<=.07 THEN LET X=1.5:GOTO 3710
3690 IF FRACTION<=.16 THEN LET X=1:GOTO 3710
3695 IF FRACTION<=.31 THEN LET X=.5:GOTO 3710
3700 LET X=.001
3710 WHILE P>=FRACTION
3720 GOSUB 6000
3730 LET X=X+.001
3740 WEND
3750 LET ZF=X
3790 LET MEAN.LOG=LOG(MEDIAN):LET STAN.LOG=(LOG(GUIDELINE)-LOG(MEDIAN))/ZF
3800 RETURN
6000 REM *** SUBROUTINE FOR COMPUTING NORMAL PROBABILITIES.  FOR AN INPUT
     VALUE X, THE OUTPUT VALUE P IS THE PROBABILITY THAT A STANDARD NORMAL
     EXCEEDS X.***
6020 IF X<0 THEN LET FLAG%=1 ELSE LET FLAG%=0
6040 LET T=1/(1+.2316419#*ABS(X))
6060 LET P=.3989422804#*EXP(-X*X/2)*(.31938153#*T-.356563782#*T^2+
     1.78477937#*T^3-1.821255978#*T^4+1.330274429#*T^5)
6080 IF FLAG%=1 THEN P=1-P
6100 RETURN
```

INTERNAL DISTRIBUTION

1. J. A. Atencio
2. D. K. Barslund
3. B. A. Berven
4. W. D. Cottrell
5. M. Cristy
6. T. A. Cronk
7. K. S. Dickerson
8. C. E. Easterly
9. K. F. Eckerman
10. M. L. Espegren
11. R. D. Foley
12. L. G. Greeley
13. D. W. Greene
14. D. K. Halford
15. S. C. Hall
16. A. R. Hawthorne
17. M. K. Jensen
18. P. M. Kearl
19. G. D. Kerr
20. F. F. Knapp
21. R. R. Knott
22. D. C. Kocher
23. N. E. Korte
24. D. C. Landguth
25-30. R. W. Leggett
31. R. P. Lenc
32. N. F. Lewis
33. C. A. Little
34. C. A. Muhr
35. P. T. Owen
36. D. A. Pickering
37. E. M. Pilz
38. J. L. Quillen
39. C. D. Retolaza
40. C. R. Richmond
41. T. H. Row
42. D. R. Smuin
43-48. R. E. Swaja
49. P. F. Tiner
50. G. H. Triplett
51. T. V. Vo-Dinh
52. L. R. Williams
53. D. A. Witt
54. K. M. Woynowskie
55. E. A. Zeighami
56-57. Central Research Library
58. Document Reference Section
59-60. Laboratory Records
61. Laboratory Records, ORNL-RC
62. ORNL Patent Office

EXTERNAL DISTRIBUTION

63. Office of Assistant Manager, Energy Research and Development, Oak Ridge Operations Office, Oak Ridge, TN 37831

64-93. Office of Scientific and Technical Information, DOE, Oak Ridge, TN 37831

94-101. J. A. Arthur, UMTRA Project Office, U.S. Department of Energy, P.O. Box 5400, Albuquerque, NM 87115

102. R. O. Gilbert, Computation Sciences Department, Pacific Northwest Laboratory, P.O. Box 999, Richland, WA 99352

103. R. Richey, UMTRA Project Office, U.S. Department of Energy, P.O. Box 5400, Albuquerque, NM 87115

104. M. Mathews, UMTRA Project Office, U.S. Department of Energy, P.O. Box 5400, Albuquerque, NM 87115

105. M. Miller, Jacobs Engineering Group, Inc., 5301 Central Avenue Northeast, Suite 1700, Albuquerque, NM 87108

106. L. C. Brazley, U.S. Department of Energy, Division of Facility and Site Decommissioning Projects, NE-20, Washington, DC 20545