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GRAND JUNCTION REMEDIAL ACTION PROGRAM

**Analysis of Currently Approved and Proposed Procedures for
Establishing Eligibility for Remedial Action**

Final Report

December 1980

Prepared for
U.S. Department of Energy
Assistant Secretary for Environment
Operational and Environmental Safety Division

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Prepared for
U.S. Department of Energy
Assistant Secretary for Environment
Operational and Environmental Safety Division
Washington, D.C. 20545

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1. INTRODUCTION

1.1 Grand Junction Remedial Action Program

The use of uranium mill tailings as a fill material under and around building foundations produces unnecessary and non-beneficial radiation exposure to persons living or working in such buildings. The potential radiation health impact of such uses of uranium mill tailings was recognized by the Colorado Department of Health after approximately 15 years of such use in Grand Junction, Colorado. After several years of extensive investigation by the Colorado Department of Health, U.S. Public Health Service, the U.S. Atomic Energy Commission and other agencies, the Grand Junction Remedial Action Program became a reality in 1972 as a result of the passage of Public Law 92-314.

The general objective of the Grand Junction Remedial Action Program is to reduce radiation exposures to individuals and to the population as a whole by removing tailings to eliminate the source of the exposure or by modifying the structure to isolate the radiation source from the inhabitants. In order to obtain the benefits of the remedial action program, which is financed by federal and state funds, a property owner must first apply to the Colorado Department of Health for a determination of eligibility. The criteria for eligibility are contained in 10 CFR 712 Grand Junction Remedial Action Criteria (originally promulgated by the U.S.A.E.C. as 10 CFR 12, December, 1972). The criteria are based on annual average exposures to external gamma radiation or from inhalation of airborne radon daughter products resulting directly from uranium mill tailings used in conjunction with the construction of a building. Of these two possible modes of exposure, the inhalation of airborne radon daughters is by far the most important in terms of the number of locations exceeding the criterion and in terms of potential population exposure.

1.2 Factors Affecting Radon Daughter Exposures

Radium-226 in uranium mill tailings decays by alpha emission to provide a continuous supply of its daughter product, radon-222. The radon is a noble gas which can diffuse through the tailings, through concrete slabs

and into the air inside the building. As the radon decays, it forms short-lived non-gaseous decay products (isotopes of lead, bismuth and polonium), which can deposit in the respiratory tract when inhaled. It is the decay of these short-lived daughter products in the respiratory tract which deliver the radiation dose to the bronchial epithelium. Airborne radon progeny produce a radiation exposure that is primarily confined to the respiratory tract and is almost totally the result of alpha particle emissions. An increased incidence of lung cancer has been observed among uranium miners exposed to high concentrations of radon progeny. The health risk to populations exposed to low concentrations of radon progeny is generally inferred by linear extrapolation from the high exposure data on uranium miners.

In the environments normally encountered by humans (i.e. indoors or near the earth's surface) radon decay products are not observed to be in equilibrium with the radon in the atmosphere. The rate of loss of the radon progeny from the atmosphere depends upon the availability of surfaces to which they may attach and the turbulent mixing of the air to bring the daughter products into contact with surfaces. The radon progeny atoms which remain airborne for extended periods of time are those which become attached to more stable aerosols. Because of the many variables involved, the degree of equilibrium between radon and its various decay products in the atmosphere cannot be accurately predicted nor can it be adequately inferred from a single measurement of only one of the nuclides involved. It is for this reason that the radon daughter concentration (RDC) is measured in units of the working level (WL). One working level is defined as any combination of short-lived radon progeny in 1 liter of air that would ultimately produce 1.3×10^5 MeV of alpha energy by complete decay to Pb-210.

1.3 Integrated Radon Daughter Concentration Measurement (RPISU)

Since the radiation dose to the bronchial epithelium depends upon the alpha energy available from radon progeny decay (as opposed to the number

of atoms or the number of alpha disintegrations) and the unit of concentration (WL) is defined in terms of the alpha energy available from airborne radon progeny, an optimum measurement would provide a determination of the prospective alpha energy from short-lived radon progeny per unit volume of air. Such a method has been developed using thermoluminescent dosimeters to provide a response proportional to the total absorbed alpha energy. The method was first developed as a personal monitoring system for uranium miners (Mc69), but was subsequently adapted for use with an indoor area monitor (Sc71, Sc74).

The radon progeny integrating sampling unit (RPISU), as it has been dubbed by its users, was developed specifically for the Grand Junction Remedial Action Program. At the time of its development (1969-70) there was no other method available for obtaining working level measurements integrated over an extended period of time. Furthermore, not enough data had been obtained at that time to establish with any reliability the relationships between the long-term average RDC and other closely related parameters, such as radon gas concentrations, instantaneous (grab) sample data obtained under known conditions, external gamma exposure rates (an exception discussed later), etc. Consequently, the regulations implementing the remedial action criteria defined the indoor radon daughter concentration (RDC) as a concentration "determined by: (1) Averaging the results of 6 air samples each of at least 100 hours duration, and taken at a minimum of 4 week intervals throughout the year in a habitable area of a structure, or (2) utilizing some other procedure approved by the Commission" (10 CFR 712, 12.3). The 6 air samples referred to in the definition are obtained with the RPISU. To date no other procedures have been approved by the Commission or its successor organizations.

This analysis of the Grand Junction Remedial Action Program has been undertaken at the request of the Department of Energy (DOE) in response to proposals submitted by the Colorado Department of Health (CDH). In essence those proposals are for approval by DOE of alternative procedures for establishing the eligibility of structures for remedial action. Regardless of the preeminence accorded the RPISU method in the regulation, it is appropriate to question the assumption that this method gives better estimates of

average long-term exposure than other potential methods of evaluation. Since the intent of the Surgeon General's Guidelines (St71) is to preclude the long-term exposure of any individual to an average concentration that exceeds the limit of 0.05 WL and to reduce total population exposures by permitting remedial action for any long-term average exposure that exceeds 0.01 WL*, it is appropriate to ask how well the RPISU measurements expedite the achievement of these objectives. One must then ask whether or not the RPISU measures the appropriate parameter and also determine the precision and accuracy with which the measurement is accomplished.

The TLD used in the RPISU does not measure the RDC directly; it gives a response that is proportional to the time integral of RDC in working levels. However, the proportionality constant can be determined only by calibration against known concentrations of radon daughters in a test atmosphere and these concentrations are only determined by the use of other methods of measurement. The accuracy of the RPISU does depend, however, upon measurements being made in exactly the same manner in the field as they were made during the calibrations. This limitation on accuracy was exemplified by the neglect of this criterion during the original calibrations of the RPISU.

During the first two years of the program the RPISU filter/TLD holders were located inside the housing. Subsequently, it was determined that this location of the holder introduced an average decrease in TLD response by approximately a factor of 2, due to plateout of radon progeny entering the unit. However, the units had been calibrated with a different housing which did not introduce this error. To compensate for this oversight, the data obtained during the early years of sampling were subsequently increased by a factor of 2. However, the actual error for any given location may have been more or less than a factor of 2 depending upon the degree of attachment of radon progeny to other aerosols. The uncertainty in sampling data due to this oversight precludes a valid case-by-case comparison of the early sampling data with later data (obtained with the filter holders outside the RPISU housing).

*The criterion of 0.01 WL is in addition to the average background concentration for the local area.

During the initial development of the RPISU, numerous replicate measurements were made under controlled exposure conditions. Although these calibration data indicated a coefficient of variation of only 13%, they were obtained over relatively short periods of time and were derived from new equipment, new TLDs, etc. (Sc71). During the track etch demonstration program in 1973-74, 49 duplicate RPISU measurements were made which satisfied the basic criteria for a one-week sample (Lo75). The average relative difference between pairs was 18.2%. One can show that the coefficient of variation for paired measurements is half of the relative difference and that the average coefficient of variation is half of the average relative difference. The coefficient of variation for replication of measurements from these data was 9.1%, compared with the value of 13% obtained previously. Although the 1973-74 data are subject to some uncertainty as a result of several recalibrations, they provide the only estimate of variability due to replication during actual field use.

Data obtained from the intensive sampling performed during the track-etch demonstration program are contained in Tables 1-3. The average coefficient of variation for sampling conducted weekly throughout the year was 56.2% (Table 1). For locations sampled one week out of every month, the average coefficient of variation was 58.5% (Table 2). These large variations are largely due to seasonal fluctuations in indoor ventilation rates. The ratios of weekly measurements to annual average concentrations are listed by monthly intervals in Table 3 and displayed graphically in Figure 1. In the form in which these data are available, it is difficult to separate the variability due to seasonal effects and the variability among the structures sampled from that due to replication of samples and intermittency of sampling (in the case of those locations sampled 12-13 times during the year.)

Coefficients of variation of working levels measured by the RPISU method in 580 Grand Junction buildings were also calculated by Breslin of the ERDA Health and Safety Laboratory. "The average standard error of the annual mean working level was 22%, based on the specified six weekly measurements" (Br79).^{*} If the coefficient of variation for the detector replication is approximately 9% and the coefficient of variation of the annual mean working level is 22% with six measurements, the coefficients of variation due to the intermittency of

^{*} This statement was interpreted as meaning that the average coefficient of variation of the mean annual working level, as determined from the specified six measurements, was 22%. The coefficient of variation for the individual measurements may also be inferred from this statement to be: $\sqrt{6} \cdot 22\% = 54\%$.

TABLE 1
AVERAGE RADON DAUGHTER CONCENTRATION FOR LOCATIONS MEASURED WEEKLY FROM
OCTOBER 1973 THROUGH SEPTEMBER 1974

Location No.	No. of Weeks	Radon Daughter Concentration (WL)				
		Average	S.D.	C.V.%	Geom.Mean	G.S.D.
99000	50	0.00827	0.00384	46.4	0.00718	1.78
99001	50	0.00853	0.00427	50.1	0.00721	1.91
99003	52	0.01120	0.00708	63.2	0.00865	2.22
99004	52	0.01052	0.00598	55.1	0.00854	2.04
99006	51	0.01392	0.00434	31.2	0.01314	1.44
99007	51	0.01597	0.01120	70.1	0.01407	1.62
99009	52	0.02636	0.01254	47.6	0.02287	1.81
99010	52	0.00728	0.00340	46.7	0.00651	1.65
99012	52	0.02975	0.01654	55.6	0.02392	2.16
99013	52	0.02772	0.01344	48.5	0.02386	1.85
99015	51	0.04712	0.02082	44.2	0.04294	1.55
99016	51	0.05543	0.02805	50.6	0.04834	1.75
99018	52	0.02645	0.00987	37.3	0.02452	1.52
99019	52	0.01940	0.00878	45.3	0.01714	1.73
99021	49	0.03516	0.01280	36.4	0.03260	1.52
99022	49	0.02523	0.02132	84.5	0.02091	1.89
99024	52	0.04234	0.02524	59.6	0.03307	2.20
99025	52	0.03897	0.02087	53.6	0.03226	1.99
99027	52	0.02753	0.02151	78.1	0.01750	3.01
99028	52	0.02943	0.02431	82.6	0.01766	3.19
99030	51	0.04844	0.03986	82.3	0.02665	3.76
99031	51	0.05135	0.04144	80.7	0.02884	3.65
99033	52	0.04244	0.01819	42.9	0.03896	1.52
99034	52	0.04321	0.01507	34.9	0.04087	1.40
99042	52	0.08226	0.05823	70.8	0.05623	2.72
99043	52	0.07879	0.05181	65.8	0.06020	2.22
99048	50	0.03973	0.02757	69.4	0.03331	1.77
99049	51	0.03834	0.02466	64.3	0.02981	2.16
99051	50	0.06066	0.03143	51.8	0.04943	2.10
99052	52	0.15970	0.08277	51.8	0.14256	1.60
99053	50	0.14157	0.06040	42.7	0.12788	1.64
99054	51	0.18189	0.09684	53.2	0.15678	1.77
99055	50	0.08517	0.05020	58.9	0.07402	1.69
Averages: (N=33)		0.047	0.0265	56.2	0.034	2.02

TABLE 2
AVERAGE RADON DAUGHTER CONCENTRATIONS FOR LOCATIONS MEASURED DURING ONE
WEEK IN EACH MONTH FROM OCTOBER 1973 THROUGH SEPTEMBER 1974

Location No.	No. of Weeks	Radon Daughter Concentration (WL)				
		Average	S.D.	C.V.%	Geom. Mean	G.S.D.
99002	13	0.00875	0.00380	43.4	0.00806	1.54
99005	13	0.00816	0.00692	84.8	0.00635	2.02
99008	13	0.00943	0.00577	61.2	0.00740	2.22
99011	12	0.00834	0.00403	48.3	0.00748	1.64
99014	13	0.01860	0.01121	60.3	0.01501	2.12
99017	13	0.03854	0.01939	50.3	0.03435	1.65
99020	13	0.01485	0.00845	56.9	0.01257	1.91
99023	13	0.02346	0.00775	33.0	0.02215	1.46
99026	13	0.04140	0.02563	61.9	0.03083	2.53
99029	13	0.03030	0.02628	86.7	0.01881	3.28
99032	12	0.05403	0.01577	29.2	0.05166	1.38
99035	13	0.01048	0.00565	53.9	0.00867	2.02
99044	13	0.04048	0.03693	91.2	0.02065	3.99

Averages	0.0236	0.0137	58.5	0.01877	2.14
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N = 13

$$\text{Also: CV} = \frac{0.0137}{0.0236} = 58.0\%$$

RATIO OF WEEKLY AVERAGE RADON DAUGHTER CONCENTRATIONS TO ANNUAL AVERAGE
BY MONTHLY INTERVALS

Month	Ratio $\pm$ S.D.	CV(%)
Jan	1.43 $\pm$ 0.51	36
Feb	1.27 $\pm$ 0.40	31
Mar	1.25 $\pm$ 0.53	42
Apr	0.94 $\pm$ 0.37	39
May	0.70 $\pm$ 0.38	54
Jun	0.45 $\pm$ 0.33	73
Jul	0.57 $\pm$ 0.41	72
Aug	0.67 $\pm$ 0.55	82
Sep	0.88 $\pm$ 0.37	42
Oct	1.18 $\pm$ 0.48	41
Nov	1.40 $\pm$ 0.45	32
Dec	1.32 $\pm$ 0.50	38

Average CV =

48.5

Figure 1. Ratio of Weekly to Annual RDC by Months.

sampling is approximately 20%, i.e. $(22^2 - 9^2)^{\frac{1}{2}} = 20.1$.

RPISU Data Significance. The direct measurement of average RDC with the RPISU can be assumed to establish the current occupancy average exposure within the uncertainties discussed above. However, the CDH has quite properly pointed out that the structure lifetime annual average exposure is more relevant to the determination of eligibility for remedial action. Since long-term adverse health effects are presumed to be related to long-term or lifetime exposures, the average exposure rates referred to in the Surgeon General's Guidelines should not be implied to refer only to current annual average exposures. The determination of an annual exposure rate averaged over the lifetime of the structure would comply with the intent of the Surgeon General's Guidelines to limit annual exposures to any individual, without specifying whether or not they are the current occupants of the structure. The annual average exposure obtained under current occupancy conditions could be higher or lower than an annual exposure averaged over the lifetime of the structure. Consequently, the RPISU data alone do not necessarily provide the best or only criterion for complying with the intent of the Surgeon General's Guidelines. Any method of measurement or justifiable adjustments to measurement data that would produce a better estimate of the structure lifetime annual average exposure would provide a technical improvement to the program.

RPISU measurements are typically obtained in only one room of a structure. The general practice of CDH personnel is to place the RPISU in the room with the highest anticipated RDC or, in some cases, in a room where the RPISU will not interfere with normal family activities. In structures with basements, the RPISU is frequently placed in the basement. In structures with crawl spaces or slab on grade construction, the RPISU is often placed in the room with the highest gamma exposure rate. Although there are some legitimate and practical reasons for these practices on the part of CDH personnel, the RDCs measured by RPISUs tend to be substantially higher than the average RDC throughout the habitable area of the structure. For example,

in control structures, RDC measurements in basements averaged 37% higher than RDC measurements in rooms at ground level (based upon 9 determinations in control structures at ground level and 4 determinations in control structure basements). There has been no systematic evaluation of the ratio of RDC measurements in basements to those in ground floor rooms in structures influenced by tailings deposits. Consequently, it is impossible to state with certainty the degree of bias introduced when RPISUs are placed in only one room of a structure. A determination of remedial action eligibility based on measurements in several rooms would be preferable to the RPISU, at least in this one aspect. Because of the bias potentially introduced by RPISU sampling in only one room of a structure, the use of these data to validate alternative sampling methods must be undertaken with a large degree of discretion.

Although sources of uncertainty in RPISU measurements are recognized, other methods for determining eligibility for remedial action must be compared with the RPISU for at least two reasons: (1) the RPISU measures the parameter of interest, namely the average RDC in units of WL and (2) the RPISU is the only currently approved method and has been the basis for determining eligibility of all of the structures completed to date.

1.4 Current Program Needs

In order to expedite the remedial action program, the CDH has proposed several alternative methods for determining eligibility of structures for remedial action. There are several legitimate reasons for the desire to expedite the program:

(1) More rapid remedial action means greater dose reduction for the money spent. Any remedial action completed this year rather than next year means that the occupants of that structure receive an unnecessary dose for one less year.

(2) If the effort to determine eligibility can be reduced, the relative amount of the total program budget available for actual remedial action (dose reduction) will be increased.

(3) The earlier that appropriated funds can be utilized in the program, the less will be the reduction of buying power of those funds due to inflation.

(4) Greater flexibility in making eligibility determinations will provide for more effective use of existing personnel, both for measurements and for actual remedial action (construction work).

The DOE requires evidence that the proposed alternative methods of measurement will determine eligibility for remedial action with a satisfactory degree of reliability. In this case, satisfactory is interpreted to mean a reliability comparable to that achieved by the RPISU method in meeting the intent (not simply the numerical criteria) of the Surgeon General's Guidelines. In addition the DOE needs standard procedures or guidelines to assure that any methods of measurement and eligibility determinations are applied consistently and objectively in all situations. Although it is recognized that determinations of eligibility cannot be based on a cookbook approach, the judgement to be exercised by CDH personnel must be based on objective, predetermined criteria to avoid future conflict over eligibility for remedial action.

Both the CDH and the DOE are interested in any improvements that can be made in the cost effectiveness of the remedial action program. Each of the proposed alternative methods for determining eligibility entails certain costs for the required measurements. Also each proposed method incorporates various uncertainties in the measurements, which could result in unnecessary remedial actions on ineligible structures or the exclusion of some structures from justifiable remedial actions. In theory, the differential costs of various alternative measurement techniques could be balanced against the differential costs of unwarranted remedial actions. In practice, however, these differential costs are difficult to ascertain with any certainty. Other, more important cost-benefit factors are discussed below (Sec. 1.6).

As pointed out by the DOE (Mo79), the reliability of measurements is of greatest importance. In the opinion of this reviewer, "the reliability of measurements" refers to the capability of any measurement method to determine eligibility for remedial action within the intent of the Surgeon General's Guidelines. Also, any acceptable measurement technique should be

capable of verifying the satisfactory completion of remedial actions. More explicitly "reliability of measurement" must refer to the ability of any measurement technique to predict the anticipated average exposure rate of any occupant during any year of occupancy of a structure. This capability is therefore given the highest priority in evaluation of the proposed alternative measurement methods.

1.5 Objectives of this Review

(1) Review the reliability of the methods of measurement authorized by 10 CFR 12, i.e. the RPISU 6 sample method for determining RDC and the presumptive tests based on the indoor net average gamma exposure rate.

(2) Evaluate the reliability of the alternative measurement methods proposed by the CDH for determining eligibility for remedial action. (This evaluation is to be based on existing data readily available from the CDH.)

(3) Recommend for DOE approval specific methods and applicable procedures that may be used to determine eligibility for remedial action with at least the same reliability as presently achieved with the RPISU 6 sample method.

1.6 Cost-Benefit Considerations

An important consideration in proposing any method for determining eligibility for remedial action is the cost that will be incurred and the benefit that might accrue from use of the proposed method. The cost of the equipment for making any of the proposed measurements will not be discussed here as it is very small in comparison to any other costs and benefits that might be involved. In addition, the CDH already has much of the equipment that would be required for any of the proposed methods; additional acquisitions required to utilize any alternative methods would be quite modest. The personnel costs involved in making the measurements for determining eligibility and for verifying the effectiveness of completed

remedial action are more significant than the equipment costs, but would not be greatly affected by the use of any of the alternative measurement methods. The CDH estimates that determination of eligibility requires about eight man-hours per location utilizing the RPISU method, the radon profile method or passive radon monitors (La79). Only the use of track-etch films reduces significantly the hours required per location. In any event, eliminating all of the time required for measurements would only reduce the program cost by approximately \$100-\$200 per location.

The most significant program costs are those of the engineering assessment and direct construction activities involved in remedial actions. The CDH estimates the average cost of remedial action in a residence to be \$14,000. The average indoor RDC was reduced from 0.035 WL to 0.014 WL by remedial action completed in residences to date. Based upon these data one can calculate the cost-benefit ratio of the remedial action program as indicated in Table 4. The calculations indicate that the cost per unit dose reduction is approximately \$100 per lung rem. This is only one tenth of the cost per unit dose reduction recommended as a criterion by the U.S. Nuclear Regulatory Commission (10 CFR 50, Appendix I); it is a value believed by this author to be an appropriate radiation protection criterion in applying the philosophy of reducing radiation doses to levels that are as low as reasonably achievable.

Errors in determining eligibility are most likely to occur in the evaluation of structures that are marginal with respect to the eligibility criterion. This is true regardless of the method of measurement used to determine eligibility. The consequences of such errors must be considered with respect to the health impacts on the individuals that may be involved and with respect to the monetary costs to the remedial action program. With regard to health impacts, there is essentially no net effect of errors made in determining eligibility near the 0.01 WL criterion.* A few structures with true lifetime average RDCs exceeding 0.01 WL may be incorrectly evaluated and excluded from remedial action. However, these errors will be almost

*The 0.01 WL criterion is in addition to the normal background concentration.

TABLE 4. COST-BENEFIT CALCULATIONS

COST

Average direct cost of remedial action in residences:	\$ 14,000.*
Estimated indirect cost per residence:	\$ 6,000.
Assumed total cost per residential remedial action:	\$ 20,000.

BENEFIT

Average RDC before remedial action:	0.035 WL*
Average RDC after remedial action:	0.014 WL*
Average net RDC reduction:	0.021 WL
Average annual individual dose reduction:	0.5 WLM**
Estimated average residential occupancy:	2.5 persons
Lung dose conversion factor:	5 rem/WLM
Collective dose rate reduction per residential remedial action:	6 lung-rem/yr
Estimated average structure lifetime:	33 years
Total collective dose reduction per residential remedial action:	200 lung-rem

COST/BENEFIT RATIO

Monetary cost per unit dose avoided:	\$ 100/lung-rem
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*Data provided by CDH; all other values in the table are estimated or calculated by K.J. Schiager.

** In the general population, spending approximately 80% of the time indoors and with a breathing rate approximately half that of a working uranium miner, a constant concentration of 1 WL produces the equivalent of 25 WLM exposure (E177).

exactly compensated for by providing remedial action in structures with true lifetime average RDCs of less than 0.01 WL^{*}. The total population dose reduction which is the most valid index of validity of remedial actions at the lower end of the discretionary range would be essentially the same regardless of the error rate in the eligibility measurements. It is important, however, to assure that one method of measurement does not include a systematic bias with respect to other methods of measurement; which could in effect produce inadvertently a different remedial action criterion.

The monetary costs of errors in eligibility determinations near the 0.01 net WL criterion also tend to be nil so long as the errors are not extremely large and are randomized in both directions, i.e. above and below the 0.01 net WL criterion. For example, a structure with a true annual average RDC of 0.012 net WL might be inadvertently excluded from remedial action while another structure with a true annual average RDC of 0.008 net WL might be mistakenly included in the remedial action program. On the average, the cost of remedial action in either structure would have been the same, but the total dose reduction would probably be slightly greater in the structure that started with the higher average RDC. In either case, however, the monetary cost per unit dose reduction would probably be considerably larger than the average for the entire remedial action program. Consequently, from a cost-benefit viewpoint one would argue that measurement errors that incorrectly designated a structure as eligible for remedial action are more serious than errors which incorrectly exclude remedial action on a structure.

An appropriate level of uncertainty in determining eligibility at RDCs near background can be inferred from the variability of the natural outdoor radon concentration. Measurements made by the U.S. Atomic Energy Commission and the U.S. Public Health Service in 1968 and by the U.S. Environmental Protection Agency in 1975 indicate that for 8 sampling stations more than 0.75 miles from the tailings pile, the average radon concentration was 0.74 pCi/L with a coefficient of variation of 20% (Du77). For the 5 locations believed to best represent the natural background in the Grand Junction area, the measurements at individual locations are best represented by log-normal distributions with geometric standard deviations ranging from 1.5 to 2.2 (See Table 5). Among the 5 locations the coefficient of variation of the means is 17%.

* In addition to background.

TABLE 5. OUTDOOR RADON CONCENTRATIONS AT BACKGROUND (OFF-PILE) LOCATIONS
IN GRAND JUNCTION*

Loc. No.	No. of Measurements	Concentration (pCi/L)	
		Linear $\bar{x} \pm s$	Logarithmic $\bar{x}_g : s_y$
9	16	0.63 ± 0.34	$0.56 : 1.6$
13	16	0.77 ± 0.48	$0.63 : 1.9$
14	16	0.89 ± 0.49	$0.79 : 1.6$
19	17	0.62 ± 0.29	$0.52 : 2.2$
20	15	0.61 ± 0.25	$0.57 : 1.5$
All of above	80	0.70 ± 0.39	$0.61 : 1.8$
5 Location Means		0.70 ± 0.12	$0.61 : 1.2$

* Data from (Du77)

The indoor RDC is always expected to be much more variable than the outdoor radon concentration. In control locations (no tailings involvement) in Grand Junction, the CDH found that the background concentrations were log-normally distributed with a median of 0.0072 WL and a geometric standard deviation of 1.7 (Pe77). These data imply that the arithmetic average background RDC is 0.0083, i.e. $0.0072 e^{0.5(\ln 1.7)^2}$. They also imply that the total coefficient of variation, T, including replication (or reproducibility), R, intermittancy of sampling, I, seasonal variations, S, and location differences, L, is in the order of 70%, i.e.:

$$T^2 = R^2 + I^2 + S^2 + L^2 = 0.7^2$$

As already noted, the components of variability due to the measurement method, i.e. reproducibility and intermittancy, contribute approximately 22% to the total coefficient of variation. From these observations it seems appropriate to accept a coefficient of variation of approximately 20-25% for any method used to determine eligibility. Any criterion more demanding than this would add unnecessary costs to the program, but provide no commensurate benefits.

2. ALTERNATIVE MEASUREMENTS FOR DETERMINING ELIGIBILITY

2.1 Relationships Among Measured Parameters

Although potential health risks and remedial action criteria are based primarily on the average indoor RDC, there are other radiological parameters directly related to the RDC which might be used as remedial action criteria*. It is apparent that there can be no airborne concentration of radon daughters without a corresponding concentration of radon gas. In fact, the RDC can never exceed the concentration that would be in equilibrium with the radon present in the atmosphere. Any measurements indicating an RDC greater than the equilibrium value are the result of errors in measurement. The RDC can be substantially lower than the equilibrium value. Normal indoor atmospheres, however, exhibit a rather limited range of equilibrium values; for Grand Junction, this range is approximately $40\% \pm 20\%$. The possible use of radon concentrations as criteria for remedial action will be discussed in more detail below.

Although some indoor radon comes from the outside atmosphere, most of it is generated by decay of radium in structural or adjacent materials. If an excessive radon and radon daughter concentration is due to uranium mill tailings, it is possible that eligibility for remedial action can be determined on the basis of a gamma survey to detect the presence and distribution of the tailings. The use of external gamma exposure rates as surrogate remedial action criteria will be discussed later*.

The radiological parameter of greatest importance and interest, i.e. the RDC, also happens to be the variable for which it is most costly and difficult to obtain a valid annual average. The 6-sample RPISU method was adopted as a compromise between continuous integrated monitoring to obtain a true annual average, and grab sampling a few times during a year to obtain a rough estimate of an annual average concentration. At the time the program was initiated, there were not sufficient data available to develop reliable correlations between short term (grab) samples and annual average

*The remedial action criterion based on the dose from external gamma radiation (0.05 mR/hr) is not included in this discussion since no alternatives for gamma measurements are necessary or proposed.

concentrations of either radon daughters or radon. Now that the measurement program has been in operation for more than 10 years, and thousands of individual measurements have been accumulated, the correlations between annual average radon daughter concentrations and other radiological parameters can be quantified to a greater extent.

Some of the proposed alternative methods for determining eligibility may depend on the average relationships between various radiological parameters based on observations throughout the community. The use of community averages obtained over one or more years to represent annual averages for any structure throughout its lifetime, regardless of specific occupancy conditions, is logical and strongly endorsed. Specifically, the community averages for the following ratios are recommended for use as default values for determining eligibility of any individual structure:

- $\frac{\text{average radon concentration}}{\text{maximum radon concentration}}$
- $\frac{\text{average radon daughter concentration}}{\text{average radon concentration}}$

= Average equilibrium factor

Since both of these ratios increase as ventilation rates and air exchange with the outside atmosphere decrease, these community average ratios may tend to increase as more energy conservation measures are applied. Consequently, any determination of eligibility that utilizes these community average ratios would not be likely to show a loss of eligibility if evaluated at some future date; if anything, the average RDC may tend to increase with time.

Unless the conditions at the time of measurement are normalized in some manner, there is no way to relate values obtained in an individual structure to the community average ratios of RDC-to-average-radon concentration or average-to-maximum-radon concentration. Measurements obtained with the RPISU or any other integrating device are dependent upon the

current use of the structure and the habits of the occupants. Short-term measurements of RDC and radon concentrations may be normalized, however, by closing up the structure to maximize the concentrations. The proposed procedure and data supporting this proposal are discussed below under Section 2.2 Grab Sampling Methods.

2.2 Grab Sampling Methods

The general term, grab sampling, can refer to any measurements of airborne concentrations that are obtained almost instantaneously at specific points in time. Grab sampling data for both radon and radon daughters obtained in 127 locations under a variety of conditions were reviewed during this study. Of these locations, 48 exhibited grab sampling data that could be compared directly with annual average RDCs measured by the RPISU method. These 48 sets of data are listed in Table 6. Both linear and logarithmic regression analysis were performed to investigate correlations between RDC grab samples (Kusnetz method) and RPISU data, RDC grab samples with radon grab samples (scintillation flasks), and RPISU data with radon grab samples. The correlation statistics obtained from these analysis are listed in Table 7.

The correlations of RDC grab samples with RPISU data are shown in Figures 2 and 3. These figures show the full range of the data and also indicate the regression lines obtained for residential and for commercial structures. The logarithmic regression and confidence limits^{*} for 30 residences and other structures combined are shown in Figure 4. The one-sided 80% confidence limit is also shown in Figure 4 to indicate the RPISU value that would be exceeded 80% of the time for any given grab sample value.

With one exception (Loc. No. 00118), all of the paired data for RDC grab samples vs. RPISU measurements were obtained in structures eligible for remedial action. For the 9 residences, all of the grab samples also indicated eligibility with RDC estimates averaging approximately 16% greater than the RPISU values. For the commercial structures, however, 8 of the 21 grab samples failed to indicate eligibility in locations that were found to be eligible from RPISU measurements.

^{*}For a discussion of the calculations of confidence limits, see Appendix.

Since no comparable data were available for ineligible structures, there is no basis for estimating the number of grab samples that would have indicated the need for remedial action in structures that were not, in fact, eligible based on RPISU data. Because of this lack of data for ineligible structures, there is no sound basis for establishing a criterion for the use of individual RDC grab samples for establishing remedial action eligibility. It is most probable that any additional data corresponding to RPISU values of less than 0.017 WL would add to the scatter of data and indicate even less reliability for individual grab samples.

One interesting observation that can be made from the RDC grab sample data is that the grab sample values are generally lower than the RPISU values. This was true for all except the linear regression of the 9 data points for residences. For the 21 commercial structures, the grab samples averaged slightly less than 80% of the RPISU values. This observation leads to at least 3 possible implications: (1) The average air exchange rate at the sampling location in these structures was lower on a long-term basis than it was during the "closed-up, maximized conditions" under which the grab samples were obtained. (2) The calibration of the grab sampling equipment contains a systematic error that biases the samples on the low side. (3) The calibration of the RPISUs contains a systematic error that biases those readings on the high side. This observation also raises the question as to what is the significance of "closed-up, maximized conditions". In any event, it is obvious that remedial action eligibility cannot be established simply on the bias of individual maximized RDC grab samples.

The comparison of radon gas grab samples with both RDC grab samples and RPISU data is shown in Figures 5 and 6. The linear regression lines are indicated in the region of low sample values in Figure 6. At the eligibility criterion of 0.017 WL as measured by grab sampling, the regression line for residential structures indicates a radon concentration of 11.5 pCi/L. This indicates an average equilibrium of only 15% for the radon daughters at this concentration. In the commercial structures, the indicated radon concentration is only 7.8 pCi/L, leading to a calculated equilibrium factor of 22%. For 180 pairs of grab sample data, some from pre-remedial and some from post-remedial measurements, the radon daughter equilibrium factor was found to be $38\% \pm 20\%$ (1 S.D.). For the 29 data pairs listed in Table 6, the equilibrium factor is $35\% \pm 17\%$. These results strongly suggest that biases in the RDC grab samples may have occurred only during specific intervals throughout the remedial action program.

The RPISU data, on the other hand, indicated the possibility of just the opposite kind of a bias. When these data are extrapolated linearly down to the level of the eligibility criterion, they indicate that the RPISU would detect more than 0.02 WL with no radon present. This obviously impossible interpretation apparently results from the fact that the data are biased by including no structures that were not eligible for remedial action.

On the basis of the data shown in Figures 5 and 6, the criteria proposed by the CDH (Ha79) for determining eligibility on the basis of radon grab sampling appears to be quite conservative. A concentration of 15 pCi/L would correspond to approximately 0.06 WL in both residential and commercial structures. A maximized radon grab sample of 10 pCi/L would indicate greater than 0.017 WL based on either the RPISU or the grab sampling data for both residential and commercial structures. For commercial structures, a maximized radon grab sample of 20 pCi/L would indicate an expected RDC of 0.07 WL. The uncertainties in the regression lines on which these proposed criteria are based is essentially a factor of 2 (the geometric standard deviation). At maximized radon concentrations of 10 pCi/L for residences and 20 pCi/L for commercial and other structures, it would be greater than an 85% probability that the average RDC for the structure would exceed 0.017 or

0.037 WL gross respectively. These recommended criteria for establishing eligibility are based on a ratio of average to maximized radon concentrations of approximately 75%, in agreement with observations of the CDH (Ha79), but on an average radon daughter equilibrium ratio of approximately 40% rather than the 30% suggested by the CDH (Ha79).

From the data available at present, it does not appear that any criterion for declaring a structure clearly ineligible based on radon grab samples can be proposed at this time. For structures exhibiting lower maximized radon concentrations, eligibility would have to be determined by other types of measurements

TABLE 6. PRE-REMEDIAL AIR CONCENTRATION DATA

Loc. No.	RPISU		Grab Samples		
	(WL)	(No.)	RDC (WL)	Rn (pCi/L)	Equil.(%)
RESIDENCES:					
00034	0.024	6	0.023	18.1	15
00104	0.049	5	0.050	14.8	34
00122	0.165	2	0.404	70.8	57
01063	0.064	3		7.2	
03265	0.079	2		1.2	
03366	0.018	6	0.024	10.5	23
04864	0.193	2	0.191	66.8	29
07175	0.018	6	0.029		
09064	0.024	6	0.035	9.4	37
13380	0.032	6		10.5	
13683	0.080	2	0.104	26.1	40
15494	0.026	4		11.0	
33022	0.168	2	0.041	22.3	18
COMMERCIAL AND OTHERS:					
00011	0.059	3		34.2	
00045	0.043	6	0.007	2.3	30
00048	0.119	6		30.0	
00052	0.036	6		79.3	
00062	0.038	6		54.4	
00118	0.021	6	0.020	13.8	14
00135	0.041	6	0.036	13.6	26
00138	0.109	2	0.131	37.0	35
00168	0.091	6		52.6	
00180	0.086	5	0.097	18.1	54
00189	0.113	6	0.108	38.9	28
00274	0.163	6	0.086	31.9	27
00292	0.067	6	0.327	66.2	49
00298	0.091	6	0.083	20.8	40

TABLE 6. CONTINUED...

Loc. No.	RPISU		Grab Samples		
	(WL)	(No.)	RDC (WL)	Rn (pCi/L)	Equil. (%)
00375	0.038	6	0.014	15.0	9
00424	0.090	6	0.025	18.0	14
00425	0.230	6	0.149	24.8	60
00456	0.062	6	0.020	9.5	21
00489	0.621	6		186.1	
00849	0.072	6		13.6	
00935	0.021	6		7.3	
00981	0.164	2		60.2	
02021	0.137	2		53.2	
02781	0.107	6		45.0	
02835	0.048	6	0.031	12.8	24
02849	1.220	6		422.8	
03225	0.068	5	0.091	21.3	43
03821	0.488	6		100.3	
05077	0.056	3	0.029	11.2	26
05244	0.210	6	0.065	10.8	60
05554	0.055	5	0.028	4.4	64
05867	0.083	6	0.107	63.6	17
09542	0.040	6		14.4	
10920	0.160	6	0.109	19.4	56
31617	0.430	2	0.407	68.5	59

TABLE 7. GRAE SAMPLING CORRELATION STATISTICS FOR PREREMEDIAL MEASUREMENTS

Type of Structure	Variables			Linear Regression	Logarithmic Regression
	N	X	Y		
Residences	9	RPISU (WL)	RDC Grab (WL)	$Y = 1.16X + 0.005$ $S_{yx} = 0.10, r = 0.67$	$Y = 0.61X^{0.80}$ $S_{yx} = 1.9, r = 0.80$
	8	Rn Grab (pCi/L)	RDC Grab (WL)	$Y = 0.0048X - 0.035$ $S_{yx} = 0.060, r = 0.91$	$Y = 0.0014X^{1.2}$ $S_{yx} = 1.6, r = 0.90$
	12	Rn Grab (pCi/L)	RPISU (WL)	$Y = 0.0022X + 0.027$ $S_{yx} = 0.041, r = 0.79$	$Y = 0.023X^{0.34}$ $S_{yx} = 2.2, r = 0.43$
Commercial and Others	21	RPISU (WL)	REC Grab	$Y = 0.77X - 0.011$ $S_{yx} = 0.073, r = 0.71$	$Y = 0.79X^{1.05}$ $S_{yx} = 2.1, r = 0.72$
	21	Rn Grab (pCi/L)	REC Grab (WL)	$Y = 0.0043X - 0.016$ $S_{yx} = 0.060, r = 0.82$	$Y = 0.0033X^{0.95}$ $S_{yx} = 2.2, r = 0.72$
	35	Rn Grab (pCi/L)	RPISU (WL)	$Y = 0.0028X + 0.020$ $S_{yx} = 0.088, r = 0.92$	$Y = 0.013X^{0.59}$ $S_{yx} = 2.0, r = 0.66$
All Categories	30	RDC Grab (WL)	RPISU (WL)	$Y = 0.54X + 0.048$ $S_{yx} = 0.066, r = 0.67$	$Y = 0.37X^{0.57}$ $S_{yx} = 1.8, r = 0.71$

Figure 2. Radon daughter grab samples vs. integrated (RPISU) samples - logarithmic.

Figure 3. Radon daughter grab samples vs. integrated (RPISU) samples - linear

Figure 4. Logarithmic regression and confidence limits for predicting an integrated RDC from grab sampling.

Figure 5. Radon daughter vs. radon gas concentration.

Figure 6. Radon daughter vs. radon gas concentrations - linear regressions.

2.3 "Radon Profile" Analysis

The "radon profile" method of grab sampling and interpretation described by Tappan (Ta77) was completed in 25 structures for which RPISU data were also available. The data are listed in Table 8 and displayed in Figures 7 and 8. For all 25 locations including those with rather high RDCs, the linear correlation appears quite good ($r = 0.93$). The 80% confidence limits for predicting the results of RPISU sampling, based on the radon profile analysis are shown in Figure 9. In spite of the non-linear response indicated by the log-log regression, there is greater than 80% confidence that any structure (residential or other) found eligible for remedial action by the radon profile method would also be found eligible by RPISU sampling.

TABLE 8. RADON PROFILE AND RPISU ESTIMATED ANNUAL AVERAGE RDC (WL)

<u>Location</u>	<u>RPISU</u>	<u>Profile</u>
00030	0.412	0.318
00048	0.119	0.042
00168	0.091	0.073
00239	0.026	0.006
00274	0.156	0.068
00292	0.067	0.075
00375	0.038	0.027
00424	0.090	0.017
00489	0.621	0.671
00935	0.021	0.037
00981	0.164	0.054
02781	0.107	0.226
02862	0.018	0.019
03366	0.018	0.026
03821	0.488	0.402
03927	0.019	0.044
04867	0.250	0.304
05077	0.056	0.014
05148	0.036	0.005
05211	0.202	0.184
05244	0.210	0.056
05867	0.083	0.048
07173	0.019	0.023
09542	0.040	0.038
10514	0.153	0.147

Figure 7. Radon profile vs RPISU estimates of annual average RDC (WL) - logarithmic regression.

Figure 8. Radon profile vs RPISU estimates of annual average RDC (WL) - linear regression.

Figure 9. Confidence limits for predicting RPISU results from a radon profile analysis.

2.4 Indoor Gamma Exposure Rates

The correlation between the indoor net average gamma (NAG) exposure rate and the indoor radon daughter concentration (RDC) was investigated, primarily to determine the reliability of the presumptive test authorized in 10 CFR 712. Section 12.8(b)(1)(ii)(a) states: "It may be presumed that if the external gamma radiation level is equal to or exceeds 0.02 mR/hr above background, the indoor radon daughter concentration level equals or exceeds 0.01 WL above background."

The following definition is found in Section 12.3(e): "External gamma radiation level" means the average gamma radiation exposure rate for the habitable area of a structure as measured near floor level."

The cumulative frequency distribution of the internal net average gamma exposure rates indicate a lognormal distribution as shown in Figure 10. The distribution statistics are shown in Table 9.

TABLE 9. DISTRIBUTION OF INDOOR NET AVERAGE GAMMA EXPOSURE RATES.

NAG (mR/hr)	All Structures		Residences	
	No.	Σ %	No.	Σ %
≤ 0.003	307	28.7	277	33.5
≤ 0.005	127	40.6	112	47.1
≤ 0.01	258	64.7	212	72.8
≤ 0.02	209	84.3	148	90.7
≤ 0.05	139	97.3	66	98.7
≤ 0.01	28	99.9	11	100.
> 0.01	1	100.	0	
TOTAL:	1069		826	
Geom. Mean, $\bar{X}_g =$	0.0068 mR/hr		0.0054 mR/hr	
GSD =	2.8		2.7	

A regression analysis of all locations (669) having the $NAG \geq 0.001$ mR/hr produced the following results:

$$\begin{aligned}\text{Linear regression: } NAG &= 0.00207 (RDC) + 0.0108 \\ r &= 0.15 \quad S_{yx} = 0.011\end{aligned}$$

$$\begin{aligned}\text{Logarithmic regression: } NAG &= 0.0383 (RDC)^{0.411} \\ r &= 0.52 \quad S_{yx} = 2.04\end{aligned}$$

The linear correlation is almost non-existent and the logarithmic correlation, although better, is not impressive. The analysis of the 80 locations exhibiting NAGs greater than or equal to 0.02 mR/hr produced weak correlations on both linear and logarithmic bases:

$$\begin{aligned}\text{Linear regression: } NAG &= 0.025 (RDC) + 0.032 \\ r &= 0.37 \quad S_{yx} = 0.014\end{aligned}$$

$$\begin{aligned}\text{Logarithmic regression: } NAG &= 0.043 (RDC)^{0.102} \\ r &= 0.30 \quad S_{yx} = 1.44\end{aligned}$$

The reliability of the NAG to determine eligibility in 826 residences is indicated in Table 10. The NAG exceeded 0.020 mR/hr in 80 residences and correctly indicated eligibility 75 times (94%). In 157 cases, the NAG was less than 0.001 mR/hr and 130 of those locations were actually ineligible for remedial action; the NAG was correct in 83% of these cases. However, in 589 (71%) the NAG was in the range between 0.001 and 0.020 mR/hr and could not be used to determine either eligibility or ineligibility. However, the decision making levels appear to be appropriate for this eligibility criterion, since they result in correct decisions over 80% of the time at the low end and more than 90% of the time at the high end of the range.

TABLE 10. DISTRIBUTION OF INDOOR NET AVERAGE GAMMA (NAG) EXPOSURE RATES
VERSUS ELIGIBILITY FOR REMEDIAL ACTION BASED ON INDOOR RADON
DAUGHTER CONCENTRATION.

	Eligible RDC $\geq$ 0.017 WL	Ineligible RDC < 0.017 WL	Totals
NAG $\geq$ 0.020	75	5	80
0.020 > NAG $\geq$ 0.001	266	323	589
NAG < 0.001	27	130	157
TOTALS	368	458	826

Figure 10. Cumulative frequency distribution of indoor net average gamma (NAG) exposure rates.

A presumptive test based on external gamma radiation levels is not permitted for non-residential structures under the current provisions of 10 CFR 712. That exclusion was included in the regulation initially because of the lack of sufficient data upon which to base a presumptive criterion for commercial structures. Since that time, however, numerous commercial and institutional structures have been surveyed and provide a data base suitable for proposing an equivalent criterion for remedial action in these structures. Survey data include 35 non-residential structures in which the NAG was greater than or equal to 0.04 mR/hr. Of these 35 locations, 29 (83%) exhibited a gross RDC $\geq$ 0.037 WL.

The NAG eligibility criterion of 0.05 mR/hr for non-residential structures would provide no improvement in reliability. The data base includes only 16 such structures, 13 of which (81%) were found to be eligible for remedial action on the basis of an RDC $\geq$ 0.037 WL. It is recommended that an eligibility criterion based on a NAG $\geq$ 0.04 mR/hr used for non-residential structures. The gamma survey measurements used in computing the NAG should be obtained in the same manner as they are for residential structures, i.e. each reading should represent about 25 square feet of the indoor area.

2.5 Gamma Exposures Over Adjacent Slabs

A situation analogous to the indoor gamma exposure rate criterion arises when tailings are found under attached exterior concrete slabs, e.g. patios, driveways, etc. Due to lateral diffusion, tailings under such slabs can serve as a source for radon to enter the structure. Survey data from 23 residences found to have tailings under adjacent slabs were examined to determine the degree of correlation between gamma exposure rates* over the slabs and indoor RDC. These data are shown in Table 11. The column in the table labeled "Slab Type" indicates whether the slab was open to the outdoor atmosphere, e.g. a driveway or patio, or if it was closed, e.g. an attached garage. Of the 23 structures, 3 had basements

*The "gamma exposure rates" referred to in this section are uncorrected meter readings taken at ground level. They are intended for use only as field data that can be correlated with remedial action eligibility.

(2 eligible, 1 ineligible), 17 had crawl spaces (11 eligible, 6 ineligible), 1 was a slab on grade structure (ineligible) and for 2 (eligible) the type of structure was unrecorded.

The correlation of gross RDC with the gamma exposure rate is somewhat better than the correlation of the net RDC with the gamma exposure rate. Also, the correlations on a logarithmic basis are somewhat better than those on a linear basis, indicating that the contribution of radon to the indoor RDC from tailings under slabs is not a linear function (Table 12). The linear regression for gross indoor RDC as a function of gamma exposure rates over adjacent slabs is shown in Figure 11.

The CDH has proposed (La79) an eligibility criterion of 80 $\mu\text{R/hr}$ average over adjacent slabs. They note that from this set of 23 locations, 87% of those that exceeded 80 $\mu\text{R/hr}$ average over adjacent slabs were found to be eligible based upon measured indoor RDCs. Although this observation is true for this particular set of data, the regression analysis indicates that the criterion should be set at approximately 110 $\mu\text{R/hr}$ to achieve a reliability of determination of eligibility of approximately 80%. Note that the 80% one-sided confidence limit crosses the eligibility criterion at 110 $\mu\text{R/hr}$ (Figure 11). If the eligibility criterion was changed at some future time, for example, because of a better determination of the natural background RDC, this proposed criterion for external gamma exposure rates over adjacent slabs would also have to be changed. For instance, if the natural background RDC was determined to be 0.01 WL instead of 0.007 WL, the proposed gamma exposure criterion would have to be increased to 120 $\mu\text{R/hr}$ to achieve the same level of reliability. On the basis of the current knowledge of background RDC and the needs of the program, an average exposure rate of 110 $\mu\text{R/hr}$ over adjacent slabs should be considered a sufficient presumptive test for remedial action eligibility. This presumptive test should only be applied to residences with basements or crawl spaces, since those are the only types of structures for which the existing data are adequate. The average exposure rate should be obtained by the same procedures as used for determining the indoor NAG, i.e. there

should be one measurement representing approximately each 25 square feet of adjacent slab area. Since no statistical difference was found between contributions from open or enclosed slabs, it is proposed that open patios, carports, sidewalks, etc. be treated the same as enclosed garages and storage sheds. In the case of driveways, only the portion within 20 feet of the house should be included in the survey for determining average gamma over adjacent slabs. This portion of a driveway would be equivalent to the length of a carport or patio.

In the case of adjacent slabs, the accuracy in determining eligibility for remedial action is of even less importance than it is in many cases where tailings are under the building itself. For the 9 eligible structures on which cost data are available, the average cost of remedial action for removal of tailings under adjacent slabs was \$5675. Since this is only a little more than a third of the average cost of remedial action in residences, the benefit-to-cost ratio for removal of tailings from under slabs will be even better than it is for the average remedial action.

TABLE 11.

LOCATIONS WITH TAILINGS UNDER AN ATTACHED CONCRETE SLAB

Loc.No.	Eligible	Slab Type	Gamma Exposure (μ R/hr)		Indoor RDC (WL)	
			Average	No. Readings	Gross	Net
00104	yes	open	89.1	12	0.049	0.042
00239	yes	open	182.2	37	0.026	0.019
00269	yes	encl	137.5	6	0.038	0.031
00410	yes	encl	76.5	10	0.037	0.030
00586-b	no	open	32.1	12	0.015	0.008
02073	yes	open	119.3	8	0.034	0.027
02774	no	open	119.2	12	0.013	0.006
03397	yes	encl	93.0	4	0.033	0.026
04935-b	yes	open	106.7	3	0.063	0.056
05381-s	no	open	62.1	6	0.011	0.004
05604	yes	encl	106.7	6	0.044	0.037
06012	yes	open	120.0	6	0.034	0.027
10801	no	open	51.4	7	0.006	0.
00769	yes	open	118.0	5	0.025	0.018
13432-b	yes	encl	128.0	6	0.026	0.019
03069	yes	encl	121.0	5	0.053	0.046
08483	yes	both	123.0	22	0.030	0.023
00202	no	both	64.3	8	0.007	0.
02891	no	encl	110.0	4	0.016	0.009
04775	no	encl	60.0	9	0.012	0.005
08135	no	encl	77.5	10	0.016	0.009
00267	yes	encl	111.7	6	0.065	0.058
05171	yes	open	51.0	5	0.019	0.012

b = basement; s = slab-on-grade; all others had crawl spaces.

TABLE 12. CORRELATION STATISTICS BETWEEN GAMMA EXPOSURE RATE OVER
ADJACENT SLABS AND INDOOR RDC

	Linear Regression	Logarithmic Regression
Gross RDC	$Y = 0.00021X + 0.0087$ $S_{yx} = 0.016, \quad r = 0.42$	$Y = 0.00034X^{0.94}$ $S_{yx} = 1.7, \quad r = 0.57$
Net RDC	$Y = 0.00020X + 0.0036$ $S_{yx} = 0.017, \quad r = 0.39$	$Y = 0.0000056X^{1.7}$ $S_{yx} = 3.1, \quad r = 0.54$

X = Gamma (μ R/hr), Y = RDC (WL)

Figure 11. Indoor gross RDC vs gamma exposure rate over adjacent concrete slab.

2.6 Track-Etch Film Measurements

Track-Etch Demonstration Program

The CDH has accumulated numerous measurements with track-etch films in structures of all types. An intensive program was conducted during 1973-74 with participation by the General Electric Company (Lo75) and the ERDA Health and Safety Laboratory (Co75, Co76). Fifty-five locations were sampled continuously by RPISUs and track-etch films. The paired RPISU data from these locations are listed in Tables 1 and 2, pp. 6 and 7. For year-long exposures in residential buildings using non-wiped films, the regression equation for predicting the integrated RDC in WL from track density was (Lo75):

$$X(WL-hr) = [Y(\#/mm^2) - 2.683] / 0.0912$$

or expressed in the usual format:

$$X(WL-hr) = 10.97Y (\#/mm^2) - 29.43$$

The error contribution to the prediction of $X(WL-hr)$ due to replication of film results was found to be 8.2%. The error contribution due to disequilibrium between radon and its progeny was 13.7% and "is the major source of uncertainty in the prediction of exposure from exposed track-etch films." (Lo75, p.35).

For films exposed in 44 pairs during the 1973-74 experiments performed by HASL (Co75), the coefficient of variation due to lack of replication of individual measurements was found to be approximately 7%.

Countess (Co76) reported the response of Kodak-Pathe LR115 Type II film determined from controlled laboratory exposures to be:

$$Y = 4.2 \times 10^{-4}X + 6.8$$

where: Y = track density, tracks/mm²
 X = time-integrated airborne alpha concentration, pCi-hr/L
 (radon plus progeny)

These calibrations were performed in atmospheres exhibiting short ingrowth times and equilibrium factors in the range of 0.02 to 0.18. For an equilibrium factor of approximately 0.5, the film response was:

$$Y = 0.209X + 6.52$$

where Y = track density, tracks/mm²

X = time integrated concentration of radon progeny, WL-hr

The small positive intercept in both of these equations represented the film background for these experiments.

The variation in response as a function of the equilibrium factor, calculated from the 24 data sets reported by Countess, is:

$$Y = 0.097F^{-0.85}$$

where Y = track density (tracks/mm²) per unit time-integrated radon progeny concentration (WL-hr)

F = equilibrium ratio, $100 [WL] / [Rn]$

At an average equilibrium factor for Grand Junction residences of 0.486 (La77), the predicted track density would be 0.18 tracks/mm² per WL-hr. This estimate leads to a calculated net value of 27 tracks/mm² for a one-year exposure in a concentration of 0.017 WL. However, the variability in track densities resulting from variations in the equilibrium factor is somewhat larger than the variability of the equilibrium factor itself. Furthermore, the variability of track densities will be skewed, as indicated by the following calculations:

	$\bar{F} - S$	$\bar{F}$	$\bar{F} + S$	Approx. C.V.
$F = 0.486 \pm 0.195$:	0.291	0.486	0.681	40%
$Y = 0.097F^{-0.85}$:	0.28	0.18	0.13	$\frac{100(0.28-0.13)}{2(0.18)} = 46\%$
$\frac{100 Y - \bar{Y} }{\bar{Y}} (%)$:	56%		28%	$\frac{56+28}{2} = 42\%$

For the equilibrium factors expected in Grand Junction residences (see next paragraph), the coefficient of variation of track densities may be expected to be approximately 40-45%.

Equilibrium Ratio

The disequilibrium between radon and its progeny was determined from 83 measurements made over 48-hour intervals during the summer of 1974. The disequilibrium factor was reported as the inverse of the normal, i.e. radon concentration divided by 100 times the radon progeny concentration in working levels. The mean value was 2.1 with a standard deviation of 1.25 (Lo75). Converted to the usual expression of the equilibrium factor, the value is 0.48 with a relative standard deviation of 60%.

For 29 paired grab samples (Table 6) the equilibrium ratio is $34.8\% \pm 16.5\%$ (CV = 55%). All of these data indicate that the mean equilibrium ratio in Grand Junction structures is in the range of 35 to 50% and that the coefficient of variation of any short-term measurements will be in the range of 50-60%.

Primary Calibrations

Data obtained from calibration of track-etch films in a small exposure chamber are listed in Tables 13 and 14. The track densities versus integrated alpha exposures are shown in Figure 12. A correlation coefficient of 0.98 was obtained for these data with a regression equation of $Y = 0.00046X + 2.06$. The fact that the atmosphere in the box was much further from equilibrium than a normal indoor atmosphere is indicated by the activity ratios. The RaC' -to-Rn concentration ratio in the chamber was 0.048 ± 0.016 , corresponding to an ingrowth time from radon of 16 minutes. The RaA -to-Rn concentration ratio was 0.31 ± 0.05 , corresponding to an ingrowth time of 2 minutes. From the available data, the RaB concentration cannot be inferred with any reasonable reliability; therefore, the concentration in WL is unknown. The high correlation coefficient however, implies that a bare track-etch film is a highly reliable indicator of total airborne alpha exposure.

The difference in equilibrium between normal indoor atmospheres and the atmosphere in a small chamber (approximately 1 m^3 volume) would be expected to produce different calibration equations for converting track densities to average RDCs in units of WL. It is important, therefore, that track-etch films be calibrated in atmospheres exhibiting equilibrium ratios comparable to those anticipated during field usage.

TABLE 13

EXPOSURE CONDITIONS DURING PRIMARY CALIBRATION OF TRACK-ETCH FILMS BY CDH
June 1978

Cumulative Exposure Time (hrs)	Alpha Concentration (pCi/L)			Comments
	Ra	RaA	RaC'	
0.15	584.3	213.1	10.8	Cards A & H installed
1.52	-	188.6	56.4	
4.40	-	198.0	50.5	
12.42	663.9	205.4	30.7	
21.42	854.9	258.8	41.8	Card F installed
29.42	953.8	240.2	32.9	
36.42	870.8	260.1	33.8	Card C installed
45.42	1145.2	270.6	41.6	
53.27	999.8	-	-	Card D installed
54.00	-	275.0	49.1	
60.43	1061.6	411.9	94.0	
69.70	1176.2	408.3	42.5	Card E installed
77.17	1170.7	372.7	69.6	
84.43	1226.2	357.2	63.6	Card B installed
93.43	1295.8	464.1	57.2	
101.47	756.5*	483.7	98.1	End of exposure

*The inconsistency of the final radon measurement led to the conclusion that it was incorrect; an extrapolated value was used for calculation of total exposure.

TABLE 14.

EXPOSURE AND TRACK DENSITY DATA FOR CDH PRIMARY CALIBRATION FILMS

Card	Integrated Alpha Exposures (pCi-hr/L)				Track Density ^b	
	Rn ^a	RaA	RaC'	Total	#/field	#/mm ²
G	0	0	0	0	0.72	1.13
B	22434	7682	1194	31310	10.90	17.11
E	39504	13129	2074	54707	15.43	24.22
D	57274	19395	3221	59890	20.40	32.03
C	74711	23911	3914	102536	35.00	54.95
F	88332	27658	4446	120436	32.00	50.24
A	102918	32226	5303	140447	45.67	71.70
H	102918	32226	5303	140447	39.67	62.28

a Based on extrapolated value for last Rn concentration in Table

b Films etched 6-7-78; counted 7-19-78 using 10X objective. Minimum of 100 tracks counted per film.

Figure 12 . Track density vs integrated alpha exposure for CDH primary calibration films

Comparative Calibrations

A comparison of track-etch films and RPISU data over the range of equilibrium conditions encountered in Grand Junction was performed by attaching the film to the outside of the RPISU housing during all periods when the RPISU was in use. When the RPISU was not in use, the film was placed in a storage container to prevent additional exposure. The data obtained over a period of a year for 16 such pairs are listed in Table 15 and displayed in Figure 13. The linear regression equation for the gross track density versus integrated exposure, as measured by the RPISU, is:

$$Y = 0.213X + 4.71 \quad ; \quad r = 0.92$$

Because the background accumulated by the film was expected to be different in the storage container than during normal exposure conditions, a multiple regression analysis was performed to estimate the effect of storage time on the total background. The calculated regression equation for the 16 sets of data is:

$$Z = 0.155X - 0.00172Y + 17.9$$

where: Z = gross track density ($\#/mm^2$)
 X = integrated exposure (WL - hrs)
 Y = storage time (hrs)

The coefficient of determination, r^2 , for this equation is 0.85 ($r = 0.92$). The negative coefficient for the term related to storage time (Y) may be interpreted to mean that the background is effectively reduced by storage in the container.

An effective background track density was calculated by inserting the number of hours of storage time for each film in the following relationship:

$$\text{Effective background} = 17.9 - 0.00172 (\text{storage time})$$

The calculated effective background track density, and the net track density presumably produced by the known exposure are shown in the last two columns of Table 15. The regression equation for the net track density versus the RPISU data is:

$$Y = 0.208X - 2.8 \quad ; \quad r = 0.87$$

For integrated exposure as a function of net track density, the equation becomes:

$$Y = 4.81X + 13.5 \quad ; \quad r = 0.87$$

This regression line and the 80% confidence limits are shown in Figure 14.

TABLE 15.

TRACK-ETCH FILM COMPARISON WITH COMMUNITY AVERAGES
RPISU DATA, 1978*

Film No.	Exposure Time (hrs)	Storage Time (hrs)	Exposure (WL-hrs)	Track Density (#/mm ²)		
				Gross	Effective Bkg.	Net
CE-1	2784	5976	48.60	26.47	7.60	18.87
CE-2	2688	6072	47.22	19.18	7.44	11.74
CE-4	2808	5952	30.63	12.20	7.64	4.56
CE-5	3000	5760	42.67	10.11	7.97	2.14
CE-6	1896	6864	58.04	11.32	6.07	5.25
CE-7	1992	6768	21.34	10.02	6.24	3.78
CE-8	1440	7320	11.76	8.01	5.29	2.72
CE-9	1512	7248	18.88	8.08	5.41	2.67
CE-10	1200	7560	10.54	5.07	4.88	0.19
CE-11	1704	7056	32.66	11.77	5.74	6.03
CE-12	1416	7344	22.30	6.67	5.25	1.42
CH-1	6360	2400	175.24	41.99	13.75	28.24
CH-2	5184	3576	96.43	27.74	11.73	16.01
CH-3	4224	4536	77.80	19.62	10.08	9.54
CH-4	3984	4776	89.61	21.59	9.67	11.92
CH-5	4008	4752	64.82	16.01	9.71	6.30

*Track-etch films attached to RPISU units while RPISUs were in use in many locations.

Figure 13. Gross track density vs integrated RDC exposure from RPISU measurements.

Figure 14. Integrated RDC exposure predictions from net track densities.

Eligibility Determinations: Film vis-a-vis RPISU

Comparative data between track etch films and RPISUs obtained since 1974 are listed in Table 16. The track densities shown in the last column were converted to time integrated RDC exposures using the equation:

$$\text{WL-hr} = 4.34 T - 11.05 \quad (\text{Co75})$$

The average RDC (WL) was obtained by dividing the exposure in WL-hrs by the number of hours the film was exposed; the results are also shown in the last column of Table 16.

Two anomalies in the tabulated data (Locations 6012 and 2951) were included in all of the statistical analyses although it was determined later that additional data should have been used. In Loc. 6012, the 4 RPISU samples indicating an average RDC of 0.006 WL were obtained in the living room; the track etch film, indicating 0.020 WL was located in a bedroom. Subsequent RPISU sampling in the basement produced an average value exceeding 0.017 WL, making the house eligible for remedial action.

At Loc. 2951, 2 RPISU samples during 1975-76 gave an average value of 0.026 WL. A track etch film in the same room (basement) indicated an annual average RDC of only 0.004 WL. Additional RPISU samples collected during 1976-77 verified that the average RDC was less than 0.017 WL, making the structure ineligible for remedial action.

The inclusion of these two erroneous sets of data probably has little effect on the averages since they tend to cancel each other. The major statistical effects would be on variances, but even those effects are not likely to be so large as to justify recomputation of all the statistical analyses.

The means and standard deviations for 3 parameters listed in Table 16, i.e. R = RPISU data (WL), T = track density ($\#/\text{mm}^2$) and F_j = RDC (WL) derived from T , for various groups of structures were calculated and are listed in Table 17. As expected from the nature of the measurements, the coefficient of variation for RPISU measurements is always greater than that for track densities or for the RDC derived from track densities. Equations, correlation coefficients and 95% confidence limits for linear regressions among the 3 parameters are given in Table 18. Log-log regressions were also calculated but did not produce correlation coefficients much different from the linear regressions.

Not surprisingly, the 34 non-residential structures, with an average RDC exceeding 0.04 WL, exhibited a much stronger correlation ($r^2 = 0.83$) between film and RPISU data than was shown by the 64 residences having a mean RDC of only 0.0245 WL ($r^2 = 0.49$). Limiting the analyses to structures in which 3 or more RPISU samples had been obtained did not improve the correlation (71 or 98 total structures; 48 of 64 residences). However, the correlation for 85 structures with an average RDC of less than 0.06 WL was much worse than for all 98 structures.

Comparison of the Variances of Paired RPISU and Film Measurements

Because the annual average radon daughter concentration based on RPISU data is derived from a limited number of discrete measurements distributed throughout the year, a larger variance might be expected than from track-etch film measurements. Since there is a strong correlation between the RPISU and the film data, and the paired data can be assumed to follow a bivariate normal distribution, the following test is used to determine whether or not the variances exhibited by the two methods are significantly different (Sn67, Ma70).

If the variances (σ^2_{RPISU} and σ^2_{FILM}) are significantly different, a t-test with N-2 degrees of freedom will be significant. If the t-test is not significant, the variances are not considered to be significantly different.

$$t = \frac{r_{\text{DS}}(N-2)^{\frac{1}{2}}}{(1-r_{\text{DS}}^2)^{\frac{1}{2}}}$$

$$r_{\text{DS}} = \frac{F-1}{((F+1)^2 - 4r^2F)^{\frac{1}{2}}}$$

$$F = \frac{s^2(\text{RPISU})}{s^2(\text{FILM})}$$

r = correlation between RPISU and FILM

The calculated values and significance levels are shown in Table 19. The variance of the RPISU measurements is significantly greater than the variance of the film measurements for almost all groupings of structures, thus confirming the intuitive expectation.

TABLE 16.

RADON DAUGHTER CONCENTRATIONS ESTIMATED FROM INTEGRATING-TLD SAMPLERS (RPISU)
AND FROM PASSIVE TRACK-ETCH FILMS (Co75)

Location No.-Type ^a	Eligible	Estimated Gross Annual Average WL	
		RPISU(#) ^b	Film(T/mm ²)
00011-0 ^a	yes	0.059(3)	0.050(102.6)
00097-R ^a	yes	0.091(1)	0.069(143.1)
00138-0	yes	0.109(2)	0.073(151.5)
00140-0	no	0.030(1)	0.028(60.8)
00153-0	no	0.029(5)	0.029(61.2)
00176-0	yes	0.072(2)	0.072(150.5)
00404-0	no	0.030(5)	0.021(45.1)
00452-0	no	0.010(2)	0.016(34.4)
00607-R	no	0.005(4)	0.009(20.)
00928-R	no	0.014(6)	0.012(25.0)
00944-R	no	0.009(4)	0.009(20.3)
00981-0	yes	0.164(2)	0.120(246.4)
02739-R	yes	0.032(2)	0.024(51.6)
02749-0	no	0.029(6)	0.022(50.6)
03077-R	no	0.008(4)	0.012(24.6)
03097-R	yes	0.024(1)	0.037(77.8)
03495-R	no	0.012(6)	0.020(42.0)
03496-R	no	0.001(4)	0.012(27.0)
03722-R	yes	0.065(2)	0.058(122.7)
03927-R	yes	0.019(5)	0.030(64.5)
04004-R	no	0.004(4)	0.003(8.9)
04048-R	yes	0.026(3)	0.033(71.2)
04065-R	yes	0.143(2)	0.047(98.8)
04094-R	yes	0.029(2)	0.054(115.0)
04234-R	no	0.005(4)	0.010(22.8)
04787-R	no	0.013(6)	0.025(57.2)
04930-R	yes	0.041(2)	0.025(54.9)
05069-R	no	0.017(6)	0.037(36)

TABLE 16. Continued...

Location No-Type ^a	Eligible	Estimated Gross Annual Average WL	
		RPISU(#) ^b	Film(T/mm ²)
05421-R	no	0.008(4)	0.009(21.0)
05756-R	yes	0.021(1)	0.017(37.9)
05785-0	no	0.024(2)	0.018(39.3)
05946-R	yes	0.042(2)	0.033(77.8)
06012-R	yes ^c	0.006(4)	0.020(44.0)
07600-R	yes	0.026(6)	0.016(34.6)
09566-0	no	0.023(5)	0.017(36.1)
10670-R	yes	0.019(5)	0.010(22.0)
11827-R	yes	0.049(3)	0.032(68.5)
12419-R	no	0.008(4)	0.007(16.7)
13384-R	yes	0.019(5)	0.034(73.5)
14378-R	yes	0.020(4)	0.029(63.4)
14639-R	no	0.010(6)	0.012(26.8)
14716-R	no	0.011(1)	0.007(16.1)
14718-R	no	0.006(4)	0.005(12.9)
15084-R	yes	0.021(5)	0.026(57.6)
15494-R	yes	0.026(4)	0.027(61.3)
17704-0	no	0.014(4)	0.038(80.0)
00233-R	no	0.013(3)	0.014(16.0)
00460-0	no	0.017(5)	0.012(29.0)
00826-0	no	0.014(2)	0.002(5.6)
00980-R	yes	0.123(2)	0.046(104.6)
01025-0	no	0.007(3)	0.004(9.5)
01509-0	no	0.011(6)	0.008(18.8)
02220-R	no	0.008(4)	0.007(10.4)
03874-0	yes	0.149(2)	0.078(158.5)
04442-R	yes	0.032(3)	0.020(46.3)
04447-0	no	0.011(3)	0.011(25.1)
04789-R	no	0.016(6)	0.017(38.2)
04822-R	no	0.006(4)	0.009(20.8)
05040-0	yes	0.108(3)	0.043(89.7)
05200-0	no	0.011(5)	0.005(11.8)
05554-0	yes	0.059(4)	0.018(40.3)
05590-R	yes	0.022(6)	0.009(20.0)
05775-0	yes	0.066(4)	0.040(82.8)
05897-0	no	0.005(5)	0.002(6.0)

TABLE 16. Continued...

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Location No-Type ^a	Eligible	Estimated Gross Annual Average WL	
		RPISU(#) ^b	Film(T/mm ²)
05936-R	yes	0.020(4)	0.012(26.6)
06370-0	no	0.026(4)	0.010(22.5)
07470-R	yes	0.025(4)	0.013(30.7)
14787-R	no	0.004(2)	0.001(4.8)
00180-0	yes	0.086(5)	0.049(102.8)
02765-R	no	0.012(2)	0.005(12.4)
02909-R	no	0.012(3)	0.004(11.6)
02951-R	no ^d	0.026(2)	0.004(11.8)
09630-R	no	0.007(2)	0.007(18.0)
00039-R	yes	0.052(1)	0.048(95.6)
00045-0	yes	0.043(6)	0.048(100.0)
00104-0	yes	0.050(5)	0.022(46.1)
00156-R	no	0.008(4)	0.008(19.2)
00249-R	yes	0.043(3)	0.031(65.0)
00306-0	yes	0.046(5)	0.044(95.3)
00410-R	yes	0.037(3)	0.062(124.7)
00459-0	no	0.022(3)	0.019(39.2)
30707-0	yes	0.157(1)	0.147(300.0)
00476-0	no	0.009(5)	0.014(31.1)
00610-R	no	0.006(3)	0.006(14.2)
00730-R	yes	0.032(5)	0.044(89.5)
01063-R	yes	0.064(3)	0.035(73.6)
02073-R	yes	0.034(4)	0.035(70.0)
03330-R	yes	0.020(5)	0.031(67.9)
03493-R	no	0.012(5)	0.022(44.2)
04339-R	no	0.007(19)	0.016(34.4)
04752-R	yes	0.039(3)	0.021(45.2)
04894-R	no	0.009(5)	0.014(29.7)
05056-0	no	0.005(2)	0.007(14.0)
05058-0	no	0.006(2)	0.011(36.1)
05193-R	no	0.010(6)	0.012(33.0)
05555-0	no	0.007(6)	0.016(35.7)
10556-R	no	0.014(6)	0.021(44.9)
11938-R	no	0.006(3)	0.012(27.8)

a. R = Residence or School; 0 = Other

b. Number of RPISU samples

c. Determined to be eligible by additional sampling in another location.

d. Additional sampling in 1976-77 produced an average RDC of < 0.017 WL.

TABLE 17.

SAMPLING STATISTICS FOR TE FILM AND RPISU PAIRED SAMPLES

<u>No. and Type of Structures</u>	<u>Variable (Units)</u>	<u>Mean</u>	<u>Std. Dev.</u>	<u>CV (%)</u>
98 Residences and Others	RPISU ($\overline{WL}$)	0.0314	0.0351	112
	FILM ($\overline{WL}$)	0.0256	0.0236	92
	FILM (t/mm^2)	54.36	48.16	89
71 Residences & Others with 3 or more RPISU Samples	RPISU ($\overline{WL}$)	0.0227	0.0202	89
	FILM ($\overline{WL}$)	0.0205	0.0135	66
85 Residences and Others with RPISU Average < 0.06 WL	RPISU ($\overline{WL}$)	0.0198	0.0139	70
	FILM ($\overline{WL}$)	0.0192	0.0133	69
64 Residences	RPISU ($\overline{WL}$)	0.0245	0.0260	106
	FILM ($\overline{WL}$)	0.0218	0.0158	72
48 Residences with 3 or more RPISU Samples	RPISU ($\overline{WL}$)	0.0176	0.0131	74
	FILM ($\overline{WL}$)	0.0190	0.0122	64
	FILM (t/mm^2)	40.12	24.36	61
34 Non-Residential Structures	RPISU ($\overline{WL}$)	0.0444	0.0454	102
	FILM ($\overline{WL}$)	0.0328	0.0330	101

TABLE 18.
CORRELATIONS BETWEEN TRACK-ETCH FILM AND RPISU DATA

In the following regression equations, $R = \text{RPISU } (\overline{\text{WL}})$, $F_i = \text{Film } (\overline{\text{WL}})$ and $T = \text{Film } (t/\text{mm}^2)$.

For 98 Structures (Residences and Others):

Equation:	F_i	=	$0.568 R + 0.0078$	$r^2 = 0.71$
Std. Error:	0.013		0.037 0.0017	
Lower 95% CL:	-		0.499 0.0045	-
Upper 95% CL:	-		0.637 0.011	-

Equation:	R	=	$1.25 F_i - 0.00066$	$r^2 = 0.71$
Std. Error:	0.019		0.81 0.0028	
Lower 95% CL:	-		1.10 -0.0060	-
Upper 95% CL:	-		1.40 0.0046	-

Equation:	T	=	$1165 R + 18$	$r^2 = 0.72$
Std. Error:	25.6		74 3.5	-
Lower 95% CL:	-		1026 11	-
Upper 95% CL:	-		1304 24	-

Equation:	R	=	$0.00062T - 0.0022$	$r^2 = 0.72$
Std. Error:	0.019		0.00004 0.0029	-
Lower 95% CL:	-		0.00054 -0.0075	-
Upper 95% CL:	-		0.00069 0.0032	-

TABLE 18. Continued...
CORRELATIONS BETWEEN TRACK-ETCH AND RPISU DATA

For 71 Structures (Residences and Others) with 3 or more RPISU Samples:

Equation:	$F_i = 0.464 R + 0.0100$	$r^2 = 0.48$
Std. Error:	0.0098 0.0578 0.0018	-
Lower 95% CL:	- 0.355 0.0067	-
Upper 95% CL:	- 0.572 0.0133	-

Equation:	$R = 1.041 F_i + 0.0014$	$r^2 = 0.48$
Std. Error:	0.015 0.130 0.0032	-
Lower 95% CL:	- 0.796 -0.0046	-
Upper 95% CL:	- 1.285 0.0074	-

For 85 Structures (Residences and Others) with Average RPISU Measurements

Less Than 0.06 WL:

Equation:	$F_i = 0.651 R + 0.0063$	$r^2 = 0.46$
Std. Error:	0.0098 0.077 0.0019	-
Lower 95% CL:	- 0.507 0.0028	-
Upper 95% CL:	- 0.796 0.0098	-

Equation:	$R = 0.711 F_i + 0.0061$	$r^2 = 0.46$
Std. Error:	0.010 0.084 0.0020	-
Lower 95% CL:	- 0.553 0.0024	-
Upper 95% CL:	- 0.869 0.0098	-

TABLE 18. Continued...

CORRELATIONS BETWEEN TRACK-ETCH AND RPISU DATA

For 64 Residences:

Equation:	$F_i = 0.425 R + 0.011$	$r^2 = 0.49$
Std. Error:	0.011 0.0548 0.0020	-
Lower 95% CL:	- 0.322 0.0077	-
Upper 95% CL:	- 0.528 0.015	-

Equation:	$R = 1.16 F_i - 0.00073$	$r^2 = 0.49$
Std. Error:	0.019 0.149 0.0040	-
Lower 95% CL:	- 0.876 -0.0083	-
Upper 95% CL:	- 1.44 0.0068	-

For 48 Residences with 3 or More RPISU Samples:

Equation:	$R = 0.00037T + 0.0028$	$r^2 = 0.47$
Std. Error:	0.0096 0.00006 0.0027	-
Lower 95% CL:	- 0.00026 -0.0024	-
Upper 95% CL:	- 0.00048 0.0079	-

Equation:	$R = 0.724 F_i + 0.0038$	$r^2 = 0.45$
Std. Error:	0.0098 0.118 0.0026	-
Lower 95% CL:	- 0.500 -0.0012	-
Upper 95% CL:	- 0.948 0.0089	-

For 34 Non-Residential Structures:

Equation:	$F_i = 0.660 R + 0.0035$	$r^2 = 0.83$
Std. Error:	0.014 0.054 0.0034	-
Lower 95% CL:	- 0.557 -0.0030	-
Upper 95% CL:	- 0.763 0.010	-

TABLE 18. Continued...

CORRELATION BETWEEN TRACK-ETCH AND RPISU DATA

For 34 Non-Residential Structures Continued:

Equation:	R	=	1.25 F _i + 0.0034	r ² = 0.83
Std. Error:	0.019		0.102 0.0047	-
Lower 95% CL:	-		1.06 -0.0056	-
Upper 95% CL:	-		1.45 0.0124	-

TABLE 19.

SIGNIFICANCE OF DIFFERENCES IN VARIANCES FOR PAIRED RPISU AND
FILM MEASUREMENTS

<u>Structure Group</u>	<u>N</u>	<u>F</u>	<u>r</u>	<u>r_{DS}</u>	<u>t</u>	<u>p-level</u>
<u>Residences and Others</u>						
All (linear)	98	2.20	0.084	0.602	7.38	<0.01
All (logarithmic)	98	1.15	0.766	0.108	1.07	~0.15
RPISU 0.06 WL	85	1.09	0.680	0.060	0.55	n.s.
≥ 3 RPISU Samples	71	2.24	0.695	0.500	4.79	<0.01
< 3 RPISU Samples	27	2.06	0.866	0.594	3.69	<0.01
<u>Residences</u>						
All	64	2.72	0.701	0.591	5.77	<0.01
≥ 3 RPISU Samples	48	1.16	0.672	0.101	0.69	n.s.
<u>Non-Residences</u>						
All	34	1.89	0.909	0.282	1.67	~0.10
≥ 3 RPISU Samples	23	3.05	0.746	0.662	4.04	<0.01

Non-Parametric Test

Because of the lack of independence of RPISU and film measurements obtained in the same atmosphere, and because of the difficulties in separating the errors due to replication, disequilibrium, intermittancy, etc. a non-parametric test was employed for further comparisons of film and RPISU data. A simple 2x2 matrix was constructed for each of the structural groupings used in Tables 17 and 18. For each matrix, the elements were the number of locations exceeding a stated RDC and those equal to or less than that RDC, as determined by RPISU and film measurements. The selected RDC values were the current remedial action criteria for residences and other structures, and values slightly above and below the current eligibility criteria. The data are shown in Table 20.

Agreement for determining eligibility or lack of eligibility ranged from 78% to 94%, with an agreement of 85% for all 98 structures. A χ^2 test was used to determine whether or not the values not showing agreement were randomly distributed or possibly biased one way or the other (Sn67). The matrix is arranged as follows:

	$X_i < C$	$X_i \geq C$
$Y_i < C$:	a	b
$Y_i \geq C$:	c	d

The χ^2 statistic was calculated for both of the following relationships:

$$\chi^2 \text{ (uncorrected, 1 d.f.)} = \frac{(b-c)^2}{b+c} \text{ and}$$

$$\chi^2 \text{ (corrected, 1 d.f.)} = \frac{(|b-c| - 1)^2}{b+c}$$

Although the significance of the test is limited in some cases by the small numbers, the small χ^2 values generally indicate randomness of the disagreements between the two methods. The corrected χ^2 value of 0.071 represents a probability of less than 25% that the lack of agreement is the result of bias. The χ^2 of 0.8 (for non-residences using a critical RDC of 0.03 WL) indicates approximately a

52% chance that the lack of agreement is not random and that film might underestimate average RDCs compared with RPISU measurements. However, the small data base makes this interpretation inconclusive.

The general conclusion derived from both the correlation analyses and the non-parametric test is that track etch film will determine remedial action eligibility at least as reliably as the 6-sample RPISU method.

TABLE 20.

NON-PARAMETRIC COMPARISON OF RPISU AND TE FILM MEASUREMENTS FOR DETERMINING
REMEDIAL ACTION ELIGIBILITY

Eligibility Criteria and Sampling Matrices			Percentage Agreement and χ^2 Values
<u>64 Residences</u>			
RPISU:	<0.015	≥ 0.015	Agreement: 53/64 = 83%
Film: <0.015	24	5	χ^2 (uncorrected): 0.091
≥ 0.015	6	29	χ^2 (corrected): 0
RPISU:	<0.017	≥ 0.017	Agreement: 52/64 = 81%
Film: <0.017	25	6	χ^2 (uncorrected): 0
≥ 0.017	6	27	χ^2 (corrected): 0.083
RPISU:	<0.02	≥ 0.02	Agreement: 50/64 = 78%
Film: <0.02	27	6	χ^2 (uncorrected): 0.29
≥ 0.02	8	23	χ^2 (corrected): 0.071
<u>34 Non-Residences</u>			
RPISU:	<0.03	≥ 0.03	Agreement: 29/34 = 85%
Film: <0.03	18	4	χ^2 (uncorrected): 1.8
≥ 0.03	1	11	χ^2 (corrected): 0.8
RPISU:	<0.037	≥ 0.037	Agreement: 31/34 = 91%
Film: <0.037	20	2	χ^2 (uncorrected): 0.33
≥ 0.037	1	11	χ^2 (corrected): 0
RPISU:	<0.04	≥ 0.04	Agreement: 32/34 = 94%
Film: <0.04	21	2	χ^2 (uncorrected): 2.0
≥ 0.04	0	11	χ^2 (corrected): 0.5
<u>All 98 Structures</u>			
(Eligibility Criteria: Res. ≥ 0.017 WL; Other ≥ 0.037 WL)			
RPISU:	Ineligible	Eligible	Agreement: 83/98 = 85%
Film: Ineligible	45	8	χ^2 (uncorrected): 0.67
Eligible	7	38	χ^2 (corrected): 0

2.7 TLD Passive Radon Monitors

Passive radon monitors using thermoluminescent dosimeters as the detectors offer another potential alternative for determining average indoor RDCs. The passive radon monitor can provide a time-integrated response proportional to the average radon concentration. It is then necessary to apply an average equilibrium factor to determine the average RDC. In Grand Junction, the data on average equilibrium factors come primarily from grab samples; it appears to be approximately $40\% \pm 20\%$. For use with passive radon monitors, the average equilibrium ought to be determined by long-term integrating samplers rather than simply from grab samples. For example, passive radon monitors should be run in parallel with RPISU samplers to assure that the average equilibrium applied to the passive radon monitor data would accurately predict the RPISU measurements.

At least four versions of passive radon monitors are currently available (3 commercially and 1 which can be custom-ordered using the specifications from the DOE Environmental Measurements Laboratory). The current cost for the passive radon monitors is from \$300 - 600 each depending upon the specific version. To acquire a large number of such monitors would be an unnecessary additional expense to the Grand Junction program. Initiating a new monitoring method requiring substantial calibration efforts and time before the system would be completely operational could be a detriment to the program. The CDH already has capabilities for grab sampling and track-etch film processing in addition to the RPISU samplers. Although passive radon monitors might be appropriate for other locations or organizations that might not have all of the capabilities that the CDH has, it does not seem to be a necessary or advantageous addition to the program in Grand Junction.

3. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

3.1 Calibrations

There appear to be some discrepancies in the grab sampling data. Average equilibrium factors for radon daughter concentrations appear to be low, particularly for conditions that are intended to be maximized with respect to ingrowth of radon daughters. The data would suggest that all calibrations of radon and radon daughter grab sampling equipment should be carefully rechecked to look for any systematic errors. Also, the procedures for collecting grab samples should be carefully reviewed to assure that the atmospheric stability in a structure is not unduly disturbed by the sampling activities. Even though the structure may have been closed and unventilated for several hours prior to the grab sampling effort, it may be that this condition is being disturbed excessively by the movement of the sampling personnel into and throughout the structure or by the air sampling equipment, etc.

There were no indications of significant bias in comparing data from measurement methods other than grab sampling with the data obtained from the RPISU samples. Because of the response of track etch films to total airborne alpha activity, rather than to radon progeny only, it is important that the equilibrium ratio either be similar during calibration to that experienced in field use or that the ratio be corrected for properly.

3.2 Recommended Alternative Eligibility Criteria

The recommended criteria for remedial action eligibility based on measurement methods other than the RPISU are shown in Table 21. All of these recommended criteria are based on comparisons with the 6 sample RPISU method as specified in 10 CFR 712. It should be reemphasized that the use of the RPISU data as the basis for recommending alternative criteria does not imply that the RPISU method is without error or that it is a standard of any kind. The RPISU data provide a frame of reference simply because this method is believed to measure the quantity of interest, namely the

average RDC in units of WL, and there is no other data base from which to establish conclusively the accuracy and precision of any of the potential methods of measurement including the RPISU.

All of the eligibility criteria listed in Table 21 are based on an estimated confidence limit of approximately 80%. As discussed under Sec. 1.6, the benefit-cost ratio is sufficiently large for remedial actions undertaken within this program as to make higher confidence limits inappropriate. It is recommended that the DOE adopt a philosophical criterion based on this type of cost-benefit consideration. For example, this general criterion, whether stated explicitly or simply inferred, should provide for the use of any measurement method that can be demonstrated from adequate empirical data to determine the long-term average RDC at the level of the eligibility criterion with a confidence level of 80%. The acceptance of this general criterion would then allow for subsequent revisions of the specific eligibility criteria as measurement methods are improved or as additional data become available. For example, very rapid determinations of eligibility might be based on the simple, quiet, and inexpensive technique of radon grab sampling. This, of course, would depend upon an adequate data base from which to develop correlations between average and maximized radon concentrations and between average RDC and radon concentrations. In order to improve the reliability of this method in the future, it is recommended that maximized radon concentration samples be collected at least once in every structure for which RPISU data have been or are being accumulated.

3.3 Limitations and Conditions of Use for Alternative Measurement Methods

Detailed written procedures should be developed for each of the measurement methods used in the Grand Junction Remedial Action Program. To the maximum extent practicable, the methods of making measurements and the interpretations of the measurements should not be dependent upon the judgement of the individuals making the measurements. This recommendation does not imply any lack of competence or good judgement on the part of

program personnel. The purpose of this recommendation is to standardize measurement methods as much as possible and thus reduce the scatter in the data. Many of the data available from the program at this time cannot be adequately interpreted or utilized by an outside investigator. There are simply too many uncertainties with respect to the way the measurements were made or interpreted. Even the 6 sample RPISU method, which was used as the basis for estimating the reliability of other methods, is not used in accordance with a definitive procedure. For example, the locations in which samplers are placed varies considerably depending upon the preferences of the house owners or occupants of other structures. In many cases, the remedial action program personnel have essentially no choice in locating the samplers, but this disadvantage might be overcome if other methods of measurement (passive detectors) could be more widely adopted. Regardless of the limitations that may occur in actual practice, the sampling locations and conditions of measurement should be adequately described in written records so that an outside investigator could utilize the data with a high degree of confidence in the comparability of measurements made in all locations.

3.4 Conclusions

The Grand Junction Remedial Action Program has generated an extensive body of data on radon and radon daughter concentrations in structures having uranium mill tailings under or around the buildings. The CDH personnel rightfully want to utilize these data to the maximum extent possible to expedite the remedial action program. Several alternative measurement methods are recommended for use in addition to the 6 sample RPISU method. Criteria for establishing eligibility or ineligibility based on these alternate methods have been proposed. These criteria are all considered to be appropriate in consideration of the favorable cost-benefit ratios obtained by the remedial action program.

It is important for the radiation protection community to preserve, augment and utilize the wealth of data already available from the Grand Junction Remedial Action Program. Arrangements should be made to extract and analyze all of the data now available and integrate the data to be obtained in the future with it. The value of the data can be greatly enhanced by assuring that detailed written records of methods and procedures are preserved along with the actual measurement data. Personnel of the CDH are to be commended for the conscientious and competent management of a large program and a large accumulation of data. However, to achieve the ultimate value from the program, provisions should be made for more comprehensive data analyses to extract correlations and interpretations that could be extremely beneficial to other similar programs.

TABLE 21. RECOMMENDED CRITERIA FOR DETERMINING REMEDIAL ACTION ELIGIBILITY USING VARIOUS MEASUREMENT METHODS

Method of Measurement	Structure Type	Eligible	Ineligible
Radon concentration under maximized conditions, i.e. occupied but closed up for ≥ 6 hours, minimal HVAC, steady barometric pressure	Residential	≥ 10 pCi/L	No criterion
	Non-residential	≥ 20 pCi/L	No criterion
"Radon Profile" sampling and interpretation as described by Tappan (Ta77)	Residential	≥ 0.017 WL	No criterion
	Non-residential	≥ 0.03 WL	No criterion
Indoor net average gamma (NAG) exposure rates	Residential	≥ 20 μ R/hr	< 1 μ R/hr.
	Non-residential	≥ 40 μ R/hr	No criterion
Average gamma exposure rate over adjacent concrete slab	Residential, with basements or crawl spaces	≥ 110 μ R/hr	No criterion
	Others	No criterion	No criterion
Track-etch films calibrated and processed by the methods used by CDH in 1979	Residential	≥ 0.017 WL	< 0.017
	Non-residential	≥ 0.037 WL	< 0.037
TLD Passive Radon Monitors	Any	Not recommended for use in Grand Junction	

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APPENDIX - STATISTICAL CALCULATIONS

The following equations were used to calculate arithmetic and geometric means and standard deviations:

Arithmetic mean and standard deviation:

$$\bar{X} = \frac{\Sigma X}{N} \quad S = \left[\frac{\Sigma X^2 - (\Sigma X)^2/N}{N - 1} \right]^{1/2} \quad \underline{A1}$$

Geometric mean and standard deviation:

$$\bar{X}_g = \exp \frac{\Sigma \ln X}{N} \quad \underline{A2}$$

$$S_g = \exp \left[\frac{\Sigma (\ln X)^2 - (\Sigma \ln X)^2/N}{N - 1} \right]^{1/2} \quad \underline{A3}$$

The following equations were used to calculate the parameters of a linear regression, $Y = mX + b$ (Di57):

$$m = \frac{\Sigma XY - (\Sigma X \Sigma Y)/N}{\Sigma X^2 - (\Sigma X)^2/N} \quad \underline{A4}$$

$$b = \frac{\Sigma Y - m \Sigma X}{N} \quad \underline{A5}$$

$$r = mS_x/S_y \quad \underline{A6}$$

$$S_{yx} = \left[\frac{N-1}{N-2} (S_y^2 - m^2 S_x^2) \right]^{1/2} \quad \underline{A7}$$

The preceding equations were converted to log-log regression parameters as follows, i.e. $Y = aX^p$:

$$a = \exp \left[\frac{\sum \ln Y - p \sum \ln X}{N} \right] \quad A8$$

$$p = \frac{\sum \ln X \ln Y - (\sum \ln X \sum \ln Y)/N}{\sum (\ln X)^2 - (\sum \ln X)^2/N} \quad A9$$

$$r = \frac{p \ln S_{gx}}{\ln S_{gy}} \quad A10$$

$$S_{gyx} = \exp \left[\frac{N-1}{N-2} ((\ln S_{gy})^2 - p^2 (\ln S_{gx})^2) \right]^{1/2} \quad A11$$

The 80% Confidence Limits indicate the 100 (1 - α) per cent confidence band for the mean of Y at any particular value of X (Di57):

$$\bar{Y}_x + t_{\alpha/2} S_{yx} \sqrt{\frac{1}{N} + \frac{(X - \bar{X})^2}{(N-1)S_x^2}} < \mu_{yx} < \bar{Y}_x + t_{1-\alpha/2} S_{yx} \sqrt{\frac{1}{N} + \frac{(X - \bar{X})^2}{(N-1)S_x^2}} \quad A12$$

where the t is taken from tabulated values of the sampling statistics for the t distribution with $\alpha = 0.20$ and $N - 2$ degrees of freedom.

The expected value of $\bar{Y}_x$ for any specified X is :

$$\bar{Y}_x = mX + b \quad A13$$

The 80% Confidence Limit, or Prediction Band, for estimating the value of Y for a single observed value of X is obtained from the following equation (Di57):

$$\bar{Y}_x \pm t_{\alpha/2} S_{yx} \sqrt{1 + \frac{1}{N} + \frac{(X - \bar{X})^2}{(N-1)S_x^2}} < Y < \bar{Y}_x \pm t_{1-\alpha/2} S_{yx} \sqrt{1 + \frac{1}{N} + \frac{(X - \bar{X})^2}{(N-1)S_x^2}} \quad A14$$

The preceding equation is used to calculate the two-sided prediction band. The one-sided confidence limit (as used in figures 4, 9 and 11) is calculated from the following equation derived from A14 :

$$Y > \bar{Y}_x + t_{\alpha} S_{yx} \sqrt{1 + \frac{1}{N} + \frac{(X - \bar{X})^2}{(N-1)S_x^2}} \quad \text{A15}$$