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EVALUATION OF ENVIRONMENTAL MONITORING THERMOLUMINESCENT DOSIMETER LOCATIONS

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ABSTRACT

Geostatistics, particularly kriging, has been used to assess the adequacy of the existing NTS thermoluminescent dosimeter network for determination of environmental exposure levels. (Kriging is a linear estimation method that results in contour plots of both the pattern of the estimated gamma radiation over the area of measurements and also of the standard deviations of the estimated exposure levels.) Even though the network was not designed as an environmental monitoring network, it adequately serves this function in the region of Pahute and Rainier Mesas. The Yucca Flat network is adequate only if a reasonable definition of environmental exposure levels is required; it is not adequate for environmental monitoring in Yucca Flat if a coefficient of variation of 10 percent or less is chosen as the criterion for network design. A revision of the Yucca Flat network design should be based on a square grid pattern with nodes 5000 feet (about one mile) apart, if a 10 percent coefficient of variation criterion is adopted. There were insufficient data for southern and western sections of the NTS to perform the geostatistical analysis. A very significant finding was that a single network design cannot be used for the entire NTS, because different areas have different variograms. Before any design can be finalized, the NTS management must specify the exposure unit area and coefficient of variation that are to be used as design criteria.

TABLE OF CONTENTS

	<u>Page</u>
Abstract	ii
List of Figures	iv
List of Tables	v
1.0 Introduction	1
2.0 The Data	2
Monitoring Locations	2
Data Sampling and Screening	6
3.0 Data Analyses	10
Methodology	10
Variogram Analysis	10
Kriging and Cross-Validation	11
Contouring	14
4.0 Discussion	20
5.0 Summary	23
References	25
Appendix	26
Distribution List	34

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	TLD Locations	3
2	1990 Pahute Mesa TLD Locations, mR/yr	4
3	1990 Yucca Flat TLD Locations, mR/yr	5
4	1990 TLD Data	9
5	Pahute Mesa Variogram	12
6	Kriging Estimates for Yucca Flat	15
7	Kriging Standard Deviations for Yucca Flat	16
8	Kriging Estimates for Pahute Mesa	19
9	Kriging Standard Deviations for Pahute Mesa	19

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	1990 Data that is Above 250 mR/yr	7
2	Variograms	11
3	Correspondence of Standard Deviation to Coefficient of Variation . .	17

EVALUATION OF ENVIRONMENTAL MONITORING THERMOLUMINESCENT DOSIMETER LOCATIONS

1.0 INTRODUCTION

Thermoluminescent dosimeters (TLDs) have been placed at monitoring locations around the Nevada Test Site (NTS) for a number of years for the purpose of monitoring potential worker exposure to external gamma radiation. The locations for monitoring were chosen to be in areas where work was in progress or where there was reason to expect elevated environmental gamma radiation levels, such as adjacent to waste management sites. Traditionally the locations of these monitoring stations were visually estimated by health physicists from maps. The gamma exposures derived from these TLDs have secondarily been used to estimate potential radiation doses for annual reports which are required by the U.S. Department of Energy. Recently the TLD locations have been accurately measured by Reynolds Electrical & Engineering Co., Inc. (REECo) surveyors using a satellite Global Positioning System (GPS). This system was used to locate NTS TLDs with an error factor of less than 30 meters (100 feet).

This better location information offers the opportunity to perform a statistical assessment of the gross gamma estimation errors at any unmonitored location using spatial statistics methodologies. Prior to this GPS survey, coordinates were not recorded for all monitoring locations and the accuracy of the recorded monitoring locations was unknown. Thus, any conclusions reached using the earlier data could easily be challenged. The methodology chosen for this analysis is called *kriging*. Kriging has been used extensively at the NTS to estimate radiological inventories by the Nevada Applied Ecology Group (NAEG) and the Radiological Inventory and Distribution Program (RIDP). Kriging is a linear estimation method that results in contour plots of both the pattern of the estimated gamma radiation over the area of measurements and also in contour plots of the standard deviations of the estimated levels. The plot of standard deviations can be used to define confidence limits on exposure estimates, and these limits, in turn, can be used as criteria to determine statistically whether additional monitoring locations are needed and where they should be located. This determination is accomplished by setting a maximum permissible error or confidence

level for estimation; then, using the plots of standard deviations, any areas that exceed the criteria are candidates for additional monitoring stations. The standard deviations from kriging depend in part on the design of the sampling network that produced the data. Regions with low sampling density will tend to have higher standard deviations of estimated levels, and hence additional sampling locations will be indicated in these regions. The standard deviations also depend upon the variability within the data and the relationship of that variability to the spatial relationships of the sampling locations; this is measured by the variogram, which is discussed later.

2.0 THE DATA

Monitoring Locations

The Appendix contains a listing of the current TLD locations and the 1990 exposures at each location. Figure 1, is a graphic showing the NTS operational areas and the locations of the TLD monitoring stations. The abscissa and ordinate are central Nevada plane coordinates in feet, the traditional units used to establish NTS locations. The clusters of points in Areas 3, 5 and 23 actually contain more sampling locations than appear at this scale. The dotted lines in Figure 1 delineate parts of the NTS that are significant to the data analysis that follows. The area in the upper left of the northwest corner contains Pahute and Rainier Mesas, the area detailed in Figure 2. The upper and central right, or eastern and northeastern section of the NTS contains Yucca Flat, the area detailed in Figure 3.

An examination of Figure 1 shows that there are no monitoring stations in areas 14, 16, 26, 29, 30 and most of Area 18. These are locations where no work is currently conducted and where access is restricted. The east part of Area 29 and the northeast part of Area 25 contain Shoshone Mountain, a rugged terrain feature that has few roads and has never been used for weapons testing. Areas 18 and 30 contain Buckboard Mesa, a formerly-used location that is now inactive. Areas 12, 19 and 20 contain Pahute Mesa, which is occasionally used for underground testing and where a number of post-test activities are in progress; Rainier Mesa, also in this sector, is used for testing in tunnels. The bulk of the remaining locations are in the northeast part of the NTS, Areas 6 and 11, and all Areas to the north of these. This region contains

Figure 1. TLD Locations.

Figure 2. 1990 Pahute Mesa TLD Locations, mR/yr.

Figure 3. 1990 Yucca Flat TLD Locations, mR/yr.

Yucca Flat, the main underground testing area of the NTS. The remaining part of the NTS is the southern third which is not currently used for testing, but contains support facilities. This area has few monitoring locations.

Data Sampling and Screening

The statistical assessment of environmental monitoring will be limited to those areas of the NTS where there is potential for new sources of exposure: Pahute and Rainier Mesas and Yucca Flat. (In other parts of the NTS there is negligible current potential for new exposure, and there is scant data for statistical analysis.) Since these two areas have very different physiographic characteristics they will be considered separately. Pahute and Rainier Mesas are a high plateau area with Great Basin types of plants and a hard rocky soil. Yucca Flat is a lower valley with alluvial soil and transitional type vegetation. To facilitate the separation of the data for these two analytical groups, the mesas will be defined as sampling locations north of Nevada Grid Coordinates 875000N and west of 650000E. Yucca Flat will be defined as east of 650000E and north of 780000N. These grid coordinates were used to define the dotted lines in Figure 1. This division defines two approximately rectangular areas containing adequate data for the statistical analysis.

The initial step in this statistical study is to use the techniques of exploratory data analysis to determine whether the underlying assumptions of kriging are met. Kriging provides a minimum variance unbiased linear estimator of a spatial variable at any specified location. This is called local estimation. In this study the spatial variable is the gross gamma exposure determined from the TLDs. Ordinary kriging assumes that there is no "drift" in the data, which means that the data values are a realization of a two-dimensional random process. Exploratory data analysis techniques showed that the assumptions were satisfied by the data. Since the evaluation of the adequacy of the TLD network will use linear combinations of the standard errors of local estimates, it will also be necessary that the data have a normal (bell-shaped) probability density function.

The first step in the data screening was to examine normal probability plots of all the data, which are listed in the last column of the Appendix . If the data have a normal

density they will approximately plot on a straight line in such a probability plot. The data did not meet this criterion, but the shape of the plot suggested that the data might have a lognormal density. (A lognormal density is such that the logarithms of the data have a normal density.) Figure 4 is a normal probability plot of the natural logarithms of the data. This plot shows two segments that join at a normal score value of about 1. This pattern is diagnostic of a mixture of data from two normal populations. Since the lower segment is approximately a straight line, that portion of the data can be assumed to have a lognormal density. It is convenient to separate the data populations at the slight break in the data at a log-mR value of 5.5, or an mR/yr value of about 250. Table 1 lists the data that fall into the upper population in Figure 4.

Table 1 shows that most of the high-value data are from the TLDs that monitor the Radiological Waste Management Site (RWMS). All except one of the remaining locations in Table 1 are within areas of known contamination from early atmospheric tests. Stake J-31 is in the extreme northwest of the NTS and is approximately one mile north of Palanquin, a cratering test which had its plume carried north. The TLD locations in Table 1 cannot be considered environmental monitors for the purpose of evaluating the TLD network.

The purpose of this network design analysis is to evaluate its adequacy for environmental analysis. Since the sampling locations listed in Table 1 do not represent typical environmental conditions, they should not be used to evaluate the environmental monitoring network. Because the data in the lower segment of Figure 4 have a lognormal density, the logarithms of the data have a normal density and thus satisfy the underlying assumptions necessary for kriging. Thus only these data will be used in the remaining analyses.

Table 1. 1990 Data Above 250 mR/yr

<u>ID</u>	<u>Location Name</u>	<u>East</u>	<u>North</u>	<u>mR/yr</u>
235	Building 610 Bay	697215	693775	674
278	U3ax/bl Northeast	688497	838220	319
288	U3by North	687490	833436	310

Table 1. 1990 Data Above 250 mR/yr (Continued)

<u>ID</u>	<u>Location Name</u>	<u>East</u>	<u>North</u>	<u>mR/yr</u>
289	U3co North	686689	834258	1147
290	U3co South	686879	833701	710
294	Stake A-9	664507	854035	1408
297	Stake N-8	660199	869659	1445
302	Sedan West	679299	883293	482
314	7-300 Bunker	687589	849218	375
323	T-Tunnel #2 Pond	647100	897963	394
377	Stake J-31	542993	927073	380
605	RWMS TRU Pad North	708748	766248	829
610	RWMS MSM-1 Southeast	710165	771839	487
611	RWMS MSM-1 East	710144	771894	1007
612	RWMS MSM-1 Northeast	710111	771930	566
613	RWMS MSM-1 North-Northeast	710016	771893	2659
614	RWMS MSM-1 North-Northwest	709934	771861	874
615	RWMS MSM-1 Northwest	709845	771827	885
616	RWMS MSM-1 West	709866	771774	2240
617	RWMS MSM-1 Southwest	709883	771729	935
618	RWMS MSM-1 South-Southwest	709976	771765	938
619	RWMS MSM-1 South-Southeast	710068	771801	1434
620	RWMS MSM-2 Northeast	709852	771577	1414
621	RWMS MSM-2 North	709792	771544	2279
622	RWMS MSM-2 Northwest	709734	771513	1388
623	RWMS MSM-2 West	709767	771454	2939
624	RWMS MSM-2 Southwest	709801	771391	1140
625	RWMS MSM-2 South	709861	771424	3791
627	RWMS MSM-2 Southeast	709919	771455	1789
627	RWMS MSM-2 East	709886	771515	5581

Figure 4. 1990 TLD Data.

3.0 DATA ANALYSES

Methodology

Kriging is a sophisticated spatial statistics method developed to estimate ore reserves for the mining industry. It has been used extensively to analyze the spatial extent and concentrations of pollutants. The theory of kriging is much too lengthy to review in this document. Most current mathematical geology and statistical geology texts have several chapters describing kriging. A comprehensive presentation of kriging may be found in Journé and Huijbregts (1978). The implementation of kriging used for this paper was the personal computer program **GEO-EAS** available from the U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, Nevada (Englund and Sparks, 1990). The following discussion of the kriging analysis of the NTS TLD data necessarily uses a number of terms unique to geostatistics, and which are not defined in this presentation because the definitions are lengthy and require a mathematical background to understand. There are three major steps in the kriging process: variogram analysis, kriging, and contouring.

Variogram Analysis

Kriging requires as input a description of how the variability between data values is related to the distance and direction between them. This relationship is provided by a curve or mathematical function called the variogram, or more correctly the semivariogram. This function is estimated by analyzing the data using the **GEO-EAS** modules **PREVAR** and **VARIO**. Variogram analysis has several steps itself, and there is no absolutely correct variogram; rather, a good variogram is chosen based on the data and the judgment of the investigator.

One of the steps in variogram analysis is to determine whether the data show anisotropy, a dependence of the variogram on the compass direction between sample stations. Four divisions of compass direction were used for this analysis: **N-S**, **NE-SW**, **E-W**, and **SE-NW**. The variogram of the subsets of the data related by these directions showed hardly any structure for either the mesas or Yucca Flat. The variogram plots for each area showed only random fluctuations around a sill, and the sills

for the several directions were approximately the same. The sill is the value of the variogram when the distances between sampling locations are large enough to invalidate spatial relationships between locations; this is illustrated in Figure 5. Thus it was concluded that the data were isotropic or omnidirectional for both Yucca Flat and the mesas.

The next variogram step is to approximate the mathematical functions estimating the variogram. (In kriging there are several standard functions, of which one is always used.) **GEO-EAS** allows a choice of only these functions. Table 2 gives the variogram models that were chosen for the analyses in this report. For convenience the Nevada Grid Coordinates describing the locations of sampling stations were divided by 1000 before the variogram and kriging analyses. Thus a range of 45 is geographically 45,000 feet and a location of 645E is 645,000E.

Table 2. Variograms

	<u>Mesas</u>	<u>Yucca Flat</u>
Shape	gaussian	spherical
Nugget	0.002	0.01
Sill	0.018	0.06
Range	45	15

Kriging and Cross-Validation

The actual kriging was accomplished using the **GEO-EAS** module **KRIGE**. Input to this module is the variogram model and the data. The module was set up to do ordinary block kriging on square blocks 5000 feet on a side. The module output is an estimated average and standard deviation for each block, which may be contoured for visualization of patterns. Figures 2 and 3 show the locations of the TLD's for the mesas and Yucca Flat respectively and divide the exposure level data into *quartiles*. Quartiles, by definition, divide the data into four parts, each containing one-fourth of the data. For the convenience of the reader, gamma radiation levels rather than the corresponding logarithms were used for these figures. There are substantial portions

Figure 5. Pahute Mesa Variogram.

of the mesas with no TLD stations, particularly in the south-central and northeastern parts of Figure 2. The dotted line in Figure 2 approximates the northwestern boundaries of the NTS. Figure 2 should be compared to Figure 1 for perspective.

Figure 3 details the locations and quartiles of the Yucca Flat data. This figure should be compared to Figure 1 for perspective. The "x" in the center of Figure 3, slightly above 680 East and 840 North, is the sampling station at the BJY road junction, a major landmark location for the NTS. BJY is close to the place where Areas 4, 7, 1 and 3 join (see Figure 1). An important characteristic of Figure 3 is that there are several clusters of sampling locations, particularly the large cluster just southeast of BJY which shows the many TLDs around the Bulk Waste Management Facility. These clusters are important to the data cross-validation which is discussed next. The square with a plus inside at the bottom center of the figure represents the two sampling locations at the Control Point (CP), the location where test directors control nuclear tests. The arc of x's and +'s in a northwesterly direction from the CP are stations along the Tippipah Highway. There are no sampling stations southwest of this highway because of inaccessible mountainous terrain.

Cross-validation is a procedure that determines whether the kriging estimates adequately approximate the observed data values. This is performed by deleting the data values one-by-one from the data set and then kriging an estimate of the deleted value using the remaining data values. The deviation between each data value and its estimate, or the residual, can then be examined for spatial pattern. The results of this analysis indicated that the assumed variogram models are acceptable.

The plot of cross-validation residuals for Yucca Flat showed small residuals where the sampling stations are spread out. At the locations where stations are clustered, these residuals tend to show both large positive and large negative values. (The term "large" as used here is relative; these "large" residuals were very small when compared to the range of the data values. They are only large when compared to the residuals found at the more isolated sampling locations.) This spread in values indicates that kriging produced estimates in the middle of the data values, even though there are some differences among data values that are spatially close together. The

mean residual, in natural logarithms, for Yucca Flat was 0.013 and the standard deviation was 0.226.

The cross-validation results for Pahute and Rainier Mesas were similar to the Yucca Flat results, although the clustering effect was much less distinct because the clustering consists of only a few pairs of points. Thus the conclusion that kriging adequately models the TLD spatial variability at the NTS is reasonable. The mean residual, in natural logarithms, for Pahute and Rainier Mesas was -0.001 with a standard deviation of 0.12.

Contouring

The kriging module of **GEO-EAS** creates a regular grid of values from the irregularly located data points. For the NTS TLD data, the grid consists of kriged block $\ln(\text{mR/yr})$ averages, standard deviations, and the location coordinates of the center of each block. The **CONREC** module in **GEO-EAS** uses spline functions to calculate isopleth contours from the regular grid of values. The user can specify the contour levels and the contour labels. This feature was used to draw and label contours at specified mR/yr levels even though the kriging used the natural logarithms of the data. This was done to make the interpretation of radiation levels more understandable for the reader.

Figure 6 shows the mR/yr levels for Yucca Flat, and Figure 7 shows the corresponding kriging standard deviations in the log scale. Note that no contours are to be found in the southwest corner of Figure 6; there is insufficient data for that area to calculate kriging estimates. This lack of data was described in the discussion of Figure 3. The general shape of the contours in Figure 6 agrees in shape with the contours of other radiological surveys of Yucca Flat. Thus it may be concluded that the TLD network, as it now exists, produces enough information to reasonably define the general pattern of environmental exposure levels in Yucca Flat, and that the pattern agrees with the results of surveys that were done in the past to define radiological exclusion areas. The contours of the kriging standard deviations are in the log scale since lognormal kriging was used with this data, so a conversion is necessary before these contours can be compared to the actual data from the mR/yr contours. A convenient and

Contours are Kriging Standard Deviations

$\ln(mR/Y)$

Figure 7. Kriging Standard Deviations for Yucca Flat.

commonly used transformation of the standard deviation is the coefficient of variation or relative standard deviation. This coefficient expresses the standard deviation as a fraction or multiple of the corresponding mean value. One of the characteristics of lognormally distributed data is that the standard deviation is not constant, rather, it is proportional to the mean. As a result of this, the coefficient of variation is constant and is typically used by statisticians to record lognormal variability. Equation 1 is used to convert the logarithmic standard deviation, denoted by σ , to the arithmetic coefficient of variation (cv).

$$cv = (\exp(\sigma^2) - 1)^{1/2} \quad (1)$$

Applying this equation to some typical values from Figures 7 and 9 gives the following table of correspondences:

Table 3. Correspondence of Standard Deviation to Coefficient of Variation.

<u>σ</u>	<u>cv</u>
0.04	0.040016
0.06	0.060054
0.10	0.10025
0.16	0.16103
0.20	0.20202
0.24	0.24350

Thus, for the range of values of the kriging standard deviations of the natural logarithms of the data found in Figures 7 and 9, these standard deviations are a reasonable approximation of the coefficient of variation of the kriging estimates. In the following discussion the coefficient of variation and standard deviation will be used interchangeably. It should be remembered that the coefficient of variation is a unitless ratio which specifies the magnitude of the standard deviation relative to the corresponding mean, and the standard deviation has the same units of measurement as the mean. For the special case of this data set, it coincidentally happens that the magnitude of the standard deviations of the logarithms of the data is almost the same

as the magnitude of the coefficient of variation of the data (without the logarithmic transformation).

Figure 7 gives the kriging standard deviations (in the natural logarithm scale) corresponding to Figure 6. This figure shows that the coefficients of variation are typically around 20 percent with a few areas of lower values, and a few areas of 24 percent or higher. The lower value areas are places where there are many TLDs: the Bulk Waste Management site and CP, as indicated in Figure 3. The high-value areas tend to be around the periphery where there are few TLD stations. The extreme southwest corner of Figure 7 is the southwest half of Area 6, which was explained in the discussion of Figure 3. The high-value area at the northwest corner of Figure 7 is the eastern quarter of Area 12 and the western part of Areas 8 and 15. These parts of the NTS are also difficult to access. The high-value area along the upper right of Figure 7 contains the extreme eastern quarters of Areas 7, 9, 10 and 15, which is a mountainous sector with poor access. The area in the central west portion of Figure 7, with a standard deviation of 0.2 or greater is in the western half of Yucca Flat. This area is accessible, but currently is not being used for testing. This pattern of standard deviation contours indicates that the kriging estimation errors are strongly influenced by the monitoring station locations, and for much of Yucca Flat, the coefficient of variation is 20 percent or higher.

Figures 8 and 9 present the contours for Pahute and Rainier Mesas corresponding to the Yucca Flat data in Figures 6 and 7. The contours of these figures do not completely fill the southwest and northeast corners which are located outside the NTS; this exclusion was discussed in the description of Figure 2. The northwestern boundaries of the NTS are indicated by the dotted lines. Figure 8 shows a central high region: note that there is no 200 mR/yr contour within this region, thus the highest estimated radiation levels are less than 200. This high-value region is in the north-central part of Area 19, a region where there has been a number of underground tests, some of which are seeping radioactive noble gasses. The increasing values indicated toward the southwest are due to the single high-value (207 mR/yr) at boundary station 350. The asterisk in the lower left of Figure 2 indicates the location of this station. Additional monitoring stations in this localized region could substantially change the estimated contour pattern and could be recommended. Contour levels decline toward the

Figure 8. Kriging Estimates for Pahute Mesa.

Figure 9. Kriging Standard Deviations for Pahute Mesa.

northwest and east where the boundaries of Figure 8 approximate the northern and eastern boundaries of the NTS.

The contours of the lognormal kriging standard deviations for the mesas (Figure 9) show a general pattern of central low values with values increasing towards the boundaries of the figure. Note that there is no 0.02 contour in the center of the figure so it may be concluded that all values are above 0.02. Contour values increase more rapidly in the lower central section of Figure 9, because there are no sampling stations between the Pahute Mesa Highway and the Buckboard Mesa Highway. Pahute Mesa Highway approximately follows the 0.04 contour in the lower central portion of Figure 9, and Buckboard Mesa Highway is below the lower edge of the figure. Rugged terrain without access roads also predominates in the area of the NTS between these highways.

A comparison of Figures 6 and 7, giving the results for Yucca Flat, with Figures 8 and 9, giving the results for the mesas, shows some notable patterns. The mR/yr levels for Yucca Flat are slightly lower than for the mesas. The mesas show essentially a single large central area of high values with decreasing values as one moves away from this central area. Yucca Flat shows a more intricate pattern with several small high-value regions and a couple of localized low regions. Values also decrease toward the periphery of Figure 8. The comparison of Figures 7 and 9, the standard deviations for Yucca Flat and the mesas, also shows a much more intricate pattern for Yucca Flat. However, in contrast to the gamma levels, the standard deviations are lower on the mesas than on Yucca Flat. The kriging standard deviations are strongly influenced by the spacing of sampling locations and the variogram. The localized low regions in Figure 7 correspond to the clusters of sampling locations identified in Figure 3. What clustering of locations occurs on the mesas, as shown in Figure 2, consists of no more than two locations close together, and this is insufficient to significantly influence the pattern in Figure 9.

4.0 DISCUSSION

Figures 6 and 8, and the cross-validation results indicate that kriging has satisfactorily modeled the spatial variability of annual gross gamma exposures for Yucca Flat, and

for Pahute and Rainier Mesas when the high-data values from the radiological waste management facilities are deleted. The cross-validation showed that the estimation errors are small compared to the range of values of the data. Figures 6 and 8 showed that the patterns of regions of high and low values agree with the results of other radiological surveys of the NTS (unpublished radiological safety maps). Thus it is reasonable to use the kriging standard deviations to determine where additional sampling locations would most reduce the estimation errors, or where sampling locations could be removed without substantially increasing estimation errors. At the NTS it is operationally unreasonable to eliminate the clusters of sampling locations because those clusters were established to monitor very localized phenomena, such as which direction from a waste management site an exposure plume would travel.

The major factors influencing the kriging estimation errors that are controlled by the network designer at the NTS are the location and spacing of sampling stations. There are a few NTS areas where desired sampling locations are difficult to access because of rugged terrain and lack of roads. A comparison of Figures 3 and 7 shows that the standard deviations for Yucca Flat are close to 0.2 mR/yr where the sampling locations are about 10,000 feet (about two miles) apart. Wider spacing is associated with larger standard deviations, and closer spacing, with smaller standard deviations. The comparison of Figures 2 and 9 shows that the standard deviations for the mesas are about 0.04 where the sampling locations are close to 10,000 feet apart. The difference between the standard deviations of Yucca Flat and the mesas for similarly-spaced locations is due to the differences in the variograms which most likely are expressions of the different physical geographies of the two regions.

The fact that a single variogram does not seem to be applicable to all parts of the NTS is a very important consideration for any future environmental sampling design. The shape of the variogram is determined by spatial correlations, and the differing shapes noted in this report may be due to the several physical geographies found within the NTS. For the southern and western areas of the NTS (which were not considered in this report because of inadequate data) it may be desirable to use a two-stage network design, i.e., first, an exploratory network to estimate the variogram and kriging standard deviations; second, the variogram and kriging standard deviations thus estimated can be used to design a network that meets requirements.

Before using environmental sampling design to modify the existing networks or to establish designs for regions not now monitored, it is necessary to have a management decision specifying the required degree of accuracy. A reasonable measure of accuracy for radiological monitoring and kriging is a specification of an upper limit for the kriging estimation coefficient of variation. As a starting point, a coefficient of variation of 10 percent for active areas and 20 to 25 percent for inactive areas is suggested. A final choice of such criteria should include consideration of a cost-benefit analysis. Using these suggested criteria, the current sampling locations on the mesas are adequate, except possibly for a portion of the region between the Pahute Mesa and Buckboard Mesa highways. However, almost none of Yucca Flat meets these criteria, indicating that an extensive redesign of the sampling network in that region may be necessary.

Geostatisticians have shown that a regularly-spaced grid of sampling locations is theoretically the most efficient design for minimizing kriging standard deviations and that as the spacing between locations decreases, so do the standard deviations (Parkhurst, 1984; Olea, 1984). These design criteria should be used for any new design or for an extensive redesign of an existing network. The existing network for Yucca Flat showed a 20 percent coefficient of variation for a spacing of 10,000 feet with an irregular pattern of sampling locations. This result suggests that a spacing of 5,000 feet and a regular grid of locations should readily achieve a maximum coefficient of variation of 10 percent. Another important statistical consideration is the specification of the size of the kriging blocks. Size determines the "area of concern" for a hypothetical worker; confidence in exposure estimates is a function of the size of this area. The 5000 feet (about one mile) on-a-side kriging grid size was used in this study, because it seemed a reasonably-sized environmental unit; a more rigorous evaluation could change this specification.

An alternate design strategy typically is used in situations where only a limited portion of an existing network does not meet the design criteria. Such is the case for Pahute and Rainier Mesas. The strategy would be to add sampling stations only in those regions that exceed the design criteria. For the mesas this strategy calls for additional stations in the region between the Pahute Mesa and Buckboard Mesa highways. Since a coefficient of variation of 0.04 is associated with a sample spacing of

10,000 feet on the mesas, linear interpolation would indicate that a sample spacing of 25,000 feet (about five miles) should be adequate to achieve a coefficient of variation of 10 percent. These highways delimit an approximately rectangular region somewhat less than 10 miles southwest to northeast and somewhat more than 10 miles northwest to southeast. Thus two additional sampling locations are suggested, one in the northwest quadrant of this region and one in the southeast quadrant. These stations should be about five miles apart and also five miles from existing monitoring locations. Thus, on Figure 2, a station should be located about 585,000 East and 895,000 North. The second station should be located just off the south boundary of this figure about 595,000 East and 790,000 North. Since these locations have no roads, are not used for any human activities, and are in rugged terrain, the expense of helicopter access becomes an important consideration in determining whether establishing these additional stations would be cost-effective. It may be that these additional stations could be implemented only when the potential for human exposure increases in this region and access roads are built.

A final statistical consideration should be mentioned. In this presentation the contours of exposure levels were used only in a restricted way for several reasons. First, the backtransform from logarithms to the original measurement units introduces some bias into the results. Since the bias varies with the estimated levels and standard deviations, it is difficult to account for in the analysis. Second, the kriging block averages are typically used to calculate an inventory for the region kriged, but an inventory is a meaningless concept for gross gamma exposure levels. Other NTS radiological surveys have reported results in units such as $\mu\text{Ci/gm}$ of soil or nCi/M^2 which are not directly convertible into mR/yr ; thus only the pattern of high and low values can be compared.

5.0 SUMMARY

Geostatistics, particularly kriging, has been used to assess the adequacy of the existing thermoluminescent dosimeter network for determination of environmental exposure levels. Even though the network was not designed as an environmental monitoring network, it adequately serves this function in the region of Pahute and Rainier Mesas. The network is not adequate for environmental monitoring in Yucca

Flat if a coefficient of variation of 10 percent or less is chosen as the criterion for network design. A revision of the Yucca Flat network design should be based on a square grid pattern with nodes 5000 feet (about one mile) apart, if a 10 percent coefficient of variation criterion is adopted. There was insufficient data for other sections of the NTS to perform the geostatistical analysis. A very significant finding was that a single network design cannot be used for the entire NTS because different areas have different variograms. Before any design can be finalized the NTS management must specify the exposure unit area and coefficient of variation that are to be used as design criteria.

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APPENDIX DATA LISTING

This appendix contains a listing of the data used in this report. The first two columns contain the monitor station identification code and standard name. The next two columns contain the location in Central Nevada State Plane Coordinates, the traditional measurement method for establishing locations within the Nevada Test Site. Plane Coordinates are measured feet from an arbitrary origin. Since Kriging uses linear measures of location it was more convenient to use these traditional measures than to work with degrees, minutes and seconds of latitude and longitude. The final column contains the 1990 gross gamma mR/yr measures for each location.

<u>ID</u>	<u>Location Name</u>	<u>East</u>	<u>North</u>	<u>mR/yr</u>
0230	Building 650 Storage Room	697193	694633	87
0231	Building 650 Dosimetry	697193	694633	73
0232	Building 650 Roof	697193	694633	69
0233	Post Office	696663	694923	83
0234	Building 610 Gate	697107	693995	75
0235	Building 610 Bay	697215	693775	674
0236	Gate 100	694944	691032	71
0237	Desert Rock Control Tower	688168	680732	83
0238	Building 190 Bench Drawer	696748	696903	156
0239	Building 180 Scaler Room	697070	697858	113
0240	NRDS Warehouse	610646	739173	142
0241	25-4P Gate	581006	734581	145
0242	25-7P Gate	591211	753923	159
0243	E-MAD North	605516	747154	125
0244	E-MAD East	607032	750226	135
0245	E-MAD South	606986	747930	134
0246	E-MAD West	605892	748822	128
0247	Henre	626993	743136	143
0248	Area 27 Cafeteria	662018	737354	146
0249	Well 5B	704109	747097	125

<u>ID</u>	<u>Location Name</u>	<u>East</u>	<u>North</u>	<u>mR/yr</u>
0250	RWMS East 1500'	709401	766499	139
0251	RWMS East 1000'	709401	766997	144
0252	RWMS East 500'	709403	767603	139
0253	RWMS Northeast Corner	709401	767997	139
0254	RWMS North 1500'	708907	767999	139
0255	RWMS North 1000'	708400	768001	141
0256	RWMS North 500'	707913	767999	152
0257	RWMS Northwest Corner	707413	767998	145
0258	RWMS West 500'	707410	767497	142
0259	RWMS West 1000'	707413	766998	153
0260	RWMS West 1500'	707400	766503	149
0261	RWMS Southwest Corner	707413	765995	136
0262	RWMS South 500'	707909	765997	142
0263	RWMS South Gate	708385	765998	119
0264	RWMS East Gate	708901	765989	136
0265	RWMS Office	709153	766093	110
0266	CP-6	679787	795283	90
0267	CP-2 Logistic Desk	679368	795534	88
0268	CP-50 Calibration Door	679370	795332	162
0269	CP-50 Calibration Bench	679370	795332	111
0270	Yucca Oil Storage Area	684588	798472	116
0271	Decontamination Pad Office	683815	796175	120
0272	Decontamination Pad Back Room	683835	796155	111
0273	Gate 293	705882	802248	132
0274	Stake OB-11.5	697902	818016	145
0275	Stake OB-20	695768	836475	104
0276	U3AX/BL South	688231	837837	173
0277	U3AX/BL Southeast	688500	837677	196
0278	U3AX/BL Northeast	688497	838220	319
0279	U3AX/BL Northwest	687843	838436	208
0280	LANL Trailers	684749	833432	141
0281	Stake A-6.5	684816	830562	186

<u>ID</u>	<u>Location Name</u>	<u>East</u>	<u>North</u>	<u>mR/yr</u>
0282	U3DU South	686049	832898	203
0283	U3BY South	687637	832928	181
0284	U3BZ South	688526	832934	164
0285	U3EY South	690015	832000	159
0286	U3CJ North	689191	833443	196
0287	U3BZ North	688236	833457	230
0288	U3BY North	687490	833436	310
0289	U3CO North	686689	834258	1147
0290	U3CO South	686879	833701	710
0291	U3DU North	684898	830551	186
0292	Well 3	679401	817544	123
0293	BJY	679190	842543	139
0294	Stake A-9	664507	854035	1408
0295	Stake M-130	675185	856133	135
0296	Stake M-140	669965	865670	150
0297	Stake N-8	660199	869659	1445
0298	Stake L-9	662802	874065	236
0299	Stake M-150	664351	878928	152
0300	Cable Yard	674840	880871	167
0301	Stake CA-14	676603	881940	153
0302	Sedan West	679299	883293	482
0303	Sedan East Visitor Box	680472	884372	174
0304	Stake A-24	681353	886666	210
0305	EPA Complex	682225	895840	124
0306	Stake K-25	678231	901465	122
0307	Office	677684	903525	109
0309	Lamp Shack	676999	901038	143
0310	Substation U15E	676864	901293	109
0312	Circle & L Road	687772	886490	142
0313	9-300 Bunker	682162	864586	148
0314	7-300 Bunker	687589	849218	375
0315	Stake TH-1	679931	802637	91

<u>ID</u>	<u>Location Name</u>	<u>East</u>	<u>North</u>	<u>mR/yr</u>
0316	Stake TH-9	672453	809306	126
0317	Stake TH-18	665498	816964	110
0318	Stake TH-28	661212	828922	125
0319	Stake TH-38	657119	845547	139
0320	Stake TH-48	650386	854672	148
0321	Stake TH-58	652830	873165	112
0322	Stake TH-68.5	652944	885966	119
0323	T-Tunnel #2 Pond	647100	897963	394
0324	Building 12-10	648447	889884	146
0325	Upper N Pond	640216	891443	155
0326	Stake M-168	643132	885372	143
0327	Upper Haines Lake	640102	887100	131
0328	Stake M-170	645156	889109	138
0329	Stake M-175	641715	883624	147
0330	Stake M-185	635376	878321	154
0331	Stake M-190	629087	873872	174
0332	Stake M-196	622186	873642	171
0333	Stake P-35	618466	873058	179
0334	Stake P-39	618113	877808	172
0335	Stake P-41	617713	880295	183
0336	Stake P-46	616051	886405	162
0337	Stake P-54	610779	890838	154
0338	Stake P-59	614422	905613	190
0339	Stake P-66	606258	902981	187
0340	Stake P-71	603890	908680	174
0341	Upper Well U19C Reservoir	601250	916701	172
0342	Stake C-31	602521	945306	174
0343	Stake C-27	602672	940484	178
0344	Stake C-25	604528	938666	172
0345	Stake C-16	606420	28871	168
0346	Boundary TLD Station 346	671355	674614	83

<u>ID</u>	<u>Location Name</u>	<u>East</u>	<u>North</u>	<u>mR/yr</u>
0347	Boundary TLD Station 347	638710	732411	119
0348	Boundary TLD Station 348	556412	759934	165
0349	Boundary TLD Station 349	557892	833950	174
0350	Boundary TLD Station 350	556098	886398	207
0351	Boundary TLD Station 351	527800	948800	173
0352	Boundary TLD Station 352	558448	944597	113
0353	Boundary TLD Station 353	611581	954202	157
0354	Boundary TLD Station 354	637495	933423	165
0355	Boundary TLD Station 355	635530	904470	114
0356	Boundary TLD Station 356	684659	907578	180
0357	Boundary TLD Station 357	690664	875015	95
0358	Boundary TLD Station 358	704945	843555	88
0359	Boundary TLD Station 359	709501	789449	175
0360	Boundary TLD Station 360	713111	712618	81
0361	Stake P-77	600660	915405	192
0362	Stake P-88	591382	922412	200
0363	Stake P-91	585996	915364	188
0364	Stake P-98	574924	921213	177
0365	Stake R-29	586092	953278	172
0366	Stake R-26	585663	949445	178
0367	Stake R-18	584602	940864	170
0368	Stake R-8	584583	929136	197
0369	Stake R-3	583368	923109	195
0370	P & K Road Junction	574296	920114	169
0371	Stake P-116.5	568157	912038	170
0372	Stake P-120.5	563935	909870	166
0373	Stake P-124	558798	911202	174
0374	Stake P-129.5	555002	914630	183
0375	Stake P-134.5	551628	919859	174
0376	Stake J-24	550159	927574	168
0377	Stake J-31	542993	927073	380
0378	Stake J-16	557705	927530	175

<u>ID</u>	<u>Location Name</u>	<u>East</u>	<u>North</u>	<u>mR/yr</u>
0379	Stake J-6	568320	923335	188
0380	Stake A-106	569434	878901	177
0381	Sandbag Storage Hut	656397	842004	132
0600	RWMS Pit 3 North Side	709132	767971	140
0601	RWMS Pit 3 South Side	709072	767685	132
0602	RWMS Pit 4 North Side	707651	767324	148
0603	RWMS Pit 4 South Side	707830	767318	176
0604	RWMS TRU Pad Northeast	709024	766232	177
0605	RWMS TRU Pad North	708748	766248	829
0606	RWMS TRU Pad Northwest	708505	766244	140
0607	RWMS TRU Pad Southwest	708481	766167	124
0608	RWMS TRU Pad South	708733	766071	180
0609	RWMS TRU Pad Southeast	708968	766010	125
0610	RWMS MSM-I Southeast	710165	771839	487
0611	RWMS MSM-I East	710144	771894	1007
0612	RWMS MSM-I Northeast	710111	771930	566
0613	RWMS MSM-I North-Northeast	710016	771893	2659
0614	RWMS MSM-I North-Northwest	709934	771861	874
0615	RWMS MSM-I Northwest	709845	771827	885
0616	RWMS MSM-I West	709866	771774	2240
0617	RWMS MSM-I Southwest	709883	771729	935
0618	RWMS MSM-I South-Southwest	709976	771765	938
0619	RWMS MSM-I South-Southeast	710068	771801	1434
0620	RWMS MSM-2 Northeast	709852	771577	1414
0621	RWMS MSM-2 North	709792	771544	2279
0622	RWMS MSM-2 Northwest	709734	771513	1388
0623	RWMS MSM-2 West	709767	771454	2939
0624	RWMS MSM-2 Southwest	709801	771391	1140
0625	RWMS MSM-2 South	709861	771424	3791
0627	RWMS MSM-2 Southeast	709919	771455	1789
0627	RWMS MSM-2 East	709886	771515	5581

<u>ID</u>	<u>Location Name</u>	<u>East</u>	<u>North</u>	<u>mR/yr</u>
0628	AH/AT North	686972	838328	151
0629	AH/AT South	686888	835727	227
0630	AH/AT East	686907	836167	148
0631	AH/AT West	686864	837751	150
0632	AH/AT South Gate	687139	837465	152

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