PNL-4591
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NUREG/CR-3106
PNL-4591

Comparison of Five-Minute Radon Daughter Measurements With Long-Term Radon and Radon Daughter Concentrations

Prepared by J. A. Young, P. O. Jackson, V. W. Thomas

Pacific Northwest Laboratory
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Comparison of Five-Minute Radon Daughter Measurements With Long-Term Radon and Radon Daughter Concentrations

Manuscript Completed: December 1982
Date Published: January 1983

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Prepared for
Division of Health, Siting and Waste Management
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN B2370

Comparison of Five-Minute Radon Daughter Measurements With Long-Term Radon and Radon Daughter Concentrations

Manuscript Completed: December 1982
Date Published: January 1983

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Washington, D. C. 20555
NRS-PH-8230

ABSTRACT

Pacific Northwest Laboratory (PNL) has made five-minute air filter radon daughter measurements in 84 buildings in Edgemont, South Dakota, in which annual average radon daughter concentrations have been determined from six 100-hour Radon Progeny Integrating Sampling Unit (RPISU) measurements. Average radon concentrations were also determined in 50 of these buildings using Terradex Track Etch® detectors. The standard deviation of the difference between the (natural) logarithms of the RPISU annual averages and the logarithms of the air filter measurements (S.D.-ln) was found to be 0.52. This S.D.-ln is considerably smaller than the S.D.-ln of 0.71 between the RPISU annual averages and the air filter measurements reported by ALARA at Grand Junction, Colorado; presumably because a considerable number of air filter measurements in Edgemont were disregarded because of short turnover times or high wind speeds. Using the S.D.-ln of 0.52 it can be calculated that there would only be a 5% probability in Edgemont that the RPISU annual average would be greater than 0.015 WL if the five-minute measurement were equal to 0.010 WL. This indicates that the procedure used in Edgemont of clearing buildings from remedial action if the five-minute measurement were less than 0.010 WL was reasonable. There was about a 28% probability that the RPISU annual average would be less than 0.015 WL if the five-minute measurement were 0.033 WL, indicating that the procedure of performing an engineering assessment if the average of two five-minute measurements was greater than 0.033 WL was also reasonable. Comparison of the S.D.-ln's between the RPISU annual averages and individual measurements in Edgemont indicates that a single RPISU measurement taken in the months of September through April would provide a somewhat better estimate of the RPISU annual average than would a single air filter measurement, but that the average of two RPISU measurements taken six months apart would provide a considerably better estimate of the annual average. It also appears that a two-month Track Etch® measurement would provide a considerably poorer estimate of the annual average than would a five-minute air filter measurement, but that a six-month Track Etch® measurement could provide a slightly better, and a one-year Track Etch® measurement a considerably better, estimate of the annual average than an air filter measurement.

ABSTRACT

Pacific Northwest Laboratory (PNL) has made five-minute air filter radon daughter measurements in 84 buildings in Edgemont, South Dakota, in which annual average radon daughter concentrations have been determined from six 100-hour radon progeny integrating sampling units (RPI2U) measurements. Average radon concentrations were also determined in 50 of these buildings using Track-Etch detectors. The standard deviation of the difference between the (natural) logarithms of the RPI2U annual averages and the logarithms of the air filter measurements (2.0-in) was found to be 0.52. This 2.0-in is considerably smaller than the 2.0-in of 0.71 between the RPI2U annual averages and the air filter measurements reported by ARA at Grand Junction, Colorado, presumably because a comparable number of air filter measurements in Edgemont were discarded because of short turnover times or high wind speeds. Using the 2.0-in of 0.52 it can be calculated that there would only be a 5% probability of 0.015 WLM if the RPI2U annual average would be greater than 0.015 WLM. The five-minute measurement was equal to 0.010 WLM. This indicates that the procedure used in Edgemont of clearing buildings from remedial action if the five-minute measurement were less than 0.010 WLM was reasonable. There was about a 50% probability that the RPI2U annual average would be less than 0.015 WLM if the five-minute measurement were 0.010 WLM, indicating that the procedure of performing an engineering assessment if the average of two five-minute measurements was greater than 0.015 WLM was also reasonable. Comparison of the 2.0-in between the RPI2U annual averages and individual measurements in Edgemont indicates that a single RPI2U measurement taken in the month of September through April would provide a somewhat better estimate of the RPI2U annual average than would a single air filter measurement, but that the average of two RPI2U measurements taken six months apart would provide a considerably better estimate of the annual average. It also appears that a two-month Track-Etch measurement would provide a considerably poorer estimate of the annual average than would a five-minute air filter measurement, but that a six-month Track-Etch measurement could provide a slightly better and a one-year Track-Etch measurement a considerably better estimate of the annual average than an air filter measurement.

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ACKNOWLEDGEMENTS

The authors would like to express their appreciation to the EPA/Las Vegas Facility for providing the RPISU's and analyzing the TLD's from the RPISU samplers used at Edgemont, S.D. We also thank R. R. Kinnison of the Pacific Northwest Laboratory for statistical consultations.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to the EPA's West Valley for providing the RP12U's and analyzing the TDS from the RP12U samples used at Edgemont, S.D. We also thank R. R. Kinnison of the Pacific Northwest Laboratory for statistical consultations.

COMPARISON OF FIVE-MINUTE RADON DAUGHTER MEASUREMENTS WITH LONG-TERM RADON AND RADON DAUGHTER CONCENTRATIONS

J. A. Young, P. O. Jackson and V. W. Thomas

INTRODUCTION

The Environmental Protection Agency (EPA) interim radon daughter standard requires that remedial action be performed if residual radioactive materials from inactive uranium processing sites cause average annual radon daughter concentrations exceeding 0.015 working levels (WL)* in any occupied or occupiable building. This standard was published in the Federal Register in January 1981 (40 CFR 192). However, the EPA has recently proposed that the standard be changed to require that radon daughter concentrations shall not exceed 0.030 WL, and, to the extent practical, shall achieve 0.020 WL.

Average annual radon daughter concentrations in buildings can only be determined accurately from long-term measurements, because radon daughter concentrations vary widely on all time scales because of changes in factors such as humidity, aerosol concentration, ventilation rate and forced air circulation by air conditioners and central heating systems. The generally accepted method for determining the annual average has been to make measurements of 100 hours or longer every other month during the course of a year using Radon Progeny Integrating Sampling Units (RPISU). The RPISU measures radon concentrations by drawing air through a filter next to which is placed a thermoluminescent dosimeter (TLD) chip. When an alpha particle strikes the TLD chip, electrons are promoted into metastable, elevated energy states. The TLD chip is later analyzed by heating it to the temperature at which the electrons return to the ground state, giving off energy in the form of light in the process. The light is measured using a photomultiplier to determine the total exposure of the TLD chip, and therefore the average radon daughter concentration during the measurement period.

RPISU measurements have proven to be costly and time consuming to perform. Also, the RPISU's are bulky and produce a humming noise, so many people object to the use of RPISU's to measure radon daughter concentrations in their homes. The time required to make year-long RPISU measurements can result in a considerable delay in the implementation of remedial action, especially if radon daughter concentrations need to be measured in more buildings than can be handled using the available RPISU's. It should always be remembered that delays in the implementation of remedial action can result in a larger radiation dose to the population than minor errors in the determination of where remedial action should be performed. Therefore, it could prove to be advantageous to use short-term radon daughter or radon measurements to determine whether buildings can be

* Although working level is considered to be a unit of concentration in 40 CFR 192, working level is more properly a unit of exposure rate. The term, concentration, will be used throughout this report for consistency with 40 CFR 192 and common usage.

cleared from remedial action, even if these short-term measurements provide estimates of average annual radon daughter concentrations that are somewhat less accurate than those provided by six 100-hour RPISU measurements. Therefore, Pacific Northwest Laboratory (PNL) is making comparisons between short-term radon and radon daughter measurements and RPISU average annual average radon daughter concentrations in Edgemont, South Dakota, to determine the reliability of the estimates of annual averages provided by these measurements. This report will compare the standard deviations between RPISU annual averages and (1) single air filter measurements; (2) single RPISU measurements; (3) two 100-hour RPISU measurements made six months apart; and (4) two-month, six-month and 12-month Terradex Track Etch® measurements to provide an indication of which of these techniques provided the most accurate estimates of RPISU average annual radon daughter concentrations.

COMPARISON OF FIVE-MINUTE AIR FILTER AND RPISU AVERAGE ANNUAL RADON DAUGHTER CONCENTRATIONS AT EDMONT, SOUTH DAKOTA

Radon daughter concentrations are being measured in five-minute air filter samples collected in buildings in Edgemont using the Thomas modification of the Tsivoglou method (Thomas, 1972) to screen out buildings that should not require long-term radon daughter measurements. The occupants are asked to keep the buildings closed up as tightly as possible for at least four hours before the measurements to provide standardized measurement conditions so that the measurements will have a consistent relationship to annual averages.

If the radon daughter concentration in an air filter sample is greater than 0.033 WL, a second measurement is made to confirm the elevated concentration. If the average of the two measurements is greater than 0.033 WL, it is assumed that the annual average will be greater than 0.015 WL, so the building is scheduled for engineering assessment to locate any residual radioactive materials that could be causing the elevated concentrations. If the concentration in a valid air filter measurement is less than 0.010 WL, it is assumed that the annual average will be less than 0.015 WL, so the building is cleared from engineering assessment and remedial action. A measurement is considered to be invalid if it was taken when the wind speed at the local meteorological station was greater than 8 mph, or if the turnover time of the radon daughters in the structure was too short. The turnover time of the radon daughters in the air in a structure prior to a five-minute measurement can be calculated from the disequilibrium between the daughters ^{218}Po , ^{214}Pb and ^{214}Bi using equations reported by Morken and Scott (1966). The turnover time can be calculated from the concentrations of any two of the three daughters, but at Edgemont the turnover times were calculated using the ^{218}Po - ^{214}Bi and the ^{214}Pb - ^{214}Bi pairs (Young, et al., 1982). If the turnover time calculated from either pair was either positive and shorter than 32 minutes or negative and shorter than 100 minutes, the measurement was considered to be invalid. The calculated turnover time becomes negative if the measured activity of a daughter is lower than the activity of its daughter. Negative turnover times can result from statistical fluctuations in the measurements, or from rapid variations in the plateout rate, which is significantly greater for ^{218}Po than it is for the other daughters.

The intermittent operation of a circulating heating system is one possible cause of variations in the plateout rate.

If a measurement is found to be invalid, the measurement is repeated at later dates until a valid measurement is obtained. However, if it is judged that a valid measurement will be difficult to obtain in a building, that building is scheduled for long-term RPISU radon daughter measurements. A fairly large fraction of air filter measurements were later found to be invalid. About 66% of the measurements were found to be valid, 17% were found to be invalid because of short turnover times, (if the turnover time was too short, the wind speed was not checked) and 17% were found to be invalid because the wind speed was greater than 8 mph. Of course, the number of measurements that were later found to be invalid because of high wind speeds could have been decreased considerably if fewer measurements had been made under marginal wind conditions.

Long-term RPISU measurements are also being made in buildings that show radon daughter concentrations ranging from 0.010 to 0.033 WL in the air filter samples, because it is considered that five-minute measurements in this range will not provide a sufficiently reliable indication of whether the annual average will be greater than 0.015 WL.

Radon daughter concentrations in buildings in which air filter measurements and six 100-hour RPISU measurements have been made on the same floor are shown in Table 1. There was considerable variation between the RPISU annual averages and the air filter measurements. The linear correlation coefficient, r , between the RPISU annual averages and the air filter measurements was only 0.60.

The air filter measurements also averaged considerably higher than the RPISU annual averages. Since both the RPISU annual averages and the air filter measurements showed approximately log normal distributions (Figures 1 and 2), it is appropriate to express the difference between the RPISU and the air filter measurements in terms of the (natural) logarithm of the RPISU to air filter ratio. This is, of course, equal to the logarithm of the RPISU measurement minus the logarithm of the air filter measurement. The average difference in the logarithms was found to be -0.46 ± 0.52 . This corresponds to an average ratio between the RPISU annual averages and the air filter measurements of $\exp -0.46 = 0.63$. In subsequent discussions, 0.63 times the air filter concentration will be referred to as the corrected air filter concentration.

The air filter measurements were higher than the RPISU annual averages presumably because the air filter measurements were made in closed-up buildings. It has been estimated that a building in an area with a climate similar to that of Edgemont will be closed-up about 60% of the time, and will be open to the outside about 40% of the time. The radon daughter concentration should be negligible when the building is open, so the annual average should be about 0.6 times the concentration measured when the building is closed (Giedt, 1980; Lloyd, 1981).

The real test of the usefulness of the air filter radon daughter measurements lies in how well they predict whether the average annual radon daughter concentration will exceed a remedial action standard,

Table 1. RPISU and Valid Five-Minute Air Filter Radon Daughter Measurements in Buildings in Edgemont, South Dakota

Building Identification Number		RPISU Average Annual Radon Daughter Concentration (WL)	Air Filter Radon Daughter Concentration (WL)
EPA	PNL		
71	173	0.0398	0.1033
71	173		0.0726
86	243	0.0245	0.0812
86	243		0.0369
106	54	0.0183	0.0720
106	54		0.0414
136	121	0.0059	0.0048
151	119	0.0138	0.0290
181	105	0.0065	0.0123
201	277	0.0065	0.0104
246	182	0.0102	0.0083
261	73	0.0174	0.0361
261	73		0.0271
266	144	0.0255	0.0410
266	144		0.0230
271	147	0.0260	0.0323
276	25	0.0159	0.0149
286	74	0.0037	0.0124
291	34	0.0073	0.0206
306	67	0.0142	0.0254
311	3	0.0119	0.0157
316	6	0.0086	0.0217
321	55	0.0097	0.0240
326	56	0.0069	0.0193
331	53	0.0203	0.0224
336	104	0.0076	0.0147
341	11	0.0133	0.0249
351	83	0.0077	0.0190
371	167	0.0061	0.0163
376	132	0.0108	0.0128
399	299	0.0149	0.0178
396	266	0.0132	0.0282
401	106	0.0054	0.0101
406	300	0.0055	0.0038
416	130	0.0058	0.0094
436	87	0.0104	0.0314
441	283	0.0185	0.0302
446	48	0.0262	0.0111
451	200	0.0142	0.0158
456	2	0.0118	0.0281
461	94	0.0111	0.0200
466	282	0.0141	0.0273
471	287	0.0198	0.0389
471	287		0.0258

Table 1. RPISU and Valid Five-Minute Air Filter Radon Daughter Measurements in Buildings in Edgemont, South Dakota (continued)

Building Identification Number		RPISU Average Annual Radon Daughter Concentration	Air Filter Radon Daughter Concentration
<u>EPA</u>	<u>PNL</u>	<u>(WL)</u>	<u>(WL)</u>
476	129	0.0134	0.0074
486	107	0.0062	0.0100
506	97	0.0081	0.0226
511	15	0.0074	0.0171
516	9	0.0129	0.0159
521	7	0.0163	0.0241
531	295	0.0092	0.0192
536	294	0.0146	0.0163
541	76	0.0271	0.0131
546	131	0.0046	0.0117
551	91	0.0071	0.0042
556	35	0.0144	0.0544
556	36		0.0185
561	153	0.0101	0.0233
566	71	0.0212	0.0322
576	133	0.0079	0.0042
581	231	0.0080	0.0349
581	231		0.0179
586	262	0.0158	0.0112
591	220	0.0154	0.0189
596	220	0.0163	0.0165
601	14	0.0172	0.0270
606	137	0.0099	0.0174
611	217	0.0132	0.0172
616	214	0.0108	0.0146
621	31	0.0105	0.0235
627	165	0.0181	0.0175
631	185	0.0165	0.0137
651	324	0.0084	0.0161
656	359	0.0078	0.0044
681	172	0.0133	0.0378
681	172		0.0283
686	222	0.0111	0.0231
691	215	0.0071	0.0193
696	201	0.0179	0.0341
696	201		0.0182
701	39	0.0049	0.0088
706	346	0.0178	0.0253
711	241	0.0112	0.0243
716	258	0.0357	0.0347
716	258		0.0231
721	169	0.0063	0.0189

Table 1. RPISU and Valid Five-Minute Air Filter Radon Daughter Measurements in Buildings in Edgemont, South Dakota (continued)

Building Identification Number		RPISU Average Annual Radon Daughter Concentration (WL)	Air Filter Radon Daughter Concentration (WL)
EPA	PNL		
726	1	0.0197	0.0317
731	21	0.0207	0.0318
736	66	0.0091	0.0160
746	362	0.0153	0.0122
751	176	0.0205	0.0243
756	149	0.0077	0.0283
766	303	0.0094	0.0281
776	250	0.0059	0.0129
786	298	0.0091	0.0112

FIGURE 1. Frequency Distribution of Air Filter Radon Daughter Measurements

FIGURE 2. Frequency Distribution of RPISU Average Annual Radon Daughter Concentrations

such as 0.015 or 0.020 WL. The probability that the RPISU annual average will exceed a given value can be obtained as a function of the corrected air filter measurement using a table of the ordinates and areas of the normal distribution and the standard deviation of the difference between the (natural) logarithms of the RPISU annual averages and the logarithms of the air filter measurements ($S.D. - \ln = 0.52$). Figure 3 shows the probabilities that the RPISU averages will be greater than 0.015, 0.020, 0.025 and 0.030 WL as a function of the air filter concentration. The figure indicates that if the air filter measurement is 0.010 WL, there should be only a 5% probability that the RPISU annual average would be greater than 0.015 WL, and only a 1.4% probability that it would be greater than 0.020 WL.

The actually observed probabilities that the RPISU annual average would be greater than 0.015 WL for given ranges of the corrected and uncorrected air filter measurements are shown in Figure 4. (Linear coordinates are used in this figure, rather than log-probability coordinates, because linear coordinates demonstrate the correspondence between the observed and calculated probabilities better.) The observed and calculated probabilities agree fairly well. The differences that are observed are likely to be due primarily to the relatively small number of measurements in each concentration range. However, the deviations may also be partly due to the fact that the frequency distribution of the air filter measurements shows two breaks, indicating the presence of three separate populations (Figure 1). The population of radon daughter concentration measurements greater than about 0.050 WL could have been due to residual radioactivity. The two populations at lower concentrations could have resulted from differences in the ^{226}Ra concentrations in the soil underlying the buildings. Bentonite clay deposits, having somewhat elevated ^{226}Ra concentrations, are found beneath some of the buildings in Edgemont. However, the two populations at lower concentrations could also have resulted from differences in ventilation rates. New homes with low ventilation rates might be expected to have higher radon daughter concentrations than older homes. Correlations of radon daughter concentrations with ^{226}Ra concentrations in soil and turnover times will be studied in the future to indicate the reasons for the variations in radon daughter concentrations.

Figures 3 and 4 indicate that buildings in Edgemont could safely be cleared from remedial action if the (uncorrected) air filter radon daughter measurement was less than 0.010 WL. If the radon daughter standard is changed to require that the radon daughter concentrations achieve 0.020 WL to the extent that is possible, and shall not exceed 0.030 WL, then the value for the air filter measurement below which buildings should be cleared from remedial action should be raised accordingly. According to Figure 3, if the air filter measurement is 0.015 WL, there should be only a 7.5% probability that the RPISU annual average will be greater than 0.020 WL, and only a 1.2% probability that it will be greater than 0.030 WL. The actual decision level chosen should be based upon a decision concerning what probability can be tolerated that a building will be cleared from remedial action even though its average annual radon daughter concentration is greater than the existing standard.

FIGURE 3. Probabilities that the RPISU Average Annual Radon Daughter Concentration will be Greater than 0.015, 0.020, 0.025 and 0.030 WL

FIGURE 4. Probability that the RPISU Annual Average will be Greater than 0.015 WL as a Function of the Value for the air Filter Measurement

It should be remembered that the percentage of buildings cleared from remedial action in Edgemont that actually had average annual radon daughter concentrations greater than 0.015 WL should have been considerably less than the value of 5% shown in Figure 3 for a five-minute measurement of 0.010 WL. This is because most of the buildings cleared would have had five-minute concentrations less than, rather than equal to, 0.010 WL. The actual percentage of buildings cleared incorrectly was estimated from the frequency distribution of the air filter measurements that are shown in Figure 1. The number of buildings in a given concentration range that were cleared incorrectly was estimated by multiplying the number of buildings in the concentration range by the average probability for that concentration range that the buildings were cleared incorrectly. The total number of buildings having five-minute concentrations less than or equal to 0.010 WL that were cleared incorrectly was estimated by taking the sum of the buildings cleared incorrectly for each of the concentration ranges below and including 0.010 WL. The fraction of the total number of buildings measured that were cleared incorrectly was then estimated by dividing this sum by the total number of buildings measured. Using this procedure it was estimated that only 1.1% of the buildings cleared from remedial action on the basis of the air filter measurements would have had RPISU annual averages greater than 0.015 WL. If buildings having air filter measurements of 0.015 WL or less had been cleared, then 5.1% of the buildings cleared would have had RPISU annual averages greater than 0.015 WL. However, the percentage of buildings cleared would have been raised from 28 to 45%.

Buildings were scheduled for engineering assessment at Edgemont if the average of two or more air filter radon daughter concentration measurements was greater than 0.033 WL. Figure 3 indicates that if one air filter measurement was 0.033 WL, there would be about a 28% probability that the RPISU annual average would be less than 0.015 WL. However, the S.D.-ln between the average of two measurements and the RPISU annual average would be expected to be smaller than that between a single air filter measurement and the RPISU annual average. Therefore, the probability that the RPISU annual average would be less than 0.015 WL when the average of two air filter measurements was 0.033 WL would be expected to be less than 28%. There were only 11 buildings in Edgemont in which RPISU measurements and two air filter measurements were made on the same floor. The S.D.-ln between the RPISU annual averages and the average of the two measurements was found to be 0.42. However, this S.D.-ln is probably not a very reliable indicator of the variability that would be expected between future RPISU and five-minute measurements, because it is based on such a limited number of measurements, and because the duplicate measurements were all made in buildings having high radon daughter concentrations. Since the S.D.-ln between the RPISU averages and single five-minute measurements was 0.52, it would be expected that the S.D.-ln between the RPISU averages and the average of two five-minute measurements would be $0.5(0.52^2 + 0.52^2)^{1/2} = 0.37$, if the five-minute measurement error were entirely random, and the RPISU measurement error were negligible. Using a S.D.-ln of 0.37, it can be calculated that there would be about a 20% probability the the RPISU average would be less than 0.015 WL if the average of two air filter measurements were equal to 0.033 WL.

The above calculations indicate that a considerable number of the buildings in Edgemont that were scheduled for engineering assessment because of air filter radon daughter concentrations greater than 0.033 WL would have had RPISU annual averages less than 0.015 WL. However, this fact should not have increased the cost of the remedial action program, because buildings are cleared from remedial action if no residual radioactive material is discovered during engineering assessment. It has also been found that about the same number of man-hours (8) is required to perform an engineering assessment as is needed to perform a RPISU measurement series to determine whether an engineering assessment is required (ALARA, 1980; Young et al., 1982). It is unlikely that residual radioactive material would be discovered around many buildings that had average annual radon daughter concentrations less than 0.015 WL, but were scheduled for engineering assessment on the basis of the air filter measurements.

The comparable cost of performing engineering assessments and six 100-hour RPISU measurements suggests that considerable money could have been saved in Edgemont if engineering assessments, rather than RPISU measurements (followed by any engineering assessments required), had been performed for buildings having air filter radon daughter concentrations ranging from 0.010 to 0.033 WL. The frequency distribution of the air filter measurements (Figure 1) indicates that if engineering assessments had been performed in all buildings having air filter measurements greater than 0.010 WL, then engineering assessments would have been performed in 72% of the buildings. The percentage of these buildings that would have actually had RPISU annual averages less than 0.015 WL can be calculated from the frequency distribution of the air filter measurements, and the S.D.-ln between the RPISU annual averages and the air filter measurements. This was done by first dividing the air filter concentrations into intervals. The probability that a building would have an air filter measurement in each interval was then multiplied by the average probability for this concentration interval that the RPISU annual would be less than 0.015 WL to obtain the probability that a building would have an air filter measurement in this interval and a RPISU annual average less than 0.015 WL. The probabilities for all concentration intervals greater than 0.010 WL were then summed to obtain a total probability of 50% that the air filter measurement would be greater than 0.010 WL, but the RPISU annual average would be less than 0.015 WL.

In the same manner it can be calculated that if engineering assessments had been performed in all buildings having air filter measurements greater than 0.015 WL, then engineering assessments would have been performed in 55% of the buildings, and 31% of these engineering assessments would have been performed in buildings having RPISU annual averages less than 0.015 WL.

COMPARISON OF AIR FILTER AND RPISU AVERAGE ANNUAL RADON DAUGHTER CONCENTRATIONS IN GRAND JUNCTION, COLORADO

ALARA (1980) has reported air filter radon daughter measurements in 30 buildings in Grand Junction, Colorado, in which six 100-hour RPISU measurements were also made. The difference between the (natural) loga-

rithms of RPISU annual averages and the logarithms of the air filter measurements averaged 0.21 ± 0.71 . This corresponds to an average RPISU to air filter ratio of 1.2, which is considerably higher than the ratio of 0.63 found at Edgemont. Therefore, the valid air filter measurements at Edgemont averaged much higher, relative to the RPISU annual averages, than did those at Grand Junction. The S.D.-ln of 0.71 between the logarithms of the RPISU annual averages and the logarithms of the air filter measurements at Grand Junction was also much higher than the S.D.-ln of 0.52 found at Edgemont.

The higher concentrations and the lower variability, relative to the RPISU annual averages, found in the valid air filter measurements at Edgemont probably resulted from the fact that many air filter measurements in Edgemont were disregarded because of either short turnover times or high wind speeds. The radon daughter concentrations were measured using the Kusnetz method (Kusnetz, 1965) in Grand Junction. This method does not provide concentrations of the individual radon daughters. Therefore, turnover times cannot be calculated, so measurements having short turnover times cannot be screened out. There is also no indication that air filter measurements in Grand Junction were discarded when the wind speed was found to be too high. For these reasons, it would be expected that the entire set of air filter measurements in Edgemont (both valid and invalid) would be more nearly comparable to the air filter measurements in Grand Junction than would the valid measurements. The difference between the logarithms of the RPISU annual averages and the logarithms of the valid and invalid air filter measurements in Edgemont was found to be -0.31 ± 0.65 . This S.D.-ln was only slightly lower than the S.D.-ln of 0.71 between the RPISU annual averages and the air filter measurements found in Grand Junction. However, the average ratio of the RPISU annual averages to the air filter measurement was only $\exp -0.31 = 0.73$, which is considerably lower than the ratio of 1.2 found in Grand Junction. These results indicate that the variation between RPISU annual averages and air filter measurements can be decreased considerably if measurements are made only when the wind speed is below 8 mph, and if measurements showing short turnover times are disregarded.

COMPARISON OF RPISU AND TERRADEX TRACK ETCH® MEASUREMENTS IN EDMONT

There are several measurement techniques that can use sampling periods of considerably less than one year to provide estimates of annual average radon daughter concentrations. In evaluating the usefulness of air filter measurement, it is instructive to compare the reliability of the estimates of annual averages provided by some of these techniques with those provided by the air filter measurements.

One method for measuring radon and radon daughter concentrations involves the use of alpha sensitive materials as Track Etch® detectors. When an alpha particle strikes the alpha sensitive material, a damage track is produced that can later be made visible by etching the material with a caustic solution. The tracks per unit area are then counted to obtain the cumulative exposure of the detector to radon and its daughters.

PNL has used Terradex Type F Track Etch® detectors to measure radon concentrations continuously for an entire year in 50 buildings in Edgemont. The measurements were made at the same locations in the buildings as the six 100-hour RPISU radon daughter measurements. One Track Etch® detector was installed in each of these buildings at the same time as a RPISU was installed. Each detector was then replaced by another detector approximately two months later when the next RPISU measurement was made. Another Track Etch® detector was left at the same location in each building for an entire year.

The Type-F detector that PNL has used in Edgemont is mounted inside a plastic cup. A special filter is installed over the mouth of the cup to prevent the entry of radon daughters. Therefore, the detector measures only radon (and radon daughters produced by the decay of radon within the cup). Radon daughter concentrations can be calculated from the radon concentrations if a value is assumed for the ratio of the radon to the radon daughter concentration. The Track Etch® radon concentrations measured in Edgemont were converted to radon daughter concentrations by dividing by the average, for all of the buildings measured, of the ratio of the Track Etch® radon concentrations to the RPISU average annual radon daughter concentrations.

The Type-F detector was used in Edgemont, rather than a bare detector that measures both radon and radon daughters, because it has been reported that variability in the rate of plateout of radon daughters on the surface of the bare detector can lead to a less reliable measure of the radon daughter concentration than is obtained using a Type-F detector.

The standard deviation between the logarithms of the RPISU annual averages and the two-month Track Etch® radon measurements in Edgemont was found to be 0.70, considerably higher than the S.D.-ln of 0.52 between the RPISU annual averages and the air filter measurements, indicating that the air filter measurements provided a significantly better estimate of the annual average radon daughter concentrations than did two-month Track Etch® measurements. However, some of the variability of the Track Etch® measurements was due to the large seasonal variation of these measurements. The average seasonal variation is shown in Figure 5. The seasonal variations in individual buildings often departed considerably from the average. The concentrations measured in May through August averaged considerably lower and showed greater variability than those measured during the rest of the year. The coefficient of variation of the Track Etch® measurements was 0.83 for June-July, but was only 0.37 for November-December. These results indicate that two-month measurements made in the months of September through April would probably provide better estimates of annual averages than would measurements during the entire year. It was found the S.D.-ln between the RPISU annual averages and two-month Track Etch® measurements made in September through April was 0.61, considerably smaller than the S.D.-ln of 0.71 for the entire year, but still significantly larger than the S.D.-ln of 0.52 between the RPISU annual averages and the air filter measurements.

A considerable portion of the variability of the two-month Track Etch® measurements was probably due to variations in the degree of disequilibrium between radon and its daughters. The statistical counting

FIGURE 5. Average Seasonal Variation of Radon and Radon Daughter Concentration Measurements

error of the Track Etch® measurements presumably contributed also, since the counting error ranged from 10 to 25%. (Terradex provides the analysis of their detectors. They will analyze larger areas of the detectors to provide lower counting errors for an additional fee.) If statistical counting error contributed significantly to the variability of Track Etch® measurements, it would be expected that the variability would be greater at lower concentrations where the counting error would be a larger fraction of the total concentration. However, the S.D.-ln between the RPISU averages and two-month Track Etch® measurements made in September through April was 0.65 for cases in which the RPISU average was less than 0.010 WL, only slightly larger than the S.D.-ln of 0.61 for all cases.

It might be expected that Track Etch® measurements made over longer time periods would show a better correlation with the RPISU annual averages. In view of the large seasonal variation of the measurements, measurement periods of either six months or one year would appear to be most suitable. The S.D.-ln between the RPISU averages and the averages of three consecutive two-month measurements was found to be 0.46, somewhat smaller than the S.D.-ln of 0.52 between the RPISU averages and the five-minute measurements. The S.D.-ln between the Track Etch® annual radon daughter concentrations and the RPISU annual averages was 0.37. It therefore appears that six-month or one year Track Etch® measurements would have provided better estimates of RPISU annual averages than would single air filter measurements. It should be remembered, however, that enough side-by-side radon and radon daughter measurements would have to be made to determine the radon to radon daughter ratio characteristic of a site before the Track Etch® measurements could be used to estimate radon daughter concentrations.

COMPARISON OF INDIVIDUAL RPISU MEASUREMENTS WITH RPISU AVERAGES AT EDMONT

A single RPISU measurement of 100-hours or longer might also provide an estimate of the annual average that was reliable enough for use in screening buildings. At Edgemont, the S.D.-ln between single RPISU measurements and the RPISU averages for the same building was 0.57, somewhat higher than the S.D.-ln of 0.52 between the air filter measurements and the RPISU averages. Figure 6 shows the calculated and observed probabilities that the RPISU annual average would be greater than 0.015 WL for given values for a single RPISU measurement. The agreement between the calculated and the observed probabilities was fairly good. Some of the variation in the single RPISU measurements appeared to be due to seasonal variations in the radon daughter concentrations. The measurements showed considerable seasonal variations, but the variation was often very different for different buildings. Figure 5 shows the average seasonal variations in the RPISU, Track Etch® and air filter measurements. The average seasonal variation of the RPISU measurements was very similar to that of the Track Etch® measurements. However, it was considerably greater than that of the air filter measurements. This presumably was due to the fact that the variations were due primarily to variations in the ventilation rates. The air filter measurements were made in closed up buildings, so seasonal variations in the ventilation rate would have less effect on the air filter measurements than on the

FIGURE 6. Probability that the RPISU Annual Average will be Greater than 0.015 WL as a Function of the Value for a Single RPISU Measurement

RPISU or Track Etch® measurements. Figure 5 indicates that the RPISU measurements were considerably lower for the months of May through August than for the rest of the year. There were 32 RPISU measurements of less than 0.010 WL that were made in buildings that had RPISU annual averages greater than 0.015 WL, but 30 of these measurements were during the months of May through August. The RPISU measurements during these months also appeared to show greater variability. The coefficient of variation of the ratios of single RPISU measurements to RPISU averages was 0.55 for the month of June, but was only 0.27 for the month of November. These results suggest that if single RPISU measurements are to be used to estimate average annual radon daughter concentrations, the measurements should be made only during the months of September through April. The S.D.-ln between single RPISU measurements made during these months and the RPISU annual averages was only 0.41, considerably lower than the S.D.-ln of 0.52 between the air filter measurements and the RPISU annual averages. Figure 7 shows the calculated and observed probabilities that the RPISU annual average would be greater than 0.015 WL for given values for a single RPISU measurement made during these months.

These results indicate that single 100-hour measurements made during the months of September through April could be more useful for estimating average annual radon daughter concentrations than would single air filter measurements. However, these calculations were based upon the assumption that the RPISU annual averages are completely accurate. There undoubtedly is some error involved in the determination of the RPISU annual averages, and the RPISU annual averages are dependent upon the single RPISU measurements. Therefore, the S.D.-ln between the air filter measurements and the RPISU annual averages would be expected to be higher relative to that between the single RPISU measurements and the RPISU averages than it would be if there were no error in the RPISU annual averages. However, the S.D.-ln between the single RPISU measurements and the Track Etch® annual averages was 0.52, which is somewhat lower than the S.D.-ln of 0.60 between the air filter measurements and the Track Etch® annual averages, again indicating that single RPISU measurements taken in the months of September through April would provide somewhat better estimates of average annual concentrations than would single air filter measurements.

The usefulness of various short-term measurement techniques for determining whether buildings can be cleared from remedial action depends upon (1) the percentage of buildings cleared from remedial action by the measurements, (2) the percentage of buildings cleared that would have had RPISU averages greater than 0.015 WL, and (3) the percentage of buildings scheduled for engineering assessment that would have had RPISU averages less than 0.015 WL. These three quantities are plotted as a function of the S.D.-ln between the short-term measurements and the RPISU averages in Figure 8. They are also given for the various measurement techniques in Table 2. They were calculated assuming that (1) buildings would be cleared from remedial action if the value of the short-term measurement was less than the value at which there was a 10% probability that the RPISU average would be greater than 0.015 WL, and (2) the frequency distribution of the radon daughter concentration measurements would be the same as that given in Figure 1 for 0.63 times the air filter measurements. To make the calculations, the radon daughter concentrations were divided into 0.001 WL ranges. The probability that the radon daughter

FIGURE 7. Probability that the RPISU Annual Average will be Greater than 0.015 WL as a Function of the Value for a Single 100-hour RPISU Measurement Made in September through April

FIGURE 8. Probability at Edgemont that (1) a Building would be Cleared from Remedial Action, (2) a Building Cleared from Remedial Action would have a RPISU Average >0.015 WL, and (3) a Building Scheduled for Engineering Assessment would have a RPISU Average <0.015 WL as a Function of the S.D.-ln Between the Measurement Technique and the RPISU Average

Table 2. Comparison of Usefulness of Radon Daughter Measuring Techniques
for Screening Buildings in Edgemont, South Dakota

Measurement Technique*	S.D.-ln between RPISU Annual Averages and Measurements	Radon Daughter Concentration at which there is a 10% probability that the RPISU Annual Average will be Greater than 0.015 WL	Percentage of Buildings Cleared from Remedial Action because Concentration is less than Value Given in Previous Column	Percentage of Buildings Cleared that would have had a RPISU Annual Average Greater than 0.015 WL	Percentage of Buildings Scheduled for Engineering Assessment that would have had a RPISU Annual Average less than 0.015 WL
Two RPISU Measurements Six Months Apart	0.27	0.0106	52	1.1	35
One-Year Track Etch• Measurement	0.37	0.0093	47	1.6	43
Single RPISU Measurement in September Through April	0.41	0.0088	44	1.8	46
Six-Month Track Etch• Measurements	0.46	0.0083	40	2.0	48
Valid Edgemont Air Filter Measurement	0.52	0.0077	37	2.4	50
Single RPISU Measurement Any Time During Year	0.57	0.0072	35	2.6	52

Table 2. Comparison of Usefulness of Radon Daughter Measuring Techniques for Screening Buildings in Edgemont, South Dakota (continued)

Measurement Technique*	S.D.-ln between RPISU Annual Averages and Measurements	Radon Daughter Concentration at which there is a 10% probability that the RPISU Annual Average will be Greater than 0.015 WL	Percentage of Buildings Cleared from Remedial Action because Concentration is less than Value Given in Previous Column	Percentage of Buildings Cleared that would have had a RPISU Annual Average Greater than 0.015 WL	Percentage of Buildings Scheduled for Engineering Assessment that would have had a RPISU Annual Average less than 0.015 WL
Valid and Invalid Air Filter Measurement in Edgemont	0.65	0.0065	30	3.0	54
Two-Month Track Etch® Measurements	0.70	0.0060	28	3.2	56
Grand Junction Air Filter Measurements	0.71	0.0060	27	3.2	56

*It is assumed that the measurements have been corrected for any bias between the measurements and the RPISU annual averages.

concentration would be in a given concentration range was then obtained from Figure 1. The probability that the RPISU average would be greater than 0.015 WL for a measurement in a given concentration range was then calculated from the S.D.-ln using a table of ordinates and areas of the normal distribution. These two probabilities were then multiplied by each other to give the probability that a building would have a short-term measurement in the given concentration range and a RPISU average greater than 0.015 WL. The probabilities for all concentration ranges below a given value were then summed to obtain the probability that a building would have a short-term measurement less than the given value and a RPISU average greater than 0.015 WL. A similar procedure was used to determine the probability that a building would have a short-term measurement greater than the given value and a RPISU average less than 0.015 WL.

The S.D.-ln between the air filter measurements and the RPISU annual averages was 0.52. Figure 3 indicates that there would have been a 10% probability that the RPISU average in a building in Edgemont would be greater than 0.015 WL if the corrected air filter measurement was 0.0077 WL. Figure 8 also indicates that there would be a 10% probability that the RPISU average would be greater than 0.015 WL if a single RPISU measurement made in months other than May through August were 0.0089 WL. If buildings at Edgemont had been cleared from remedial action if they showed air filter or single RPISU measurements less than these values, then the single RPISU measurements would have cleared 44% of the buildings, and the air filter measurements would have cleared 37%. One and six-tenths percent of the buildings cleared by the single RPISU measurements, and 2.4% of the buildings cleared by the air filter measurements would have had RPISU averages greater than 0.015 WL. Forty-six percent of the buildings scheduled for engineering assessment on the basis of a single RPISU measurement and 50% of the buildings scheduled for engineering assessment on the basis of an air filter measurement would have had RPISU averages less than 0.015 WL. These numbers indicate that there would not be very much difference between the usefulness of the single RPISU and the air filter measurements for determining which buildings should be scheduled for engineering assessment.

The considerable seasonal variation of the RPISU measurements suggests that the correlation between single RPISU measurements and the RPISU averages could be improved if each RPISU measurement was corrected for the seasonal variation by dividing the RPISU measurement by the average ratio of the RPISU measurements for the same month to the RPISU averages. However, when this was done, the S.D.-ln between single RPISU measurements made from September through April and the RPISU averages was decreased only from 0.41 to 0.38. The decrease in the S.D.-ln was small because there were considerable differences in the seasonal variations of different buildings. This improvement is certainly not worth the effort required to determine the average seasonal variation for a given site.

The rather sinusoidal nature of the seasonal variation also suggests that two RPISU measurements taken six months apart might provide a good estimate of the RPISU average. It was found that the S.D.-ln between the averages of all possible pairs of two RPISU measurements taken six

months apart and the RPISU averages was only 0.27. This represents a considerable improvement over the S.D.-ln of 0.52 between the RPISU annual averages and the air filter measurements, and the S.D.-ln of 0.41 between the RPISU annual averages and single RPISU measurements in September through April. It must be remembered that the low S.D.-ln between the RPISU annual averages and two RPISU measurements taken six months apart is due partly to the fact that the RPISU annual averages are dependent upon the RPISU measurements. However, the S.D.-ln between the Track Etch® annual averages and the average of two RPISU measurements taken six months apart was 0.43, which is also significantly lower than the S.D.-ln of 0.60 between the Track Etch® averages and the air filter measurements.

According to Figure 6, two RPISU measurements taken six months apart would have cleared 52% of the buildings from remedial action in Edgemont, while the air filter measurements would have cleared only 37%. Thirty-five percent of the buildings scheduled for engineering assessment on the basis of two RPISU measurements taken six months apart would have had RPISU averages less than 0.015 WL, but 50% of the buildings scheduled for engineering assessment on the basis of one air filter measurement would have had RPISU averages less than 0.015 WL. These results indicate that two RPISU measurements taken six months apart would have been more useful for determining which buildings in Edgemont should have been scheduled for engineering assessment than air filter measurements. This is especially true since, on the average, about 1.5 five-minute measurements were required to obtain a single valid five-minute measurement. However, RPISU measurements from other sites would have to be studied to determine whether two RPISU measurements taken six months apart would provide accurate estimates of annual averages at other locations.

It might be argued that it would be cheaper to complete the set of six RPISU measurements, rather than to schedule buildings for engineering assessment if the average of two RPISU measurements was greater than 0.015 WL (see Figure 6), because 35% of the buildings scheduled for engineering assessment on the basis of the two measurements would have had RPISU averages less than 0.015 WL, and would have been cleared from engineering assessment if the RPISU measurement series had been completed. However, if it is assumed that it would take $8 \times 4/6 = 5.3$ man-hours to complete the RPISU measurement series, and 8 man-hours to perform an engineering assessment, then the number of man-hours required to complete a RPISU measurement series, and then to perform an engineering assessment if the RPISU average was greater than 0.015 WL would average $5.3 + 8X$ for buildings in Edgemont, where X is the probability that the RPISU average would be greater than 0.015 WL. According to Figure 6, X would be 0.65. Therefore, an average of 10.5 man-hours would be required to complete the measurement series and then to perform an engineering assessment if it was required. This is 2.5 man-hours more than the eight man-hours that would be required to perform an engineering assessment alone, so it would appear that extra man-hours would be required if the measurement series were completed.

SUMMARY AND CONCLUSIONS

At Edgemont, buildings were cleared from remedial action if valid five-minute air filter measurement were less than 0.010 WL, were scheduled for year-long RPISU measurements if a valid air filter measurement ranged from 0.010 to 0.033 WL, and were scheduled for engineering assessment if the average of two air filter measurements were greater than 0.033 WL. Calculations based upon the S.D.-ln of 0.52 between the RPISU annual averages and the individual air filter measurements indicate that these decision levels are reasonable. According to Figure 3, there should be only a 5% probability that the RPISU annual average would be greater than 0.015 WL if the air filter measurement were 0.010 WL. Since most of the buildings cleared from remedial action had air filter measurements less than 0.010 WL, only 1.1% of the buildings cleared should have had RPISU annual averages greater than 0.015 WL. Most of these would have had RPISU annual averages only slightly greater than 0.015 WL. It has also been found at Edgemont that residual radioactivity was very seldom discovered during the engineering assessment of buildings having RPISU annual averages slightly greater than 0.015 WL. It therefore appears that clearing buildings from engineering assessment when the air filter measurement was less than 0.010 WL did not result in a significant number of cases in which residual radioactivity went undetected.

It was estimated that there would be about a 20% probability that the RPISU annual average would be less than 0.015 WL if the average of two RPISU measurements was equal to 0.033 WL. Therefore, a significant number of buildings were probably scheduled for engineering assessment even though the RPISU annual average would have been less than 0.015 WL. However, it was found that about eight man-hours were required to perform an engineering assessment, which is about the same as that required to make six 100-hour RPISU measurements. Therefore, scheduling buildings for engineering assessment even though they had RPISU annual averages less than 0.015 WL should not have increased the cost of the remedial action program significantly, even though residual radioactivity might have been detected in a few of these cases.

The fact that the number of man-hours required to perform an engineering assessment is comparable to that required to make six RPISU measurements suggests that it might have been better to perform engineering assessments on all buildings in Edgemont having air filter measurements greater than 0.010 WL, rather than to make RPISU measurements. If this had been done, then it is estimated that engineering assessments would have been performed in 72% of the buildings, and 33% of these engineering assessments would have been performed in buildings that would have had RPISU annual averages less than 0.015.

The magnitude of the S.D.-ln between RPISU annual averages and short-term measurements provides an indication of the ability of the short-term measurements to predict the annual average. A large S.D.-ln indicates a poor ability of the short-term measurement to predict the annual average. Comparison of the S.D.-ln's between the RPISU annual averages and a few possible measurement techniques (Table 2) indicates that five-minute air filter measurements would provide estimates of RPISU average annual radon daughter concentrations that were (1) somewhat poorer than

those provided by single 100-hour RPISU measurements made in September through April, (2) considerably poorer than those provided by two RPISU measurements taken six months apart, (3) considerably better than those provided by two-month Track Etch® measurements, (4) somewhat poorer than those provided by six-month Track Etch® measurements, and (5) significantly poorer than those provided by one-year Track Etch® measurements.

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2 Publishing Coordination

NRC FORM 335 (11-81)		U.S. NUCLEAR REGULATORY COMMISSION BIBLIOGRAPHIC DATA SHEET		1. REPORT NUMBER (Assigned by DDC) NUREG/CR-3106 PNL-4591	
4. TITLE AND SUBTITLE (Add Volume No., if appropriate) Comparison of Five-Minute Radon Daughter Measurements with Long-Term Radon and Radon Daughter Concentrations				2. (Leave blank)	
7. AUTHOR(S) J. A. Young, P. O. Jackson, V. W. Thomas				3. RECIPIENT'S ACCESSION NO.	
9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Pacific Northwest Laboratory P.O. Box 999 Richland, WA 99352				5. DATE REPORT COMPLETED MONTH December YEAR 1982	
12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Division of Health, Siting and Waste Management Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission Washington, DC 20555				DATE REPORT ISSUED MONTH January YEAR 1983	
13. TYPE OF REPORT				PERIOD COVERED (Inclusive dates)	
15. SUPPLEMENTARY NOTES				6. (Leave blank)	
16. ABSTRACT (200 words or less) Pacific Northwest Laboratory (PNL) has made side-by-side five-minute air filter radon daughter measurements, 100-hour RPISU radon daughter measurements, and Terradex Track Etch® radon measurements in buildings in Edgemont, South Dakota. The standard deviation of the difference between the (natural) logarithms of the RPISU average annual radon daughter concentrations and the logarithms of single air filter measurements (S.D. -ln) was found to be 0.52. Using the S.D. -ln of 0.52 it can be calculated that there would only be a 5% probability in Edgemont that the RPISU annual average would be greater than 0.015 WL if the five-minute measurement were less than 0.010 WL was reasonable. Comparison of the S.D. -ln's between the RPISU annual averages and individual RPISU measurements in Edgemont indicates that a single RPISU measurement taken in the months of September through April would provide a somewhat better estimate of the annual average of two RPISU measurements taken six months apart would provide a considerable better estimate of the annual average. It also appears that a two-month Tract Etch® measurement would provide a considerably poorer estimate of the annual average than would a five-minute measurement, but that a six-month Track Etch® measurement or a one-year Track Etch® measurement would provide a better estimate of the annual average than would an air filter measurement.				8. (Leave blank)	
17. KEY WORDS AND DOCUMENT ANALYSIS				17a. DESCRIPTORS	
17b. IDENTIFIERS/OPEN-ENDED TERMS				10. PROJECT/TASK/WORK UNIT NO.	
18. AVAILABILITY STATEMENT				11. FIN NO. B2370	
19. SECURITY CLASS (This report) Unclassified				21. NO. OF PAGES	
20. SECURITY CLASS (This page) Unclassified				22. PRICE \$	