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K-65 SILO REMOVAL ACTION - BENTONITE EFFECTIVENESS EVALUATION DECEMBER 17, 1992

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UNITED STATES DEPARTMENT OF ENERGY
FERNALD FIELD OFFICE

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List of Acronyms and Abbreviations

AMS	Air Monitoring Station
ANOVA	Analysis of Variance
CERCLA	Comprehensive, Environmental Response, Compensation, and Liability Act
CI	Confidence Interval
CY	Calendar Year
FEMP	Fernald Environmental Management Project
FMPC	Feed Material Production Center
ISC	Industrial Source Complex
ISCLT	Industrial Source Complex Long Term
ISCST	Industrial Source Complex Short Term
pCi/l	pico Curies/liter
RCRA	Resource Conservation and Recovery Act
SAS	Special Analytical Services
STAR	Stability Array
TL	Tolerance Limit
TLD	Thermoluminescent Dosimeter
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
WEMCO	Westinghouse Environmental Management Company of Ohio

Statistical Glossary

Analysis of variance

The single factor analysis of variance (ANOVA) tests the hypothesis that means from several samples are equal. This model assumes that the data follows a normal distribution. Generally, analysis of variance is a statistical procedure that is used to determine whether means from two or more samples are drawn from populations with the same mean. The null hypothesis states that there are no differences between any of the means and the alternative hypothesis states that at least two means differ from one another. The ANOVA test has a large power in identifying relatively small difference between the group means. The null hypothesis is rejected if the F-statistic (between mean square/within mean square) is greater than F-critical value. The exact probability is provided by the p-value which is the area to the right of the F-statistic under an F distribution.

Autocorrelation

The autocorrelation procedure provides a means of testing for seasonal patterns in time series data. Data monitoring from the same site in successive time periods are dependent, as they are subjected too relatively similar meteorological conditions and other factors which may influence concentrations. Autocorrelation will identify the seasonal trends.

F-Statistic

The F statistic is used to determine whether the observed relationship between the dependent and independent variables occurs by chance. There is a relationship among the variables if the F-observed statistic (between mean square/within mean square) is greater then the F-critical value. The F-critical values are available in many statistics text books.

Practical significance

The coefficient of determination measures the practical importance of the results (R^2) or in other words, "How wrong is the null hypothesis from the ANOVA test." The R^2 is calculated by dividing the sum of the squares between groups by the sum of the squares total (between and within). This tests measures the total variability to difference among the groups. This test is insensitive to sample size and ranges from 0 to 100 percent. A relatively small R^2 indicates that the total variability is accounted for by the difference among the group means rather the differences within groups.

Prediction interval

A prediction interval is a statistical interval calculated to include one or more future observations from the same population with a specific confidence (99 percent used in this report).

Standard error of the mean

The standard error of the mean is a measure of the amount of error in the prediction of the mean. The standard error of the mean is equal to the standard deviation divided by the square root of the number of samples.

Student t-test

The t-test tests whether a sample's means are distinct, and does not assume that the variance of both populations from which the data sets are drawn are equal. A paired t-test is appropriate whenever there is a natural pairing of observations in the samples, such as when sample group is tested twice, before and after treatment.

Tolerance limit

A tolerance limit establishes a range that is constructed to contain a specific portion of the population with a specific confidence coefficient. The proportion of the population included is referred to as the coverage. The probability with which the tolerance interval include the proportion of the population is referred to as the tolerance coefficient. Both the coverage and tolerance coefficient for this study were 95 percent.

Two-sample analysis

A two sample analysis procedure is used to test a hypothesis about the means of the two samples. A one tailed t-test was used to test the hypothesis that the difference between the two means was greater than zero. The hypothesis that he means are similar is rejected if the significance level (p-value) is less than alpha (5 percent significance level).

Executive Summary

The K-65 silos were constructed at the Feed Materials Production Center (FMPC) in 1951 for dewatering and storing of radium-bearing residues formed as by-products of uranium ore processing. Uranium-rich ore called pitchblende was imported to the FMPC facility from Belgian Congo and Australia. The radium was separated from the uranium and the residues were pumped into the silos. The silos received these waste residues from 1952 to 1958. The silos now contain approximately 9,700 tons of residual solids. The range in concentration of radium-226 per unit mass of residue is on the order of 177 to 891 nCi/g. The average value is on the order of 525 nCi/g, which would correspond to a total radium inventory of approximately 4,600 curies. The total estimated mass of radium-226 in the silos is 5 kilograms and this corresponds to a concentration of 0.6 parts per million.

The relatively large quantity of radium in the silos produced and potentially released large quantities of radon (radon-222 is the daughter of radium-226 and has a 3.5 day half life). Weathering and wear over the years had degraded the silo structures and resulted in earthen berms being constructed around the silos. Two independent studies on the structural integrity of the silos indicated that the silos had lost over half of their design strength and that no life expectancy could be predicted for the dome structures.

It was assumed that silo dome failure would have resulted in a large (approximately 50 Ci) and immediate release of radon gas from the headspace of the silos to the environment. A probabilistic risk assessment (PRA) was prepared for the K-65 Silos to evaluate the potential for and consequences of silo failure and the release of radon. The results of the PRA for the silos were used in the evaluation of the threat associated with dome failure and chronic radon release. After evaluation of the risk results and through discussions with the USEPA and the public a decision was made to perform a removal action under CERCLA to mitigate or eliminate the potential and actual threats associated with the silos.

The objective of the K-65 Removal Action, as is the case with any removal action under CERCLA, was to reduce or eliminate an actual or potential threat to the health and safety of the public and the environment. The chronic release of radon and the potential structural failure of the K-65 silos indicated the need for a removal action (WEMCO, 1990). An

Engineering Evaluation and Cost Analysis (EE/CA) was developed to evaluate the possible alternatives, and to select the most appropriate, for reducing or eliminating the risk to the public and the environment.

The removal action selected involved covering the K-65 residue with a gas barrier material that would retard the emanation of radon gas into the space between the K-65 residue and the silo domes. The barrier would also address the potential for removal of residue under high wind conditions (tornado). The barrier material selected was bentonite (a type of clay). The selection of bentonite was in part due to its plasticity, the ability to retain large quantities of water, and the relative ease by which it can be placed into the silos.

The potential structural failure of the K-65 silos and the resultant release to the environment and exposure to the public indicated the need for a removal action. The removal action selected, as a best choice for reducing or eliminating these threats, was covering the K-65 residue with bentonite. The effectiveness of the removal action has been assessed on a monthly basis since January, 1992. The effectiveness was performed in accordance with the Silo 1 and 2 Removal Action Work Plan. The current model has predicted radon concentration released from the K-65 silos at the nearest resident of less than 0.015 pCi/l for each month of the assessment. The Department of Energy has questioned the implementation of this plan because it does not address the overall uncertainty in the exposure assessment.

Objectives of the Study

The objective of this study was to determine the effectiveness of the bentonite layer in reducing the radon levels in the headspace as well as to the nearest resident. There were four goals and objectives to this study which are listed as follows:

1) Illustrate through the use of mathematical and statistical analysis that the Removal Action Performance Goal, which specifies that the above background contribution from the K-65 Silos to the radon concentration at the nearest resident is limited to no more than 0.015 (pCi/l), can only be determined within a relatively low confidence level using the original model. Using the original model alone, in the determination of whether the performance goal has been met is not sufficient for evaluating the actual long term performance of the bentonite. The confidence level needed to establish the 0.015 pCi/l performance goal is much greater than what is achievable using the analytical models and the site boundary radon monitoring data.

[The results from using the original model to evaluate the radon concentration at the nearest resident indicated that the headspace concentration could approach pre-bentonite conditions and the performance goal of 0.015 pCi/l would not be exceeded. These results illustrate the high degree of uncertainty in the original model.]

2) Evaluate whether the effectiveness of the removal action and the overall performance of the bentonite can be established using the headspace concentration and dose rate data. Provided this evaluation is achievable the focus of the overall monitoring requirements would be on measurement of radon in the headspace of each silo (gamma dose rate measurement on the domes if found to be appropriate).

3) Quantify the degree to which the bentonite has been effective in reducing radon in the headspace.

4) Establish a set of monitoring criteria to routinely and eventually periodically evaluate the effectiveness and consistency of the bentonite, using radon concentrations in the headspace and if necessary and appropriate dose rate measurements on the domes.

Evaluation of the 0.015 pCi/l Performance Goal

Determining whether the performance goal, of 0.015 pCi/l of radon above background, was assessed by 1) statistically comparing the radon concentration distribution as measured at various monitoring locations to an assumed background and 2) estimating the radon concentration, as a result of atmospheric transport, using the Gaussian plume model. The statistical analyses were developed based on the data available. No additional data was collected or made available. The evaluation process focused on the degree of confidence that is implicit in the goal of 0.015 pCi/l. The performance goal represents a deviation from the assumed background location that is an order of magnitude, or more, less than the variation in mean radon levels observed around the greater Cincinnati area.

Statistical Analysis of Pylon AB-5 Monitoring Data

The time period used in the analysis of the Pylon AB-5 data for the pre-bentonite monitoring conditions was from January 1, 1991 to September 30, 1991, and for post-bentonite conditions the monitoring period was from January 1, 1992 to September 30, 1992. The results, which were based on the estimates of daily average hourly deviations from background, indicate that the daily difference from background is statistically different from zero at the exclusion fence and boundary monitoring locations in both pre- and post-bentonite time periods. The statistical differences were smaller, at both the exclusion fence and at the site boundary locations, in the post-bentonite period. The physical differences, as opposed to the statistical difference, from background at the boundary stations are all less than 0.2 pCi/l in the post-bentonite period. The small standard errors for the boundary stations indicate that the differences from background are relatively constant from day to day.

The daily differences for the exclusion fence stations, after bentonite was added, are all lower than pre-bentonite by more than a factor of 4. The difference from background at these locations is also much smaller after bentonite, by more than a factor of 5. The NE station was on the average a factor of 16 higher than background, at 8.8 pCi/l, for the pre-bentonite condition and was reduced to a factor of 3 greater than background, at an average concentration of 1.62 pCi/l, (an absolute difference from background of 1.1 pCi/l) for the post-bentonite condition.

The statistical difference is due, in part, to the frequency at which readings at these stations are higher than background, even when the difference is only 0.1 pCi/l. These results support the assertion that the background levels for the site are likely higher than those at the location 16 miles away. The small concentration difference is within the accepted variability of natural radon concentrations. The variability in natural radon is illustrated by the range in background observations from 1988 through 1992 is which was 1 pCi/l. There were several cases where the variation over a three month period at the same location had a range of 0.5 pCi/l or greater. The results of the statistical analysis of the pylon data indicates two significant considerations: 1) although there appears to be a statistical difference between "background" and the site boundary monitors the absolute difference (a measure of practical significance) is less than 0.2 pCi/l and 2) the lower limit of detection on the pylons was 1.0 pCi/l. The evaluation of the statistical results with respect to the performance goal must take into account these considerations. The limitations associated the ability to detect radon concentrations below 1 pCi/l, with the instruments employed, and the appropriateness of the assumed background location to represent the natural concentration of radon at the FEMP provides sufficient reason to argue the appropriateness of the performance goal.

Statistical Analysis of Terradex Monitoring Data

Ninety-five percent coverage (proportion), 95 percent confidence (probability) one-sided Tolerance Limits (TLs) were prepared on quarterly terradex background radon data for the post-bentonite period (January 1, 1992, through September 30, 1992) and for the pre- and post-bentonite periods combined (January 1, 1988, through September 30, 1992). In the later instance, the TL was calculated using background data for all four quarters of each year and then the TL was re-calculated utilizing only the first three quarters of each year.

The calculated TL, used for making comparisons with the compliance AMSs' values, selected from the three scenarios described above provided the tightest constraints on the statistical evaluation. A t-test was performed to confirm any statistical significance. In each of the three scenarios described above, a background TL of 1.1 pCi/l was calculated. The quarterly terradex data for the post-bentonite period for AMS 5, AMS 6, and AMS 7 were compared to the TL of 1.1 pCi/l. Results from AMS 5 exceeded the TL with a calculated first quarter (CY92) average value of 1.2 pCi/l. Each average value was based on three replicate terradex measurements. When comparing nine average values to the calculated 95 percent, 95 percent TL, one could expect one of the nine values to slightly exceed a TL (with these parameters) approximately 50 percent of the time. This could be due solely to chance variation within the compliance stations. Thus, the t-test was performed to confirm any statistical significance.

Based on a one-sided t-test using just the post-bentonite data for the background stations and AMS 5, AMS 5 was determined to be statistically greater than background ($p = 0.0160$). The 90 percent CI for the difference between the means of AMS 5 and background is 0.042 to 0.808 pCi/l. Note that the CI for the difference between these two means does not encompass zero, which also leads one to conclude that AMS 5 is different from the background. These two tests will always result in identical conclusions, if the same level of significance is used in both tests.

A quantitative and qualitative comparison between the radon measurements of three replicate terradex cups and one real-time monitor at air monitoring station (AMS) 5 was performed. This comparison was made in an attempt to explain why AMS 5 was statistically greater than background for the post-bentonite period under study (i.e., January 1, 1992, through September 30, 1992). AMS 5 is generally not downwind from the K-65 silos. AMS 6 and

AMS 7 are situated more downwind from the silos than AMS 5, and they were not statistically greater than background for this post-bentonite period. For purposes of comparison, only data collected on the monitors from January 1 through September 30 for 1991 and 1992 were considered. Real-time monitors at AMS 5 were not in place prior to January 1, 1991, and the data after September 30, 1992, have not been obtained at the time of this study. Data from October 1, 1991, through December 31, 1991, are potentially biased high since the manholes of the silos had to be opened in order to place bentonite into the headspaces during this period.

When the three terradex results are in relative agreement (standard deviation ≤ 0.15 pCi/l), then the terradex quarterly average closely agrees with the quarterly average of the real-time pylon data (absolute difference ≤ 0.18 pCi/l). On the other hand, if there is relatively high variability among the three terradex results (standard deviation ≥ 0.38 pCi/l), then the terradex quarterly average is statistically greater than the quarterly average of the real-time pylon data. In the later instance, the lower of the three replicate values closely agrees with the real-time quarterly average data (absolute difference ≤ 0.15 pCi/l). Furthermore, there is a strong positive correlation (r = 0.91) between the magnitude of the variability among the three replicate terradex cups' readings and the magnitude of the difference between the average of the three cups' readings and the average pylon real-time data for a given quarter. The probability of this being a false correlation is less than 1 percent.

Based on these observations, one may arguably conclude that when there is high variability among the terradex cup readings, some external factor or source other than the ambient radon concentration is causing one and sometimes two of the three cups to read high. When examining the real-time pylon data closer (i.e., on an hourly basis instead of a quarterly basis), virtually all of the increased readings occurred between the hours of approximately 10:00 p.m. and 10:00 a.m. These increased readings tended to occur simultaneously across the site, including the background station. This supports a theory that at least the pylon monitors are reading precisely. However, in order to conclude that the pylon monitors are measuring accurately (with low bias as well as with high precision), they would have to be subjected to a quality assurance program that tested for a bias in the low range of 0.3 to 3 pCi/l and not the much higher concentration at which they are currently being calibrated.

Gaussian Plume Model

Estimates of the radon concentration at the nearest receptor were based on calculated fluxes using the ideal gas law, with the meteorological data for the month of August, 1992 and on a long-term basis using the maximum flux associated with the uncertainty of the ideal gas law. The computer code selected to be used was the Industrial Source Complex (ISC2) Dispersion Models to maintain consistency with previous estimates of the radon concentrations in the environment.

Based on the results of the short-term model it can be stated that none of the average daily concentrations, at the site boundary or the nearest resident exceeded the 0.015 pCi/l performance goal. The maximum average daily concentration at a boundary monitoring station was 0.007 pCi/l.

The reasonable upper bound of the release was assumed to be a change of 1 percent of the total silo volume per measurement period (15 minutes). The flux is then estimated based on the assumed release of 1 percent (positive 1 percent change) of the total radon in the headspace followed by a period in which air enters the silo (negative 1 percent change). The pre-bentonite predicted concentrations using this assumption on the long-term model suggest the an annual average radon concentration would be possible to detect at the boundary locations. However, the average measured radon concentration at these locations is less than the predicted radon due to the K-65 silos alone. The post-bentonite predicted concentrations are all below the limits of the detectors capabilities. Based on the pre-bentonite results the gaussian plume model with releases of 1 percent of the silo headspace concentrations per period is not applicable to predicted actual concentrations. The original model can only be used to obtain an overall appreciation of whether the performance goal has been met. There are inherent errors and uncertainties in the use of analytical models and there is essentially no way to achieve the confidence levels needed for the 0.015 pCi/l.

Quantify the Degree of Bentonite Effectiveness

Four approaches were used to quantify the degree of bentonite effectiveness which are (1) headspace analysis, (2) comparison of actual daily radon concentration levels between pre- and post-bentonite periods at each monitoring station, (3) comparison of time series daily radon concentration levels between pre- and post-bentonite periods at each monitoring station, and (4) gamma does rate analysis.

Headspace Analysis

The headspace analysis results indicate that the radon headspace concentrations from July 1 to September 1992 are statistically lower than the pre-bentonite reading for each silo. The decrease in Silo 1 was from 25,000,000 pCi/l to 45,081 pCi/l (99.8 percent reduction) while Silo 2 concentration decreased from 30,000,000 pCi/l to 219,585 pCi/l (99.3 percent reduction). Daily changes in headspace concentrations tend to be relatively consistent among the two silos which indicates that a constant external source may effect changes in concentrations within both silos. The following meteorological effects were significantly associated with the hourly headspace concentration at the 0.01 significance level which are wind speed, outdoor temperature, and stability class. Dew point and barometric pressure were significantly associated with headspace concentrations in Silo 1 but not for Silo 2 or the sum over the two silos. These effects tend to be associates by some combination of the above three factors. In both silos, a negative effect was observed on the radon concentration by wind speed, implying that increases in the wind speed were associated with decreases in the headspace concentrations. A positive effect was observed on the radon concentration by dew point, outdoor temperature, and stability class.

Comparison of Actual Daily Radon Concentration Levels Between Pre- and Post-Bentonite Periods at Each Monitoring Station

The time periods for the Pylon AB-5 monitoring data was discussed during the assessment of statistical significance of the monitoring data from background. Based on the Pylon AB-5 monitoring data, all four exclusion fence locations and AMS 5 pre-bentonite had significantly greater radon concentrations at alpha equals 0.05 than post-bentonite radon concentrations at these locations. A significant difference was not observed at AMS 6 and AMS 7. It is hypothesized, that these distances the influence of the silos radon releases are not significant.

The time periods for the Terradex cup monitoring data was previously discussed in the assessment of statistical significance of the actual monitoring from background. Based on the Terradex cup quarterly data, the pre-bentonite means were determined to be statistically greater than post-bentonite at the 5 percent level of significance at the silo domes and exclusion fence. The largest p value was 0.0029, which was associated with Silo 2 at the SE corner.

Comparison of Time Series Daily Radon Concentration Levels Between Pre- and Post-Bentonite Periods at Each Monitoring Station

The radon concentrations at each monitoring station were collected on an hourly bases each day over a two-year period. To better estimate the presence of trends in the concentration data over the entire monitoring period, statistical analyses were performed on daily average concentration, obtained by averaging hourly data on a given data for each station. A time series statistical model was used to compare pre- versus post-bentonite concentrations at each monitoring station. The model assumes that a daily average is correlated with the daily averages for the previous two days. In addition, the daily average are effected by an overall time effect. This time effect takes the form of a cyclic yearly trend. The statistical model is presented in Equation 3-3.

The overwhelming conclusion from the time series Radon concentrations is that daily average radon concentration at the four stations along the exclusion fence are significantly lowered in the post-bentonite year compared to the pre-bentonite year. This reduction is highly significant for these stations. For the fence line stations, we can not conclude that a reduction in radon concentrations occurred. The predicted maximum concentration among the boundary stations remains higher than the predicted maximum concentration for the background station, even in the post-bentonite period. Meanwhile, for exclusion fence monitors, the predicted maximum concentration in the post-bentonite period is consistently lower than the predicted minimum concentration in the pre-bentonite period.

At this stage, conclusions made from the results of fitting the model in Equation 3-3 must be made with discretion. Because only 2 years of radon concentration data have been gathered, and because bentonite was added at the end of the first year, the effect of bentonite on the daily average concentrations is completely confounded with the yearly effect. Thus any observed differences in results between pre- and post-bentonite periods cannot be attributed solely to the effect of adding bentonite. Yearly effects (i.e., yearly changes in meteorological conditions, etc.), as well as effects due to differences in instrumentation, also contribute to the observed differences within a station. Separating yearly effects from bentonite effects can begin once a second year of post-bentonite monitoring has been completed.

Gamma Does Rate Analysis

The dose rate at the silo dome was modeled using Microshield 4.0. The results of this model are not useful due to the lack of sufficient data regarding the actual thickness and current conditions of the bentonite over the residues. The distribution of radon and its daughter products in the headspace significantly affect the results as well. In addition, the source term and distribution of the radionuclides within the residues is not adequately characterized for accurate use in the dose rate model. The use of an average bentonite thickness is not applicable to the model due to the exponential dependence of the dose rate to the shield thickness. For the above reasons the model did not appear to accurately reflect the dose rate at the silo domes.

Due to the unknown degree of uncertainty in the dose rate model and the lack of measured dose rates that correlate with the results, the measured dose rate should not be used to predict radon concentration in the silo headspace. The dose rate measurements on the silo dome are not likely to respond to changes in the radon concentration unless the change was significant (i.e., more than an order of magnitude or greater than 1,000,000 pCi/l). The dose rate may be possible to use as an indicator of catastrophic failure of the bentonite and concentrations of radon in the headspace of more than 1,000,000 pCi/l.

TLDs measurements are available at the site fence line, (AMS 5, AMS 6, and AMS 7) and four background locations. TLD data was available at the fence line and background locations since 1989 and at all locations except background locations 3 and 4 which began in 1990.

Due to the limited data a qualitative comparison of the means of these data was made as presented in Subsection 3.3.2. The TLD data would indicate a significant reduction in the dose rate at AMS 6 following the addition of bentonite with no obvious effect observed at the other locations. The dose rate at AMS 6 was an average of 12.4 microR/hour in 1991 and is currently 8.3 microR/hour in 1992. The other locations of the TLDs reported dose rates from 6.3 to 7.6 microR/hour in 1991 and from 5.6 to 7.7 in 1992.

The TLD data would seem to indicate that the dose rate has been reduced at locations close to the K-65 silos (within 380 meters). No conclusions can be inferred from the data for locations at a greater distance than this from the silos. This is most likely due to the other locations being outside of the range of the silos influence.

Recommended Monitoring Criteria

The lack of adequate methods to demonstrate compliance with the 0.015 pCi/l radon concentration at the nearest individual renders the criteria useless. No definitive statement can be presented regarding compliance. In lieu of attempting to predict exposure and off-site concentration a more reliable and easily represented monitoring regimen should be applied to determine the effectiveness of the bentonite at reducing the radon concentration.

The proposed recommendation is to monitor the headspace radon concentration directly. The effectiveness can be determined based on a comparison of the measured concentration to prediction intervals and tolerance limits.

The prediction interval can be used to determine if the current radon concentration comes from the same distribution of radon concentrations measured since July, 20, 1992. This data is used to estimate the prediction interval as described in Section 4.3.

The tolerance interval is used to set the upper bound on the radon concentration in the headspace. The tolerance limit was determined by estimating the lowest possible radon concentration in the headspace that would likely exceed the compliance criteria of 0.015 pCi/l at the nearest resident. This process was explained in Section 4.2. The concentration of Section 4.2 was further reduced because the current radon concentration was significantly below this level and it was deemed reasonable to reduce this level given the current radon concentration, past performance of the bentonite and the uncertainty in the predicted exposure.

A detailed procedure for sampling and a plan of action for determining bentonite effectiveness should be developed. The following are the recommended monitoring criteria to determine the effectiveness of the bentonite:

1) Perform both continuous and grab samples from the headspace of each silo until it can be determined that the samples from each method are obtained from the same distribution.

2) Following the collection of a significant number of grab samples reevaluate the prediction interval based on the grab sample results.

3) Collect grab samples on a weekly basis for comparison to the prediction intervals and the tolerance limit.

If a weekly sample exceeds the prediction interval, daily grab samples should be collected, to assess any trends, for a period of not less than one week or until consecutive daily samples are within the prediction interval. During the daily sampling period, assessment of the bentonite effectiveness should be made with regard to any trends in increased concentration in the headspace which might show a gradual degradation of the bentonite performance.

If a grab sample exceeds the tolerance limit, immediate actions should be taken to assess the bentonite effectiveness. Actions should include an immediate resample of the headspace to confirm validity of the measurement.

1.0 Introduction

1.1 Background on the K-65 Silos

The K-65 silos were constructed at the Fernald Environmental Management Project (FEMP), formerly known as the Feed Materials Production Center (FMPC), in 1951 for dewatering and storing of radium-bearing residues formed as by-products of uranium ore processing. Table 1-1 provides an overview, in chronological order, of the significant events and studies associated with the K-65 Silos. Uranium-rich ore called pitchblende was imported to the FMPC facility from Belgian Congo and Australia. The ore was treated with nitric acid to dissolve the uranium for extraction from the ore. The radium bearing residues were separated using a precoat rotary vacuum filter, reslurried, neutralized with lime, and pumped into the silos where the solids settled. The liquids were decanted out of the silos and pumped to an on-site treatment facility. The silos received waste residues from 1952 to 1958. The silos now contain approximately 9,700 tons of residual solids. Results of radiological analysis of the K-65 residues indicate that the range in concentration of radium-226 per unit mass of residue is on the order of 177 to 891 nCi/g. These results include both Silo 1 and Silo 2. The average value is on the order of 525 nCi/g, which would correspond to a total radium inventory of approximately 4,600 curies. It is important to note that by definition, 1 g or radium-226 is equal to 1 Curie of activity. Therefore, the total estimated mass of radium-226, in both silos, is nearly 5 kg, which corresponds to about 0.6 parts per million.

In 1963, after several years of weathering and wear, repairs were conducted to ensure that the waste material inside the silos would not be released. These repairs consisted primarily of concrete patching and a water-resistant coating applied to the exterior walls of the silos. An earthen berm was added in 1964 to assist in the structural integrity and to reduce the emission of radon gas.

Two independent studies on the structural integrity of the silos indicated that the silos had lost over half of their design strength and that no life expectancy could be predicted for the silo domes. Silo dome failure would result in an immediate release of radon gas from the headspace of the silos to the environment. A probabilistic risk assessment (PRA) was prepared for the K-65 Silos to evaluate the potential for and consequences of silo failure and the release of radon. The results of the PRA for the silos were used in the evaluation

Table 1-1. K-65 Silos Chronology of Events

DATE	Milestone or Event
1951	Construction begins
1952	Construction complete
1958	Silos filled to capacity (19,400,000 lbs)
1963	Repairs made to silos
1964	Earthen berm added
1979	Vents sealed
1983	Embankments enlarged
1985	Camargo performs non-destructive tests
1986	Protective covers added to center section of dome
1986	Water-proof membranes added to dome top
1987	Foam coating applied to domes
1989	DOE inspections
1989	Bechtel performs further analysis of integrity
1990	Probabilistic risk assessment conducted
1990	EE/CA and Removal Action Work Plan Approved
1991	Removal Action initiated in October
1991	Removal Action complete November 30

of the threat associated with dome failure and chronic radon release. After evaluation of the risk results and through discussions with the United States Environmental Protection Agency (U.S.EPA) and the public a decision was made to perform a removal action under Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) to mitigate or eliminate the potential and actual threats associated with the silos.

1.2 K-65 Bentonite Removal Action

The objective of the K-65 Removal Action, as is the case with any removal action under CERCLA, was to reduce or eliminate an actual or potential threat to the health and safety of the public and the environment. The chronic release of radon and the potential structural failure of the K-65 silos, which could result in an acute radon release to the environment and exposure to the public, indicated the need for a removal action (WEMCO, 1990).

An Engineering Evaluation and Cost Analysis (EE/CA) was developed to evaluate the possible alternatives, and to select the most appropriate action, for reducing or eliminating the risk to the public and the environment. The removal action selected involved covering the K-65 residue with a gas barrier material that would retard the emanation of radon gas into the space between the K-65 residue and the silo domes. The barrier would also address the potential for removal of residue under high wind conditions (tornado). The barrier material selected was bentonite (a type of clay). The selection of bentonite was in part due to its plasticity, its capability to hold water, and the relative ease by which it can be placed into the silos.

1.3 Objectives of the K-65 Removal Action

The objectives of the removal action were quite simple: 1) reduce the concentration of radon in the silo headspace (therefore reducing the chronic emissions to the environment), and 2) reduce the magnitude of radon and residues available for release in the event of silo dome failure. Engineering calculations and evaluations indicated that a minimum of one foot of bentonite would be needed to meet these objectives. This quantity of bentonite would sufficiently retard the diffusion of radon gas and provide an effective barrier to wind or water erosion in the event that the domes failed. The primary concern for the thickness of bentonite was focused on the ability to retard the diffusion of radon. As a result of this focus, a performance goal was imposed as part of the Removal Action Work Plan for the

K-65 Silos. The nature of the performance goal tied the K-65 Silos directly to the current estimated chronic exposure to the nearest resident.

The performance goal in effect states that the above background concentration of radon at the location of the nearest resident shall be less than 0.015 pCi/l. Implicit in this goal is the assertion that the K-65 Silos are the sole source of above background radon concentrations. Additionally, there is an implicit assumption that the background radon concentration in the vicinity of the FEMP can be established.

The effectiveness of the removal action and the assessment of whether the performance goal was met was to be determined on the basis of a model, which would address the release and transport of radon from the source (assumed to be the K-65 Silos) to the nearest resident (approximately 500 meters due west of the silos). The model selected to be used was arrived at through joint efforts by the U.S. DOE and U.S. EPA. The model consisted of the following elements: 1) estimation of the radon diffusion rate through the concrete dome, 2) evaluation of the rate of exchange of air between the environment and the silo headspace, and 3) the prediction of airborne concentration of radon at the nearest resident using a Gaussian Plume based computer code.

The effectiveness of the bentonite to mitigate the release of radon has been assessed on a monthly basis since January 1992. The effectiveness was performed in accordance with the work plan. The results of the selected model indicate that radon released from the K-65 silos would contribute radon concentrations, to the nearest resident, of less than 0.015 pCi/l above background. Initial results of the model, using data from January 1992, showed that there would be an above background contribution of 0.0003 pCi/l at the location of the nearest resident. These results were based on a combined radon flux rate of less than 100 (pCi/m^2/sec) and maximum headspace concentration of 500,000 pCi/l. Consideration of the uncertainty and the release mechanism calculations indicate that the headspace concentration could approach the 1987 values of 25 and 30 million pCi/l for Silos 1 and 2 respectively and the off-site contribution would still be less than 0.015 pCi/l. Considering these results, the U.S. DOE questioned the appropriateness of this method for determining effectiveness of the removal action.

The release and transport model, selected and approved through the joint efforts of the U.S. EPA and U.S. DOE, was not calibrated or verified specifically for the FEMP. This was in part due to the limited radon data for the silo headspace prior to placement of the bentonite. There is no way to address (quantitatively) the overall uncertainty in the approach to modeling the physical mechanisms involved with the release and transport of radon from the silos to the nearest resident over 500 meters away. This inability, due to the inherent uncertainty of the natural environment, has lead to the development of a detailed statistical analysis of the radon concentration data.

1.4 Objectives of the Detailed Statistical Analysis Study

The emphasis of this study and report is on the evaluation of the effectiveness of the bentonite to reduce the emanation and release of radon from the K-65 Silos. This study was conducted to show that the cause and effect relationship between the K-65 Silos and the radon concentration at the nearest resident cannot be established within the confidence limits required by the performance goal of 0.015 pCi/l above background. This limitation is rooted in the ubiquitous nature of radon and the subsequent low concentrations observed.

The concentration of radon in the environment is highly variable and is dependent on a variety of factors including barometric pressure and humidity. Additionally the detection limit on the radon detectors, used at the FEMP, is at best 0.2 pCi/l which is nearly an order of magnitude greater than the performance goal (the lower bound on the instrument sensitivity is on the order of 0.2 pCi/l with an expected decrease in the instruments accuracy and precision). The manufacturers of the various types of equipment, used at the FEMP, indicate that the detection limit, based on calibration methods, is actually on the order of 1 pCi/l (nearly two orders of magnitude greater than 0.015 pCi/l goal). Other factors that must be considered include the establishment of a true background for the FEMP, other radon sources, and the inherent uncertainties associated with the transport of radon in the environment.

This study was conducted to determine the effectiveness of the bentonite layer in reducing the radon levels in the headspace and thus to the nearest resident. This assumes that the mechanism affecting the release of radon from the silo is linearly related to the concentration in the headspace (a 99% decrease in radon in the headspace corresponds to 1/100 of the release rate). There were four goals and objectives to this study which are:

1) Illustrate through the use of mathematical and statistical analysis that the Removal Action Performance Goal, which specifies that the above background contribution from the K-65 Silos to the radon concentration at the nearest resident is limited to no more than 0.015 (pCi/l), can only be determined within a relatively low confidence level using the original model. Using the original model alone, for the determination of the effectiveness of the Removal Action with the performance goal is not sufficient for evaluating the actual long term performance of the bentonite. The confidence level needed to establish the 0.015 pCi/l performance goal is much greater than what is achievable using the original analytical models and the site boundary radon monitoring data.

   [The results from using the original model to evaluate the radon concentration at the nearest resident indicated that the headspace concentration could approach pre-bentonite conditions and the performance goal of 0.015 pCi/l would not be exceeded. These results illustrate the high degree of uncertainty in the original model.]

2) Evaluate whether the effectiveness of the removal action and the overall performance of the bentonite can be established using the headspace concentration and dose rate data. Provided this evaluation is achievable the focus of the overall monitoring requirements would be on measurement of radon in the headspace of each silo (gamma dose rate measurement on the domes if found to be appropriate).

3) Quantify the degree to which the bentonite has been effective in reducing radon in the headspace.

4) Establish a set of monitoring criteria to routinely and eventually periodically evaluate the effectiveness and consistency of the bentonite, using radon concentrations in the headspace and if necessary and appropriate dose rate measurements on the domes).

Sections 2 through 4 present the methodology used to meet these goals and objectives. Section 2 presents the methodology used to illustrate that the 0.015 pCi/l compliance goal can not be evaluated within acceptable confidence limits. Section 3 presents the quantification of the effectiveness of the bentonite in reducing the radon concentration. Section 4 presents the methodology used to establish monitoring criteria. Section 5 presents the inherent uncertainties and the connection to establishing cause and effect relationships. Section 6 presents conclusions and recommendations.

2.0 Evaluation of 0.015 pCi/l Removal Action Performance Goal

This section of the report addresses the fact that the evaluation of the performance goal, as established for this removal action, using available models and methods such as the approved Gaussian Plume, will have large uncertainties and low confidence limits. The large uncertainty in the original approach is not appropriate when considering a value of 0.015 pCi/l above background limit at the nearest resident. This section will illustrate through the statistical evaluation of radon monitoring data the inherent uncertainty and the overall limitations associated with assessing whether this performance goal has been met. The statistical tests employed and the results clearly indicate that there is reason to suspect that the data are not sufficiently independent and therefore can not be supported for this purpose.

2.1 Statistical Evaluation of Monitoring Data

Several approaches were used to evaluate the monitoring data prior to and after installation of bentonite. Subsection 2.1.1 presents background information on the monitoring data and instruments used to measure radon. Subsections 2.1.2 through 2.1.4 present the various statistical approaches used to interpret the monitoring data at the fence line, exclusion fence, and background.

2.1.1 Background Information on Monitoring Data and Monitoring Instrumentation

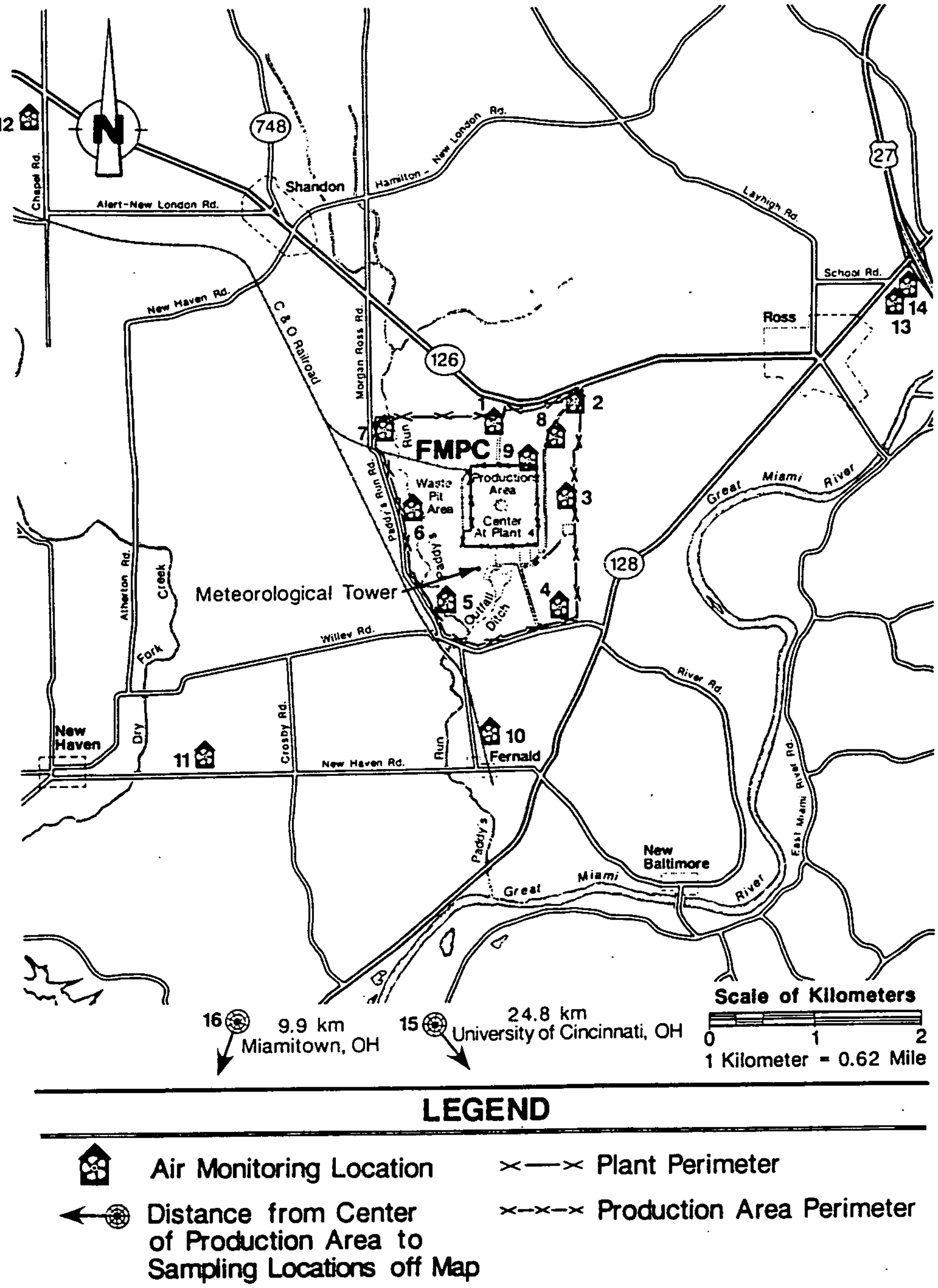
Pylons

Pylon Model 110 and 300A Lucas cells are scintillation cells. These allow the Pylon AB-5 portable radiation monitor to measure radon gas. These instruments are considered passive monitoring instruments. The sensitivity of the Pylon AB-5 is, stated by the manufacturer, 1.0 pCi/l. The sensitivity can be reduced to 0.1 pCi/l by using a Pylon AB-5 equipped with a "Pylon kettle." The FEMP currently uses the Pylon Model 110 with a 1.0 pCi/l sensitivity. Attachment A presents the procedure used to estimate the lower limit of detection and minimum detectable activity for the Pylons which are 0.36 pCi/l and 0.24 pCi/1, respectively. Radon concentrations of 0.015 pCi/l can not be measured directly with the instruments being used at the FEMP. The use of these instruments introduces considerable uncertainty which cannot be accounted for in the statistical analysis.

The time period used in the analysis for pre-bentonite monitoring data was from January 1, 1991, to September 30, 1991, while post-bentonite monitoring data was from January 1, 1992, to September 30, 1992. The time period from October 1991 through December 1991 was not included in the analysis since the preparation and installation of the bentonite was conducted during this period (these activities were known to result in acute radon releases). In addition, this data was not included since these months were not available during post-bentonite conditions. Utilizing data from these months would introduce a seasonal bias into the data analysis, which would introduce an error term that could not be accounted for in the final analysis.

The manufacturer recommends calibration of the Lucas cells approximately every 6 months. A review of the monitoring data, for purposes of evaluating all calibration concerns, indicated that the monitoring data were sufficiently similar that all of the monitoring data were satisfactory for use in the analyses. The calibration of these detectors is accomplished with a source strength of 100 pCi/l. The Pylon detectors have not been calibrated in the range of environmental radon concentrations. A signs test indicated that the variability in the data could not be attributed to randomness as would be the case if the readings were false due to instrument data, further indicating data useability.

Radon monitoring locations included in this analysis were those located at the three fence line air monitoring stations (AMS), four exclusion fence locations, four locations within the production areas and one background location (the only background location with a pylon continuous radon monitor). Figure 2-1 shows the location of the three fence line monitoring stations AMS 5, AMS 6, and AMS 7. They are denoted on the Figure by 5, 6, and 7, respectively. The four silo exclusion fence locations, labeled NW, SW, NE, and SE are located on the exclusion fence of the silo area. Theses instruments are actually located on the fence directly east and west of the silos. The NE and NW monitors are situated directly across from one another and at the mid-point of Silo 2. The monitors labeled SW and SE are situated in a similar fashion for Silo 1. The four production area sample locations considered were the Pilot Plant, Plant 2/3, Plant 5, and the Met tower (meteorological tower where wind speed and direction are also collected for the FEMP). The Met tower is shown on Figure 2-1. The background samples were collected at one location in Westwood which is 16 miles from the facility. Monitoring data was collected at these locations using Pylon AB-5s. The data, at these locations, were recorded on an hourly basis. This data was used



* Note: Pylon radon detectors are not at all air monitoring locations. AMS 5, AMS 6, AMS 7 and the Meteorological Tower have Pylon detectors. All locations shown have Terradex cups.

Figure 2-1. Air Monitoring Locations.

in the analyses and the background data was used as the actual FEMP background. This assumption may be the most limiting of the assumptions used in the statistical analyses (uncertainties imposed by this assumption will be discussed in Section 5). Natural background radon levels may vary depending on the physical surroundings such as (1) the concentration of the parent atom radium in the soil or rocks, (2) the emanation power of the soil composition, (3) the porosity, (4) atmospheric pressure differentials across the interface of the soil and atmosphere, (5) the degree of water saturation, and (6) other potential influences that can not be quantified (NCRP 1989).

Radon headspace data prior to the installation of bentonite consists of a single data point (verified by replicate samples) for each silo which was 25,000,000 pCi/l in Silo 1 and 30,000,000 pCi/l in Silo 2. These were grab samples taken from the interior of K-65 Silos 1 and 2 on November 4, 1987. Samples were taken in multilayer gas bags and glass flasks.

Radon headspace data post-bentonite was from July 20 to September 15, 1992. A Pylon AB-5 was used to continuously measure radon concentrations in the silo headspace. Samples were collected during 5-minute intervals in both silos. Each silo had only one sampling location. The intake and discharge for the sampling probe were from the same manway. In addition, grab samples were also collected from the headspace. The air collected for the continuous and grab samples travels through approximately 100 feet of stainless steel and tygon tubing to reach the analyzer where the radon concentration is measured.

Terradex Cups

To determine radon concentrations in the environment, alpha-track radon detectors in weatherproof housings are also used. Figure 2-1 shows the location of air monitoring stations. Figure 2-2 shows the location of on-site radon monitoring situations using Terradex cups. Figure 2-3 shows the location at the off-site and fence line monitoring stations which have Terradex cups. An alpha-track radon detector is a device for measuring radon concentrations in air over a long time period. The detectors, Terradex cups, are changed each calendar quarter and sent to the supplier for analysis.

The time period used in the analysis for pre-bentonite was from first quarter 1988 (after the domes were foamed) to third quarter 1991 while post-bentonite monitoring data was from first quarter 1992 to third quarter 1992. The data from third quarter 1991 was not included

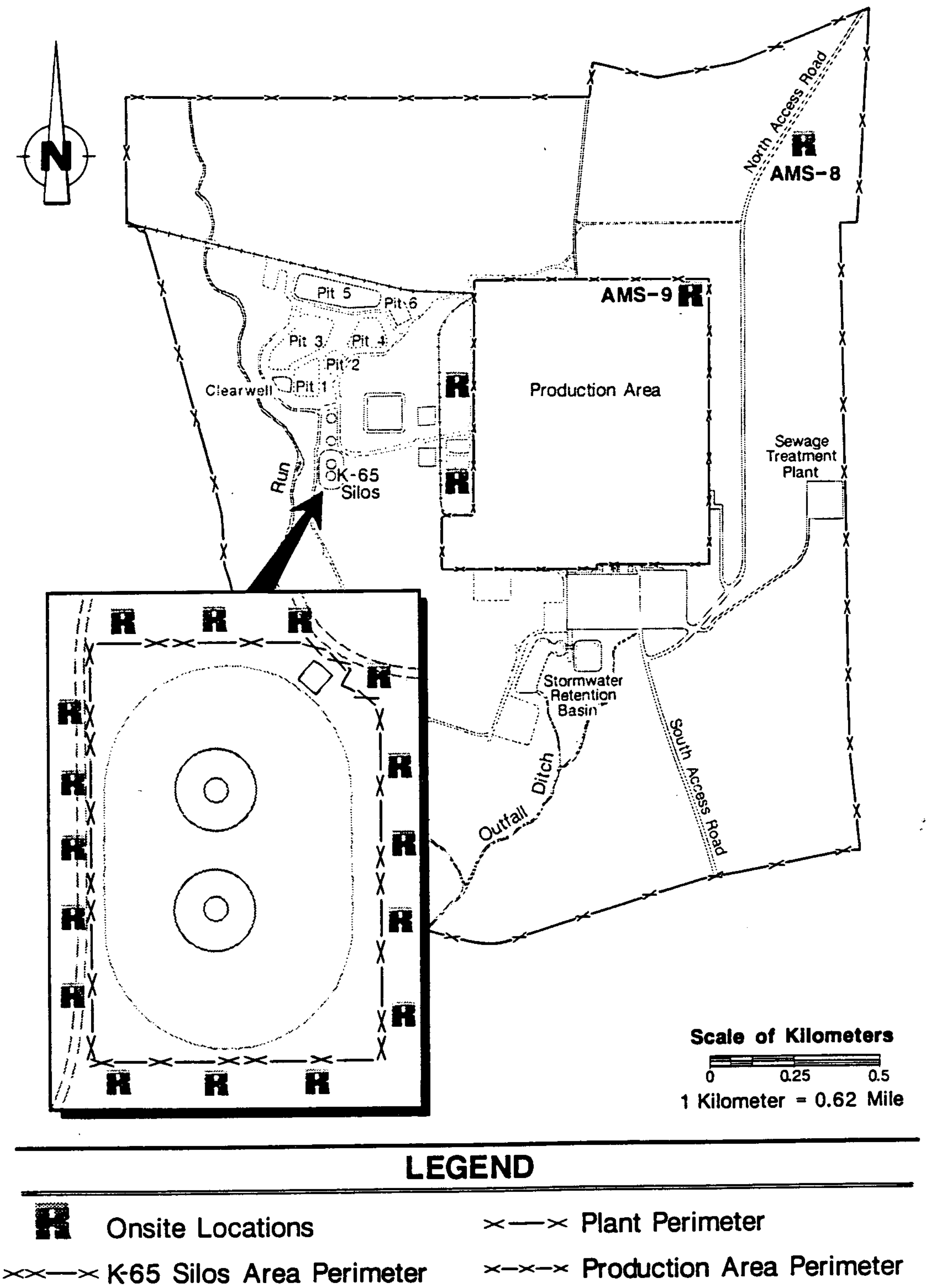


Figure 2-2. On-site Radon Air Monitoring Locations.

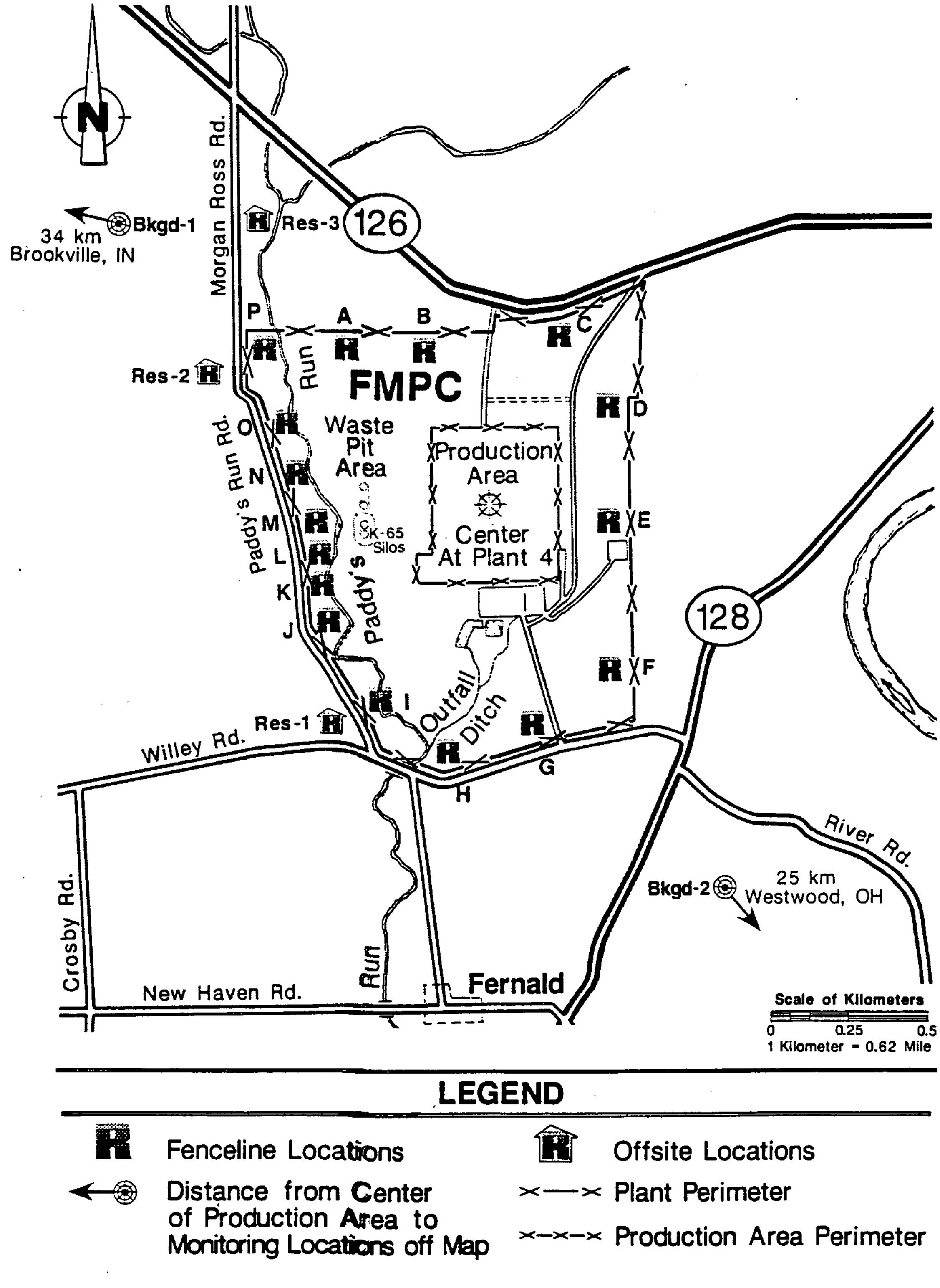


Figure 2-3. Off-Site and Fence Line Radon Air Monitoring Locations.

in the analysis since the preparation and installation of the bentonite was conducted during this period.

Radon monitoring locations included in this analysis were at the fence line, exclusion fence, and four background locations. The fence line and exclusion fence locations are at the same locations as the Pylon samplers. The four background locations are in Westwood (24 km from the site), University of Cincinnati (24.8 km from the site), Brookville (40 km from the site), and Miamitown (9.9 km from the site). Only the Westwood location has a Pylon sampler.

2.1.2 Comparison of Actual Daily Average Radon Concentration to Background at Each Monitoring Station in Pre-Bentonite and Post Bentonite Periods

2.1.2.1 Introduction

A two-sample analysis procedure was used to test the hypothesis about the means and variances of the two samples. A one tailed t-test was used to test the hypothesis that the difference between the two means was greater than zero. This test is used to determine whether pre-bentonite results are statistically higher than the post-bentonite results at various locations. An arithmetic mean was calculated on the hourly monitoring data to provide daily averages for each sample location. Tables 2-1 and 2-2 summarize statistical information on the daily Pylon radon data at boundary fence line, exclusion fence, and within the production area prior to and after installation of bentonite, respectively. Attachment B contains plots of the Pylon daily average radon data from each monitoring station. Attachment C contains plots of the Pylon daily minimum, average, and maximum radon data from each monitoring station.

2.1.2.2 Pylon Monitoring Data at the Fence Line and Within the Production Area

Six combination of observation-situations at the fence line were tested using the two-sample analysis procedure. These were: (1) pre-bentonite at AMS 5 versus pre-bentonite at the background, (2) pre-bentonite at AMS 6 versus pre-bentonite at the background, (3) pre-bentonite at AMS 7 versus pre-bentonite at the background, (4) post-bentonite at AMS 5 versus post-bentonite at the background, (5) post-bentonite at AMS 6 versus post-bentonite at the background, and (6) post-bentonite at AMS 7 versus post-bentonite at the background. Figures 2-4 through 2-6 present plots of AMS 5, AMS 6, and AMS 7 with background

Table 2-1. Summary Statistics for the Pre-Bentonite Pylon Monitoring Data (pCi/l)

Statistics	Background	Fence line			Exclusion fence				Production area			
		AMS 5	AMS 6	AMS 7	NW	SW	NE	SE	Pilot plant	Plant 2/3	Plant 5	Met. tower
Mean	0.54	0.89	0.71	0.76	4.43	5.26	8.81	6.57	0.93	0.67	0.76	1.12
Median	0.52	0.76	0.64	0.63	2.97	3.13	4.78	3.58	0.82	0.60	0.68	0.96
Mode	0.25	0.32	0.53	0.38	5.08	0.53	0.93	2.02	0.81	0.60	0.82	0.35
Standard Deviation	0.25	0.53	0.33	0.45	4.11	6.52	14.18	11.95	0.41	0.36	0.51	0.77
Variance	0.06	0.28	0.11	0.20	16.93	42.48	201.16	142.86	0.17	0.13	0.27	0.60
Kurtosis	-0.75	1.95	-0.28	1.26	6.13	14.33	50.10	91.01	2.67	4.13	136.90	1.95
Skewness	0.46	1.06	0.67	1.05	2.30	3.16	5.99	8.32	1.33	1.48	10.31	1.26
Range	1.03	3.36	1.45	2.67	25.02	52.91	148.80	146.90	2.40	2.47	7.30	4.20
Minimum	0.20	0.16	0.22	0.19	0.43	0.33	0.28	-0.22	0.40	0.22	0.38	0.25
Maximum	1.23	3.52	1.68	2.86	25.45	53.24	149.08	146.68	2.80	2.70	7.68	4.45
Sum	118.76	209.45	171.31	180.18	1120.87	1337.11	1902.32	1405.92	252.80	161.31	182.59	257.59
Count	219	236	241	238	253	254	216	214	271	241	240	231

Table 2-2. Summary Statistics for the Post-Bentonite Pylon Monitoring Data (pCi/l)

Statistics	Background	Fence line			Exclusion fence				Production area			
		AMS 5	AMS 6	AMS 7	NW	SW	NE	SE	Pilot plant	Plant 2/3	Plant 5	Met. tower
Mean	0.58	0.67	0.71	0.72	1.08	1.25	1.62	0.98	0.80	0.66	0.57	0.76
Median	0.53	0.54	0.60	0.56	0.94	1.14	1.59	0.83	0.70	0.53	0.53	0.66
Mode	0.48	0.34	0.51	0.29	0.79	1.08	0.47	0.41	0.61	0.37	0.50	0.41
Standard Deviation	0.21	0.35	0.32	0.44	0.53	0.52	0.99	0.69	0.28	0.37	0.23	0.30
Variance	0.04	0.12	0.10	0.19	0.28	0.27	0.98	0.47	0.08	0.14	0.06	0.09
Kurtosis	3.45	0.04	4.46	3.19	1.44	1.81	3.45	8.80	9.56	5.62	13.99	-0.35
Skewness	1.60	0.94	1.66	1.53	1.13	1.16	1.39	2.43	2.18	2.18	2.52	0.76
Range	1.28	1.48	2.15	2.90	2.92	2.96	6.26	4.93	2.30	2.00	2.15	1.26
Minimum	0.30	0.27	0.24	0.24	0.33	0.42	0.29	0.24	0.42	0.28	0.25	0.34
Maximum	1.58	1.75	2.40	3.14	3.25	3.38	6.55	5.17	2.71	2.28	2.40	1.60
Sum	154.29	179.76	192.53	195.46	237.29	336.63	423.50	249.08	211.92	171.74	151.97	84.70
Count	267	270	272	273	219	270	262	254	266	262	268	112

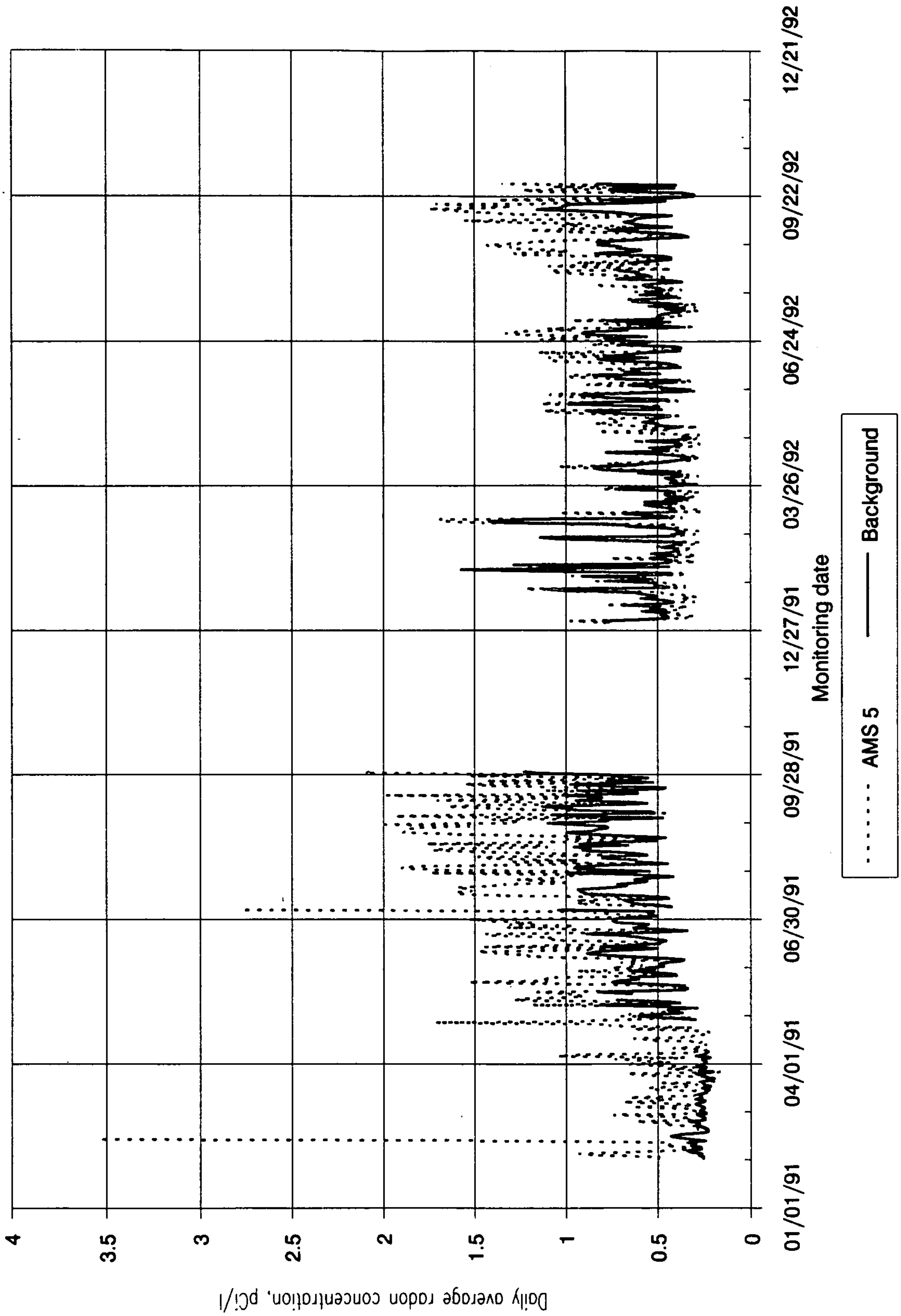


Figure 2-4. Plot of Daily Average Radon Concentration Versus Time at AMS 5 and Background.

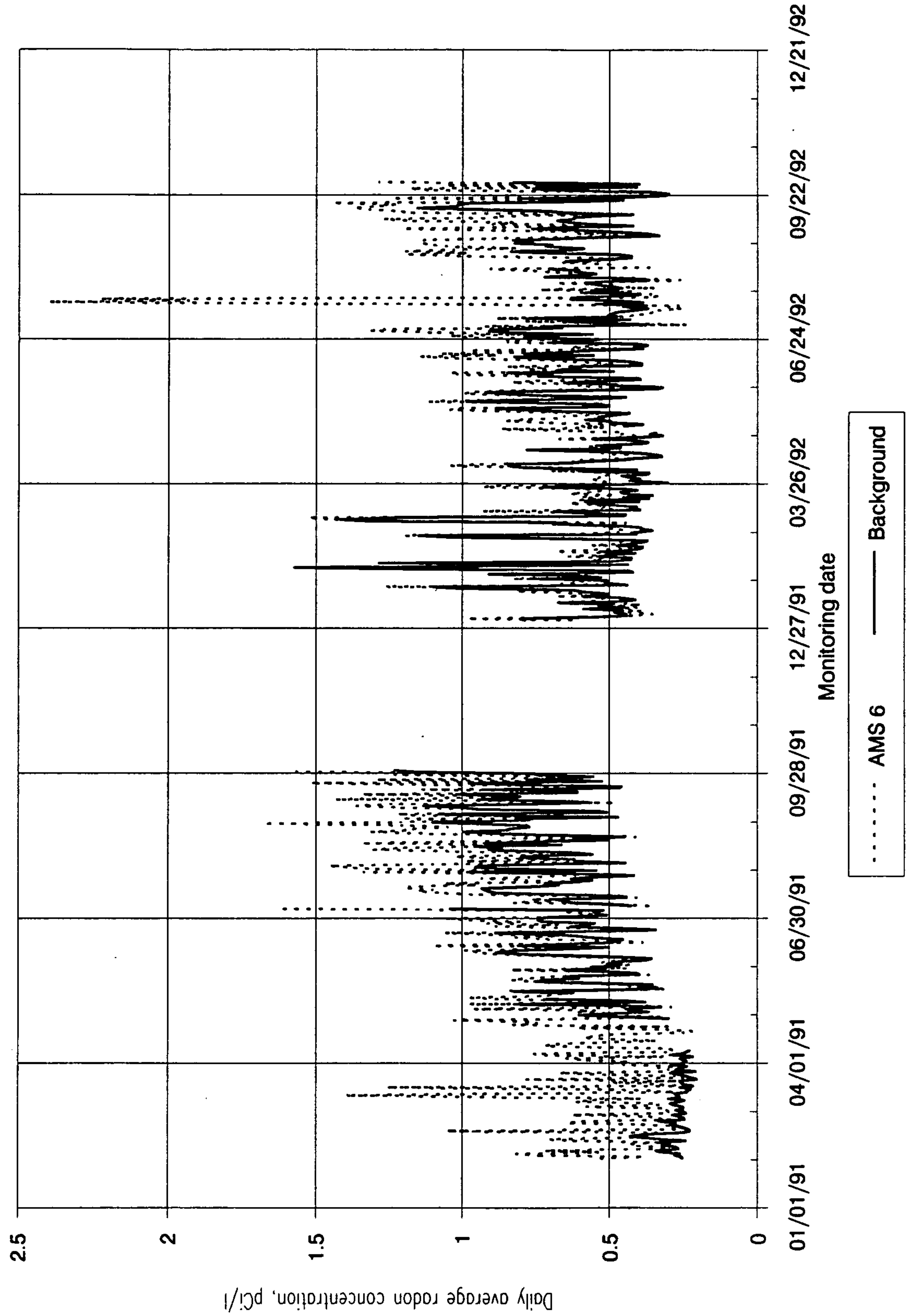


Figure 2-5. Plot of Daily Average Radon Concentration Versus Time at AMS 6 and Background.

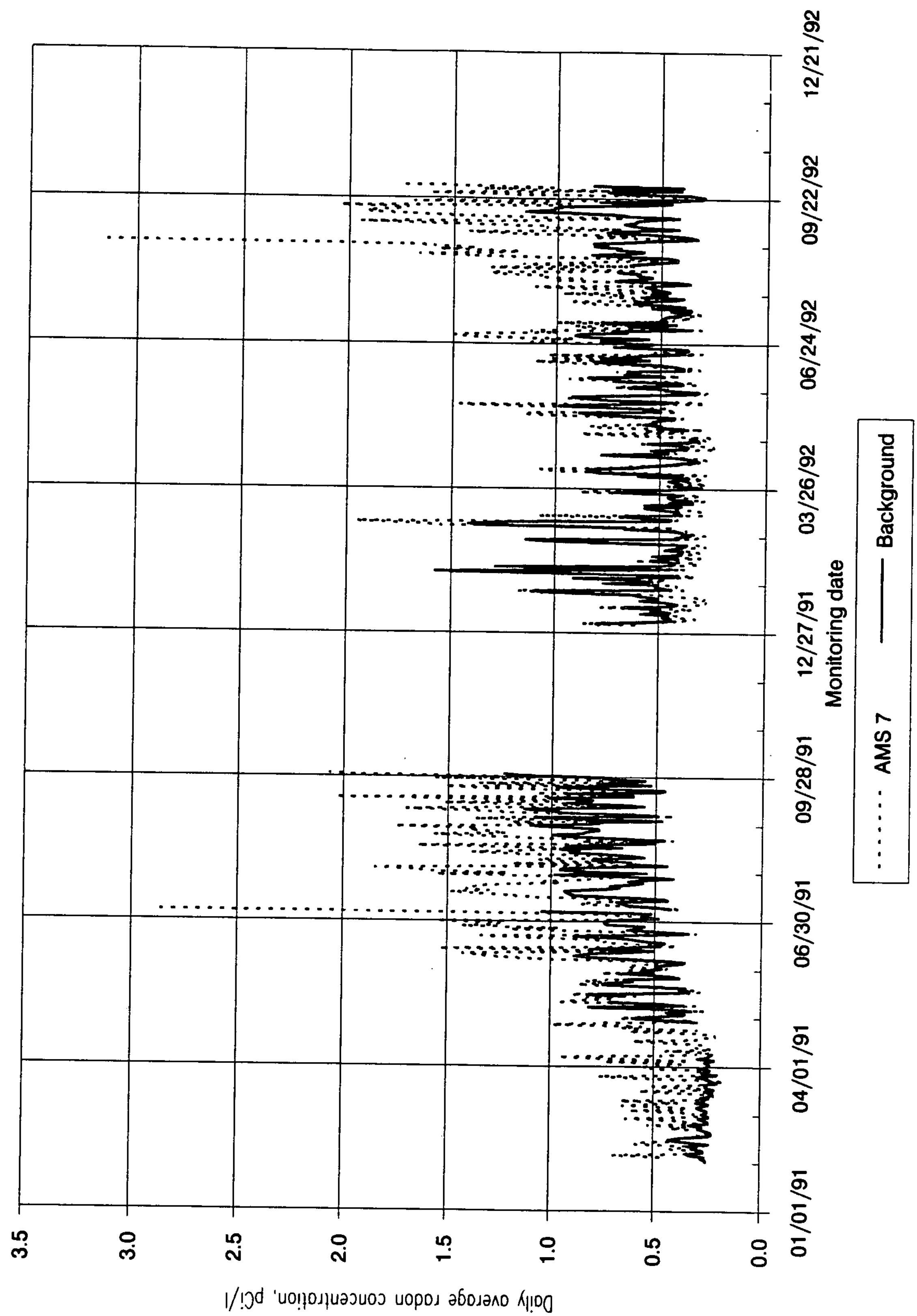


Figure 2-6. Plot of Daily Average Radon Concentration Versus Time at AMS 7 and Background.

versus time, respectively. Eight combination observation-situations within the production area were tested using the two-sample analysis procedure. These included: (1) pre-bentonite at the Pilot Plant versus pre-bentonite at the background, (2) pre-bentonite at the Plant 2/3 versus pre-bentonite at the background, (3) pre-bentonite at the Plant 5 versus pre-bentonite at the background, (4) pre-bentonite at the Met Tower versus pre-bentonite at the background, (5) post-bentonite at the Pilot Plant versus post-bentonite at the background, (6) post-bentonite at the Plant 2/3 versus post-bentonite at the background, (7) post-bentonite at the Plant 5 versus post-bentonite at the background, (8) post-bentonite at the Met Tower versus post-bentonite at the background.

Table 2-3 summarizes the two-sample results for the Pylons at the fence line and within the production area versus background. In all cases except post-bentonite at Plant 5, the results indicate that there was a statistical difference between the two means. These results indicate that the pre-bentonite at AMS 5 is statistically greater than pre-bentonite at the background at the 5 percent significance level. The mean for post-bentonite at Plant 5 was slightly lower than the mean for post-bentonite at the background (0.57 versus 0.58 pCi/l), therefore, the test could not identify a statistical difference between these two means. The results indicate that in pre-bentonite conditions at the Plant 5 can not be distinguished from background.

The results of these statistical tests provides a great deal of insight to the relationship between the release and transport of radon from the K-65 Silos. Recall that the emphasis of this section of the study deals with the ability to evaluate whether the performance goal of 0.015 pCi/l has been met at an appropriate confidence level. The plotted data show that there is only a relatively small decrease in the average radon concentration observed at the site boundary (AMS 5, 6, and 7).

It should be pointed out that there is a fundamental difference between the term 'significant' when used to indicate statistical results versus consideration of the magnitude of the observed radon. In the case of the site boundary monitors the magnitude of the difference between pre- and post-bentonite conditions is considered small since it is typically less than 0.4 pCi/l changes, and the difference in the maximum observed value, at each location, is less than 1.0 pCi/l change. This situation is considerably different at the exclusion fence monitors, where the difference in the mean values, between the pre- and post-bentonite conditions, is on the

Table 2-3. Summary of Two-Sample Analysis Results for Pylons at the Fence Line and Within the Production Area Versus Background

Sample 1		Sample 2						
Location	No. of data points	Location	No. of data points	Ratio of variance	Hypothesis to test (1)	Alpha	Signif-icance level	Hypothesis results (2)
Pre-Bentonite								
AMS 5	236	Bkgrd	219	4.55	diff = 0 vs one tail (GT)	0.05	2.69E-09	Reject HO
AMS 6	241	Bkgrd	219	1.79	diff = 0 vs one tail (GT)	0.05	1.05E-09	Reject HO
AMS 7	238	Bkgrd	219	3.31	diff = 0 vs one tail (GT)	0.05	9.44E-10	Reject HO
Pilot plant	271	Bkgrd	219	2.70	diff = 0 vs one tail (GT)	0.05	3.24E-14	Reject HO
Plant 2/3	241	Bkgrd	219	2.13	diff = 0 vs one tail (GT)	0.05	8.60E-06	Reject HO
Plant 5	240	Bkgrd	219	4.30	diff = 0 vs one tail (GT)	0.05	1.31E-08	Reject HO
Met tower	231	Bkgrd	219	9.66	diff = 0 vs one tail (GT)	0.05	3.56E-14	Reject HO
Post-Bentonite								
AMS 5	270	Bkgrd	267	2.92	diff = 0 vs one tail (GT)	0.05	2.25E-04	Reject HO
AMS 6	272	Bkgrd	267	2.37	diff = 0 vs one tail (GT)	0.05	1.50E-08	Reject HO
AMS 7	273	Bkgrd	267	4.60	diff = 0 vs one tail (GT)	0.05	2.15E-06	Reject HO
Pilot plant	266	Bkgrd	267	1.83	diff = 0 vs one tail (GT)	0.05	7.75E-09	Reject HO
Plant 2/3	262	Bkgrd	267	3.24	diff = 0 vs one tail (GT)	0.05	1.47E-03	Reject HO
Plant 5	268	Bkgrd	267	1.30	diff = 0 vs one tail (GT)	0.05	7.15E-01	Do not reject HO
Met tower	112	Bkgrd	267	2.15	diff = 0 vs one tail (GT)	0.05	2.70E-09	Reject HO

(1) A one-tailed t-test was used to test the hypothesis that the difference between the means (Sample 1 - Sample 2) was greater than 0.

(2) Rejecting the hypothesis indicated that the difference between the means is not zero and that Sample 1 mean is statistically greater than the Sample 2 mean at the 5 percent significance level.

order of a factor of 4 or greater, and the difference in the maximum values observed is a factor of 8 or greater.

The statistical results indicate that for AMS 5 and 6 there is a net decrease in the post- versus pre-bentonite conditions (as one would expect), while only AMS 5 is statistically significant. The results of the tests for AMS 7 indicate an increase in the average concentration for the post- versus pre-bentonite conditions even though this result is not statistically significant. These results tend to contradict each other and the cause is due to the inherent assumption that the K-65 Silos are the only source of radon other than background. This information is critical to the overall evaluation for two reasons; first there is considerable uncertainty associated with the actual cause and effect relationship between the observed radon concentrations at the site boundary and the radon in the silos for the pre- and post-bentonite conditions; and second there is considerable uncertainty associated with the appropriateness and applicability of the selected background location.

2.1.2.3 Quarterly Terradex Monitoring Data at the Fence Line

Table 2-4 summarizes the quarterly Terradex results. Attachment D contains plots of the quarterly Terradex measurements at each monitoring station and each background location.

Pre-Bentonite

Several one-sided t-tests were performed to test for statistical significance between the background locations and AMS 5, AMS 6, and AMS 7 for the pre-bentonite period of January 1, 1988, through September 30, 1991, using quarterly Terradex measurements.

Each value used in this statistical comparison was calculated from averaging three replicate measurements (excluding outliers) at each monitoring station. The null hypothesis in each of these statistical tests was that the pre-bentonite mean for AMS 5, AMS 6, and AMS 7 taken individually is less than or equal to the background mean. The alternative hypothesis is, therefore, that the pre-bentonite mean for each of AMS 5, AMS 6, and AMS 7 is greater than the background mean.

In each instance, the pre-bentonite means for AMS 5, AMS 6, and AMS 7 were determined to be statistically greater than the pre-bentonite mean for background at the 5 percent level of

Table 2-4. Summary of Quarterly Terradex Cup Measurements at Each Monitoring Location

Date (Quarterly)	AMS 5	AMS 6	AMS 7	BKGD-1 (Westwood)	BKGD-2 (Brookville)	BKGD-3 (U. of Cinci.)	BKGD-4 (Miamitown)
Q1/88	0.3			0.3	1.2		
Q2/88	1.9			0.3	1		
Q3/88	1.4	1.5	1.6	0.5	0.6		
Q4/88	0.9	1	2	0.4	0.5		
Q1/89	0.3	0.3	0.2	0.3	0.3		
Q2/89	0.7	0.4	0.4	0.4	0.5		
Q3/89	0.7	1.2	1	0.6	0.8		
Q4/89	1	1.8	0.7	0.4	0.7		
Q1/90	0.4	0.6	0.3	0.3	0.4	0.4	0.4
Q2/90	0.7	0.4	0.4	0.3	0.2	1.1	1.2
Q3/90	1.9	0.7	0.9	0.4	0.5	0.6	0.3
Q4/90	1.3	0.9	0.6	0.8	0.6	0.5	0.5
Q1/91	0.3	0.4	0.7	0.2	0.3	0.6	0.7
Q2/91	1.1	0.7	0.8	0.7	0.6	0.8	0.5
Q3/91	1.1	1.3	1.1	0.6	1.1	0.8	0.4
Q4/91							
Q1/92	1.2	0.5	0.5	0.5	0.8	0.4	0.5
Q2/92	0.5	0.4	0.3	0.1	0.3	0.1	0.1
Q3/92	0.9	0.8	0.9	0.4	0.6	0.7	0.8

significance with the largest p value = 0.0359 being associated with AMS 7. These results are summarized in Table 2-5.

Post-Bentonite

Ninety-five percent coverage (proportion), 95 percent confidence (probability) one-sided tolerance limits (TLs) were prepared on quarterly terradex background radon data for the post-bentonite period (January 1, 1992, through September 30, 1992) and for the pre- and post-bentonite periods combined (January 1, 1988, through September 30, 1992).

In the later instance, the TL was calculated using background data for all four quarters of each year and then the TL was re-calculated using only the first three quarters of each year. The reason for also determining a TL on just the first three quarters is because only the first three quarters were available for calendar year (CY)-1992 (i.e., the entire post-bentonite period) for all monitoring stations.

Only the post-bentonite period for the group of air monitoring stations AMS 5, AMS 6, and AMS 7 was studied and documented for this section of the report. AMS 5, AMS 6, and AMS 7 are located at the western most perimeter of the site and, therefore, represent the best available monitors for interpolating what level of concentration of radon to expect at the closest neighbor to the K-65 silos (who is located further west of the silos than are AMS 5, AMS 6, and AMS 7).

The most conservative TL calculated from the three scenarios described above would be used for making comparisons with the compliance AMSs' values. If any of the values for AMS 5, AMS 6, and AMS 7 exceeded this TL, this would be possible evidence of statistical difference. A t-test was then performed to confirm any statistical difference. In each of the three scenarios described above, a background TL of 1.1 pCi/l was calculated.

The quarterly terradex data for the post-bentonite period for AMS 5, AMS 6, and AMS 7 were compared to the TL of 1.1 pCi/l. One of the nine results, AMS 5, slightly exceeded the TL with a calculated first quarter (CY92) average value of 1.2 pCi/l. Each average value was based on three replicate terradex measurements. When comparing nine average values to the calculated 95 percent, 95 percent TL, one could expect one of the nine values to slightly exceed a TL (with these parameters) approximately 50 percent of the time. This

Table 2-5. Estimates of the Quarterly Deviations from Background for the Pre-Bentonite Period at Air Monitoring Stations 5, 6 and 7[1]

Monitoring Station	Estimate of Difference From Background (pCi/l)	Standard Error of Estimate	90% Confidence Interval	Attained Level of Signif.
AMS 5	0.40	0.14	(0.15, 0.65)	0.0064
AMS 6	0.33	0.14	(0.09, 0.57)	0.0157
AMS 7	0.29	0.15	(0.03, 0.55)	0.0359

(1) Selected outlier data excluded prior to analysis.

could be due solely to chance variation within the compliance stations. Thus, the t-test was performed to confirm any statistical difference.

Based on a one-sided t-test using just the post-bentonite data for the background stations and AMS 5, AMS 5 only was determined to be statistically greater than background ($p = 0.0160$). AMS 6 and AMS 7 were found to be within the acceptable TL of 1.1 pCi/l. The 90 percent confidence interval (CI) for the difference between the means of AMS 5 and background is 0.042 to 0.808 pCi/l. Note that the CI for the difference between these two means does not encompass zero, which also leads one to conclude that AMS 5 is different from the background. These two tests will always result in identical conclusions, if the same level of significance is used in both tests.

A quantitative and qualitative comparison between the radon measurements of three replicate terradex cups and one real-time monitor at AMS 5 was performed. This comparison was made in an attempt to explain why AMS 5 was statistically greater than background for the post-bentonite period under study (i.e., January 1, 1992, through September 30, 1992). AMS 6 and AMS 7 were not statistically greater than background for this post-bentonite period, although, they are situated more downward from the K-65 silos than AMS 5. For purposes of comparison, only data collected on the monitors from January 1 through September 30 for 1991 and 1992 were considered. Real-time monitors at AMS 5 were not in place prior to January 1, 1991, and the data after September 30, 1992, have not been obtained at the time of this study. Data from October 1, 1991, through December 31, 1991, are potentially biased high since the manholes of the silos had to be opened to place bentonite into the headspaces during this period.

Table 2-6 presents the difference between the average of the three replicate terradex results and the pylon real-time data by CY and quarter. When the three terradex results are in relative agreement (standard deviation $\leq$ 0.15 pCi/l), then the terradex quarterly average closely agrees with the quarterly average of the real-time pylon data (absolute difference $\leq$ 0.18 pCi/l). On the other hand, if there is relatively high variability among the three terradex results (standard deviation $\geq$ 0.38 pCi/l), then the terradex quarterly average is statistically greater than the quarterly average of the real-time pylon data. In the later instance, the lowest of the three replicate values closely agrees with the real-time quarterly average data (absolute difference $\leq$ 0.15 pCi/l).

Table 2-6. Comparison of Quarterly Terradex Cups to Real-Time Pylon Monitoring Data For AMS 5 (pCi/l)

Yr - Qtr	Replicate Quarterly Terradex Cups					Pylon Monitor		Terradex Minus Pylon Avgs
	1	2	3	Avg	Std Dev	Avg	Std Dev	
1991-1	0.3	0.2	0.3	0.27	0.06	0.42[1]	0.17[1]	-0.15
1991-2	1.5	0.9	0.8	1.07	0.38	0.77	0.38	0.30
1991-3	1.2	1.0	1.1	1.10	0.10	1.25	0.46	-0.15
1992-1	1.1	0.7	1.9	1.23	0.61	0.55	0.33	1.78
1992-2	0.6	0.5	0.3	0.47	0.15	0.65	0.29	-0.18
1992-3	0.9	0.8	0.9	0.87	0.06	0.82	0.39	0.05

(1) Outlier data excluded prior to analysis.

Furthermore, there is a strong positive correlation (r = 0.91) between the magnitude of the variability among the three replicate terradex cups' readings and the magnitude of the difference between the average of the three cups' readings and the average pylon real-time data for a given quarter. The probability of this being a false correlation is less than 1 percent.

Based on these observations, one may arguably conclude that when there is high variability among the terradex cup readings, some external factor or source other than the ambient radon concentration is causing one and sometimes two of the three cups to read high. When examining the real-time pylon data closer (i.e., on an hourly basis instead of a quarterly basis), virtually all of the increased readings occurred between the hours of approximately 10:00 p.m. and 10:00 a.m. These increased readings tended to occur simultaneously across the site, including the background station. This supports the hypothesis that the pylon monitor readings are precise (accuracy is an entirely different question and must be evaluated while considering the lower limit of detection of the monitor). However, in order to conclude that the pylon monitors are measuring accurately (with low bias as well as with high precision), they would have to be subjected to a quality assurance program that tested for a bias in the low range of 0.3 to 3 pCi/l and not the much higher concentration at which they are currently being calibrated.

Examination of the available data, both terradex cups and pylons, from the background locations and the on-site and boundary monitors general conclusions can be provided. The first obvious situation is the fact that most of the pylon locations had statistical differences when compared to background. There were three cases where this was not observed, terradex cups at AMS 6 and 7 and the pylon data at Plant 5. Comparisons of the raw data and consideration of the statistical anomalies a general conclusion is that the radon concentrations at the site boundary are not significantly above what is observed at the "background" location. Both the pylon data and the terradex cup data show significant variability in the radon concentrations at the AMS, on-site, and background locations. This variability and the statistical evaluations indicate small deviations between pre- and post-bentonite conditions. Tables 2-1 through 2-6 illustrate these results.

Once again these results are critical to the overall evaluation of whether the performance goal has been met within an appropriate confidence level. In the case of the pylon data for the

AMS 5 and 7 locations there was a statistically significant indication that the radon concentration was lower after bentonite and there was essentially no difference for AMS 6. All of the pylon data was observed to be statistically different from background. The results of the terradex cups indicate a statistically significant difference in the pre- to post-bentonite radon concentrations. The terradex cup data however indicates that only AMS 5 was statistically different from background. These results again tend to provide contradictory conclusions which from a statistical sense indicates that there are unknown factors contributing to the observed radon concentrations.

2.1.2.4 Pylon Monitoring Data at the Exclusion Fence Line

Eight scenarios at the exclusion fence line were also tested using the two-sample analysis procedure. These scenarios compared (1) pre-bentonite at four locations versus pre-bentonite at the background and (2) post-bentonite at four locations versus post-bentonite at the background. Table 2-7 summarizes the results from these tests. In all cases, the results indicate that the pre- and post-bentonite means are statistically greater than background at the 5 percent significance level.

These statistical evaluation results for the four pylons located at the exclusion fence provide a much different perspective than was obtained for the site boundary monitors. As presented in Table 2-7 there was a statistically significant difference observed in each case, comparing the pre- to post-bentonite situation. In each case the difference is also seen to have a significant magnitude change (pre- to post-bentonite changes are on the order of a factor of 4 for the means and as mush as a factor of 8, or more, for the maximum values) as discussed previously. These results clearly indicate there is a decrease in the radon contribution from the silos when comparing the pre- to the post-bentonite conditions. The fact that the farther the observation point is from the silos the more difficult the statistical interpretation must be considered carefully when making inferences from these statistical tests.

This effect is due to the fact that at those distances the observed concentrations are all on the order of background, therefore interferences occur that are not as relevant near the assumed source. Differentiating between the various sources of error, background, other possible sources, and the actual release and transport processes, for incorporation into the statistical models actually introduces more error than can be accounted for. These error terms are considered independent from the factors being analyzed. This independence is necessary to

Table 2-7. Summary of Two-Sample Analysis Results for Plyons at the Exclusion Fence Versus Background

Sample 1		Sample 2						
Location	No. of data points	Location	No. of data points	Ratio of variance	Hypothesis to test (1)	Alpha	Signif-icance level	Hypothesis results (2)
Pre-Bentonite								
NW	253	Bkgrd	219	274.54	diff = 0 vs one tail (GT)	0.05	5.44E-15	Reject HO
SW	254	Bkgrd	219	688.83	diff = 0 vs one tail (GT)	0.05	2.60E-08	Reject HO
NE	216	Bkgrd	219	3261.90	diff = 0 vs one tail (GT)	0.05	2.81E-09	Reject HO
SE	214	Bkgrd	219	2316.47	diff = 0 vs one tail (GT)	0.05	4.61E-09	Reject HO
Post-Bentonite								
NW	219	Bkgrd	267	6.65	diff = 0 vs one tail (GT)	0.05	1.39E-14	Reject HO
SW	270	Bkgrd	267	6.29	diff = 0 vs one tail (GT)	0.05	6.47E-08	Reject HO
NE	262	Bkgrd	267	23.08	diff = 0 vs one tail (GT)	0.05	6.06E-08	Reject HO
SE	254	Bkgrd	267	11.09	diff = 0 vs one tail (GT)	0.05	1.95E-09	Reject HO

(1) A one-tailed t-test was used to test the hypothesis that the difference between the means (Sample 1 - Sample 2) was greater than 0.

(2) Rejecting the hypothesis indicated that the difference between the means is not zero and that Sample 1 mean is statistically greater than the Sample 2 mean at the 5 percent significance level.

use many of the statistical tools available. Other methods which can account for non-linear and dependent factors require much more data than is or can be made available. The construction of a controlled situation to segregate out the dependent terms and reduce the overall error is not physically possible at the FEMP.

An example of the inability to construct a controlled environment is to consider the potential for additional radon sources other than the silos, not to mention the appropriateness of the background location. Other potential radon sources at the FEMP prior to installing the bentonite were considered as trivial in comparison to the concentration available for release from the silo headspace. After installation of bentonite, however this same assumption is no longer valid. An example is Waste Pit 5 which when not covered is potentially capable of producing a radon flux within the same order of magnitude as now seen in the silos. Likewise there is evidence of radium contamination in the Southfield and in the Active and Inactive Flyash piles. Although the actual radon contribution from these sources is small, the consideration of the location and size of these other sources leads to the conclusion that it is not physically possible to separate out these influences from the statistical evaluation and obtain the high confidence levels indicated by the performance goal of 0.015 pCi/l.

2.1.3 Single factor analysis of variance

A single factor analysis of variance (ANOVA) was used to test the hypothesis that the means from several samples are equal. A single factor ANOVA was conducted on (1) pre-bentonite at the fence line (AMS 5, AMS 6, AMS 7) and pre-bentonite at the background, (2) post-bentonite at the fence line and post-bentonite at the background, (3) pre-bentonite at the exclusion fence (NW, SW, NE, SE) and pre-bentonite at the background, and (4) post-bentonite at the exclusion fence and post-bentonite at the background. The data used in these analyses were based on daily arithmetic means.

The measure of statistical significance or in other words, "How sure can one be that the null hypothesis is wrong," is provided by the p value. The smaller the p value, the more convinced we are that the null hypothesis is false. The p-value for the pre-bentonite analysis at the fence line was 3.26×10^{-17} which indicates that the hypothesis that the means are equal is rejected. The hypothesis that the means post-bentonite at the fence line are equal is also rejected with a p-value of 4.4×10^{-6}. The p-value for pre-bentonite at the exclusion fence was 9.08 x 10^{-20} and 2 x 10^{-69} for post-bentonite at the exclusion fences. The hypotheses that the means are equal is rejected for both of these cases.

These results indicate there is reason to believe that in all cases the mean radon concentrations observed at the FEMP are different from the background. The critical considerations to be made are associated with the fence line data since one assumes that the exclusion fence results will always be different from background. The critical question is to evaluate the distance one would expect the observed values to be the same as background. Extrapolation from the exclusion fence to the site boundary should provide sufficient distance for the effect of the silos to be reduced to nearly zero (this fact will be discussed in more detail in the section covering the Gaussian Plume Model) as indicated in the original model.

In contrast to the p value, the measure of practical importance or in other words, "How wrong is the null hypothesis," is provided by the coefficient of determination (or R^2). The R^2 is calculated by dividing the sum of the squares between groups by the sum of squares total (between and within). The R^2 was 8.2 percent for pre-bentonite at the fence line, 2.5 percent for post-bentonite at the fence line, 8.4 percent for pre-bentonite at the exclusion fence, and 22.7 percent for post-bentonite at the exclusion fences. From a practical standpoint, a relatively small proportion of the total variability is accounted for by the differences among the group means. The reason for the p values being so small is because at the large sample size used in the tests (i.e., daily data collected over several months) and therefore, the ANOVA test had large power in identifying small differences between the group means.

2.1.4 Comparison of Time Series Daily Average Radon Concentration to Background at Each Monitoring Station in Pre- and Post-Bentonite Periods

2.1.4.1 Statistical Approach

The confidence in demonstration attainment of the removal action goal of 0.015 pCi/l above background is determined by statistically comparing the radon concentration distributions as measured at a monitoring station versus that measured at the background station. Any statistical difference observed with the background station would indicate that concentrations at the given monitoring station are not within removal action goal. Thus it is assumed that the levels measured at the background station are within removal action goal and are not within the silos' zone of influence. The background station is located 16 miles from the silos making the assumption concerning the silos influence reasonable; however, the background station is also located away from other sources of radon at the FEMP which contribute to the radon measurements at the FEMP fence line. A time series approach has been taken to compare the distribution of daily average radon concentration at each monitoring station with the daily average concentration distribution at background.

The availability of data over a two-year time period and the frequency of data collection at these sites allow for seasonal effects and trends in the concentrations to be evaluated and separated from other effects of interest. The concentration data collected at the monitoring sites are called "time series data," as the data represent readings from the same site over a period of time. Data monitored from the same site in successive time periods are dependent, as they are subject to relatively similar meteorological conditions and other factors which may influence radon concentration. Such time series data must be analyzed using statistical techniques which address the correlation among the data over time (known as "auto-correlation"). Time series models were fit to the daily average concentration data using Version 6 of Special Analytical Services (SAS)/ETS®, the module in the SAS® System dedicated to time series analysis.

Plots of the daily average concentrations versus time for each monitoring station display the extent of autocorrelation present in the data and any trends which may appear over time. These plots are located in Attachment B. Autocorrelation in a station's daily averages is noted by the lack of randomness from one day to another. These plots also indicate an overall trend in the concentrations which appears seasonal in nature. When viewed over the two-year period, the trend in concentrations appears be related to climatic conditions, with higher concentrations appearing in yearly seasons associated with warmer temperatures and higher humidity. Other factors which can influence the trend, such as calibration or instrumentation factors, are confounded with the seasonal trend (meaning their effects cannot be separated from within the overall trend effect). The extent of trend differs between the two years, indicating that the trend is affected by the bentonite and/or yearly effects. Thus any statistical analysis of this data must take into account the autocorrelation and trend present in the data over time.

The analysis to compare a given monitoring station with the background station considers two sets of time series data: data from the monitoring stations and data from the background stations. Because the data at each station represent the same time period and are obtained at equal intervals, a paired analysis has been implemented. This analysis is performed on a newly-created time series, equal to the daily average difference in concentration between the monitoring station and the background station. It is of interest to determine whether the overall average response in this new time series differs statistically from zero, indicating that no daily difference from background is observed. The statistical analysis of this time series is applied twice to each individual station, once for pre-bentonite data and once for post-bentonite data.

To create the time series of daily average paired differences from background at each monitoring station the hourly background concentration was subtracted from the monitoring station concentration taken at the same hour. These hourly differences were averaged within each day to obtain daily averages of the differences from background. These data are treated as a new time series from which appropriate statistical analyses are applied.

The model assumes that a daily average difference is correlated with the daily average differences for the previous two days. It is assumed that the error terms are correlated with error terms of up to two time periods previous. Correlation with any other earlier time points is assumed negligible. In addition, the daily average differences are affected by an overall time effect which is cyclical over a yearly period. Thus the statistical model takes the form

$$Y_t = \mu + \beta \sin(2\pi t/365) + \gamma \cos(2\pi t/365) + \epsilon_t \qquad \text{Equation 2-1}$$

where

Y_t = Daily average difference in concentration from background on day t
μ = An overall constant
β and γ = Effects of time constants
$\epsilon_t = \rho_1\epsilon_{(t-1)} + \rho_2\epsilon_{(t-2)} + z_t$, where z_t are independent normally-distributed error terms

This model is an autoregressive linear model with two lags (AR[2]), based on the Box & Jenkins approach to time series modeling. The Yule-Walker estimation method was used to fit the model in Equation 2-1 for the pre- and post-bentonite periods separately for each monitoring period.

The parameters β and γ in Equation 2-1 are functions of secondary parameters which determine the shift and amplitude of the cyclic time trend during the period of interest. The trend is approximated by a sine curve in the model, with period equal to one year. The presence of γ indicates that point at which the minimum/maximum of the curve occurs is not pre-determined. It is likely that the minimum of the curve, indicating the smallest difference between the station and background, occurs in cooler months when the stations report concentrations closer to the detection limit. The maximum occurs at the point where the difference between the station concentration and background is likely to be at its greatest, such as in warmer months.

The constant term μ in Equation 2-1 represents the average daily difference in concentration between the monitoring station and background, adjusted for the autocorrelation and seasonal effects present in the daily differences. Thus a test for difference between the concentrations of the station versus background is performed by testing whether the estimate of μ is statistically different from zero. Thus if $SE(\hat{\mu})$ is the standard error of the estimate $\hat{\mu}$ of μ, then an approximate 95 percent confidence interval on the estimate is given by

$$\hat{\mu} \pm t_{(0.975,dfe)} SE(\hat{\mu})$$ Equation 2-2

where $t_{(0.975,dfe)}$ is the 97.5th percentile of the Student-t distribution with degrees of freedom equal to the error degrees of freedom in the model ("dfe"). An approximate 95 percent lower confidence bound on the estimate of difference from background is given by

$$\hat{\mu} - t_{(0.95,dfe)} SE(\hat{\mu})$$ Equation 2-3

where $t_{(0.95,dfe)}$ is the 95th percentile of the Student-t distribution with "dfe" degrees of freedom.

The above tests performed on the time series of average daily differences from background serve as a statistical criterion for determining whether the readings from a given monitor differ statistically from background. If the judgment for compliance is written in terms of deviation from background (such as a 0.015 pCi/l deviation from background), then compliance can be determined by testing whether the magnitude of the deviation is contained in the confidence interval in Equation 2-2. If the compliance deviation is outside this interval, then a conclusion of non-compliance is made. In the same way, if the magnitude of the deviation falls within the confidence interval, then the readings are judged in compliance relative to background. As an example, if the compliance deviation from background is 0.015 pCi/l and the confidence interval for the average daily deviation from background is (0, 0.25), then the monitor is judged in compliance relative to background. Note that the compliance criterion is judged by the confidence interval on the average daily difference, not simply on how far the estimate of the average differs from zero. Because the interval represents a 95 percent confidence interval on the average daily difference from background, the conclusion on compliance is made at the 0.05 significance level.

2.1.4.2 Results

For the pre- and post-bentonite periods separately, the time series model in Equation 2-1 was fit to the daily average difference in concentration data from background for each of the monitoring stations. Only data collected from January to September of each of the two years were considered. Data from October to December 1991 are potentially biased due to adding the bentonite during this period. Data after September 1992 were not yet available at the time of this analysis. Data collected on February 12, 1991, February 13, 1991, and July 6, 1991 appeared to be biased across all monitoring stations, and thus this data were not included in the statistical analysis. Other highly influential data which did not appear to be accurate readings and thus were excluded from statistical analysis were the following:

1) February 28, 1991 data for the NE station,
2) August 25, 1992 data for the AMS 7 station.

The time series plot of the daily average concentrations for the background monitoring station indicated that the data collected prior to April 16, 1991, appeared much different from the remaining data at this station. The data prior to April 16, 1991, are substantially lower and less variable than for the other time periods at this station, indicating differences in accuracy and precision in the measuring instrument. These results can greatly influence the model fit during the pre-bentonite period, underestimating the overall average level across the pre-bentonite period. This underestimate can make it more likely to observe a statistically significant <u>increase</u> in background concentration after the bentonite, when in reality such an increase did not occur. For purposes of the statistical modeling, the pre-April 16, 1991, background data have been eliminated.

Table 2-8 presents the estimates of the intercept terms μ from Equation 2-1. This term is an estimate of the average difference (across the entire year) of daily differences from background at the given station, adjusted for autocorrelation and seasonal effects. An approximate 95 percent confidence interval is included in Table 2-8, as well as a 95 percent lower confidence bound on the difference from background, to address two-tailed and one-tailed test conclusions, respectively, on significance of this difference from zero. The results indicate that the daily difference from background is statistically different from zero at all monitoring stations in both pre- and post-bentonite time periods. The daily differences are much smaller for the exclusion fence stations after bentonite has been added, with only the NE station averaging as high as a 1.0 pCi/l increase from background in the post-bentonite period. Statistical differences from background are noted for the boundary stations, even though these differences are no more than 0.2 pCi/l in the post-bentonite period. The statistical significance appears to be due to the frequency at which readings at these stations are higher than background, even if the difference is only 0.1 pCi/l. The small standard errors for the boundary stations indicate that the differences from background are relatively constant from day to day.

Plots of the daily average hourly differences from background at each monitoring station are presented in Attachment E. These plots also present the predicted concentrations as determined by fitting the model in Equation 2-1 to the observed data, along with approximate 95 percent confidence bounds on the expected concentrations as determined by the model. The plots illustrate the difference in concentration at the exclusion fence sites between one year and the next. The yearly cyclic trend in the differences from background is still apparent in these plots. In the second year, these differences are more likely to be statistically insignificant early in the year, during winter or early spring.

In some cases, statistical significance due to the number of hourly data points is observed. When in fact this may not be practically significant. There is insufficient evidence to draw a conclusion that the silos are influencing the radon concentration at the air monitoring stations. The cause of the statistical significance of the above background radon concentration cannot be determined but may be due to factors such as instrument bias, natural

Table 2-8. Estimates of the Daily Average Hourly Deviations from Background for Both Pre-Bentonite and Post-Bentonite Periods at Each Monitoring Station

Monitoring Station	Estimate of Difference From Background (pCi/l)[1]	Standard Error of Estimate	Approx. 95% Confidence Interval	Approx. 95% Lower Conf. Bound	Attained Level of Significance
	Pre-Bentonite				
AMS 5	0.34	0.03	(0.28, 0.40)	0.29	0.0001
AMS 6	0.22	0.02	(0.18, 0.26)	0.19	0.0001
AMS 7	0.24	0.03	(0.18, 0.30)	0.19	0.0001
NW	3.93	0.29	(3.35, 4.51)	3.44	0.0001
SW	3.42	0.38	(2.66, 4.18)	2.77	0.0001
NE	6.71	0.89	(4.93, 8.49)	5.20	0.0001
SE	5.80	0.67	(4.46, 7.14)	5.13	0.0001
	Post-Bentonite				
AMS 5	0.11	0.02	(0.07, 0.15)	0.08	0.0001
AMS 6	0.13	0.03	(0.07, 0.19)	0.08	0.0001
AMS 7	0.18	0.03	(0.12, 0.24)	0.13	0.0001
NW	0.53	0.04	(0.45, 0.61)	0.46	0.0001
SW	0.74	0.04	(0.66, 0.82)	0.67	0.0001
NE	1.11	0.14	(0.83, 1.38)	0.87	0.0001
SE	0.54	0.06	(0.42, 0.66)	0.44	0.0001

(1) Selected outlier data excluded prior to analysis.

fluctuation in background, and other sources of radon in the vicinity of the FEMP. This bias and interference is inherently associate with the low concentrations being evaluated and can not be defined with any greater confidence.

2.2 Evaluation of the Gaussian Plume Model

This section of the report presents and discusses the approach, limitation, and overall impact of the original model used to evaluate the effectiveness of the bentonite and the attainment of the performance goal of 0.015 pCi/l. The following discussions will address the mechanisms involved and the uncertainties associated with establishing the actual cause and effect associated with observed radon concentrations and the contribution from the K-65 Silos. This section will discuss and describe the release rate mechanisms (which are diffusion and ventilation exchange) and the transport mechanism (which is the effect of particulate movement via atmospheric turbulence).

Each of the various mechanisms addressed in this report introduce error into the overall problem of estimating radon release and transport. The confidence level appropriate for the performance goal of 0.015 pCi/l would require these errors to be reduced to levels unattainable with state of the art measurements. This is due to the inherent uncertainty associated with the analytical models used. The error associated with predicted values, from a Gaussian Plume model used to consider averages over longer time periods, as compared to actual measurements is at best 20% to 30%. These error rates really can only be achieved with fully calibrated models, therefore further indicating the gross uncertainty in the models predictive capability. Other models which would take into account some of the non-linear effects would certainly begin to address the actual physical mechanisms, however as the level of complexity of the modeling effort increases the reliability of the model decreases. This effect is due to the shear amount of data that would be required in the more complex models. The net effect is that the optimization between model complexity and the acquisition and validity of required data establishes the level of confidence attainable in any situation.

2.2.1 Estimation of release rate

The estimation of the radon release rate from the silos involves the modeling of at least two separate mechanisms that of diffusion and gross ventilation exchange (these mechanisms are actually dependent on one another indicating a non-linear system). The process of diffusion is governed principally by molecular forces and requires large time scales, while the process of ventilation exchange is governed by macroscopic forces and occurs over relatively short time frames. Both of these process can be significantly affected by the physical structure of the barrier (in this case the silo dome and the foam cover). The models described here, and used in the original effectiveness model, are based on average conditions at the surface and the system is assumed to be homogeneous and isotropic. The combination of these two processes was considered sufficient for modeling the release rate of radon from the silos. The confidence level appropriate for the evaluation of the performance goal, however was not established.

2.2.1.1 Diffusion

The calculations by Borak (1985) of diffusion releases for radon were based on one dimensional steady-state diffusion equations from a National Bureau of Standards summary technical report (Colle, et. al, 1981). From the concentrations of radon in the silo air, the flux of radon diffusion through the concrete dome can be estimated by the following equation:

$$J_c = \frac{E_c \lambda_{rn} l_c C_a}{\sinh \left(\frac{L}{l_c} \right)} \qquad \text{Equation 2-4}$$

where:

J_c = Radon flux from the concrete dome surfaces to the foam, pCi/M^2/sec
E_c = Total porosity of the dome concrete, (0.3)
l_c = Diffusion length of radon in the dome concrete (12 cm)
L = Thickness of the dome concrete, cm
λ_{RN} = Decay constant of radon, 2.1 x 10^{-6} s^{-1}
C_a = Concentration of the radon in the silo air, pCi/l

The average headspace concentration from Subsection 3.1 in Silo 1 is 45,081 pCi/1 and the concentration in Silo 2 is 219,585 pCi/1. There is a foam and polyurethane coating over the surface of the concrete dome on each silo. This layer is an effective radon barrier based on the laboratory measured diffusion coefficient of 4 x 10^{-6} cm^2/s (TIM-8700/1). This foam layer will further attenuate the radon flux before the radon is emitted to the atmospheres. This attenuation is determined as follows:

$$J = J_c \exp\left(\frac{-l_f}{\sqrt{D_f/\lambda_{RN}}}\right)$$ Equation 2-5

where:

J = Radon flux emitted to the surrounding air , pCi/m^2-s
J_c = Radon flux from the concrete dome surfaces to the foam, pCi/m^2/sec
L_f = Thickness of the foam (10 cm)
D_f = Diffusion coefficient for the foam, 4 x 10^{-6} cm^2/s

The total release rate from diffusion is the product of the radon flux (J) and the surface area of the dome in square meters. Using Equations 2-4 and 2-5 the radon flux from diffusion is 2.6 x 10^{-4} pCi/1 in Silo 1 and 1.27 x 10^{-3} pCi/1 in Silo 2.

The uncertainty of the diffusion parameters are described in Table 2-9.

Table 2-9. Diffusion Parameters

Parameter	Range	Distribution	Source
Diffusion length of concrete, lc	6 cm to 23 cm	Uniform	FDRP
Porosity of concrete, Ec	0.05 to 0.265	Uniform	FDRP
Silo dome thickness, L	3 to 4 cm	Uniform	FDRP
Concentration of Radon in headspace of silo, pCi/l	Using mean and standard error	Normal distribution	Section 3.1

The decay constant of radon is assumed to have no uncertainty. The thickness of the foam cover was obtained from the Project Completion Report (Grumski and Shanks 1988) and the diffusion coefficient of the foam was obtained from the Technical Information Memorandum "Radon Diffusion Coefficient Measurements of Polyurethane Material and Radon Attenuation Calculations for K-65 silos." Based on the uncertainty in the diffusion parameters, the flux from diffusion can vary by two orders of magnitude, however, the average flux from ventilation is 3 orders of magnitude greater than diffusion.

2.2.1.2 Free Air Exchange (ventilation)

Ventilation of radon from the silo is assumed to be governed by the physics associated with the ideal gas law and, as such, is dependent upon the temperature and pressure changes of the gases in the silo headspace as a result of the changes in the ambient atmospheric conditions. The ventilation of silo gases is determined from the ideal gas law which is defined by the following:

$$PV = n\,R\,T \qquad \text{Equation 2-6}$$

where:

P = Pressure of the gases within the silo, atm
V = Volume of the silo headspace, l
n = Number of moles of the gases, moles
R = Ideal gas constant, 0.082057 atm-l/mole-K
T = Temperature, K

For air exchange emission, it is assumed that the radon concentration from the outside is negligible compared to the radon concentration inside the silo and that it does not provide a source of radon to the silo air. The ventilation of radon to the atmosphere is assumed to be small compared to the production of radon gas; therefore, the concentration of radon in the silos is assumed to be constant and does not deviate from equilibrium. Based on these assumptions the following equation describes the rate of change in the silo air for radon:

$$\frac{dC_a}{dt} = \frac{P_{RN}}{V_o} - C_a \lambda_{eff} \qquad \text{Equation 2-7}$$

where:

C_a = Concentration of the radon in the silo air, pCi/l
P_{RN} = Concentration (by the presence of the silo) rate of release of radon into the silo air (production term) from the K-65 source material (activity per time), pCi/s
V_o = Volume of the air space in the silo above the K-65 material, l
λ_{eff} = Effective removal rate of radon, s^{-1}

and

$$\lambda_{eff} = \lambda_{RN} + \lambda_v$$ Equation 2-8

where:

λ_{RN} = Decay constant of radon, 2.1 x 10^{-6} s^{-1}

λ_v = The ventilation rate due to the daily temperature and pressure changes is the fraction of the silo air exchanged per unit of time, s^{-1}

and,

$$\lambda_v = \Delta n/n_o$$ Equation 2-9

Δn = Positive change in the number of moles of gases in the silo headspace, moles/s

n_o = Initial number of moles of gas in the silo headspace, moles

The positive change in the number of moles is summed for the entire period and is then divided by the total number of seconds in the monitoring period to determine the ventilation rate. Negative mole changes are not included since only positive mole changes represent an exposition of air from inside the silo to outside the silo. Based on the assumption that radon in the headspace is in equilibrium, the following relationship is obtained:

$$P_{RN} = C_a \lambda_{eff} V_o$$ Equation 2-10

It is assumed that the air inside the silo will be well mixed because the silo air space is a single compartment volume. The air exchange release rate is described as follows:

$$Q_{exch} = C_a \lambda_V V_o$$ Equation 2-11

where:

Q_{exch} = Rate of radon released through air exchanges, pCi/s

The release rate is described by the following:

$$Q_{exch} = J A$$ Equation 2-12

where:

J = Radon flux from the silo through air exchange, $pCi/m^2/s$
A = Area of the silo dome, m^2

The ideal gas law is applicable only at conditions of low pressure and high temperature corresponding to large molal volumes. At conditions resulting in small molal volumes the attractive forces among the molecules become significant and volumes calculations from the ideal-gas law tend to be too large. In extreme cases the volume calculated from the ideal gas law can be five times the actual volume. The ideal gas law can be used for diatomic gases where the gram-molal volumes are as low as 5 liters and for gases of more complex molecular structure such as carbon dioxide, acetylene, ammonia, and light hydrocarbon vapors, where gram-molar volumes exceed 20 liters with an error of 1 percent. The rigid polyurethane foam coating, the urethane coating, and the sealing of the silos penetrations have significantly reduced the possibly of temperature and pressure changes within the silo. In addition, these coatings should also significantly reduce the possibility of any wind induced release of silo air to the surrounding environment. The release of silo air due to wind effects would result in a corresponding pressure change.

The following information was obtained from the ambient temperature and pressure data from July 20, 1992, to September 15, 1992: (1) change of temperature within a day varied between 11 and 42 degrees F, (2) change of temperature between days varied from 59.1 and 79.5 degrees F, (3) change of pressure within a day varied between 0.011 and 0.948 in Hg, (4) change of pressure between days varied from 29.274 and 30.354 in Hg.

The following information was obtained from the Silo 1 temperature and pressure data from July 20, 1992 to September 15, 1992: (1) change of temperature within a day varied between 0.3 and 1.1 degrees F, (2) change of temperature between days varied from 63.4 and 66.1 degrees F, (3) change of degree differential pressure within a day varied between 0.004 and 0.604 inches of mercury (Hg), (4) change of differential pressure between days varied between -0.110 and 0.048 inches of Hg. The ratio of changes in ambient temperature to changes in Silo 1 temperature is approximately 48. This indicates that a 1 degree F temperature change inside the silo during a day is caused by a 48 degree F change in ambient degree temperature during the day.

The following information was obtained from the Silo 2 temperature and pressure data from July 20, 1992 to September 15, 1992: (1) change of temperature within a day varied between 0.3 and 1.2 degree F, (2) change of temperature between days varied from 62.5 and 65.2 degree F, (3) change of degree differential pressure within a day varied between 0.002 and 0.658 in Hg, (4) change of differential pressure between days varied between -0.077 and 0.094 in Hg. The ratio of changes in ambient temperature to changes in Silo 2 temperature is approximately 41.

Based on the ideal gas law, the average number of moles of radon in Silo 1 and Silo 2 during August 1992 were 32,637 and 52,442 moles, respectively. The change in moles between measurements (typically 15 minutes) in Silo 1 and Silo 2 was less than 0.2 percent of the average number of moles in each silo in over 99 percent of the cases. There were only two cases out of 5,501 measurements in Silo 1 when the change in moles between measurements was approximately 1 percent. In all cases in Silo 2 the change in moles was below 1 percent. This indicates that this model may be inappropriate or to conservative.

The average moles/minute of radon released during August 1992 based on the ideal gas law was 0.230 (3.8×10^{-3} moles/second) from Silo 1 and 0.391 (6.5×10^{-3} moles/second) from Silo 2. Based on the calculations of the change in moles in the Silo headspace and the applicability of the ideal gas, the uncertainty associated with the ideal gas law is 1 percent. The average ventilation rate (λ_v) due to the daily temperature and pressure changes using Equation 2-9 is 1.17×10^{-7} s^{-1} in Silo 1 and 1.24×10^{-7} s^{-1} in Silo 2. Assuming a 1 percent uncertainty in the ideal gas law every other time period, then the maximum ventilation rate from both silos is 5.6×10^{-6} s^{-1}.

Using Equation 2-8 and the average ventilation rate, the decay constant of radon is the predominate factor for the effective removal rate of radon. The predominate factor in this equation becomes the ventilation rate when the maximum ventilation rate is used in this equation. The effective removal rates of radon using average ventilation rates for Silo 1 and Silo 2 are 2.22×10^{-6} s^{-1} and 2.22×10^{-6} s^{-1}, respectively. The effective removal rate using maximum ventilation rate for both silos is 7.70×10^{-6} s^{-1}. Using the equations in this section, the total flux ventilation is 9.0 pCi/l for Silo 1 and 74 pCi/l for Silo 2. Based on the uncertainty in the ventilation parameters, the flux from ventilation can vary up to 1.5 orders of magnitude. Based only on the 1 percent uncertainty every other 15 minute time period, the ventilation flux is 482 pCi/l for Silo 1 and 3566 pCi/l for Silo 2. These fluxes are conservative since only 2 values out of 5,501 slightly exceeded 1 percent variability in the ideal gas law.

2.2.2 Estimate of Radon Concentration in the Environment

Estimates of the radon concentration at the nearest receptor are made based on the fluxes calculated in the previous section for the month of August 1992, and on a long term basis for the maximum flux associated with the uncertainty due to the use of the ideal gas law.

The computer code Industrial Source Complex (ISC2) Dispersion Models was used to remain consistent with previous estimates of the radon concentration in the environment for the compliance report. ISC2 is a standard program which is recommended by the United States Environmental Protection Agency (US EPA) as a guideline model, widely distributed by the US EPA through the Support Center for Regulatory Air Modeling, and available through the National Technical Information Service.

The short term mode (ISCST2) was used to calculate the average daily and monthly concentrations at AMS 5, AMS 6, AMS 7, and the nearest resident. The long term mode (ISCLT2) was used to predict the off-site concentration of radon on an annual average basis using the flux associated with a 1 percent release per time period (the limitation of the ideal gas law). These fluxes were presented in the previous section.

ISCST2 meteorological input is based on the wind speed, wind direction, stability class, and an assumed mixing height of 1000 meters. ISCLT2 meteorological input is based a Stability Array (STAR) format. This is simply a matrix of joint frequency distributions of wind speed and wind direction by stability category. WEMCO has prepared a four year STAR data set from the 10 meter wind speed and direction data collected on-site for the period of October 1987, to the end of December 1990. The raw data set from which this was developed comprised of 29,257 hours of recovered data, or 83.5 percent data recovery. WEMCO has implemented this data for their annual National Emission Standards for Hazardous Air Pollutants compliance reports.

Other data required by ISCLT2, such as average mixing heights and average temperatures, were provided by WEMCO. Wind profile exponents and vertical potential temperature gradients were used as regulatory default since actual on-site measurements of those data were not available.

The results of the short term model using the predicted release of radon from the silos for the month of August 1992, is shown in Table 2-10. None of the average daily concentrations exceeded the 0.015 pCi/l removal action goal at any point. The monthly average predicted concentration was also well below 0.015 pCi/l at all locations modeled. These levels of radon can only be compared to the measured radon concentrations on a limited basis due to the relative error in the detectors as discussed previously and the variability in background radon concentration. The applicability of this model to the K-65 silos is limited by the 30 percent uncertainty in the Gaussian Plume model in addition to the errors and uncertainties with the actual versus predicted release rates.

The ideal gas law is accurate to within 1 percent at the temperature and pressures being assessed here. The majority of the releases are less than 1 percent total volume change, based on the measured temperature and pressure data. Thus the ideal gas law is not appropriate to predict a release of less than 1 percent total volume.

The reasonable upper bound of the release would be to assume a change of 1 percent of the total silo volume per measurement period (15 minutes). The flux is then estimated based on an assumed release of 1 percent (positive 1 percent change) of the total radon in the headspace followed by a period in which air enters the silo (negative 1 percent change). Under the current model this would result in the maximum release rate of radon to the atmosphere which could not be detected as a change in silo temperature or pressure.

The ISCLT2 code was used to estimate the radon concentration at AMS 5, AMS 6, AMS 7, and the nearest resident. The estimate was made using both pre-bentonite and post-bentonite headspace radon concentrations. The predicted radon concentration at these locations is shown in Table 2-11.

Table 2-10. Radon Concentrations at Various Locations Based on the Calculated Flux

August 1992	Concentration Based on Calculated Flux (pCi/L)			
	AMS 5	AMS 6	AMS 7	Nearest Resident
1	1.71E-03	8.96E-08	2.12E-03	4.51E-04
2	1.99E-07	0.00E+00	1.87E-03	7.34E-04
4	2.12E-05	2.84E-04	3.53E-03	1.11E-08
5	0.00E+00	0.00E+00	1.56E-08	0.00E+00
6	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	3.76E-04	0.00E+00	3.09E-03	1.42E-04
8	1.15E-04	6.07E-07	1.50E-05	6.21E-04
9	7.80E-05	0.00E+00	6.35E-03	2.78E-05
10	1.14E-04	0.00E+00	1.93E-03	2.44E-03
11	1.26E-09	3.58E-04	9.70E-04	7.00E-05
12	2.34E-04	4.90E-05	6.03E-06	4.61E-03
13	2.34E-04	4.90E-05	6.03E-06	4.61E-03
14	0.00E+00	2.81E-04	0.00E+00	5.97E-07
18	0.00E+00	0.00E+00	2.77E-03	7.80E-04
19	0.00E+00	0.00E+00	1.53E-03	7.06E-06
20	0.00E+00	1.11E-03	1.95E-03	0.00E+00
21	0.00E+00	2.15E-05	0.00E+00	0.00E+00
22	0.00E+00	1.25E-03	1.70E-03	9.84E-04
23	2.62E-05	0.00E+00	0.00E+00	0.00E+00
24	4.39E-04	5.92E-04	3.63E-07	2.94E-03
25	9.97E-05	0.00E+00	1.70E-03	5.39E-04
26	0.00E+00	1.35E-04	6.56E-03	1.33E-03
28	0.00E+00	9.98E-09	1.47E-03	2.32E-11
29	2.25E-04	0.00E+00	3.71E-04	4.92E-04
30	1.49E-10	0.00E+00	3.65E-03	6.09E-04
31	2.46E-05	0.00E+00	4.95E-03	1.71E-03
August Average	1.42E-04	1.59E-04	1.79E-03	8.88E-04
Long Term AVG	2.41E-04	2.01E-03	1.12E-04	5.34E-04

Table 2-11. Radon Concentration (pCi/l) Based on +/-1 Percent Release

Parameter	AMS 5	AMS 6	AMS 7	Nearest Resident
August 1992	3.20E-03	3.57E-03	4.03E-02	2.00E-02
Post-Bentonite Long Term (ISCLT)	5.42E-03	4.52E-02	2.51E-03	1.20E-02
Pre-Bentonite Long Term (ISCLT)	1.31E+00	1.10E+01	6.09E-01	2.91E+00

The model results using the pre-bentonite data (headspace concentration and meteorological data) would suggest an annual average radon concentration which would have been detected. However, the average pylon radon concentration at these locations (see Table 2-1) are less than the predicted values (the model assumes the radon is due to the K-65 silos alone). Post-bentonite, the radon concentration at all the critical locations is well below the limits of the detectors. Using the model in this capacity definitely indicates the release of radon from the silos is below the 0.015 pCi/l limit at the nearest resident, but there is considerable uncertainty in the release mechanism and the transport processes.

Field validation studies of atmospheric dispersion models have shown that estimates of model uncertainty are largely inadequate, particularly in the model's ability to quantify the representative nature of data and the non-homogeneous and stochastic nature of atmospheric dispersion which are not handled in the models. Studies have shown that predicted locations of maximum concentrations may not correspond with the actual location of the maximum concentrations.

The ISC code nor any other dispersion model has been field validated or calibrated for the FEMP. Any results of these models are thus suspect and should be considered as rough estimates. A complete and calibration effort validation for the ISC model was not practical given the existing data and is unwarranted given the inherent uncertainty in the overall model.

The largest source of potential error in the environmental radon concentration estimates is the release rate from the silos, of radon to the environment. The mechanisms of radon release is not fully understood and thus an accurate (with a confidence to verify at 0.015 pCi/l) release determination is not possible. In addition the predicted radon concentrations at the AMS locations are so low that the detector could not accurately measure the contribution of radon from the silos due to the precision and sensitivity of the radon monitors and the natural variation in background radon concentration. The Pylon radon detectors record hourly radon to the nearest 0.1 pCi/l and the standard deviation of the background measurements is approximately 0.21 pCi/l. The manufacturers recommendations, which are based on calibration methods, is a lower limit of detection of 1 pCi/l.

2.2.3 Unknown variables

The actual release mechanism of radon gas from the silos into the air can be caused by several factors. These factors include, but are not necessarily limited to, (1) diffusion of radon through the bentonite layer, the K-65 silo air and the concrete and polyurethane foam, and (2) free air exchange between the surrounding air (ventilation).

The greatest source of uncertainty in the models used to date would be in accurately representing the release of radon from the silos. The release mechanisms of radon from the silos are not fully understood. Factors and processes not accounted for in the current model could retard or assist the release of radon from the silos. These processes may never be known or fully quantified.

Any attempts to identify the processes and quantify the results through studies on the silos are not likely to be successful. These studies would need to be highly controlled in order to obtain results and these controls would render the results to be not applicable to the silos, since the physical setting would be changed during the study period.

The Gaussian plume model has not been calibrated (field verified) for the FEMP site. The terrain unique to the FEMP and K-65 silos could result in actual radon concentrations which do not correspond to the predicted radon concentration. Without the calibration of the dispersion model the accuracy and precision (representativeness and comparability are also difficult to address) of the results are not known. What is known is that even with a fully calibrated model the inherent error is on the order of 20% or more.

3.0 Quantify the Degree of Bentonite Effectiveness

3.1 Headspace Analysis

The first evaluation to consider is that the headspace analysis results indicate that the radon headspace concentrations from July 1 to September 1992 are lower than the pre-bentonite reading for each silo. These results were found, as expected, to be statistically significant. The decrease in Silo 1 was from 25,000,000 pCi/l to a mean of 45,081 pCi/l (99.8 percent reduction) while Silo 2 concentration decreased from 30,000,000 pCi/l to a mean of 219,585 pCi/l (99.3 percent reduction). Daily changes in headspace concentrations tend to be relatively consistent among the two silos indicating a constant external (not able to be accounted for in the statistical analysis) source may effect changes in concentrations within both silos.

3.1.1 Statistical Approach

Since July 20, 1992, passive monitors have been recording radon concentrations every 5 minutes within the headspace of the two silos. This information can be used to analyze variability in the recorded radon concentration and how the concentration has been affected by the presence of bentonite. In future estimates, the statistical and analytical results of the radon headspace data can be utilized as a predictor variable for radon concentrations at various locations including the site boundary or background stations. In this way concentrations at the nearest resident can also be based on meaningful and substantiated data. The objectives of this section include quantifying the radon headspace concentration, the degree to which bentonite is effective in reducing the headspace radon concentration, and the investigation of the effects of exterior variables (such as meteorological effects) on radon headspace concentration.

3.1.1.1 Statistical Summary of Daily Average Headspace Concentration

Summary of the radon headspace data and statistical comparison to pre-bentonite levels were performed on the daily averages of the recorded concentrations for each silo. All data were evaluated prior to statistical analysis for general validity. Questionable data, often taking the form of statistical outliers, were subject to omission from statistical analysis.

Assuming that the calculated daily averages adequately represent a constant radon headspace concentration over the two-month time period, the true concentration is estimated by calculating the average ($\bar{Y}$) of the daily average measurements across all study days. The standard error of this average, denoted by SE($\bar{Y}$), is equal to the standard deviation divided by the square root of the number of days (n) in which a daily average concentration was available. If the distribution of daily average data resembles a normal distribution, then an approximate 95 percent confidence interval for the daily average headspace concentration is given by

$$\bar{Y} \pm t_{(0.975,n-1)} SE(\bar{Y}) \quad \text{Equation 3-1}$$

where $t_{(0.975,n-1)}$ is the 97.5th percentile of the Student-t distribution with n-1 degrees of freedom.

Unfortunately, daily reporting of radon concentration measurements within the silo headspaces was not performed during the pre-bentonite period. Only one measured concentration is available from either silo prior to the bentonite installation (25 million pCi/l for Silo 1 and 30 million pCi/l for Silo 2). Because no variability is associated with this pre-bentonite measurement, a two-sample statistical comparison in concentration between pre- and post-bentonite periods within a silo is not possible. Instead, the pre-bentonite measurement is treated as a constant, and the average post-bentonite concentration is statistically compared to this constant. This comparison is performed by observing whether the pre-bentonite radon measurement is contained within the 95 percent confidence interval in Equation 3-1 for the post-bentonite radon concentration. If the pre-bentonite radon measurement is outside the interval, then the post-bentonite radon concentration is declared statistically different from the pre-bentonite measurement.

3.1.1.2 Effects of Meteorological Variables on Silo Headspace Concentration

It is also of interest to quantify the effects of meteorological variables on silo headspace concentration. A statistical model was fit to the <u>hourly</u> average headspace concentrations to identify those effects which significantly affect the concentration. Note that hourly concentrations are considered here rather than daily average concentrations. The effects of some meteorological variables on headspace concentrations may not be fully represented by considering headspace concentrations averaged over an entire day. Working with daily averages does not permit diurnal fluctuation in the concentrations to be determined, which is heavily affected by the values of the meteorological variables. For example, wind direction may come from opposite directions at different times of the day. Working with hourly concentrations at the silo headspace can more accurately characterize the effect of short-term meteorological changes in the atmosphere. All meteorological variables were measured daily at hourly intervals.

The following model was fit to the hourly headspace concentrations for each silo:

$$Y_t = \mu + \alpha_1 TO_t + \alpha_2 TI_t + \alpha_3 W_t + \alpha_4 PO_t + \alpha_5 D_t + \alpha_6 S_t + \epsilon_t \qquad \text{Equation 3-2}$$

where Y_t = The average headspace concentration at time t
μ = An overall constant to be estimated
$\alpha_1,\ldots,\alpha_6$ = Regression coefficients to be estimated
TO_t = The temperature outside the silo at time t
TI_t = The temperature inside the silo at time t
W_t = The wind speed (at ten meters) at time t
PO_t = The differential pressure at the silo at time t
D_t = The dew point at time t
S_t = A rank determination of overall atmospheric stability at time t
ϵ_t = A random error, assumed to be normally distributed

The value of the dependent variable Y_t may represent hourly concentration at any one silo or the sum of the hourly concentrations across both silos. The time series nature of the collected data is considered by including effects of temperature, wind speed, etc., which cause potential autocorrelation from one time point to another.

A stepwise regression procedure is initially used to fit the model in Equation 3-2 to the hourly headspace concentrations. The stepwise procedure selects only those terms whose values of α_i are significantly different from zero (based on a threshold significance level) and thus are significantly associated with the hourly average headspace concentration. The resulting fitted model identifies the significant meteorological variables in Equation 3-2, and quantifies how a unit change in each of these variables affects the concentration.

Because of the volume of hourly data considered in the statistical analysis, it is more likely to obtain statistical significance among the effects in the model in Equation 3-2 than if fewer data points were considered. Thus only factors which are highly statistically significant towards the model ($p < 0.01$) are noted in the conclusions.

3.1.2 Results and Conclusions

Prior to statistical analysis, daily averages of the 5-minute concentration measurements were calculated for both silos. These averages are plotted versus time in Figures 3-1 and 3-2. Note that Silo 2 has much greater average concentrations than Silo 1. Silo 2 has concentrations which are generally an order of magnitude higher than Silo 1. This difference is primarily attributed to the fact that there is in general less bentonite in Silo 2 and that the concentrations of radon in Silo 2 have always been greater than Silo 1. Note also, however, that the data for July 20, 1992, through July 22, 1992, and July 28, 1992, through August 12, 1992, are likely invalid for Silo 2, as it is several orders of magnitude lower than the other days. Fewer than 15 measurements were taken in this silo on these days. Thus the Silo 2 average measurements during this period have been omitted from statistical analysis.

Figure 3-3 presents a plot of the Silo 1 daily average headspace concentrations versus Silo 2 concentrations. A positive linear relationship is noted in the concentrations among the two silos. The Pearson correlation coefficient among these data is 0.78, which is statistically significantly different from zero at the 0.05 level. Thus daily changes in headspace concentrations tend to be relatively consistent among the two silos, indicating that a constant external source may affect changes in concentration within both silos.

Preliminary investigation of the daily average headspace concentrations indicates that the distribution of these daily averages tend to resemble a normal distribution for each silo. Thus the formula in Equation 3-2 can be applied to obtain a 95 percent confidence interval on the daily average concentration across the entire 2-month monitoring period. The results of these calculations are presented in Table 3-1. This table also includes the mean daily average and its standard error. The ratio of the mean to the observed pre-bentonite reading was obtained by dividing the mean by the single pre-bentonite measurement obtained in the silo. The standard error of the ratio is calculated similarly. The ratios, with their standard errors and approximate 95 percent confidence intervals, are also in Table 3-1. These results indicate that the radon headspace concentrations from July to September 1992 are statistically lower than the pre-bentonite reading for the silo. The decrease is quite substantial from pre- to post-bentonite, a difference from two to nearly three orders of magnitude.

The model in Equation 3-2 was fitted to the hourly average headspace concentration data in a stepwise fashion to determine those meteorological variables having a significant association

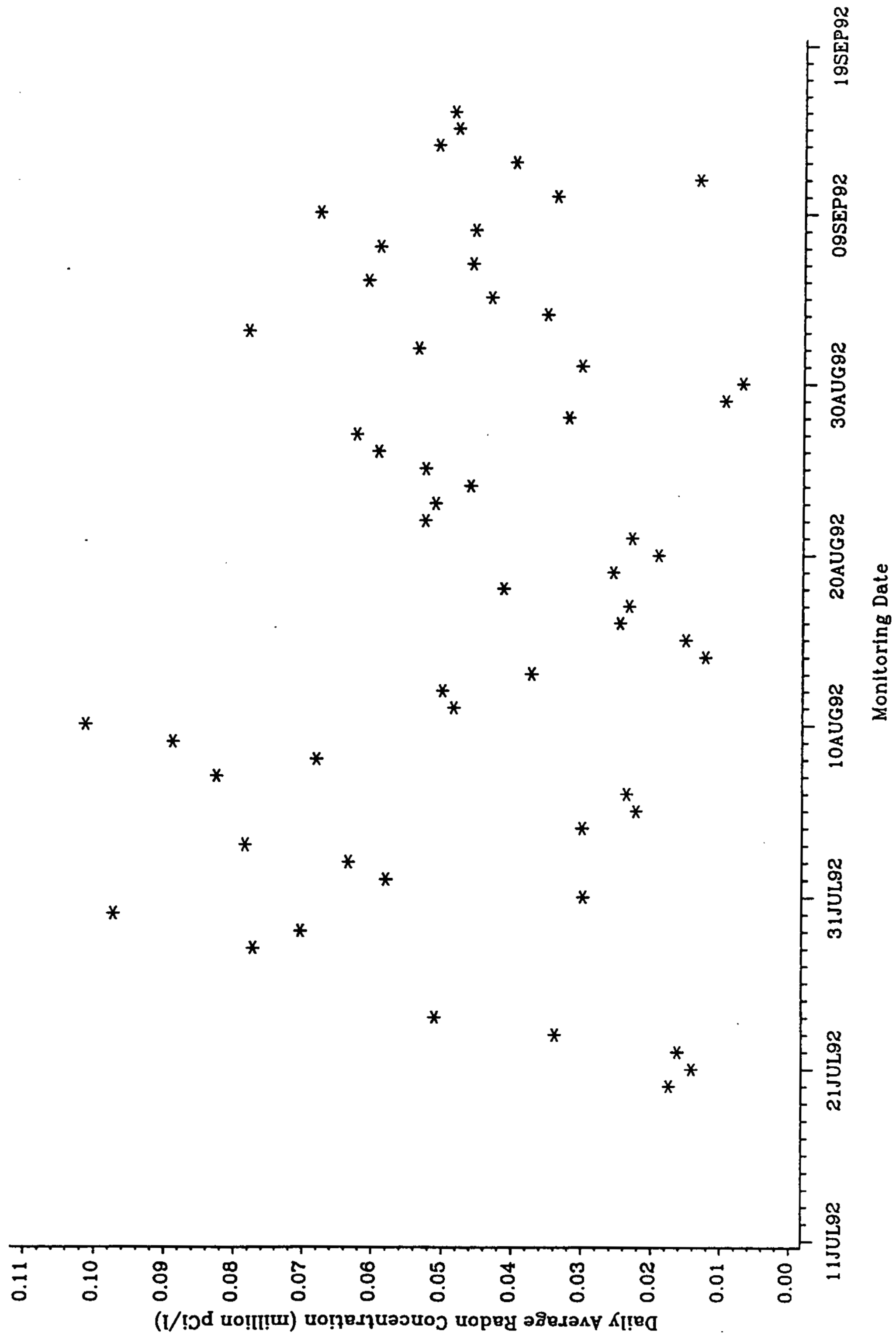


Figure 3-1. Plot of Daily Average Radon Concentration in the Headspace of Silo 1

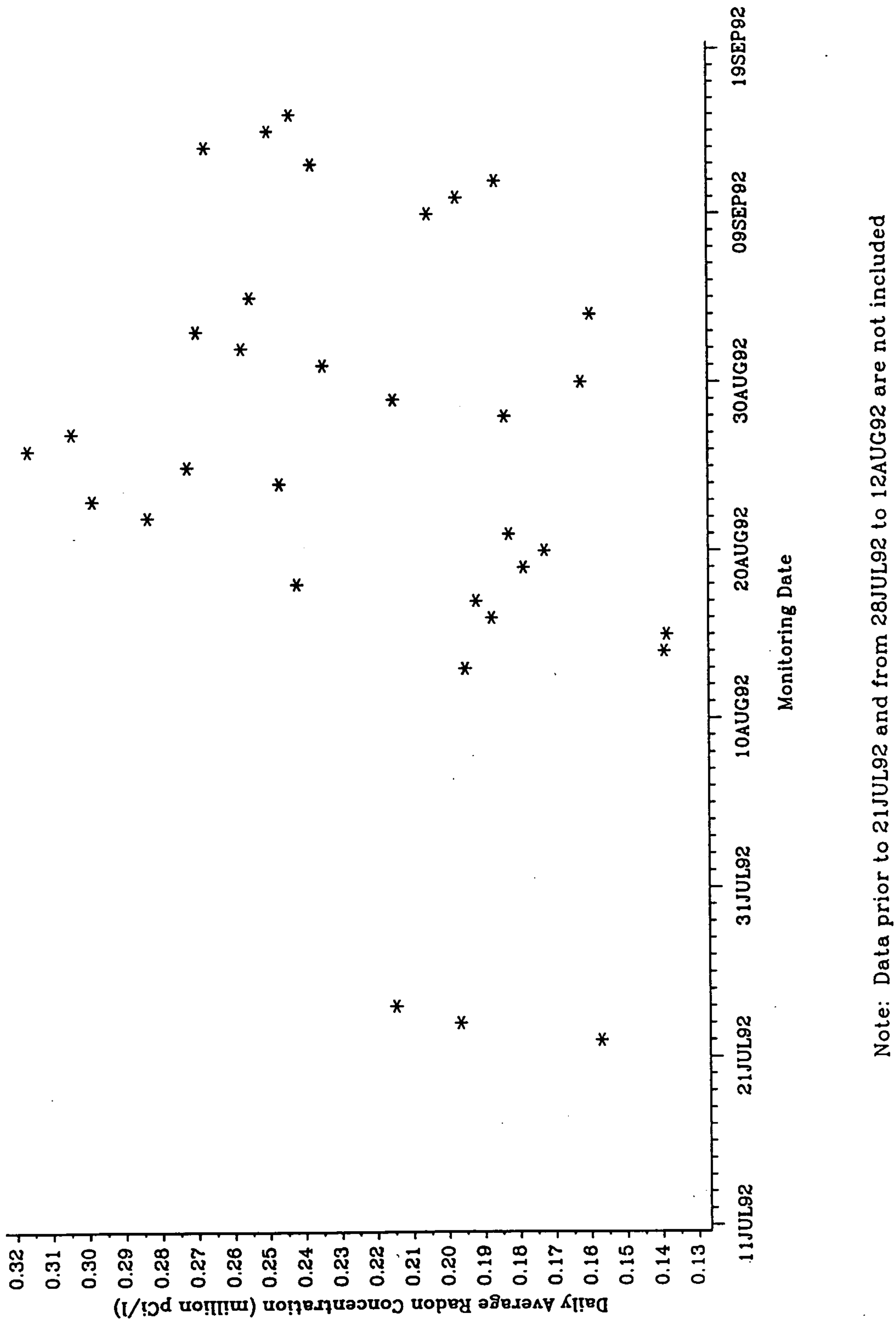


Figure 3-2. Plot of Daily Average Radon Concentration in the Headspace of Silo 2

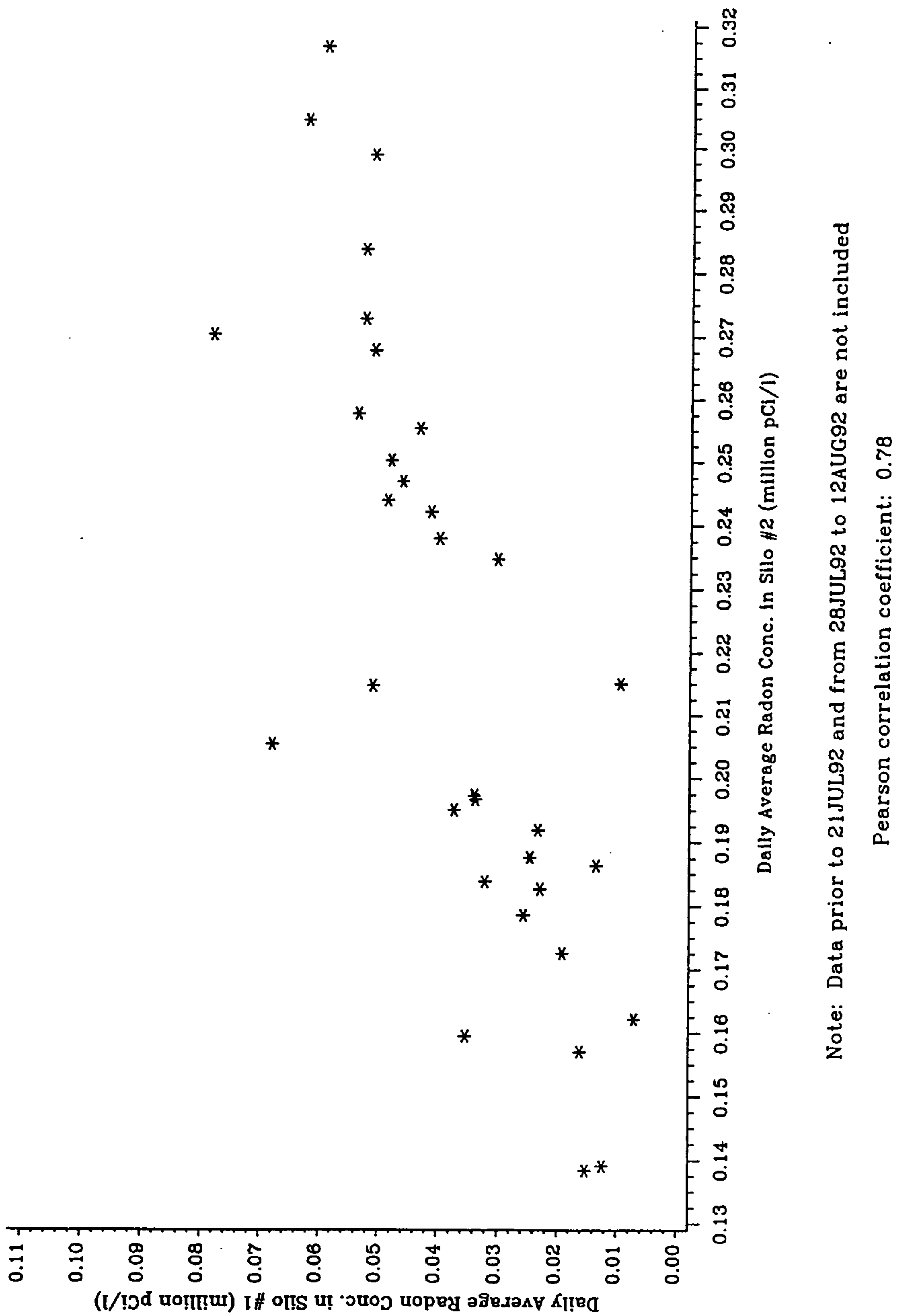


Figure 3-3. Plot of Daily Average Radon Headspace Concentrations in Silo 1 Versus Silo 2

Table 3-1. Descriptive Summary of Daily Average Radon Headspace Concentration in the Post-Bentonite Period

Silo	Number of Days Considered[1]	Daily Average Post-Bentonite Headspace Concentration (pCi/l)			Ratio of Average Post-Bentonite to Pre-Bentonite Concentration[2]		
		Mean	Standard Error of Mean	Approx. 95% Confidence Interval	Mean Ratio	Standard Error of Mean Ratio	Approx. 95% Confidence Interval
#1	55	45,081	3,127	(38,952; 51,210)	0.00180	0.00013	(0.00156; 0.00205)
#2	33[3]	219,585	8,481	(202,962; 236,208)	0.00732	0.00028	(0.00677; 0.00787)

(1) Post-bentonite headspace concentrations monitored from July 20, 1992, to September 15, 1992. Not all days were monitored during this period.

(2) Assumes a constant pre-headspace concentration of 25,000,000 pCi/l for Silo 1 and 30,000,000 pCi/l for Silo 2.

(3) Headspace data collected from July 22, 1992, to July 24, 1992, and July 28, 1992, to August 12, 1992, were considered invalid for Silo 2.

with the headspace data. Only time points with complete and valid headspace concentration and meteorological data were considered in the modeling procedure. The stepwise procedure was fit to the concentration data for each silo separately, as well as for the sum of the two silo concentrations. The following meteorological effects were significantly associated with the hourly headspace concentration at the 0.01 significance level in all three fits: 1) Wind speed, 2) Outdoor temperature, and 3) Stability class.

Dew point and barometric pressure were also significantly associated with headspace concentration in Silo 1 at the 0.01 level, but not for Silo 2 or the sum over the two silos. These latter effects tend to be explained by some combination of the above three factors. For example, dew point and outdoor temperature tend to be correlated with each other and thus would contribute similar information to the model. Thus, only one of these two correlated parameters should be included in the model. Likewise, windspeed and barometric pressure tend to be negatively correlated with each other.

Table 3-2 presents estimates of the significant effects on the hourly average headspace concentration for both silos along with standard errors of these estimates. In both silos a negative effect was observed on the concentration by wind speed, implying that increases in the wind speed were associated with decreases in the headspace concentration. The effect of dew point, outdoor temperature, and stability indicator on the concentrations is opposite that of wind speed; increases in these variables are associated with increases in the headspace concentration. Plots of this data illustrating these relationships are found in Attachment F. Note that these findings do not necessarily imply a cause and effect relationship, only that the relationships were observed between the radon headspace concentration and the meteorological variables.

In interpreting these results on headspace concentrations, it should be noted that the results reflect approximately an 8-week period in the summer of 1992. No conclusions can be made that the relationships observed in this modeling procedure will hold at other times of the year.

Table 3-2. Meterological Parameters Statistically Significantly Associated (at the 0.01 level) With Hourly Average Radon Concentration in the K-65 Silo Headspaces

Parameter	Estimated Change (pCi/l)[1]	Standard Error of Estimate	Significance Level
Silo 1[2]			
Outdoor temperature	2,855	150	0.0001
Wind Speed (10 m)	-6,167	526	0.0001
Stability Indicator	6,226	1,026	0.0001
Differential Pressure	123,966	26,210	0.0001
Dew Point	983	311	0.0016
Silo 2[3]			
Wind Speed (10 m)	-19,571	1,666	0.0001
Outdoor temperature	3,843	332	0.0001
Stability Indicator	13,454	2,953	0.0001
Sum of Two Silos[4]			
Wind Speed (10 m)	-25,204	2,098	0.0001
Outdoor temperature	6,856	431	0.0001
Stability Indicator	18,909	3,713	0.0001

(1) Estimated change in daily average headspace concentration resulting from a unit increase in the parameter value.

(2) Results reflect analysis performed on 50 daily averages from the period July 20, 1992, through September 14, 1992, on days where both average headspace concentration and complete meterological data were available and appeared valid.

(3) Results reflect analysis performed on 29 daily averages from the period July 22, 1992, through September 14, 1992, on days where both average headspace concentration and complete meterological data were available and appeared valid. Likely invalid values of concentration data were observed in Silo 2 from July 28, 1992 through August 12, 1992, and thus were not considered in the analysis.

(4) Sum of hourly average headspace concentrations across the two silos.

3.2 Comparison of Actual Daily Average Radon Concentration Levels between Pre- and Post-Bentonite Periods at Each Monitoring Station

3.2.1 Pylon data

A one-tailed two sample analysis procedure was used to test the hypothesis that pre-bentonite radon concentration was greater than post-bentonite radon concentration at each monitoring station. Table 3-3 summarizes these analysis.

All four exclusion fence locations (i.e., NW, SW, NE, SE) indicate that the pre-bentonite radon concentrations are statistically greater than the post-bentonite concentrations at the 5 percent significance level. AMS 5, Pilot Plant, Plant 5, and Met tower also indicate that pre-bentonite concentrations are statistically greater than post-bentonite concentrations at the 5 percent significance level. These results indicate that the bentonite is effective in reducing the amount of radon at these locations. The greatest reduction in radon concentrations from pre- to post-bentonite occurred at the exclusion fence.

Pre-bentonite radon concentrations at the background location were not statistically greater than post-bentonite concentration at the 5 percent significance level. This result is expected since adding bentonite should not affect the radon concentrations 16 miles from the silos.

AMS 6, AMS 7, and Plant 2/3 did not show statistical differences between pre- and post-bentonite radon concentrations. The significance level (p values) for AMS 6, AMS 7, and Plant 2/3 are 0.46, 0.15, and 0.34 respectively. The test for significance was 0.05. The statistical difference was not observed because there was only a minor decrease in the average concentrations from pre- to post-bentonite at these monitoring stations. The small decrease is attributed to the fact that at these distances (the minimum is for AMS6 which is over 400 meters from the silos) the silos have little or no contribution to the ambient radon concentration.

3.2.2 Quarterly Terradex Measurements at the Silo Domes and Exclusion Fence Line

Several one-sided t-tests were performed to test for statistical significance between the pre-bentonite and post-bentonite measurements at the silo domes and exclusion fence monitors. Table 3-4 summarizes these analyses. Only two average values (with each average value

Table 3-3. Summary of Two-Sample Analysis Results Pre-Bentonite Versus Post-Bentonite for Pylons at Fence Line, Within the Production Area, Exclusion Fence, and Background

Sample 1 Pre-Bentonite		Sample 2 Post-Bentonite						
Location	No. of data points	Location	No. of data points	Ratio of variance	Hypothesis to test (1)	Alpha	Signif-icance level	Hypothesis results (2)
AMS 5	236	AMS 5	270	2.27	diff = 0 vs one tail (GT)	0.05	1.67E-08	Reject HO
AMS 6	241	AMS 6	272	1.10	diff = 0 vs one tail (GT)	0.05	4.58E-01	Do not reject HO
AMS 7	238	AMS 7	273	1.05	diff = 0 vs one tail (GT)	0.05	1.50E-01	Do not reject HO
Pilot plant	271	Pilot plant	266	2.15	diff = 0 vs one tail (GT)	0.05	3.92E-06	Reject HO
Plant 2/3	241	Plant 2/3	262	0.96	diff = 0 vs one tail (GT)	0.05	3.36E-01	Do not reject HO
Plant 5	240	Plant 5	268	4.81	diff = 0 vs one tail (GT)	0.05	2.32E-08	Reject HO
Met tower	231	Met tower	112	6.55	diff = 0 vs one tail (GT)	0.05	1.53E-06	Reject HO
NW	253	NW	219	60.17	diff = 0 vs one tail (GT)	0.05	2.18E-14	Reject HO
SW	254	SW	270	159.59	diff = 0 vs one tail (GT)	0.05	9.64E-14	Reject HO
NE	216	NE	262	205.91	diff = 0 vs one tail (GT)	0.05	3.81E-14	Reject HO
SE	214	SE	254	304.37	diff = 0 vs one tail (GT)	0.05	2.11E-13	Reject HO
Bkgrd	219	Bkgrd	267	1.46	diff = 0 vs one tail (GT)	0.05	9.58E-01	Do not reject HO

(1) A one-tailed t-test was used to test the hypothesis that the difference between the means (Sample 1 - Sample 2) was greater than 0.

(2) Rejecting the hypothesis indicated that the difference between the means is not zero and that Sample 1 mean is statistically greater than the Sample 2 mean at the 5 percent significance level.

Table 3-4. Estimates of the Difference in Quarterly Radon Concentration Between Pre-Bentonite and Post-Bentonite Time Periods at Each Monitoring Station(1)

Monitoring Station	95% Confidence Interval for Pre-Bentonite Mean (pCi/l)	Standard Error of Estimate	Pre-Bentonite Sample Size (n)	Post-Bentonite Constant (pCi/l)	Attained Level of Signif.
Silo Domes					
North Silo-NE	(20.89, 40.71)	4.44	11	2.1	0.0001
North Silo-SE	(12.28, 49.26)	8.16	10	1.5	0.0029
North Silo-SW	(12.72, 34.98)	7.19	11	4.4	0.0015
North Silo-NW	(31.31, 60.27)	6.39	10	1.7	0.0001
South Silo-NE	(16.35, 34.03)	3.96	11	3.0	0.0001
South Silo-SE	(11.75, 16.59)	1.07	10	5.4	0.0001
South Silo-SW	(31.54, 73.24)	9.35	11	2.1	0.0002
South Silo-NW	(24.84, 61.32)	8.18	11	2.5	0.0003
OVERALL	(28.41, 38.31)	2.53	85	2.8	0.0001
Exclusion Fence					
NW	(2.78, 4.32)	0.36	15	0.8	0.0001
SW	(2.94, 6.49)	0.82	15	0.7	0.0001
NE	(4.08, 8.31)	0.98	15	0.8	0.0001
SE	(2.89, 4.61)	0.40	15	0.8	0.0001

(1) Selected outlier data excluded prior to analysis.

calculated from three replicate measurements) at each monitoring station were available for the post-bentonite period. These two values were averaged at each monitoring station to obtain the post-bentonite constant value. The null hypothesis in this statistical study was that the pre-bentonite mean is less than or equal to the post-bentonite constant. The alternative hypothesis is, therefore, that the pre-bentonite mean is greater than the post-bentonite constant. In each instance, the pre-bentonite mean was determined to be statistically greater than the post-bentonite constant at the 5 percent level of significance with the largest p value = 0.0029, which was associated with North Silo-SE.

3.3 Comparison of Time Series Daily Average Radon Concentration Levels between Pre- and Post-Bentonite Periods at Each Monitoring Station

3.3.1 Statistical Approach

The radon concentrations at each monitoring station were collected on an hourly basis each day over a 2-year period. A primary objective of this study is to note how the behavior of the concentration distribution at each monitoring site differs between pre- and post-bentonite periods. Statistical analysis using time series modeling procedures has been performed to compare radon concentrations within each monitoring station prior to bentonite installation with concentrations monitored after bentonite installation. Subsection 2.1.4 introduces the need for a time series approach to this data.

To better estimate the presence of a trend in the concentration data over the entire monitoring period statistical analyses were performed on daily average concentrations obtained by averaging the available hourly data on a given day for each station. As with the hourly concentrations, each daily average is influenced by the values of the daily averages for the previous 1 or 2 days at that station. Thus autocorrelation is likely present among the daily averages and must be recognized in the statistical analysis.

The form of the time series statistical model used to compare pre- versus post-bentonite concentrations at each monitoring station assumes that a daily average is correlated with the daily averages for the previous 2 days. In addition, the daily averages are affected by an overall time effect. This time effect takes the form of a cyclic yearly trend. Thus the statistical model is

$$Y_{tj} = (\mu + B_j) + (\beta + \beta_j)\sin(2\pi t/365) + (\gamma + \gamma_j)\cos(2\pi t/365) + \epsilon_{tj}$$

Equation 3-3

where

Y_{tj} = The daily average concentration on the t^{th} day of the j^{th} year
μ = An overall constant
B_j = The additional constant effect on data observed in the post-bentonite year (B_1 is zero)
β and γ = Effects of time constants
β_j and γ_j = Additional effects of time constants on data observed in the post-bentonite year (β_1 and γ_1 are zero)
$\epsilon_{tj} = \rho_1\epsilon_{(t-1)j} + \rho_2\epsilon_{(t-2)j} + z_{tj}$, where z_{tj} are independent normally-distributed error terms.

This model is an autoregressive linear model with two lags (AR[2]), based on the Box & Jenkins approach to time series modeling. The Yule-Walker estimation method was used to fit the model in Equation 3-3 to daily average concentration data for each monitoring station separately. Note that this model was fit to the average concentrations directly, not on a transformation of these concentrations. Sufficient need for a transformation was not warranted relative to the study objectives and the observed data distribution.

The parameters β, β_2, γ, and γ_2 in Equation 3-3 are functions of secondary parameters which determine the shift and amplitude of the cyclic time trend. The trend is approximated by a sine curve in the model with period equal to 1 year. The presence of the parameters β_2 and γ_2 indicate that cyclic trend can shift with time between pre- and post-bentonite years as well as change in amplitude. Thus the locations and magnitudes of the minimum and maximum predicted concentrations can change between the pre- and post-bentonite years. The terms β_2 and γ_2 are necessary to allow the model to reflect changes in concentration behavior between pre- and post-bentonite periods.

The term B_2 is defined in Equation 3-3 to reflect how daily average concentration differs between pre- and post-bentonite years. Fitting the model results in an estimate (b_2) for B_2 which is corrected for the effects of autocorrelation and yearly trend. The standard error associated with this estimate is used to calculate an approximate 95 percent confidence interval on the estimate. If $SE(b_2)$ is the standard error of b_2, then an approximate 95 percent confidence interval is given by

$$b_2 \pm t_{(0.975,dfe)} SE(b_2) \qquad \text{Equation 3-4}$$

where $t_{(0.975,dfe)}$ is the 97.5th percentile of the Student-t distribution with degrees of freedom equal to the error degrees of freedom in the model ("dfe"). An approximate 95 percent upper confidence bound on the estimate of post-bentonite minus pre-bentonite average concentration is given by

$$b_2 + t_{(0.95,dfe)} SE(b_2) \qquad \text{Equation 3-5}$$

where $t_{(0.95,dfe)}$ is the 95th percentile of the Student-t distribution with "dfe" degrees of freedom.

3.3.2 Results and Conclusions

The time series model from Equation 2-1 in Subsection 2.1.4.1 was fit to the daily average concentration data for each of the monitoring stations separately to compare pre- and post-bentonite periods. (See Subsection 2.1.4 for details on data excluded from this analysis.) Table 3-5 presents estimates of the difference in daily average concentration as summarized in pre- and post-bentonite years. An approximate 95 percent confidence interval and an approximate 95 percent upper confidence bound are included in this table for the post-bentonite average concentration minus the pre-bentonite average concentration, to address two-tailed and one-tailed test conclusions, respectively, on statistical significance of this difference from zero. The overwhelming conclusion is that daily average concentration at the four stations along the exclusion fence is significantly lowered in the post-bentonite year compared to the pre-bentonite year. This reduction is highly statistically significant for these stations. The differences tend to be more pronounced at the NE and SE stations. For the boundary stations, a statistically significant difference between pre- and post-bentonite periods is observed only at AMS 5. This difference was in a negative direction, resulting in overall reduction in concentration during the post-bentonite period. No statistically significant difference in daily average concentration was observed between the two periods at the background station.

Table 3-5. Estimates of the Difference in Daily Average Hourly Radon Concentration Between Post-Bentonite and Pre-Bentonite Time Periods at Each Monitoring Station

Monitoring Station	Estimate of (post-bentonite mean)-(pre-bentonite mean) (pCi/l)[1]	Standard Error of Estimate	Approx. 95% Confidence Interval	Approx. 95% Upper Conf. Bound	Attained Level of Significance
AMS 5	-0.16	0.05	(-0.27, -0.056)	-0.075	0.003
AMS 6	-0.019	0.046	(-0.11, 0.072)	0.057	0.685
AMS 7	0.003	0.056	(-0.11, 0.11)	0.095	0.957
NW	-3.51	0.35	(-4.20, -2.83)	-2.93	0.0001
SW	-3.45	0.52	(-4.46, -2.44)	-2.59	0.0001
NE	-5.79	0.76	(-7.28, -4.30)	-4.54	0.0001
SE	-4.82	0.51	(-5.82, -3.83)	-3.98	0.0001
Background[2]	-0.049	0.073	(-0.19, 0.09)	0.07	0.500

(1) Selected outlier data excluded prior to analysis.

(2) When data prior to April 16, 1991, are included in the pre-bentonite period, the estimate is 0.068 pCi/l, with a standard error of 0.028. The significance level is 0.0152. Background results presented in the table do not include data prior to April 16, 1991.

The fitted model, along with the actual observed daily averages, are plotted in Attachment G for each monitoring station. The solid-lined sinusoidal curve indicates the daily average concentration as predicted by the model. The dotted curves paralleling the predicted curve are approximate 95 percent confidence bands on the individual predicted daily averages. The predicted values on these plots do not include the effects of autocorrelated errors in their calculation. The actual observed daily averages are plotted by dots. Note that the data from October to December 1991, during the bentonite application, were ignored in the model fitting, but predicted daily averages reflecting the pre-bentonite effect were calculated in this region. These plots show the extreme difference in behavior of the daily average concentrations for the exclusion fence stations in the post-bentonite period. The seasonality trend is not as apparent in the exclusion fence readings compared to the boundary and background monitors, indicating that high concentrations along the boundary are more likely in certain times of the year than in others.

Tables 3-6 and 3-7 present a summary of the time of year when minimum predicted concentrations are observed at each station, for pre- and post-bentonite periods, respectively. Tables 3-8 and 3-9 present a summary of the time of year when maximum predicted concentrations are observed at each station, for pre- and post-bentonite periods, respectively. These tables indicate the extent to which the minimum and maximum daily average concentrations change across station locations and pre- versus post-bentonite periods. The time of year at which these minimum and maximum values occur are also determined in these tables. The lack of seasonal trends in the exclusion fence station results is evident in these tables, due to the wide confidence intervals on the time at which the minimum and maximum concentrations are observed. The boundary monitors tend to observe maximum concentrations in warmer months and minimum concentrations in cooler months. The predicted maximum concentration among boundary stations remains higher than the predicted maximum concentration for the background station, even in the post-bentonite period. Meanwhile, for exclusion fence monitors, the predicted maximum concentration in the post-bentonite period is consistently lower than the predicted minimum concentration in the pre-bentonite period.

The observed differences in results between pre- and post-bentonite periods cannot be attributed solely to the effect of adding bentonite due to the cyclic and seasonal effects observed. The headspace concentration differences are however, attributed solely to the

Table 3-6. Estimates of Predicted Minimum Daily Average Concentration as Determined by the Time Series Model, and When They Occur, for the Pre-Bentonite Period at Each Monitoring Station

Monitoring Station	Minimum Daily Average Concentration			
	Predicted Value (pCi/l)	Approx. 95% Conf. Int. on Predicted Value	Date of Predicted Value (mo/yr)	Approx. 95% Conf. Int. on Date of Pred. Value
AMS 5	0.41	(0.30, 0.53)	3/8	(< 2/1, 4/14)
AMS 6	0.46	(0.31, 0.55)	3/25	(< 2/1, 5/9)
AMS 7	0.36	(0.26, 0.47)	3/15	(2/4, 4/24)
NW	3.52	(2.87, 4.18)	6/30	(4/25, 9/16)
SW	3.41	(1.97, 4.84)	10/3	(1/1, 12/31)
NE	6.87	(5.33, 8.41)	5/10	(1/1, 12/31)
SE	5.21	(4.27, 6.16)	4/9	(1/1, 12/31)
Background[1]	0.48	(0.36, 0.60)	4/29	(4/29, 12/31)

[1] Background results presented in the table do not include data prior to April 16, 1991.

Table 3-7. Estimates of Predicted Maximum Daily Average Concentration as Determined by the Time Series Model, and When They Occur, for the Pre-Bentonite Period at Each Monitoring Station

Monitoring Station	Maximum Daily Average Concentration			
	Predicted Value (pCi/l)	Approx. 95% Conf. Int. on Predicted Value	Date of Predicted Value (mo/yr)	Approx. 95% Conf. Int. on Date of Pred. Value
AMS 5	1.32	(1.20, 1.44)	9/6	(7/31, 10/30)
AMS 6	1.03	(0.90, 1.15)	9/23	(8/9, 11/29)
AMS 7	1.18	(1.05, 1.31)	9/13	(8/4, 11/12)
NW	5.74	(4.69, 6.80)	12/30	(1/1, 12/31)
SW	6.15	(5.19, 7.11)	4/4	(1/1, 12/31)
NE	8.06	(5.59, 10.52)	11/9	(1/1, 12/31)
SE	6.68	(5.21, 8.14)	10/9	(1/1, 12/31)
Background[(1)]	0.82	(0.68, 0.97)	10/11	(8/23, 12/31)

(1) Background results presented in the table do not include data prior to April 16, 1991.

Table 3-8. Estimates of Predicted Minimum Daily Average Concentration as Determined by the Time Series Model, and When They Occur, for the Post-Bentonite Period[1] at Each Monitoring Station

Monitoring Station	Minimum Daily Average Concentration			
	Predicted Value (pCi/l)	Approx. 95% Conf. Int. on Predicted Value	Date of Predicted Value (mo/yr)	Approx. 95% Conf. Int. on Date of Pred. Value
AMS 5	0.50	(0.41, 0.59)	3/20	(1/12, 5/17)
AMS 6	0.61	(0.53, 0.69)	3/17	(1/1, 5/28)
AMS 7	0.45	(0.36, 0.54)	3/27	(2/7, 5/11)
NW	0.87	(0.17, 1.58)	3/28	(1/1, > 9/30)
SW	1.04	(0.10, 1.98)	4/14	(1/1, > 9/30)
NE	1.31	(0, 2.66)	3/22	(1/1, > 9/30)
SE	0.68	(0, 1.57)	5/8	(1/1, > 9/30)
Background [2]	0.54	(0.36, 0.60)	5/2	(1/26, 7/27)

(1) Data in the post-bentonite period only existed through September 30, 1992. Thus no predicted concentrations after this time were calculated.

(2) Background results presented in the table do not include data prior to April 16, 1991.

Table 3-9. Estimates of Predicted Maximum Daily Average Concentration as Determined by the Time Series Model, and When They Occur, for the Post-Bentonite Period[1] at Each Monitoring Station

Monitoring Station	Maximum Daily Average Concentration			
	Predicted Value (pCi/l)	Approx. 95% Conf. Int. on Predicted Value	Date of Predicted Value (mo/yr)	Approx. 95% Conf. Int. on Date of Pred. Value
AMS 5	0.90	(0.78, 1.03)	9/19	(7/24, > 9/30)
AMS 6	0.84	(0.74, 0.95)	9/16	(7/8, > 9/30)
AMS 7	1.10	(0.96, 1.23)	9/26	(8/10, > 9/30)
NW	1.37	(0.45, 2.28)	9/27	(1/1, > 9/30)
SW	1.61	(0.21, 3.00)	> 9/30	(1/1, > 9/30)
NE	2.03	(0.22, 3.85)	9/21	(1/1, > 9/30)
SE	1.47	(0.18, 2.76)	> 9/30	(1/1, > 9/30)
Background [2]	0.64	(0.57, 0.72)	> 9/30	(1/1, > 9/30)

(1) Data in the post-bentonite period only existed through September 30, 1992. Thus no predicted concentrations after this time were calculated.

(2) Background results presented in the table do not include data prior to April 16, 1991.

addition of the bentonite. Yearly effects (i.e., yearly changes in meteorological conditions, etc.), as well as effects due to differences in instrumentation, also contribute to the observed differences within a station. The differences at the exclusion fence are already significant and would not benefit from additional analysis while the differences at the site boundary are insignificant (with variability of natural background) and again would not benefit from additional analysis.

3.4 Gamma Dose Rate Reduction

A model of the silos was created to predict the dose at the silo domes. The modeled dose only roughly agrees with current dose rate measurements on the silo dome manway locations. The comparison breaks down at low dose rates and is likely attributed to the sensitivity of the dose measurements and the assumptions of homogeneous conditions within the silos.

3.4.1 Dose Rate Modeling

Dose Rate Due to Radon In The Silo Headspace:

Using Microshield 4.0, the dose contribution from the radon in the silo headspace was estimated to be 2.82E-06 mR/hour per pCi/l assuming homogenous distribution of radon and its daughter products within the silo headspace. Using a parallel method a similar number was developed based on a combination of measured dose rates and radon concentrations and a predicted radon concentration following operation of the Radon Treatment System. The alternative method resulted in an estimate of the dose rate per pCi/l of radon of 5.77E-06. This alternative calculation was performed for pre-bentonite conditions and represents information which is valid under the pre-bentonite conditions (i.e., large radon concentrations, no bentonite, larger headspace volume, etc.). The predicted value using Microshield 4.0 is reasonably close to the alternative method. Based on the average radon concentration in Silo 1, the dose rate due to radon in the headspace is estimated to be 0.26 mR/hour. For Silo 2 the dose rate is predicted to be approximately 1.3 mR/hour.

Dose Rate at the Silo Manway Due to K-65 Residue:

The waste source term, volume, and dimensions are given in the Safety Assessment performed for the bentonite addition to the K-65 silos. The Bentonite was modeled based on assumptions concerning the composition and geometry of the surface of the bentonite and residue. The bentonite surface is not a uniform plane and the thickness and composition may not be uniform throughout the silo residue surface. There is an average of 2 feet thickness of bentonite over the residue surface; however, the residue surface is not planar and there are cracks and valleys. Some parts of the residue surface have more than 2 feet of bentonite over it while other areas contain less than 2 feet. Since the dose rate is attenuated exponentially with bentonite thickness, the use of the 2-foot average thickness would under predict the dose rate and result in large uncertainties in the results. The predicted dose rates from the residues as at various bentonite thicknesses and moisture levels are shown in Figure 3-4. This curve clearly illustrates the correlation between radon concentration and dose rate. The range in dose rate due to the radon is 0.26 to 1.3 mR/hr and that due to the residues (for average 12" of bentonite) is on the order of 3 to 6 mR/hr. The dose rates at the tops of the domes are typically in the range of 3 to 10 mR/hr.

Limiting Assumptions:

Assumptions concerning the bentonite are shown in the following Figures:

Figure 3-5 - Bentonite Specific Gravity
Figure 3-6 - Bentonite chemical composition
Figure 3-7 - Bentonite Volume change with moisture

The predicted dose rates for all bentonite thicknesses and moisture levels considered are presented in Figure 3-4. The dose rate is a function of radon concentration in the headspace at the silo dome manway and is linear and dependent on the distribution of the radon daughter products within the headspace. The rate of dose rate change at the silo dome due to an incremental change in radon concentration is small such that the change in dose rate could only be used to predict large radon concentrations (i.e more than one million pCi/l). At radon concentrations less than this the dose rate change would not be detectable due to the uncertainty in the dose rate measurements.

3.4.2 Thermoluminescent Dosimeter Dose Measurements

Thermoluminescent Dosimeter (TLD) measurements included in this analysis were from three fence line (AMS 5, AMS 6, and AMS 7) and four background locations. Table 3-10 presents a summary of the hourly exposure rates at each of these monitoring stations. An arithmetic mean on the quarterly TLD data was used to calculate the hourly exposure rates

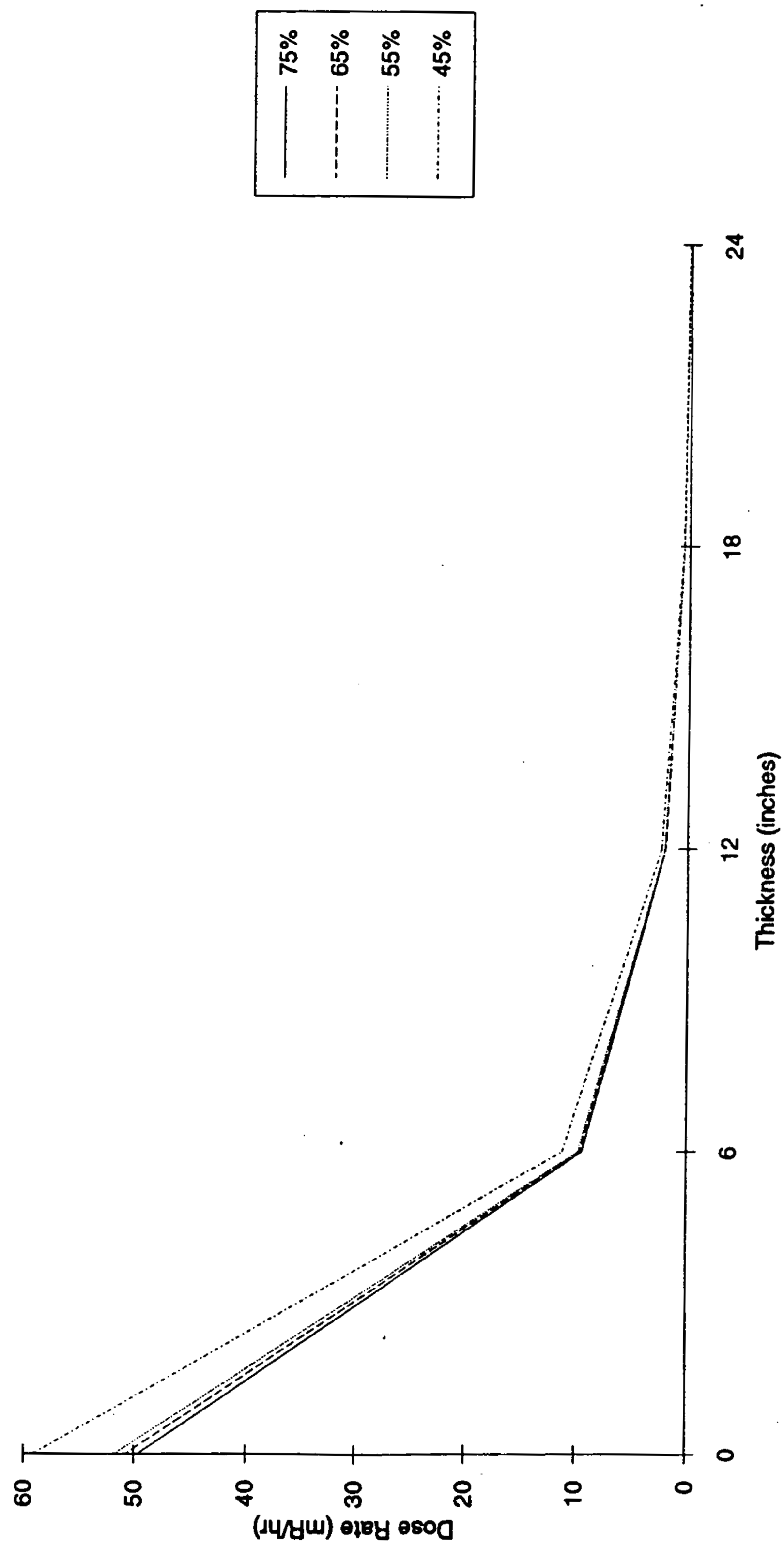


Figure 3-4. Dose at Silo Dome at Various Bentonite Thicknesses and Humidity Levels

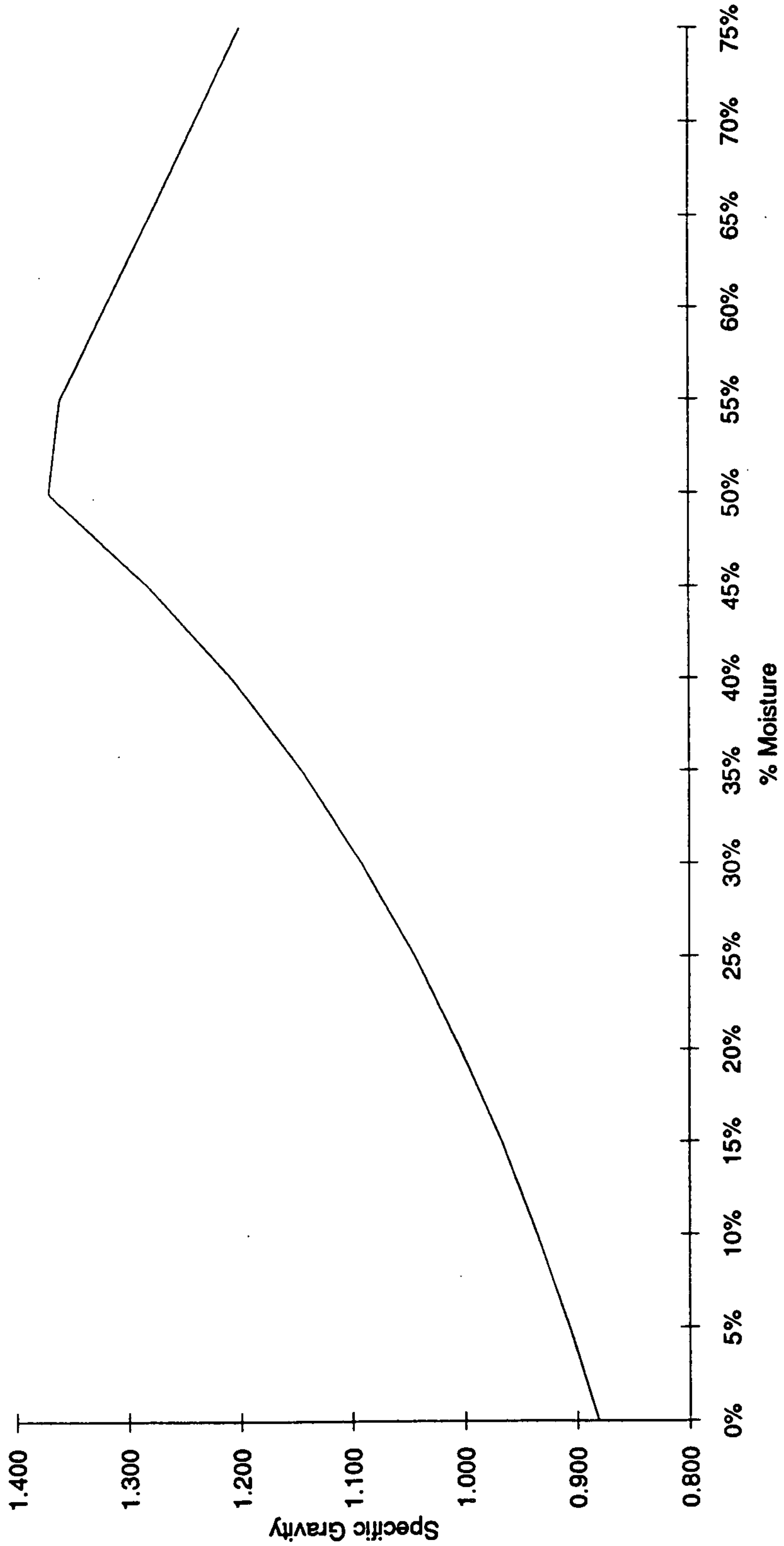


Figure 3-5. Specific Gravity of Bentonite at Various Moisture Levels

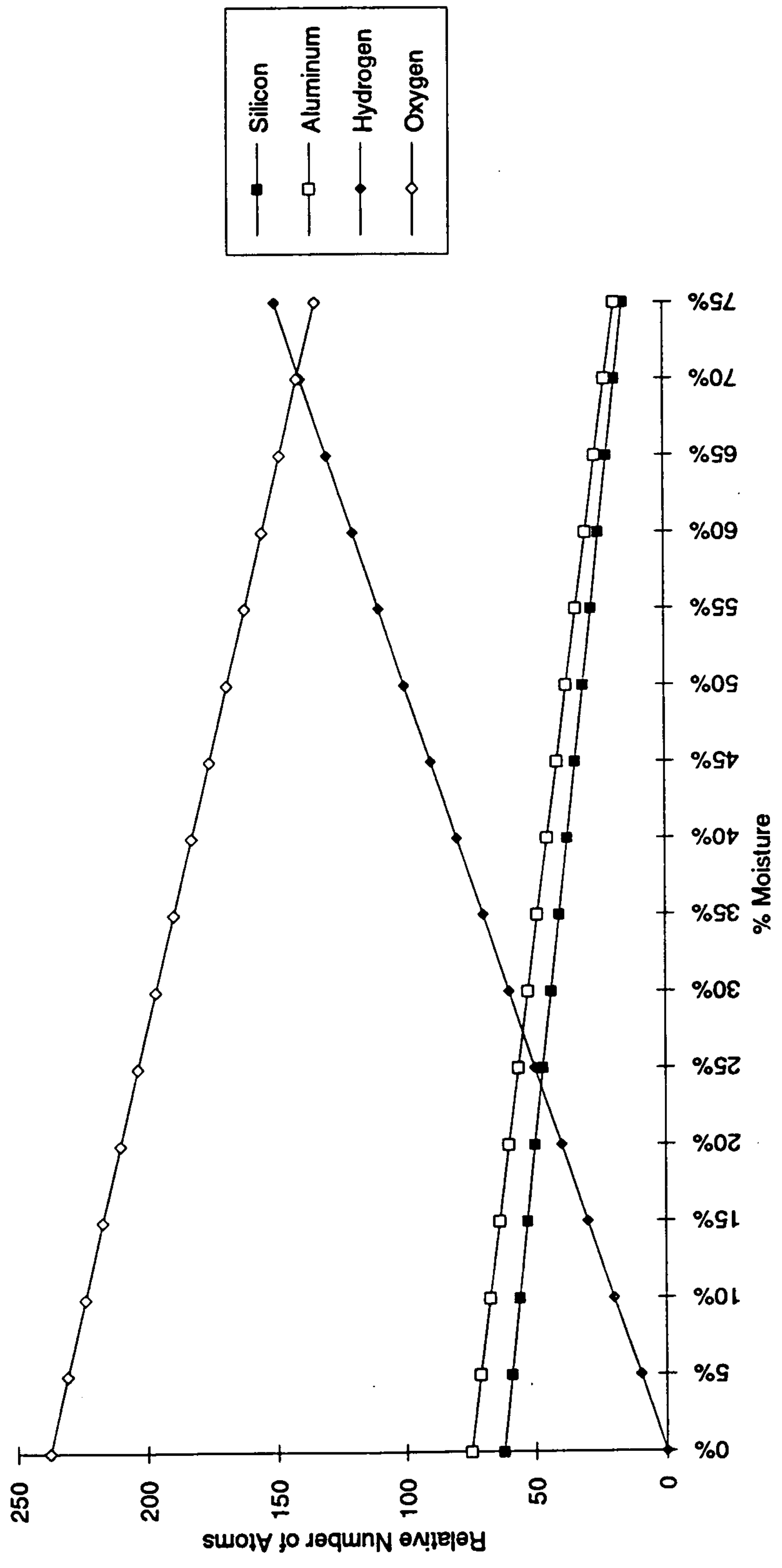


Figure 3-6. Chemical Composition of Bentonite at Various Moisture Levels

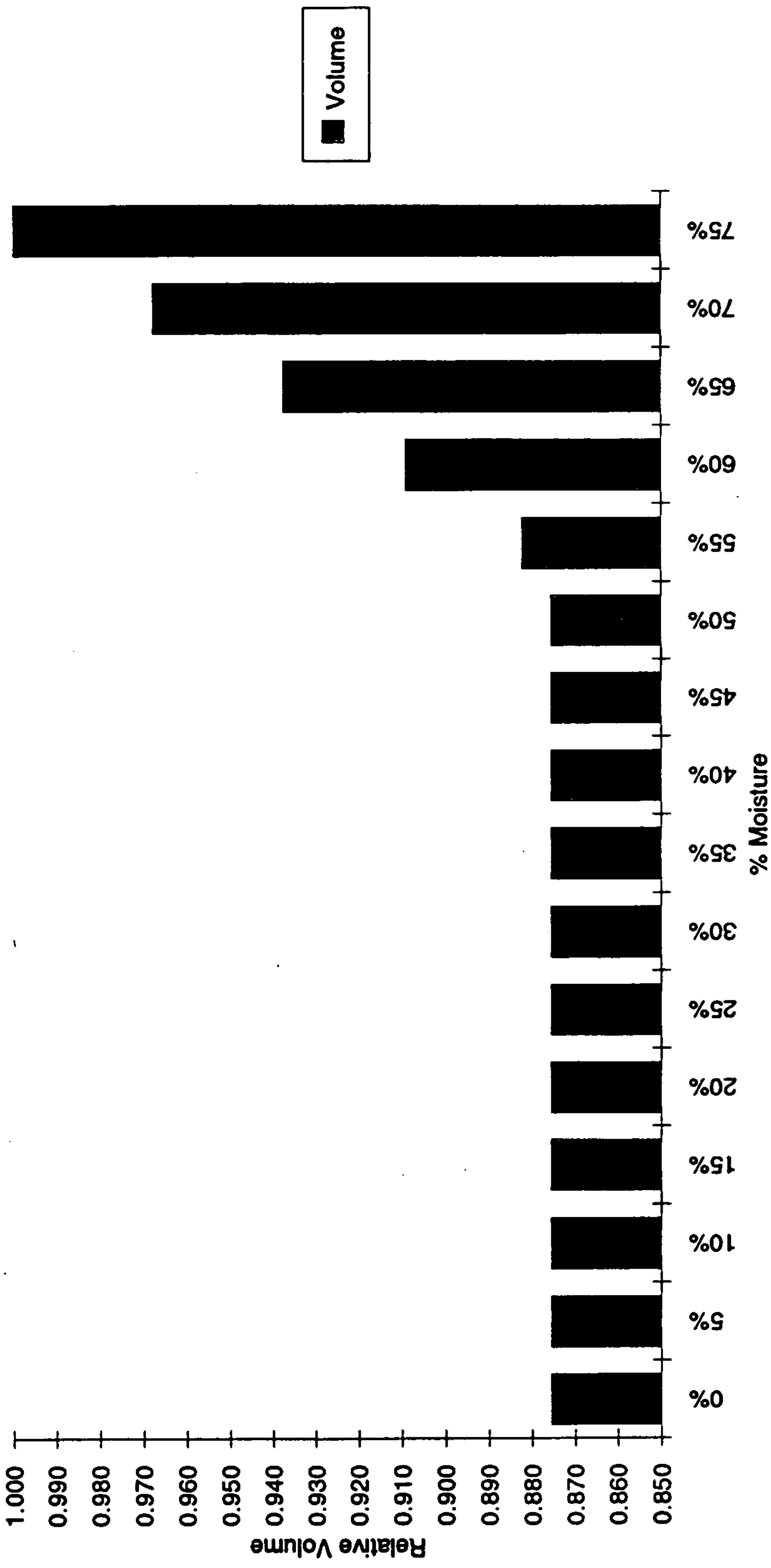


Figure 3-7. Contraction of Bentonite Due to a Loss of Moisture

presented in this table. TLD data was available at the fence line and background locations since 1989 at all locations except background locations 3 and 4, which began in 1990.

Table 3-10. Summary of TLD Results at the Fence Line and Background Locations

Location	1989 µrad/hr	1990 µrad/hr	1991 µmem/hr	1992 µrad/hr
AMS 5	11.0	7.1	7.3	7.7
AMS 6	18.0	12.8	12.4	8.3
AMS 7	12.6	7.2	6.9	7.6
Background 1 - Westwood	11.2	7.3	7.6	7.7
Background 2 - Brookville	10.0	6.4	6.5	6.7
Background 3 - Miamitown	NA	5.7	5.5	5.6
Background - U. of Cinti	NA	5.9	6.3	6.4

In all observed cases the highest hourly exposure occurred in 1989. The background TLD monitors at Westwood were always higher than the other background locations. The Westwood background location results are similar in magnitude as AMS 5 and AMS 7; however, AMS 5 and AMS 7 are approximately 1 uRad/hour higher than the other background locations. Qualitatively, the TLD data would indicate a significant reduction in the dose rate at AMS 6 following the addition of bentonite with no observed effect at the other locations.

3.5 The Mechanistic Model

A primary objective of this study is to demonstrate that the radon levels at the monitored stations are not statistically influenced more than background levels by the concentrations measured within each silo headspace. Significant influence from these silos would imply that the radon concentrations at the affected stations are not within 0.015 pCi/l above background. However, demonstrating this compliance may not be possible due to the sources of uncertainty in the estimating and variability in measured data and natural background over the region.

Statistical methods have been developed to determine the level of association between station concentration and silo headspace concentration. These methods have been developed to support the following statistical objectives:

1) Conduct analysis of variance methods to determine the effect of silo headspace concentration on concentrations at the monitored station locations (primarily the three boundary sites: AMS 5, AMS 6, AMS 7), characterizing the error level of predicted station concentrations,

2) Correct concentration data as necessary for effects of meteorological variables.

These objectives have been addressed by evaluating the concentration data according to a series of statistical models which characterize significant influences on these data.

For each station separately, the following three statistical models were fit to the hourly concentration data over the 8-week period:

Model 1

$$\log(Y_t) = \alpha_0 + \alpha_1 T_t + \alpha_2 WS_t + \alpha_4 \log(Silo_t) + \epsilon_t \ ,$$

Model 2

$$\log(Y_t) = \beta_0 + \beta_1 T_t + \beta_2 WS_t + \beta_3 \cos(\theta_t) + \beta_4 \sin(\theta_t) + \epsilon_t \ ,$$

Model 3

$$\log(Y_t) = \gamma_0 + \gamma_1 T_t + \gamma_2 WS_t + \gamma_3 \log(Silo_t * \cos(\theta_t)) + \epsilon_t \ ,$$

(if $\cos[\theta_t]$ is less than 0.1, then this value is reset at 0.1.)

The measured data are represented in the models by the following terms:

Y_t = The station concentration at time t
T_t = The outdoor temperature (C) at time t
WS_t = The wind speed (m/sec) at time t
$Silo_t$ = The sum of the hourly average headspace concentrations in the two silos at time t
θ_t = The wind direction relative to the station at time t
ϵ_t = Independent normally-distributed error terms

The parameters in the above models represent the following:

Model 1:

α_0 = An overall constant
α_1 = The effect of outdoor temperature on log concentration at each station
α_2 = The effect of wind speed on log concentration at each station
α_3 = The effect of log headspace concentration on log concentration at each station

Model 2:

β_0 = An overall constant
β_1 = The effect of outdoor temperature on log concentration at each station
β_2 = The effect of wind speed on log concentration at each station
β_3 and β_4 = Joint effects of wind direction

Model 3:

γ_0 = An overall constant
γ_1 = The effect of outdoor temperature on log concentration at each station
γ_2 = The effect of wind speed on log concentration at each station
γ_3 = The effect of headspace concentration relative to the wind direction

Fitting Model 1 to the hourly concentration data indicated that the effects of temperature and wind speed are significantly associated with log concentration at each station. The effect of log concentration at the silo headspace was significant at the 0.05 level at AMS 5, AMS 6, Met. tower, and background stations. Because of the significance noted in the background station, it is unclear that results of this significance test are accurately portraying the effect of silo headspace concentration. Attachment H contains plots of the log concentrations for the monitoring stations versus the silo headspace. The plots indicate that low silo headspace concentrations are associated with low monitoring station concentrations. However, moderate and high values of silo headspace concentration are observed with a variety of concentrations at the monitoring stations. These plots are not illustrating a cause-and-effect relationship between the monitoring stations and the silo headspace; this relationship may be caused by meteorological factors.

For each monitoring station, Attachment I contains a three-dimensional plot of the predicted concentration (as determined by the model) versus temperature and wind speed, assuming a constant headspace concentration of 300,000 pCi/l across the two silos (approximately the average daily cumulative headspace concentration over this time period). The model indicates that at this headspace concentration, temperature is more highly associated with station concentration at low wind speeds, and the wind speed is more highly associated with station concentration at low temperatures. Attachment I also contains plots of the log concentration at each monitoring station versus wind speed and temperature. These plots illustrate a strong negative relationship between the two meteorological variables and concentration at the monitoring stations.

The findings of fitting Model 1 to the monitoring station hourly concentration data imply that the effect of outdoor temperature is inversely related to the concentration. This is contrary to the conclusions of the time series analysis in Subsection 3.4, which indicated that highest concentrations were generally observed in seasons with warm temperatures. In interpreting this result, it must be noted that hourly data are being considered in this analysis rather than daily average data, as was used in Subsection 3.4. The hourly data contain diurnal variation which is not represented in daily average data. Also, the hourly data are analyzed only over an 8-week period. It is not possible to estimate the long-term effect of temperature over several seasons due to the short time period considered in this analysis.

The primary interest in this analysis is to determine the relative error associated with fitting Model 1 to the data from each monitoring station and to determine whether the predicted concentrations at each monitoring station are statistically significantly different from the predicted concentrations observed at the background station. Attachment J presents plots of the predicted concentrations at each monitoring station versus the silo headspace concentration, with 95 percent prediction bounds, as determined by fitting Model 1 to the available data. These plots assume a constant wind speed of 1 meter/second (a low wind speed, which is associated with higher monitored concentrations) and two different values of outdoor temperature (15 degrees C and 25 degrees C). The plots illustrate that increases in monitoring station concentration are associated with only minor increases in the silo headspace concentration. At both temperatures, the prediction curve for each monitoring station falls within the 95 percent prediction bounds at the background station at each silo headspace concentration. This result supports the conclusion that predicted concentration at the monitoring stations is not statistically significantly different from the prediction at the background station, as a result of fitting Model 1 separately to each station.

These results fitting Model 2 imply that the wind direction does not significantly affect station concentrations for any of the six stations. Plots of the station concentrations as a function of wind direction are presented in Attachment K. These plots illustrate that higher concentrations are not associated with any one wind direction. In fact, the distribution of station concentration is relatively constant across wind directions, indicating that wind is not introducing significant levels of radon from any one particular direction.

Results from fitting Model 3 to AMS 5, AMS 6, and AMS 7 data indicate that the effect of silo headspace concentration, as weighted by wind direction, is significant at the 0.05 level for stations AMS 6 and AMS 7. The prediction bounds generated by Model 1 (Attachment J) are a "worst-case" scenario for Model 3, where it is assumed that the wind is constantly blowing from the direction of the silos to the monitoring stations.

4.0 Establishing Monitoring Criteria

4.1 Determining the Level of Association between Monitoring Station Concentrations and Silo Headspace

4.1.1 Introduction

Radon concentration levels have been monitored at hourly intervals over the last 2 years at several monitoring stations within and in the vicinity of the FEMP. The two K-65 silos on the western edge of the FEMP contain radon-contaminated materials which can potentially influence the radon concentration levels at these stations. As discussed in Section 3 a primary objective of this study is to demonstrate that the radon levels at the monitored stations are not significantly influenced more than background levels by the concentrations measured within each silo headspace.

Note that the statistical objectives of this analysis were not intended to obtain an accurate representation of the plume of silo headspace radon as it is released from the silos. The statistical objectives are to determine the level of significant association between station concentrations and the silo headspace concentration.

4.1.2 Statistical Approach

All statistical analyses were performed on radon concentration data from hourly monitoring intervals. All station concentration data and meteorological data were collected at hourly intervals. Headspace concentration were collected at 5-minute intervals for both silos; these data were averaged within hourly intervals for purposes of this analysis.

Silo headspace concentrations have been monitored using pylons since July 20, 1992 (monitored using modified BZ detectors from December 1991 to July 1992), and data, to support the development of this report, are available through September 15, 1992. Thus the relationships evaluated in this statistical analysis are based only on data over an 8-week period in a warm season. Long-term seasonal effects on these data cannot be determined at this time.

The current boundary monitoring stations represent a limited range of distances and directions from the silos. A statistical model is fit to each station separately, thus permitting separate conclusions on the influence of silo headspace concentration to be made for each station. Separate analyses has the advantage of taking into account the distance and location of each station relative to the silos.

Characterizing the effect of silo radon concentration on concentrations at monitoring stations is based on the potential of radon release from the headspaces of the two silos, thus the hourly average headspace concentrations across the two silos are summed to obtain a single concentration. This sum is used in the statistical modeling procedure as a covariate to concentration at the monitoring stations.

4.1.3 Statistical Modeling

In order to accurately characterize the effects of silo headspace concentration and meteorological variables on the monitoring site concentrations, and to address study objectives from different viewpoints, a series of statistical models were fit to these data. The models represent the effect of silo concentration exposure in different ways. The models are multiplicative in nature; the meteorological effects are assumed to be additive on the natural logarithm of the monitoring site concentrations. The natural logarithm of the silo headspace concentration is also used as an independent variable in the models. A total of six monitoring stations were considered in this analysis:

1) AMS 5
2) AMS 6
3) AMS 7
4) Met. tower
5) Pilot plant
6) Background

Preliminary correlation analyses on the meteorological variables, and analysis of silo headspace concentration (Subsection 3.1) indicate that most of the information obtained from the class of meteorological variables is explained within the following subset:

1) Outdoor temperature
2) Wind speed
3) Stability indicator
4) Wind direction

Other available meteorological variables were primarily functions of the above variables or the observed data for these variables were not considered reliable across the 8-week monitoring period. Dew point was highly positively correlated with temperature. Barometric pressure did not add much more information than the combination of wind speed and temperature. In addition, the barometric pressures were unusually low throughout the monitoring period. Barometric pressure at the silo showed a continual decline across the monitoring period indicating instrument monitoring problems.

Determining the subset of independent (predictor) variables to include in the model is a multiple-stage process. The effect of one independent variable on the station concentration is estimated assuming that all other specified independent variables already exist in the model. Thus if two correlated independent variables are considered in the model and both highly affect the dependent variable individually, the results of the model fitting may indicate no significant effect for either variable if both are included in the model, rather than just one or the other. Thus the model building process must be done carefully in order to make proper conclusions from the process.

For each station separately, the following three statistical models were fit to the hourly concentration data over the 8-week period:

Model 1

$$\log(Y_t) = \alpha_0 + \alpha_1 T_t + \alpha_2 WS_t + \alpha_4 \log(Silo_t) + \epsilon_t \ ,$$

Model 2

$$\log(Y_t) = \beta_0 + \beta_1 T_t + \beta_2 WS_t + \beta_3 \cos(\theta_t) + \beta_4 \sin(\theta_t) + \epsilon_t \ ,$$

Model 3

$$\log(Y_t) = \gamma_0 + \gamma_1 T_t + \gamma_2 WS_t + \gamma_3 \log(Silo_t * \cos(\theta_t)) + \epsilon_t \ ,$$

(if $\cos[\theta_t]$ is less than 0.1, then this value is reset at 0.1.)

The measured data are represented in the models by the following terms:

Y_t = The station concentration at time t
T_t = The outdoor temperature (C) at time t
WS_t = The wind speed (m/sec) at time t
$Silo_t$ = The sum of the hourly average headspace concentrations in the two silos at time t
θ_t = The wind direction relative to the station at time t
ϵ_t = Independent normally-distributed error terms

The parameters in the above models represent the following:

Model 1:

α_0 = An overall constant
α_1 = The effect of outdoor temperature on log concentration at each station
α_2 = The effect of wind speed on log concentration at each station
α_3 = The effect of log headspace concentration on log concentration at each station

Model 2:

β_0 = An overall constant
β_1 = The effect of outdoor temperature on log concentration at each station
β_2 = The effect of wind speed on log concentration at each station
β_3 and β_4 = Joint effects of wind direction

Model 3:

γ_0 = An overall constant
γ_1 = The effect of outdoor temperature on log concentration at each station
γ_2 = The effect of wind speed on log concentration at each station
γ_3 = The effect of headspace concentration relative to the wind direction

All three models contain effects due to outdoor temperature and wind speed. These two meteorological variables were found to be highly associated with the radon concentrations at the boundary sites. Thus any conclusions on the association of silo headspace concentration on the monitoring site concentrations are made after adjusting for the effects of outdoor temperature and wind speed. Atmospheric stability indicator was a third meteorological variable which was significantly associated with silo headspace concentration (Subsection 3.1), but this term was not found to be significant for any of the monitoring stations when included in the above three models. Thus stability indicator was not included in the above models.

Model 1 considers silo headspace concentration and how it directly relates to monitoring station concentrations. Wind direction, which may influence the nature of how headspace concentration affects the monitoring station, is not considered in this model. Thus Model 1 provides a simple linear interpretation of the log concentration at the monitoring station, as a function of the silo headspace concentration.

Model 2 does not consider silo headspace concentration, but instead relates how wind direction is associated with station concentration. The relation of wind direction to station concentration is assumed to be sinusoidal. Thus this model will indicate if station concentration is significantly correlated with the direction from which the wind is blowing. If the effect of wind direction is not significant in the model (i.e., the terms β_2 and β_3 are jointly not significant), then this would conclude that there is no primary radon source which influences the monitoring station concentration through wind direction.

Model 3 is an extension of Models 1 and 2. It introduces the joint effect of silo headspace concentration and wind direction. This joint effect is represented by multiplying the silo headspace concentration with the cosine of the wind direction relative to the monitoring station. Thus the silo headspace concentration is weighted by the wind direction, with the maximum weight occurring when the wind is blowing from the silos in the direction of the monitoring station. This weight is never lower than 0.1, indicating that at least 10 percent of the silo headspace concentration is represented in the model. This model was fit only to the boundary site data (AMS 5, AMS 6, AMS 7). Note that Model 1 is a "worst-case" scenario of Model 3. If the wind direction is constantly from the silos to the monitoring station, then Model 3 would take the form of Model 1.

The error associated with the silo concentration measurements in Models 1 and 3 is assumed to be negligible relative to the measurements at the monitoring stations. This may not be a valid assumption. A more statistically complex procedure, using errors in variables models, would be appropriate to determine the significance of these effects. The errors in variables approach was not taken in this analysis but may be considered in future statistical analysis work in this area.

4.1.4 Results and Conclusions

The results of fitting Model 1 to data from the six monitoring stations of interest are presented in Table 4-1. This table displays the estimates (and standard errors) for the parameters in the model, results of a test for significance of the parameters in the model, the root mean square error, and the R-square term. The root mean square error is an estimate of the residual error in the data which is not explained by the terms in the model. Because the analysis was performed on log-transformed concentrations, the root mean square error is an estimate of the coefficient of variation (standard deviation divided by the mean) for the untransformed data. The R-square value is the proportion of total error in the monitoring station data which is explained by the model.

Fitting Model 1 to the hourly concentration data indicated that the effects of temperature and wind speed are significantly associated with log concentration at each station. The effect of log concentration at the silo headspace was significant at the 0.05 level at AMS 5, AMS 6, Met. tower, and background stations. Because of the significance noted in the background station, it is unclear that results of this significance test are accurately portraying the effect of silo headspace concentration. Attachment H contains plots of the log concentrations for the monitoring stations versus the silo headspace. The plots indicate that low silo headspace concentrations are associated with low monitoring station concentrations. However, moderate and high values of silo headspace concentration are observed with a variety of concentrations at the monitoring stations. These plots are not illustrating a cause-and-effect relationship between the monitoring stations and the silo headspace; this relationship may be caused by meteorological factors.

For each monitoring station, Attachment I contains a three-dimensional plot of the predicted concentration (as determined by the model) versus temperature and wind speed, assuming a constant headspace concentration of 300,000 pCi/l across the two silos (approximately the average daily cumulative headspace concentration over this time period). The model indicates that at this headspace concentration, temperature is more highly associated with station concentration at low wind speeds, and the wind speed is more highly associated with station concentration at low temperatures. Attachment I also contains plots of the log concentration at each monitoring station versus wind speed and temperature. These plots illustrate a strong negative relationship between the two meteorological variables and concentration at the monitoring stations.

Table 4-1. Results of Fitting Model 1 to Hourly Concentration Data from Each Monitoring Station

Monitoring Station	Parameter Estimate (Standard Error) (Significance Level)				Root Mean Square Error[1]	R-Square
	Intercept	Temper-ature	Wind Speed	Log (Silo Conc.)		
AMS 5	1.828 (0.141) (0.0001)	-0.077 (0.006) (0.0001)	-0.156 (0.014) (0.0001)	0.151 (0.055) (0.0064)	0.493	0.606
AMS 6	1.520 (0.145) (0.0001)	-0.071 (0.006) (0.0001)	-0.111 (0.014) (0.0001)	0.151 (0.058) (0.0096)	0.492	0.514
AMS 7	1.928 (0.137) (0.0001)	-0.080 (0.006) (0.0001)	-0.145 (0.013) (0.0001)	0.081 (0.054) (0.13)	0.472	0.619
Met tower	1.513 (0.120) (0.0001)	-0.066 (0.005) (0.0001)	-0.130 (0.012) (0.0001)	0.119 (0.047) (0.012)	0.422	0.603
Pilot Plant	0.778 (0.106) (0.0001)	-0.041 (0.004) (0.0001)	-0.080 (0.010) (0.0001)	0.042 (0.042) (0.31)	0.37	0.421
Background	0.508 (0.101) (0.0001)	-0.033 (0.004) (0.0001)	-0.116 (0.010) (0.0001)	0.081 (0.040) (0.041)	0.353	0.506

(1) An estimate of the coefficient of variation in the untransformed concentrations for the monitoring station. This is also an approximation to the standard error of an individual predicted value of log concentration (the proper estimate of this standard error depends on the values of the dependent variables at which the prediction is being made.).

The findings of fitting Model 1 to the monitoring station hourly concentration data imply that the effect of outdoor temperature is inversely related to the concentration. This is contrary to the conclusions of the time series analysis in Subsection 3.4, which indicated that highest concentrations were generally observed in seasons with warm temperatures.

Of primary interest in this analysis is to determine the relative error associated with fitting Model 1 to the data from each monitoring station, and to determine whether the predicted concentrations at each monitoring station are statistically significantly different from the predicted concentrations observed at the background station. Attachment J presents plots of the predicted concentrations at each monitoring station versus the silo headspace concentration, with 95 percent prediction bounds, as determined by fitting Model 1 to the available data. These plots assume a constant wind speed of 1 m/second (a low wind speed, which is associated with higher monitored concentrations) and two different values of outdoor temperature (15 degrees C and 25 degrees C). The plots illustrate that increases in monitoring station concentration are associated with only minor increases in the silo headspace concentration. At both temperatures, the prediction curve for each monitoring station falls within the 95 percent prediction bounds at the background station at each silo headspace concentration. This result supports the conclusion that predicted concentration at the monitoring stations is not statistically significantly different from the prediction at the background station as a result of fitting Model 1 separately to each station.

The results of fitting Model 2 to the station concentration data are presented in Table 4-2. These results imply that the wind direction does not statistically significantly affect station concentrations for any of the six stations. Plots of the station concentrations as a function of wind direction are presented in Attachment K. These plots illustrate that higher concentrations are not associated with any one wind direction. In fact, the distribution of station concentration is relatively constant across wind directions indicating that wind is not introducing significant levels of radon from any one particular direction.

Results from fitting Model 3 to the AMS 5, AMS 6, and AMS 7 data are presented in Table 4-3. These results indicate that the effect of silo headspace concentration, as weighted by wind direction, is significant at the 0.05 level for stations AMS 6 and AMS 7. The prediction bounds generated by Model 1 (Attachment J) are a "worst-case" scenario for

Table 4-2. Fitting Model 2 to Hourly Concentration Data From Each Monitoring Station

Monitoring Station	Significance Level for Wind Direction	Root Mean Square Error[1]	R-Square
AMS 5	0.121	0.504	0.572
AMS 6	0.413	0.529	0.444
AMS 7	0.177	0.486	0.557
Met tower	0.182	0.449	0.529
Pilot Plant	0.288	0.379	0.380
Background	0.652	0.353	0.435

(1) An estimate of the coefficient of variation in the untransformed concentrations for the monitoring station.

Table 4-3. Results of Fitting Model 3 to Hourly Concentration Data From Each Monitoring Station

Monitoring Station	Parameter Estimate (Standard Error) (Significance Level)				Root Mean Square Error[1]	R-Square
	Intercept	Temper-ature	Wind Speed	Log(Silo Conc.)		
AMS 5	1.484 (0.112) (0.0001)	-0.069 (0.005) (0.0001)	-0.178 (0.012) (0.0001)	-0.012 (0.020) (0.54)	0.496	0.601
AMS 6	1.440 (0.112) (0.0001)	-0.067 (0.005) (0.0001)	-0.122 (0.012) (0.0001)	0.062 (0.020) (0.0017)	0.490	0.517
AMS 7	1.964 (0.109) (0.0001)	-0.079 (0.005) (0.0001)	-0.148 (0.012) (0.0001)	0.057 (0.019) (0.003)	0.469	0.624

(1) An estimate of the coefficient of variation in the untransformed concentrations for the monitoring station.

Model 3, where it is assumed that the wind is constantly blowing from the direction of the silos to the monitoring stations.

The monitoring processes in this study, such as the location and time frame of radon concentration monitoring, were not established as the result of a valid statistical design criteria. Although some hypotheses cannot be completely addressed in this study for example, the availability of only three boundary monitoring stations, all in the northwest and southwest quadrants relative to the silos, introduces uncertainty as to the overall accuracy and completeness associated with the characterization of the effect of silo headspace concentration as it relates to distance and direction from the silos. What is conclusive is that at large distances, 400 meters or greater, there is little ability to detect silo effects on the ambient radon concentration.

When silo headspace concentration was directly incorporated in the models, mixed results were seen across the monitoring stations. The effect of headspace concentration on the concentrations at the monitoring stations occasionally was significant at the 0.05 significance level. However, no cause or effect relationship with silo headspace concentration can be made as a result of this finding. Instead, this significance may indicate that other meteorological factors which are not considered in the model are significantly associated with radon concentration at both the silo headspace and the monitoring stations.

Fitting Model 1 to the radon concentration data collected over the 8-week period resulted in relatively large prediction intervals for monitoring station concentration based on the silo headspace concentration. Evidence exists that the predicted concentrations at the monitoring stations are not statistically significantly different from those predictions at the background station. Thus the relatively large variability present in the data prevents differences from background from being observed.

4.2 Establishing Upper Bound Concentration On the Headspace Radon

A parameter of importance is the radon concentration in the headspace which would result in a long-term average off-site radon concentration at the nearest receptor of greater than 0.015 pCi/l. Due to the variability of the data and the uncertainty ranges associated with the mechanistic model, an approach to estimate this was developed.

The approach was to back calculate a release rate from the silos based on the ISCLT2 computer code runs for a unit flux release from the silos. The pre-bentonite concentration in each silo was assumed to be approximately the same. This appears reasonable based on the single measurements of radon concentration in the headspace pre-bentonite.

The release rate could then be used to determine the release fraction from the silos. Since the release mechanism should not be affected by the addition of bentonite over the residue, it is assumed that the release fraction of the silo headspace gases will be the same over a long period of time. The release rate in conjunction with the removal action goal of 0.015 pCi/l can be used to assess the acceptable radon concentration in the silos. A graph illustrating the optimum concentrations for both silos so as not to exceed the 0.015 pCi/l above background concentration was developed. This graph provides Silo 1 headspace concentration versus silo 2 radon concentration such that if the average radon concentrations in each silo fall below the line on the graph then the headspace concentration is considered as in compliance with the 0.015 pCi/l performance goal (as estimated at the nearest resident). Any point (combination of Silo 1 and Silo 2 headspace radon concentration) above the line would indicate that the contribution to the nearest resident is greater than 0.015 pCi/l. The maximum radon concentration, assuming both silos are equal, is on the order of 4 x 10^6 pCi/l in each silo. These radon concentrations are a direct result of applying the Gaussian Plume model to the release and transport of radon from the silos. It is important to note that the statistical results provided upper limits on the daily average concentrations, that would be expected based on the observed distributions, of 108,000 and 355,000 pCi/l for Silos 1 and 2 respectively. The bottom line is that statistical methods have provided a much better estimate of the expected radon concentration and these estimates are an order or more less than those predicted by using the original model alone.

The graph is shown in Figure 4-1.

The results of this assessment are limited by the applicability of the ISCLT2 code to the actual conditions at the FEMP. The lack of FEMP specific field validation of the ISCLT2 or any other gaussian plume based code results in a limited confidence in any estimate predicted by the code.

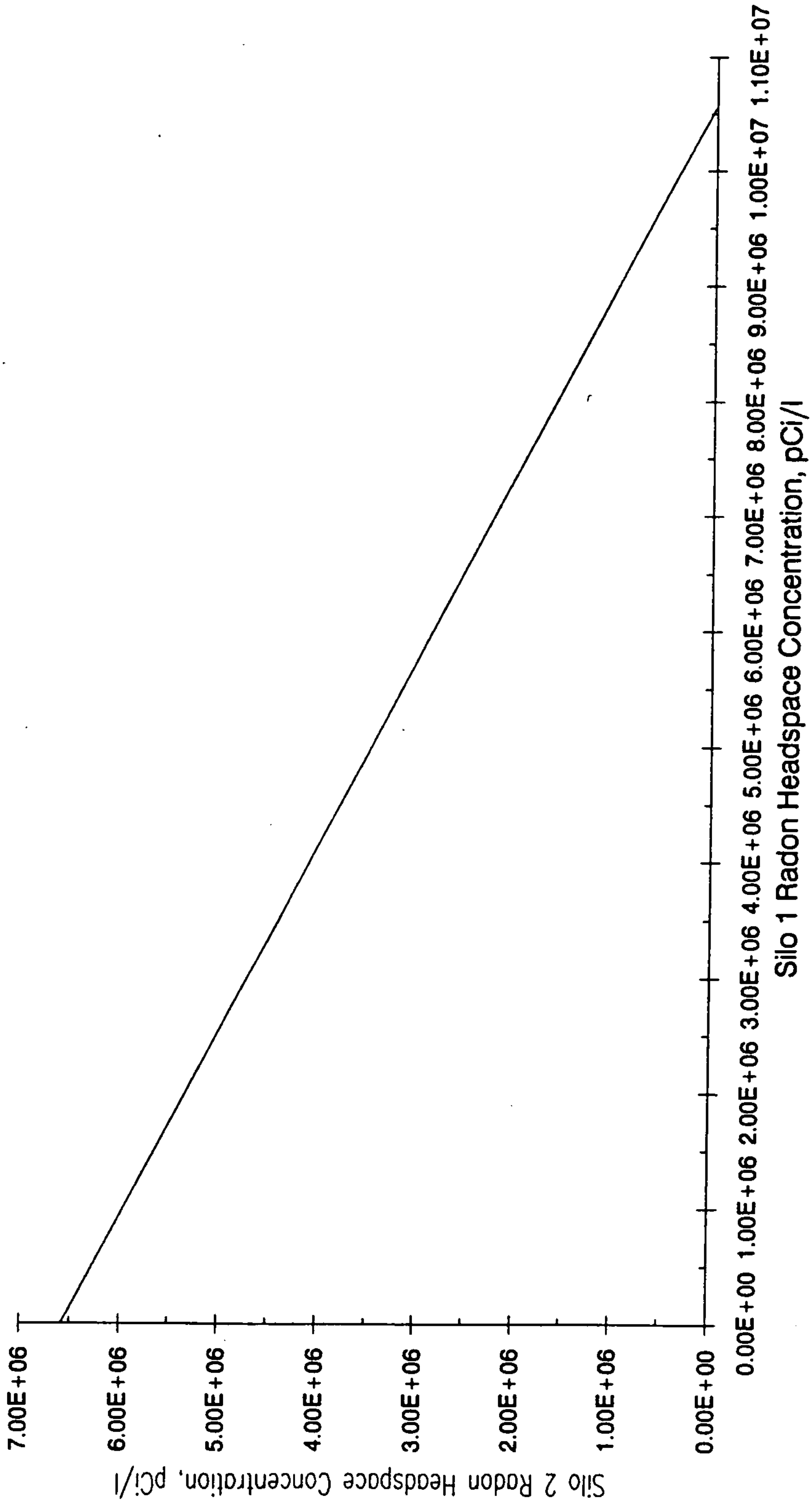


Figure 4-1. Radon Concentration in Silo Headspace Required to Exceed 0.015 pCi/l at Nearest Resident

Based on the results predicted in Figure 4-1, the tolerance limit on the radon concentration in each silo is determined. The tolerance limit is the radon concentration which if exceeded may result in noncompliance with the 0.015 pCi/l limit at the nearest receptor. Figure 4-1 is assumed to represent a type of tolerance limit for the concentration of radon in the head-space. A headspace concentration of 4×10^6 pCi/l in each silo will not result in an off-site radon concentration greater than 0.015 pCi/l on a long term average basis (based on the Gaussian Plume Model). Should the concentration in the headspace of either silo begin to approach 1×10^6 or higher there would be reason to suspect that there is some degradation of the bentonite.

4.3 Prediction intervals

A prediction interval is a statistical interval calculated to include one or more future observations from the same population with a specific confidence. The prediction interval is constructed assuming that the headspace data follows a normal distribution. The concentration of radon in the headspace since July 20 are used to establish an interval within which "m" future observations are expected to lie within a specific confidence. The prediction interval is presented in the following equation:

$$X \pm S \sqrt{\frac{1}{m}+\frac{1}{n}}\, t_{(0.99,\, n-1)} \qquad \text{Equation 4-4}$$

where:

X = Mean
S = Standard deviation
m = Number of future observations at a single silo
n = Number of daily headspace measurements used to calculate the mean
t = The 99th percentile of the Student t-distribution with n-1 degrees of freedom.

The mean, standard deviation, and number of daily headspace measurements used to calculate the mean for Silo 1 are 45,081 pCi/l, 23,190 pCi/l, and 55, respectively. The mean, standard deviation, and number of daily headspace measurements used to calculate the mean for Silo 2 are 219,583 pCi/l, 48,720 pCi/l, and 33, respectively. The student t for Silo 1 is 2.670 and 2.738 for Silo 2. Based on these values the prediction interval for Silo 1 assuming one future observation is between 0 and 108,000 pCi/l and between 108,000 and 355,000 pCi/l for Silo 2.

5.0 Cause-Effect Relationships

This section will present a summary of the results of the various statistical analyses which were previously presented. The purpose is to draw some logical conclusions and inferences concerning the cause-effect relationship between the data collected at the monitoring stations and the radon in the silo headspace.

5.1 Site Fence Line

The silos zone of influence on radon in the environment is not completely known. The statistical analysis presents conflicting results as to the statistical significance of the radon concentration indicated by the Pylon and Terradex cup detectors at the AMS stations.

The statistical evaluations presented in Section 2 and 3 are performed without consideration to the cause-effect relationship. No cause effect relationship can be established concerning the K-65 silos and the radon concentration at the site fence line Pylon monitors. In an analysis of AMS 5, AMS 6, and AMS 7, the post-bentonite data is not different from the pre-bentonite data except at AMS 5. AMS 5 post-bentonite concentrations are lower than the pre-bentonite concentrations. The same results are obtained when the data is evaluated in a time series manner.

A comparison of the pre-bentonite site fence line (Pylon and Terradex cups) data with the respective pre-bentonite background data shows a radon concentration that is greater than background at all fence line stations. No inferences as to the cause of the radon being above background can be inferred due to several factors.

The lack of consistent conclusive evidence that the bentonite placement was related to any detectable change in the radon concentration at the site fence line indicates that the site fence line was not affected by the silos in both the pre- and post-bentonite periods. In addition, any results are confounded by the spatial variability which exists in the natural background level of radon and any other potential sources which may contribute to an elevated background of radon at the FEMP. The actual background at the FEMP is not known nor will it ever be known due to the past operations at the FEMP possibly leading to a slight increase in radon due to the handling and storage of uranium, radium and thorium bearing materials.

The data collected at the site fence line Pylon monitors are typically less than 1 pCi/l which is below the manufacturer's specified detection limit. Adding to the uncertainty in the conclusions for the results at the site fence line is the fact that these concentrations are very similar to the background concentration which is monitored with a Pylon detector at only one location 16 miles from the site. This adds uncertainty to the practical conclusions which can be drawn from the statistical analysis.

The differing conclusions drawn from the statistical analysis of the site fence line radon concentrations would indicate that it cannot be conclusively decided if the site fence line radon concentration is greater than the background radon concentration. There is no physical evidence that any radon at the site fence line originated within the silos, but there is substantive statistical evidence that the silos have no effect on the site boundary monitors.

5.2 Level of Association Between Monitoring Station Concentrations and Silo Headspace

Correlation analyses on the meteorological variables, and analysis of silo headspace concentration (Subsection 3.1) indicate that most of the information obtained from the class of meteorological variables is explained within the following subset:

1) Outdoor temperature
2) Wind speed
3) Stability indicator

Other available meteorological variables were primarily functions of the above variables or the observed data for these variables were not considered reliable across the 8-week monitoring period.

The modeling procedure addressed predicting radon concentrations at the monitoring stations as a function of silo headspace concentration and meteorological variables. The effects of some meteorological variables on the concentration were found to be highly significant at both the monitoring stations and at the silos. These variables include wind speed and outdoor temperature. However, wind direction was not significantly associated with concentration levels at any of the monitoring stations. This latter result implies that radon levels do not appear to be affected by any one particular radon source which would influence the levels through wind direction toward the monitor, thereby illustrating the inability to establish cause-effect relationship to the K-65 Silos.

When silo headspace concentration was directly incorporated in the models, mixed results were seen across the monitoring stations. The effect of headspace concentration on the concentrations at the monitoring stations occasionally was significant at the 0.05 significance level. No cause or effect relationship with silo headspace concentration can be made as a result of this finding. The same factors are known to influence radon emanation from the ground into the environment affect the emanation from the residues through the bentonite and into the headspace in a similar manner.

The prediction interval for the radon concentration at the monitoring stations as a function of silo headspace and the other significant meteorological variables is shown in Attachment J. The results presented in Attachment J indicate that the silos do not have a significant effect on the majority of monitoring stations evaluated in this study.

The purpose of these models was to develop a statistical determination of the level of significance between the silos radon concentration and the radon concentration measured at several of the Pylon detectors on the FEMP site boundary, production area and a background location. The results of this effort indicate that no cause-effect relationship can be established between the silos headspace radon concentration and the radon concentration at the monitoring location along the site boundary and in the production area.

The wind direction was shown not to be correlated with radon concentration at any of the detector locations. The absence of wind direction as a significant parameter in predicting the radon concentration indicates that no one dominant source of radon can be identified. Based on the results of the statistical modeling efforts, the site boundary, production area, and background monitors are located outside of the influence of K-65 Silos. Any radon which is released from the silos into the environment is so dilute at these detector locations that any contribution cannot be statistically attributed to the silos due to the variability of the data and the possible influence of other sources of radon than the silos.

5.3 K-65 Exclusion Fence

Similar statistical methods as those applied to the site fence line monitoring station were used to evaluate the radon concentration at the K-65 exclusion fence line. The radon concentrations at these locations were compared for statistical significance for the pre- versus post-bentonite time periods and pre-bentonite versus background and post-bentonite versus background.

Unlike the results obtained at the site fence line, the results from the monitoring stations along the exclusion fence line were consistent. Pre-bentonite radon concentration was always greater than the post-bentonite concentration at all locations. Assuming no other changes in the environs surrounding the exclusion fence line, this would indicate that the bentonite was effective at significantly reducing the radon concentration at those points. However, both pre- and post-bentonite radon concentrations were significantly greater than background.

A greater level of confidence is shown for the data at the exclusion fence line due to the radon concentrations being greater then background and therefore easier to detect. A greater amount of this data was above the manufacturers recommended detection limit of 1.0 pCi/l which also adds confidence to the results.

5.4 Silo Headspace

Based on a comparison of the pre-bentonite radon concentration based on one grab sample confirmed by replicate sampling and the measured radon concentration post-bentonite and the dose rate reduction measured at both the silo dome and the site fence line, it can be concluded that the bentonite has significantly reduced the radon concentration in the silo headspace.

The reduction in headspace concentration may be even greater than indicated by a comparison of pre- versus post bentonite concentrations. This is due to the fact that the pre-bentonite grab samples were collected prior to the foam cover being placed over the silo domes. This foam would theoretically result in a lesser release of radon which would increase the equilibrium concentration of radon in the headspace. No measurements were taken to confirm this, so there is no evidence to support the theoretical supposition. If the theoretical position is true, the bentonite is actually more efficient than actually observed due to a lack of applicable data to the silo headspace concentration immediately prior to the bentonite application.

5.5 Conclusions Concerning Cause-Effect Relationships

The conflicting results and low confidence associated with the site fence line data and the inability to demonstrate a cause-effect relationship between the radon at these monitoring locations and the silos radon would indicate that it is not possible to directly measure the impact of radon released from the silos into the environment. Without the ability to conclusively detect radon at a point away from the silos it is not possible to calibrate a model and estimate the actual release rate.

Based on the results close in to the silos, from the exclusion fence line inward, there is high levels of confidence in the radon measurements. This is illustrated by the consistency of the pre- versus post-bentonite statistical analysis. Thus, it can be inferred that the silos do have an influence on the observed radon concentrations at those locations. Based on the discussion above, the data obtained from the silo headspace sampling is the only data available which can be used to directly measure the effectiveness of the bentonite.

6.0 Conclusions

The statistical analyses performed in this study was developed based on the total quantity of data available. The analyses is limited by both the ability to detect radon concentrations to levels below 1 pCi/l, with the instruments employed in the data collection, and the appropriateness and applicability of the assumed background concentration at the FEMP for radon in the air. The background was established using observed values at a location of 16 miles from the FEMP and is assumed to be representative (for the purposes of the statistical analysis) of the background radon at the FEMP. This assumption, as discussed previously, introduces error terms into the statistical analysis that can not fully taken into account. This is due to both the ubiquitous nature of radon and the myriad of radon sources at the FEMP. Natural background radon levels vary depending on the physical surroundings such as (1) the concentration of the parent atom radium in the soil or rocks, (2) the emanation power of the soil composition (physical makeup of the soil), (3) the porosity, (4) pressure differentials across the interface of the soil and atmosphere, (5) the degree of water saturation, and (6) other minor influences (NCRP 1989). Past operations of the FEMP have gradually increased the background radium concentration in the soils in areas surrounding the waste pits, flyash pile and south field area (as illustrated in the RI/FS soil sampling data). These facts place constraints on the ability to achieve high confidence levels associated with the statistical evaluations and further limits the inferences that can be made concerning the K-65 silos contribution to ambient radon concentrations.

6.1 The 0.015 pCi/l Removal Action Performance Goal

The determination of whether the performance goal of 0.015 pCi/l above background has been achieved is assessed through the statistical comparison of the radon concentration distributions as observed at various monitoring stations to the radon distribution observed at the background station. The underlying premise with which the performance goal evaluation is based is that differences between background and any monitoring station is due to the K-65 silos. In this case a statistical difference between the background and a particular monitoring station would indicate that the radon concentrations at a given monitoring station are not within the removal action performance goal.

Implicit in this ascertain is that the radon levels observed at the background location are not within the influence of the silos <u>and</u> that the background location is appropriate for evaluating conditions at the FEMP. This basic assumption is valid in a general sense, since there is little or no possibility that radon could migrate to a location 16 miles away, due to both the transport processes and the decay rate. The assumption that the background location is appropriate for use in the analysis at the FEMP is only valid within a confidence interval established by the variance of the background data. The difficulty includes both the appropriateness of the background and how the information is used. Using the background concentration to evaluate the effectiveness of the bentonite and the attainment of the performance goal produces difficulties in establishing the absolute confidence level necessary for a tolerance of 0.015 (as illustrated in Section 2 and 4 of this report the original Gaussian Plume model severely underestimates the limit on the radon concentration in the headspace). This is due to the small radon levels observed and the small tolerances that are required to establish a level of 0.015 pCi/l above background. All of the site boundary monitors are within a 0.5 pCi/l level of background and most are within a 1.1 pCi/l confidence level (see Section 2.1.2.3). The background data has a variance between 0.06 and 0.04 which is in itself a factor of 2.5 to 4 above the threshold level established by the performance goal. The range of the background data is 1.03 and 1.28 for pre- and post-bentonite conditions respectively (minimum and maximum values of 0.2/1.23 and 0.3/1.58 for the pre- and post-bentonite conditions respectively), thus illustrating that the variability of radon in the environment is greater than the tolerance limit established by the performance goal. The critical fact is that at these small concentration changes, at the site boundary, it is not possible to establish that the cause of the observed variations, from background, are due to the K-65 Silos.

6.1.1 Pylon AB-5 Data

The Pylon AB-5 results, based on the estimates of daily averages of hourly deviations from background, indicate that the daily difference from background is statistically different from zero at all monitoring stations in both pre- and post-bentonite time periods. The daily differences for the exclusion fence stations, after bentonite was added, are all lower than pre-bentonite by more than a factor of 4. The difference from background at these locations is also much smaller after bentonite, by more than a factor of 5. The NE station was on the average a factor of 16 higher than background, at 8.8 pCi/l, for the pre-bentonite condition and was reduced to a factor of 3 greater than background, at an average concentration of 1.62 pCi/l, (only an absolute difference from background of 1.1 pCi/l) for the post-bentonite condition. Statistical differences from background are noted for the boundary stations, even though these differences are less than 0.2 pCi/l in the post-bentonite period (which is essentially the variance in the data set). The statistical difference is due, in part, to the frequency at which readings at these stations are higher than background, even when the difference is only 0.1 pCi/l. The small standard errors for the boundary stations indicate that the differences from background are relatively constant from day to day. These results support the ascertain that the background levels for the site are likely higher than those at the location 16 miles away. The small concentration difference is well within the accepted variability of natural radon concentrations.

Plots of the daily average hourly differences from background at each monitoring station are presented in Attachment E. These plots also present the predicted concentrations as determined by fitting the model (Equation 2-1) to the observed data, along with approximate 95 percent confidence bounds on the expected concentrations (as determined by the model). The plots illustrate the difference in concentration at the exclusion fence monitoring locations between one year and the next. The yearly cyclic trend in the differences from background is still apparent in these plots. The seasonality illustrates that in the second year, these differences are more likely to be statistically insignificant early in the year, during winter or early spring.

6.1.2 Terradex Cup Data (Quarterly)

Ninety-five percent coverage (proportion), 95 percent confidence (probability) one-sided Tolerance Limits (TLs) were prepared on quarterly terradex background radon data for the post-bentonite period (January 1, 1992, through September 30, 1992) and for the pre- and post-bentonite periods combined (January 1, 1988, through September 30, 1992). In the later instance, the TL was calculated using background data for all four quarters of each year and then the TL was re-calculated utilizing only the first three quarters of each year.

The calculated TL, used for making comparisons with the compliance AMSs' values, selected from the three scenarios described above provided the tightest constraints on the statistical evaluation. A t-test was performed to confirm any statistical significance. In each of the three scenarios described above, a background TL of 1.1 pCi/l was calculated. The quarterly terradex data for the post-bentonite period for AMS 5, AMS 6, and AMS 7 were compared to the TL of 1.1 pCi/l. Results from AMS 5 exceeded the TL with a calculated first quarter (CY92) average value of 1.2 pCi/l. Each average value was based on three replicate terradex measurements. When comparing nine average values to the calculated 95 percent, 95 percent TL, one could expect one of the nine values to slightly exceed a TL (with these parameters) approximately 50 percent of the time. This could be due solely to chance variation within the compliance stations. Thus, the t-test was performed to confirm any statistical significance.

Based on a one-sided t-test using just the post-bentonite data for the background stations and AMS 5, AMS 5 was determined to be statistically greater than background ($p = 0.0160$). The 90 percent CI for the difference between the means of AMS 5 and background is 0.042 to 0.808 pCi/l. Note that the CI for the difference between these two means does not encompass zero, which also leads one to conclude that AMS 5 is different from the background. These two tests will always result in identical conclusions, if the same level of significance is used in both tests.

A quantitative and qualitative comparison between the radon measurements of three replicate terradex cups and one real-time monitor at air monitoring station (AMS) 5 was performed. This comparison was made in an attempt to explain why AMS 5 was statistically greater than background for the post-bentonite period under study (i.e., January 1, 1992, through September 30, 1992). AMS 5 is generally not downwind from the K-65 silos. AMS 6 and AMS 7 are situated more downwind from the silos than AMS 5, and they were not statistically greater than background for this post-bentonite period. For purposes of comparison, only data collected on the monitors from January 1 through September 30 for 1991 and 1992 were considered. Real-time monitors at AMS 5 were not in place prior to January 1, 1991, and the data after September 30, 1992, have not been obtained at the time of this study. Data from October 1, 1991, through December 31, 1991, are potentially biased high since the manholes of the silos had to be opened in order to place bentonite into the headspaces during this period.

When the three terradex results are in relative agreement (standard deviation $\leq$ 0.15 pCi/l), then the terradex quarterly average closely agrees with the quarterly average of the real-time pylon data (absolute difference $\leq$ 0.18 pCi/l). On the other hand, if there is relatively high variability among the three terradex results (standard deviation $\geq$ 0.38 pCi/l), then the terradex quarterly average is statistically greater than the quarterly average of the real-time pylon data. In the later instance, the lower of the three replicate values closely agrees with the real-time quarterly average data (absolute difference ≤ 0.15 pCi/l). Furthermore, there is a strong positive correlation (r = 0.91) between the magnitude of the variability among the three replicate terradex cups' readings and the magnitude of the difference between the average of the three cups' readings and the average pylon real-time data for a given quarter. The probability of this being a false correlation is less than 1 percent.

Based on these observations, one may arguably conclude that when there is high variability among the terradex cup readings, some external factor or source other than the ambient radon concentration is causing one and sometimes two of the three cups to read high. When examining the real-time pylon data closer (i.e., on an hourly basis instead of a quarterly basis), virtually all of the increased readings occurred between the hours of approximately 10:00 p.m. and 10:00 a.m. These increased readings tended to occur simultaneously across the site, including the background station. This supports a theory that at least the pylon monitors are reading precisely. However, in order to conclude that the pylon monitors are measuring accurately (with low bias as well as with high precision), they would have to be subjected to a quality assurance program that tested for a bias in the low range of 0.3 to 3 pCi/l and not the much higher concentration at which they are currently being calibrated.

6.1.3 The Original Modeling Effort

Estimates of the radon concentration at the nearest receptor were made based on the fluxes calculated using the ideal gas law for the month of August 1992, and on a long term basis for the maximum flux associated with the uncertainty due to the use of the ideal gas law. The computer code ISC2 Dispersion Models was used to remain consistent with previous estimates of the radon concentration in the environment for the compliance report.

Based on the results of the short term model, none of the average daily concentrations exceeded the 0.015 pCi/l removal action goal at any point. The monthly average predicted concentration was also well below 0.015 pCi/l at all locations modeled. These levels of radon cannot be compared to the measured radon concentrations due to the limitations of the detectors as discussed previously and the variability in background radon concentration. The applicability of this model to the K-65 silos can only be assessed in general qualitative terms.

The ideal gas law is accurate to within 1 percent at the temperature and pressures being assessed here. The majority of the releases are less than 1 percent total volume change, based on the measured temperature and pressure data. This tends to reduce the confidence in the use of the ideal gas law for predicting radon releases from the K-65 Silos. The reasonable upper bound of the release is a change of 1 percent of the total silo volume per measurement period (15 minutes). The flux is estimated based on the release of 1 percent (positive 1 percent change) of the total radon in the headspace followed by a period in which air enters the silo (negative 1 percent change). Under the current model this would result in the maximum release rate of radon to the atmosphere which could not be detected as a change in silo temperature or pressure.

The ISCLT2 code was used to estimate the radon concentration at AMS 5, AMS 6, AMS 7, and the nearest resident. The estimate was made using both pre-bentonite and post-bentonite headspace radon concentrations. The predicted radon concentration at these locations is shown in Table 2-11. The model prediction using the pre-bentonite data suggests an annual average radon concentration which should be detected. This does not correspond to the actual measured radon concentration at the site boundary locations. Model predictions using post-bentonite data show radon concentrations at all of the site boundary locations to be below the limits on the detectors capabilities and therefore not observed. Based on the pre-bentonite results the uncertainty in the model, considering a release of 1 percent of the silo headspace contents per period, indicates that is not appropriate for predicting radon concentrations for the purposes of attaining the performance goal of 0.015 pCi/l.

Field validation studies of atmospheric dispersion models have shown that estimates of model uncertainty are largely inadequate, particularly in the model's ability to quantify the representative nature of data and the non-homogeneous and stochastic nature of atmospheric dispersion which are not handled in the models. Studies have shown that predicted (resulting from applying the Gaussian Plume Model) locations of maximum concentrations may not correspond with the actual location of the maximum concentrations. ISC nor any other dispersion model has been field validated for the FEMP site. Any results of these models are thus suspect. Validation of the ISC model was not possible given the existing data. There have been no controlled studies of the dispersion of airborne particles at the FEMP.

The largest source of potential error in the environmental radon concentration estimates is the release rate of radon to the environment. Not all of the mechanisms of release are fully known and thus an accurate release determination is not possible. In addition, the predicted radon concentrations at the AMS locations are so low that the detector could not accurately measure to these levels (See Sections 2, 3, and 5).

The ideal gas law is not considered appropriate for predicting releases of less than 1% of the volume of the headspace. Over 99% of the releases during the intervals were less than a 1% change in the overall contents of the silos. The conclusion is therefore that the original model is not appropriate for determining compliance with the 0.015 pCi/l value due to the unknown confidence in the use of the gaussian plume model at the site. This model should only be used if the results are used as a screening technique where results, with tight constraints on the accuracy and precision, are not essential.

6.2 Degree of Bentonite Effectiveness

6.2.1 Headspace Analysis

The headspace analysis results indicate that the radon headspace concentrations from July to September 1992, are statistically lower than the pre-bentonite reading for each silo. The decrease in Silo 1 was from 25,000,00 pCi/l to a mean value 45,081 pCi/l (based on daily averages) while Silo 2 concentration decrease was from 30,000,000 pCi/l to a mean value of 219,585 pCi/l. The largest radon concentrations, and therefore the smallest percentage reduction, was found to be associated with a maximum daily average on the order of 320,000 pCi/l in Silo 2. This correlates to a 98.9% effectiveness rating. On the average the bentonite in Silo 2 is better than 99.2% effective and the bentonite in Silo 1 is better than 99.8% effective in reducing radon concentrations in the headspace.

A positive linear relationship is noted in the headspace concentrations among the two silos. The Pearson correlation coefficient among these data is 0.78, which is statistically different from zero at the 0.05 level. Therefore, daily changes in headspace concentrations tend to be relatively consistent among the two silos which indicates that a constant external source (external source in this case refers to a dependent factor not accounted for in the statistical evaluation) may affect changes in concentration within both silos. Since the variation in the observed values within the silo headspace is essentially constant the root effect on the ability to establish an upper bound is nearly zero (the variation can be accounted for and reliable predictions can be proposed).

The hourly average headspace concentration data was fitted to the model (Section 3, Equation 3-2) in a stepwise fashion to determine those meteorological variables which have a statistically significant association with the headspace data (statistical relationships are not to be confused with cause and effect relationships). At a 0.01 significance level, the following parameters were found to be statistically significant in association with hourly headspace concentrations: wind speed, outdoor temperature, and stability class. To adequately establish the stability class parameter detailed information on the wind speed, pressure, and the environmental lapse rate are required. This fact illustrates the non-linearity and overall dependence of the various aspects of the meteorology on the release and transport of radon in the environment.

Dew point and barometric pressure were as expected found to be statistically significantly associated with headspace concentration in Silo 1 at the 0.01 level. A somewhat surprising result was that this was not the case for Silo 2 or when both silos were considered together. These latter effects tend to be explained mathematically by examining the combination of the above three factors. Consider that the dew point and outdoor temperature are physically related to each other and thus would contribute similar information to the model. Only one of these two correlated parameters should be included in the model to reduce the potential of masked results. In a similar manner windspeed and barometric pressure are in the a physical sense inversely related to each other, therefore increasing the potential for the results to be masked.

In both silos, a statistically negative effect was observed when the headspace concentration was evaluated with the wind speed. The statistical result indicates that increases in the wind speed were associated with decreases in the headspace concentration. A positive effect was observed on the headspace concentration by dew point, outdoor temperature, and stability class. These are statistical results and therefore can not be inferred as establishing a cause and effect relationship. These results actually only show that there is reason to suspect that a relationship exists between the headspace concentration and the meteorological variables or that there are dependent factors that are not accounted for in the model. The latter case is the most realistic since similar relationships exist at the background location where the source is assumed to be infinite in extent, thus eliminating the suspicion for the same relationship.

6.2.2 Comparison of Actual Daily Average Radon Concentration Levels between Pre- and Post-Bentonite Periods at Each Monitoring Station

Based on the Pylon data, all four exclusion fence locations and AMS 5 pre-bentonite had statistically greater radon concentrations at alpha equals 0.05 than post-bentonite radon concentrations. A statistical difference between AMS 6 and AMS 7 pre- to post-bentonite was not observed (however there was a net decrease in the absolute magnitude of the observed radon concentrations). The only reasonable hypothesis is that at these distances the influences, directly related to the K-65 Silos radon releases, are not significant (statistically or in absolute magnitude). In addition, Subsection 5.1 addresses other potential biases which could effect radon concentrations measured at monitoring stations away from the silos.

Based on the Terradex cup quarterly data, the pre-bentonite mean was determined to be statistically greater than the post-bentonite constant at the 5 percent level of significance at the silo domes and at the exclusion fence line. The largest p value was 0.0029, which was associated with Silo 2 at the Southeast corner. These results tend to contradict the results from the pylon data.

Visual and statistical comparison of the terradex cup data to pylon data suggests that the pylons are reading with a high level of precision. There is still considerable uncertainty associated with the absolute accuracy, particularly at the low concentrations observed at the site boundary. The net result is that the combined data and results tend to suggest that there is little if any measurable impact from the silos on the radon measurements at the site boundary. The closer the monitoring location is to the silo the greater the ability to get high levels of precision and accuracy (and therefore confidence). The conclusion is then measure the source and perform the applicable and appropriate evaluations based on observed values that can be sufficiently quantified.

6.2.3 Comparison of Time Series Average Radon Concentration Levels between Pre- and Post-Bentonite Periods at Each Monitoring Station

The overwhelming conclusion from the time series Radon concentrations is that daily average radon concentration at the four stations along the exclusion fence are statistically significantly lowered in the post-bentonite year compared to the pre-bentonite year. This reduction is highly statistically significant for these stations. For the fence line stations, we can not conclude that a reduction in radon concentrations occurred. The reason for this conclusion was stated previously.

The plots in Attachment G show the extreme difference in behavior of the daily average concentrations for the exclusion fence stations in the post-bentonite period. The seasonality trend is not as apparent in the exclusion fence readings. Differences in concentrations compared along the boundary are more likely in certain times of the year. Tables 3-6 and 3-7 present a summary of the time of year when minimum predicted concentrations are observed at each station for pre- and post-bentonite periods, respectively. Tables 3-8 and 3-9 present a summary of the time of year when maximum predicted concentrations are observed at each station for pre- and post-bentonite periods, respectively. The boundary monitors tend to observe maximum concentration in warmer months and minimum concentration in cooler months. The predicted maximum concentration among the boundary stations remains higher than the predicted maximum concentration for the background station, even in the post-bentonite period. Meanwhile, for exclusion fence monitors, the predicted maximum concentration in the post-bentonite period is consistently lower than the predicted minimum concentration in the pre-bentonite period.

Although bentonite addition has resulted in an observed radon concentration reduction overall, differences in the observed results between pre- and post-bentonite periods cannot be attributed solely to the effect of adding bentonite. Yearly effects (i.e., yearly changes in meteorological conditions, etc.), as well as effects due to differences in instrumentation, also contribute to the observed differences within a monitoring station.

6.2.4 Gamma Dose Rate Analysis

The dose rate at the silo dome was modeled using Microshield 4.0. The distribution of radon and its daughter products in the headspace are expected to significantly affect the results. The use of an average bentonite thickness introduces uncertainties in the model results due to the exponential dependence of the dose rate to the shield thickness. The fact remains however that there was a significant (magnitude) reduction in the dose rates measured at the top of the domes after the bentonite was installed. Pre-bentonite dose rates were observed to range from 150 to 250 mR/hr (the dose rates were also observed to increase after the foaming in 1987 indicating greater quantities of radon were being retained in each of the silo's headspace). Dose rate readings after bentonite have been reduced to levels ranging from 3 to 10 mR/hr, which in general corresponds to reductions over 90%.

The uncertainty in the dose rate model and the marginal correlation of radon concentration to dose rates, the measured dose rate will only provide a rough estimate of the radon concentration in the silo headspace. The dose rate measurements on the silo dome are not likely to respond to changes in the radon concentration unless the change was significant (i.e., more than an order of magnitude or greater than 1,000,000 pCi/l). The dose rate may be possible to use as an indicator of catastrophic failure of 10 bentonite and concentrations of radon in the headspace of more than 1,000,000 pCi/l.

TLDs measurements are available at the site fence line, (AMS 5, AMS 6, and AMS 7) and four background locations. TLD data was available at the fence line and background locations since 1989 and at all locations except background locations 3 and 4 which began in 1990. A qualitative comparison of the means of these data was made and presented in Subsection 3.3.2. The TLD data would indicate a significant reduction in the dose rate at AMS 6 following the addition of bentonite with no obvious effect observed at the other locations. The dose rate at AMS 6 was an average of 12.4 microR/hour in 1991 and is currently 8.3 microR/hour in 1992. The other locations of the TLDs reported dose rates from 6.3 to 7.6 microR/hour in 1991 and from 5.6 to 7.7 in 1992. The TLD data would seem to indicate that the dose rate has been reduced at locations close to the K-65 silos (within 380 meters). No conclusions can be inferred from the data for locations at a greater distance than this from the silos. This is consistent with the exponential reduction in gamma dose with distance from the source (these locations are outside the range of influence from the silos).

6.3 Monitoring Criteria

The lack of physical, scientific, or statistically adequate methods to demonstrate compliance with the 0.015 pCi/l radon concentration at the nearest resident renders the criteria useless. In lieu of attempting to predict exposure and off-site concentration a more reliable and easily represented monitoring regimen is proposed to determine the effectiveness of the bentonite in reducing the radon emendation and release. The proposed recommendation is to monitor the headspace radon concentration directly. The effectiveness can be determined based on a comparison of the measured concentration to prediction intervals and tolerance limits.

The prediction interval is used to determine if the current radon concentration comes from the same distribution of radon concentrations measured since July, 20, 1992. This data is used to estimate the prediction interval as described in Section 4.3 and provides for the expectation value for future observations. The upper limit on the prediction interval for Silo 1 is 108,000 pCi/l and for Silo 2 is 355,000 pCi/l. Since the data used to construct this prediction interval is based on the daily average headspace concentration single grab sample results are not sufficient alone to compare to the prediction interval. The prediction interval would be applied by using the continuous pylon data over a single day and use the calculated mean for that day as the future observation in the comparison.

The tolerance interval is used to set the upper bound on the radon concentration in the headspace. The tolerance limit was determined by estimating the lowest possible radon concentration in the headspace that would likely exceed the removal action goal of 0.015 pCi/l at the nearest resident. This process was explained in detail in Section 4.2. The result and conclusion reached was that the radon concentration in the headspace of both silos could reach 4 x 10^6 pCi/l and the contribution to the nearest resident would be less than 0.015 pCi/l above background.

A detailed procedure for sampling the silo headspace along with a method for determining bentonite effectiveness has been developed and is currently in the review and approval stage. The procedure has been developed in accordance with the Site-Wide CERCLA Quality Assurance Project Plan (SCQ). The following are recommendations related to monitoring criteria for determining the effectiveness of the bentonite:

1) Perform both continuous and grab samples from the headspace of each silo until it can be determined that the samples from each method are obtained from the same distribution.

2) Following the collection of a significant number of grab samples the prediction interval would be reevaluated.

3) Grab samples would be collected on a weekly basis for comparison to the prediction intervals and the tolerance limit.

If a weekly sample exceeds the prediction interval, daily grab samples should be collected, to assess any trends, for a period of not less than one week or until consecutive daily samples are within the prediction interval. During the daily sampling period, assessment of the bentonite effectiveness should be made with regard to any trends in increased concentration in the headspace which might show a gradual degradation of the bentonite performance. If a grab sample exceeds the tolerance limit, immediate actions would be taken to assess the bentonite integrity. Actions will include at a minimum resampling of the headspace to confirm the observation.

6.4 Summary

The statistical analyses presented in this study were based on available data at the site boundary, silo exclusion fence, four off-site locations, five locations within the site, and within the silo headspace (both Silo 1 and Silo 2). This summary addresses the types of findings presented throughout the report. These include the large differences, between pre- and post-bentonite conditions, in measured headspace radon concentration compared to the much smaller changes as the distance from the silos is increased. The effect of the location taken as representative of background on the statistical analysis resulted in the consideration of the appropriateness of the overall comparison to "background". The basic conclusion drawn from the data, statistical results (conflicting information), and the nature of the radon emendation and release is that the absolute cause and effect relationship (between site boundary observations and the K-65 Silo contribution) can not be established. The true cause and effect mechanisms can not be established since there is no statistical means available to extract or separate the unknown contributors and thus reduce the overall error. The following elements summarize the results of this study:

1) There are statistically significant changes in the radon concentration in the head-space between pre- and post-bentonite conditions. The variation in observed values is due to errors inherent in making observations and due to meteorological conditions. The variability can not be reduced and is consistent with the variability in the data sets at low concentrations found at the site boundary and at the background location. The percent decrease in silo headspace radon concentration is at a minimum 98.9% (Silo 2 worst case based on a maximum daily average of 320,000 pCi/l) and on the average better than a 99.2% for Silo 2 and 99.8% for Silo 1. The variability in the radon concentration in the headspace can be reflected in the percent effective range. Considering the average daily measurements and taking into account the maximum and minimum observed values the effective range in percent, for Silo 1, is 99.96% > effective reduction > 99.59%.

2) There are also statistically significant differences in the observed radon concentration at the exclusion fence for the comparison of pre- to post-bentonite conditions. The decrease, although not as great in magnitude as the headspace, the results are consistent with the reduction in concentration over distances (seen also in the dose rate measurements). There are also significant indications that less radon has or is escaping from the silos than previously thought.

3) There is a lack of statistically significant differences at the site boundary than would be anticipated if the silos were major contributors to off-site radon concentrations. Statistically there is little of no difference at AMS 6 while there is small decreases evident when daily averages are evaluated. Contradictory results when evaluating terradex versus pylon data are indicative of the inability to establish high confidence in the actual contribution from the K-65 Silos. The background location was found to exhibit the same trends and relationships thereby indicating that the true background for the FEMP may actually be greater than that observed at the Westwood location. The absolute difference in the background versus site boundary values is very small on the order of 0.15 pCi/l, while the detection limits are on the order of 1 pCi/l. The AMS 6 and 7 locations show almost no change from pre- to post-bentonite, again indicating the inability to observe changes on such a small scale. Also this result indicates there is reason to believe that the number and nature of factors which influence radon release and transport can not be identified and modeled at the confidence levels indicated by the 0.015 pCi/l performance goal.

4) Results show overwhelmingly that the determination of whether the 0.015 goal has been achieved can not be established statistically or mathematically within an appropriate confidence level. Compliance with 40 CFR 192, however can be established and verified even when considering the location used as background. This requires no greater than 0.5 pCi/l contribution at the edge of the waste unit (in this case considered the site boundary). Statistically and mathematically the observed radon concentrations are all found to be less than 0.5 pCi/l (as required by 40 CFR 192) above what is considered ambient background at the FEMP. The criteria of 0.5 pCi/l above background is also within the variability of all the site boundary monitors and the background location.

5) The radon concentration in the headspace can be determined with high confidence levels and with the use of a statistical method, typically applied to RCRA groundwater wells, an upper limit on the expected radon concentration in the headspace that could be considered part of the observed distribution was developed. The method utilized to establish both the bentonite effectiveness and any trends, that may be used to indicate potential difficulties, is the Prediction Interval . The upper limit for the headspace radon concentration for each silo, obtained from the prediction interval (based on daily averages), is 108,000 pCi/l for Silo 1 and 355,000 pCi/l for Silo 2.

Based on the results predicted using the Gaussian Plume model (shown in Figure 4-1 repeated here for clarity), the tolerance limit on the radon concentration in each silo is determined. The tolerance limit is the radon concentration which if exceeded would indicate that the performance goal, 0.015 pCi/l limit at the nearest receptor, was exceeded. Figure 4-1 is in effect the tolerance limit for the headspace radon concentration. For the purposes of ease of use the tolerance limit for each silo will be set at 4.0 x 10^6 pCi/l. This value would not be expected to result in an off-site radon concentration greater than 0.015 pCi/l on a long term average basis, but can be considered to indicate potential bentonite degradation.

If the average radon in either silo exceeds 1.0E6 pCi/l it can be assumed that the bentonite is beginning to show signs of deterioration and the condition should be assessed and addressed before any additional deterioration occurs.

The modeling procedure addresses predicting radon concentrations at the monitoring stations as a function of silo headspace concentration and meteorological variables. The effects of some meteorological variables on the concentration were found to be highly significant at both the monitoring stations and at the silos. These variables include wind speed and outdoor temperature. However, wind direction was not found to be statistically associated with concentration levels at any of the monitoring stations. This latter result implies that there are other unknown factors that inhibit the ability to observe a connection between radon levels the possible source and the wind direction. The physical reality of the situation still exists that if the dominant source of the radon, observed at the monitors, is the K-65 Silos then there is a dependence on wind direction. This is particularly true when the monitors are located over 300 meters away. The inability to establish a statistical relationship between the wind direction and the radon concentration indicates the existence of dependent factors that have been unaccounted for.

When silo headspace concentration was directly incorporated in the models, mixed results were seen across the monitoring stations. The relationship of headspace concentration on the observed radon levels at the monitoring stations was found to be occasionally significant at the 0.05 significance level. The physical cause and effect relationship with silo headspace concentration can not be established as a result of this statistical correlation. The statistical significance of this relationship indicates that there are other factors, probably meteorological in nature and not considered in the model, responsible for the apparent connection between radon concentration in the silo headspace with the observed values at the monitoring stations.

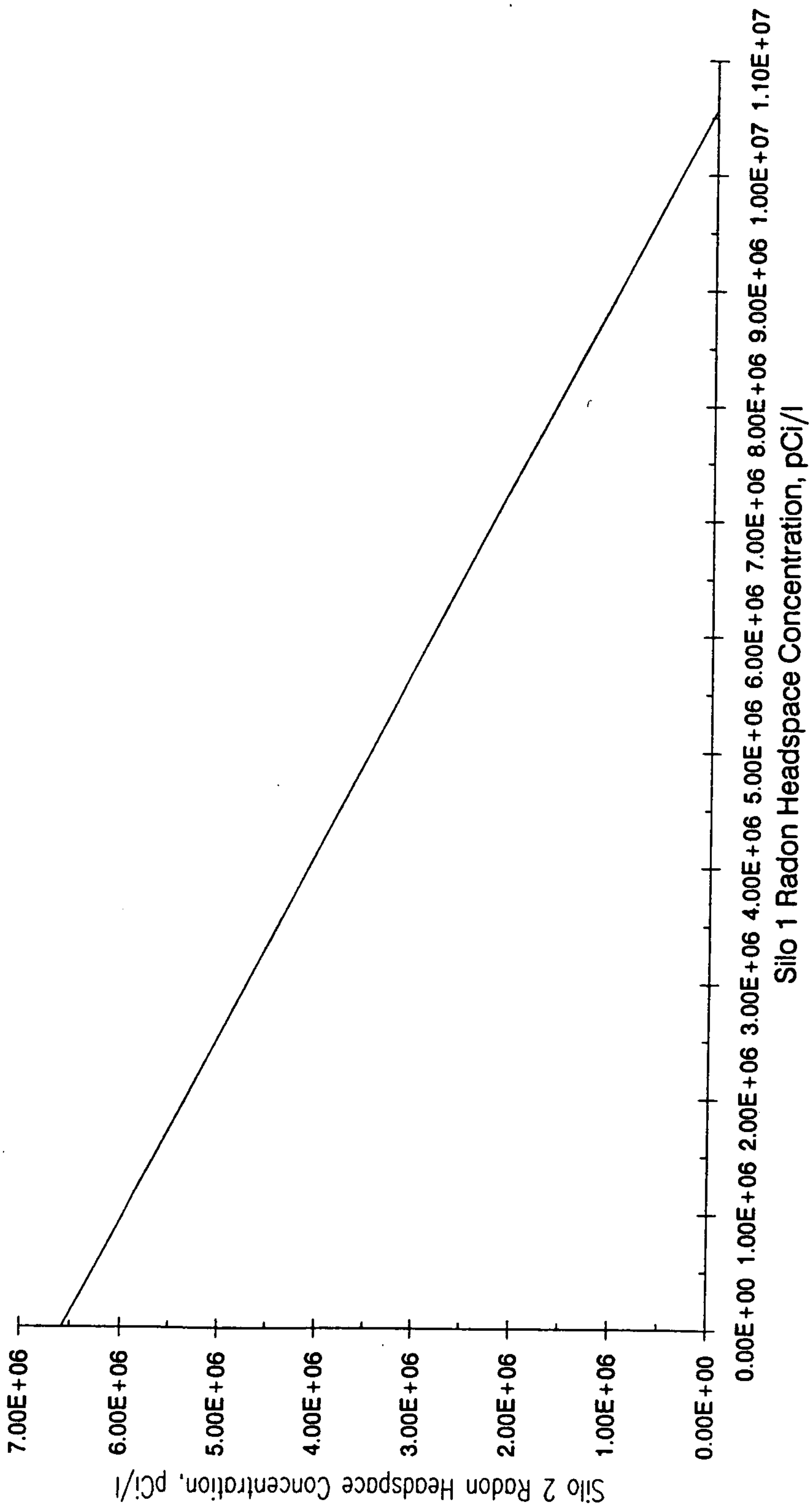


Figure 4-1. Radon Concentration in Silo Headspace Required to Exceed 0.015 pCi/l at Nearest Resident

Barometric pressure is known to effect the radon release rate from soil. This factor is affecting all of the monitoring stations simultaneously and it can not be guaranteed that the affect is the same at all the locations (recall the release of radon from a solid matrix is dependent on soil characteristics, moisture content, average concentration of radium, and the actual source location among others). The barometric pressure measurements used in this study were at a confidence such that the statistical model showed no significant contribution. This is an illustration of the physical world inhibiting the level of certainty that is available in any statistical analysis.

Fitting Model 1 to the radon concentration data collected over the 8-week period resulted in relatively large prediction intervals for the monitoring station concentrations based on the measured radon levels in the silo headspace. The statistical evidence shows that the predicted concentrations at the monitoring stations are not statistically significantly different from those predictions at the background station. Thus the relatively large variability present in the data prevents differences, that would correspond to the performance goal of 0.015 pCi/l, from background from being observed.

7.0 References

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ATTACHMENT A

LOWER LIMIT OF DETECTION AND MINIMUM DETECTABLE ACTIVITY FOR REAL-TIME PYLON MONITORING DATA

The data used in this bentonite effectiveness study was derived from a sampling program that was designed to demonstrate compliance with the requirements contained in Department of Energy (DOE) Order 5400.5, titled, "Radiation Protection of the Public and the Environment." These requirements contain radon concentration limits that are magnitudes higher than the threshold levels that are considered in this study (3.0 pCi/L gross radon concentrations at the facility fence-line vs. 0.015 pCi/L above background concentration at the residence nearest the K-65 silos). As a result of this, real-time radon monitoring instruments were selected that had a manufacturers detection level specification of 1 pCi/L. Manufacturers studies indicate that when the instruments are calibrated in the 100 pCi/l range the calibration curve is linear throughout the range including the 1 pCi/l range where observations are commonly recorded.

The data obtained from monitoring activities represented gross radon concentration data with no accounting for individual instrument electronic background. In addition not all data was taken with calibrated instruments during all monitoring times.

Approximately 100 times more data was utilized in the statistical analyses when considering the real-time monitor data as opposed to the alpha track-etch cup data. Therefore due to the relatively large sample size more precision is available in estimating the mean concentration at the monitoring locations using the real-time data as opposed to the alpha track-etch data. Furthermore, the triplicate alpha track-etch cup data at each location did not display the higher level of precision, which can be identified with the real-time monitor data as described below. The calculations of the Lower Limit of Detection (LLD) and Minimum Detectable Activity (MDA) for the real-time monitor data are presented below to present the argument that the level of 0.015 pCi/L concentration of radon above background cannot be determined post hoc using the best data we have available on a sample observation by observation basis.

The LLD is the smallest amount of sampled radioactivity that has a 95 percent probability of being detected, i.e., of being distinguished from background. It is calculated based on the following formulas:

LLD CALCULATION

Assumptions: 1. Alpha and beta values are at the same levels. Alpha equals the risk of falsely concluding that activity is present and beta equals the risk of falsely concluding that activity is not present.

2. Assume that the gross and background count rates have homogeneous variance.

Then

$$LLD = 2Z \times \sqrt{2} \times \sigma_{bg}$$

Therefore at the 95 percent confidence level

$$LLD = 2 \times 1.645 \times \sqrt{2} \times \sigma_{bg}$$

and

$$LLD = 4.65 \times \sigma_{bg}$$

So, for example, based on information obtained from the manufacturer the background of the instrument is 0.75 count per minute (cpm). Using a 60 minute count time the LLD equals:

$$4.65 \times \sqrt{\frac{0.75}{60}} = 0.52\ cpm$$

1.45 cpm = 1 pCi/L (based on the following formula provided by the manufacturer)

$$S = CPM - \frac{Bkg}{activity}$$

0.52 cpm = 0.36 pCi/L = LLD.

The Minimum Detectable Activity equals the amount of activity which, in the same counting times, gives a count that differs from background by three times the standard deviation of the background count. It is calculated based on the following formulas:

MINIMUM DETECTABLE ACTIVITY CALCULATION

So, for example, based on information obtained from the manufacturer the background of the instrument is 0.75 cpm. Using a 60 minute count time the LLD equals:

$$\sigma(countrate) = \sqrt{\frac{R_{bkg}}{t_{bkg}}}$$

$$MDA = 3\sqrt{\frac{R_{bkg}}{t_{bkg}}} = 0.34\ cpm$$

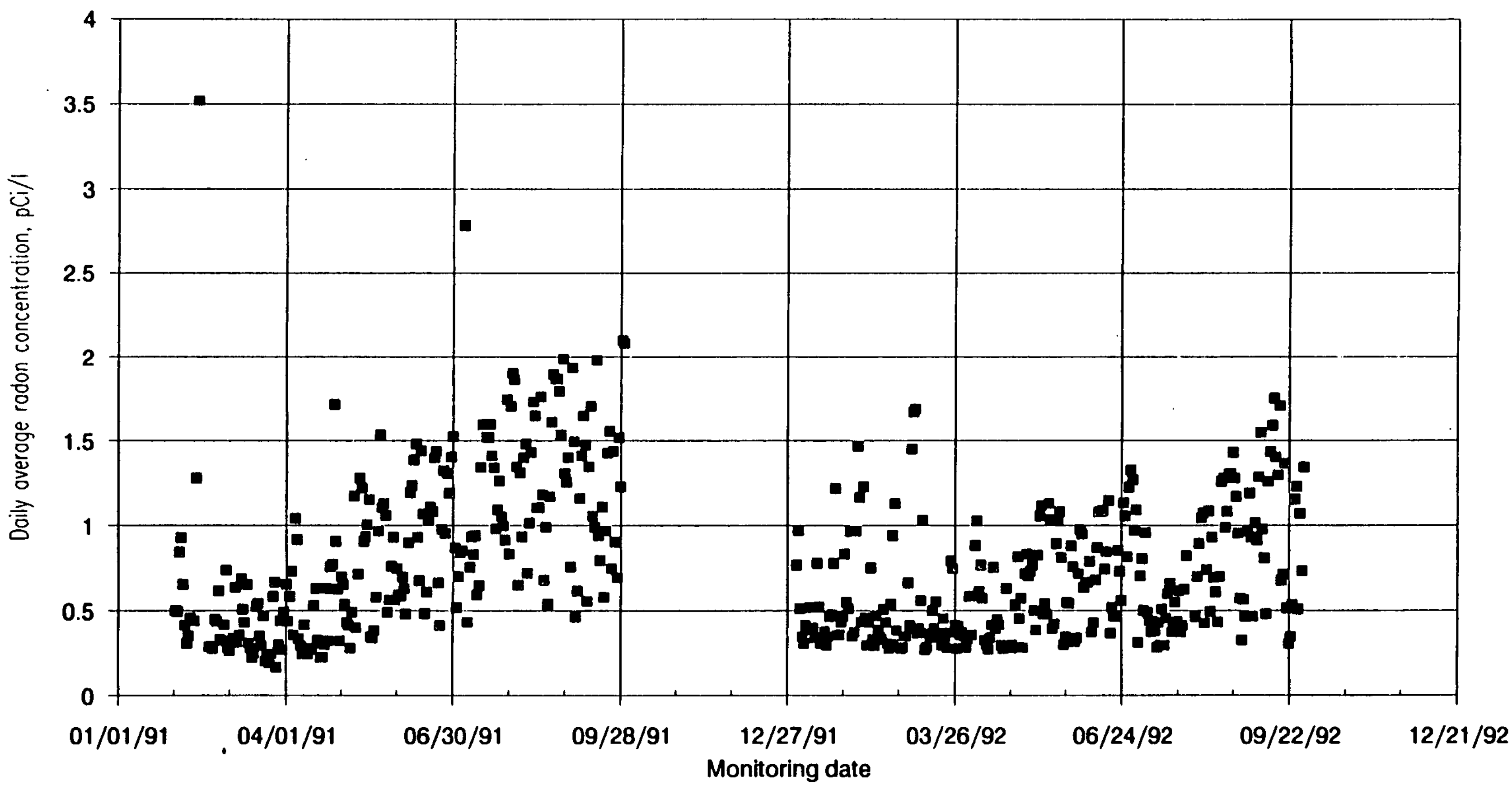
1.45 cpm = 1 pCi/L
0.34 cpm = 0.24 pCi/L = MDA

This means that real-time monitors are capable of accurately detecting radon concentrations of 0.36 pCi/L and greater.

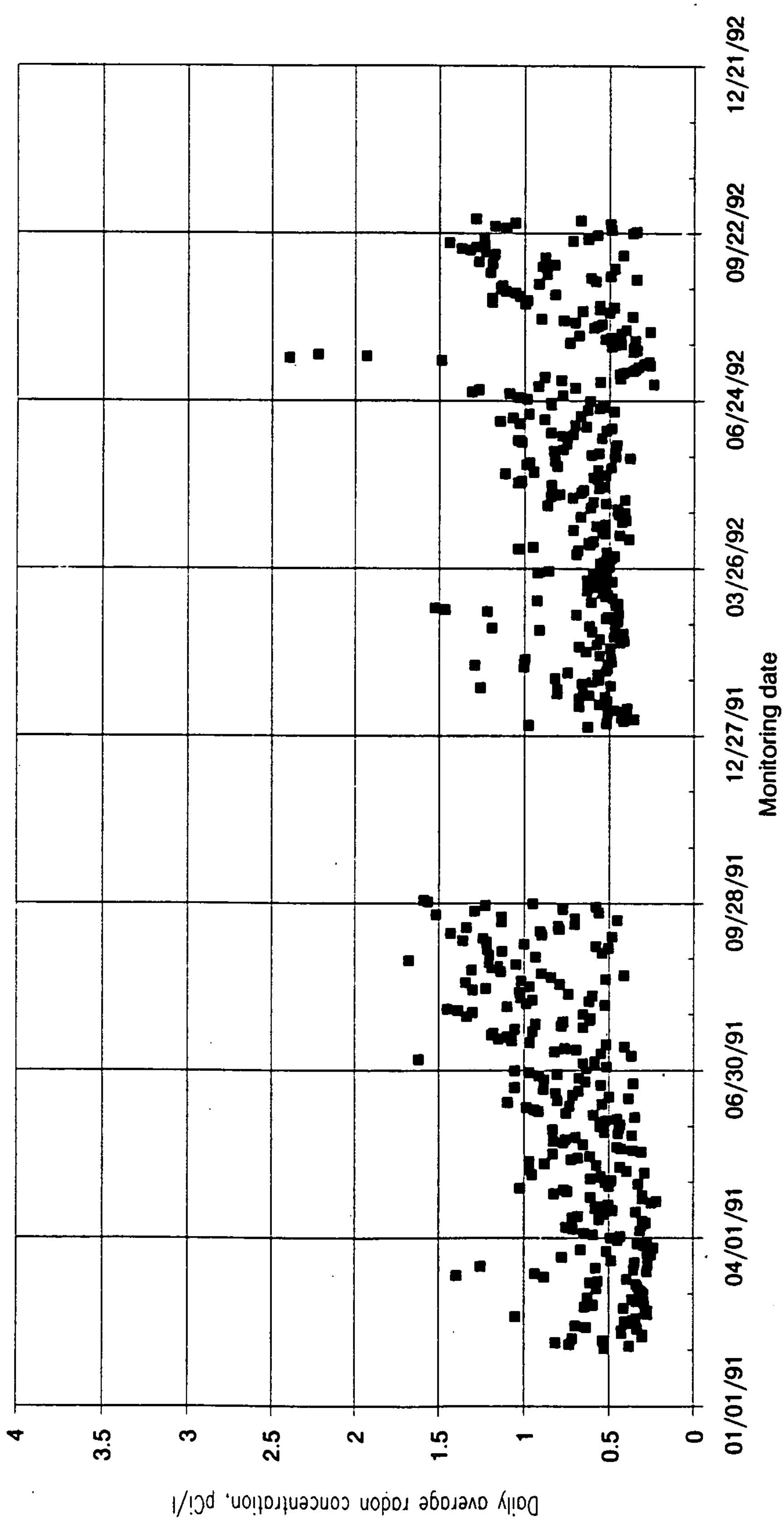
ATTACHMENT B

PLOT OF DAILY AVERAGE RADON CONCENTRATION VERSUS TIME AT EACH MONITORING STATION

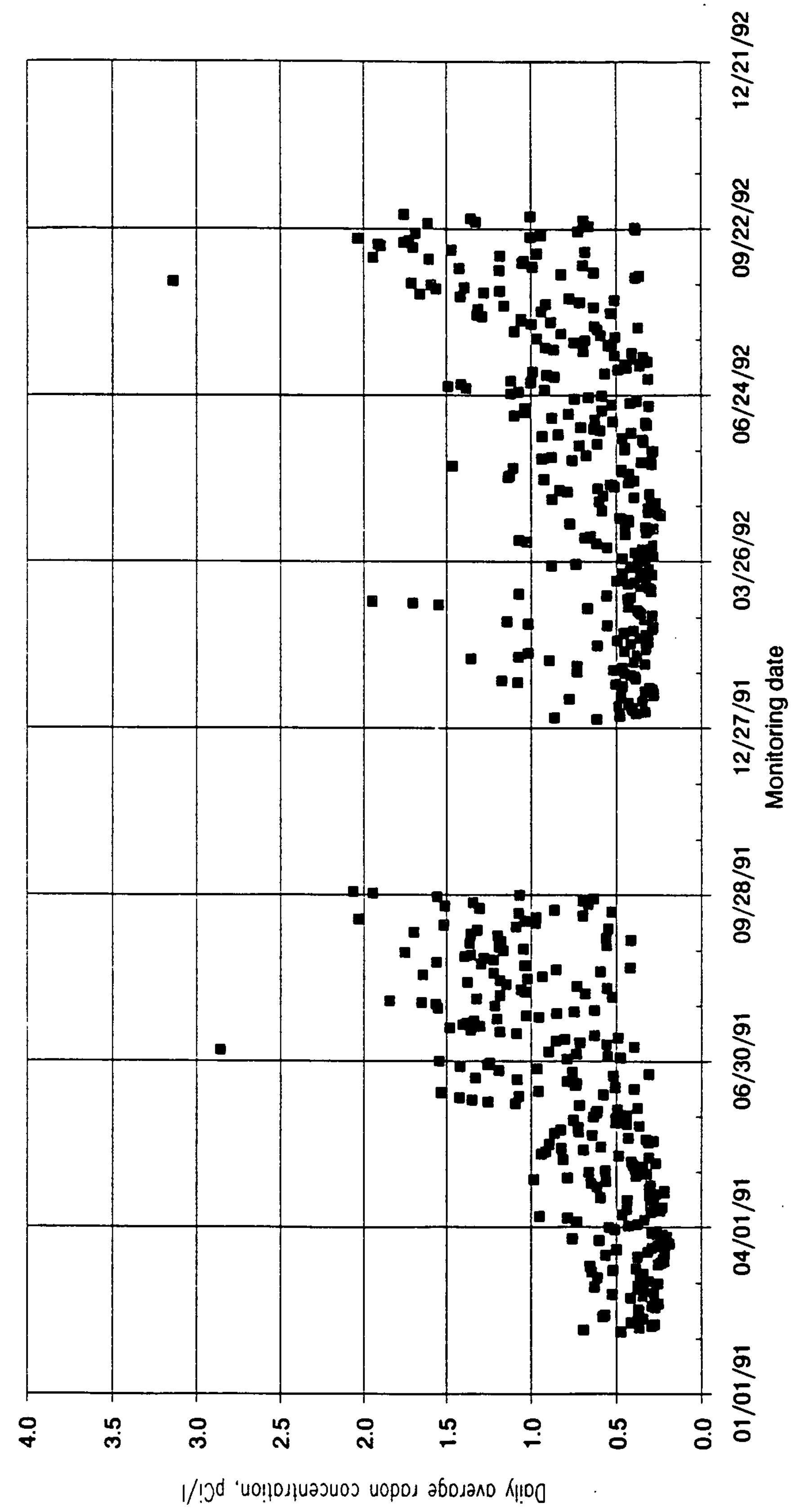
Plot of Daily Average Radon Concentrations Versus Time at AMS 5



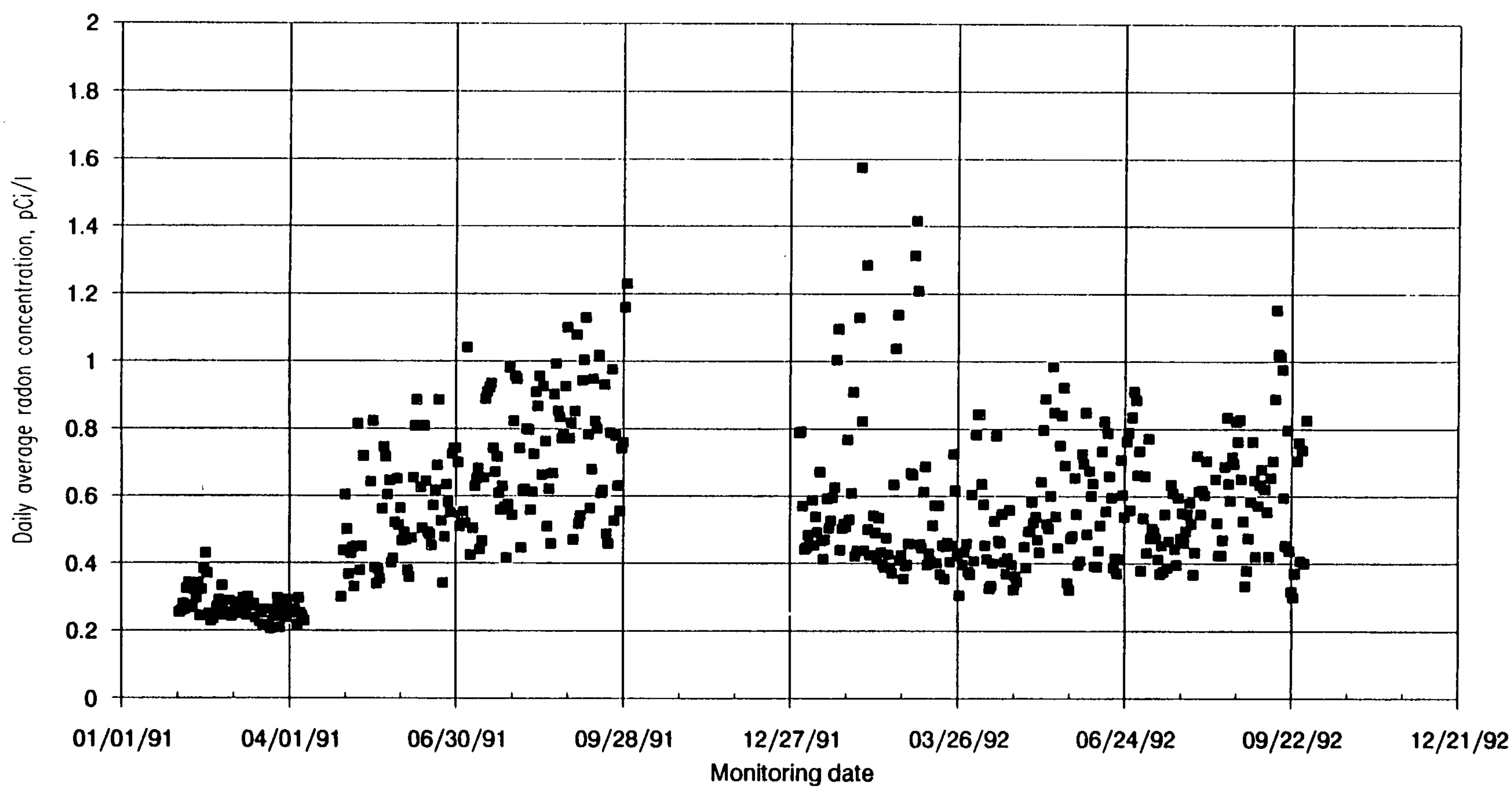
Plot of Daily Average Radon Concentrations Versus Time at AMS 6



Plot of Daily Average Radon Concentrations Versus Time at AMS 7



Plot of Daily Average Radon Concentrations Versus Time at the Background Station



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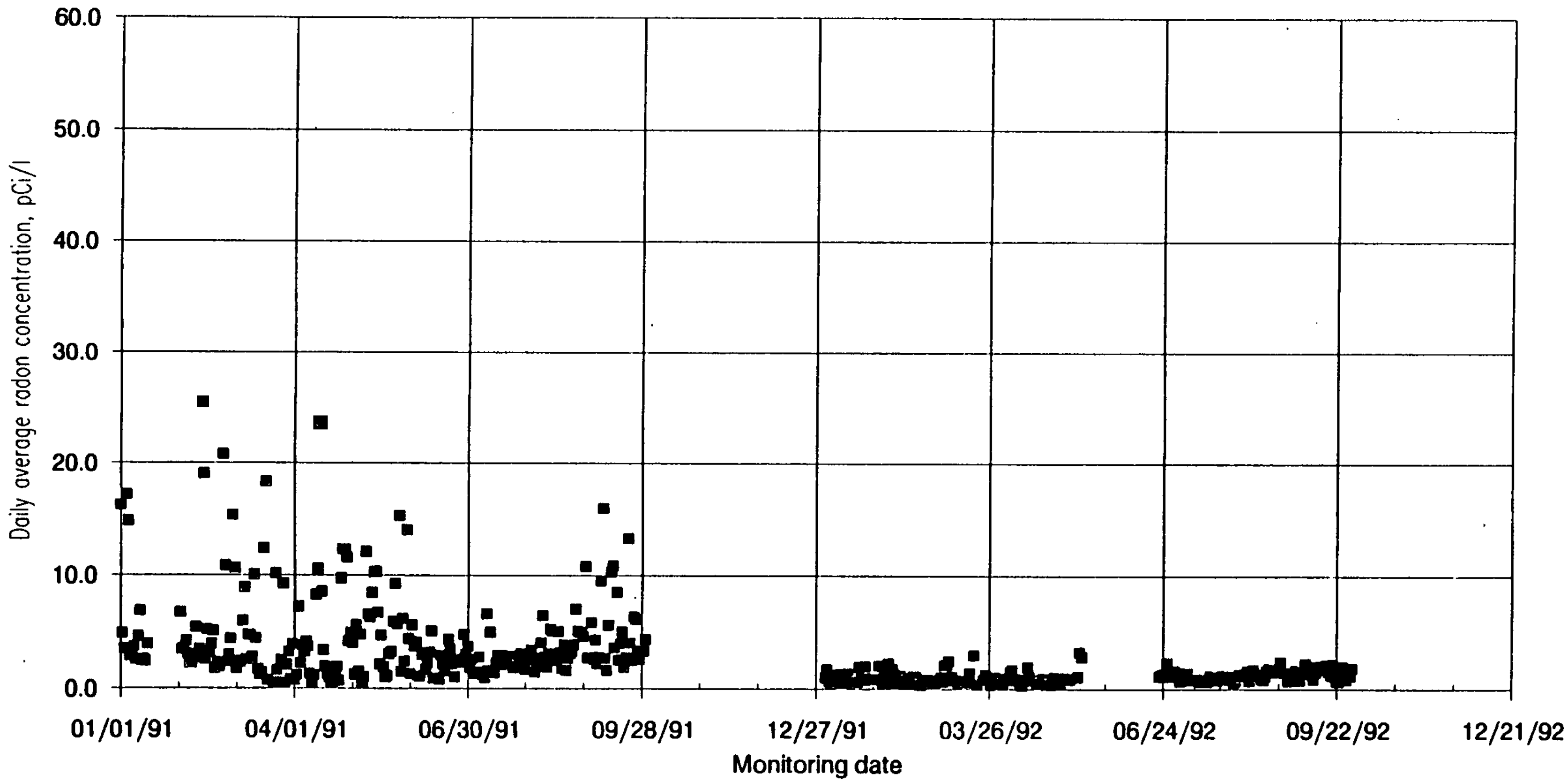
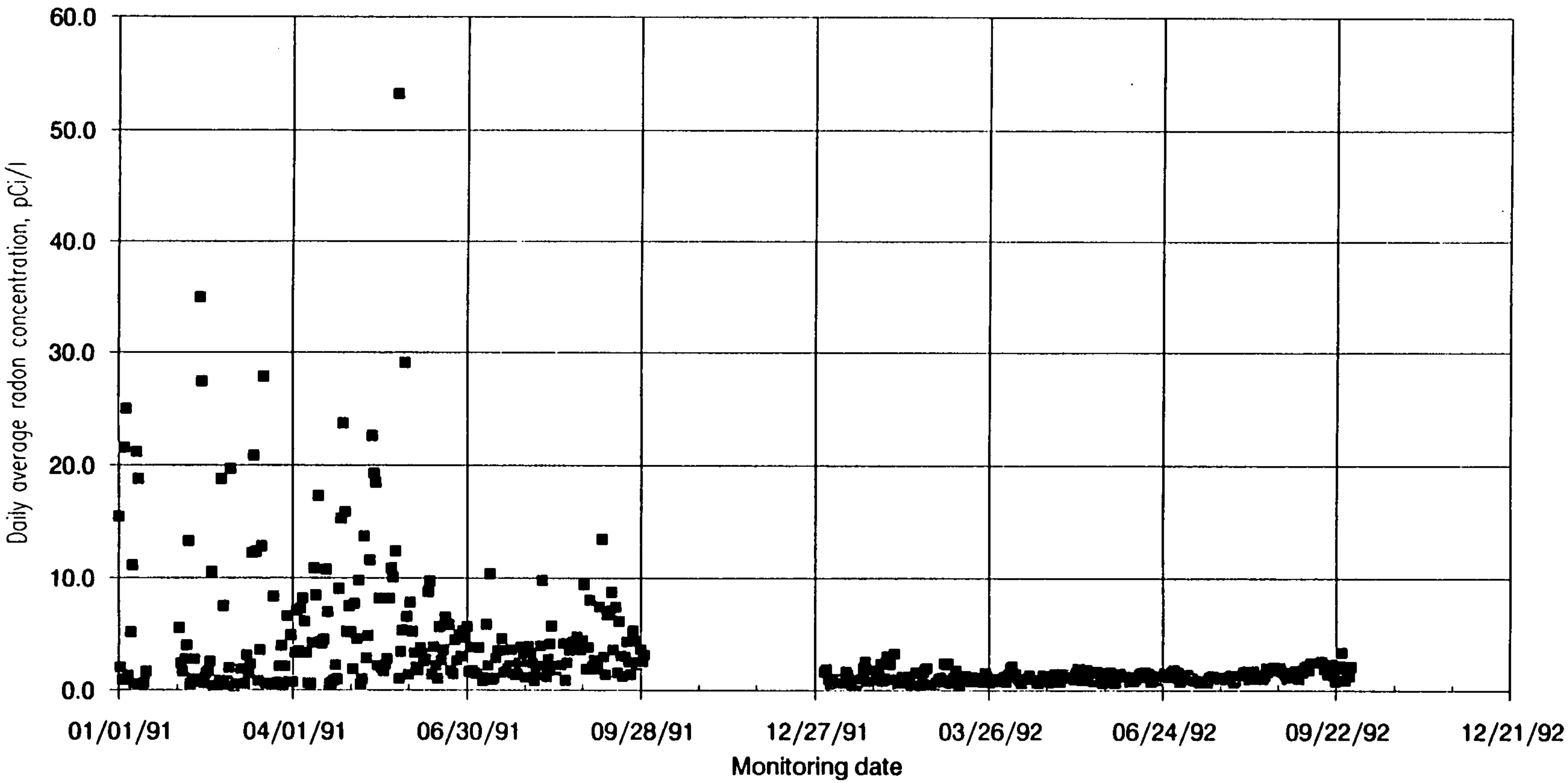
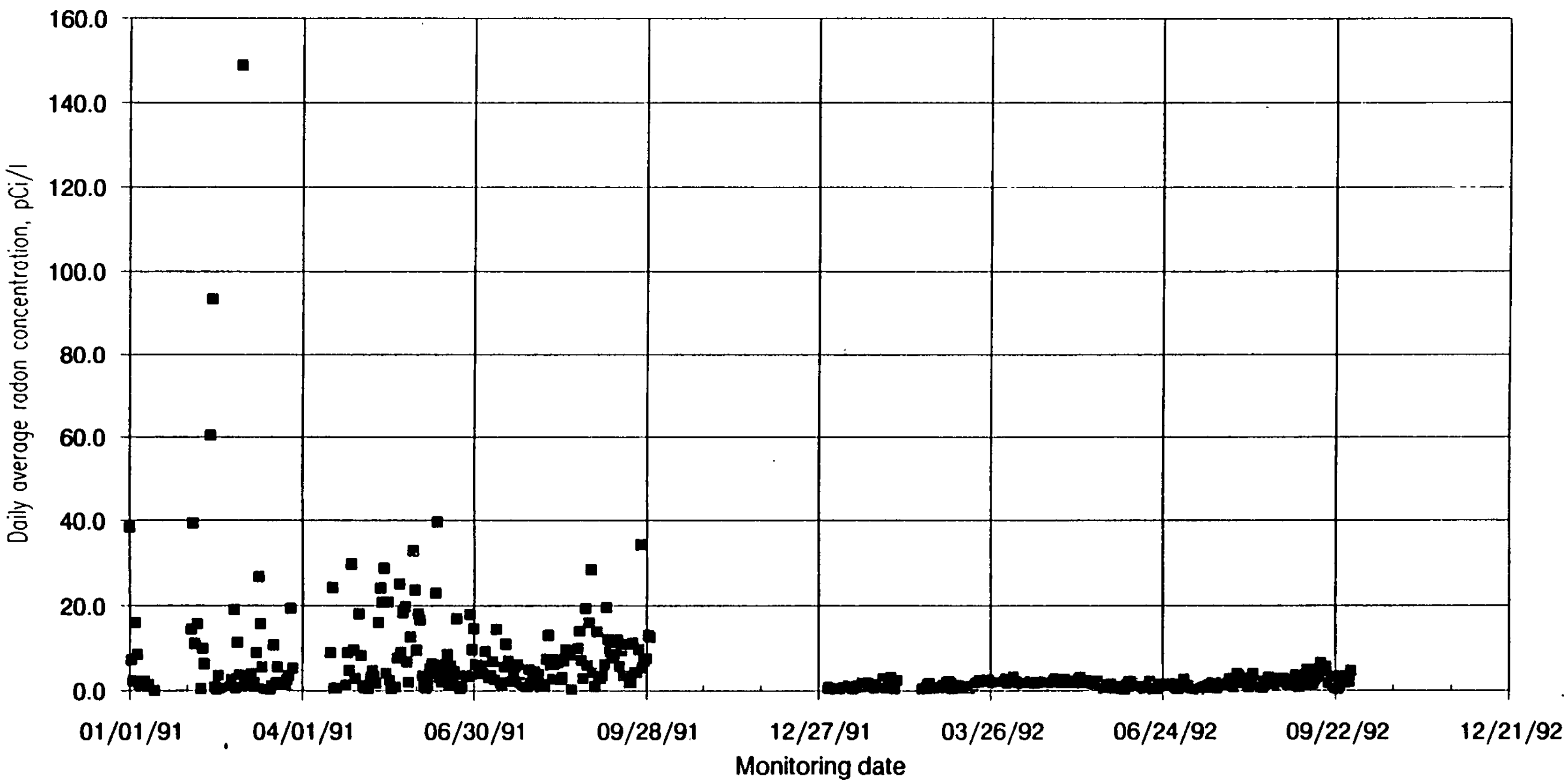
Plot of Daily Average Radon Concentrations Versus Time at the Exclusion Fence - Northwest



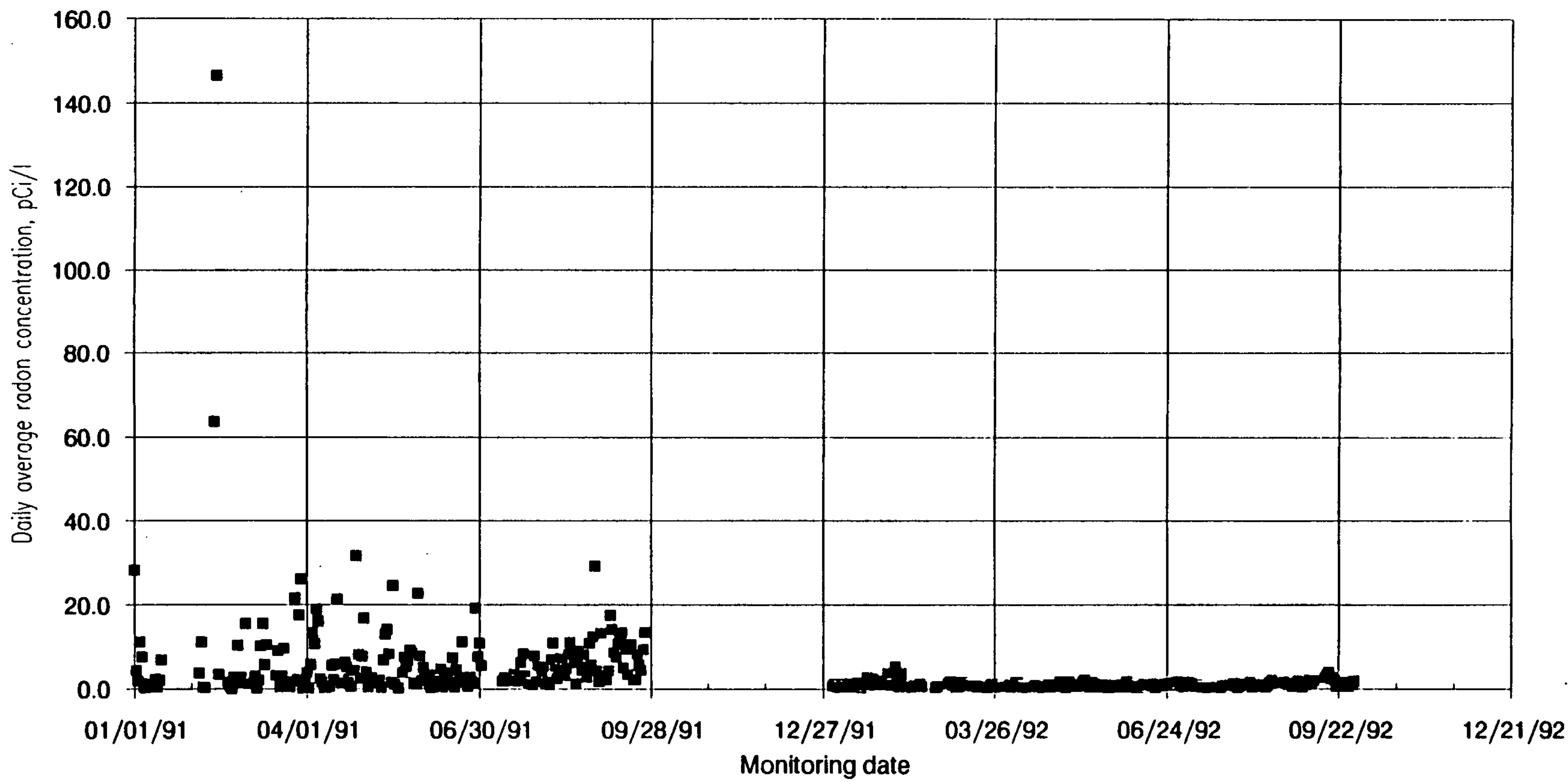
Plot of Daily Average Radon Concentrations Versus Time at the Exclusion Fence - Southwest



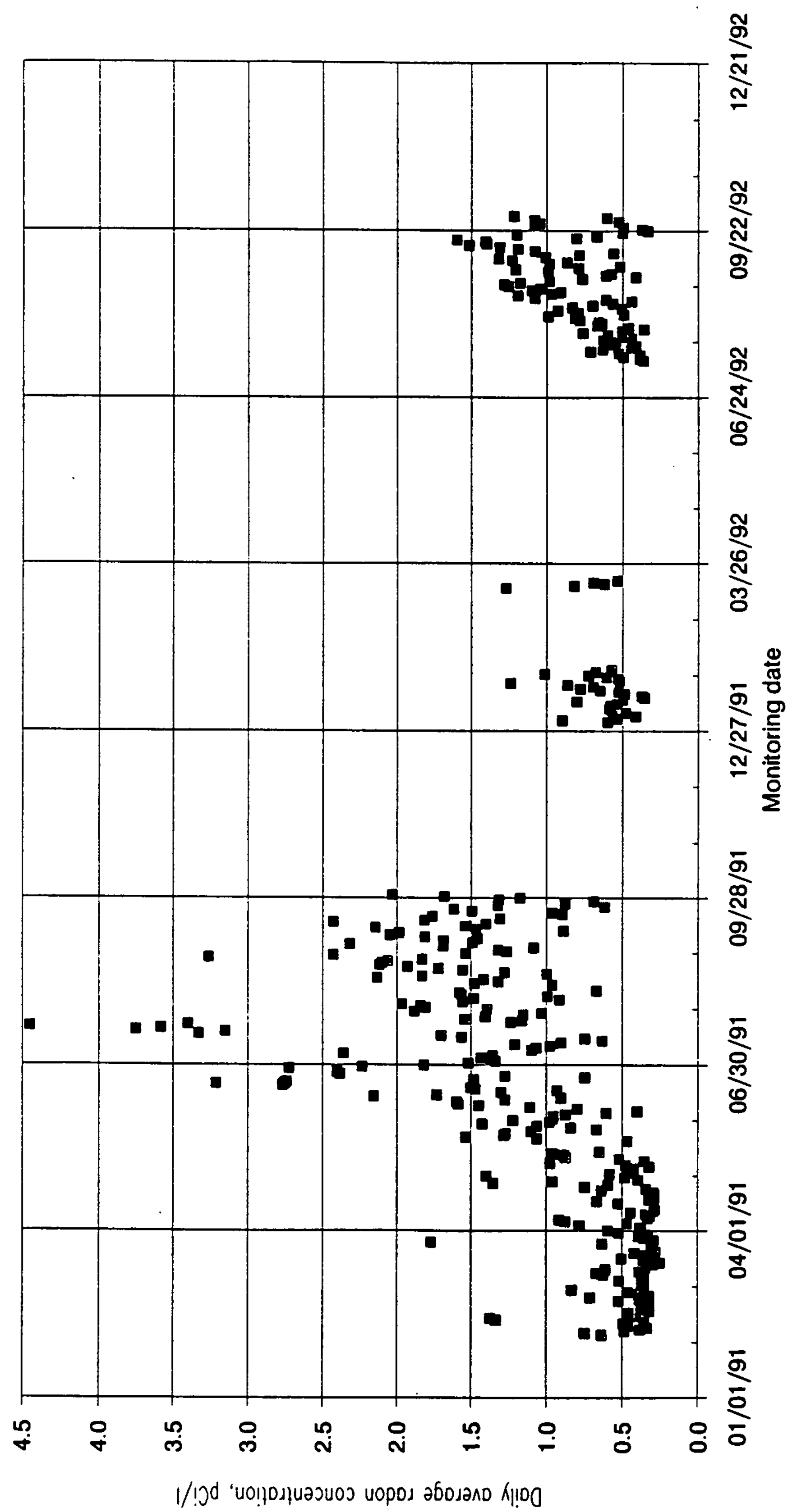
Plot of Daily Average Radon Concentrations Versus Time at the Exclusion Fence - Northeast



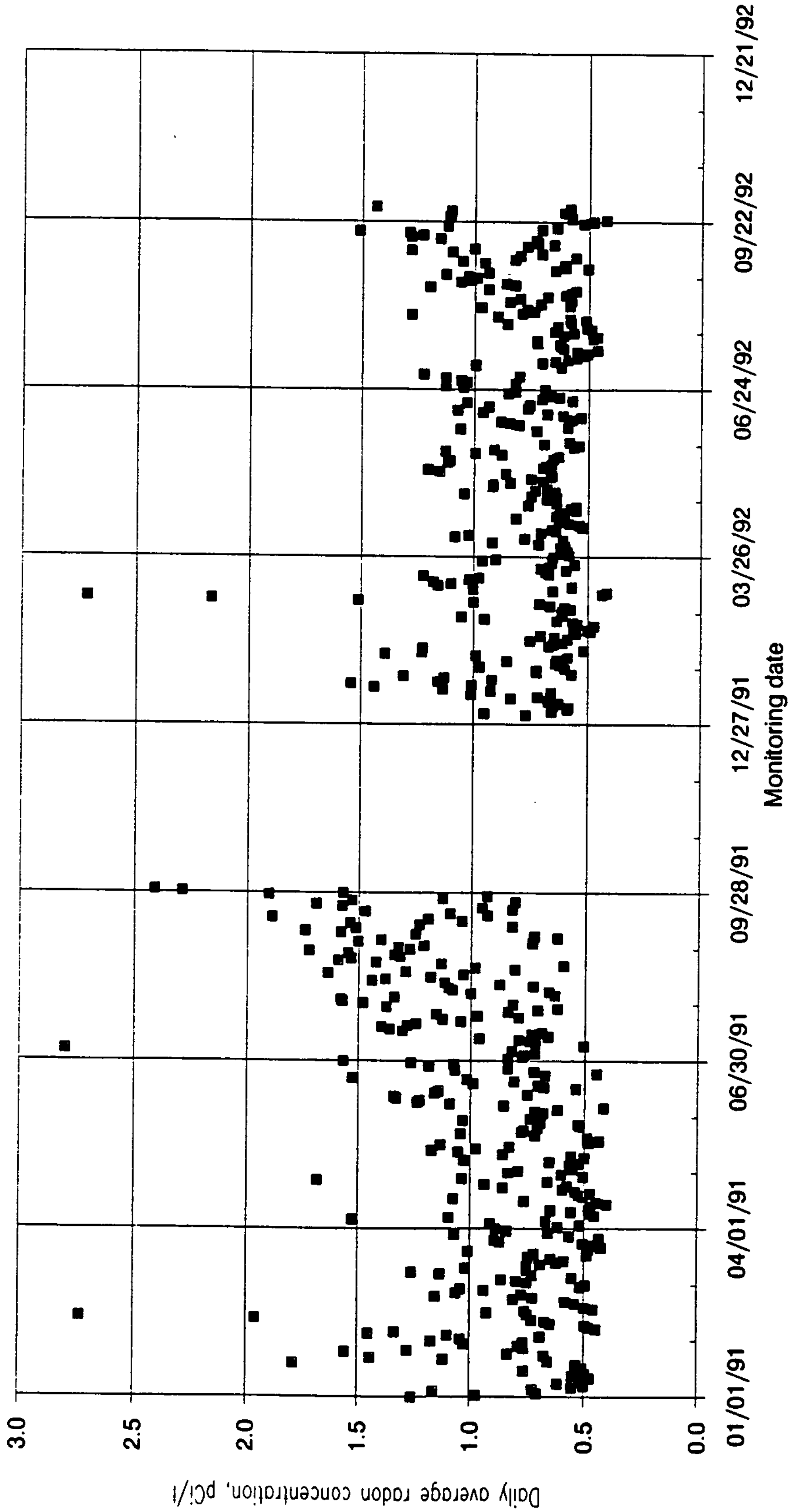
Plot of Daily Average Radon Concentrations Versus Time at the Exclusion Fence - Southeast



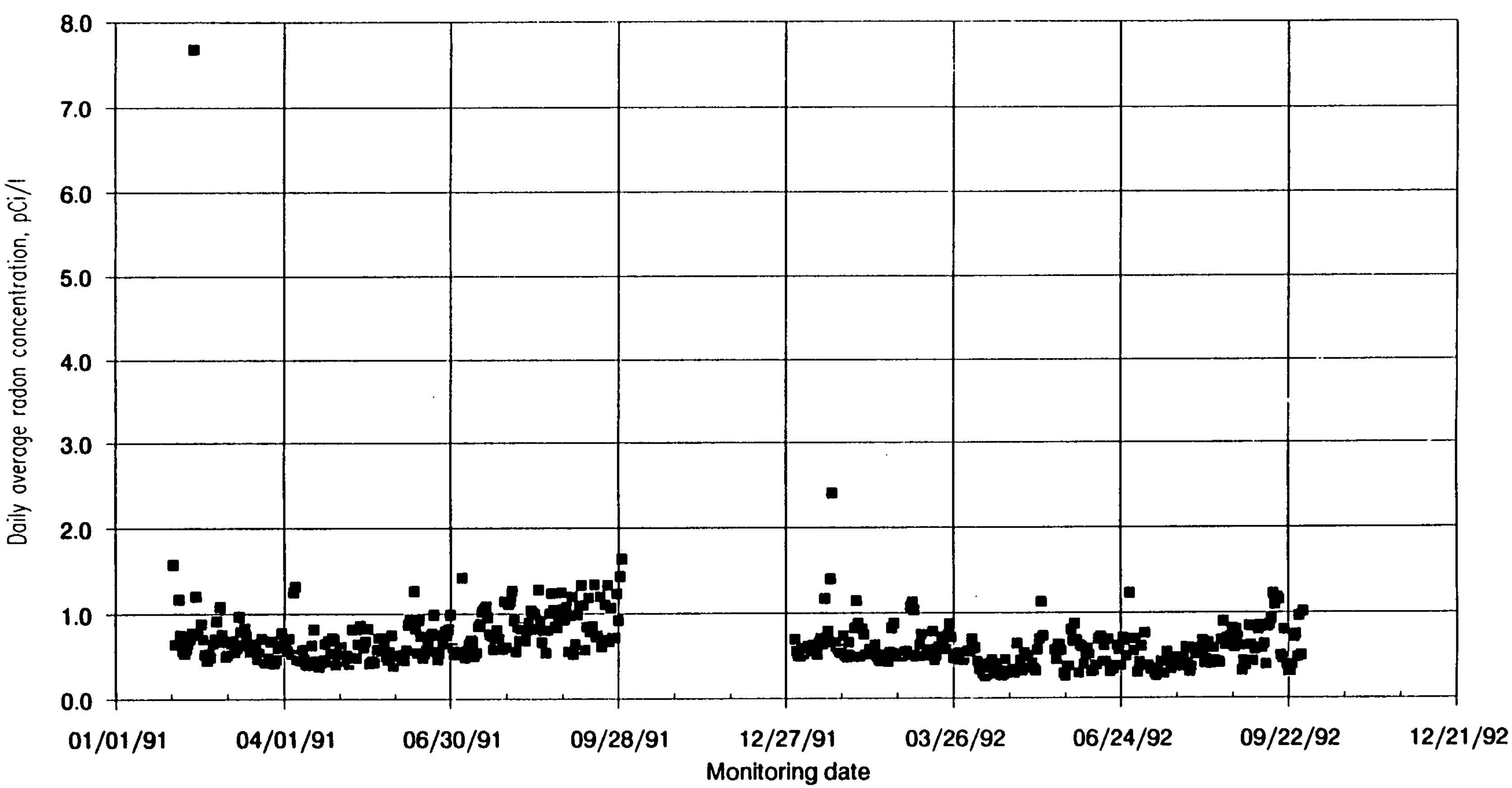
Plot of Daily Average Radon Concentrations Versus Time at the Met. Tower

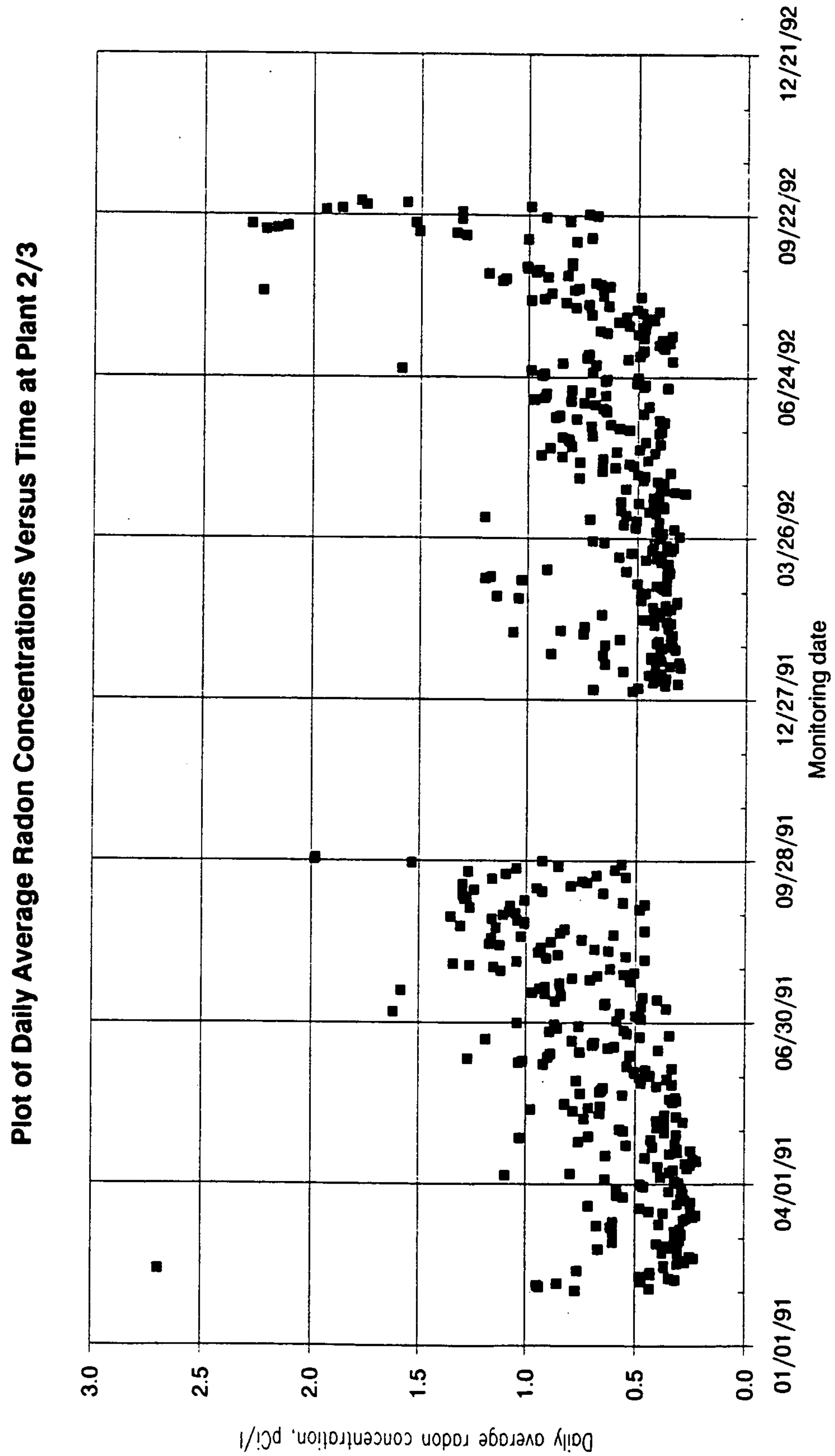


Plot of Daily Average Radon Concentrations Versus Time at the Pilot Plant



Plot of Daily Average Radon Concentrations Versus Time at Plant 5

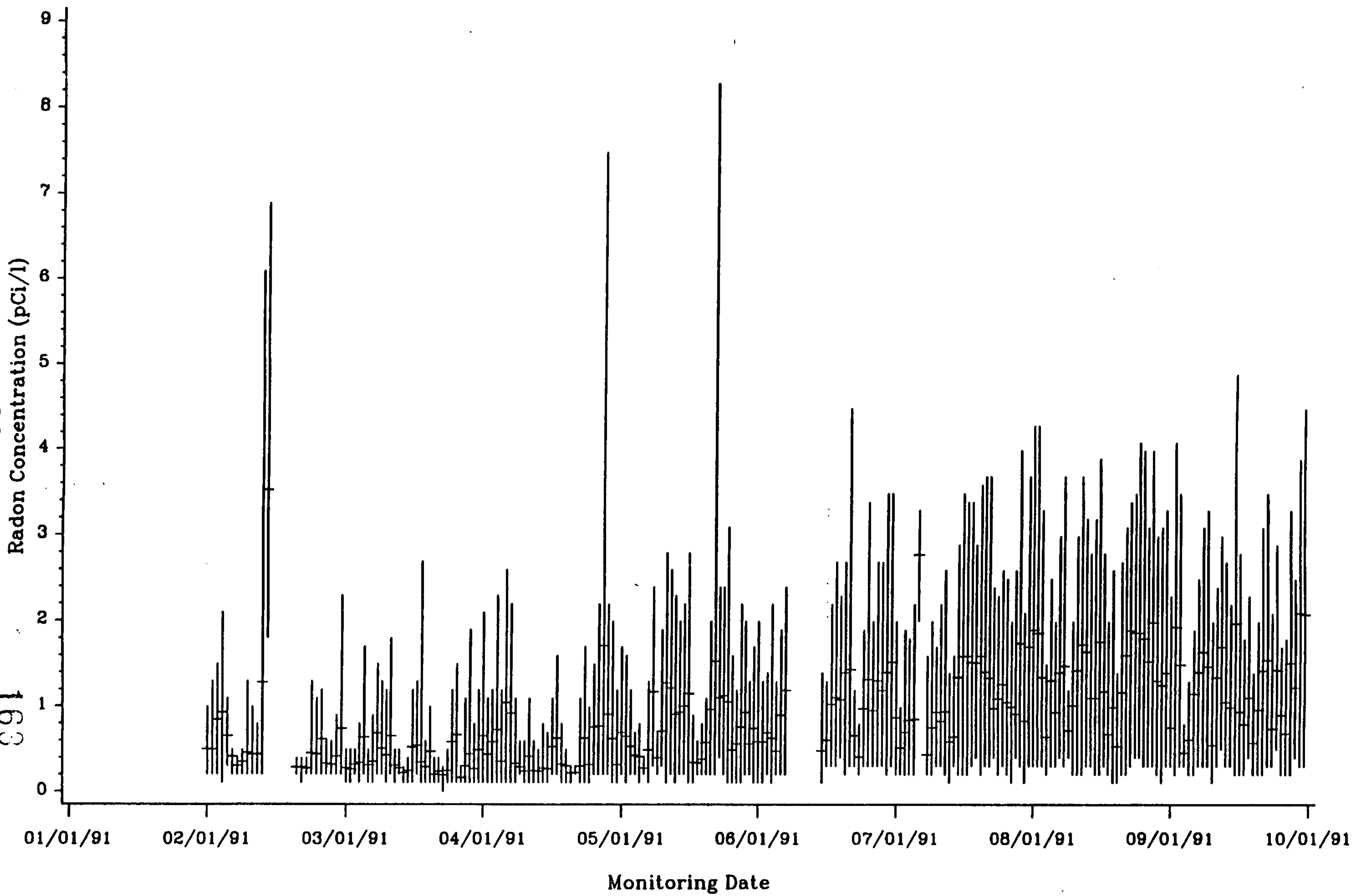



Plot of Daily Average Radon Concentrations Versus Time at Plant 2/3
Daily average radon concentration, pCi/l
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Monitoring date
01/01/91
04/01/91
06/30/91
09/28/91
12/27/91
03/26/92
06/24/92
09/22/92
12/21/92

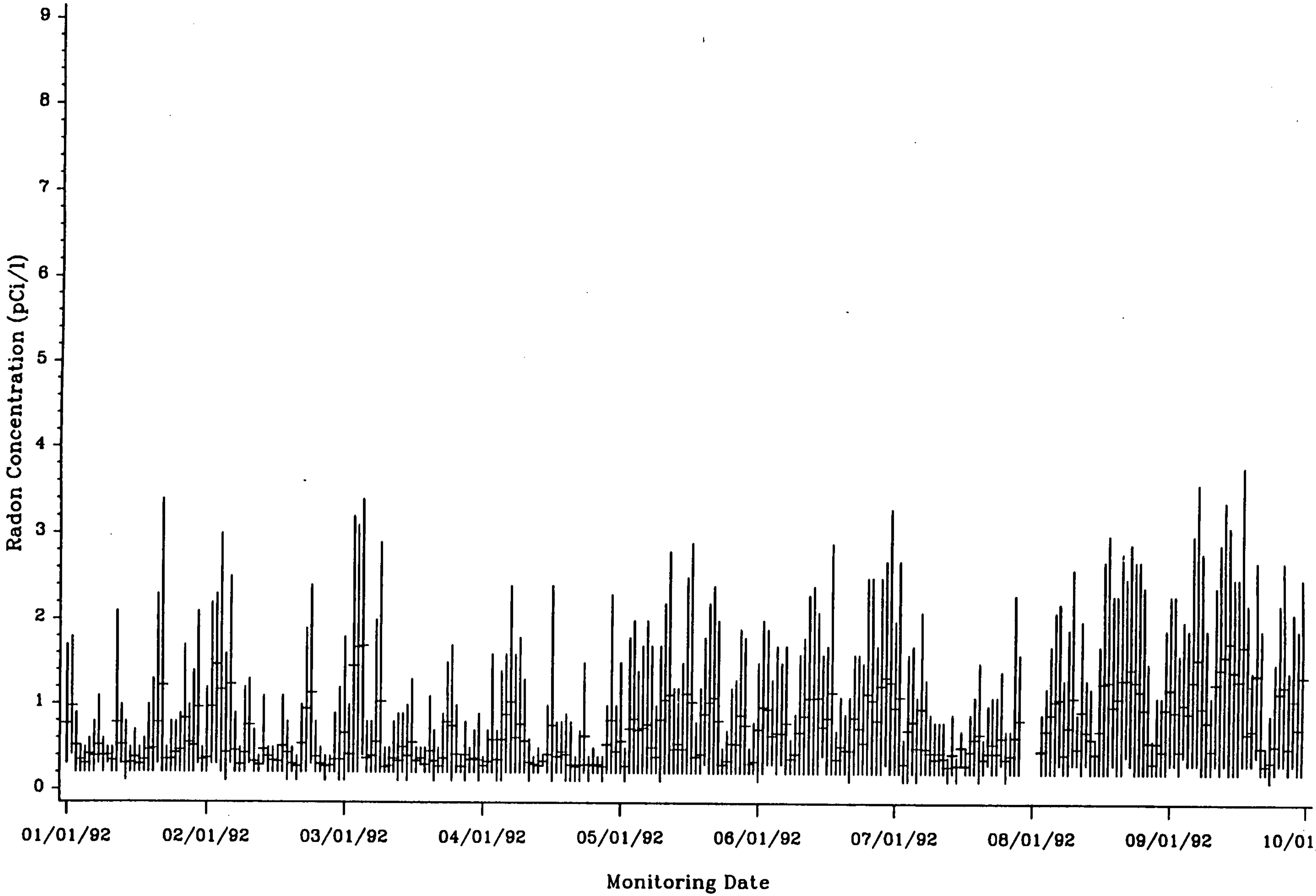
APPENDIX C

PLOT OF PYLON DAILY MINIMUM, AVERAGE, AND MAXIMUM RADON CONCENTRATIONS AT EACH MONITORING STATION

Daily Range of Hourly Radon Concentrations at AMS5 during 1991
(Daily average indicated by tick mark)

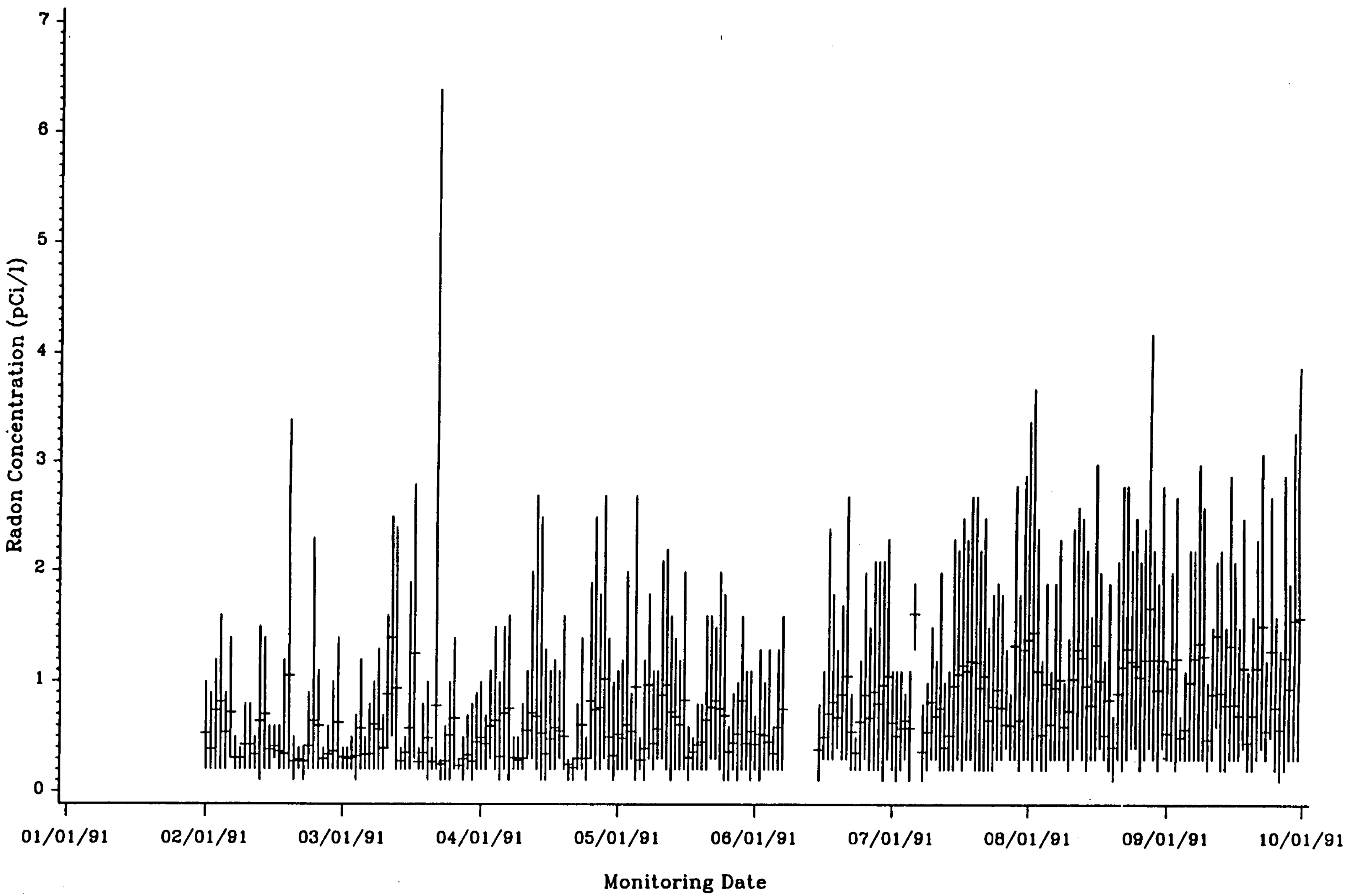


Daily Range of Hourly Radon Concentrations at AMS5 during 1992
(Daily average indicated by tick mark)

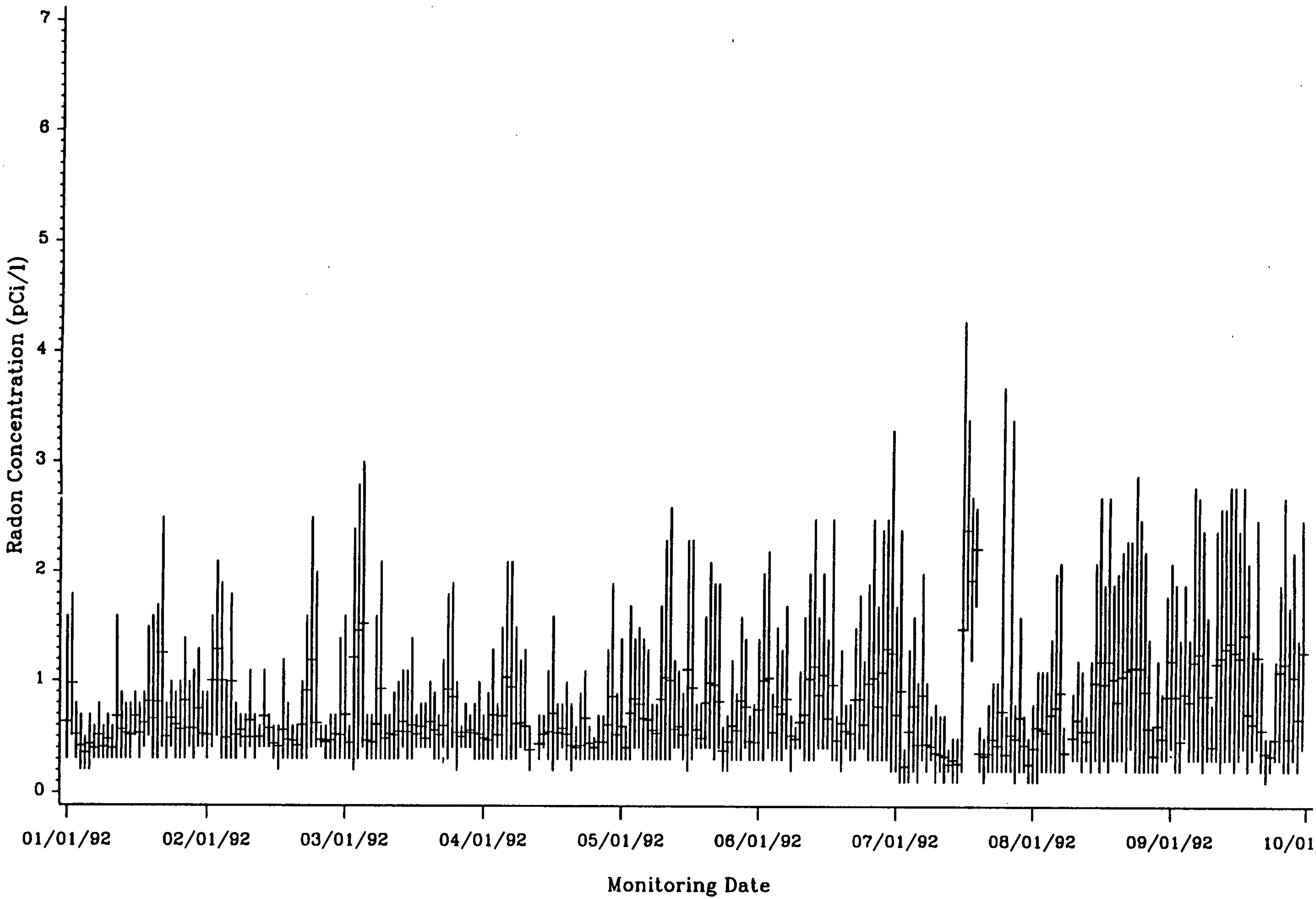


2010

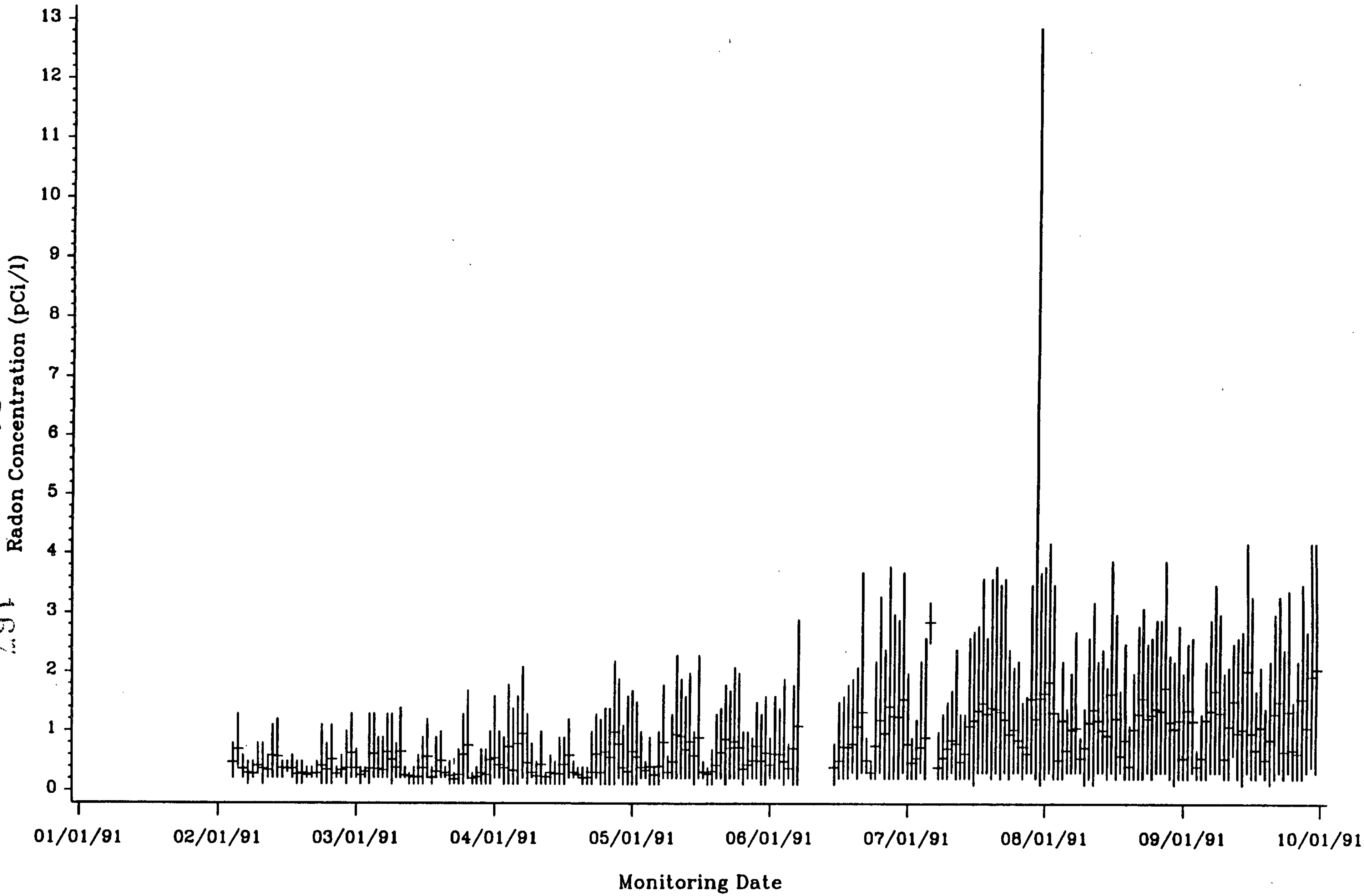
Daily Range of Hourly Radon Concentrations at AMS6 during 1991
(Daily average indicated by tick mark)



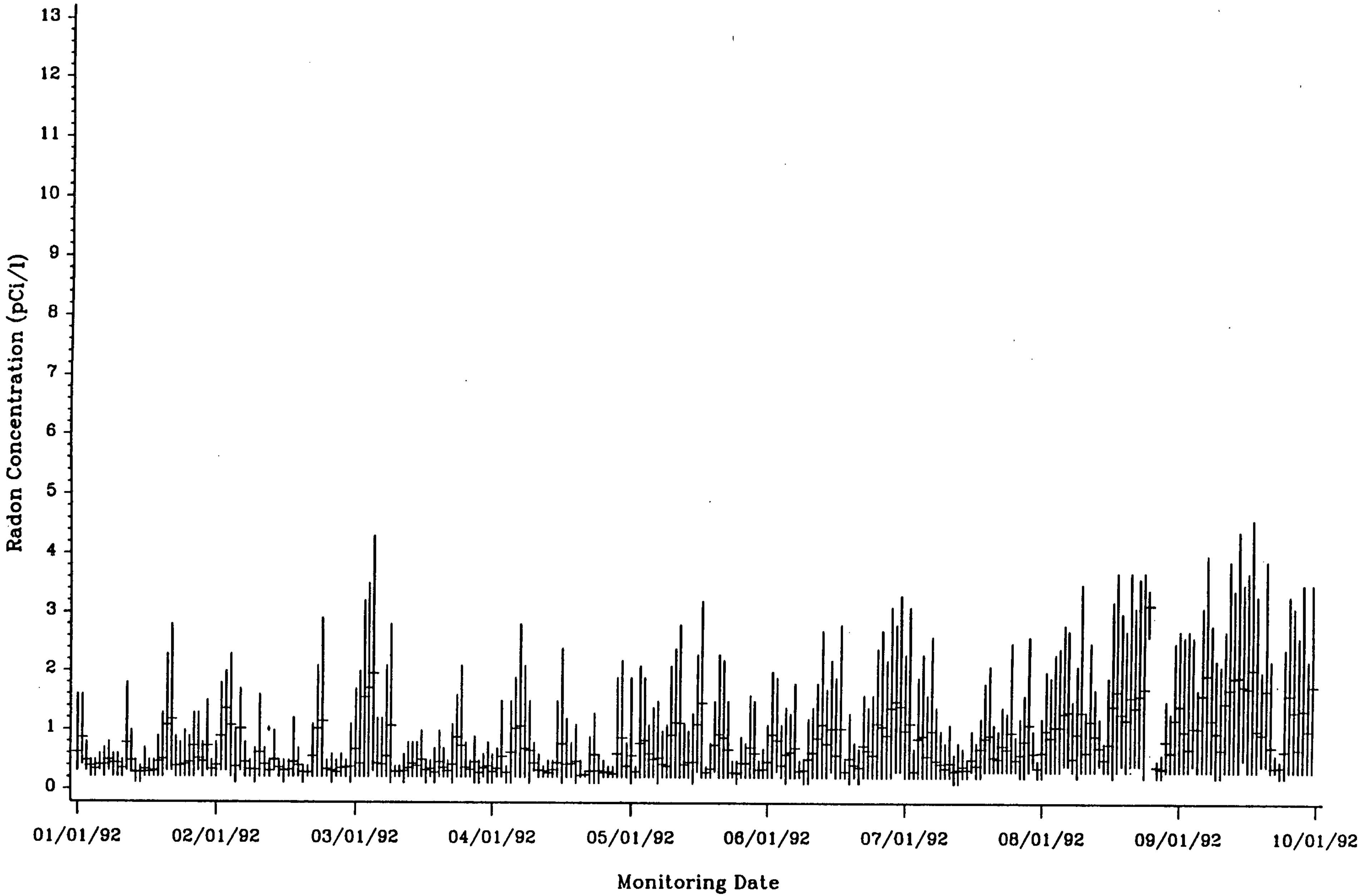
Daily Range of Hourly Radon Concentrations at AMS6 during 1992
(Daily average indicated by tick mark)



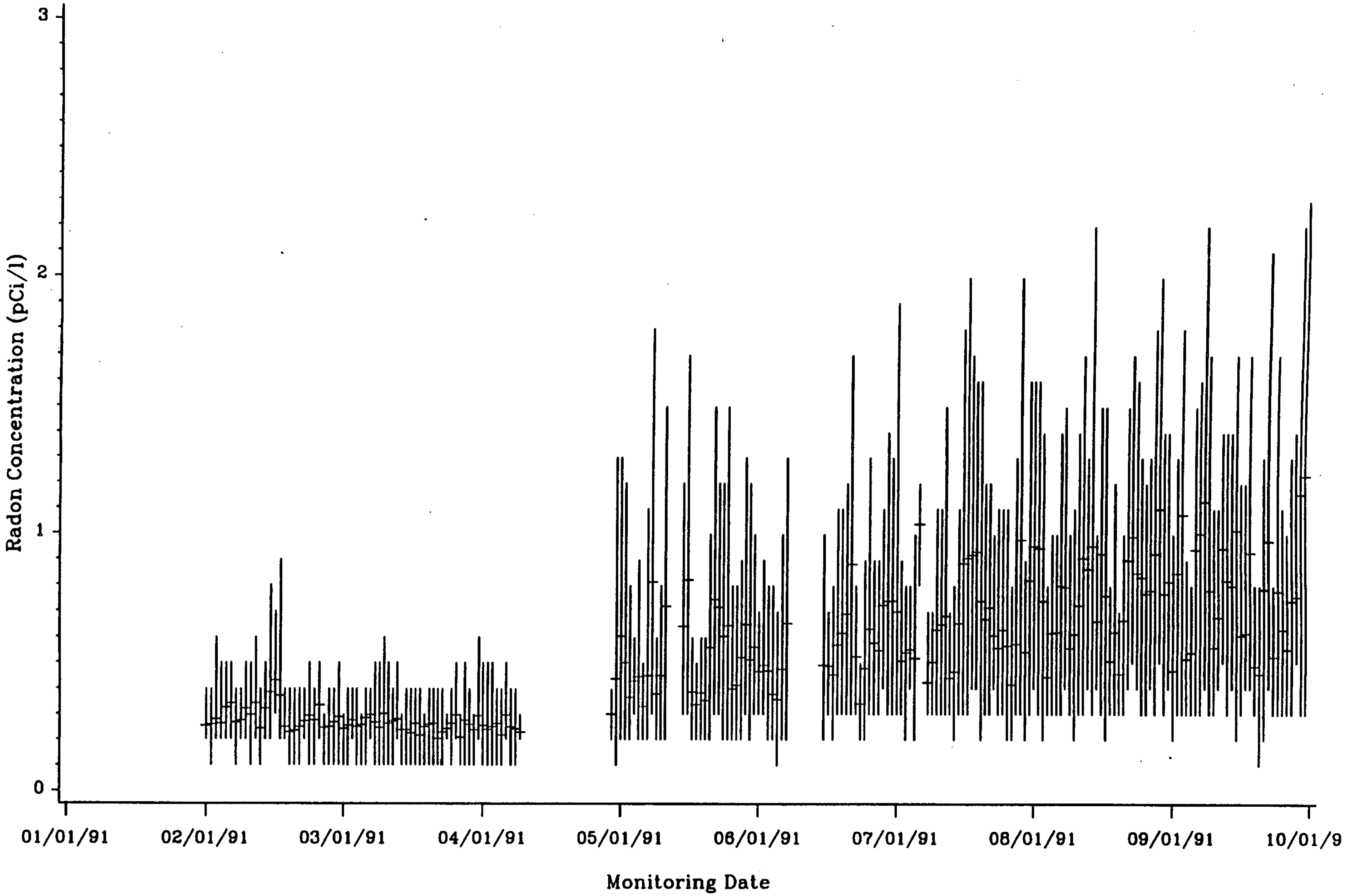
Daily Range of Hourly Radon Concentrations at AMS7 during 1991
(Daily average indicated by tick mark)



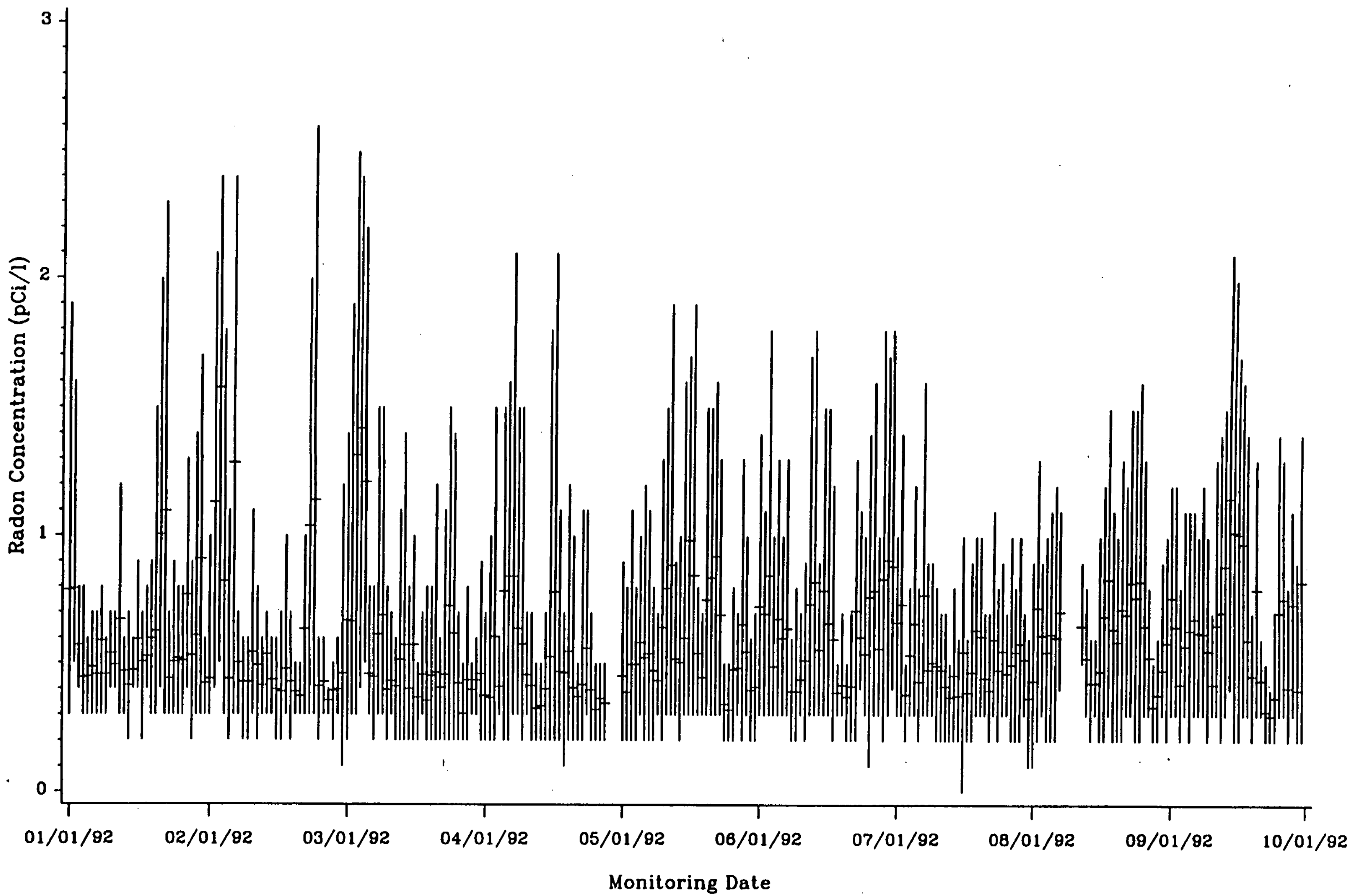
Daily Range of Hourly Radon Concentrations at AMS7 during 1992
(Daily average indicated by tick mark)



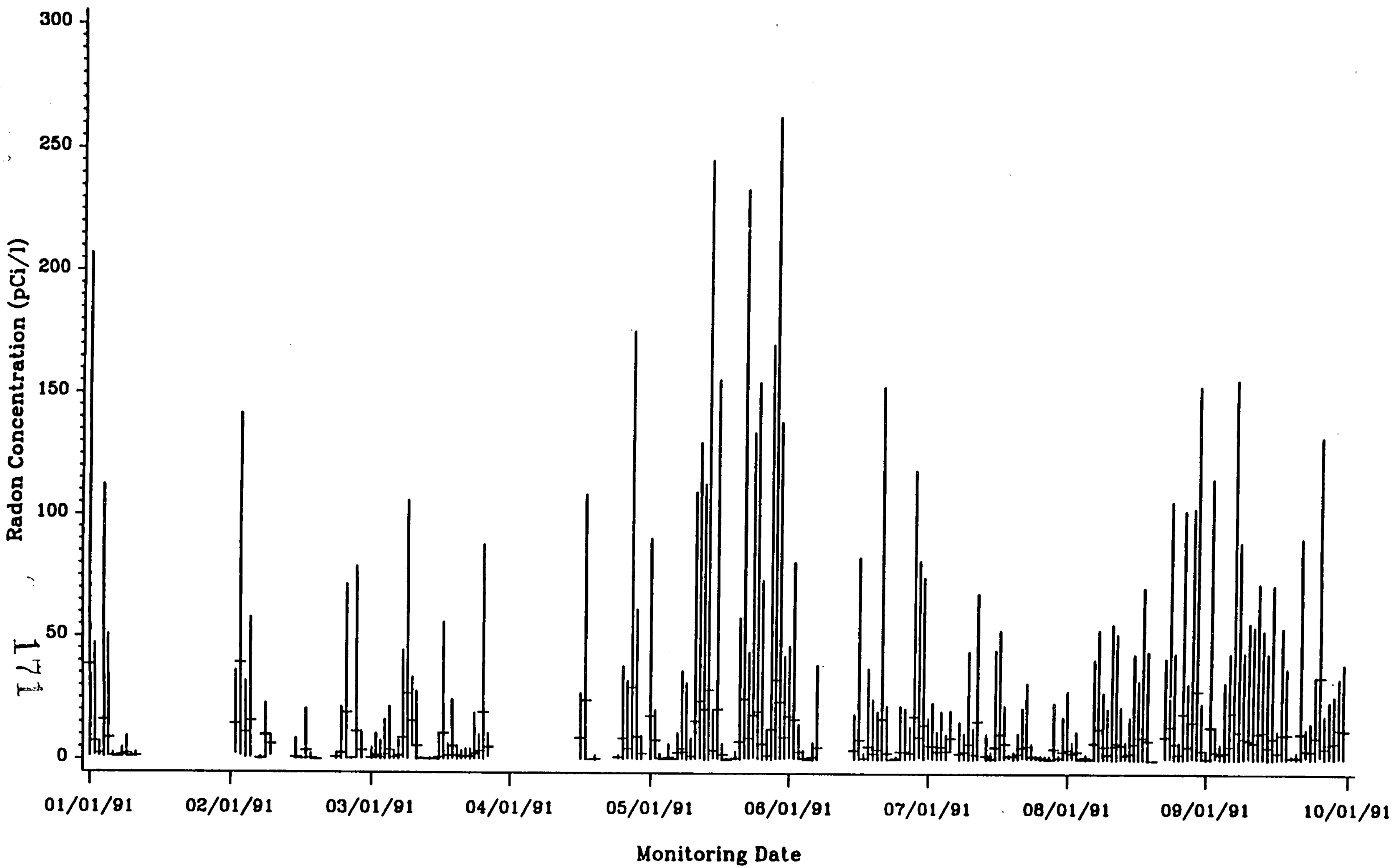
Daily Range of Hourly Radon Concentrations at Background during 1991
(Daily average indicated by tick mark)



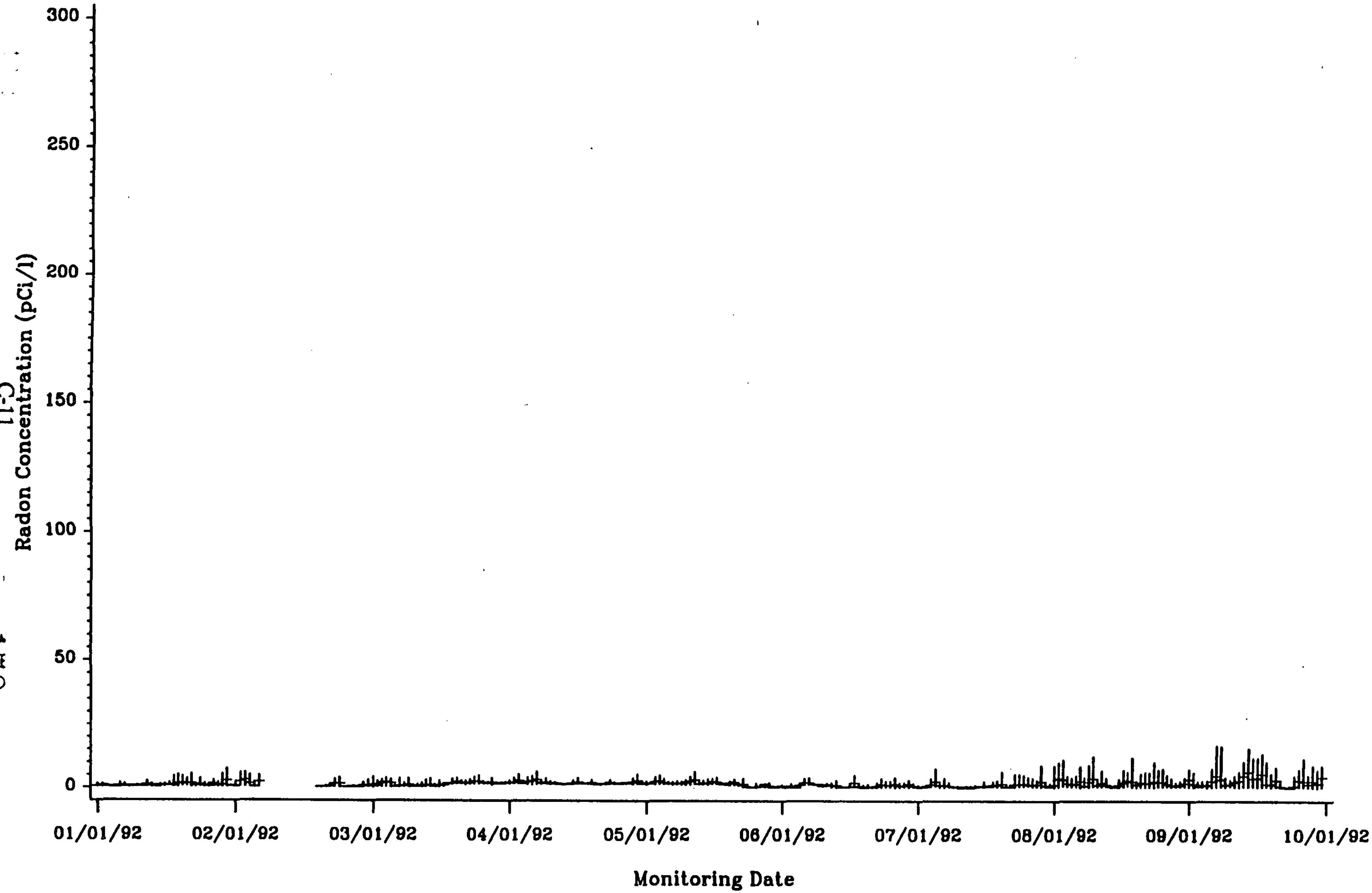
Daily Range of Hourly Radon Concentrations at Background during 1992
(Daily average indicated by tick mark)



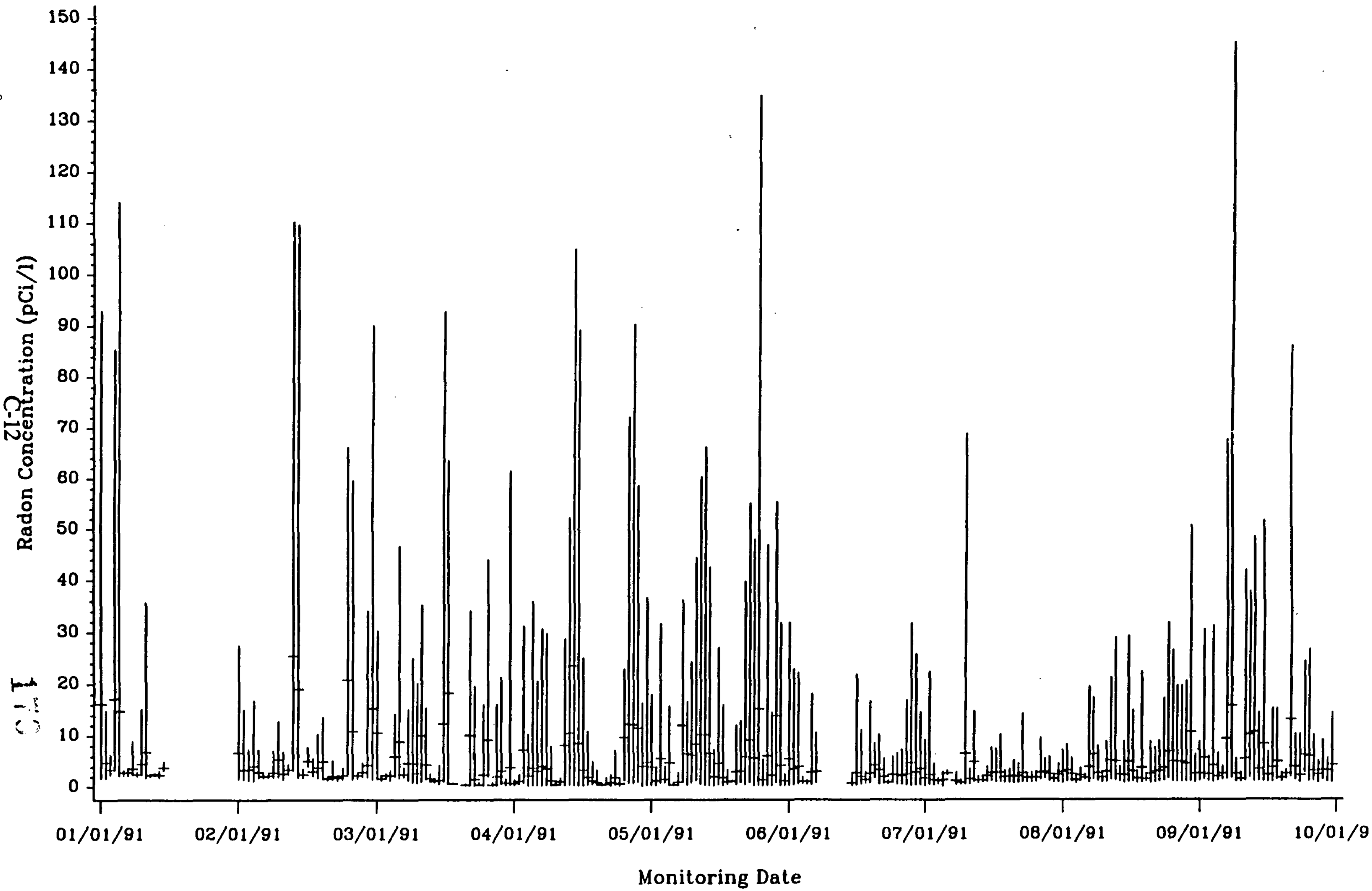
Daily Range of Hourly Radon Concentrations at the NE Exclusion Fence during 1991
(Daily average indicated by tick mark)



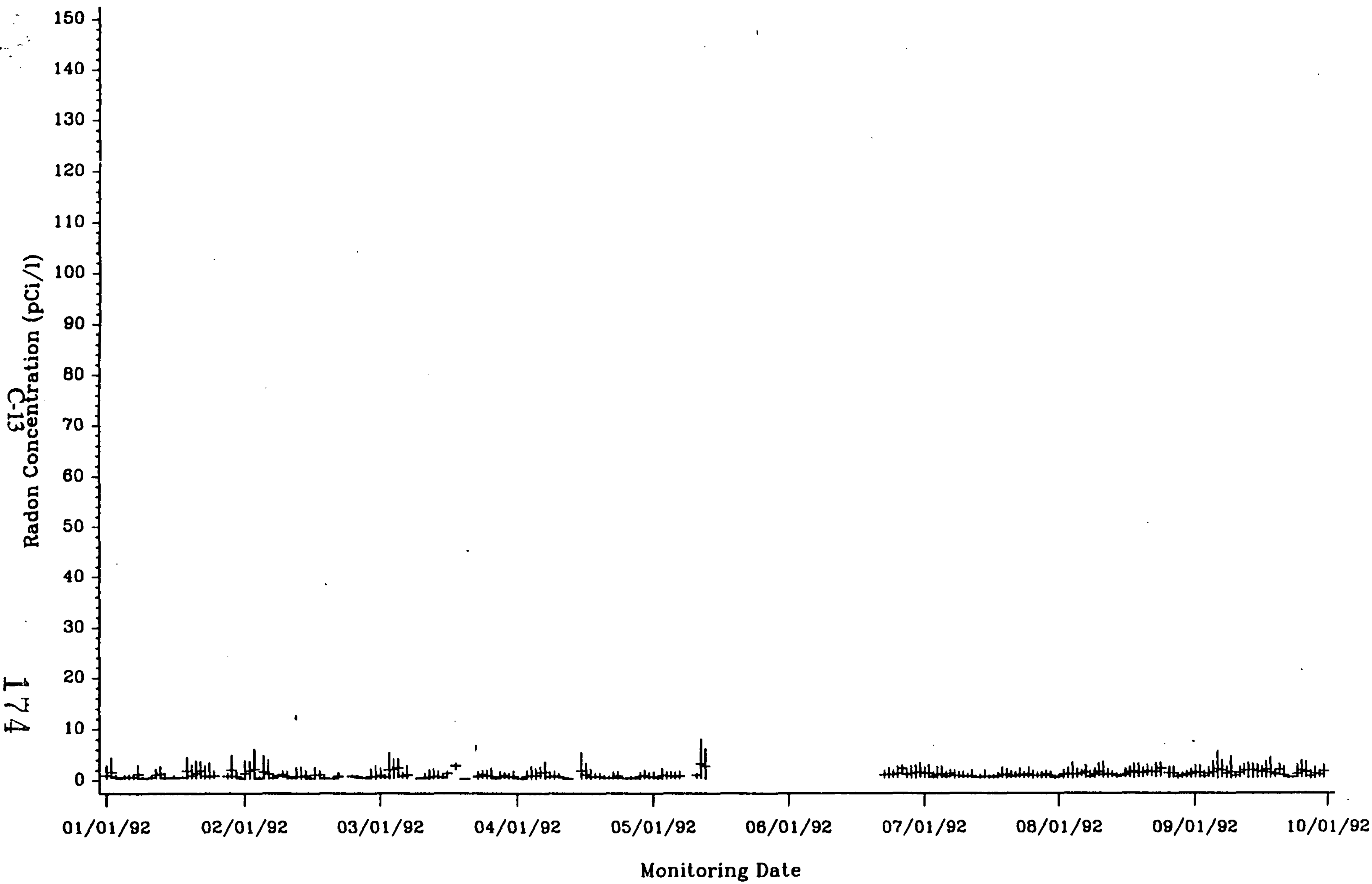
Daily Range of Hourly Radon Concentrations at the NE Exclusion Fence during 1992
(Daily average indicated by tick mark)



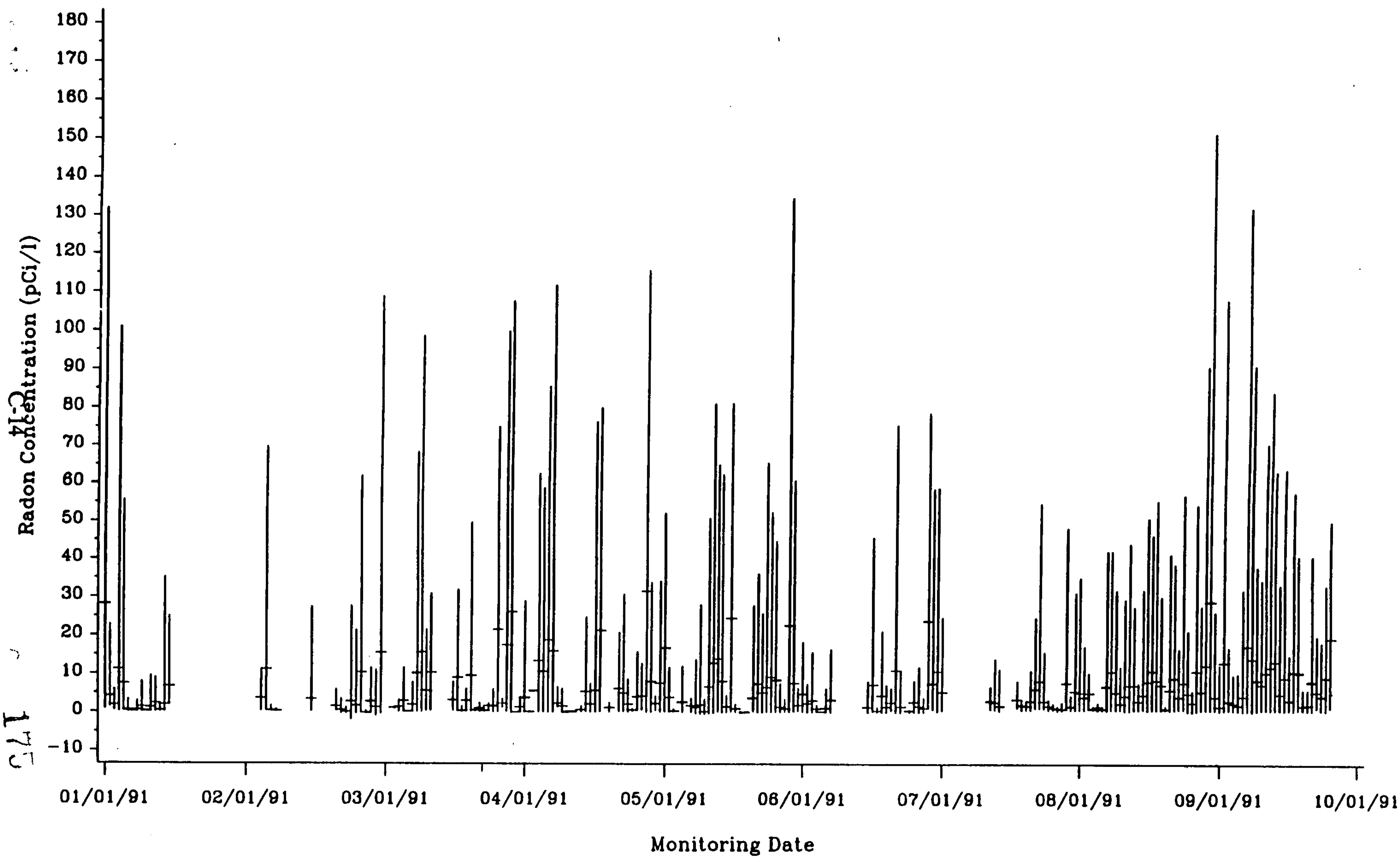
Daily Range of Hourly Radon Concentrations at the NW Exclusion Fence during 1991
(Daily average indicated by tick mark)



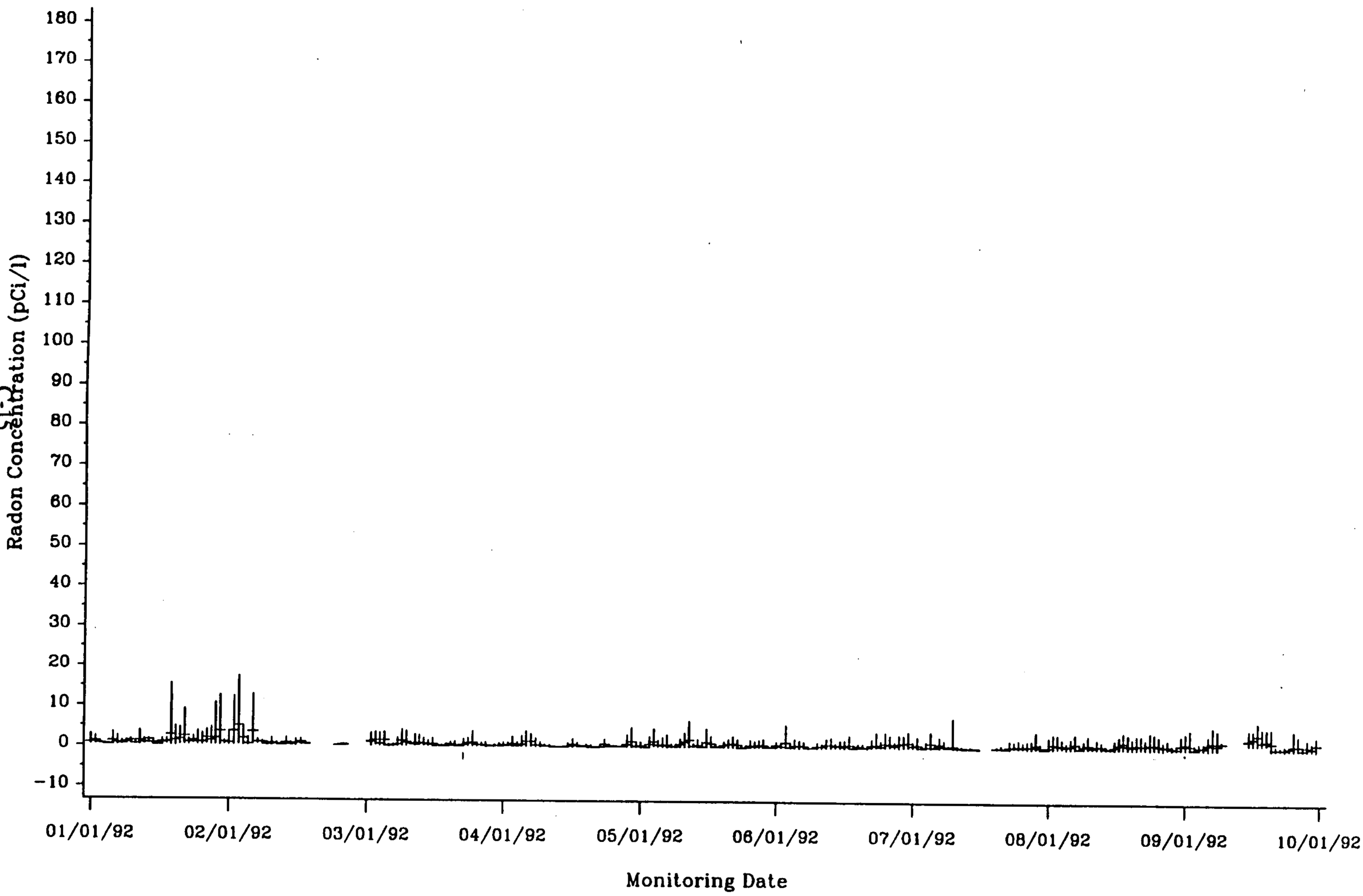
Daily Range of Hourly Radon Concentrations at the NW Exclusion Fence during 1992
(Daily average indicated by tick mark)



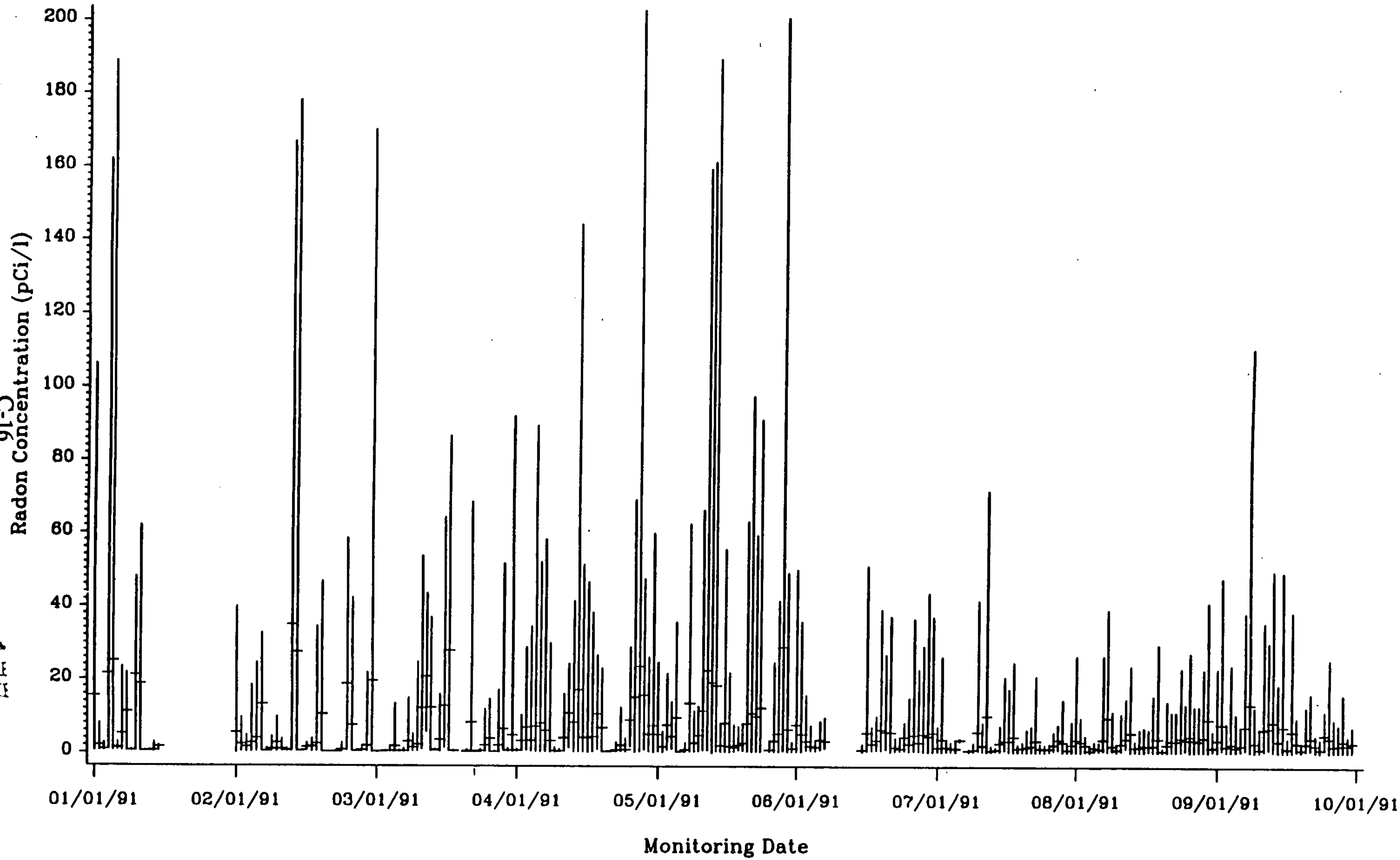
Daily Range of Hourly Radon Concentrations at the SE Exclusion Fence during 1991
(Daily average indicated by tick mark)



Daily Range of Hourly Radon Concentrations at the SE Exclusion Fence during 1992
(Daily average indicated by tick mark)

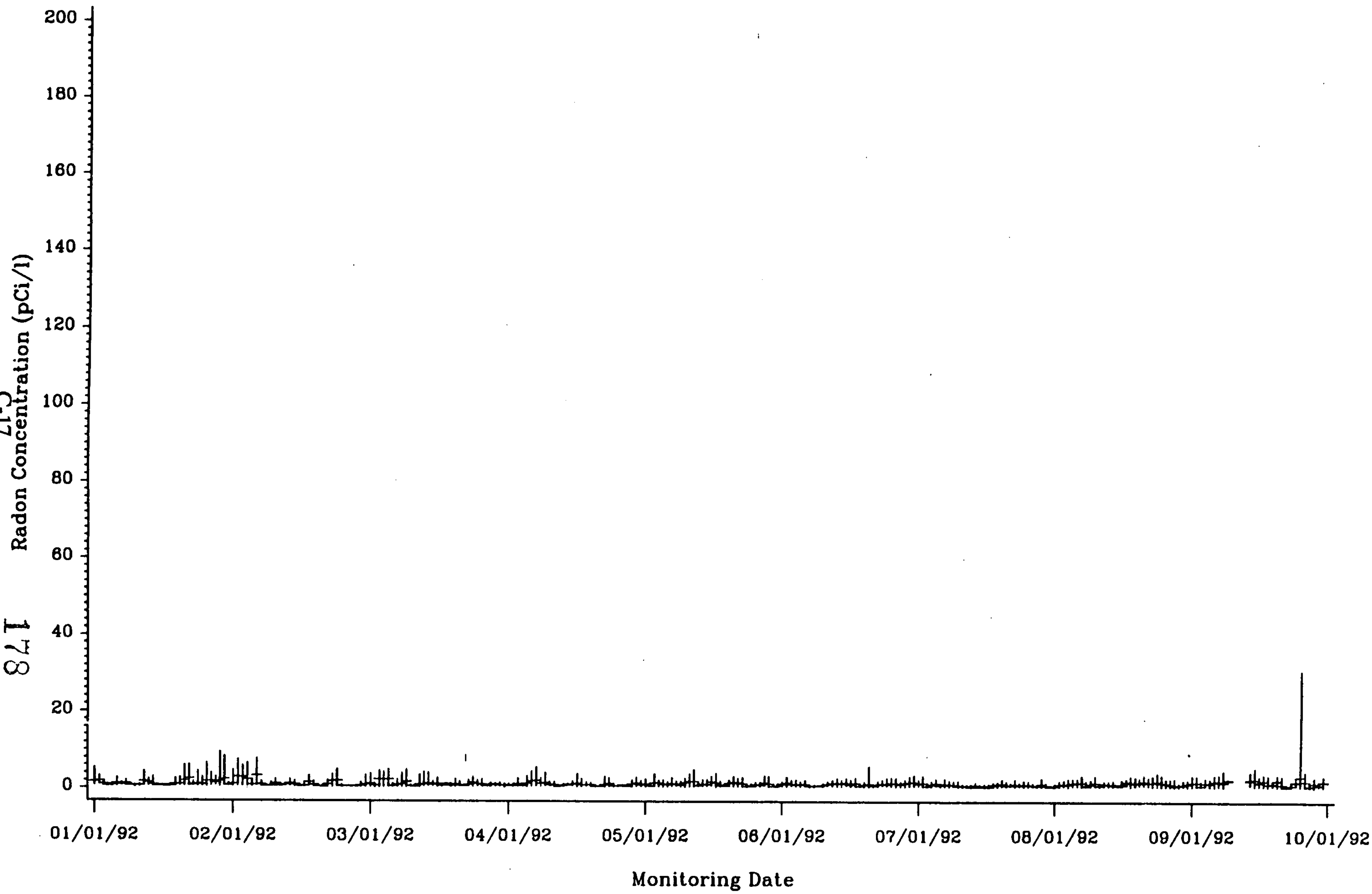


Daily Range of Hourly Radon Concentrations at the SW Exclusion Fence during 1991
(Daily average indicated by tick mark)

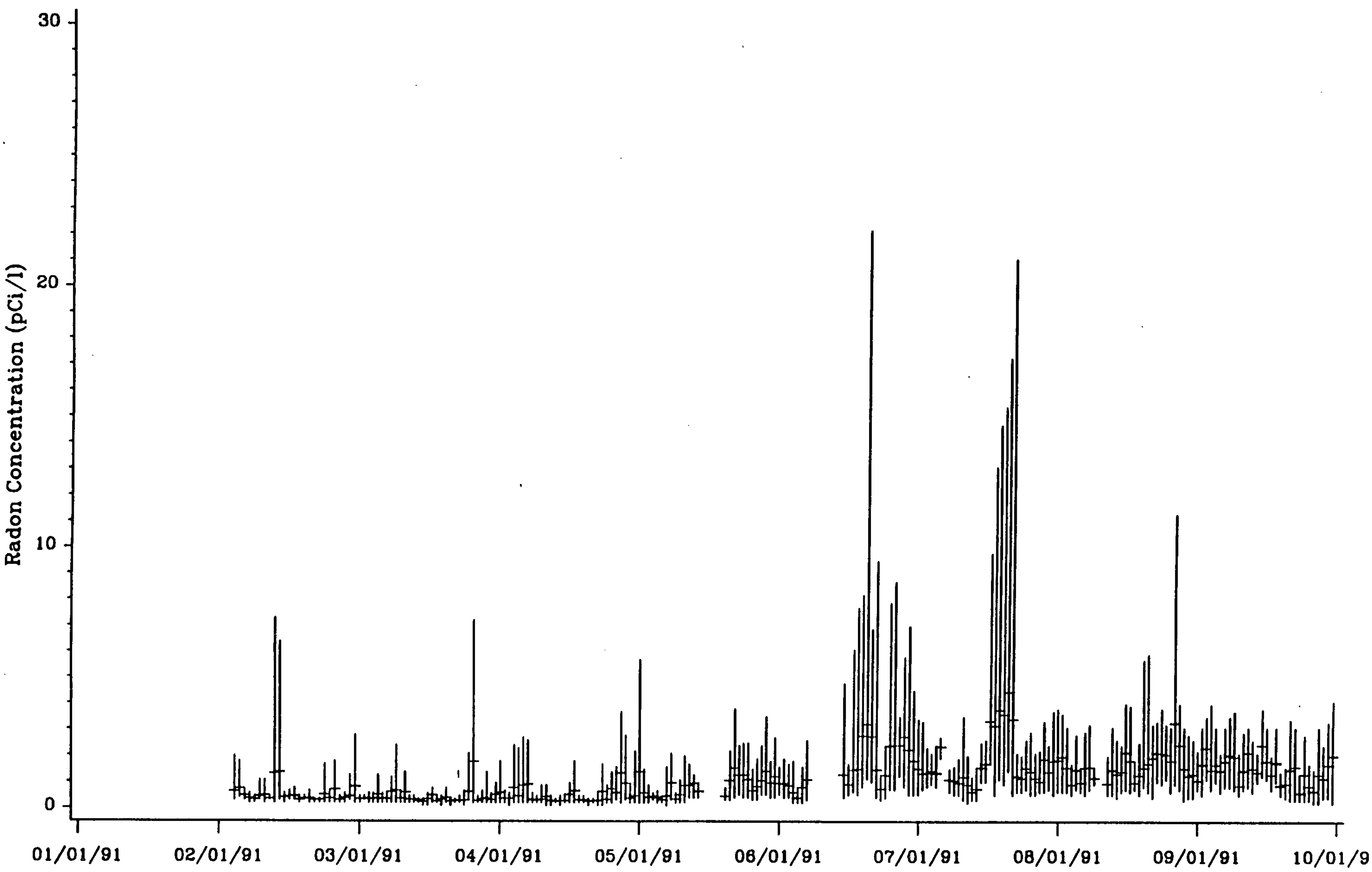


Note: Data for 5/25/91 not represented on this plot.

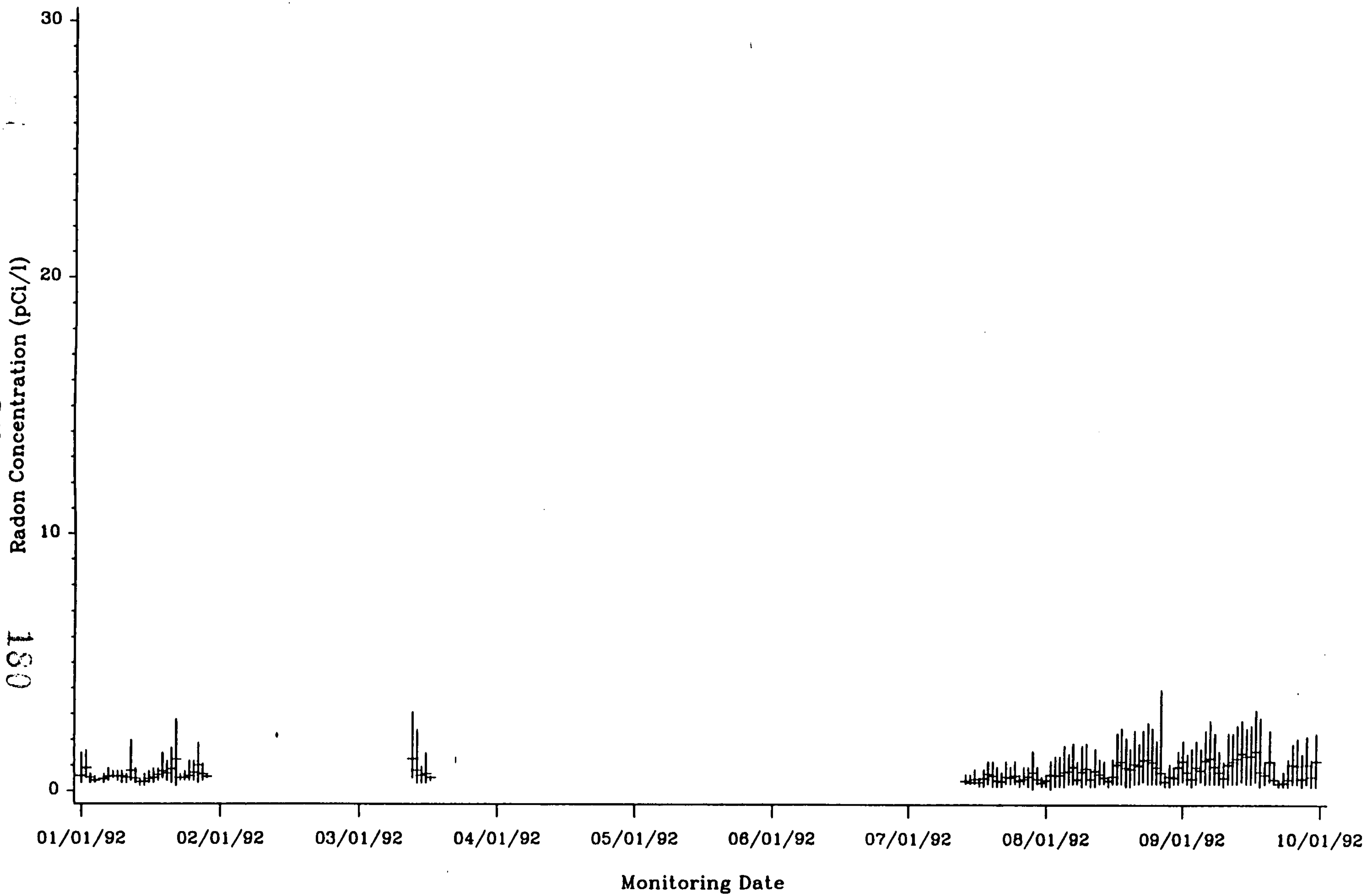
Daily Range of Hourly Radon Concentrations at the SW Exclusion Fence during 1992
(Daily average indicated by tick mark)



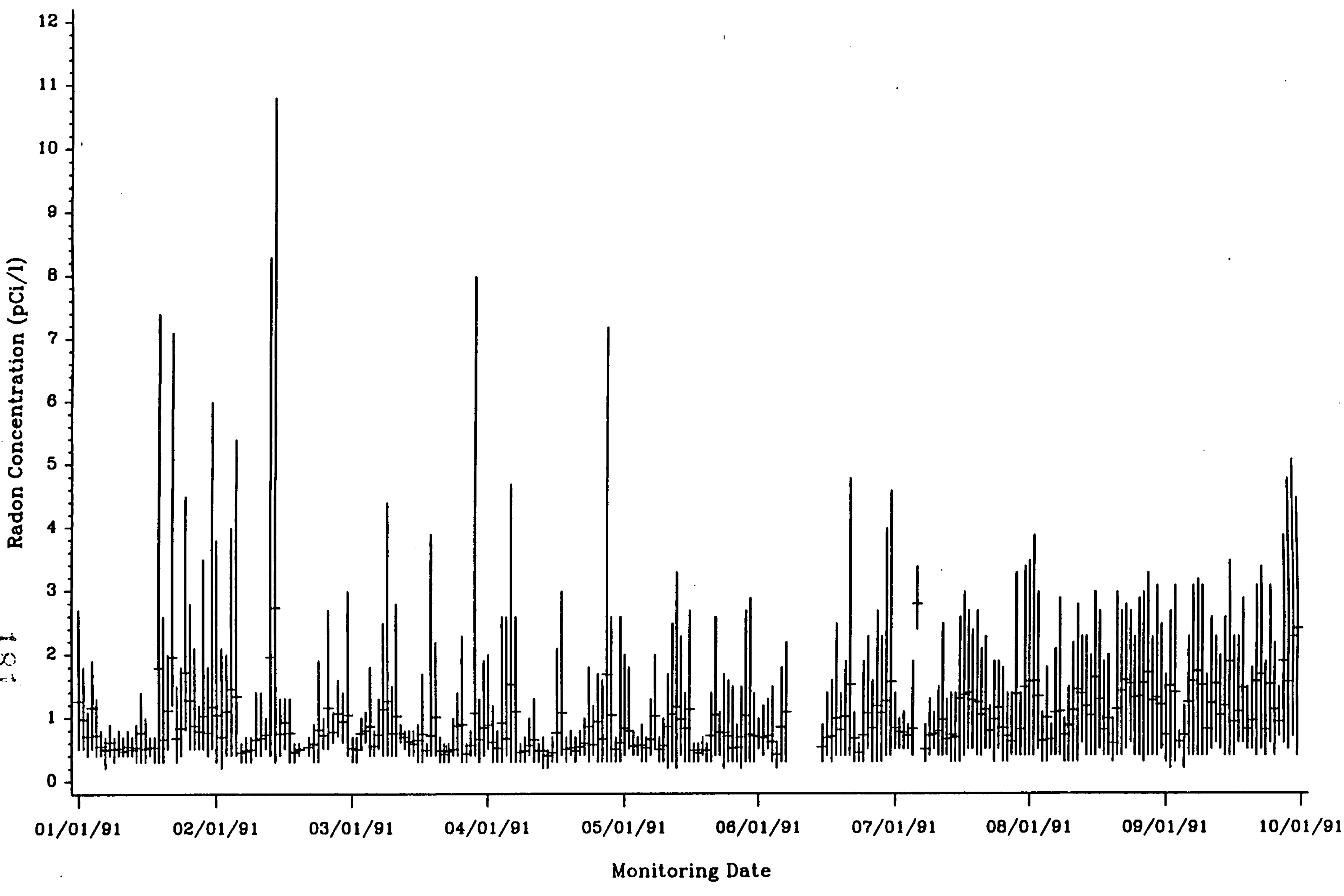
Daily Range of Hourly Radon Concentrations at the Met. Tower during 1991
(Daily average indicated by tick mark)



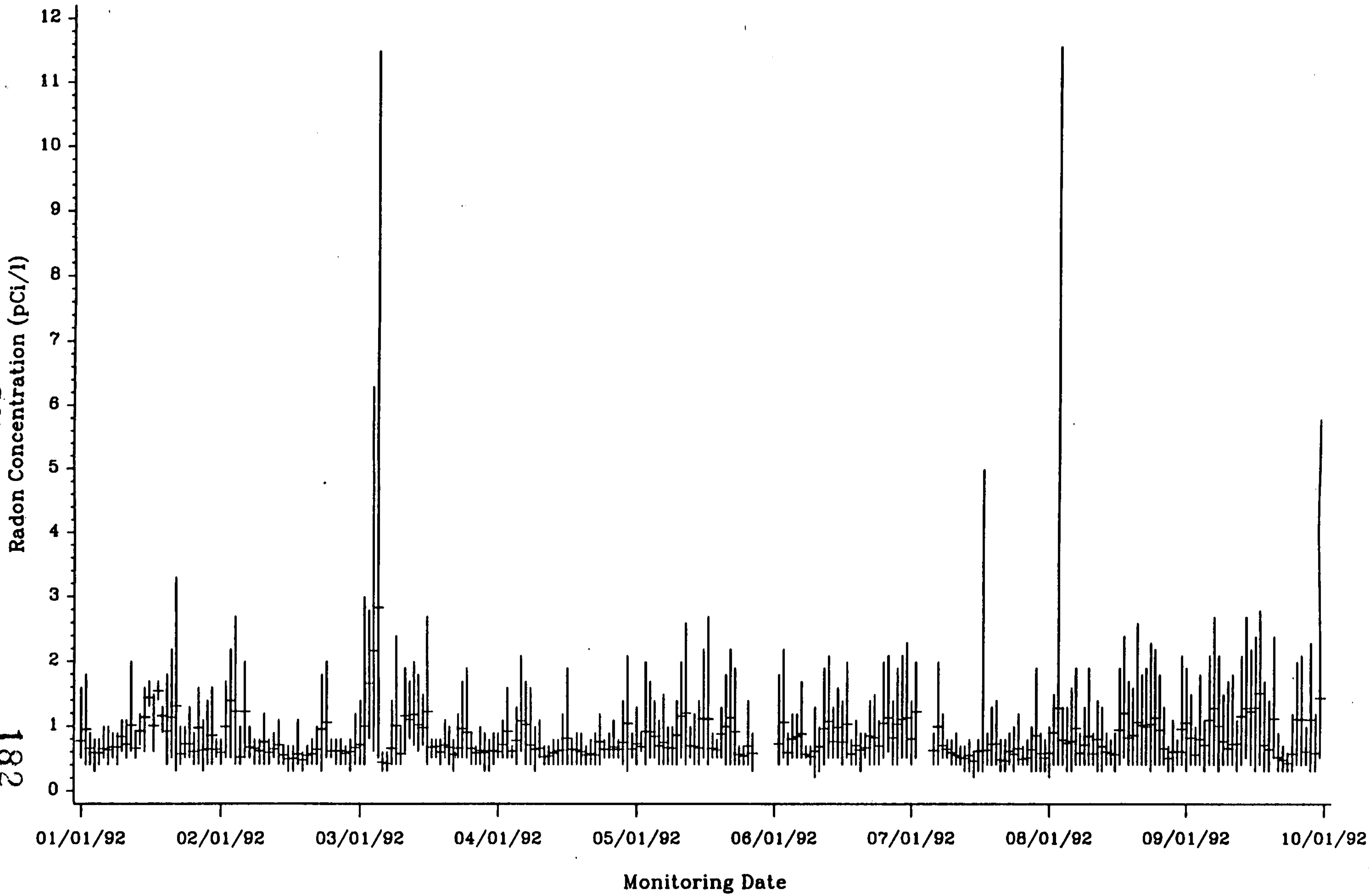
Daily Range of Hourly Radon Concentrations at the Met. Tower during 1992
(Daily average indicated by tick mark)



Daily Range of Hourly Radon Concentrations at the Pilot Plant during 1991
(Daily average indicated by tick mark)



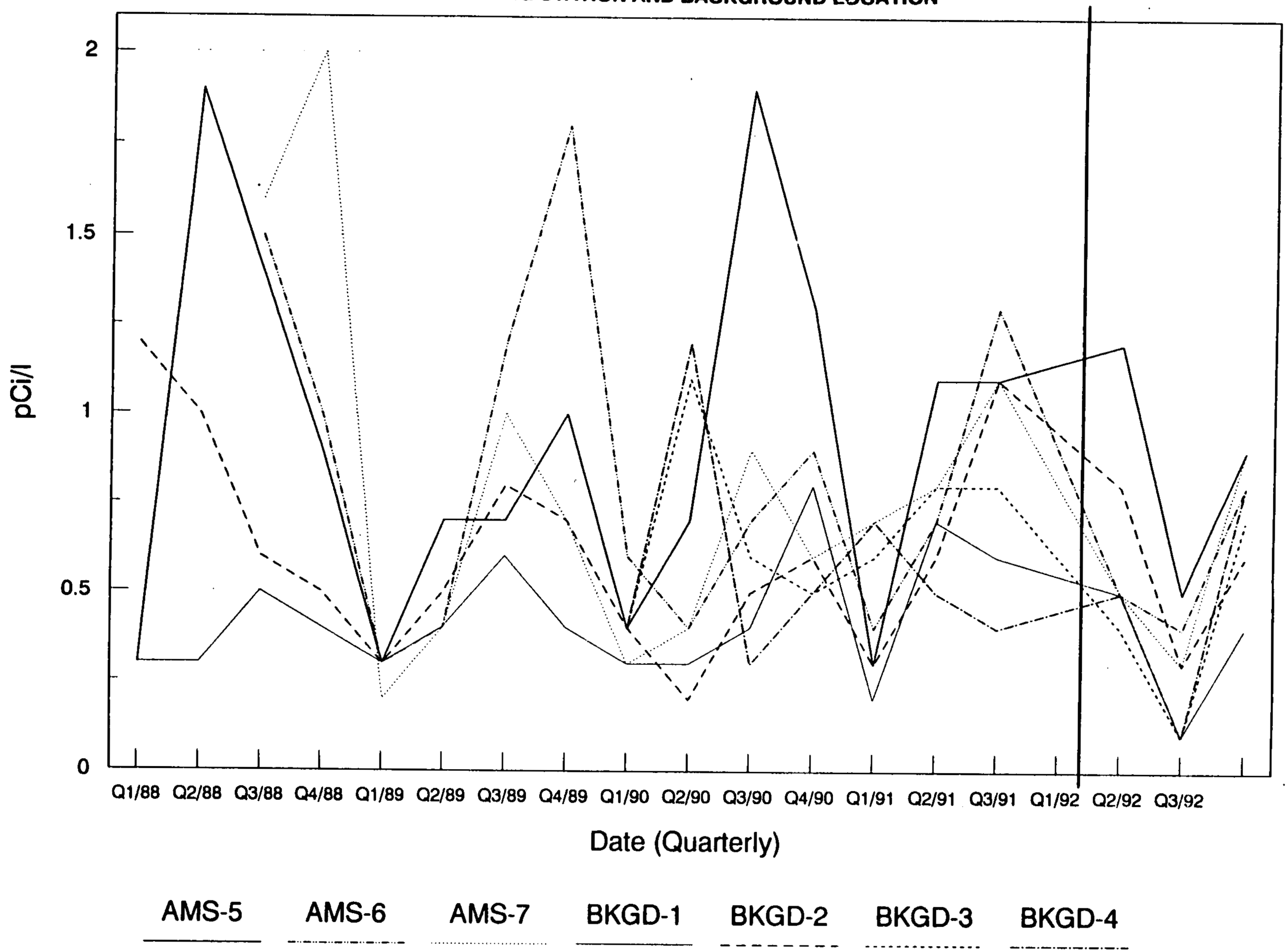
Daily Range of Hourly Radon Concentrations at the Pilot Plant during 1992
(Daily average indicated by tick mark)

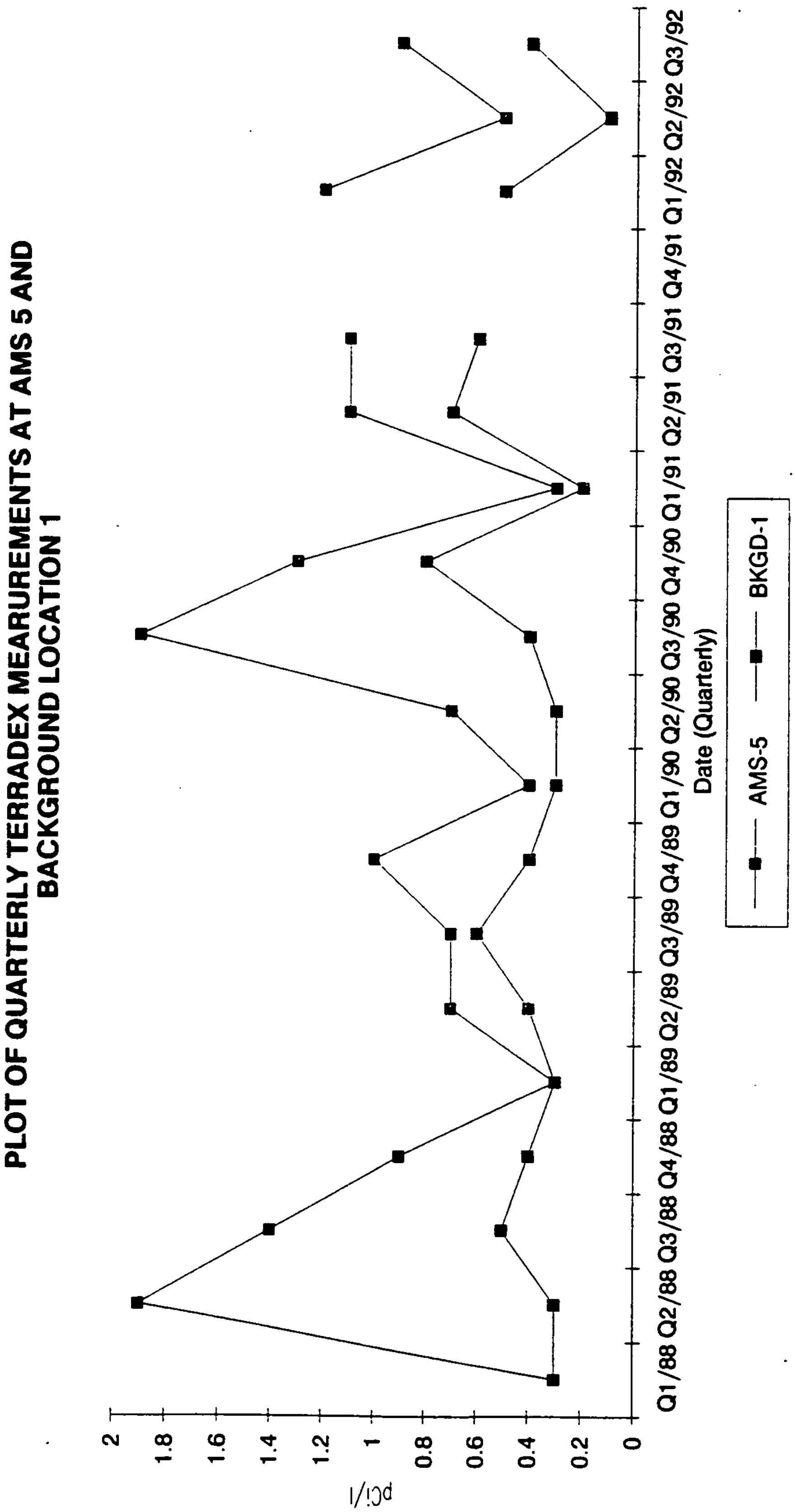


ATTACHMENT D

PLOT OF QUARTERLY TERRADEX MEASUREMENTS AT EACH AIR MONITORING STATION AND BACKGROUND LOCATION

PLOT OF QUARTERLY TERRADEX MEASUREMENTS AT EACH AIR MONITORING STATION AND BACKGROUND LOCATION

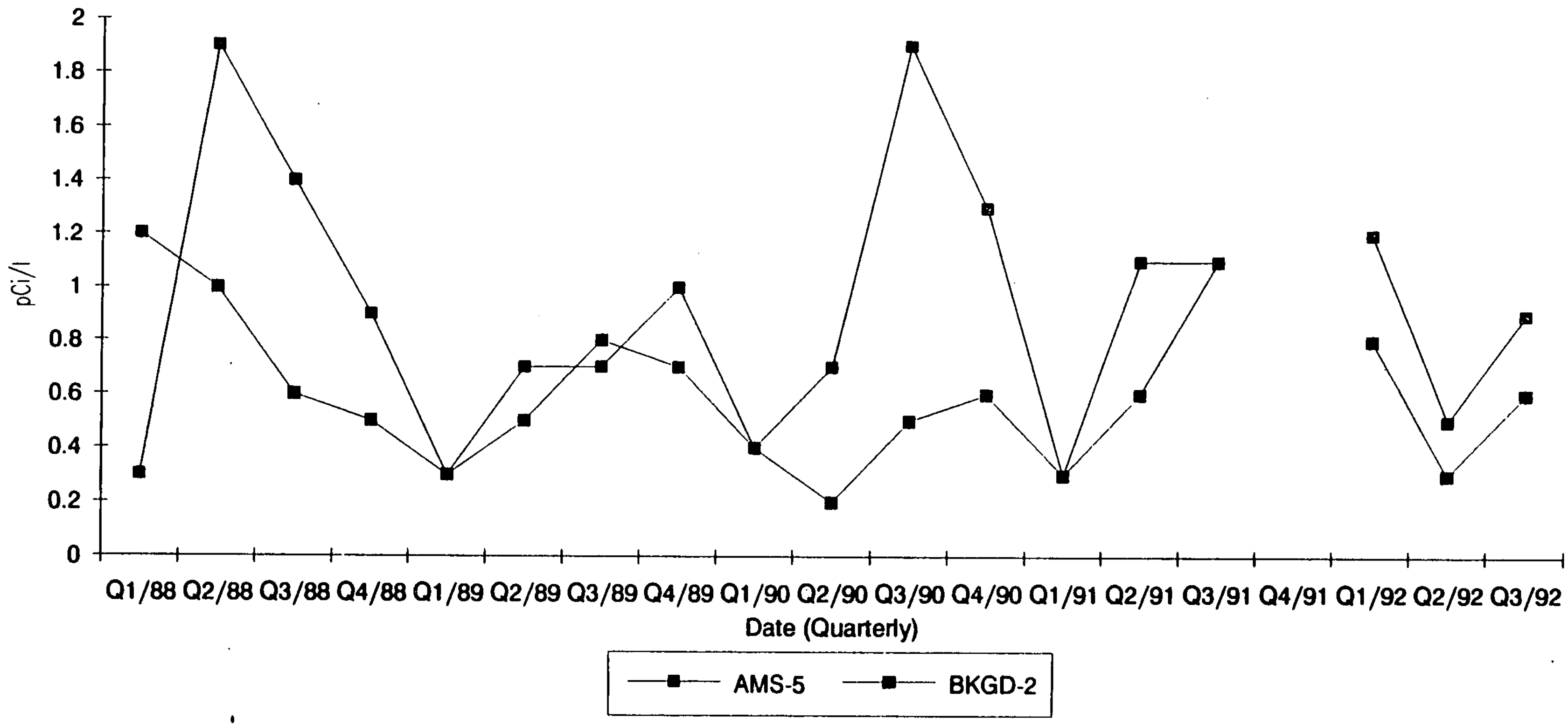




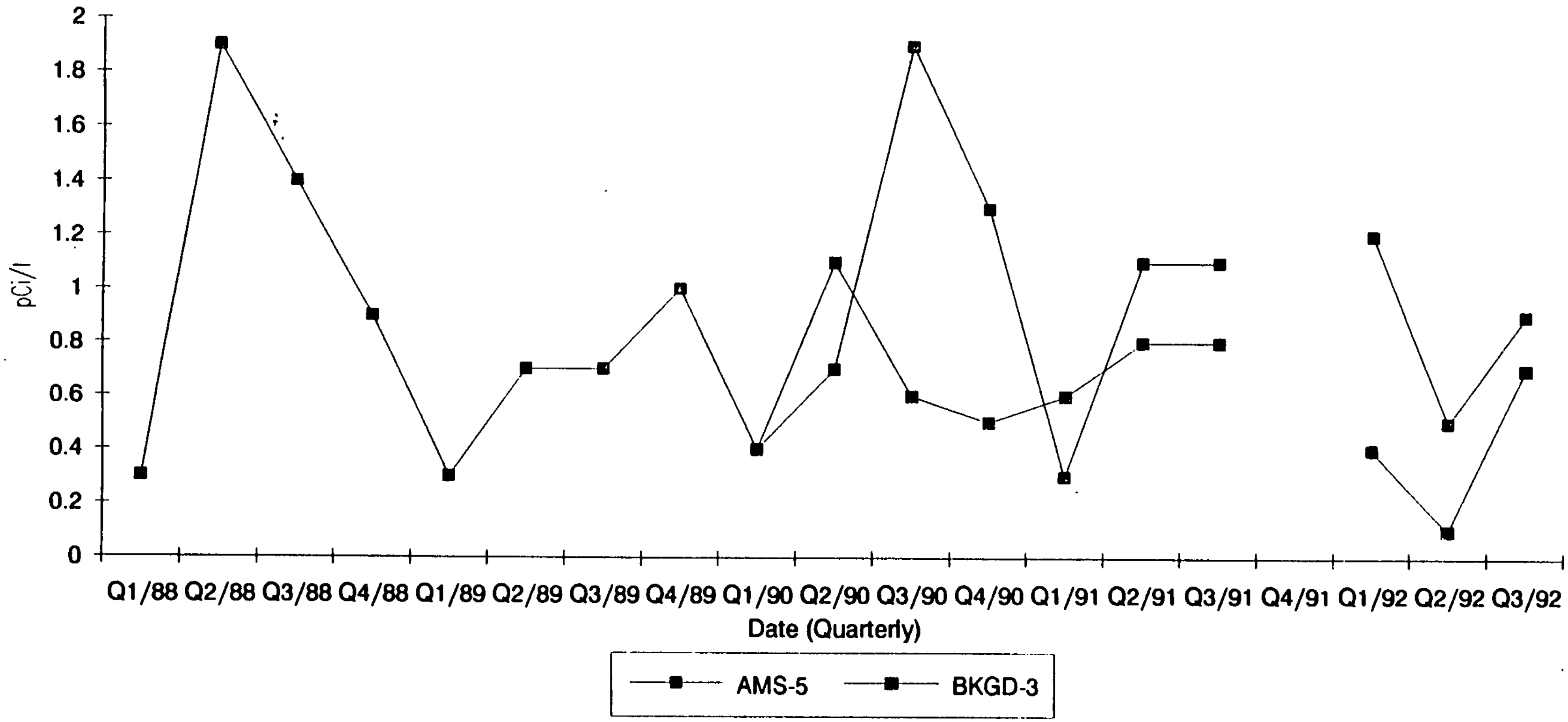
PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 5 AND BACKGROUND LOCATION 1
pCi/l
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Q1/88 Q2/88 Q3/88 Q4/88 Q1/89 Q2/89 Q3/89 Q4/89 Q1/90 Q2/90 Q3/90 Q4/90 Q1/91 Q2/91 Q3/91 Q4/91 Q1/92 Q2/92 Q3/92
Date (Quarterly)
AMS-5
BKGD-1

D-3

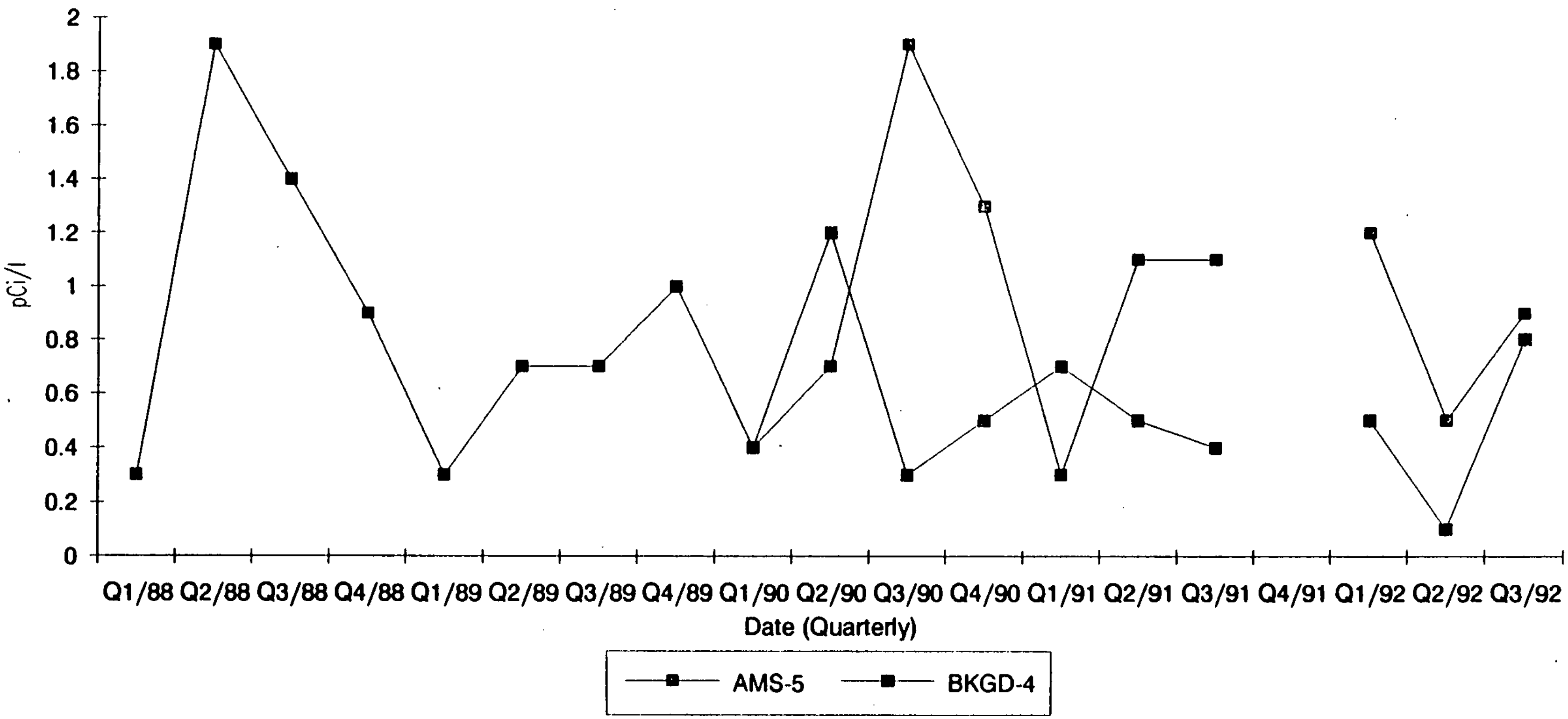
PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 5 AND BACKGROUND LOCATION 2



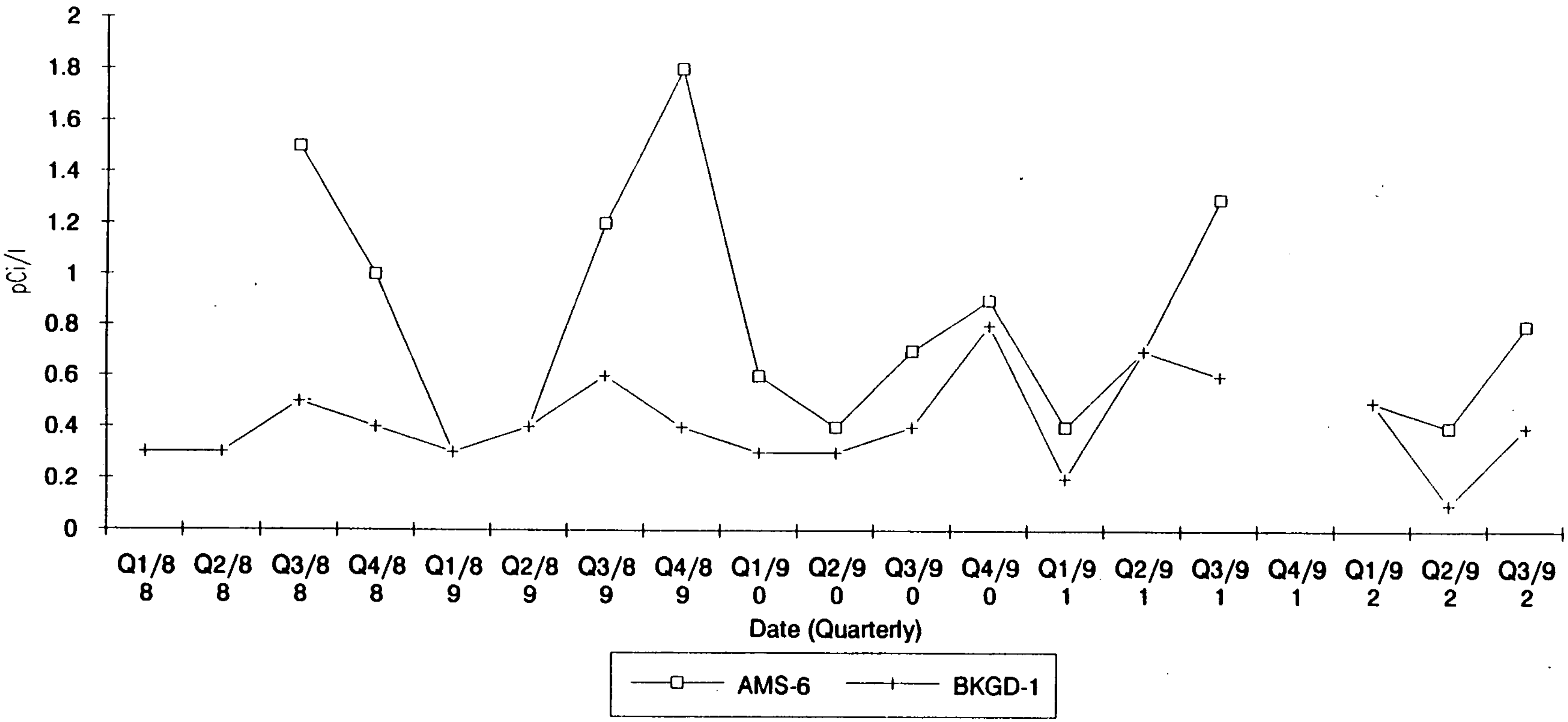
PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 5 AND BACKGROUND LOCATION 3



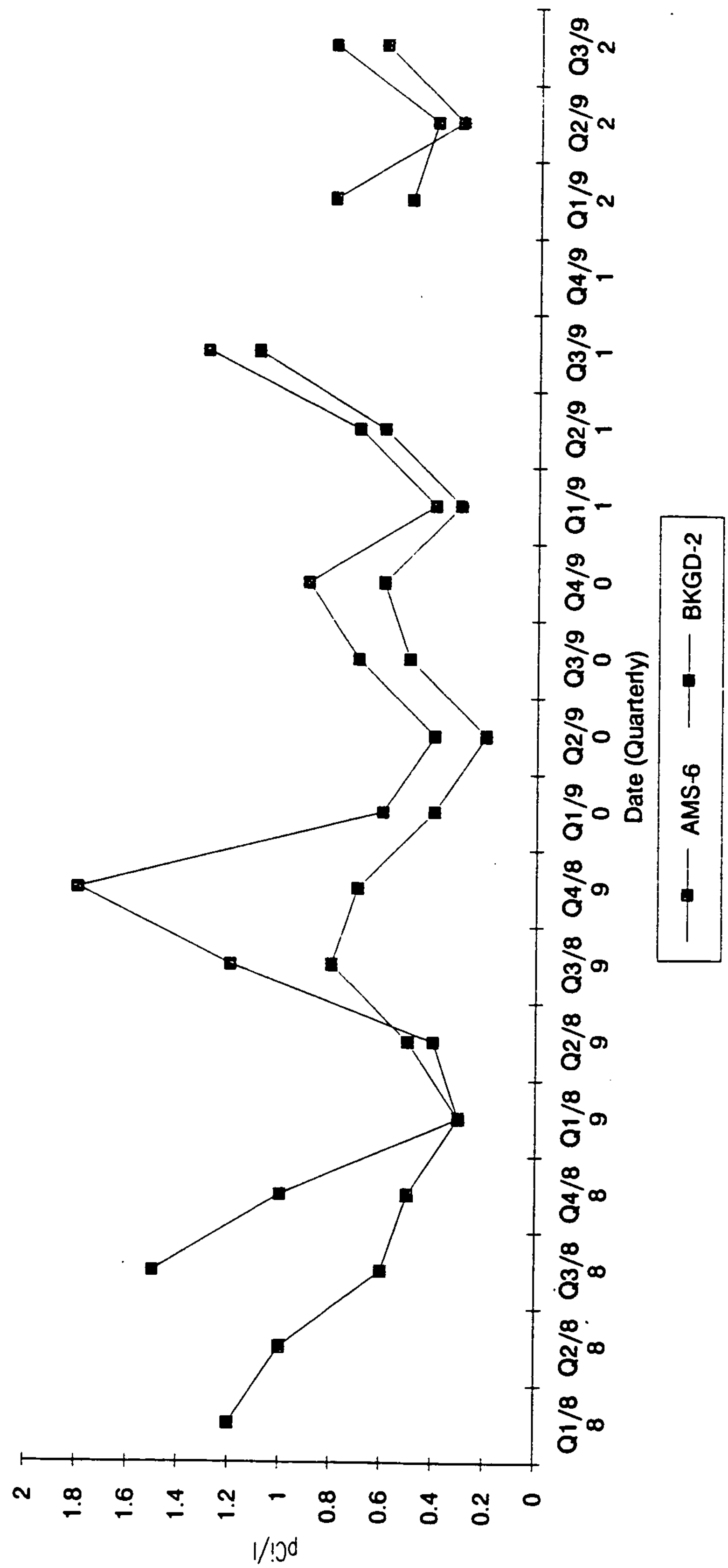
PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 5 AND BACKGROUND LOCATION 4



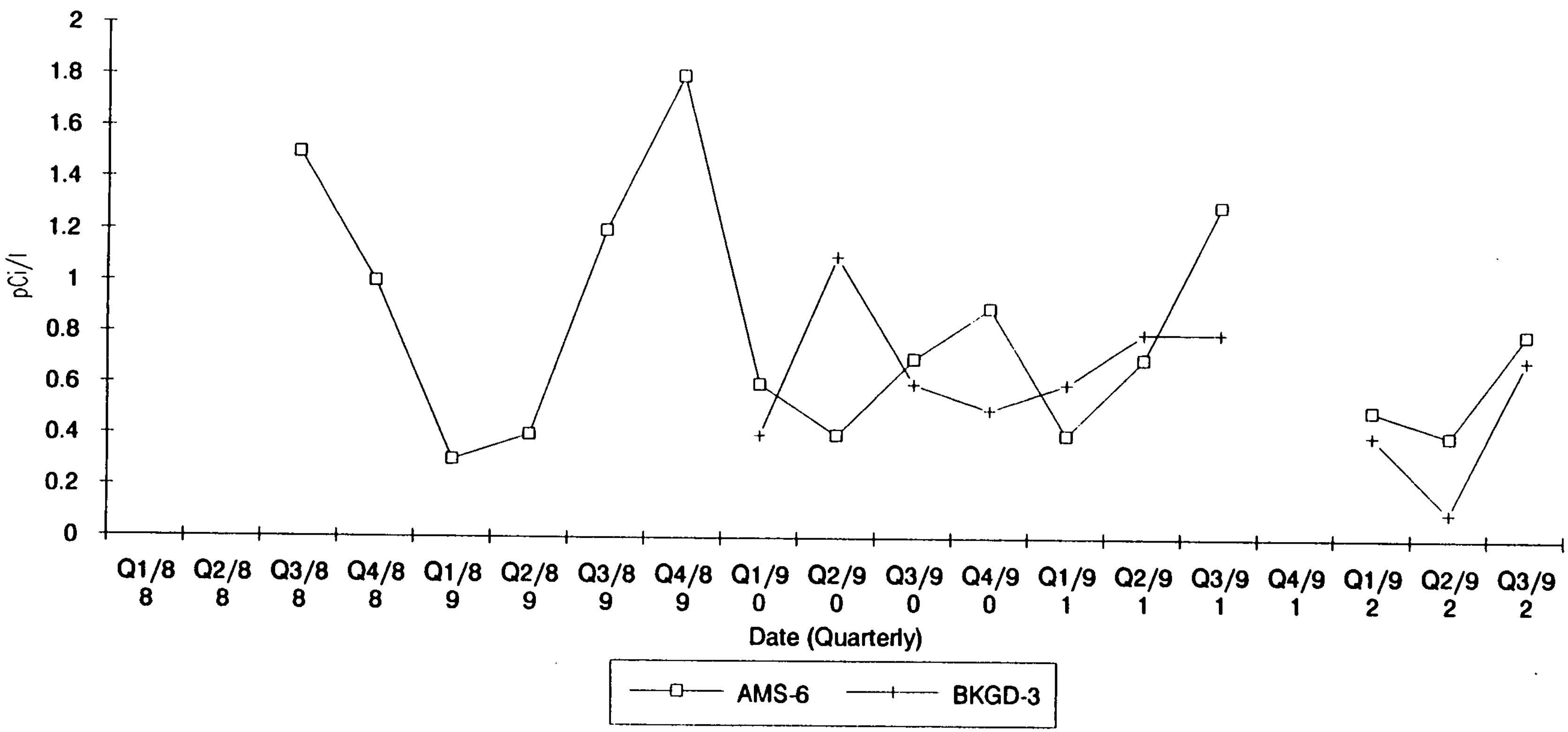
PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 6 AND BACKGROUND LOCATION 1



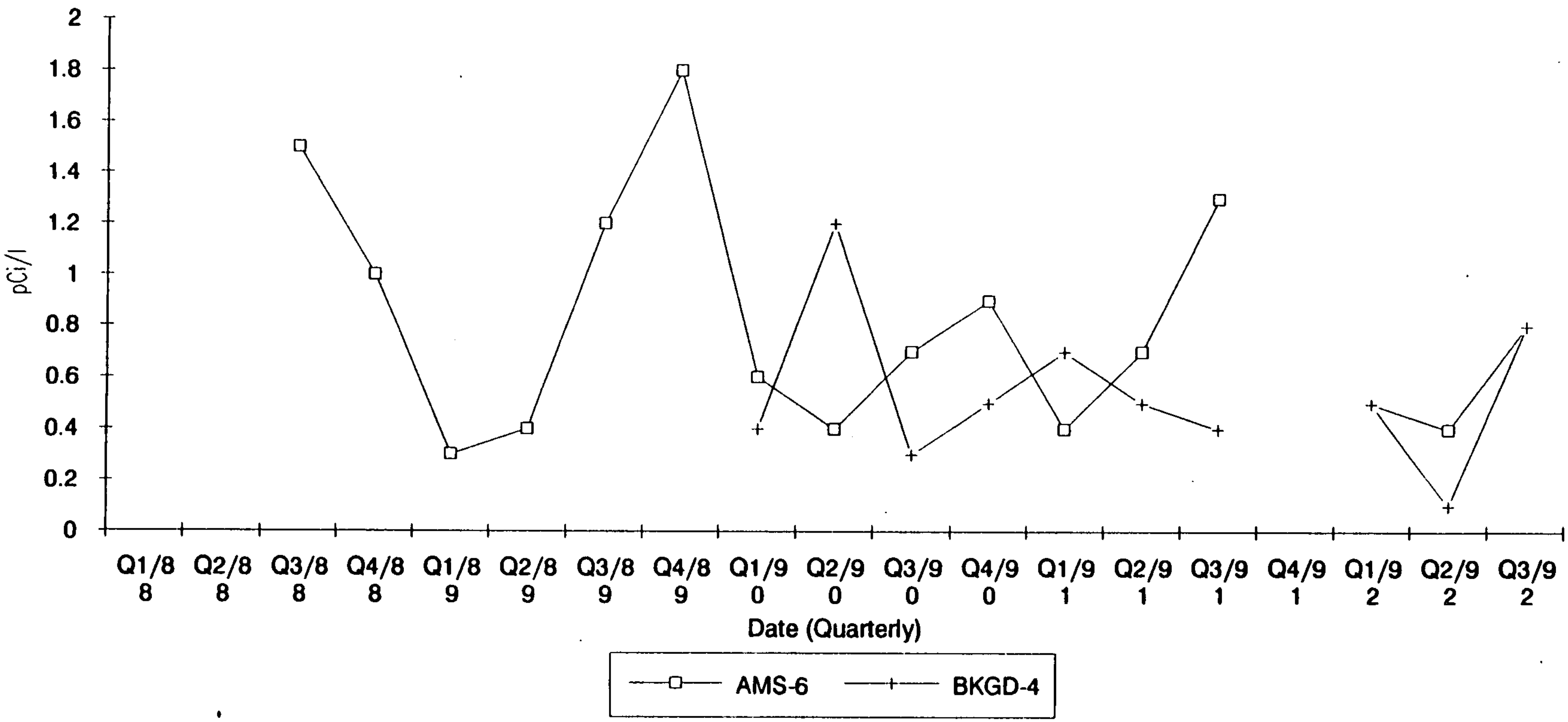
PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 6 AND BACKGROUND LOCATION 2



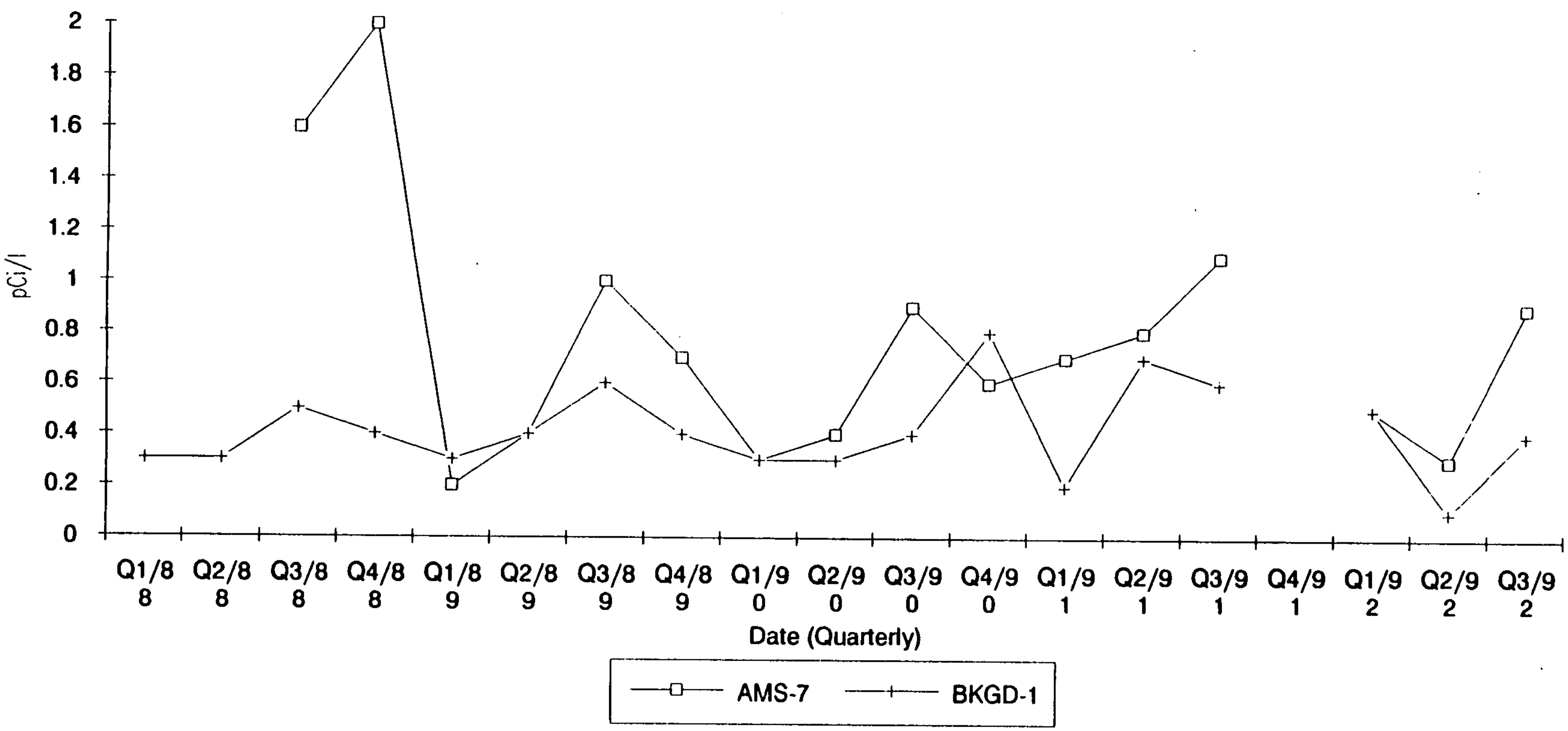
PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 6 AND BACKGROUND LOCATION 3



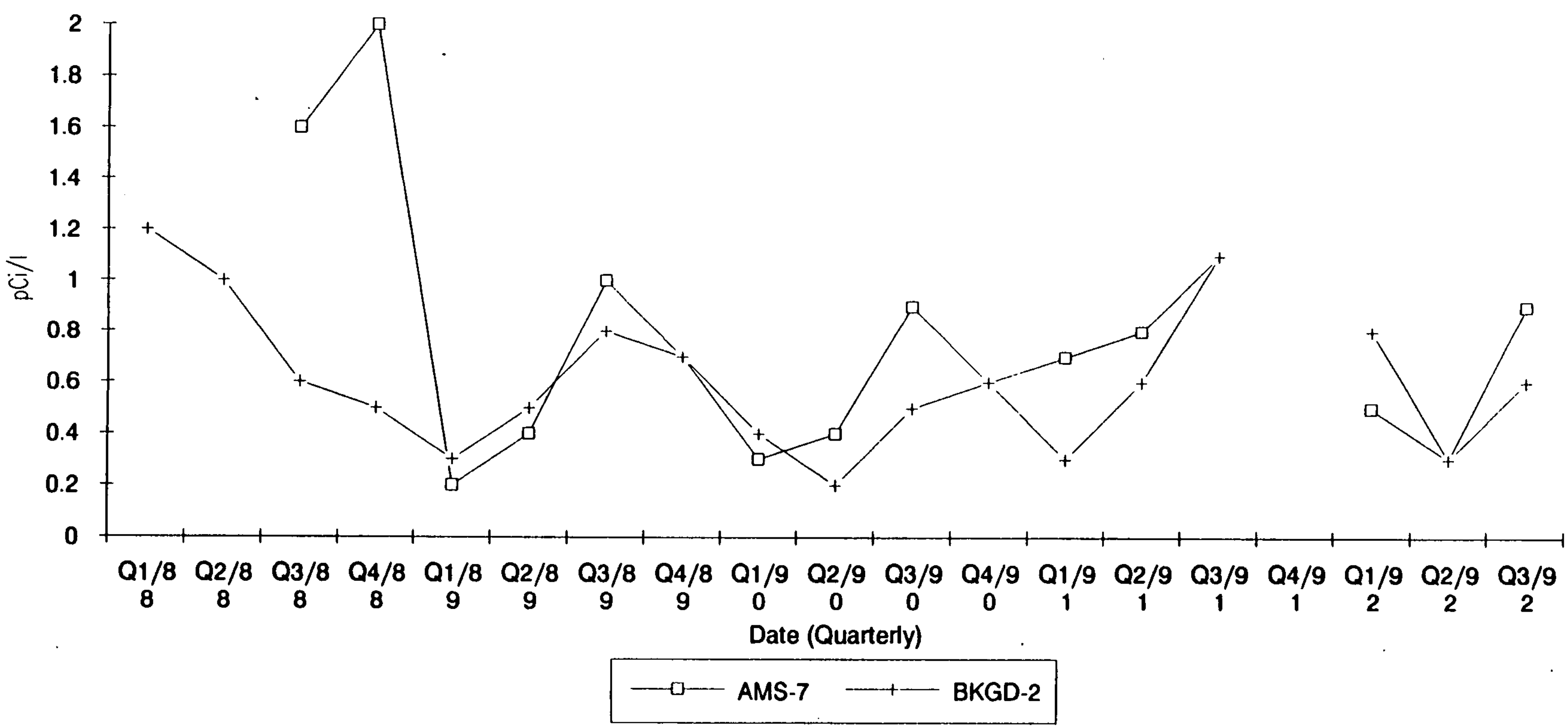
PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 6 AND BACKGROUND LOCATION 4

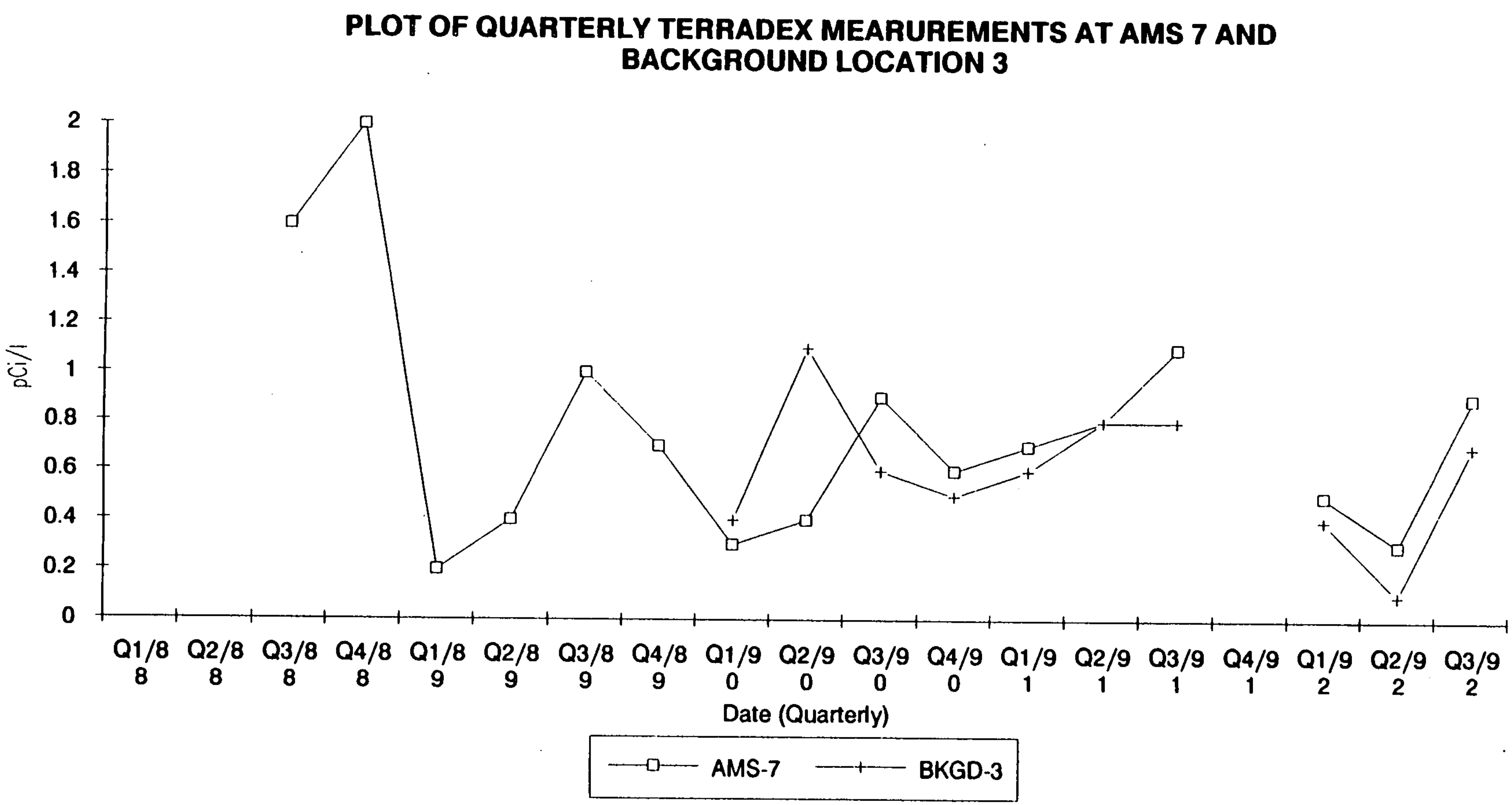


PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 7 AND BACKGROUND LOCATION 1

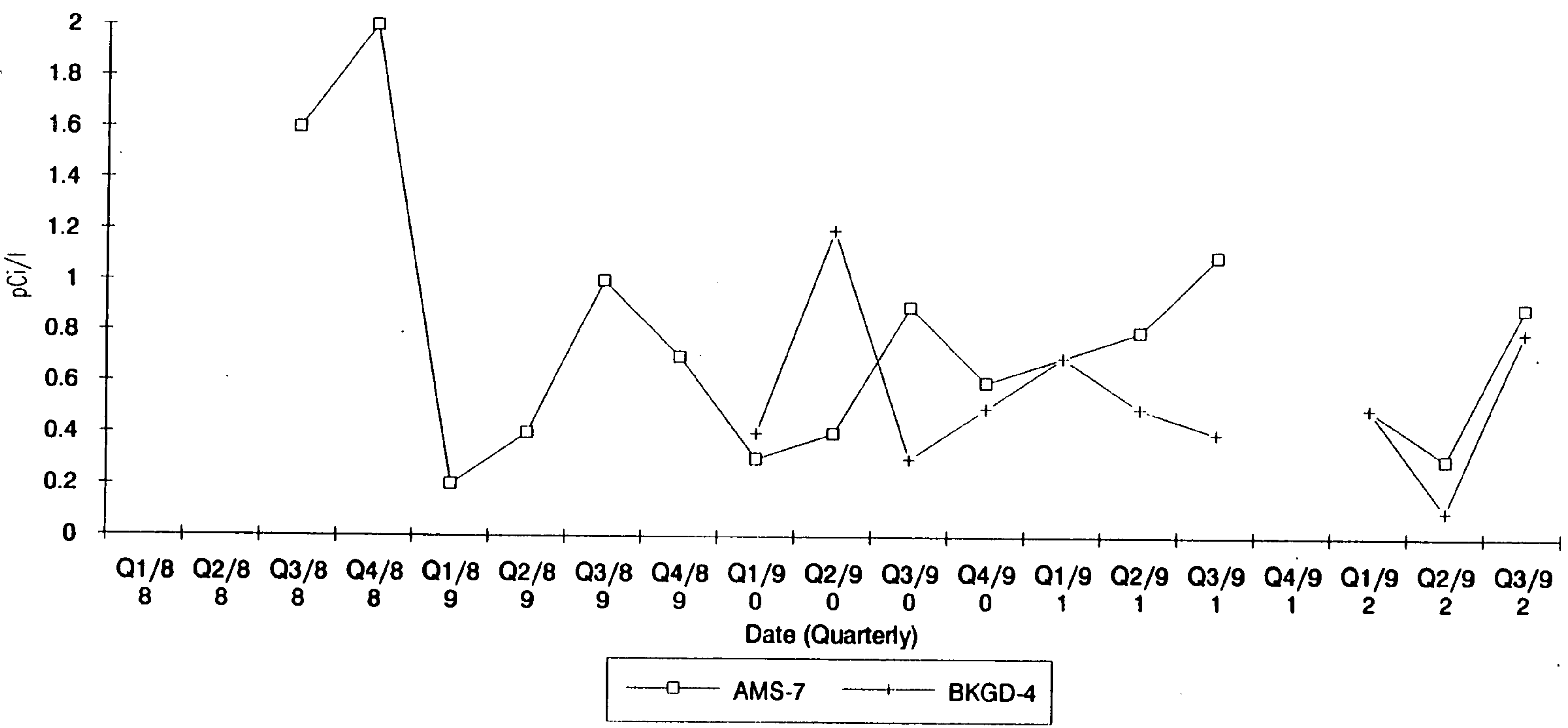


PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 7 AND BACKGROUND LOCATION 2




PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 7 AND
BACKGROUND LOCATION 3
pCi/l
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Q1/8 8
Q2/8 8
Q3/8 8
Q4/8 8
Q1/8 9
Q2/8 9
Q3/8 9
Q4/8 9
Q1/9 0
Q2/9 0
Q3/9 0
Q4/9 0
Q1/9 1
Q2/9 1
Q3/9 1
Q4/9 1
Q1/9 2
Q2/9 2
Q3/9 2
Date (Quarterly)
AMS-7
BKGD-3

PLOT OF QUARTERLY TERRADEX MEARUREMENTS AT AMS 7 AND BACKGROUND LOCATION 4

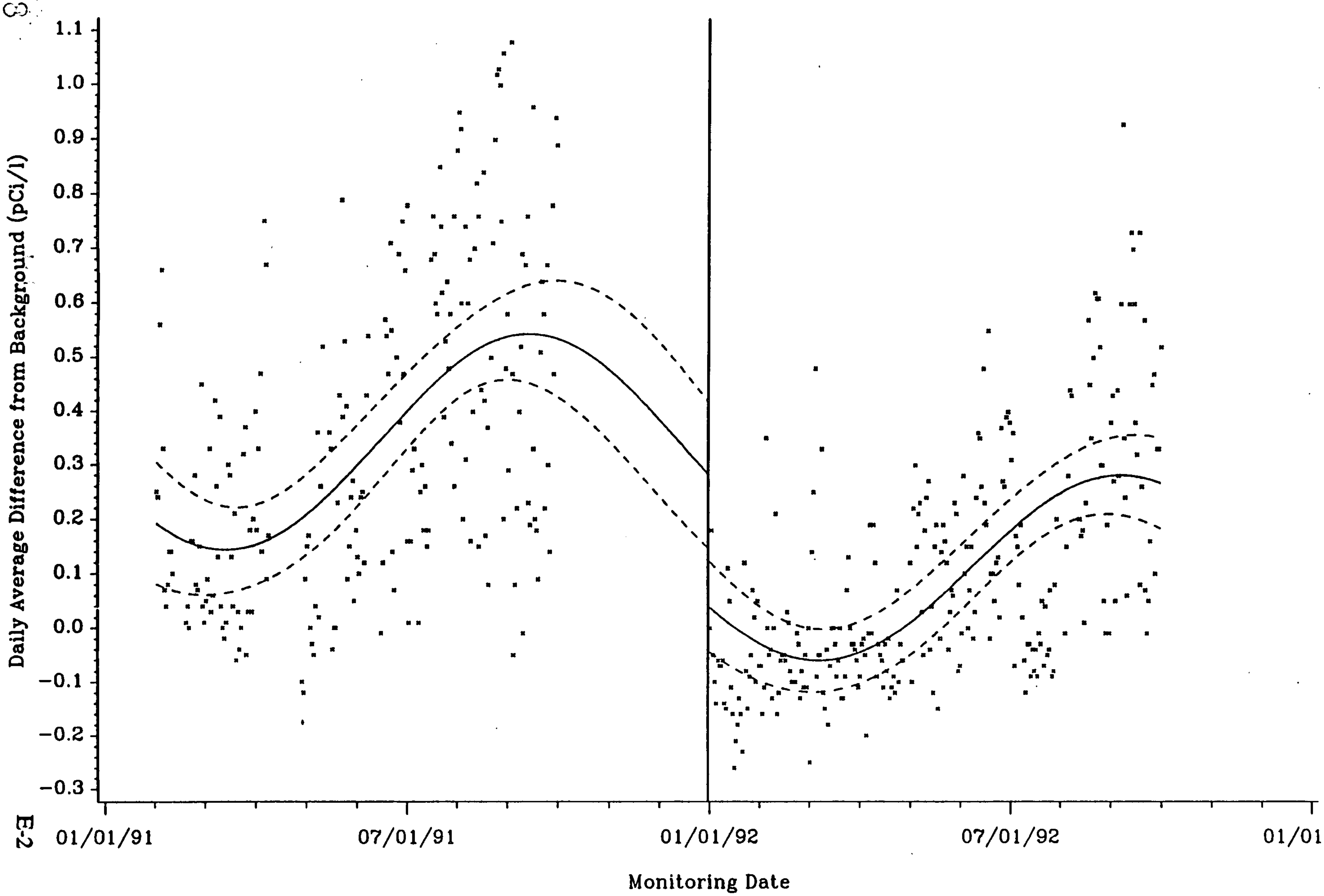


ATTACHMENT E

DAILY AVERAGE DIFFERENCE IN RADON CONCENTRATIONS FROM BACKGROUND WITH PREDICTED DIFFERENCE AND APPROXIMATE 95 PERCENT CONFIDENCE BOUNDS AS DETERMINED BY THE TIME SERIES MODEL

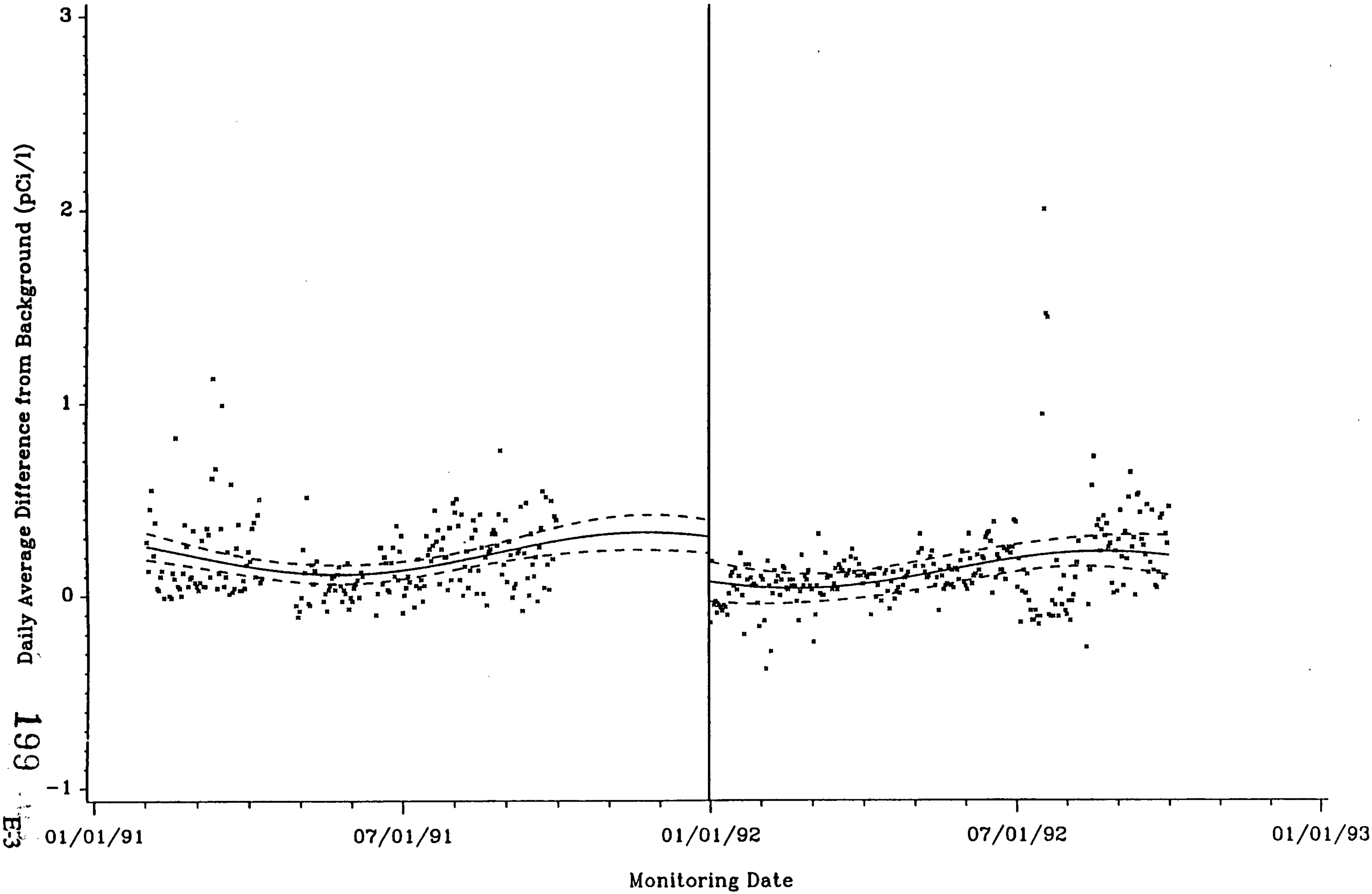
Daily Average Difference in Radon Concentration from Background, with Predicted Difference and Approximate 95% Confidence Bounds as Determined by the Model

Monitoring Station=AMS5



Daily Average Difference in Radon Concentration from Background, with Predicted Difference and Approximate 95% Confidence Bounds as Determined by the Model

Monitoring Station=AMS6



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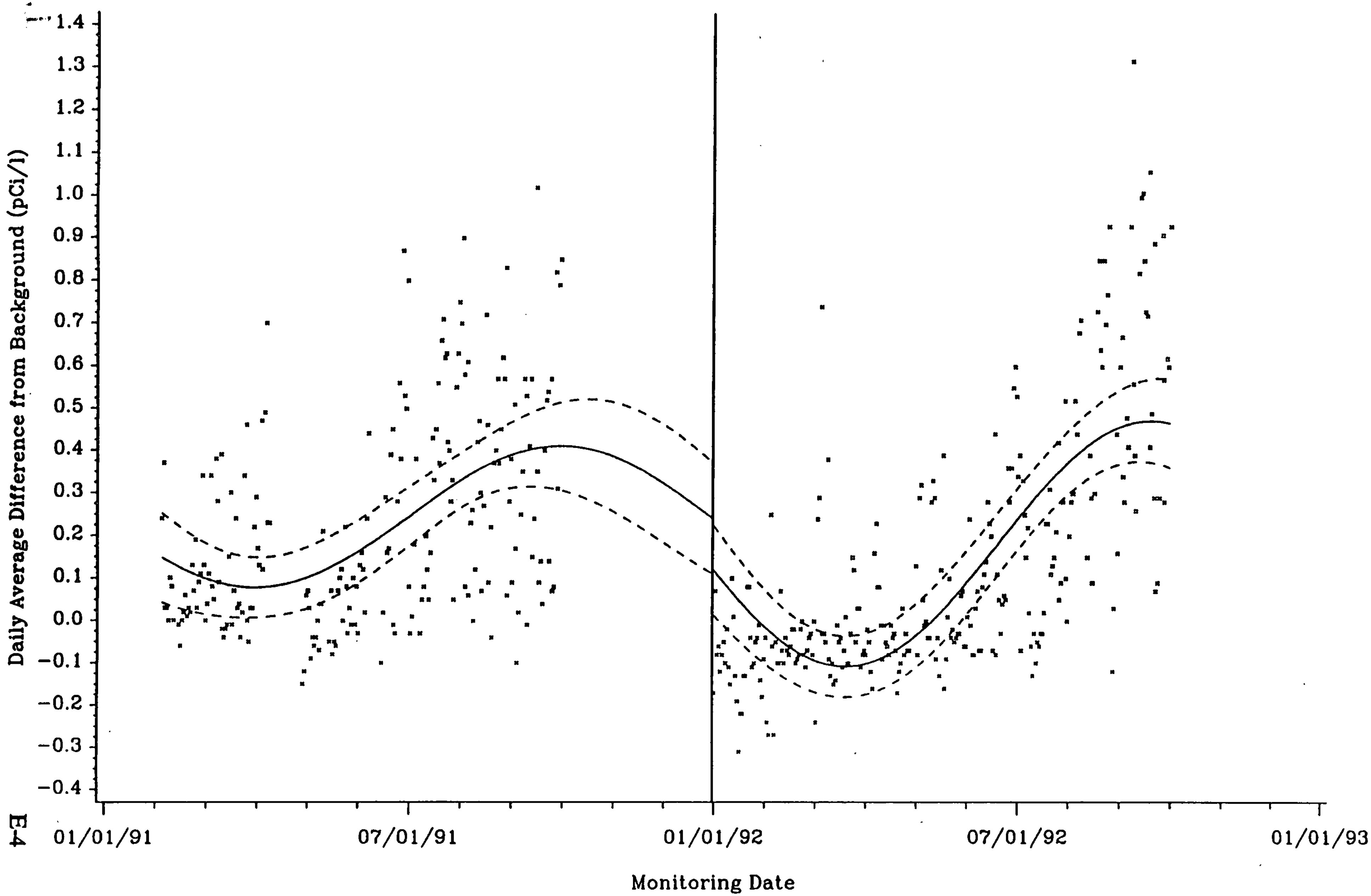
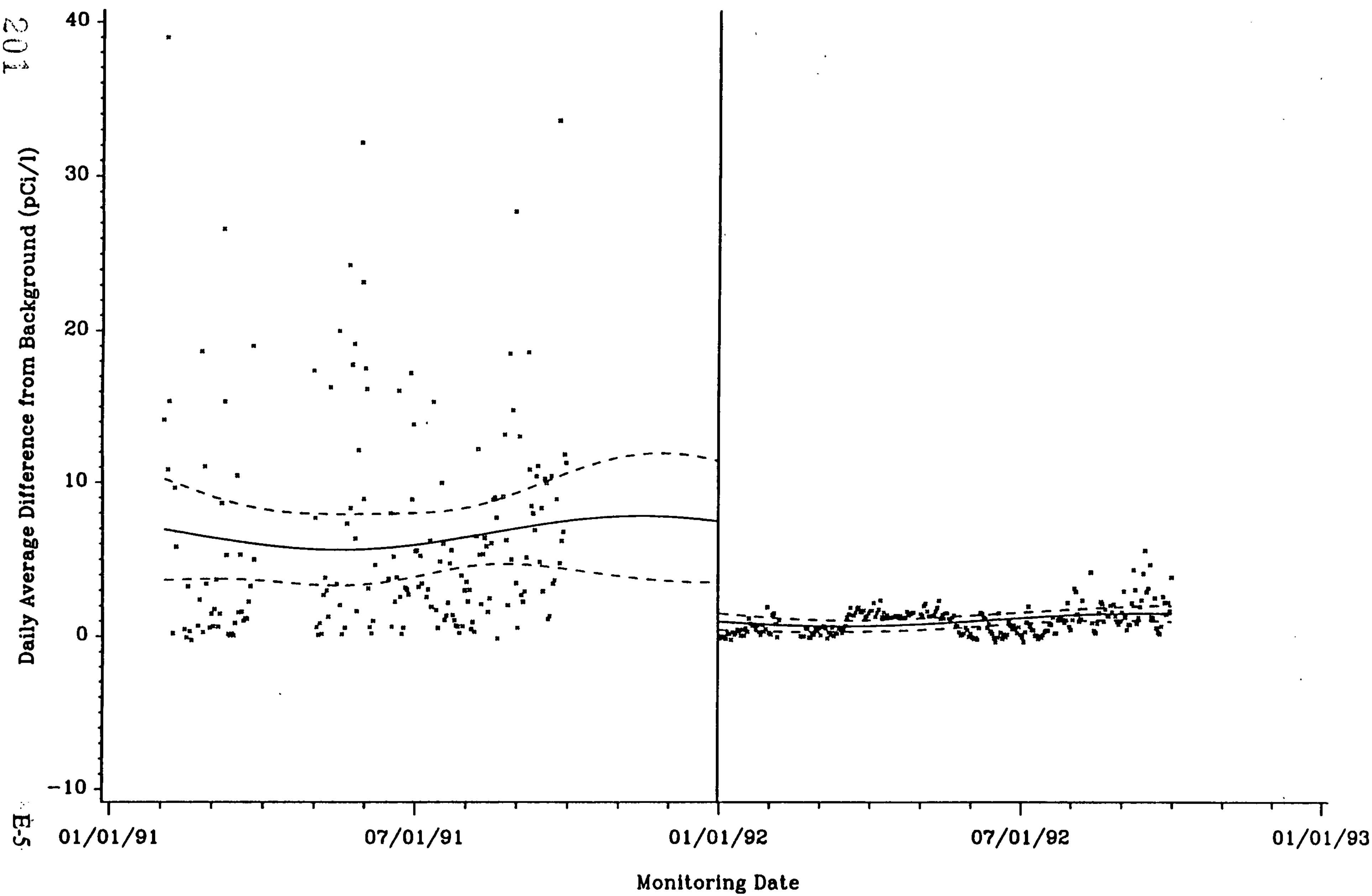
Daily Average Difference in Radon Concentration from Background, with Predicted Difference and Approximate 95% Confidence Bounds as Determined by the Model

Monitoring Station=AMS7



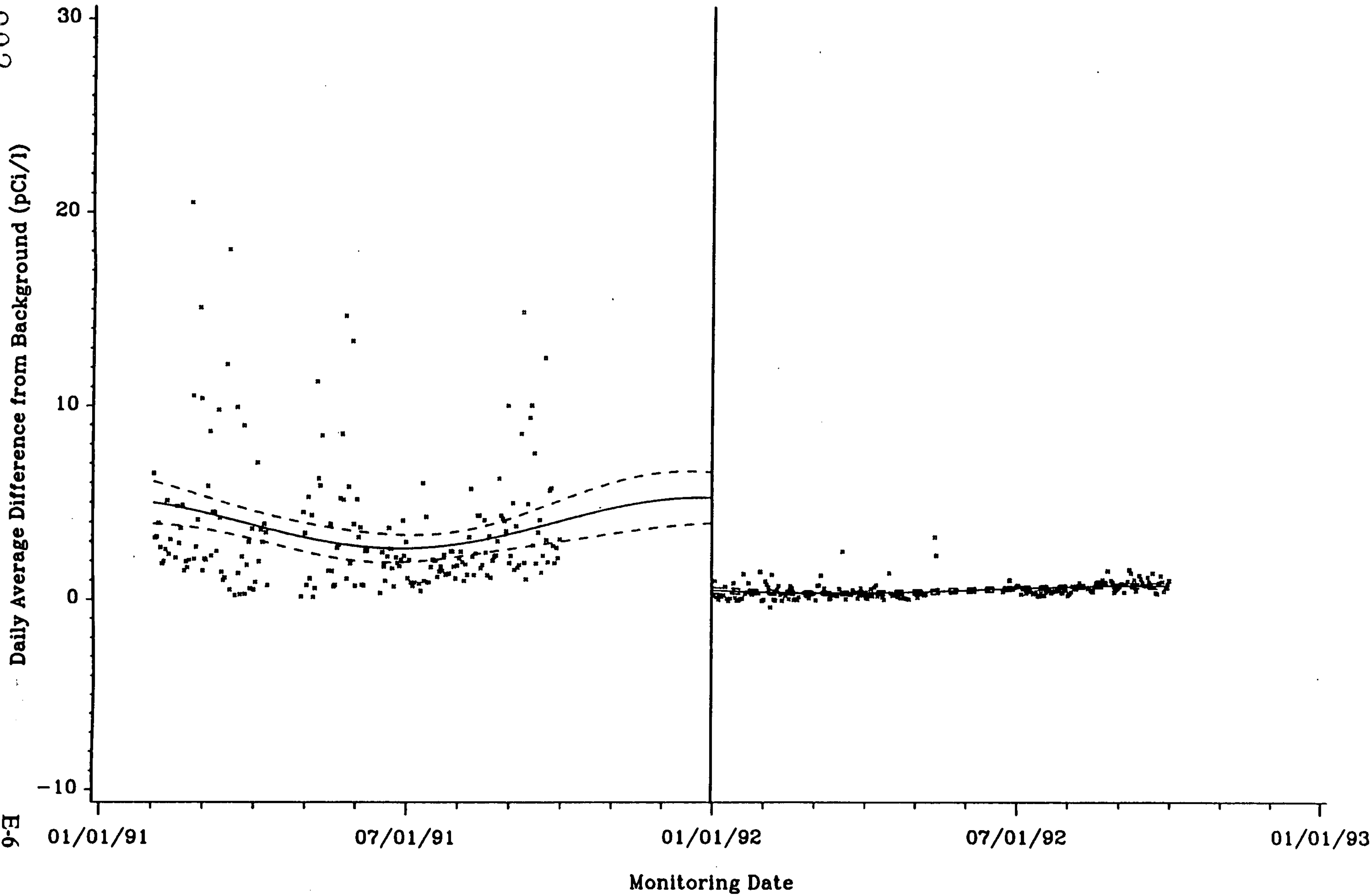
Daily Average Difference in Radon Concentration from Background, with Predicted Difference and Approximate 95% Confidence Bounds as Determined by the Model

Monitoring Station=K_65_NE

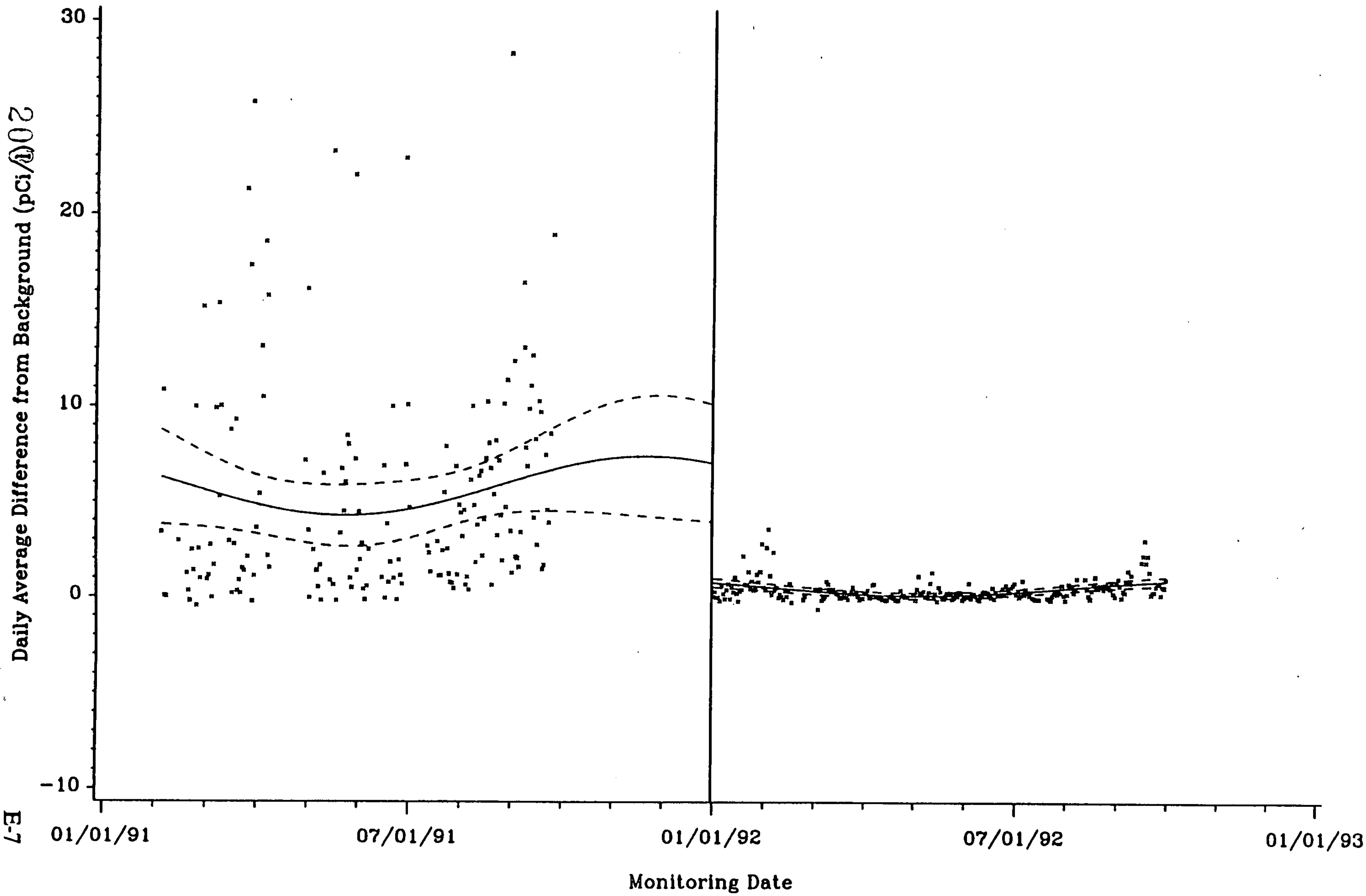


Daily Average Difference in Radon Concentration from Background, with Predicted Difference and Approximate 95% Confidence Bounds as Determined by the Model

Monitoring Station=K_65_NW

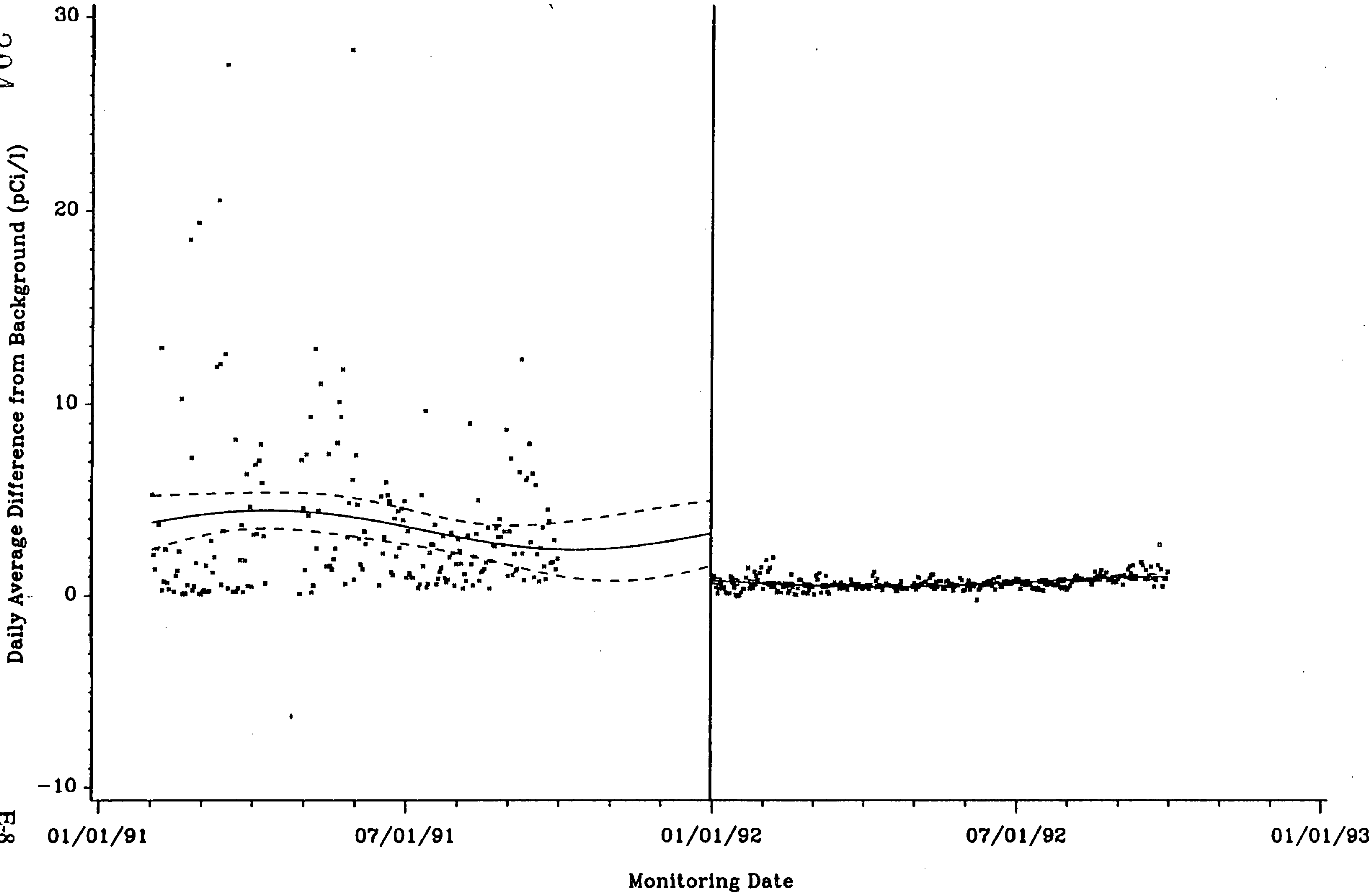


Daily Average Difference in Radon Concentration from Background, with Predicted Difference and Approximate 95% Confidence Bounds as Determined by the Model
Monitoring Station=K_65_SE



Daily Average Difference in Radon Concentration from Background, with Predicted Difference and Approximate 95% Confidence Bounds as Determined by the Model

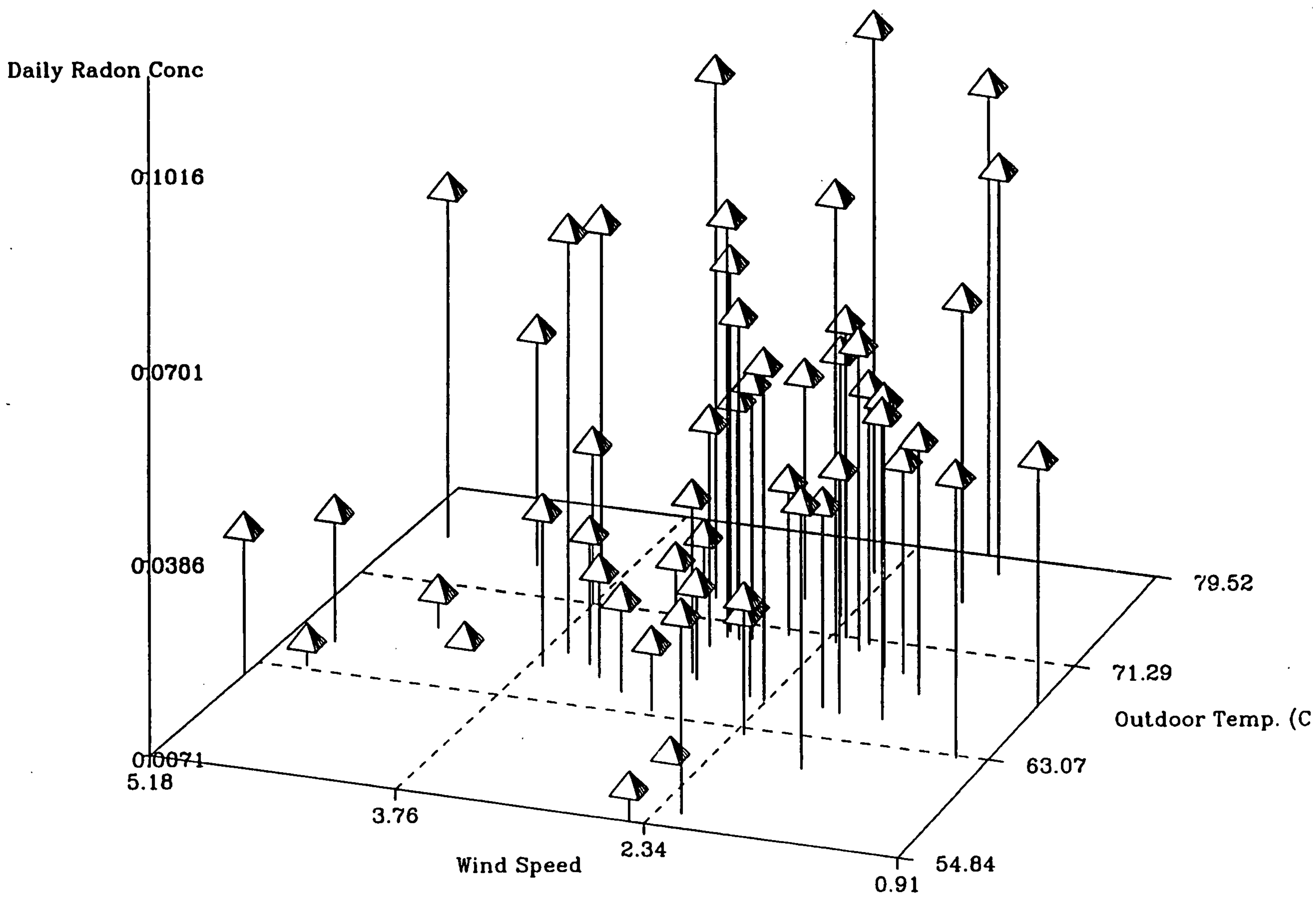
Monitoring Station=K_65_SW



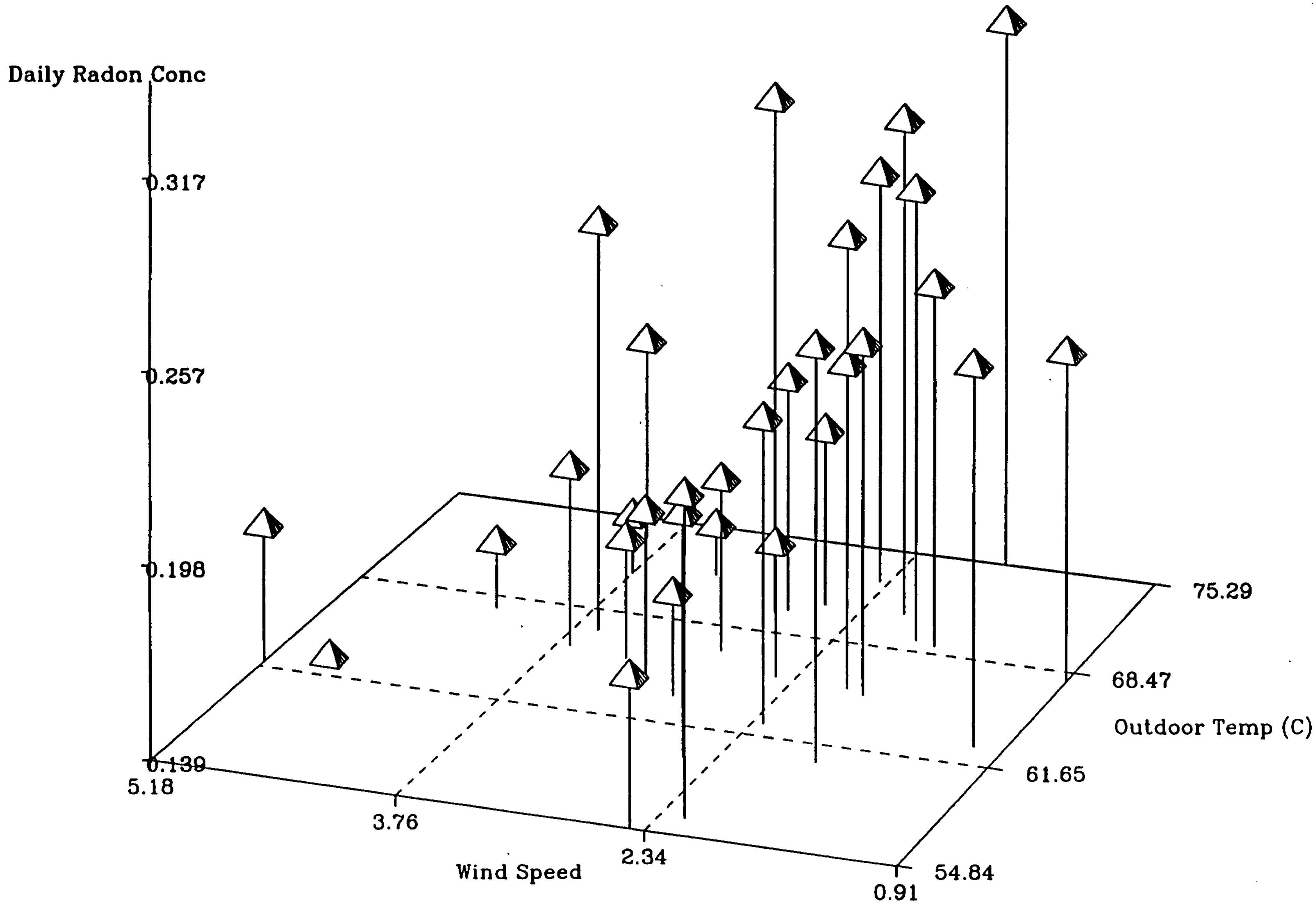
ATTACHMENT F

PLOT OF DAILY AVERAGE RADON CONCENTRATION IN THE SILO HEADSPACE AS A FUNCTION OF WIND SPEED AND OUTDOOR TEMPERATURE

Plot of Daily Average Radon Concentration (million pCi/l) in the Headspace of Silo #1
as a Function of Wind Speed (at Ten Meters) and Outdoor Temperature

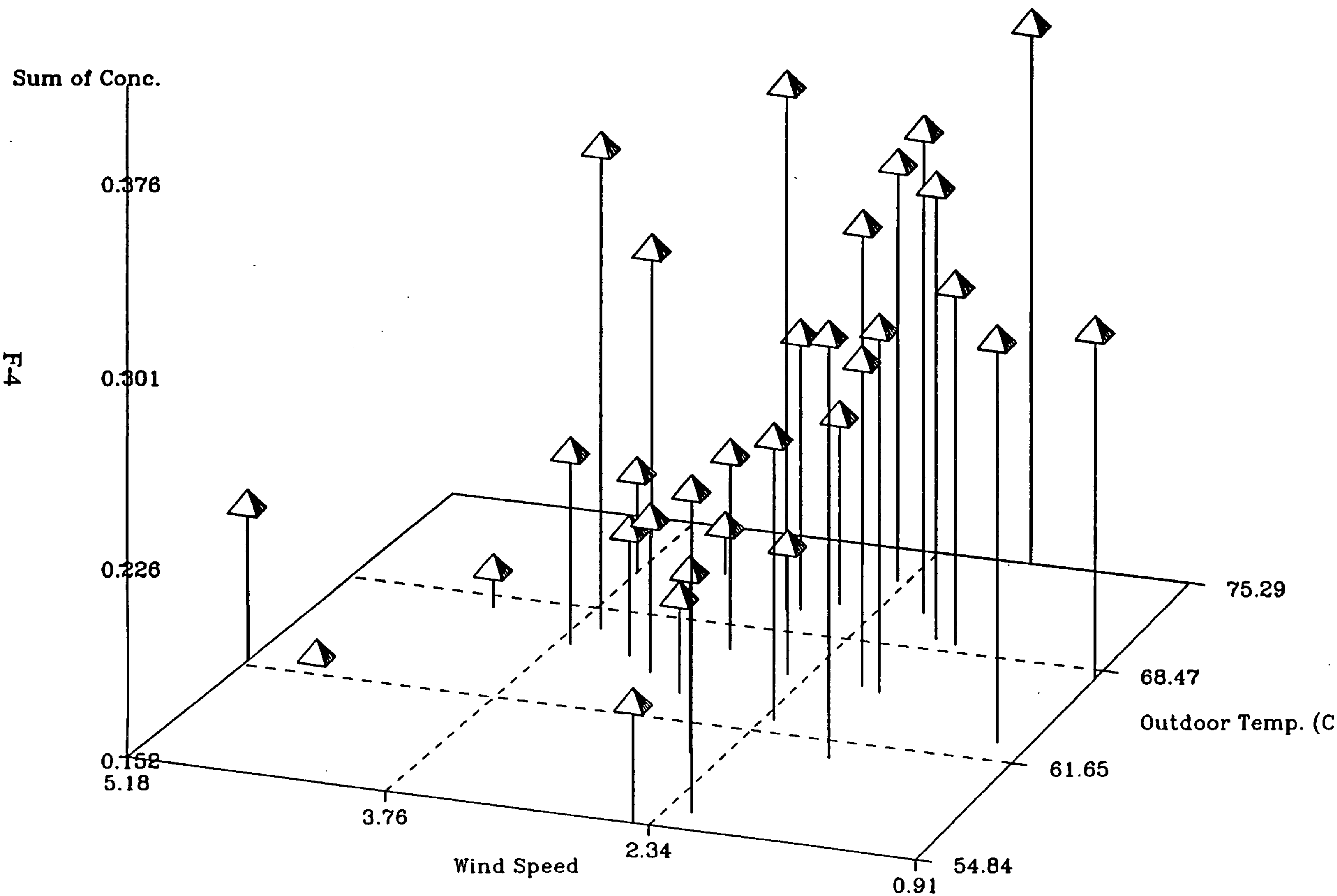


Plot of Daily Average Radon Concentration (million pCi/l) in the Headspace of Silo #2
as a Function of Wind Speed (at Ten Meters) and Outdoor Temperature



F-3

Plot of Daily Average Headspace Radon Concentration (million pCi/l) (Summed Over the Two Silos) as a Function of Wind Speed (at Ten Meters) and Outdoor Temperature

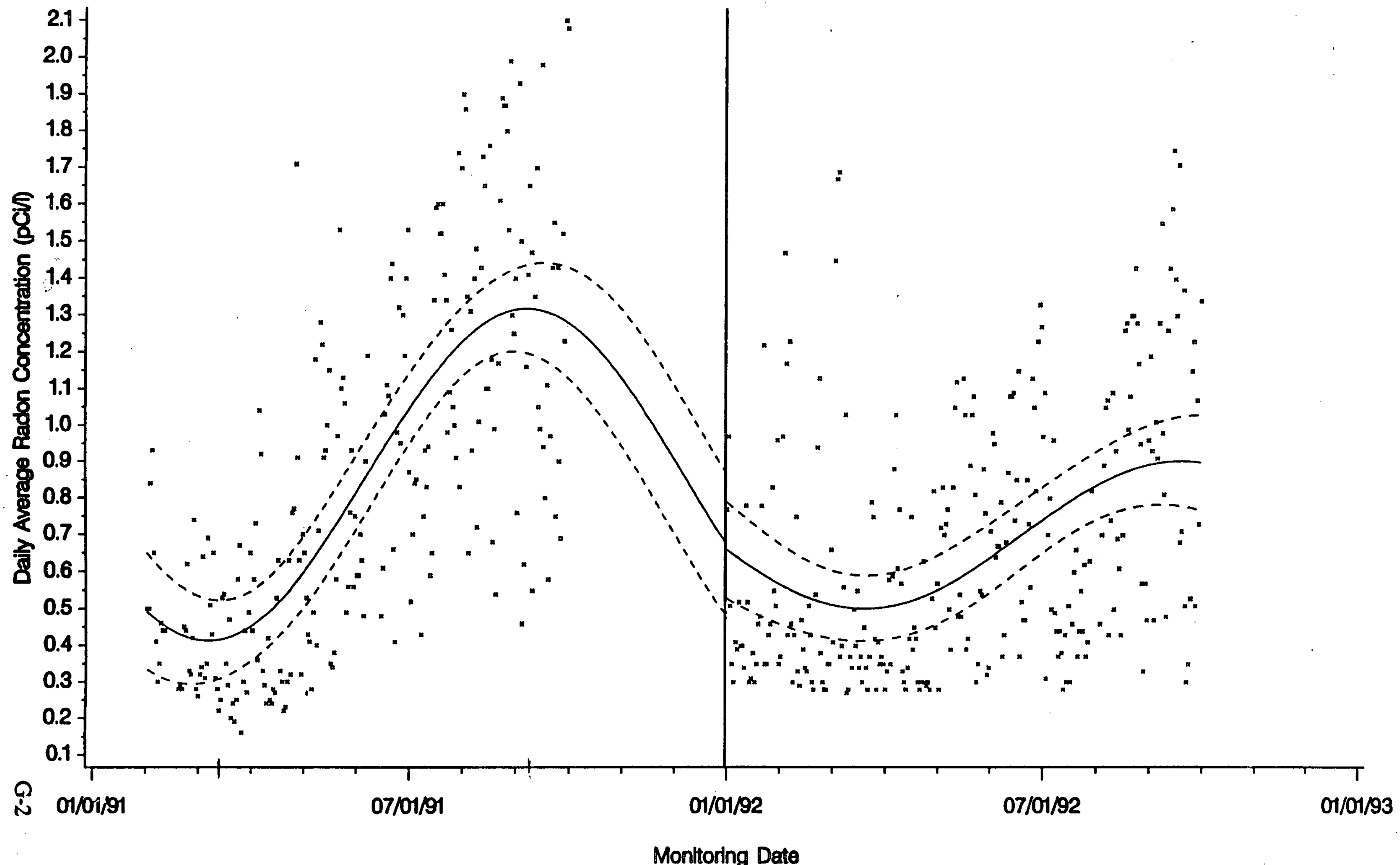


F-4

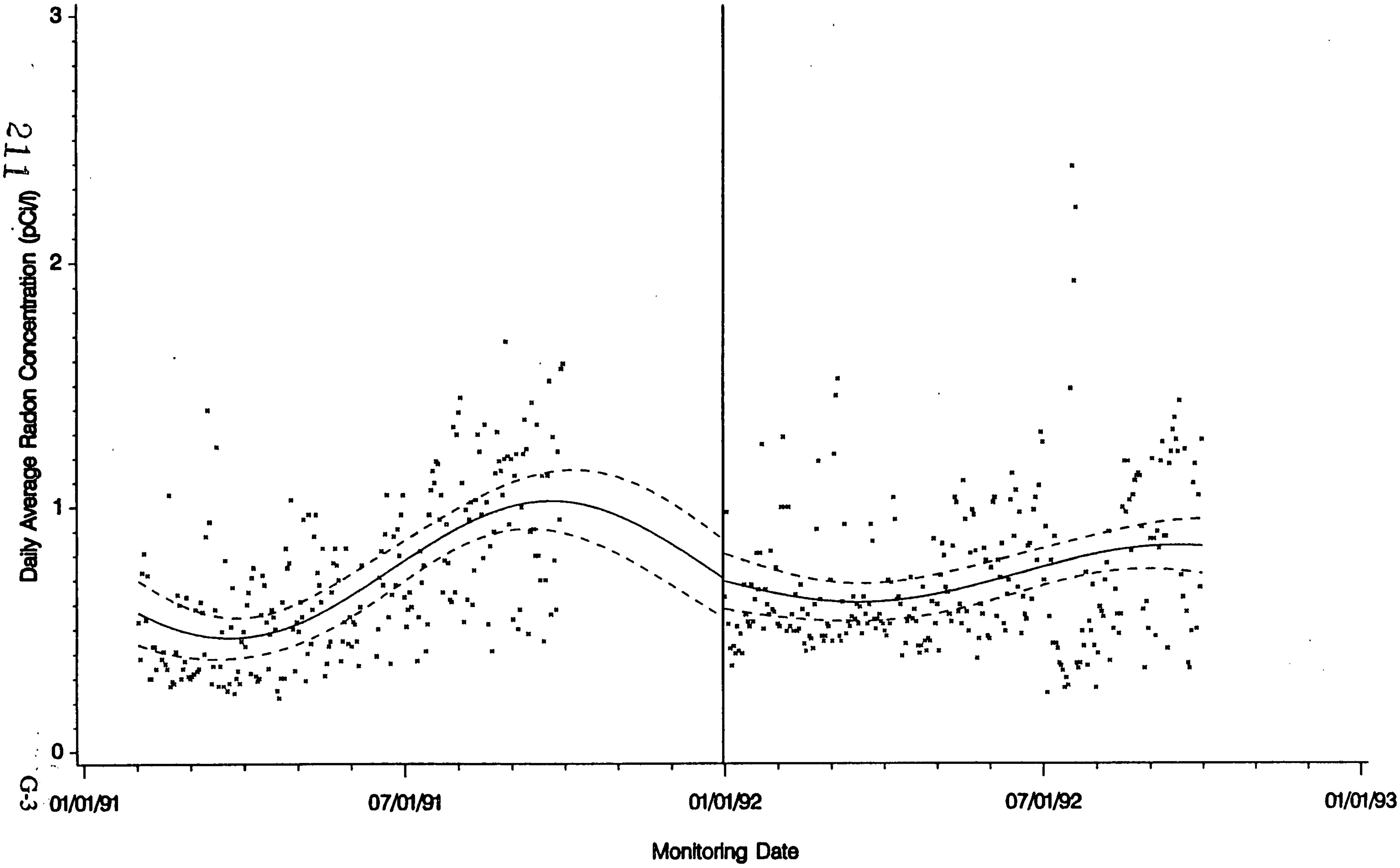
ATTACHMENT G

DAILY AVERAGE RADON CONCENTRATIONS, WITH PREDICTED CONCENTRATIONS AND APPROXIMATE 95 PERCENT CONFIDENCE BOUNDS AS DETERMINED BY THE TIME SERIES MODEL

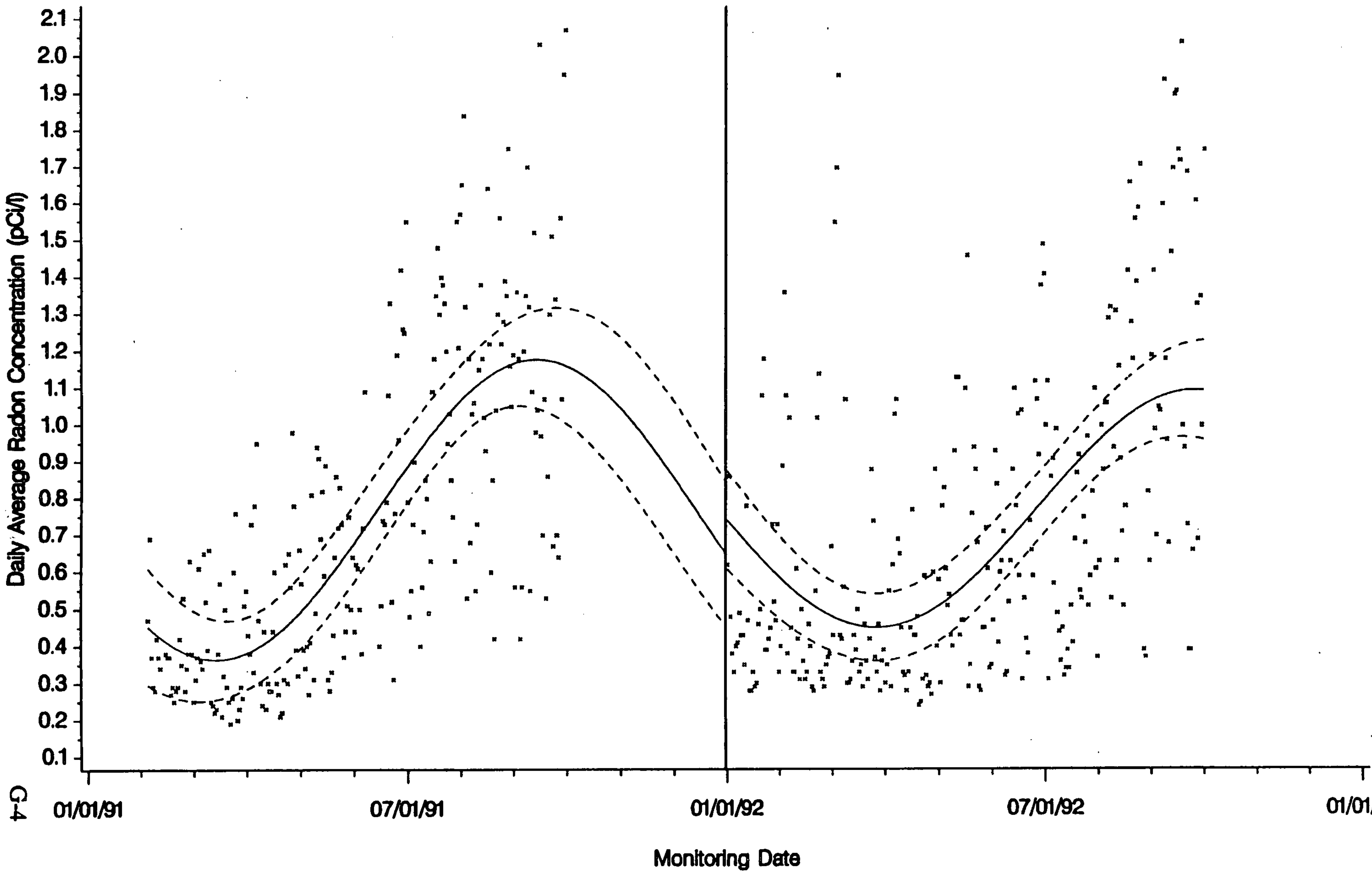
Daily Average Radon Concentration, with Predicted Concentration
and Approximate 95% Confidence Bounds as Determined by the Model
Monitoring Station=AMS5



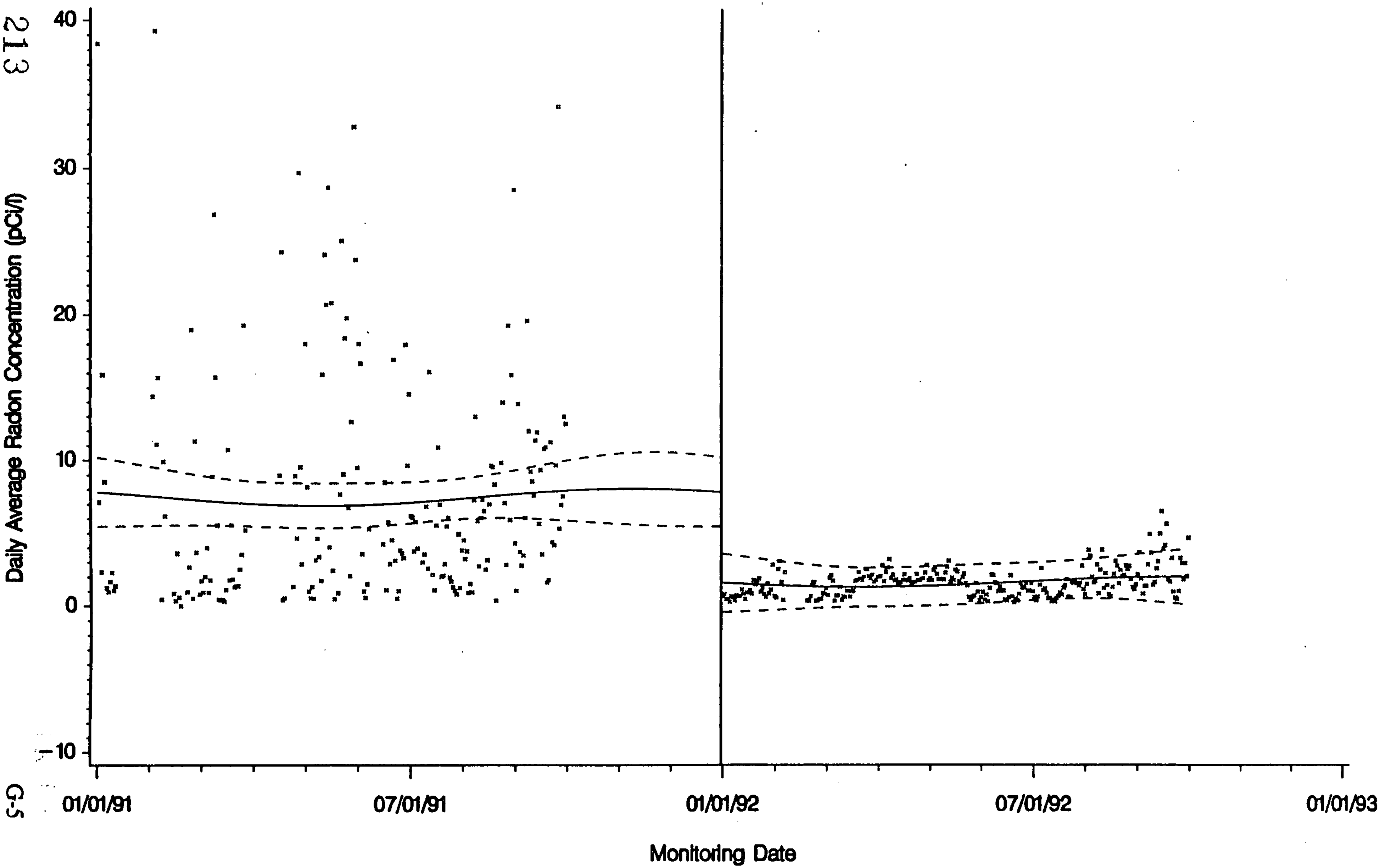
Daily Average Radon Concentration, with Predicted Concentration
and Approximate 95% Confidence Bounds as Determined by the Model
Monitoring Station=AMS6



Daily Average Radon Concentration, with Predicted Concentration
and Approximate 95% Confidence Bounds as Determined by the Model
Monitoring Station=AMS7

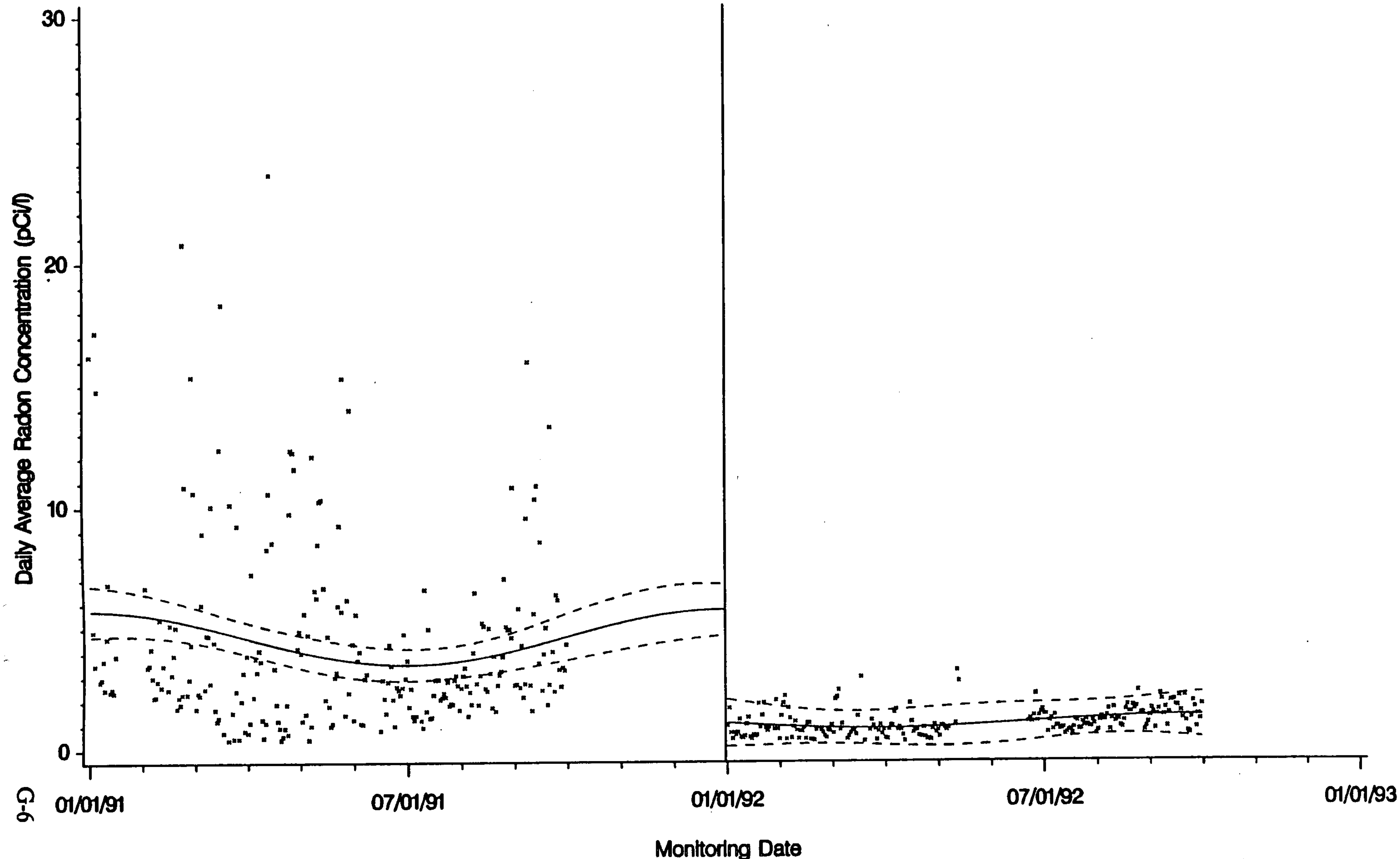


Daily Average Radon Concentration, with Predicted Concentration
and Approximate 95% Confidence Bounds as Determined by the Model
Monitoring Station = K_65_NE

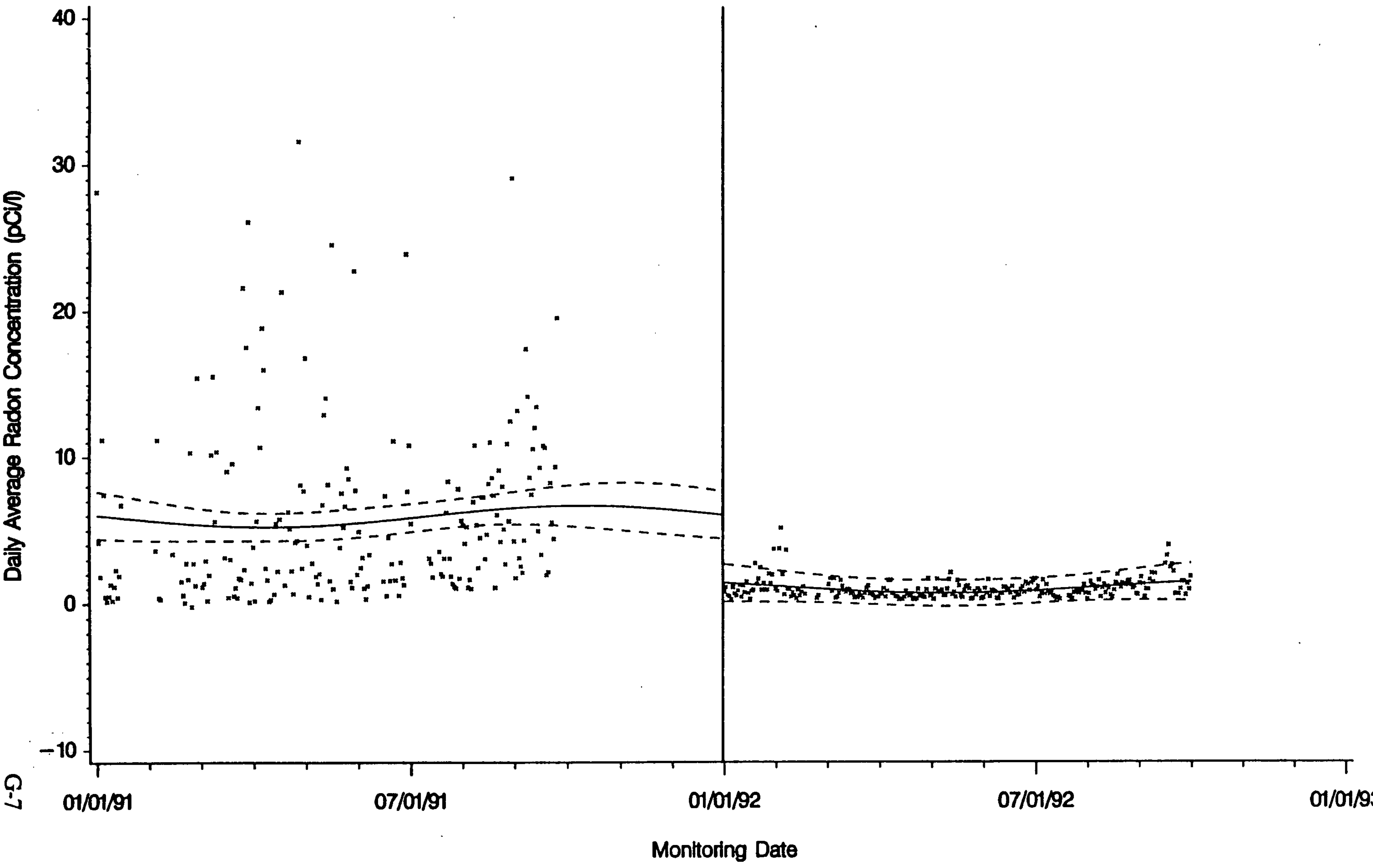


Daily Average Radon Concentration, with Predicted Concentration and Approximate 95% Confidence Bounds as Determined by the Model

Monitoring Station=K_65_NW

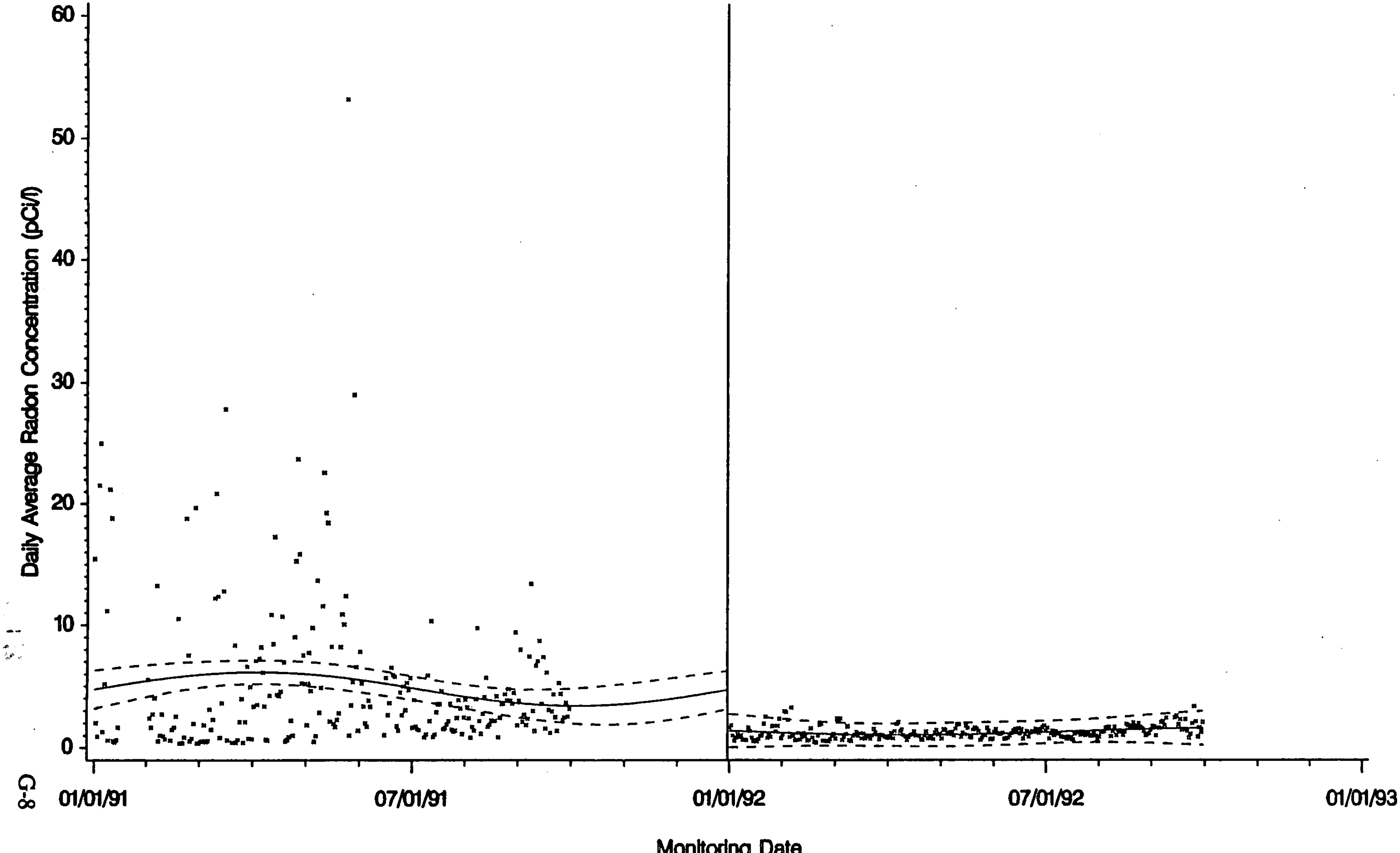


Daily Average Radon Concentration, with Predicted Concentration
and Approximate 95% Confidence Bounds as Determined by the Model
Monitoring Station=K_65_SE

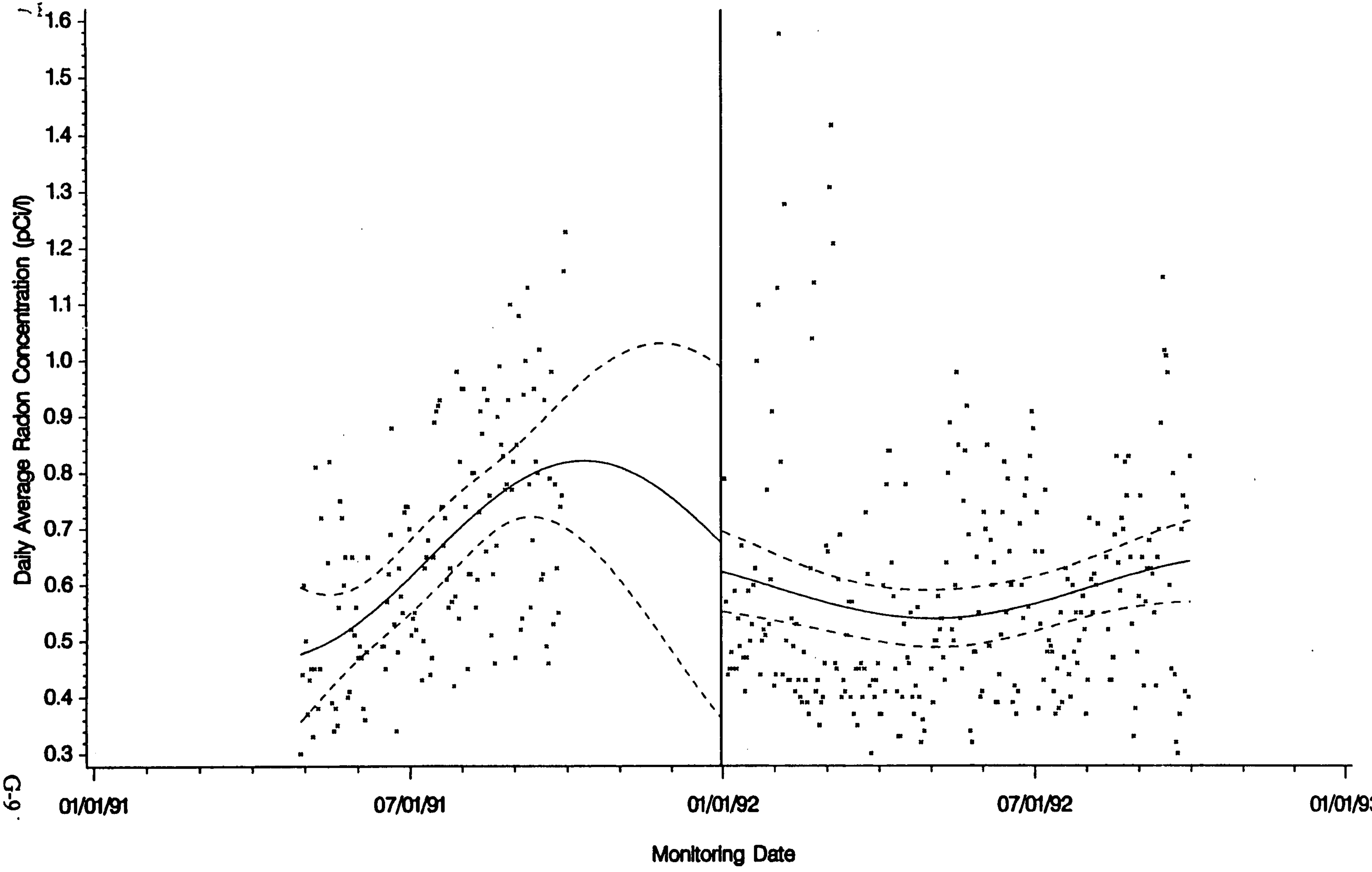


Daily Average Radon Concentration, with Predicted Concentration and Approximate 95% Confidence Bounds as Determined by the Model

Monitoring Station=K_65_SW



Daily Average Radon Concentration, with Predicted Concentration
and Approximate 95% Confidence Bounds as Determined by the Model
Monitoring Station = Background (pre – 4/16/92 data EXCLUDED)

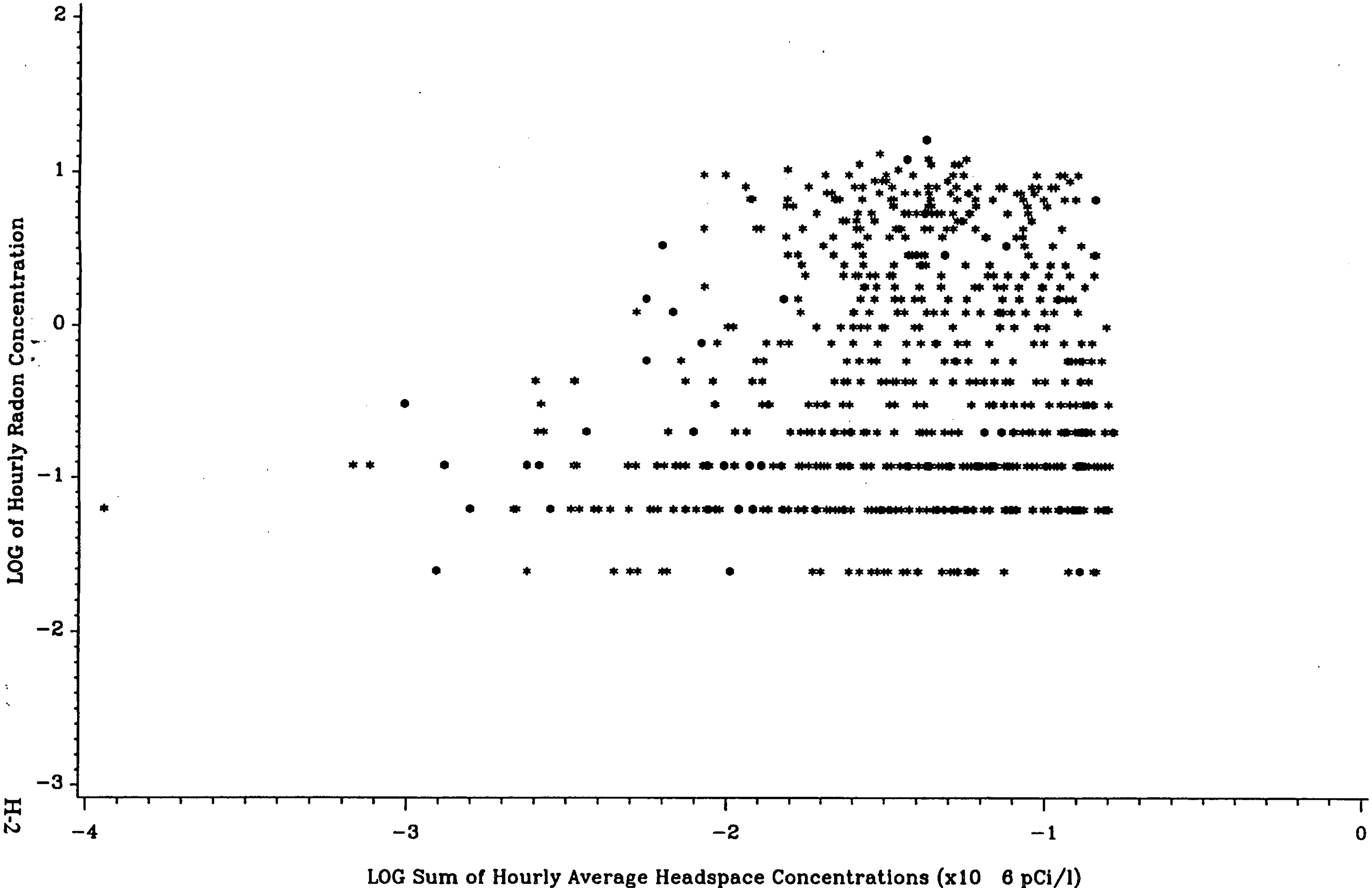


4010

ATTACHMENT H

PLOT OF LOG HOURLY RADON CONCENTRATIONS AT EACH MONITORING STATION VERSUS SUM OF HOURLY HEADSPACE CONCENTRATIONS OF THE TWO SILOS

Plot of LOG Hourly Radon Concentration at AMS5 Versus LOG Sum of Hourly Average Headspace Concentrations of the Two Silos



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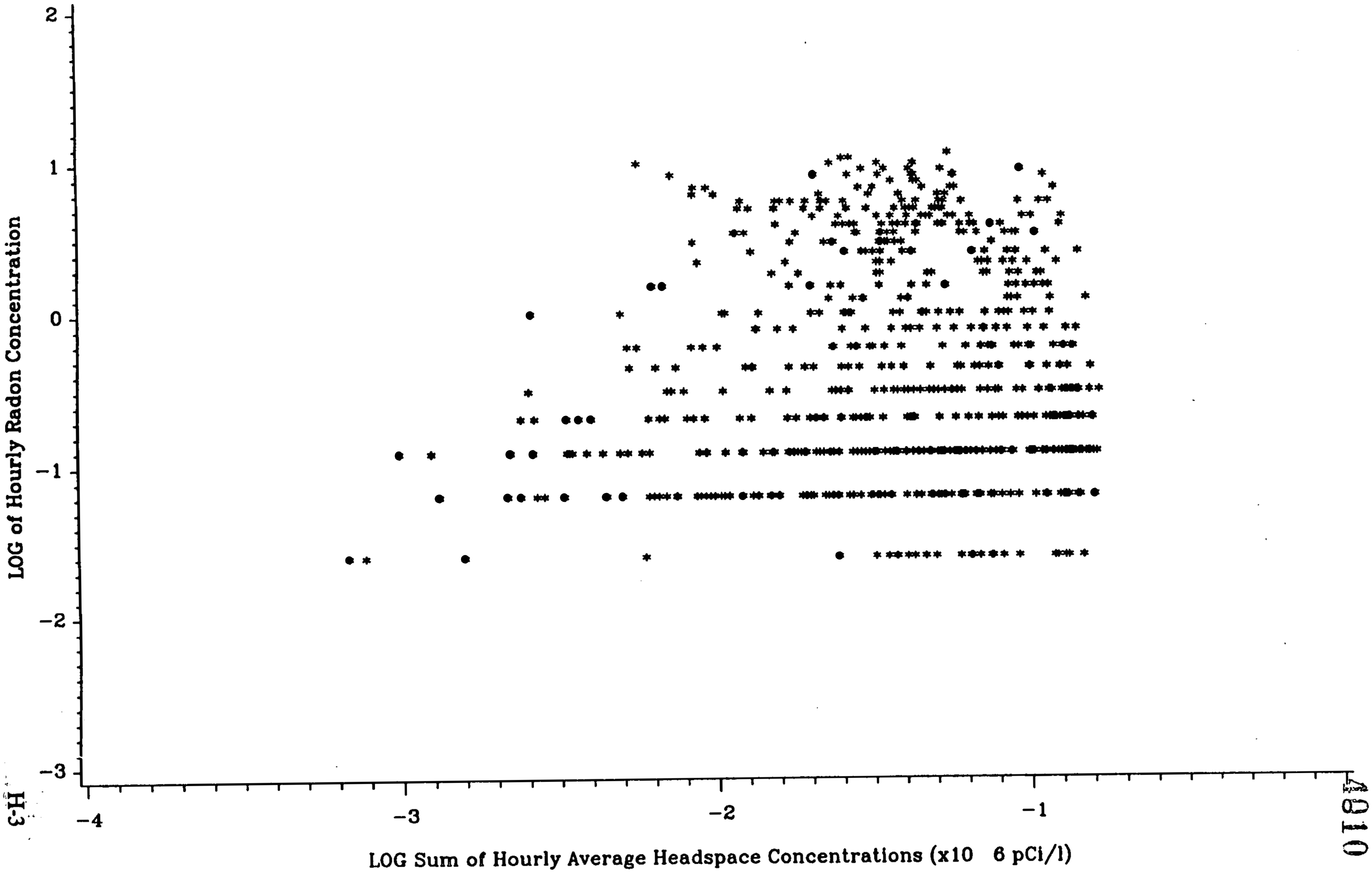
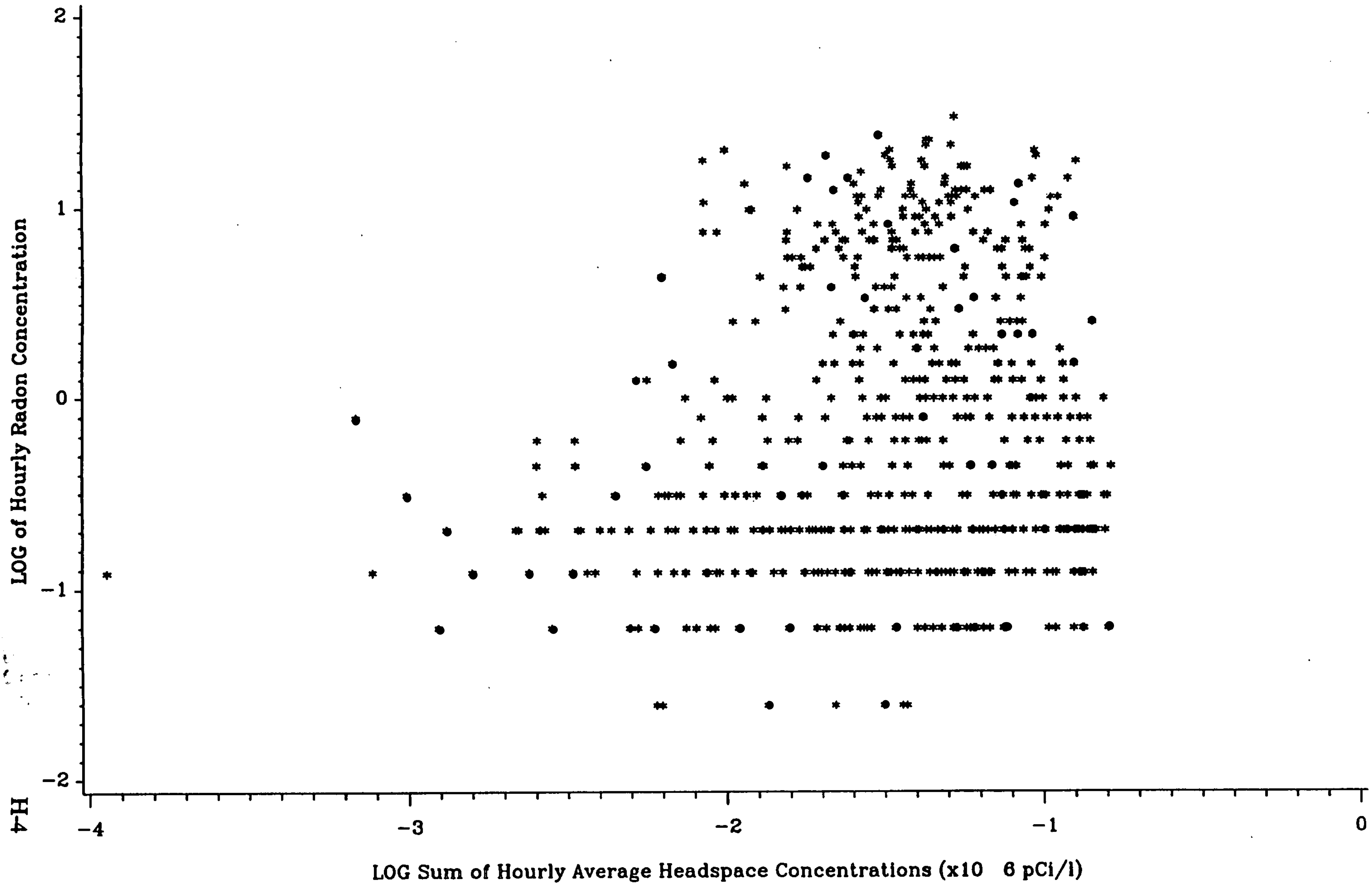
Plot of LOG Hourly Radon Concentration at AMS6 Versus LOG Sum of Hourly Average Headspace Concentrations of the Two Silos

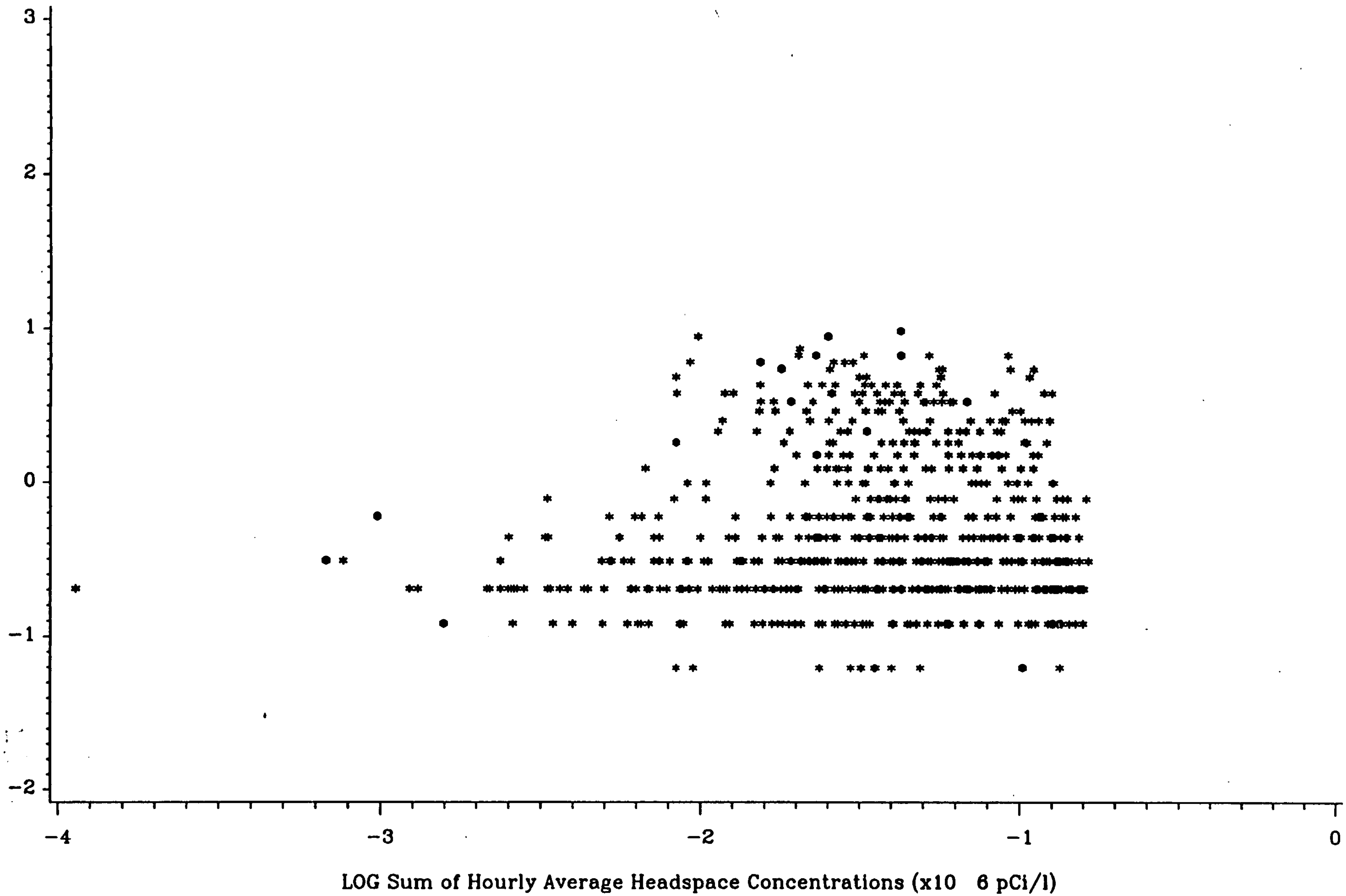


221

Plot of LOG Hourly Radon Concentration at AMS7 Versus LOG Sum of Hourly Average Headspace Concentrations of the Two Silos

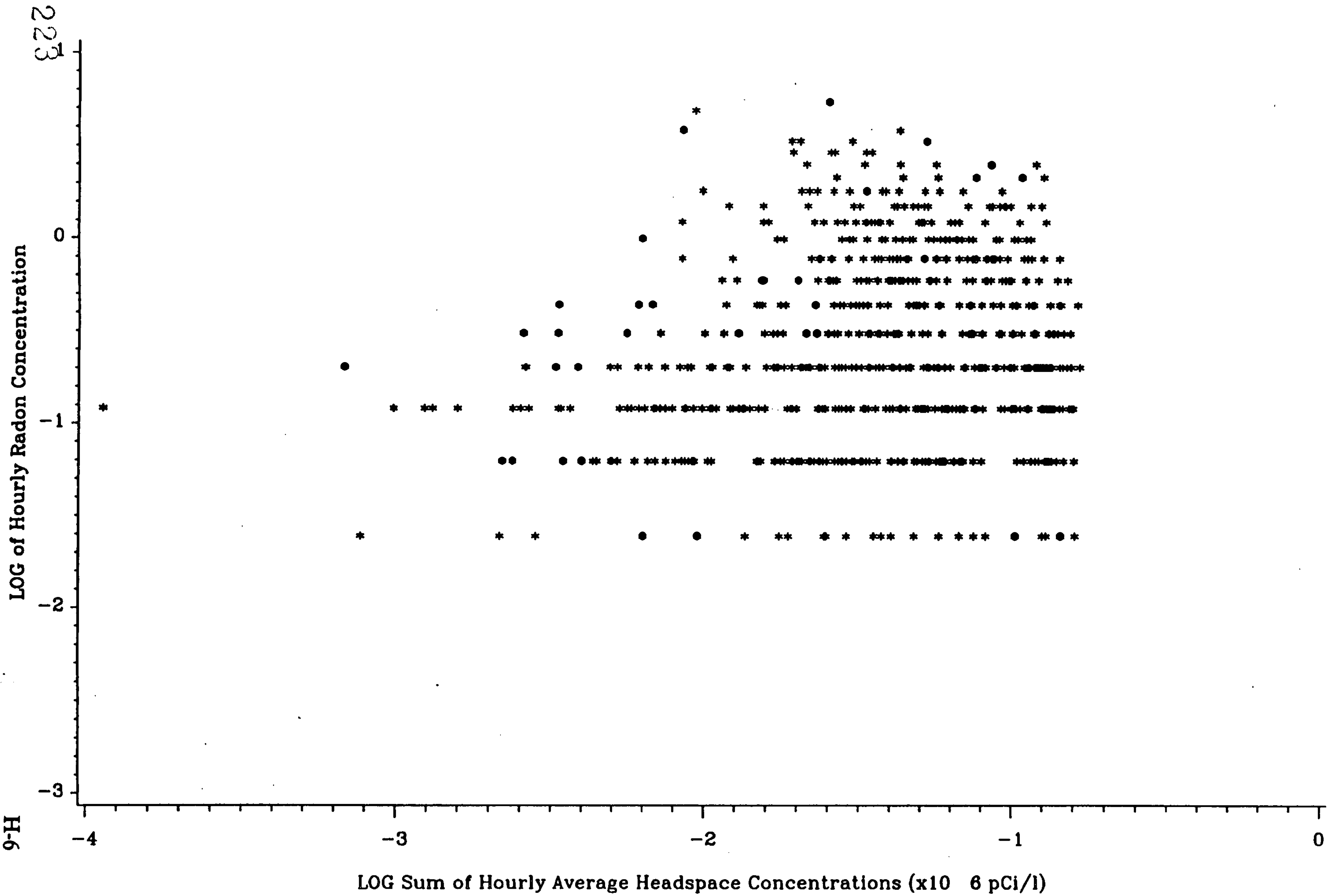


Plot of LOG Hourly Radon Concentration at Pilot Plant Versus LOG Sum of Hourly Average Headspace Concentrations of the Two Silos

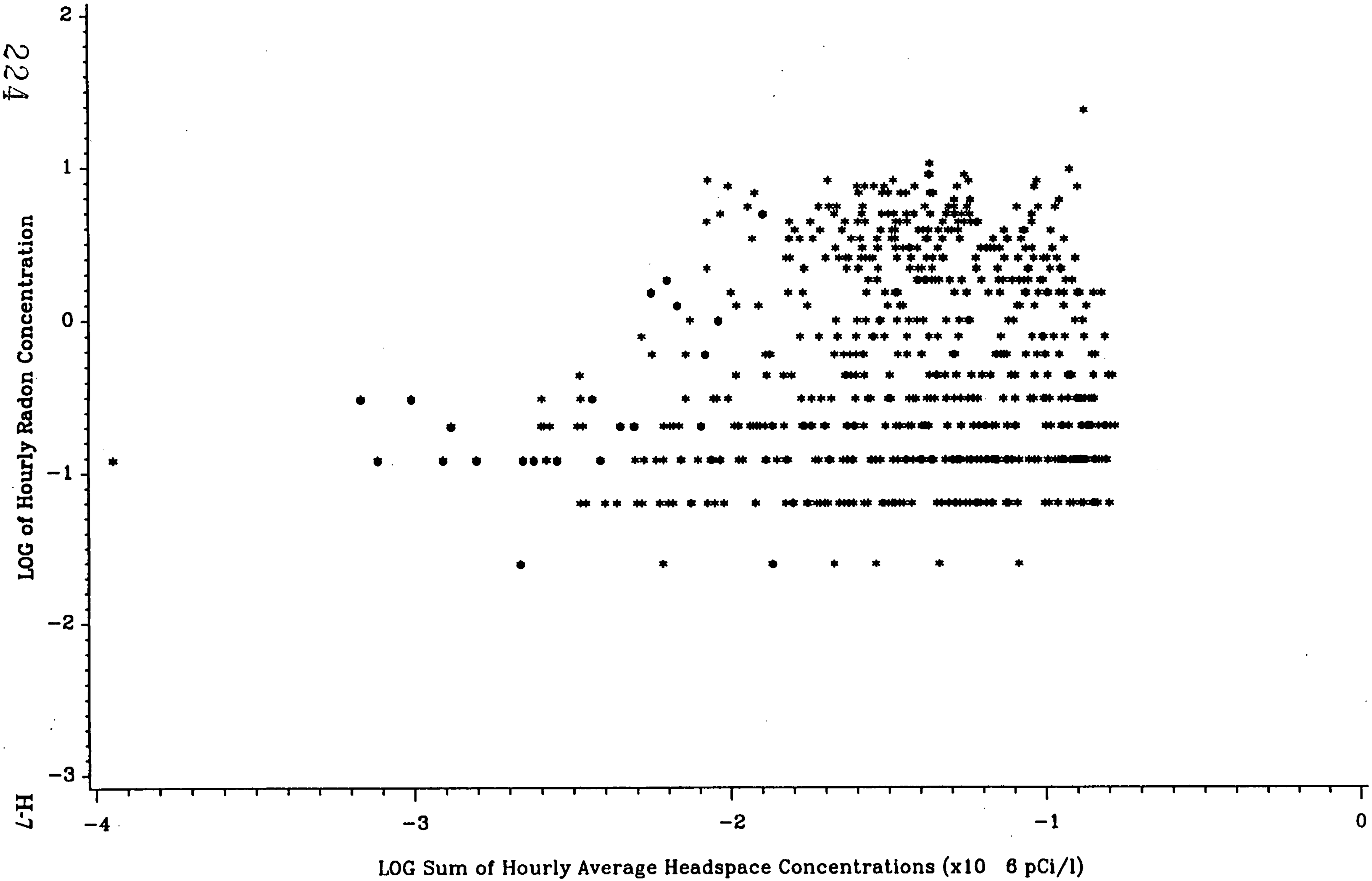


222

Plot of LOG Hourly Radon Concentration at Background Versus LOG Sum of Hourly Average Headspace Concentrations of the Two Silos



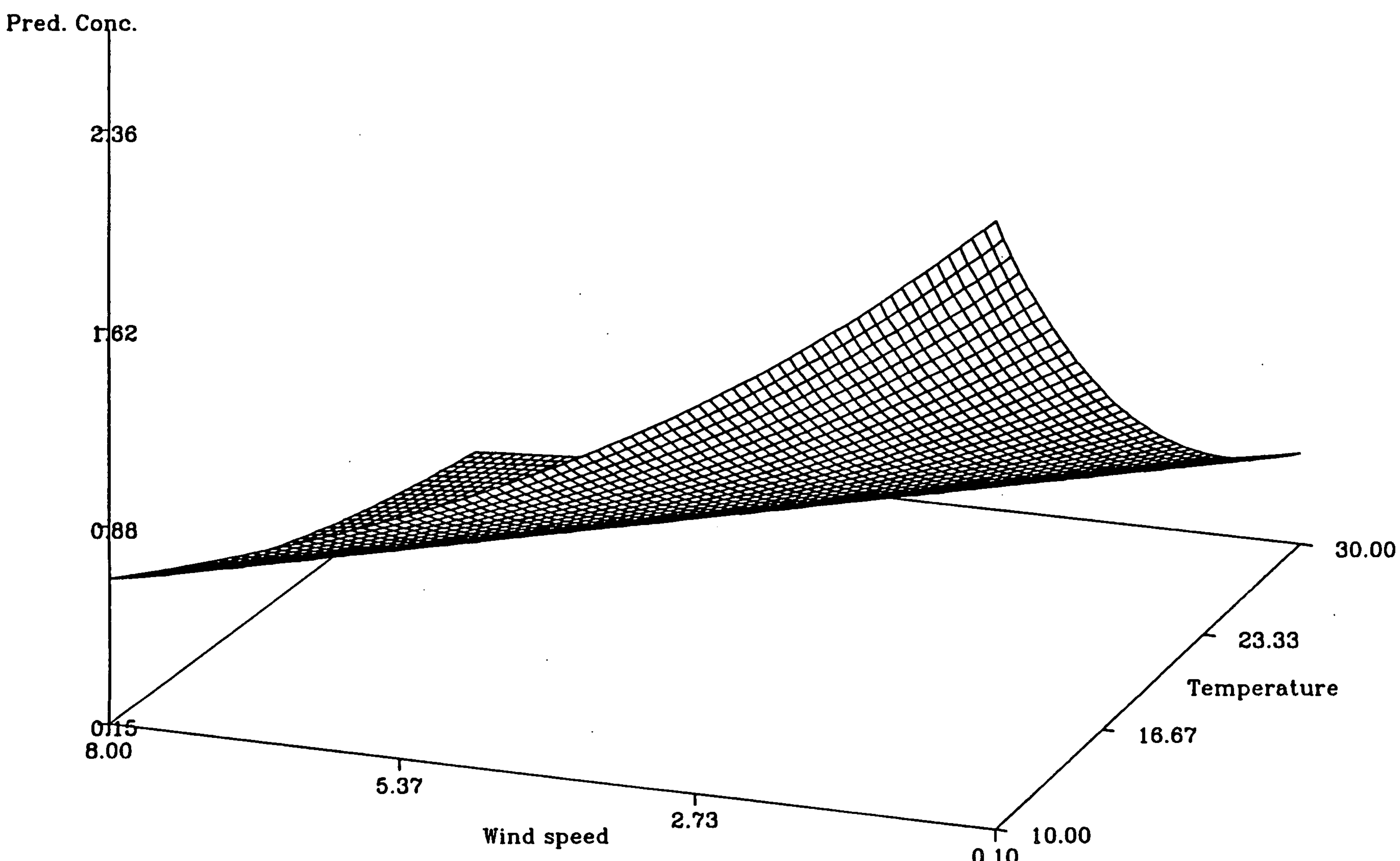
Plot of LOG Hourly Radon Concentration at Met. Tower Versus LOG Sum of Hourly Average Headspace Concentrations of the Two Silos



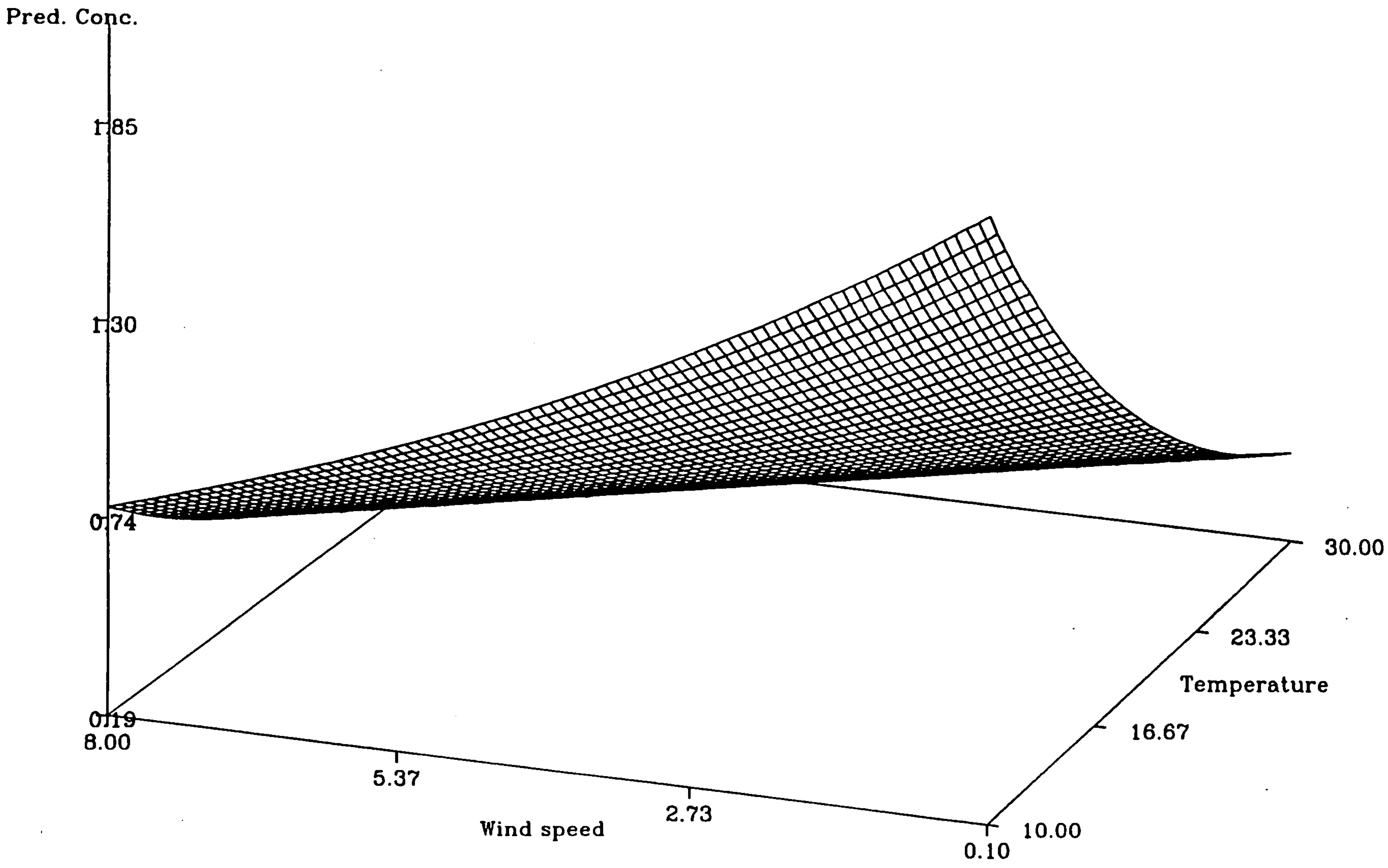
ATTACHMENT I

PLOT OF PREDICTED CONCENTRATIONS AT EACH MONITORING STATION AS A FUNCTION OF OUTDOOR TEMPERATURE AND/OR WIND SPEED

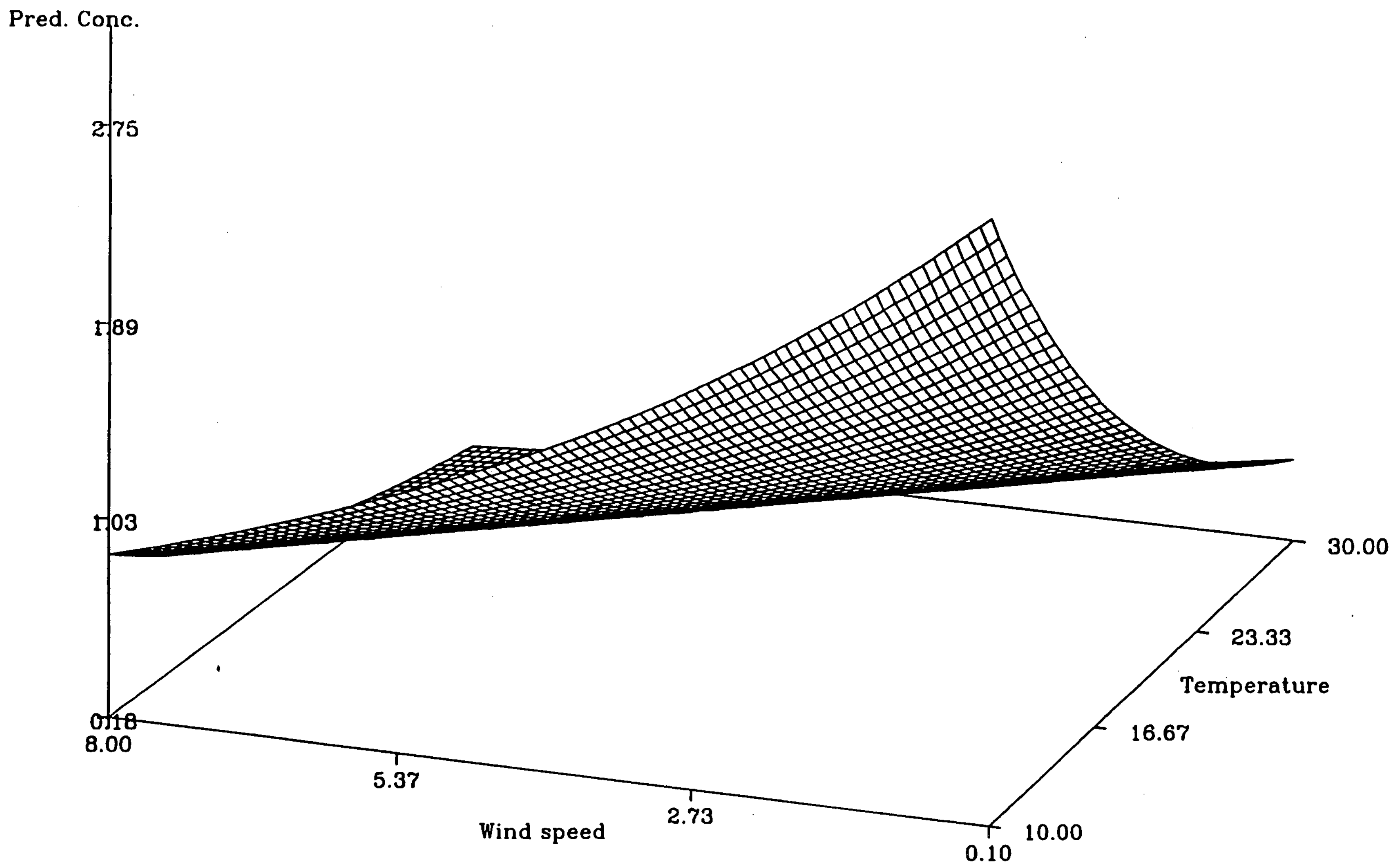
Plot of Predicted Hourly Concentration (pCi/l) at AMS5 at a Silo Headspace Concentration of 300,000 pCi/l, as a Function of Outdoor Temperature (C) and Wind Speed (m/sec)



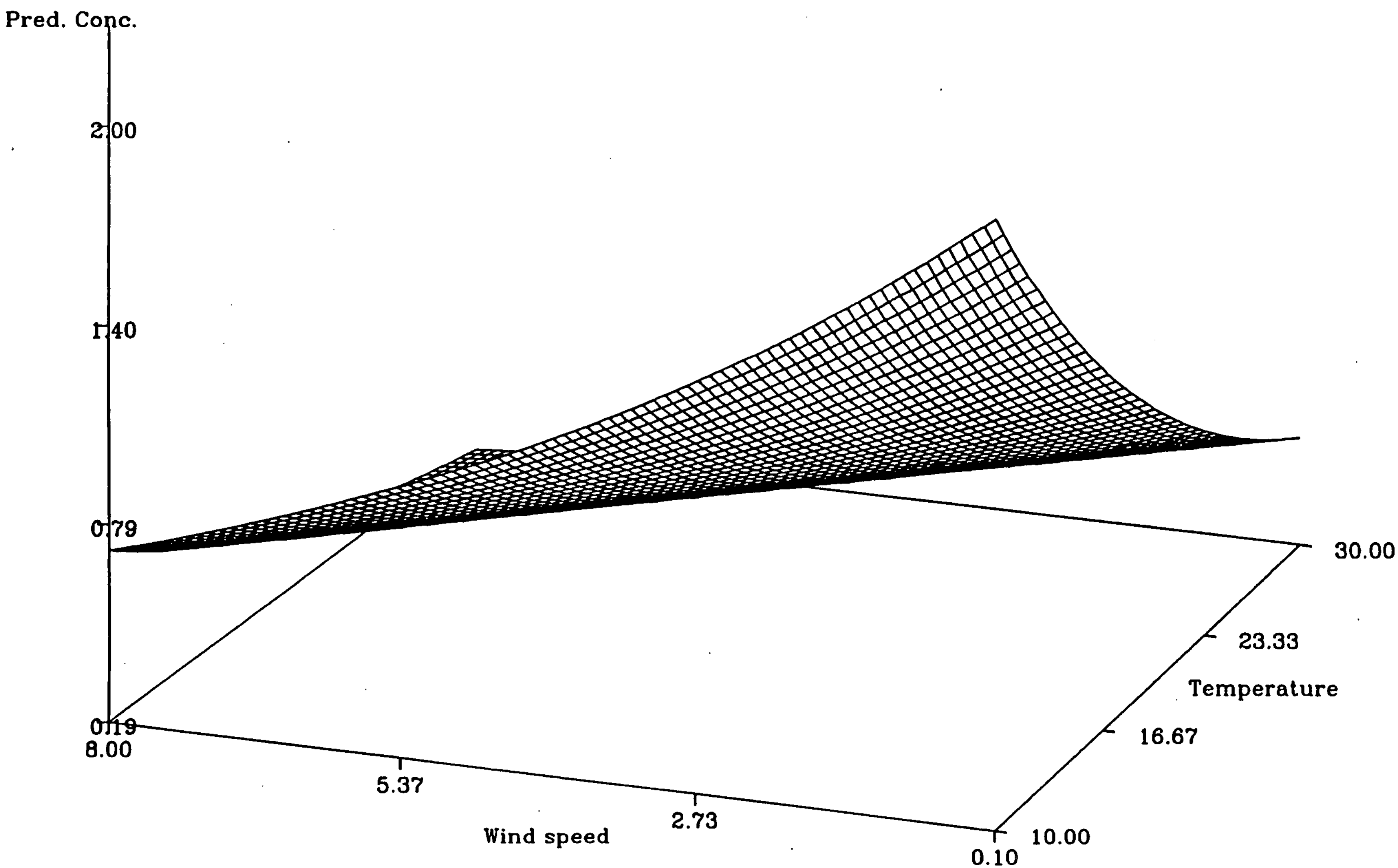
Plot of Predicted Hourly Concentration (pCi/l) at AMS6 at a Silo Headspace Concentration of 300,000 pCi/l, as a Function of Outdoor Temperature (C) and Wind Speed (m/sec)



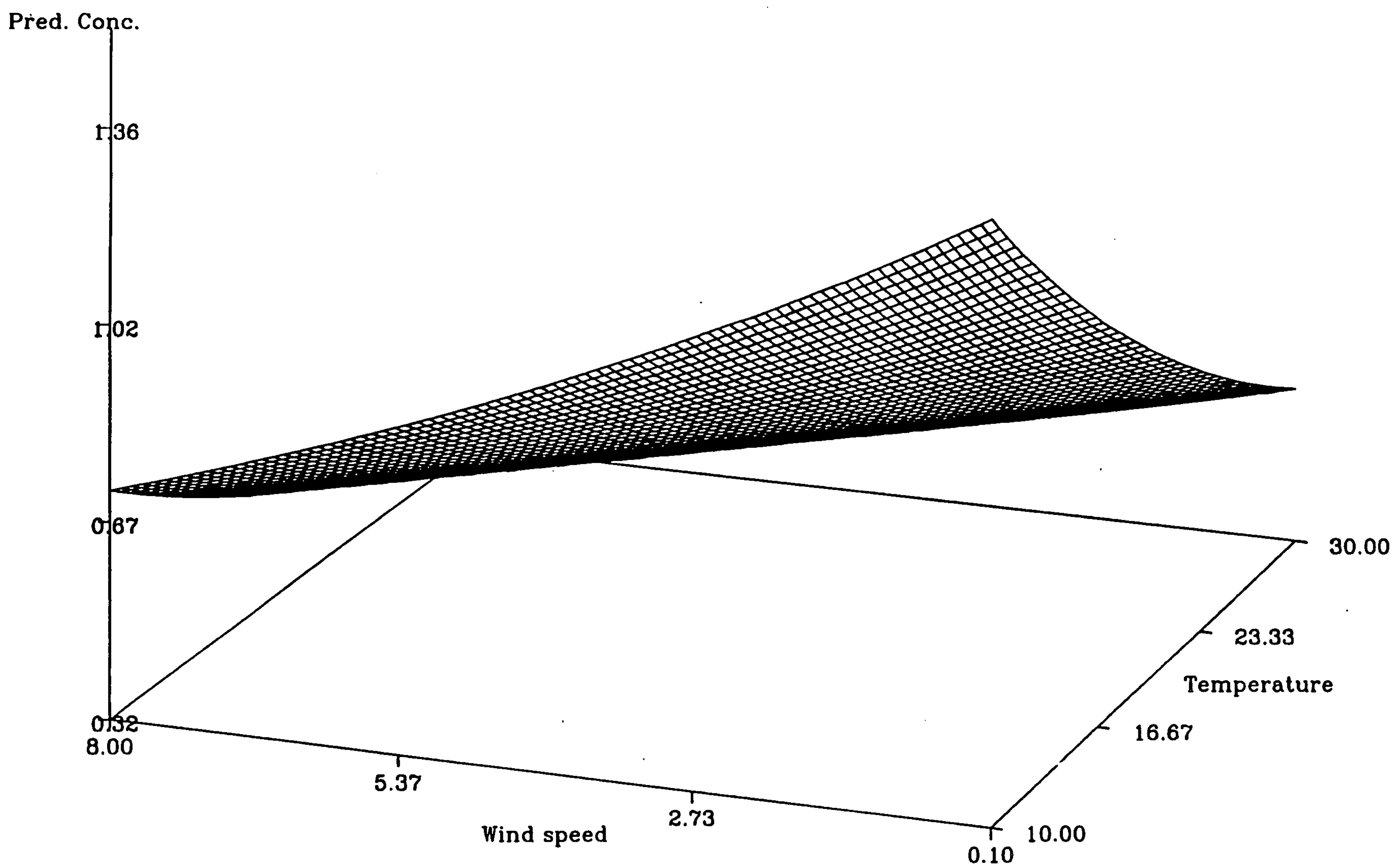
Plot of Predicted Hourly Concentration (pCi/l) at AMS7 at a Silo Headspace Concentration of 300,000 pCi/l, as a Function of Outdoor Temperature (C) and Wind Speed (m/sec)



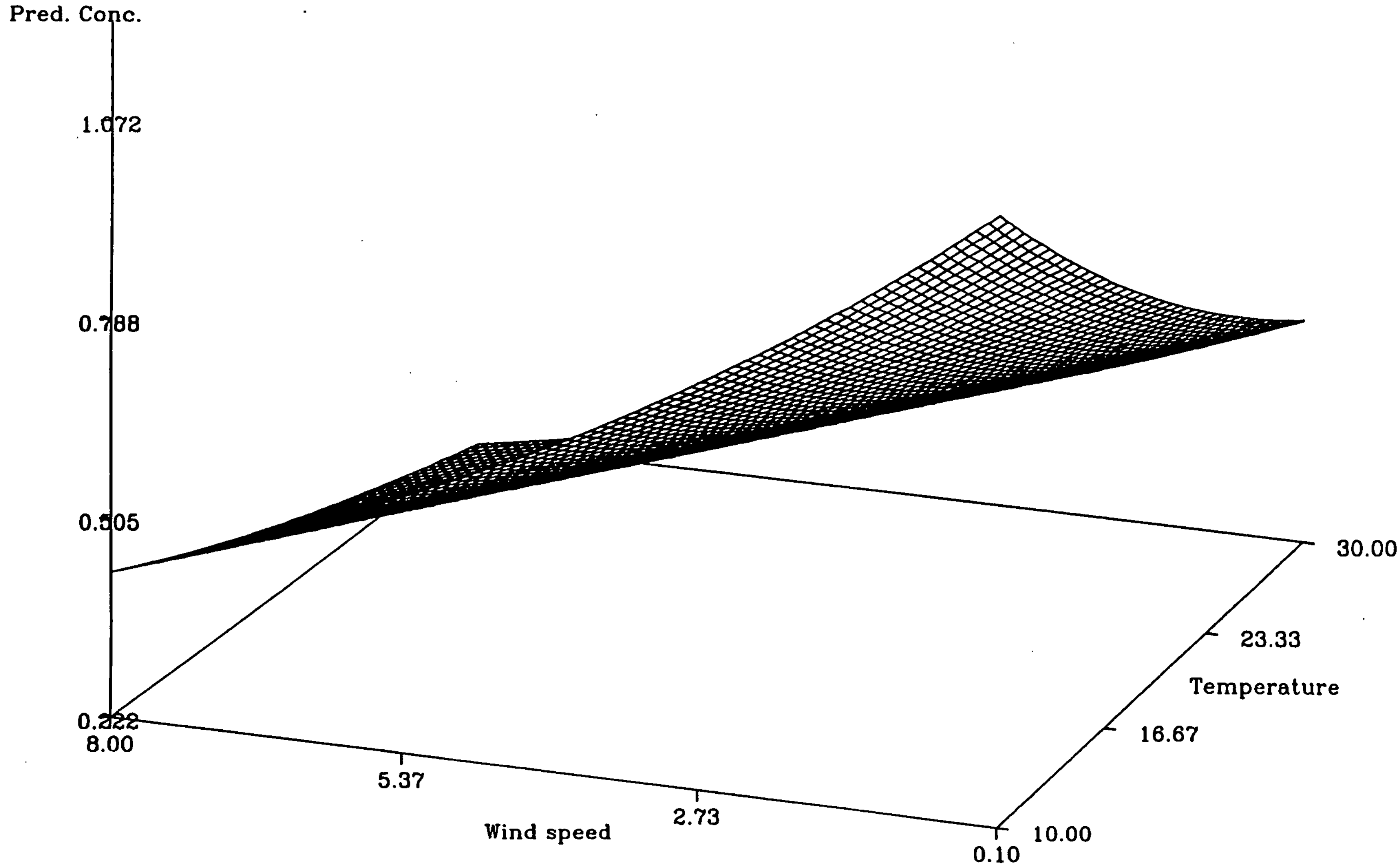
Plot of Predicted Hourly Concentration (pCi/l) at Met. Tower at a Silo Headspace Concentration of 300,000 pCi/l, as a Function of Outdoor Temperature (C) and Wind Speed (m/sec)



Plot of Predicted Hourly Concentration (pCi/l) at Pilot Plant at a Silo Headspace Concentration of 300,000 pCi/l, as a Function of Outdoor Temperature (C) and Wind Speed (m/sec)



Plot of Predicted Hourly Concentration (pCi/l) at Background at a Silo Headspace Concentration of 300,000 pCi/l, as a Function of Outdoor Temperature (C) and Wind Speed (m/sec)



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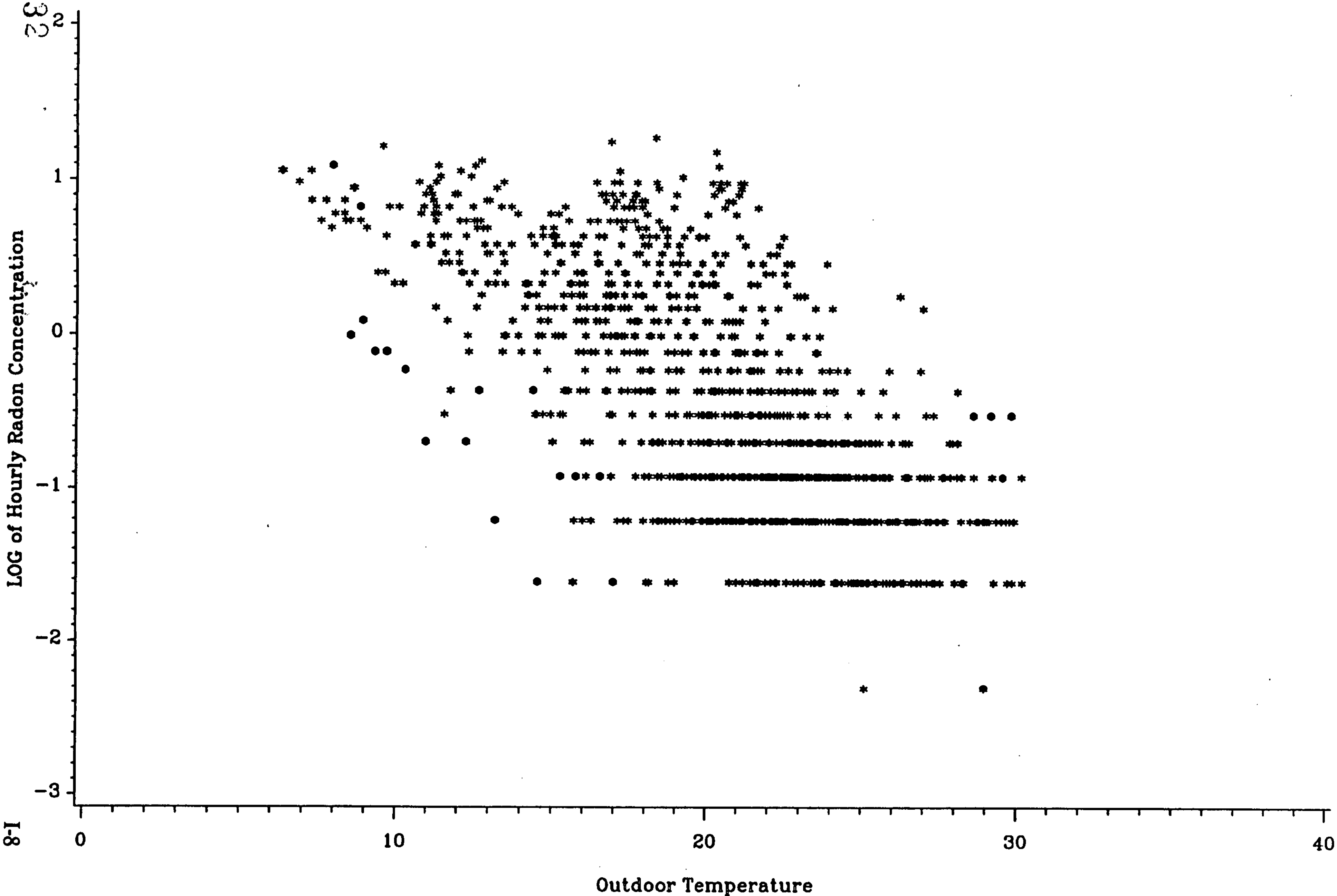
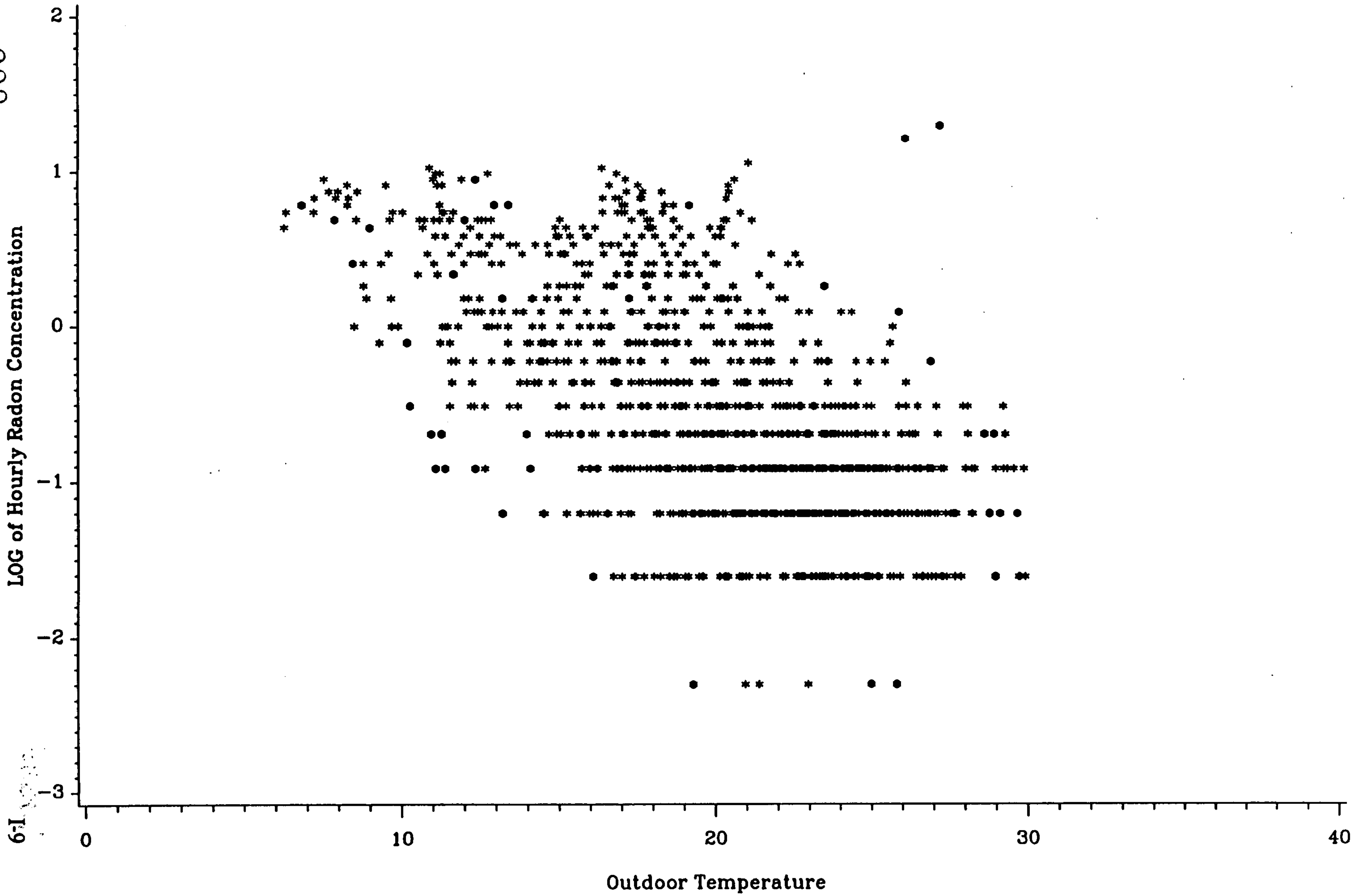
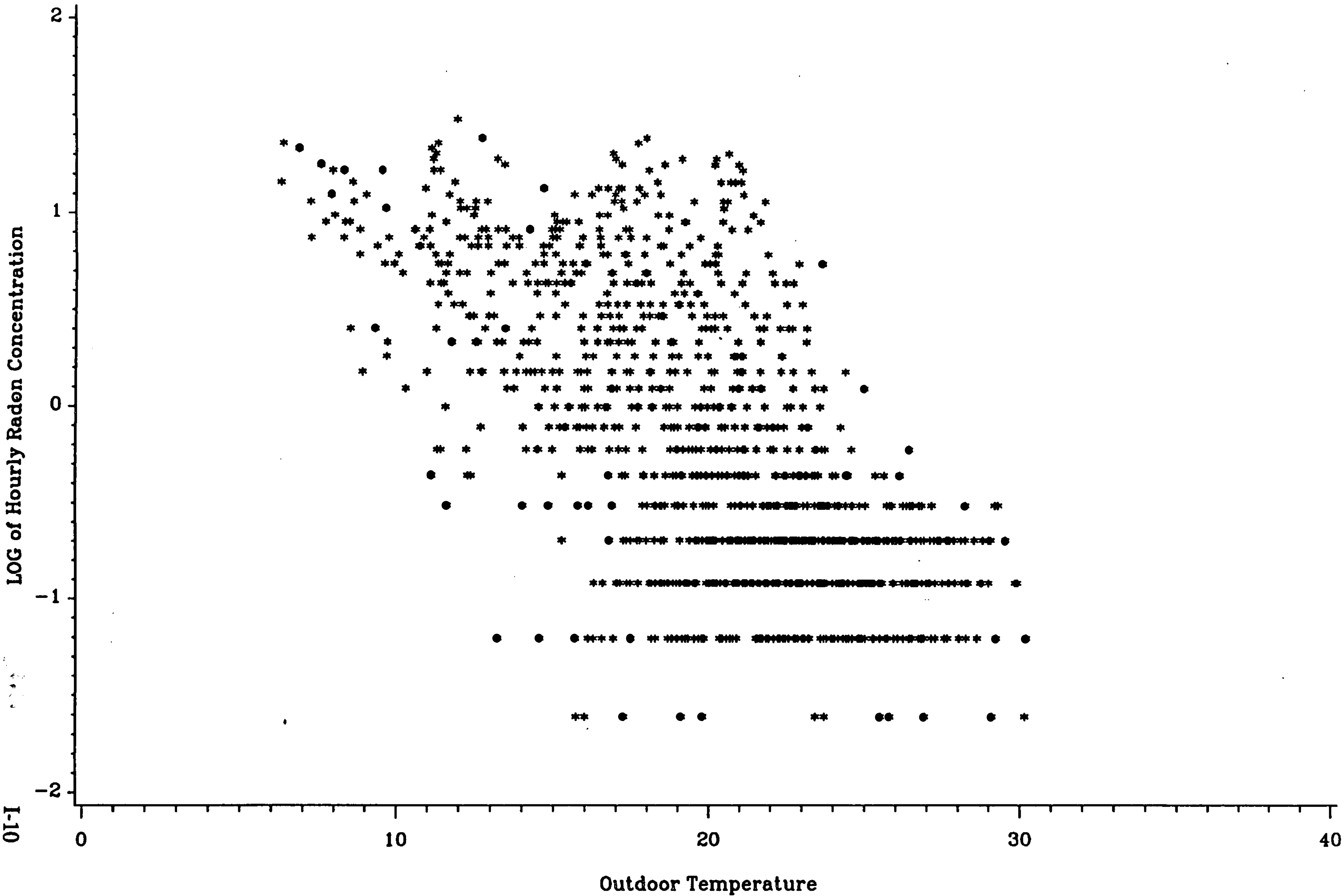
Plot of LOG Hourly Radon Concentration at AMS5 Versus Outdoor Temperature



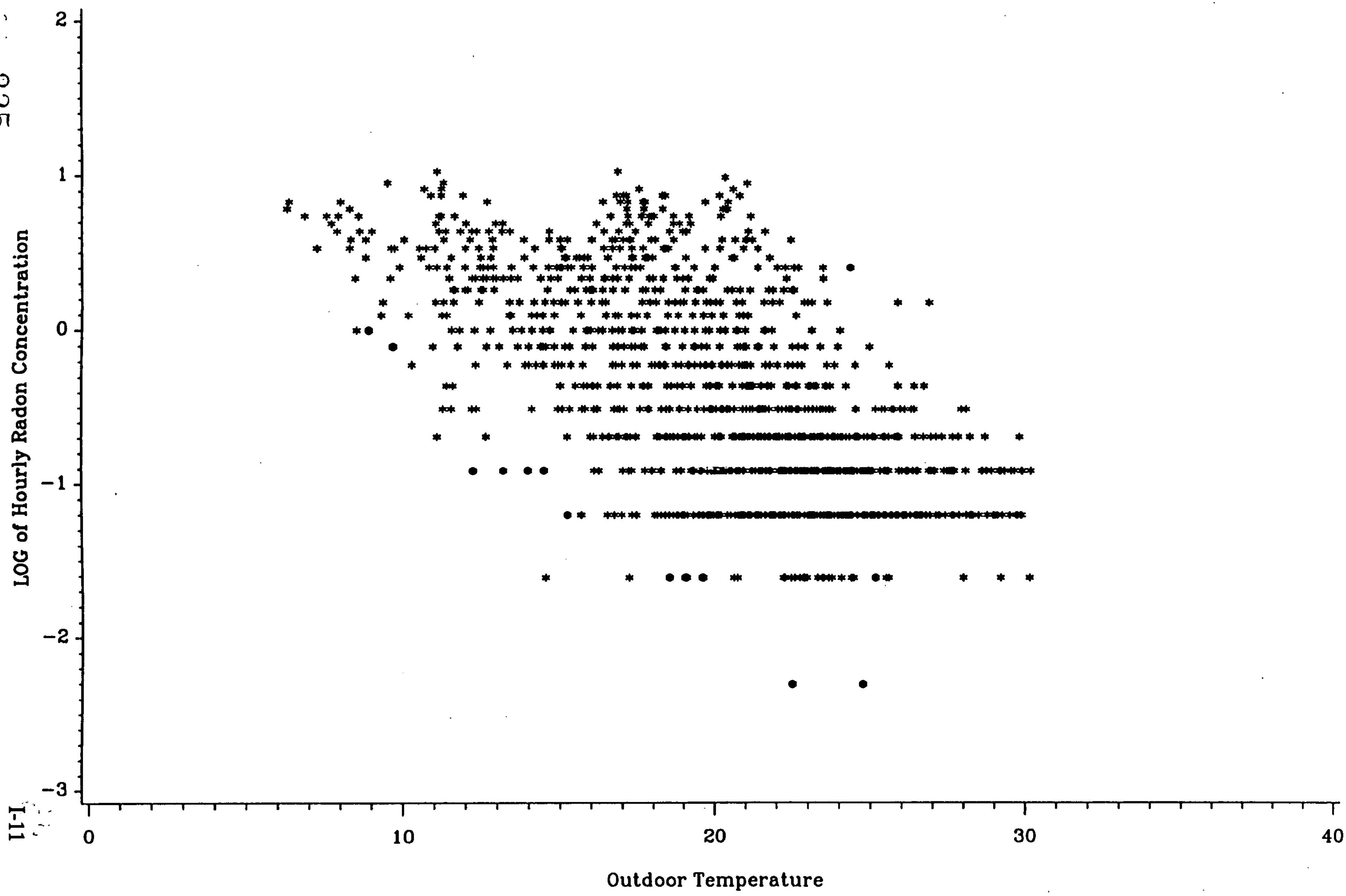
Plot of LOG Hourly Radon Concentration at AMS6 Versus Outdoor Temperature



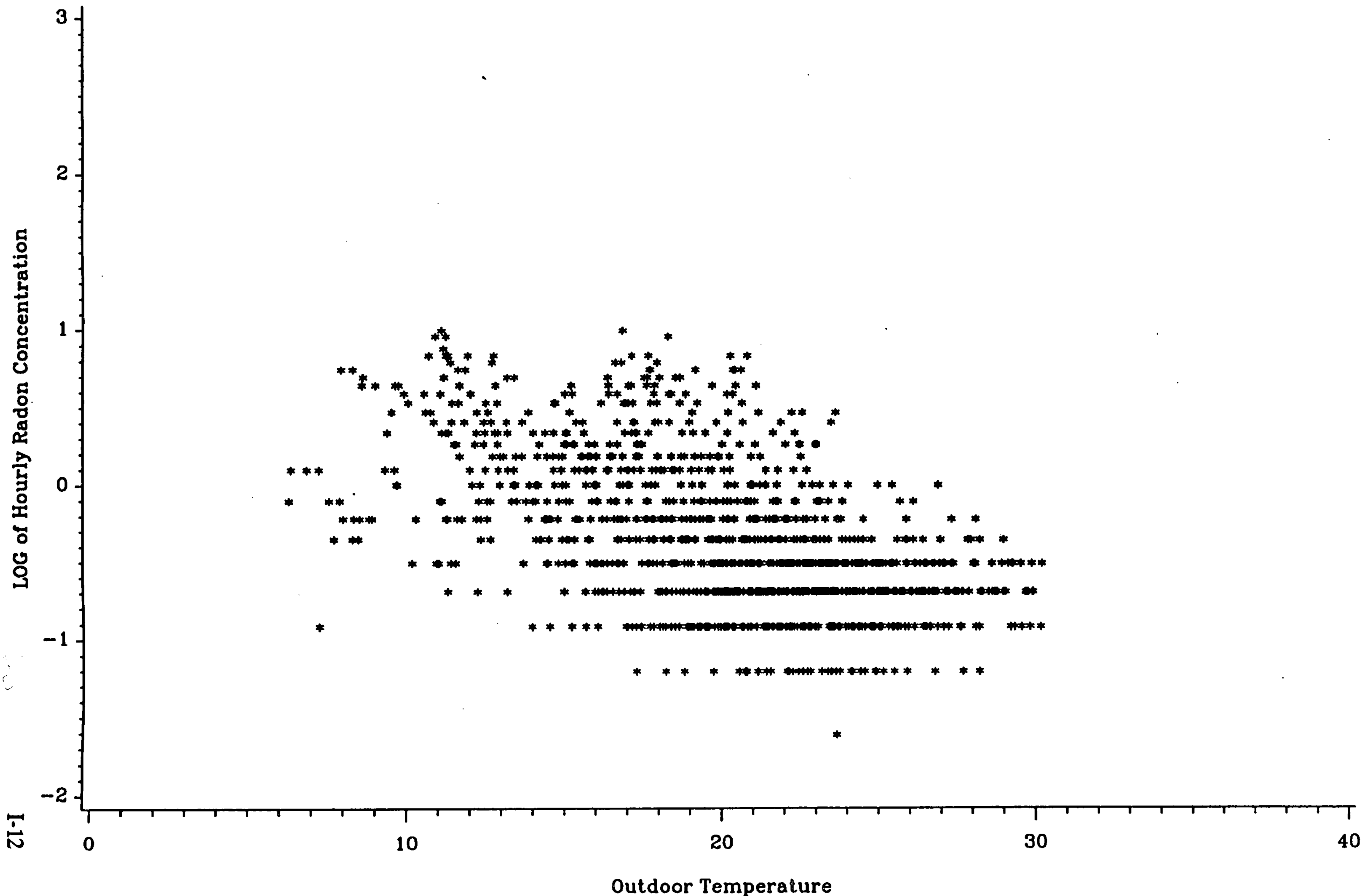
Plot of LOG Hourly Radon Concentration at AMS7 Versus Outdoor Temperature



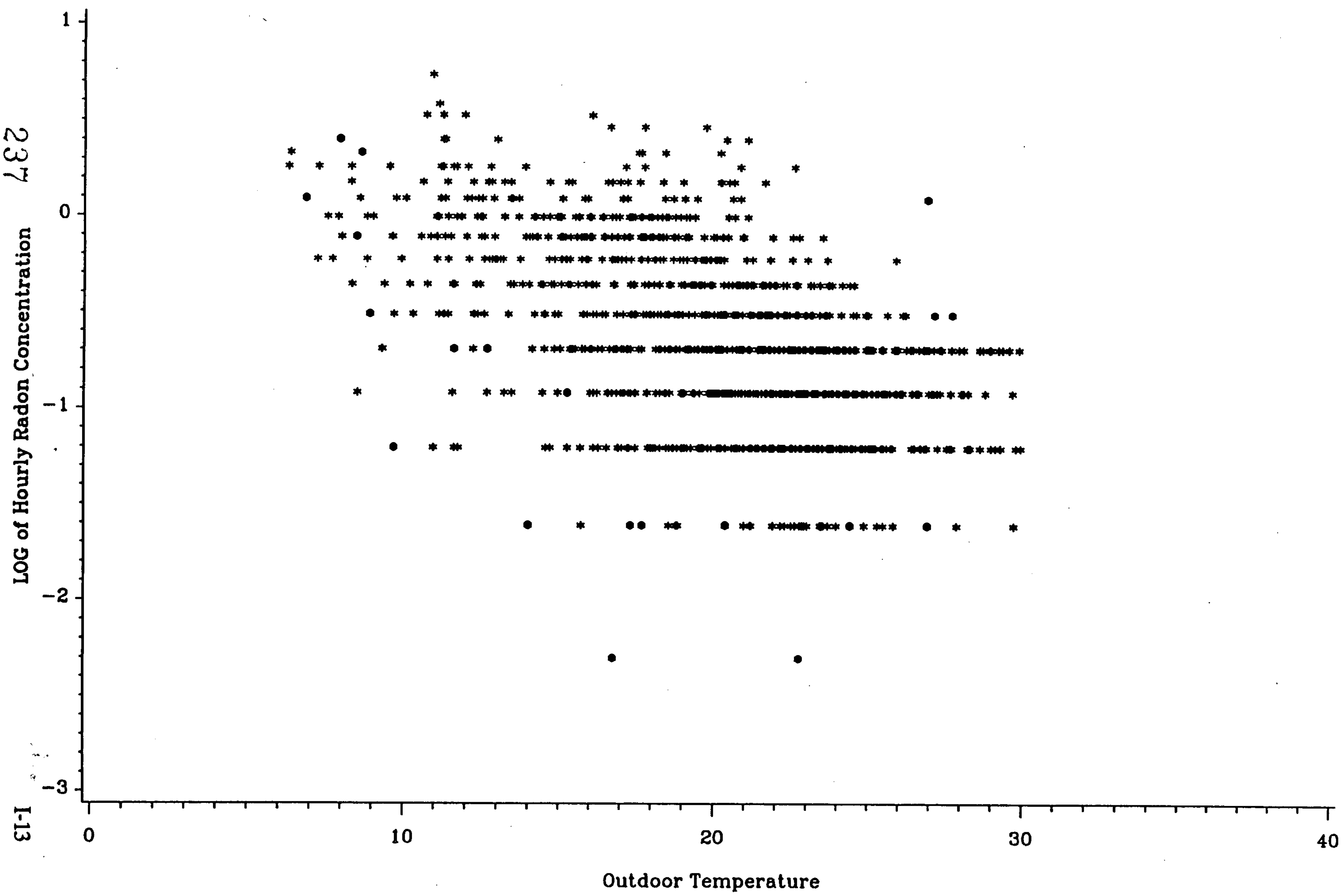
Plot of LOG Hourly Radon Concentration at Met. Tower Versus Outdoor Temperature



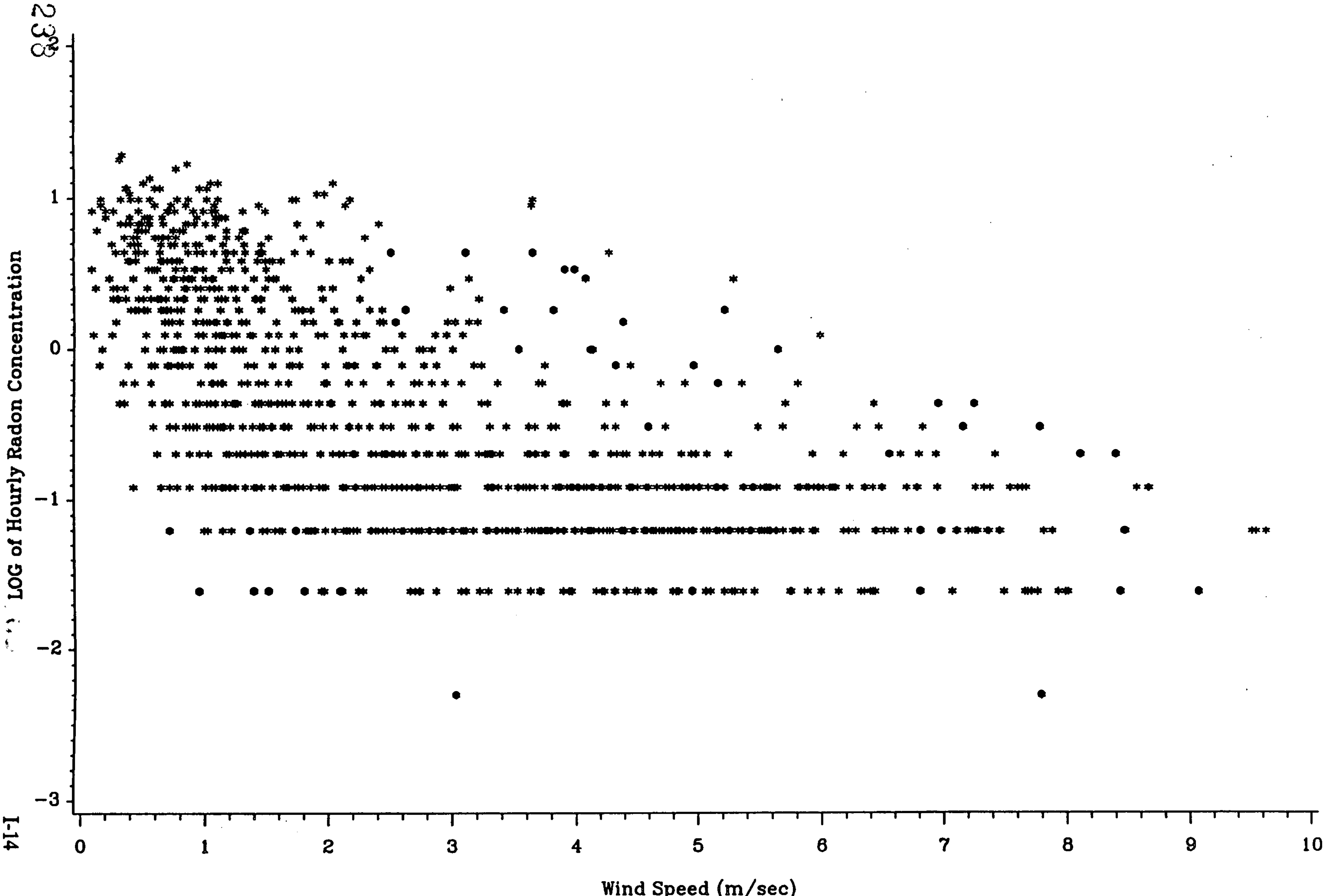
Plot of LOG Hourly Radon Concentration at Pilot Plant Versus Outdoor Temperature



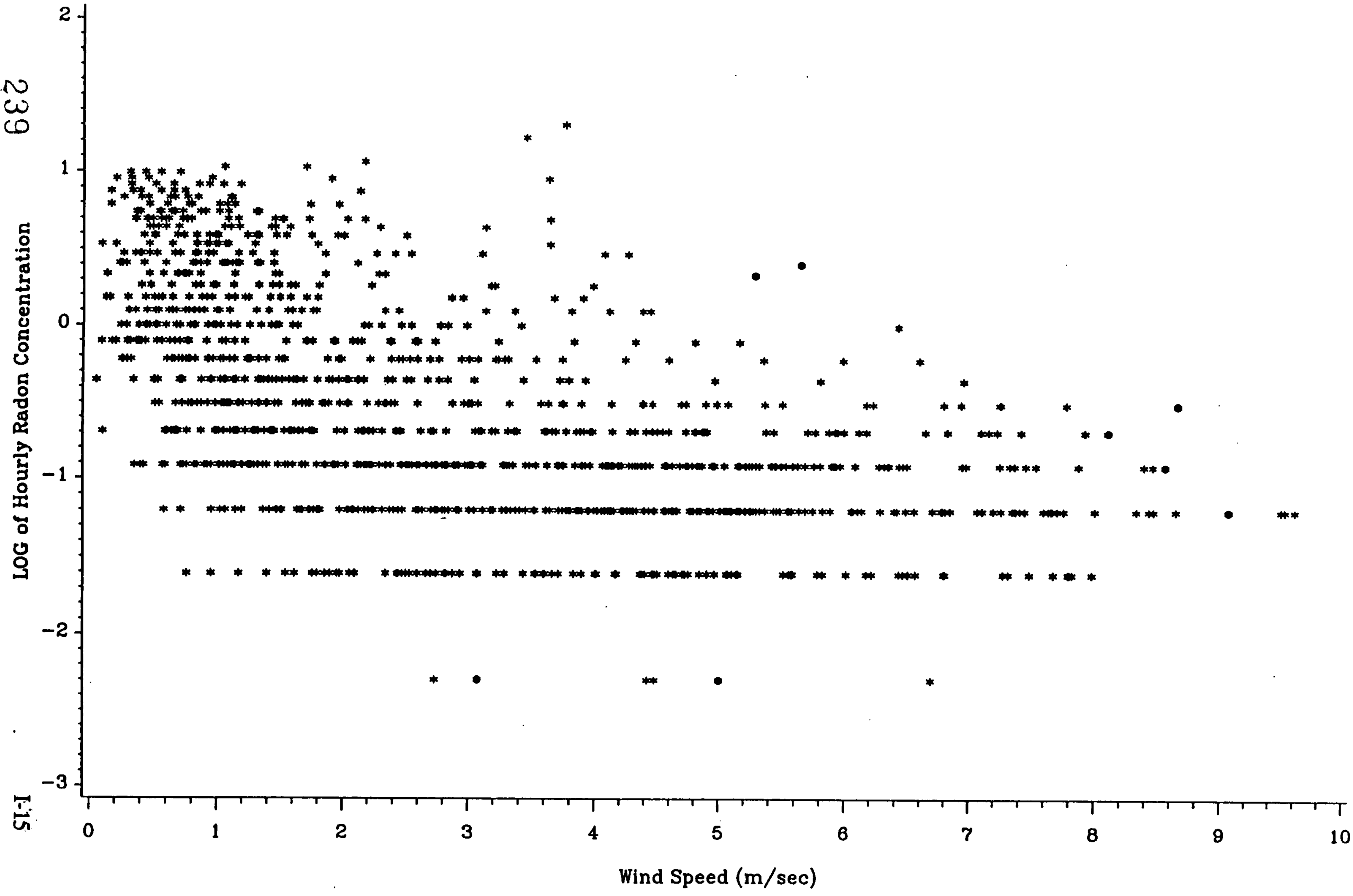
Plot of LOG Hourly Radon Concentration at Background Versus Outdoor Temperature



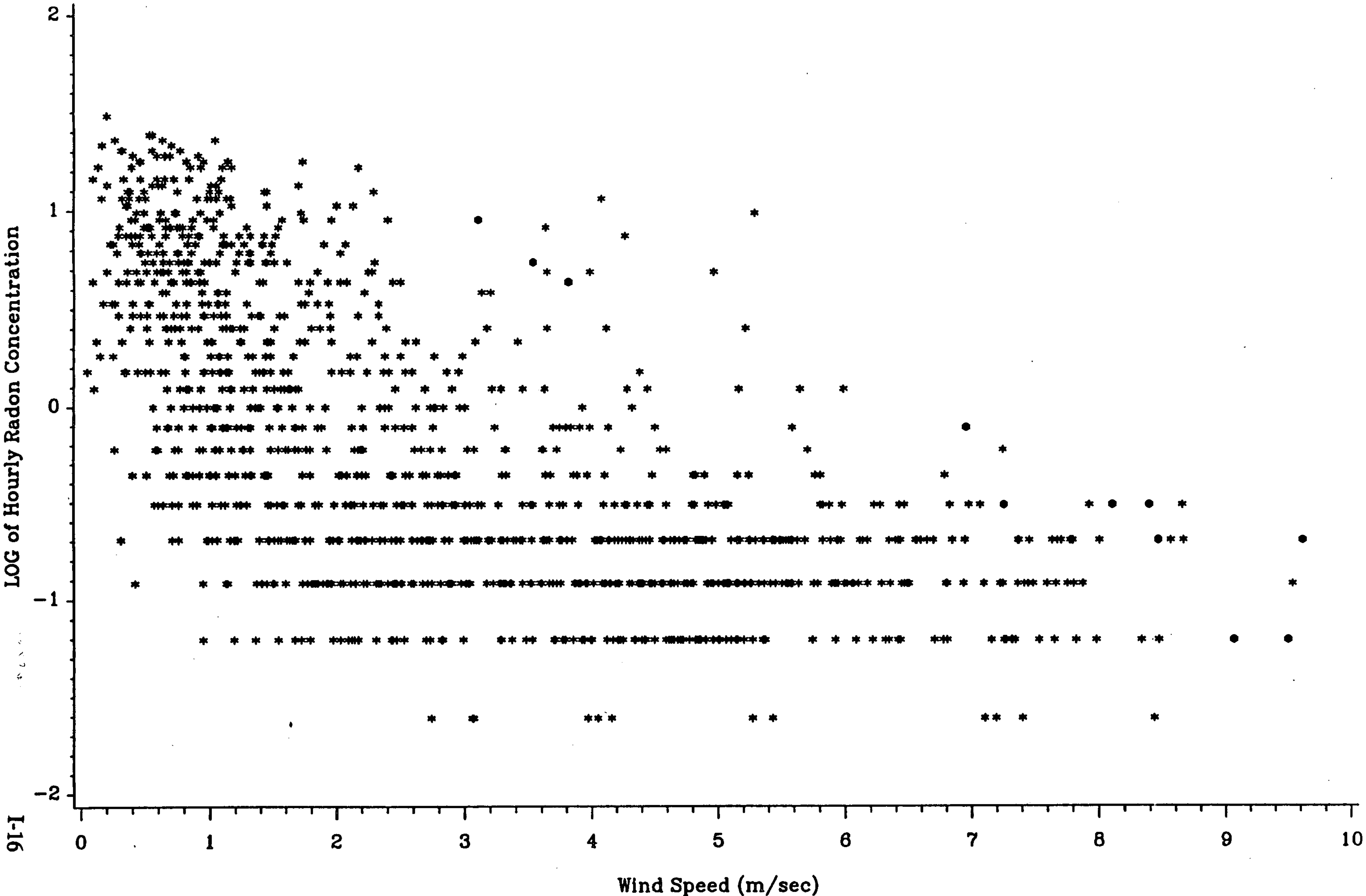
Plot of Hourly Radon Concentration at AMS5 Versus Wind Speed



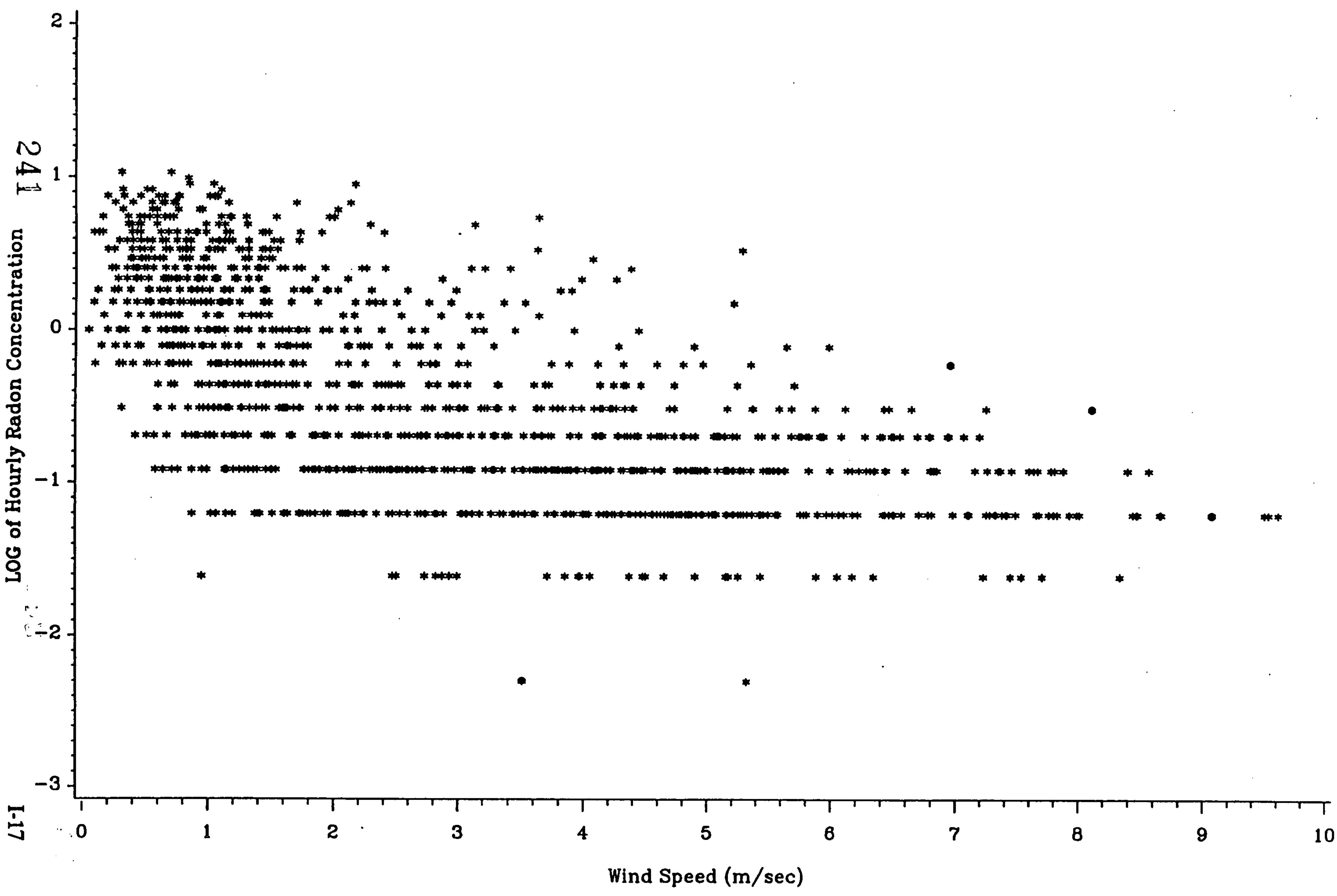
Plot of Hourly Radon Concentration at AMS6 Versus Wind Speed



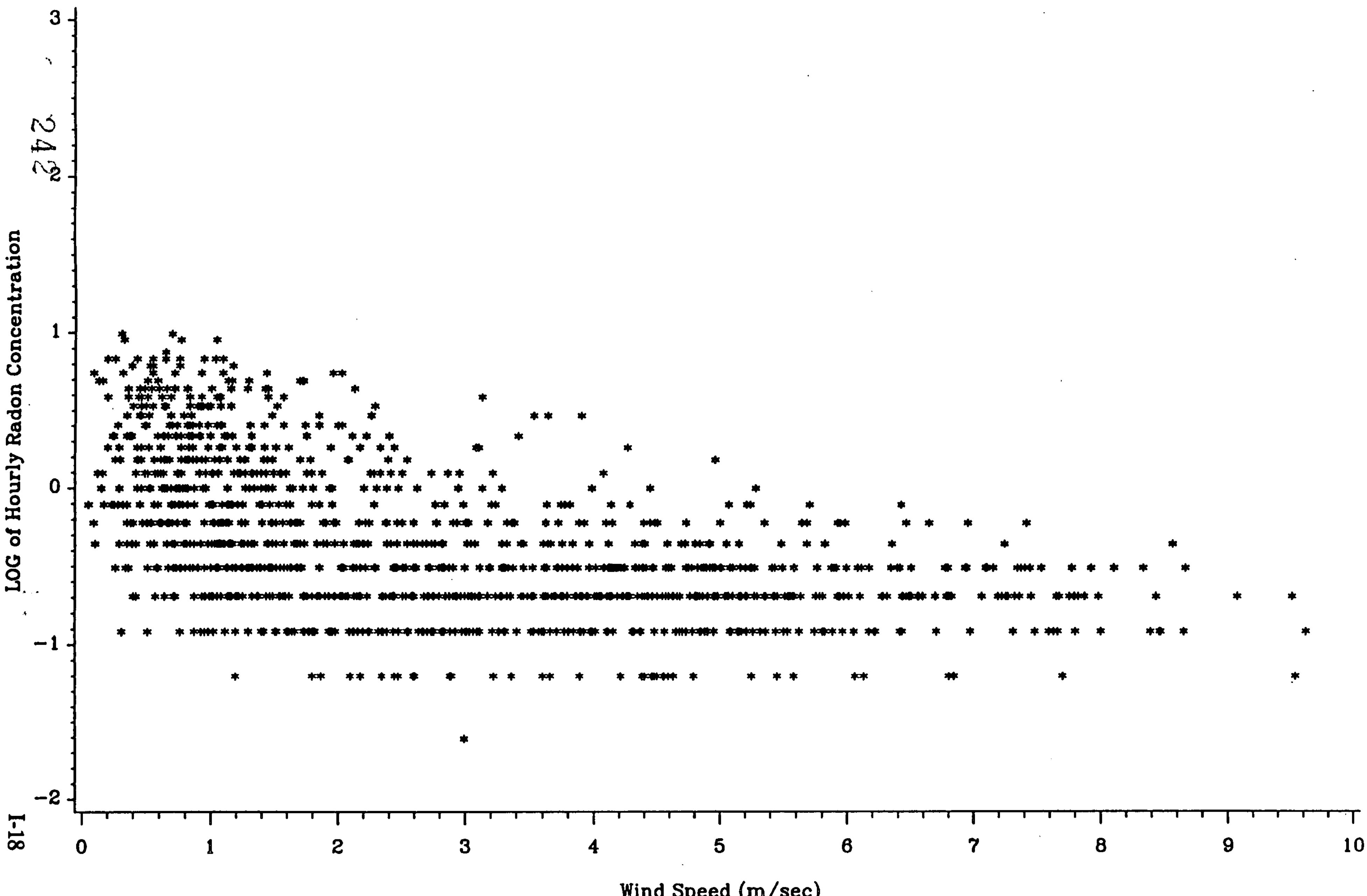
Plot of Hourly Radon Concentration at AMS7 Versus Wind Speed



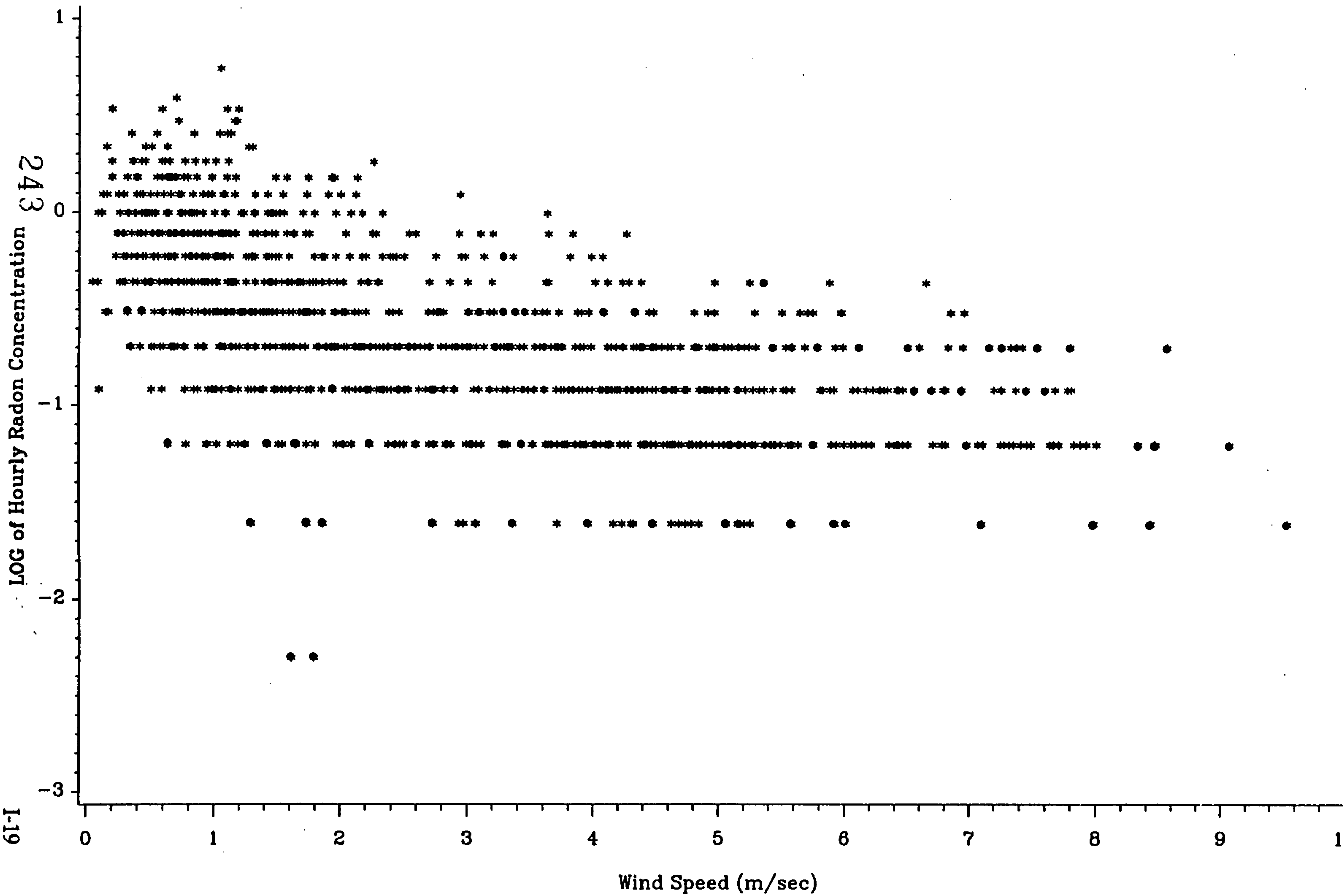
Plot of LOG Hourly Radon Concentration at Met. Tower Versus Wind Speed



Plot of LOG Hourly Radon Concentration at Pilot Plant Versus Wind Speed



Plot of LOG Hourly Radon Concentration at Background Versus Wind Speed

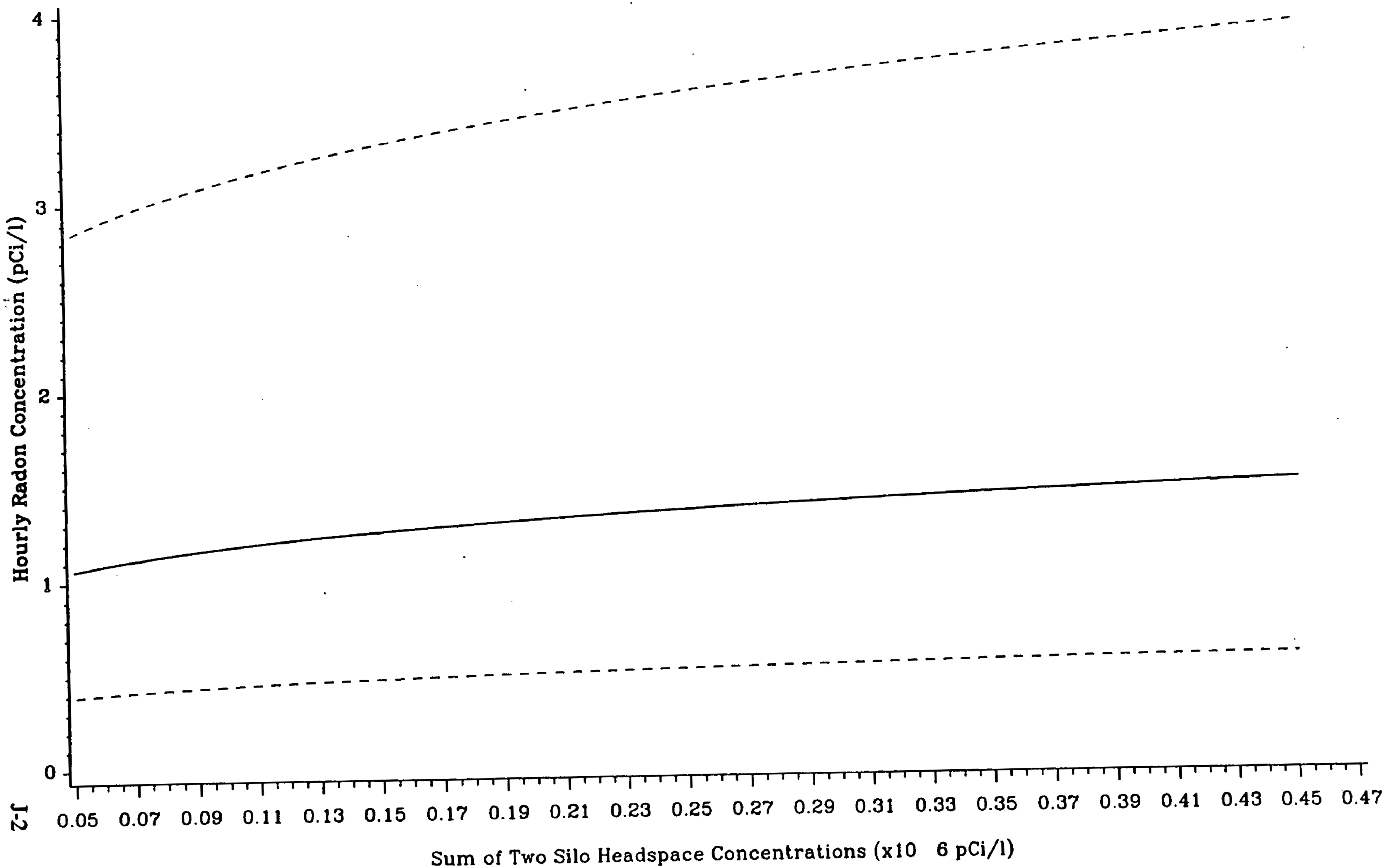


ATTACHMENT J

PLOT OF PREDICTED HOURLY CONCENTRATIONS AT EACH MONITORING STATION WITH 95 PERCENT PREDICTION INTERVALS, AS A FUNCTION OF SILO HEADSPACE CONCENTRATION, OUTDOOR TEMPERATURE, AND WIND SPEED

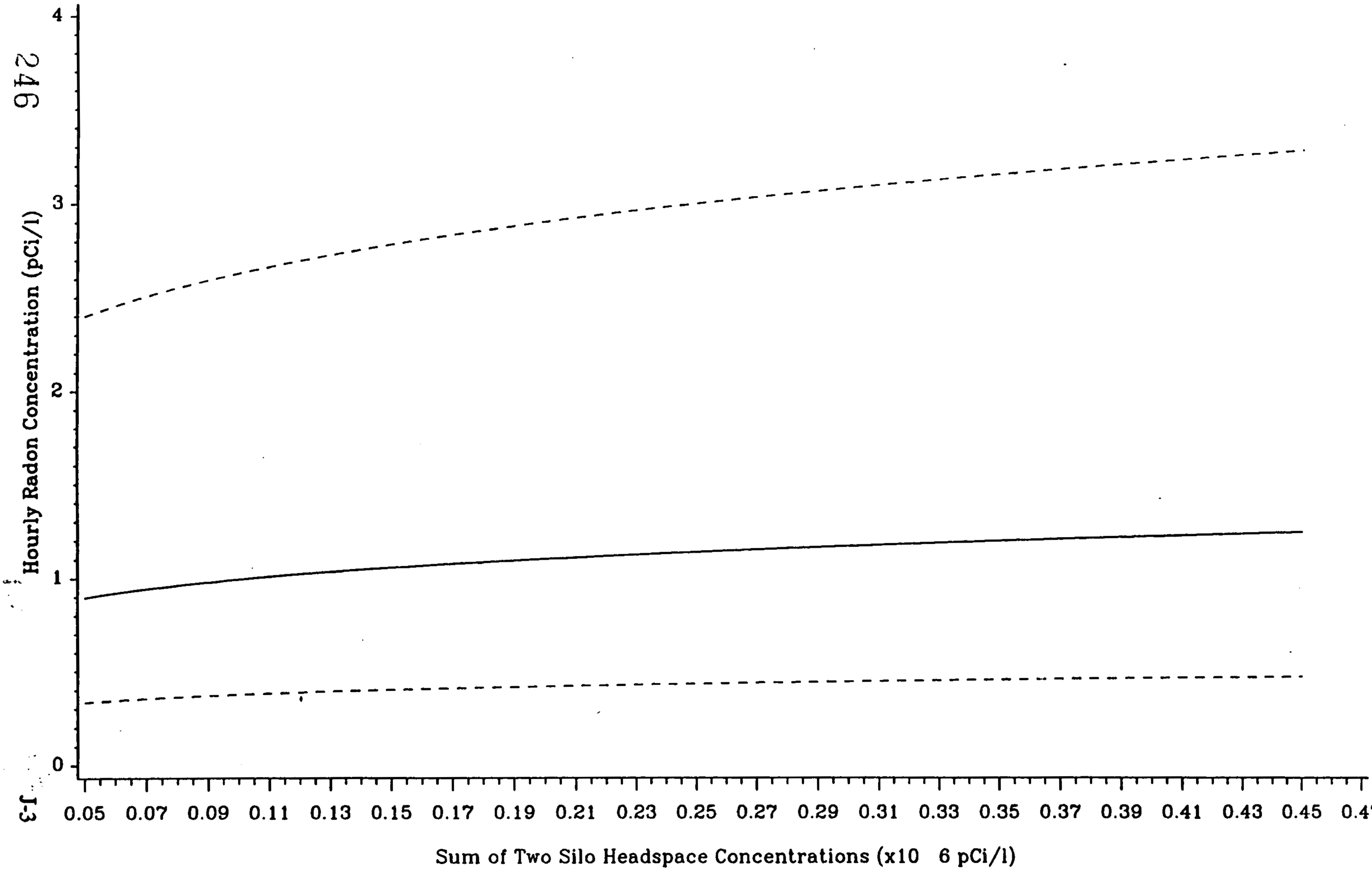
Plot of Predicted Hourly concentration at AMS5, with 95% Prediction Interval, as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed

Outdoor temperature (C)=15 , Wind speed (m/sec)=1



Plot of Predicted Hourly concentration at AMS6, with 95% Prediction Interval, as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed

Outdoor temperature (C)=15 , Wind speed (m/sec)=1



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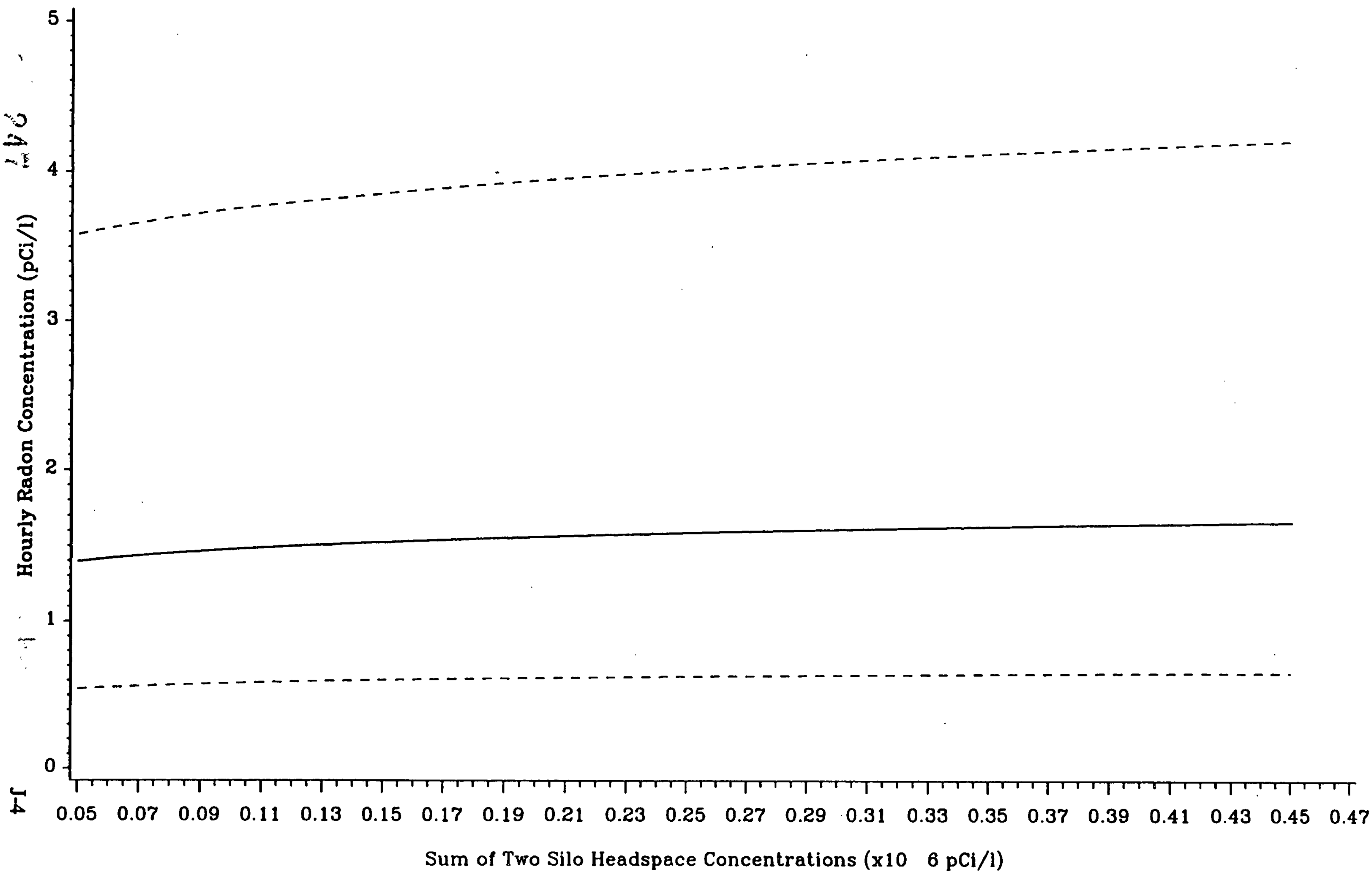
Plot of Predicted Hourly concentration at AMS7, with 95% Prediction Interval,
as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed
Outdoor temperature (C)=15 , Wind speed (m/sec)=1



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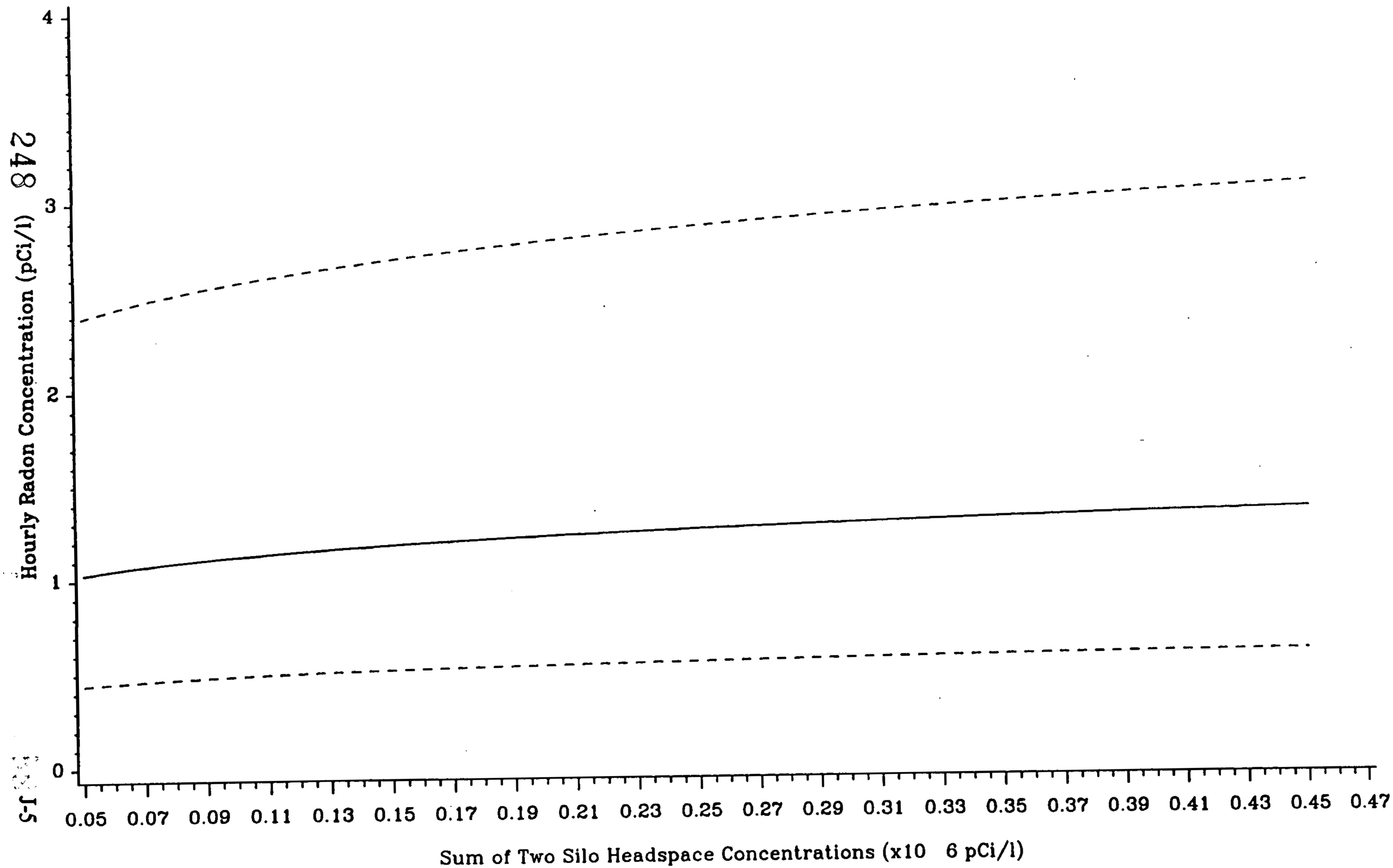
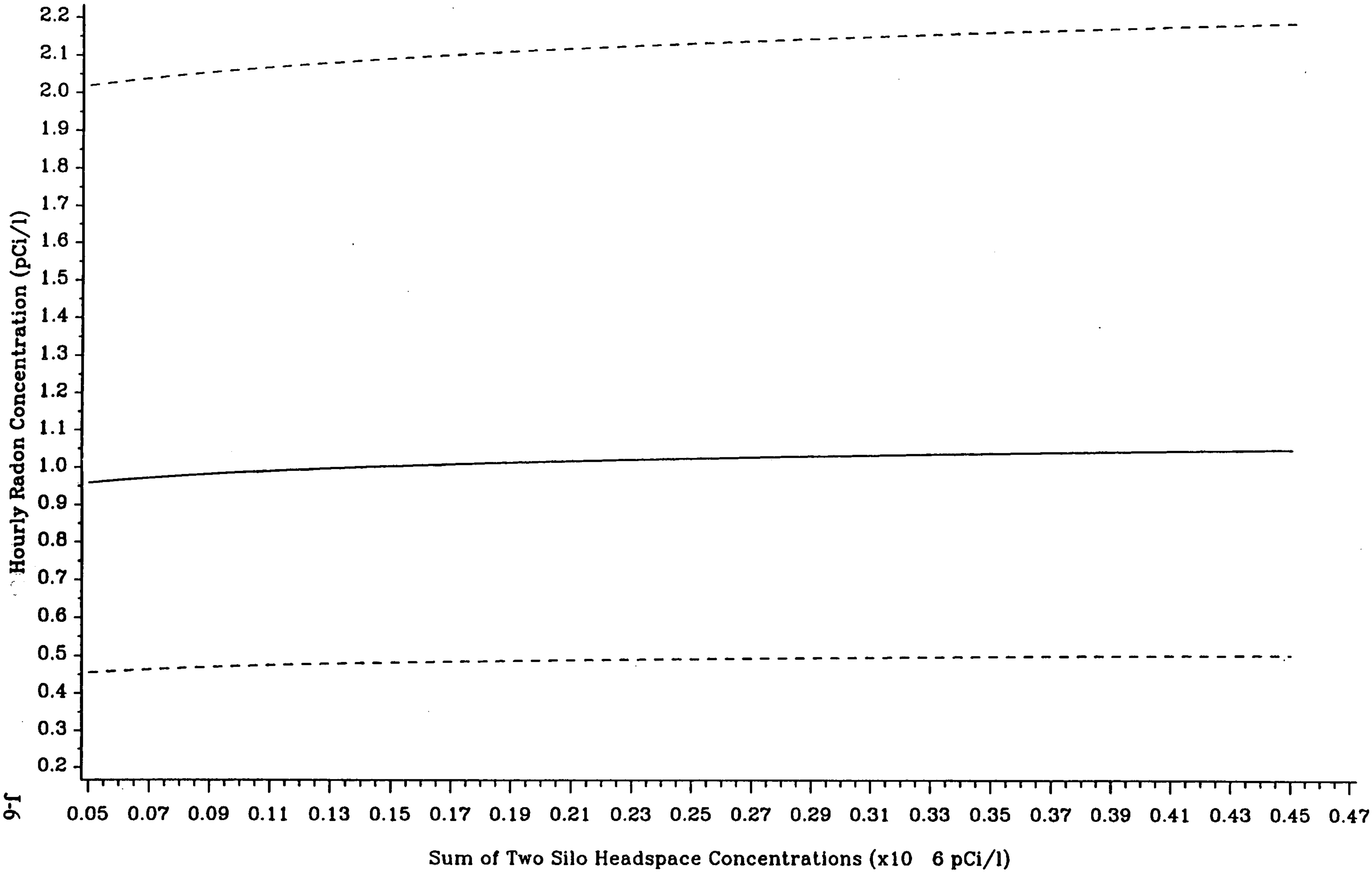
Plot of Predicted Hourly concentration at Met. Tower, with 95% Prediction Interval, as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed
Outdoor temperature (C)=15 , Wind speed (m/sec)=1



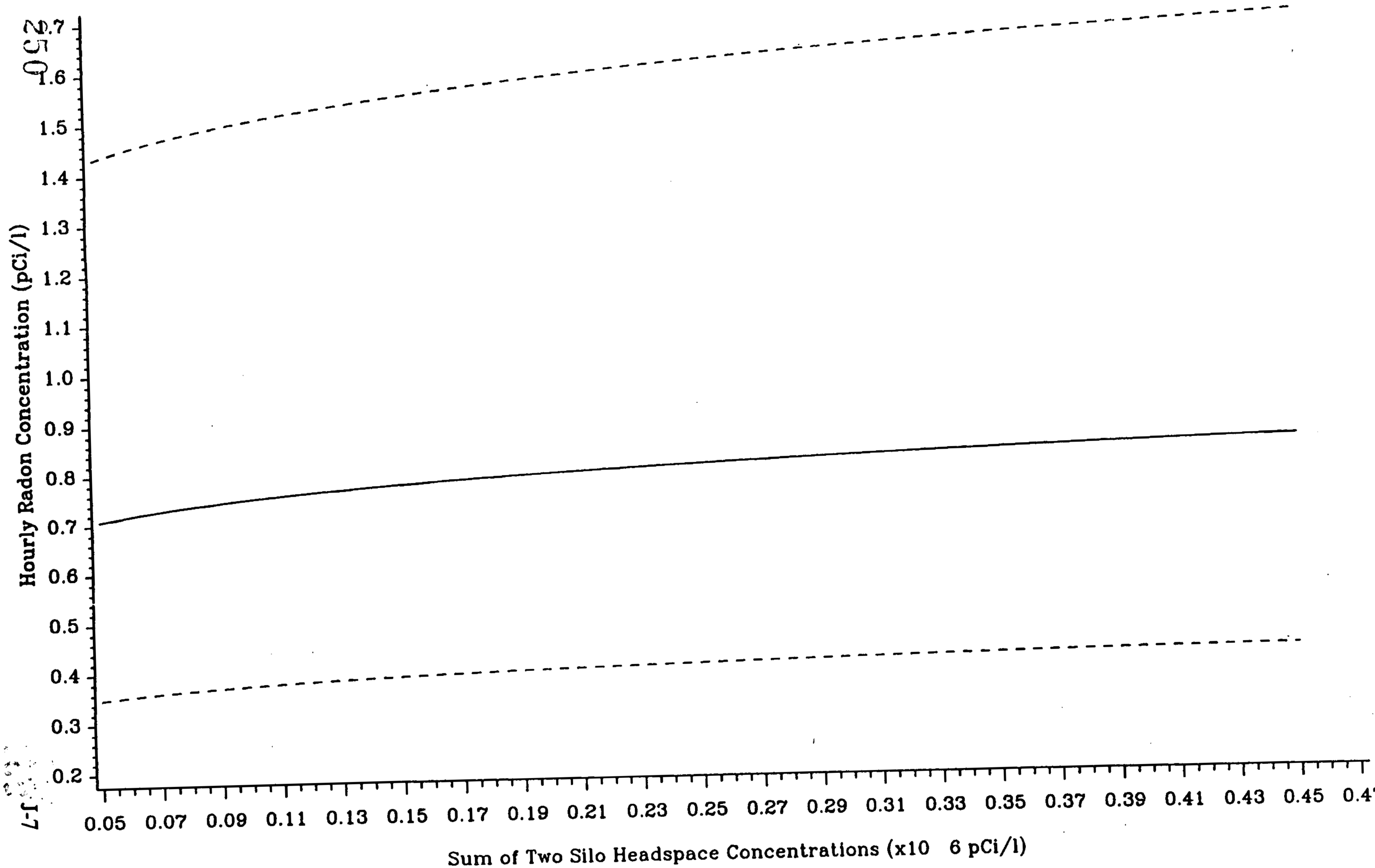
Plot of Predicted Hourly concentration at Pilot Plant, with 95% Prediction Interval, as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed

Outdoor temperature (C)=15 , Wind speed (m/sec)=1



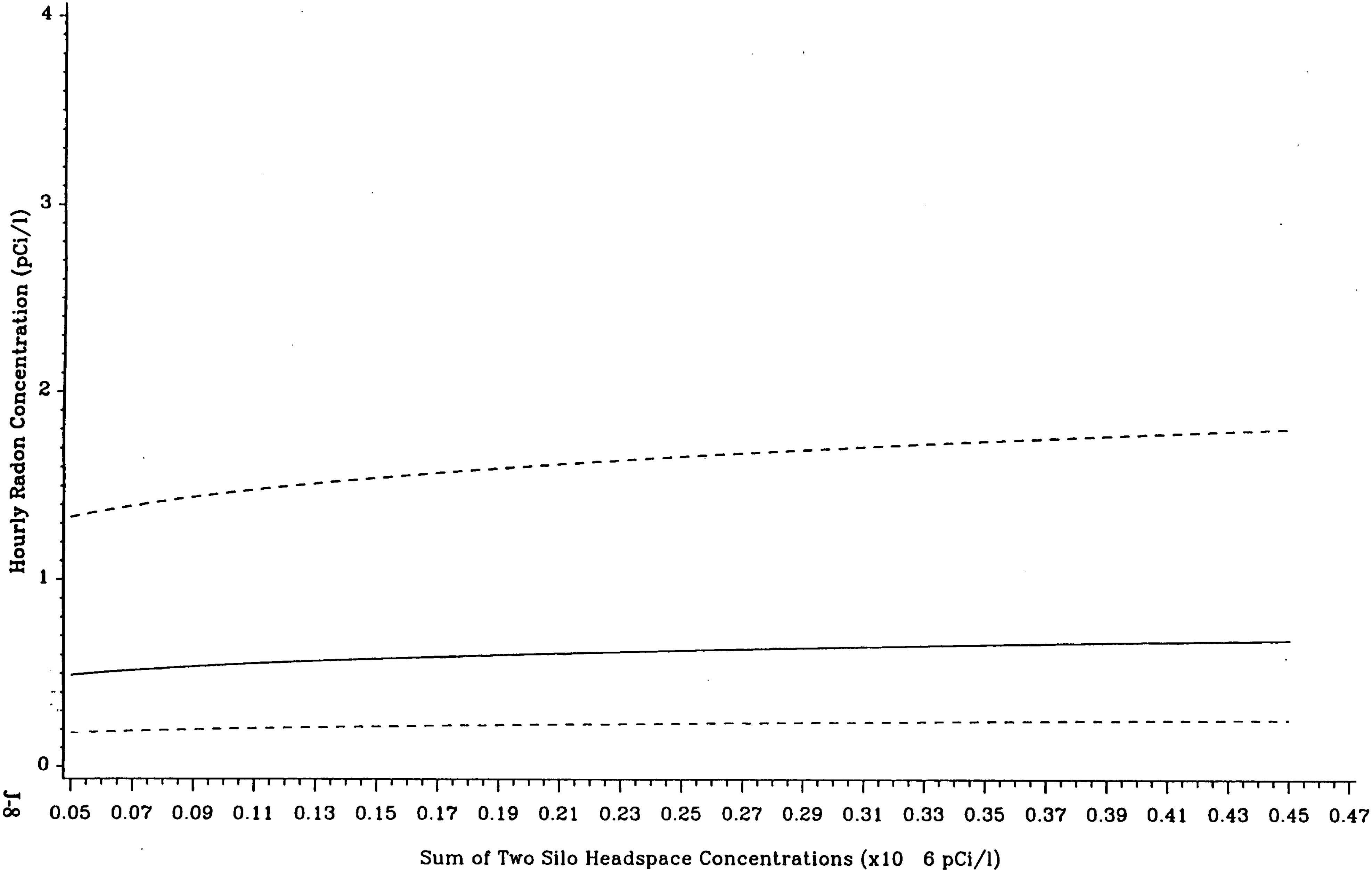
Plot of Predicted Hourly concentration at Background, with 95% Prediction Interval, as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed

Outdoor temperature (C)=15 , Wind speed (m/sec)=1



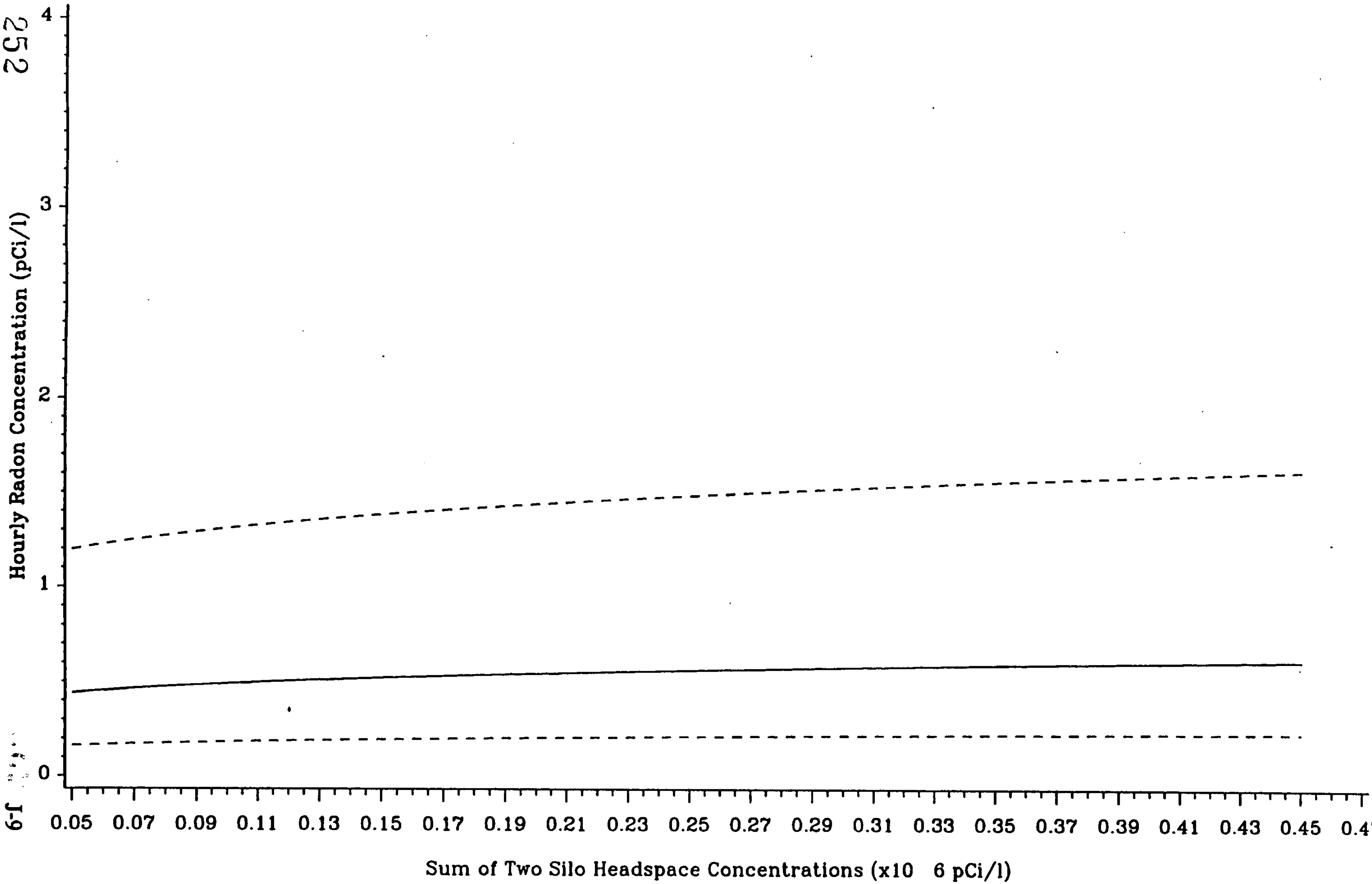
Plot of Predicted Hourly concentration at AMS5, with 95% Prediction Interval, as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed

Outdoor temperature (C)=25 , Wind speed (m/sec)=1



Plot of Predicted Hourly concentration at AMS6, with 95% Prediction Interval, as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed

Outdoor temperature (C)=25 , Wind speed (m/sec)=1



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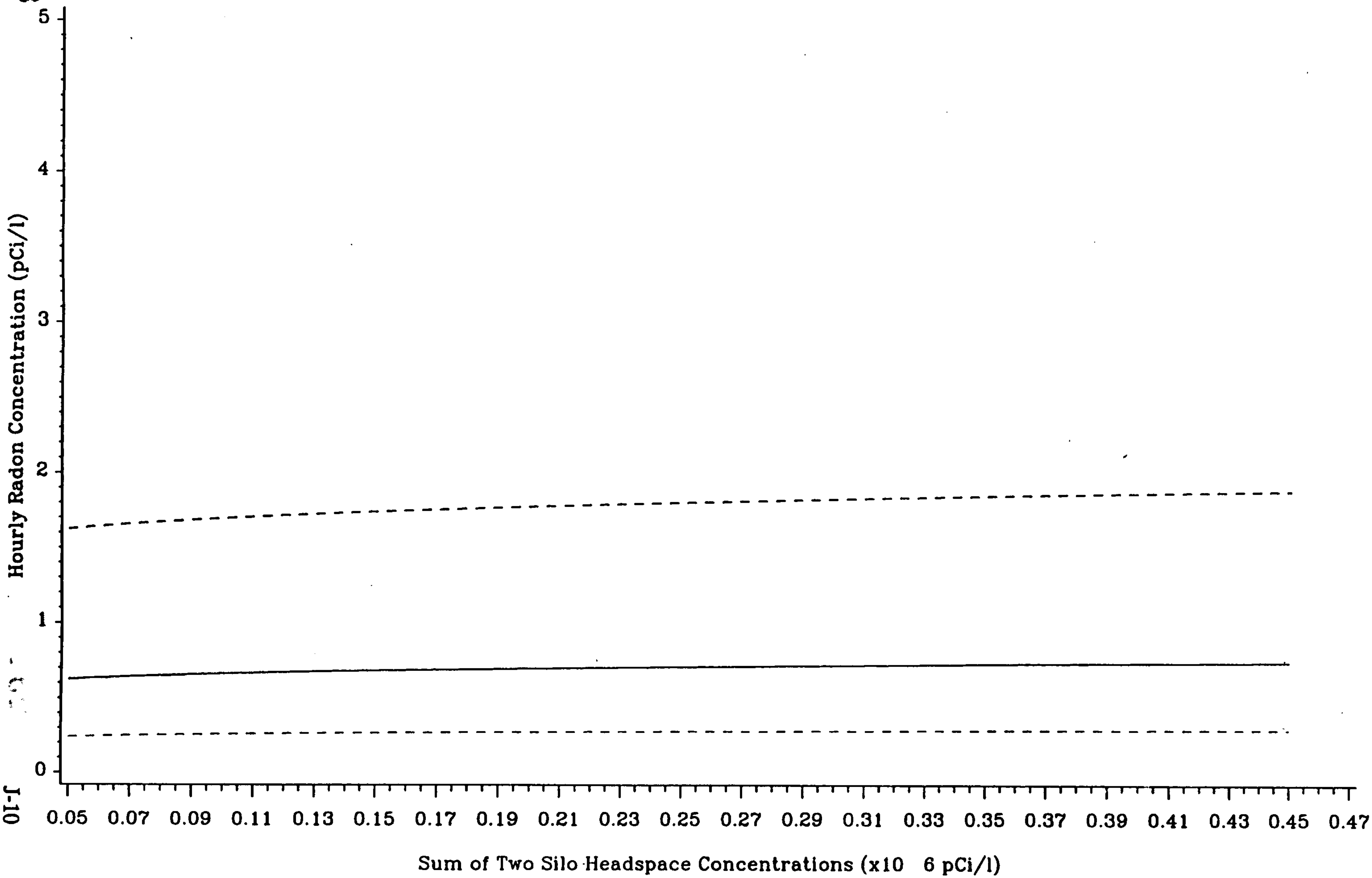
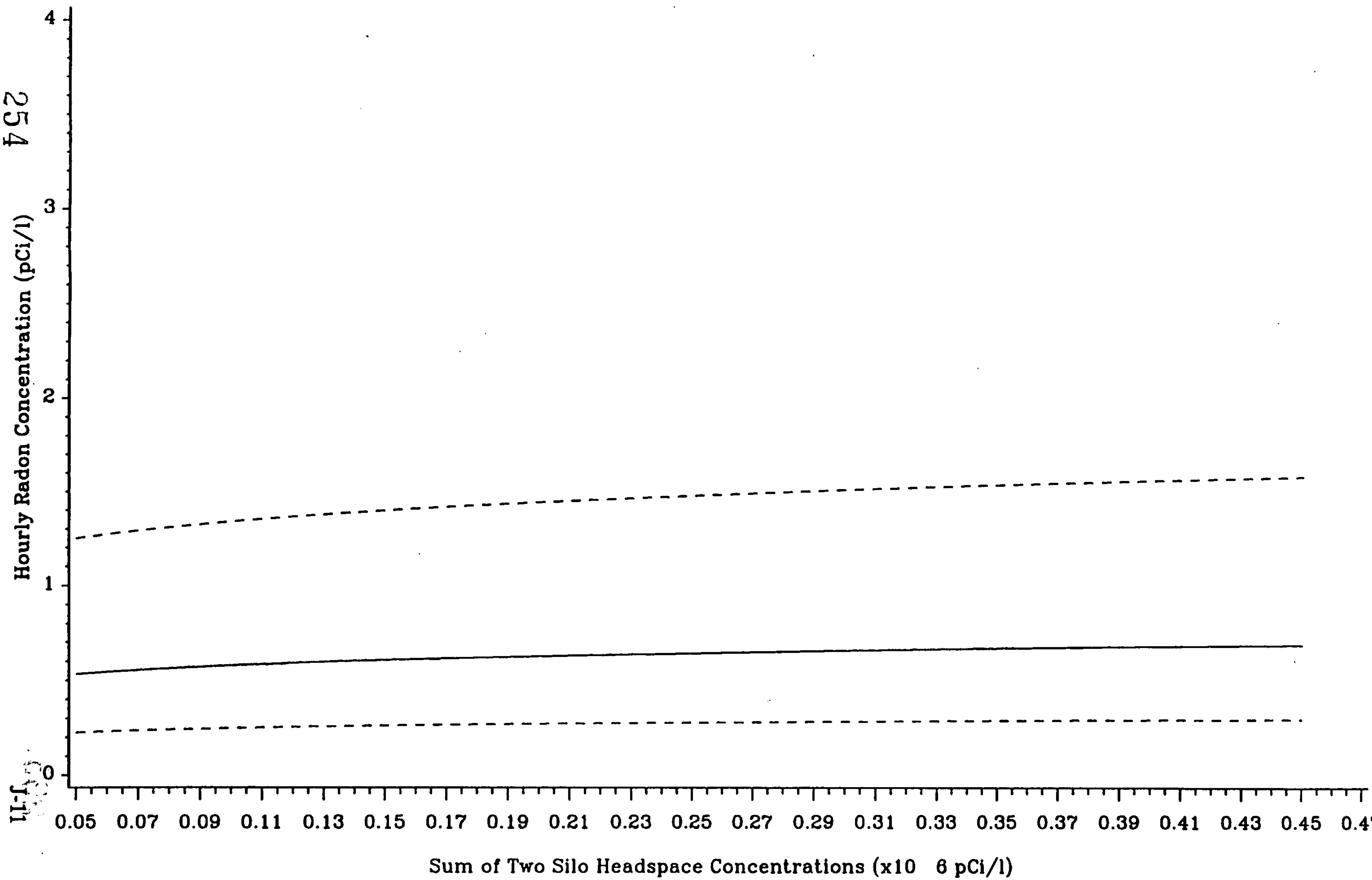
Plot of Predicted Hourly concentration at AMS7, with 95% Prediction Interval,
as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed
Outdoor temperature (C)=25 , Wind speed (m/sec)=1



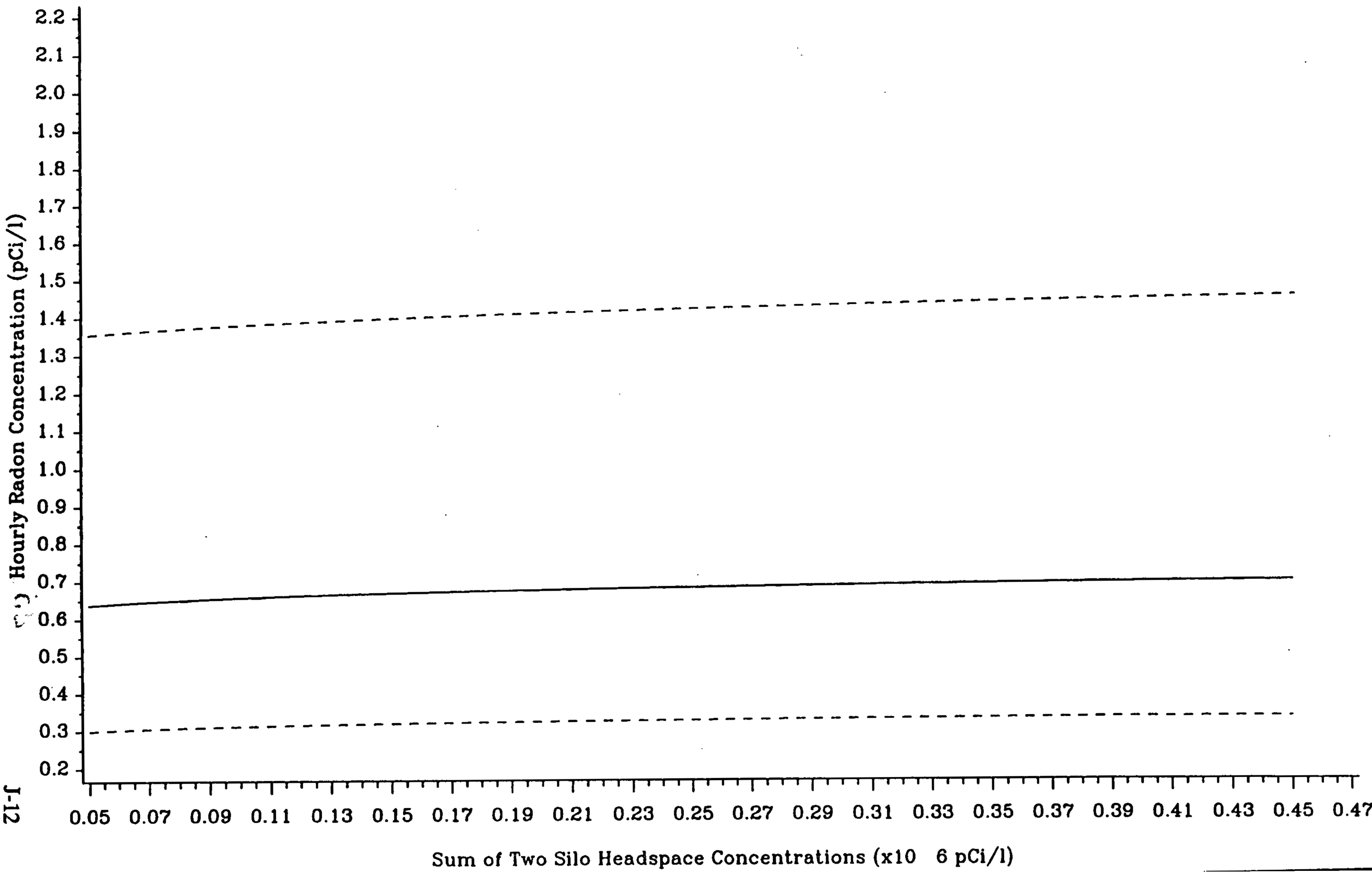
Plot of Predicted Hourly concentration at Met. Tower, with 95% Prediction Interval, as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed

Outdoor temperature (C)=25 , Wind speed (m/sec)=1



Plot of Predicted Hourly concentration at Pilot Plant, with 95% Prediction Interval, as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed

Outdoor temperature (C)=25 , Wind speed (m/sec)=1



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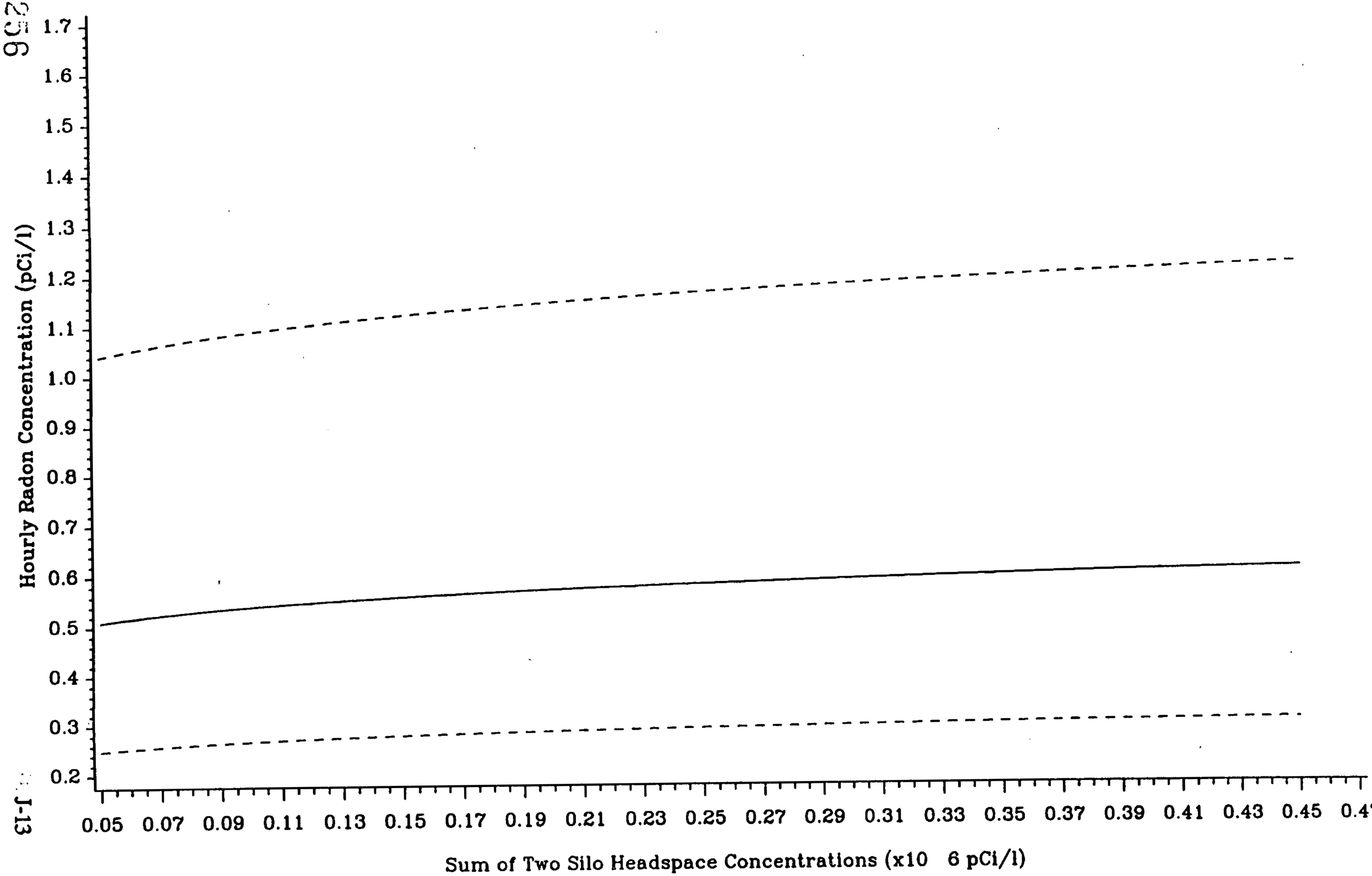
Plot of Predicted Hourly concentration at Background, with 95% Prediction Interval, as a Function of Silo Headspace Concentration, Outdoor Temperature, and Wind Speed

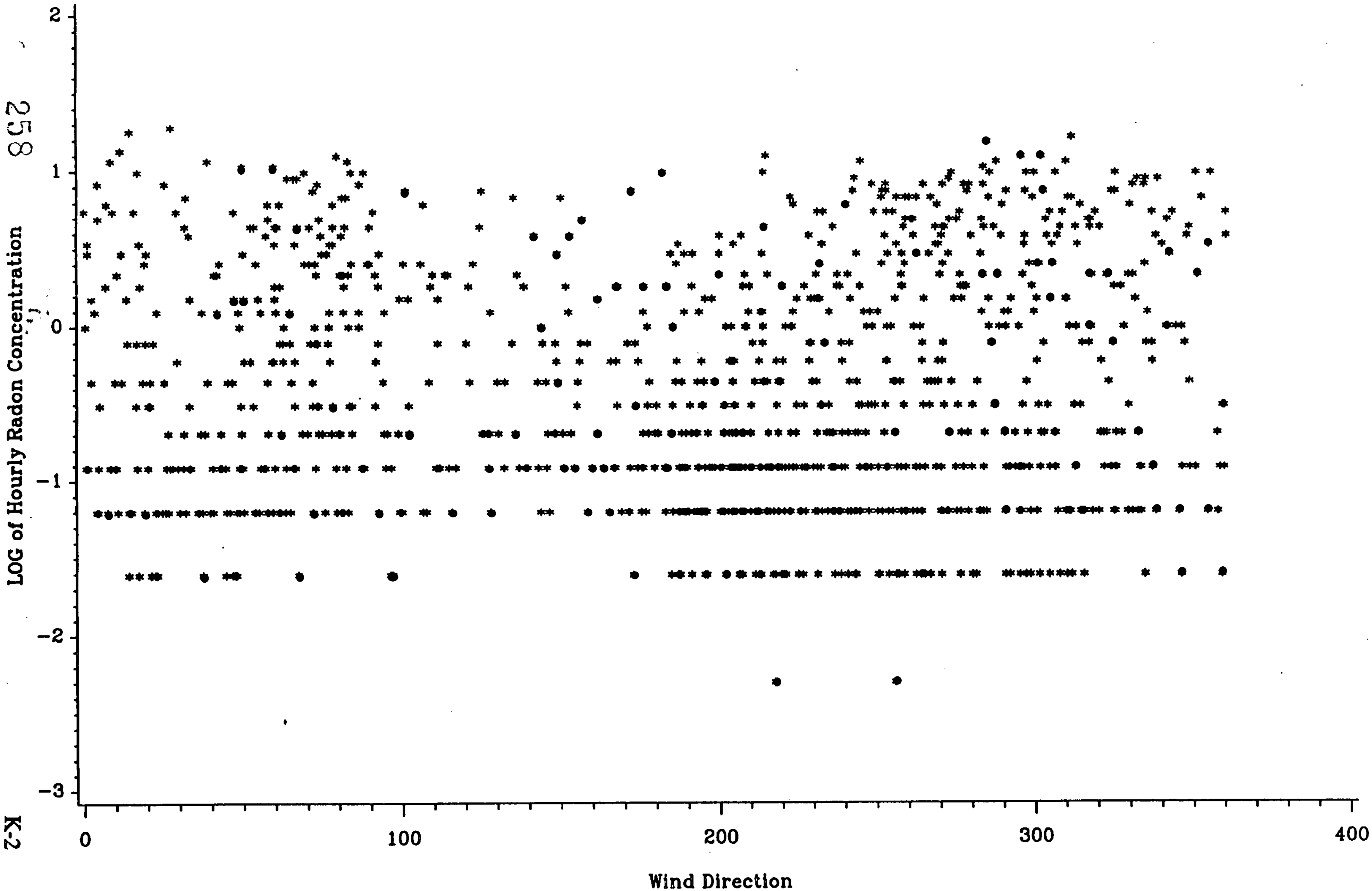
Outdoor temperature (C)=25 , Wind speed (m/sec)=1



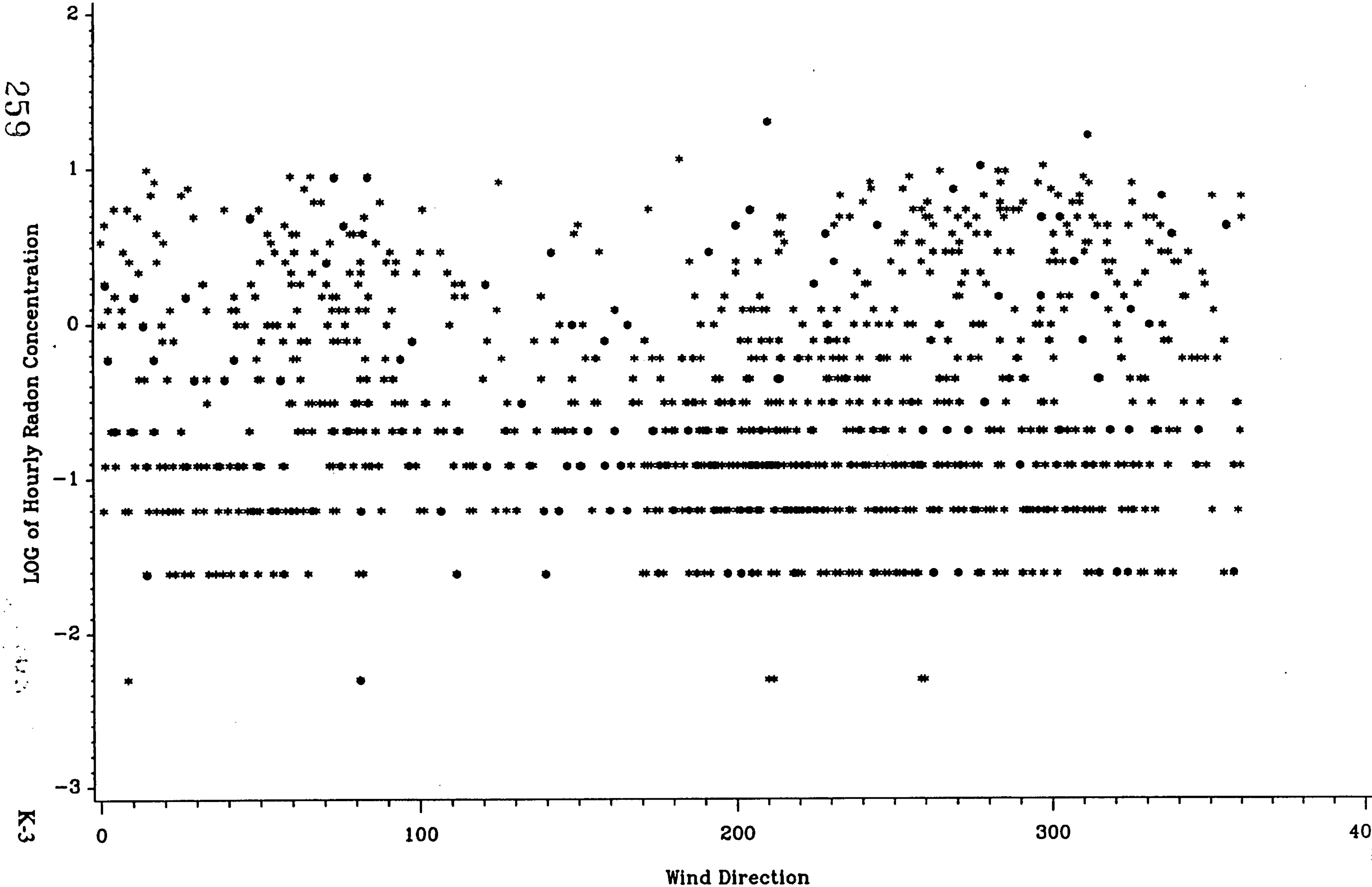
ATTACHMENT K

PLOT OF HOURLY RADON CONCENTRATIONS AT EACH MONITORING STATION VERSUS WIND DIRECTION

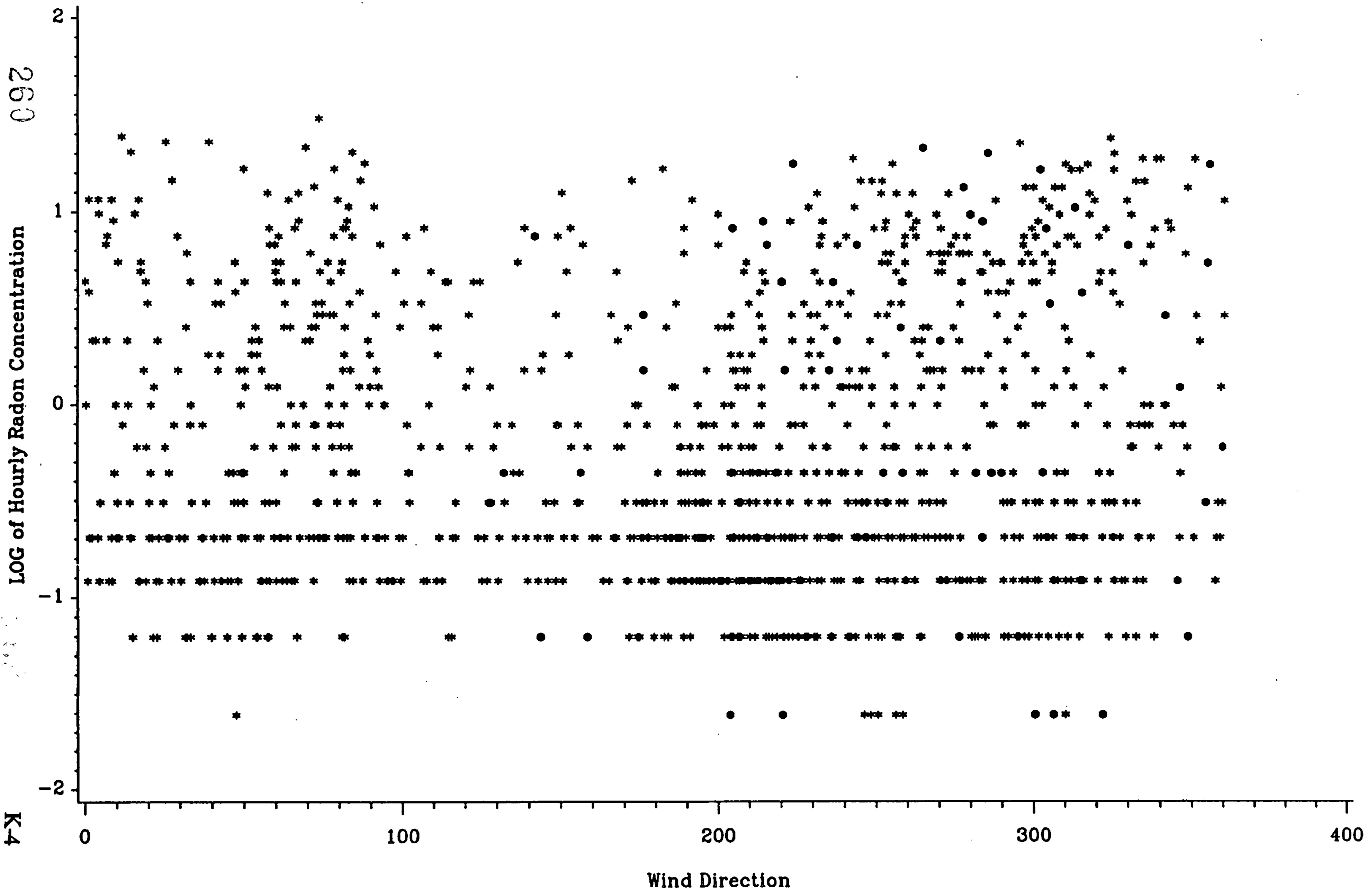
Plot of LOG Hourly Radon Concentration at AMS5 Versus Wind Direction



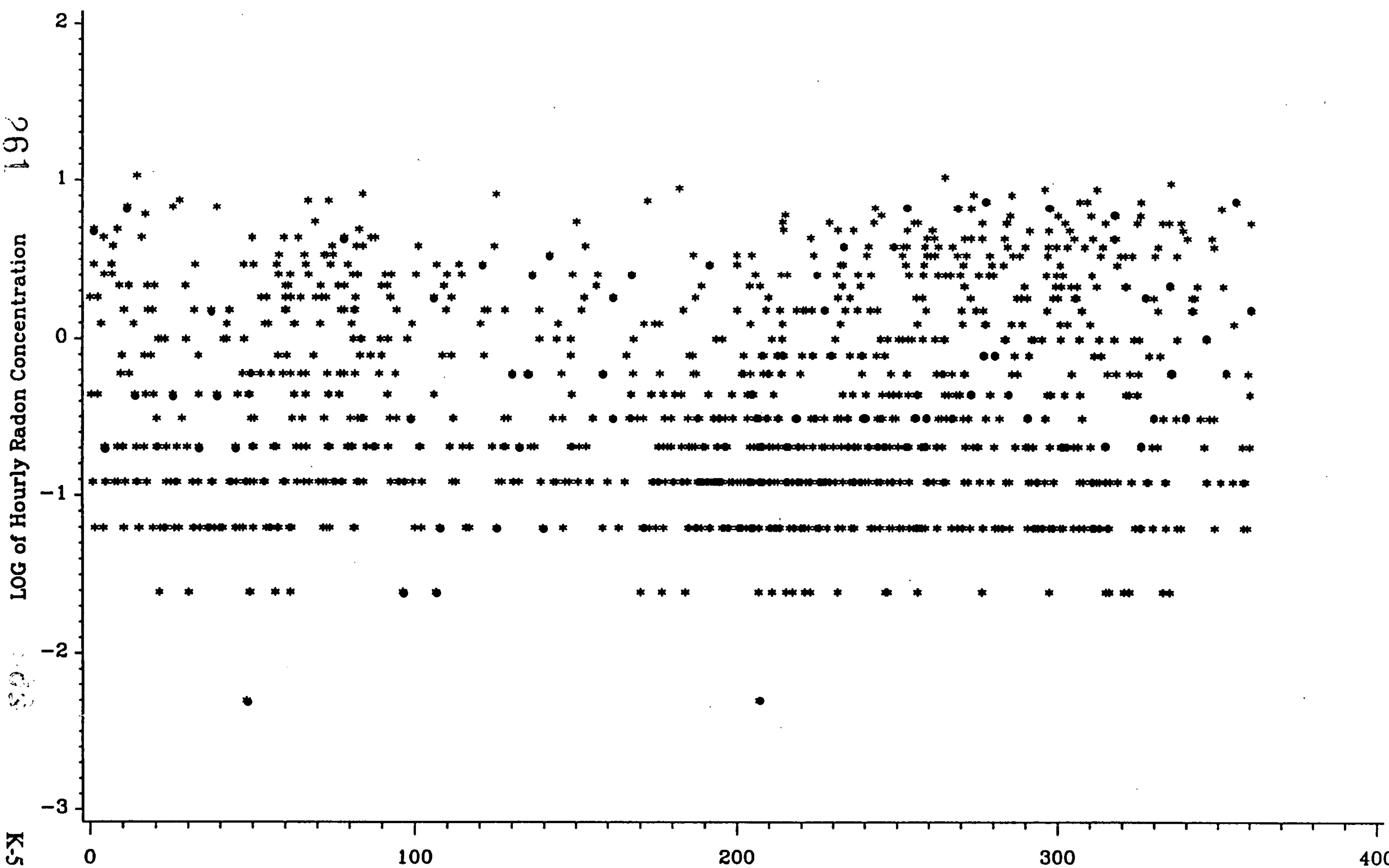
Plot of LOG Hourly Radon Concentration at AMS6 Versus Wind Direction



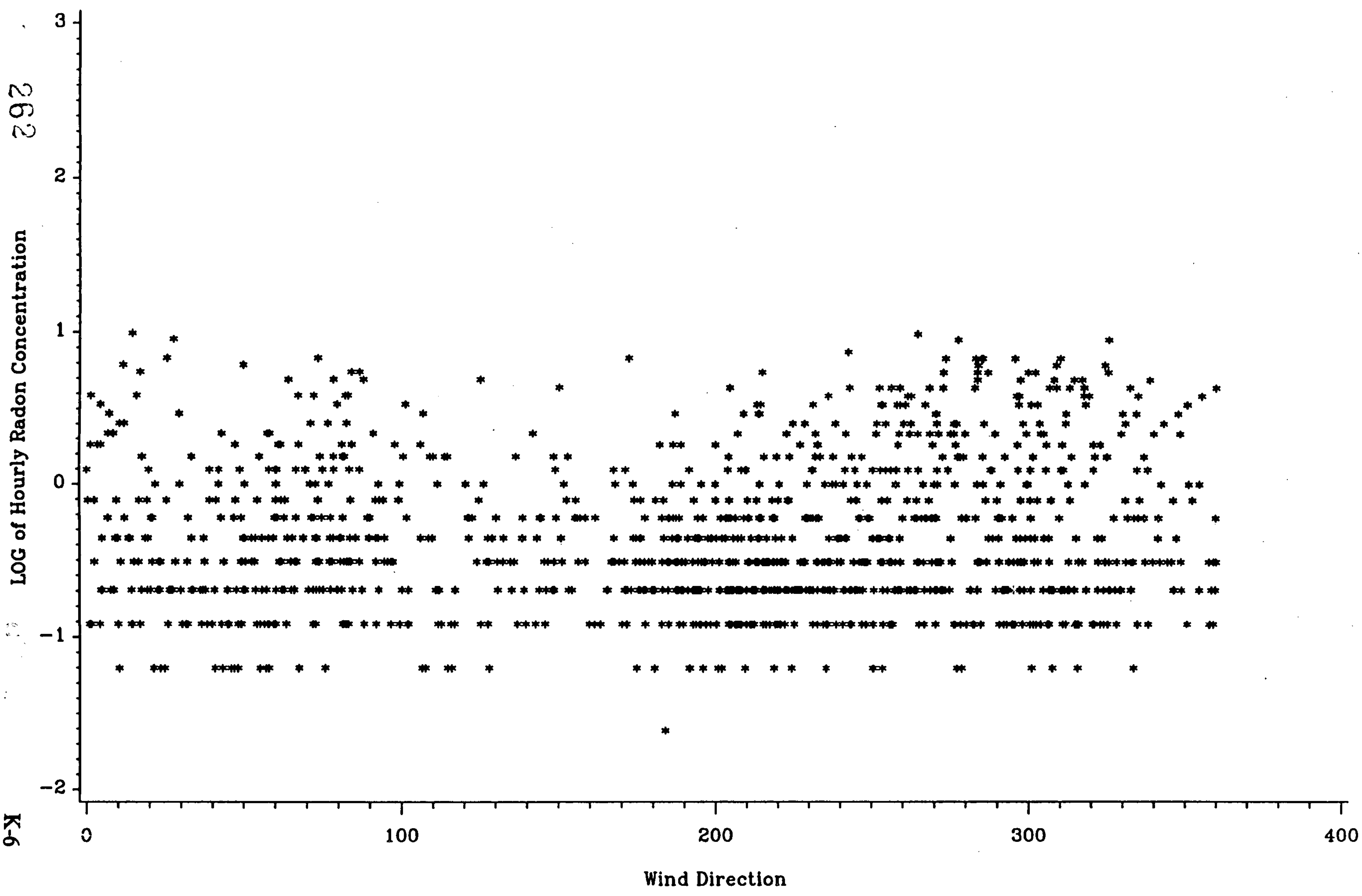
Plot of LOG Hourly Radon Concentration at AMS7 Versus Wind Direction



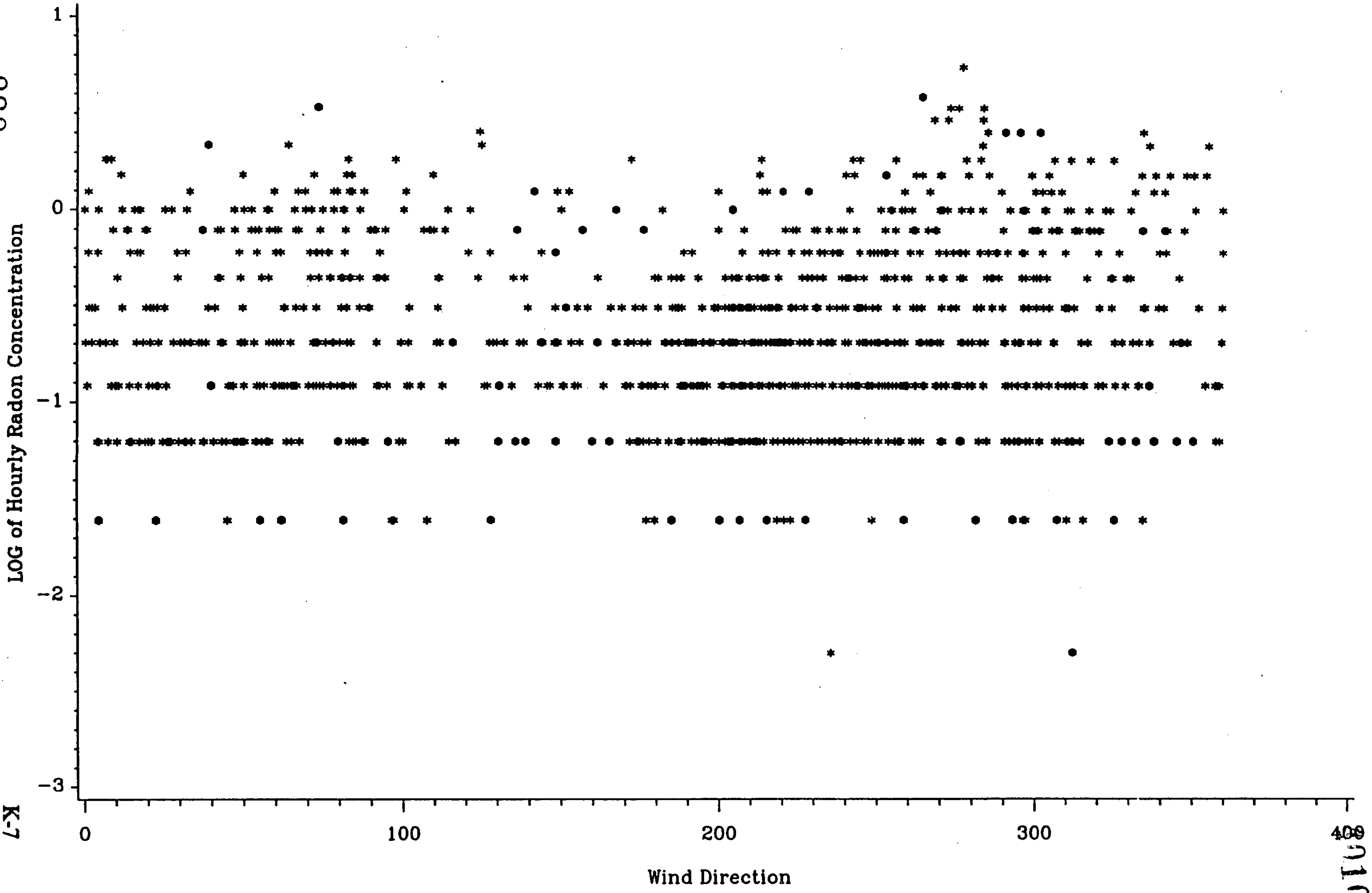
Plot of LOG Hourly Radon Concentration at Met. Tower Versus Wind Direction



Plot of LOG Hourly Radon Concentration at Pilot Plant Versus Wind Direction



Plot of LOG Hourly Radon Concentration at Background Versus Wind Direction



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