

Probabilistic Estimates of Dose and Indoor Radon Concentrations Attributable to Remediated Oilfield Naturally Occurring Radioactive Material (NORM)

Exploration and Production Department
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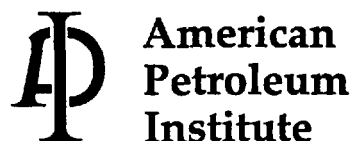
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FOREWORD

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EXECUTIVE SUMMARY

The objective of the work described in this report was the preparation of a brief technical document evaluating the concentration limit of 30 pCi/g Ra-226 in pipe scale and sludge left near the surface of remediated oil field sites and returned to unrestricted public access. Radiation survey protocols used by the oil companies and the variability of radioactivity in the NORM material ensure that only small isolated areas may contain Ra-226 at the concentration limit, while the concentration throughout most of the site is well below the limit. Analysis was based on estimates (by modeling) of the potential transfer of radioactivity through environmental pathways and of potential exposures to people using the remediated site. The scope of work included an assessment of potential dose from radioactivity in pipe scale and sludge to users of remediated pits, tank battery sites, and land farms. In this assessment, an estimated distribution of radium concentration in NORM material, ranging from 30 pCi/g down to natural background levels (based on Otto's data 1989), was included as an integral component of the pathways and exposure models. This fundamental difference in waste characterization sets this assessment apart from all previous work. The probabilistic method used for calculating the potential doses and indoor radon concentrations is consistent with the new policy announced by EPA's Science Policy Council in February 1997 which recommends application of such methods.

This assessment focussed on external gamma doses and indoor radon concentrations to which users of remediated oil field sites as housing developments would be potentially exposed. An empirical model using the large data base of measured radon concentrations in homes across the United States was developed to estimate the annual average radon concentration in homes built on remediated sites. The external gamma radiation model was based on dose calculations and factors reported in NCRP #94 (1987). Both models were assessed using probabilistic methods so that the predicted distribution of doses incorporated the uncertainty and variability of input parameters. Using the distribution of Ra-226 concentrations in NORM material predicted by Rogers et al. (1989) and based on Otto's measurements (1989) (except that all material above 30 pCi/g was removed), the incremental gamma radiation doses to residents of homes built on remediated sites (no cover over the NORM) and total indoor radon concentrations were calculated to be:

Executive Summary

Remediated Site	Incremental External Gamma Dose, mrem/y from Ra-226 only		Indoor Radon Concentration (total), pCi/L	
	Mean	95 th Percentile	Mean	95 th Percentile
Pit and Tank Battery	17	70	1.4	4.6
Landfarm	6.9	35	1.4	4.0
Natural Background*	4.2	5.9	1.3	3.9

Note:

- Gamma dose for total Ra-226 in natural background.

The values for natural background were modeled using a Ra-226 concentration in soil of 1.1 pCi/g.

The distributions of predicted indoor radon levels from the distribution of Ra-226 concentrations in remediated pits and land farm applications were almost indistinguishable from the measured distribution of indoor radon levels from natural background Ra-226 in soil. This is largely a result of the low radon emanation fraction for oil field NORM.

The annual external gamma dose rate from Ra-226 in NORM is higher than the corresponding dose rate attributable to Ra-226 in natural background. However, the extreme (95th percentile) dose is substantially less than the 100 mrem/y limit set by the Nuclear Regulatory Commission on licenced facilities.

For comparison, distributions of dose and indoor radon concentrations were calculated for the scenario in which all soil at the remediated site contained Ra-226 at 30 pCi/g. The results were

Remediated Site	External Gamma Dose, mrem/y from Ra-226 only		Indoor Radon Concentration, pCi/L	
	Mean	95 th Percentile	Mean	95 th Percentile
Pit and Tank Battery	110	160	6.1	21
Landfarm	48	100	2.5	8.4

These results are similar to the results of studies described by Rogers and Associates (1994, 1990), Ashland Exploration Inc. (1994) and Auxier and Associates (1994) when the differences in source terms and models are taken into account.

Executive Summary

A second approach to estimating doses and indoor radon concentrations to which residents on remediated oil field sites may be exposed was based on the external gamma and soil survey methodology used by oil companies during remediation of sites before release to unrestricted public access. The major advantage of this approach was that there was no dependence on measured or assumed radium concentration distributions in NORM (e.g. Otto's data). In this approach, an area of elevated radium concentration remaining on a remediated site was characterized based on the survey criteria. Using output from MicroShield, it was demonstrated that gamma and soil surveys (3 m between grid points) using a 2x background criterion would ensure that 9 m² was the largest area containing Ra-226 at a concentration of 30 pCi/g that would be left on a remediated site. Using probabilistic methods and the indoor radon method described in this report, it was determined that such an area of elevated Ra-226 would result in a doubling (from 5% to 10%) of the expected fraction of homes that would have indoor radon concentrations in excess of 4 pCi/L compared to average background conditions.

In conclusion, where management practices ensure that Ra-226 concentrations in soil at remediated sites do not exceed 30 pCi/g, it was shown that the reasonable maximum external gamma doses and indoor radon concentrations were in compliance with regulatory limits and guidelines. However, an essential feature of the analysis described here was that the distribution of Ra-226 concentrations in oil field NORM was similar to that developed using methods from Rogers et al. (1989) using Otto's data (1989), except that all materials above 30 pCi/g were excluded. Also, it was shown that external gamma and soil survey methodologies used by oil companies during remediation of sites before release to unrestricted public access facilitate compliance with the standards.

FOREWORD

This document was prepared under the direction of Dr. Douglas B. Chambers, Director of Radioactivity and Risk. Major contributors to this work were Morley W. Davis, Ronald H. Stager, Sylvain St-Pierre and Dr. Leo M. Lowe.

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GLOSSARY

CRCPD	Conference of Radiation Control Program Directors
dose	throughout the document, dose from ionizing radiation refers to committed effective dose
land farm	areas in which oil field wastes have been spread as part of reclamation actions required by U.S. EPA
NORM	Naturally Occurring Radioactive Material
radon emanation fraction	the fraction of the radon (Rn-222) produced by Ra-226 decay that is available to diffuse through and escape from the matrix (e.g. soil) containing the Ra-226, unitless;
radon exhalation rate	the rate at which radon is emitted per unit surface area of soil, $\text{pCi m}^{-2} \text{ s}^{-1}$
radon exhalation rate factor	the rate at which radon is emitted per unit surface area of soil per unit Ra-226 concentration in the soil, $\text{pCi m}^{-2} \text{ s}^{-1}$ per $\text{pCi (Ra-226) g}^{-1}$
WL	Working Level - 100 pCi/L each of Rn-222 and short-lived progeny down to Po-214
WLM	Working Level Month - exposure to 1 WL for 170 hours

1.0 INTRODUCTION

1.1 BACKGROUND

Oil and natural gas reservoirs typically contain large quantities of saline water which are produced with the oil and gas. Approximately 92% of produced water is reinjected for disposal or enhanced recovery, and the remainder may be disposed on the surface or reused for other purposes such as a source of irrigation water. Radioactivity concentrations in produced water from most wells (at least 75%) are at natural background levels, but in water from some wells, the radium (Ra-226, Ra-228) concentration can be as high as thousands of picocuries per liter (pCi/L) usually attributable to local high concentrations of radium in the rock formations. Occurrences of elevated levels of naturally occurring radioactive material (NORM), particularly radium, in produced water have been reported widely around the world.

At the surface, produced water is exposed to changing physical and chemical environments that often cause the radium, when it is present, to precipitate onto piping and other process vessels. Typically, the radioactivity is found in pipe scale near the well head or in sludges separated from the produced water. At intervals, pipe scale and sludge are removed and disposed to maintain process equipment. The pipe scale and tank bottoms can end up in waste pits, in seepage into soil under tank batteries, or at land farms.

Several researchers have identified the radioactive species in oil field NORM and have measured their concentrations in pipe scale and sludge. Other characteristics have also been measured such as radon (Rn-222) emanation fraction, radon exhalation rate, leachability, etc. Based on these data, estimates of potential radiation doses to members of the public who may live on or otherwise use remediated oil field sites have been made. The results of some of these assessments indicate that potential exposures and doses may be in excess of regulatory criteria or guidelines. Those assessments were made using simplifying assumptions which tended to increase the predicted doses over those which are likely to occur. Other studies indicate very little probability that exposures will be in excess of regulatory criteria or guidelines. This analysis was carried out to more accurately portray the variability in radium concentration in NORM material and to remove some of those overly-conservative assumptions, while retaining many conservatisms in the modelling to ensure that predicted doses and radon concentrations would exceed those which may actually occur.

1.2 OBJECTIVE AND SCOPE

The objective of the work described in this report was to prepare a brief technical analysis of the radium concentration limit of 30 pCi/g in pipe scale and sludge left near the surface of remediated oil field sites and returned to unrestricted public access. Analysis of this limit was based on modelling of the potential transfer of radioactivity through environmental pathways and of potential exposures to people using the remediated oil field site. Estimated exposures and doses were compared to regulatory limits and guidelines. This document may also serve as the basis for discussion on limits with state regulators, for example concerning part N of the draft recommendations from the Conference of Radiation Control Program Directors (CRCPD).

The scope of work included an assessment of potential dose and indoor radon concentration from radioactivity in pipe scale and sludge to users of remediated pits, tank battery sites, and land farms. The assessment considered existing sites and future sites that have been and will be remediated under the criterion that all material containing Ra-226 at concentrations greater than 30 pCi/g will be disposed by alternate means. Therefore, potential doses from NORM containing Ra-226 concentrations in excess of 30 pCi/g were beyond the scope of this report. In this assessment, an estimated distribution of radium concentration in waste (based on Otto's data 1989), ranging from 30 pCi/g down to natural background levels, was included as an integral component of the pathways and exposure models. This fundamental difference in waste characterization sets this assessment apart from all previous work. The probabilistic method used for calculating the potential doses and indoor radon concentrations are consistent with the new policy announced by EPA's Science Policy Council in February 1997 which recommends application of these methods.

1.3 STUDY APPROACH AND CONTENTS OF THIS REPORT

To estimate potential doses to members of the public and indoor radon concentrations to which they may be exposed, a three stage approach was used: (1) radioactive source (NORM) characterization; (2) screening assessment of potential exposure pathways by deterministic methods to identify those pathways which contribute the largest dose; and, (3) assessment of the major contributing exposure pathways by probabilistic methods to estimate the potential doses and indoor radon concentrations, and the variability in these estimates.

A computerized literature search was carried out to identify information that would be useful to this study. Copies of potentially useful information that were not available at SENES were requested from the American Petroleum Institute and its members, or directly from the authors. The data were

reviewed and summarized in Chapter 2 and Appendix A of this report. The review focussed on the key parameter values such as the distribution of radium concentration in NORM, the radon emanation fraction, and the radon exhalation rate.

The potential doses to users of remediated sites as a housing development would exceed potential doses from all other foreseeable uses. The largest contributors to incremental dose to residents who may live on the remediated oil field sites were identified by a screening assessment which included evaluation of the following pathways: external gamma radiation; inhalation of resuspended dust; ingestion of dust and dirt; ingestion of well water; consumption of vegetables from a backyard garden; and consumption of beef, milk, eggs and poultry meat. The pathways and dose calculations are described in Chapter 3 and Appendix C. Throughout this document, dose refers to committed effective dose unless otherwise indicated.

External gamma radiation and exposure to radon progeny (Po-218 to Po-214) were determined to be the largest contributors to potential doses to residents. Exposure models and the best available distributions for parameter values were developed to implicitly include the uncertainty and variability in the input data. Potential doses from external gamma radiation and the estimated total concentration of radon in indoor air were estimated by probabilistic calculations. Finally, the estimates of mean and extreme (95th percentile) values of dose and radon concentrations were compared to criteria and guidelines. The models and probabilistic calculations are described in Chapter 3 and Appendix D and the results are presented in Chapter 4. The application of these results to the development of criteria for disposal of oil field NORM are discussed in Chapter 4.

A second approach to estimating doses and indoor radon concentrations to which residents on remediated oil field sites may be exposed was made based on the external gamma and soil survey methodology used by oil companies during remediation of sites before release to unrestricted public access. The major advantage of this approach was that there was no dependence on measured or assumed radium concentration distributions in NORM (e.g. Otto's data (1989)). In this approach, an area of elevated radium concentration remaining on a remediated site was characterized based on the survey criteria. Probabilistic calculations of the doses to residents in homes on the site and of the indoor radon concentrations were made assuming that the sizes and locations of the area of elevated radium concentrations were distributed over all possible values consistent with the survey criteria; and that the locations of the houses were distributed over all possible locations on the site. The distributions of expected doses and indoor radon concentrations were compared to applicable criteria.

Numerous assessments of potential radiation doses to members of the public using decommissioned oil field sites have been made in recent years. A detailed evaluation of these assessments and their results was beyond the scope of this report. However, a preliminary review was made of selected parts of the assessments related to the remediation of the Martha Kentucky oil fields by Ashland Exploration Inc. (1994) and to the assessments of oil field NORM by the US EPA (1993). The results of these assessments are discussed (Appendix E) and the conclusions are presented in Chapter 5.

1.4 RADON AND RADIATION DOSE CRITERIA

Regulations and recommendations regarding radon and radiation dose criteria have been issued by federal and state regulatory agencies and by other expert organizations. A summary of selected regulations and recommendations are provided in Table 1.1.

Table 1.1
RADON AND RADIATION DOSE CRITERIA

Radon Criteria	Description	Reference
20 pCi m ⁻² s ⁻¹	Annual average radon exhalation rate from inactive uranium mill tailings	40 CFR 61 (T)
0.02 WL	Radon progeny in a structure	40 CFR 192
4 pCi/L	Rn-222 concentration in a dwelling	EPA (draft) CRCPD 1996
2 WLM (10 pCi/L)	Remedial action level for NORM	NCRP #116 1993
Other Criteria	Description	Reference
500 mrem/y	Remedial action level for NORM excluding radon	NCRP #116 1993
20 µR/h	Gamma exposure rate above natural background inside a habitable building	40 CFR 192
5/15 pCi/g	5 pCi/g Ra-226 above natural background in top 15 cm layer and 15 pCi/g Ra-226 in subsequent layers (averaged over 100 m ²)	40 CFR 192
30 pCi/g	Ra-226 plus Ra-228 in soil averaged over 100 m ² (provided radon exhalation rate is less than 20 pCi m ⁻² s ⁻¹)	State regulations Texas, Louisiana and Mississippi
100 mrem/y	To control the receipt, possession, use, transfer and disposal of licensed material by any NRC licensee	10 CFR 20 1991 (NRC)
5 pCi/g	Ra-226 or Ra-228 concentration above background in any 15 cm layer	CRCPD Part N (Draft)

2.0 WASTE MANAGEMENT PRACTICES AND DESCRIPTION OF WASTE

Waste management practices and the description of NORM waste summarized in this chapter are based on the more detailed description in Appendix A.

2.1 WASTE PITS

Typically, waste pits are constructed by excavating earth to create a shallow pit and containment berms. Many pits are now lined to prevent leakage of their contents to groundwater. Typically, at closure, berms are bulldozed over the contents of the pits, and a clean layer of clay approximately 6 inches thick is placed on top. However, there is some state-to-state variation in this practice. The contents of the pits are usually several feet thick (approximately 1 meter), and the area of the site is approximately 1/4 acre (range from 1/4 to 1 acre). A typical remediated site may contain NORM in both scale and sludge.

2.2 TANK BATTERIES

Tank batteries are usually located over gravel pads, and are usually surrounded by an earthen berm. Periodically, produced water is disposed into Class II disposal wells (evaluation of NORM in produced water is not part of this assessment) and sludge accumulated in the tank batteries may be disposed in a nearby waste pit. Tank battery sites are approximately 1/4 acre in area. Water leaks and sludge spillage from the tanks into gravel and soil are the subject of this scenario.

2.3 LAND FARMING SITES

Biodegradable oil field wastes are also transported to land farms where the waste is spread onto the surface and degraded by the sun and other natural forces. Sometimes, the land is tilled to promote microbial and other degradation processes. Some scale and sludges containing NORM may be transported to land farms after passing site radiation surveys (see Section 5.1). There is wide variability in the rate at which oil field waste is applied to land farms. Therefore, the radioactivity concentration in the top 15 cm (plow depth) was assumed to be distributed from 0 to 30 pCi/g for this assessment. Land farms are typically of large extent (greater than several acres) and were considered to be much greater in area than the typical house lot size used in this assessment.

2.4 PIPE SCALE

The primary radionuclide in pipe scale is Ra-226. However, at the time radium precipitates from produced water, Ra-228 may also be present. The Ra-226/Ra-228 ratio is usually in the range 0.4 to 1.8, although higher values have been reported. The ratio is a function of many factors - mainly the relative concentrations of Ra-226 and Ra-228 in the sediments from which the water originates; and the length of time since the scale was formed. The Ra-228 contribution usually becomes insignificant after a few years as it decays with a half-life of 5.8 years.

Scott et al (1994) measured radon emanation fractions ranging from 0.001 to 0.067 in 9 waste samples from three pipe yards near Martha, Kentucky. The mean radon emanation fraction was calculated by SENES to be 0.017.

Scott et al (1994) measured radon exhalation from soil surfaces at nine locations at two pipe yards where pipes from the Martha, Kentucky oil field were cleaned. The two highest exhalation rates measured were 2.5 and 1.3 pCi m⁻² s⁻¹. The corresponding Ra-226 concentrations in soil were reported to be 1014 and 48.5 pCi/g. Using these data, SENES calculated the radon exhalation rate factors to be 0.0025 and 0.027 pCi m⁻² s⁻¹ per pCi/g. Scott et al (1994) also measured the radon exhalation from soil surface in an unreclaimed area near a reclaimed waste pit at a tank battery site. They reported a radon exhalation rate of 7.7 pCi m⁻² s⁻¹ and a mean Ra-226 concentration in soil at 147 pCi/g ranging from 67.9 to 226 pCi/g over a depth of 30 cm. Using these data, SENES calculated the radon exhalation rate factor to be 0.052 pCi m⁻² s⁻¹ per pCi/g from tank battery waste.

2.5 SLUDGE

Nielson, Rogers and Pollard (1988) reported an average radon emanation fraction of 0.10 from measurements on 21 pipe scale and sludge samples.

Scott et al (1994) measured radon emanation fractions in 4 waste samples from two tank batteries near Martha, Kentucky ranging from 0.002 to 0.047. The mean radon emanation fraction was calculated by SENES to be 0.021.

Scott et al (1994) measured the radon exhalation from the soil surface in an unreclaimed area near a reclaimed waste pit at a tank battery site. They reported a radon exhalation rate of 7.7 pCi m⁻² s⁻¹ and a mean Ra-226 concentration in soil at 147 pCi/g ranging from 67.9 to 226 pCi/g over a depth of 30 cm. Using these data, SENES calculated the radon exhalation rate factor to be 0.052 pCi m⁻² s⁻¹ per pCi/g from tank battery waste.

3.0 EXPOSURE SCENARIOS AND PATHWAYS

Dose assessment requires characterization of the exposure. Doses from radium arise from numerous pathways but, depending on the particular scenario, the contribution to total dose can be dominated by one or two pathways.

This chapter describes the potential exposure pathways that were considered and describes a screening level assessment that indicated that gamma radiation and indoor radon are, by far, the primary exposure pathways. These two exposure pathways and the methodology for estimating exposures from source term scenarios are described.

3.1 SCREENING PATHWAYS ASSESSMENT

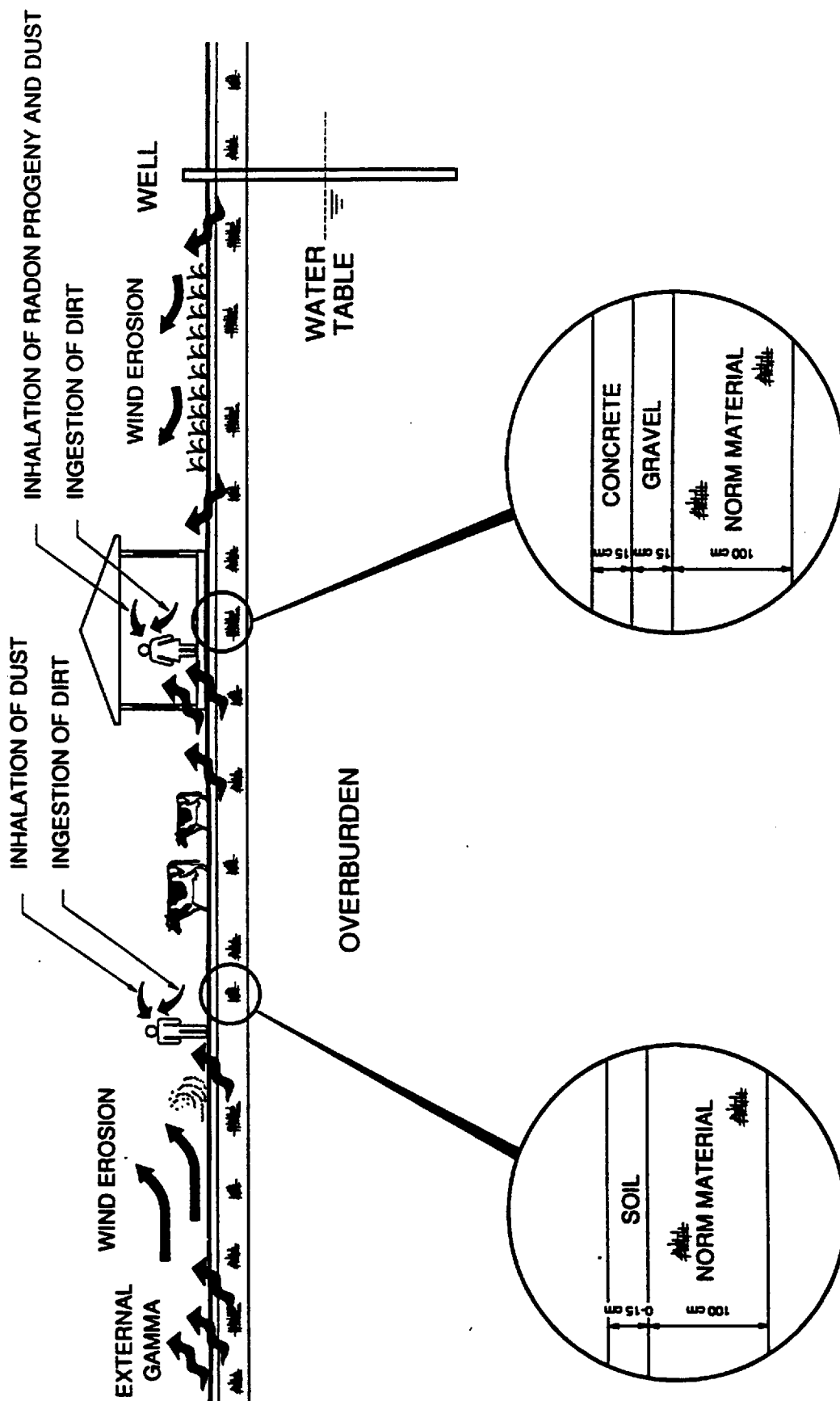
The potential doses to users of remediated sites are critically dependent upon the exposure frequency and duration. Therefore, the potential doses to residents living in homes built on remediated oil field sites would exceed corresponding doses from any other foreseeable use. The largest contributors to the incremental dose to residents who may live on the remediated oil field sites were identified by a screening assessment. Pathways illustrated in Figure 3.1, were included in the screening evaluation: external gamma radiation; inhalation of resuspended dust; ingestion of dust and dirt; ingestion of well water; consumption of vegetables from a backyard garden; and, consumption of beef, milk, eggs and poultry meat.

The pathways and dose calculations were based on models recommended by the US Nuclear Regulatory Commission (NRC 1992). The mathematical models and calculations are provided in Appendix C. Parameter values were also taken from NRC (1992) and tend to overestimate the predicted doses.

The results of the screening calculations show that the external gamma dose typically comprises more than 80% of the total incremental dose (excluding radon). The dose from consumption of well water (which was assumed to have percolated through the remediated soil) and from consumption of garden produce grown in the remediated soil, each contributed less than 10% to the incremental dose. Under almost all exposure scenarios, the external gamma pathway will contribute to and dominate total dose. Many residents will not have wells nor backyard gardens and these exposure pathways may not always contribute to total dose. Therefore, it was concluded that the remainder of the assessment would focus on a more detailed evaluation of only the external gamma radiation and radon pathways.



FIGURE 3.1
SCHEMATIC REPRESENTATION
OF POTENTIAL ROUTES OF EXPOSURE



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3.2 SOURCE SCENARIOS

Source terms were developed assuming that NORM exceeding 30 pCi/g was diverted prior to land disposal. The distribution of Ra-226 in NORM, after material in excess of 30 pCi/g had been excluded, was derived from a comprehensive database of gamma radiation measurements collected from oil field equipment. The gamma radiation data are likely biased to overestimating the occurrence of NORM exceeding 30 pCi/g. However, the distribution of NORM below 30 pCi/g was assumed equal to the distribution below 30 pCi/g derived from the gamma radiation data.

3.2.1 Remediated Pits

Remediated pits were modeled as infinitely thick (effectively equivalent to a 1 meter thickness) and were assumed to cover the entire property. Two sub-scenarios were considered; one where there was a 15 cm (6") cover over the NORM and another where no cover was present. The no-cover scenario is conservative because most remediated sites will have cover material.

Ra-226 concentrations in the NORM were assumed to vary according to the distribution of combined sludges and scales described in Chapter 2 and Appendix B. The distribution characterizes Ra-226 concentrations in sludges and scales where Ra-226 levels higher than 30 pCi/g were excluded.

3.2.2 Land Farming

The surface layer was assumed to be a mixture of NORM and natural soil with the proportion of NORM varying uniformly from 0 to 100%. The layer was assumed to be between 15 and 23 cm thick (6 to 9") and to cover the entire property. No cover material was assumed to be over this layer. The NORM concentrations vary according to the distribution of Ra-226 concentrations described in Chapter 2 and Appendix B for sludges alone after NORM >30 pCi/g has been removed.

3.3 PATHWAY DESCRIPTIONS

3.3.1 Gamma Radiation

Gamma radiation is emitted from the decay progeny of Ra-226 and the dose from this pathway depends on the source strength, on the duration of exposure and on the shielding (or attenuation) present.

Residential structures provide shielding from the floor and walls and, hence, the indoor gamma radiation exposure rate is generally lower than the outdoor exposure rate for a given source characterization. The calculation of indoor exposure rates is complex and information on several parameters is required; hence, it is common practice to use factors that are, in effect, the ratio of indoor exposure rate to the outdoor exposure rate. Example values for this factor are 0.33 and 0.70 (NRC 1982, 1992).

The dose also depends on the amount of time spent on the property. People generally spend a much higher proportion of their time on the property indoors compared to outdoors and a fraction of the day is often spent off-site. These durations are typically about 75% of a day on-site with a few hours per week spent outdoors.

3.3.2 Indoor Radon

Ra-226 in NORM (and soil) decays to radon-222 which is a gas that remains physically imbedded in the soils or is released (emanated) and travels by diffusion or advection through the soil. Portions of this radon are released to the atmosphere and into residential structures with concentrations higher in buildings compared to outdoors.

3.4 METHODOLOGY

3.4.1 General Approach

Estimated doses to residents and indoor radon concentrations on properties containing Ra-226 in NORM will vary considerably from person to person and house to house for a given scenario due to variations in source concentration, site-specific property and housing characteristics, and the occupant's personal habits. As a result of this variability, the assessment of the distribution of potential doses and indoor radon levels is more informative, and more useful, than a single number.

Probabilistic assessment, or Monte Carlo simulation, is a technique whereby the variation in parameter values of factors that affect the exposures can be incorporated. Each probabilistic trial consists of randomly selecting a parameter value(s) from the appropriate known (or estimated) distribution(s) and calculating an estimated radon concentration (or dose) for that trial. A distribution of estimated radon concentrations (or doses) is produced after repeating several trials.

3.4.2 Gamma Radiation

The total time spent on the property and the time spent outdoors were sampled each trial. Total time on the site was varied from 12 to 24 hours per day following a triangular distribution having a mean value of 18 hours per day (EPA 1989). Time spent outdoors varied uniformly from 0 to 6 hours per week (EPA 1989).

The Ra-226 concentration in soil varied according to the distribution of Ra-226 in NORM for the scenario. Ra-226 concentrations for the remediated pit scenario were sampled from the distribution of mixed scales and sludges after NORM with >30 pCi/g was excluded. Land farming concentrations were based on a similar distribution for sludges only.

Shielding from the soil was assumed to be 80% for the scenario with 15 cm of cover over the remediated pit. Additional shielding for indoor exposures was uniformly distributed between 0.33 and 0.70 (NRC 1982, 1992).

The source layer for the land farming had two types of additional variability. The thickness was varied uniformly between 15 and 23 cm (6-9") and the mixing proportion between NORM and soils varied between 0 and 100%.

A more detailed description of the probabilistic model is provided in Appendix D.

3.4.3 Indoor Radon

Source characteristics and Ra-226 concentrations were modeled in a similar manner as used for the gamma radiation pathways.

The relationship between Ra-226 concentrations in soil and indoor radon is complex and highly variable from site-to-site. An empirical/physical model was developed to incorporate this uncertainty and was calibrated to measured data from a subset of housing in the U.S. These homes have some contact with the soil and include a mixture of slab-on-grade and basement homes. A distribution of housing factors that can be interpreted as the incremental indoor radon level for an incremental Ra-226 concentration in soil formed the basis of the model.

The model included modifying factors that account for the variation in emanation fraction for the NORM and differences in the source geometry. A more complete description of the model is provided in Appendix D.

4.0 RESULTS

This chapter presents the predicted incremental gamma radiation doses and total indoor radon concentrations for remediated oil field properties containing NORM. These were shown to be the major pathways of exposure in the screening analysis described in Chapter 3.

Predictions are presented for residential settings where the NORM is either present in a remediated pit or on a land farmed area. For each scenario, predicted doses and indoor radon levels are presented for a hypothetical situation where the Ra-226 concentration in the NORM is uniformly 30 pCi/g throughout, and for the more realistic scenario where the Ra-226 concentration in the NORM varies from property to property according to the distribution of NORM below 30 pCi/g.

Variability in lifestyle patterns, site-specific physical characteristics and concentration levels in NORM were included in the prediction of incremental doses and indoor radon levels through the use of probabilistic modeling. Therefore, the predictions also were variable and are presented as distributions. Predictions are summarized by average levels, reasonably maximum levels and the percentage of properties where the predicted levels exceed generally accepted levels.

4.1 DESCRIPTORS OF EXPOSURE

4.1.1 Exposure Estimates

Gamma radiation doses are reported as incremental doses above background Ra-226 conditions. Negative incremental exposures were calculated in some trials since the estimated distribution of Ra-226 concentrations in NORM included values that were below the 1.1 pCi/g concentration assumed to be the background level.

Indoor radon concentrations are presented as total due to the high natural variability in background levels. Estimated indoor levels under the NORM scenarios are frequently lower than natural background levels for two reasons. First, the radon emanation fraction for oil field NORM was substantially lower than the radon emanation fraction in background soils. Second, a portion of the properties had Ra-226 concentrations in NORM that were lower than the background Ra-226 levels.

4.1.2 Summary Statistics

Four summary statistics were calculated from each distribution of estimated exposures generated using the probabilistic analyses. The first two statistics are measures of central tendency in that they describe average or typical values in the distribution. The arithmetic mean is relevant for population exposure estimates in that it provides an estimate of the average exposure over all the exposed population. The median value applies more to individuals since it is the value where 50% of people have lower exposures and 50% have higher exposures.

The 95th percentile relates to extreme individual dose in that it is the estimated dose level that is exceeded by only 5% of individuals exposed under the scenario. This value is considered by many to be a reasonably maximal dose from probabilistic analyses (Federal Register, Vol. 57, No. 104, pp. 22923).

An estimate of the number of individuals whose exposures (or doses) would exceed values of regulatory concern is included.

4.2 INCREMENTAL GAMMA RADIATION DOSES

Table 4.1 shows selected summary statistics of the predicted incremental gamma radiation doses calculated for the remediated pit and land farming scenarios where Ra-226 concentrations are distributed according to the truncated (<30 pCi/g) Otto data. The table includes summary statistics of the distribution of total background doses from Ra-226 at 1.1 pCi/g in soil for comparison. These values are about 4 mrem/y. For comparison purposes, total terrestrial gamma radiation levels are typically 20 to 60 mrem/y depending on the location. The estimated background doses in the table are lower for two reasons. First, a substantial proportion of total gamma radiation is attributable to thorium and potassium. Second, only a portion of the day is spent on the site and the majority of that time is indoors where the house structure provides substantial shielding.

Predicted median, or the 50th percentile, incremental doses for the NORM sources, range between 1.2 and 5.9 mrem/y depending on the particular scenario, with the highest doses occurring for an uncovered remediated pit. The distributions of incremental doses for the various scenarios are discussed in the following sections.

Table 4.1
SUMMARY OF PREDICTED INCREMENTAL GAMMA RADIATION DOSES (mrem/y)
FOR DISTRIBUTION OF NORM EQUAL TO OR BELOW 30 pCi/g

	Summary Statistics			
	Mean	Median	95 th Percentile	Percent over 100 mrem/y
Remediated Pit Exposure Scenario^{a)}				
Distribution of Combined Scales and Sludges ^c (with cover)	3.3	1.2	14.0	<0.1
Without cover	17	5.9	70	1.1
Land Farming Exposure Scenario^{a,b}				
Distribution of Sludges	6.9	1.3	35	<0.1
Natural Background Dose (total)				
1.1 pCi/g	4.2	4.1	5.9	<0.1

Notes:

- a) excluding any NORM greater than 30 pCi/g;
- b) surface layer of mixed soil and NORM covering entire property.
- c) infinitely thick NORM covering entire property below 15 cm of soil cover;

4.2.1 Remediated Pit Scenario

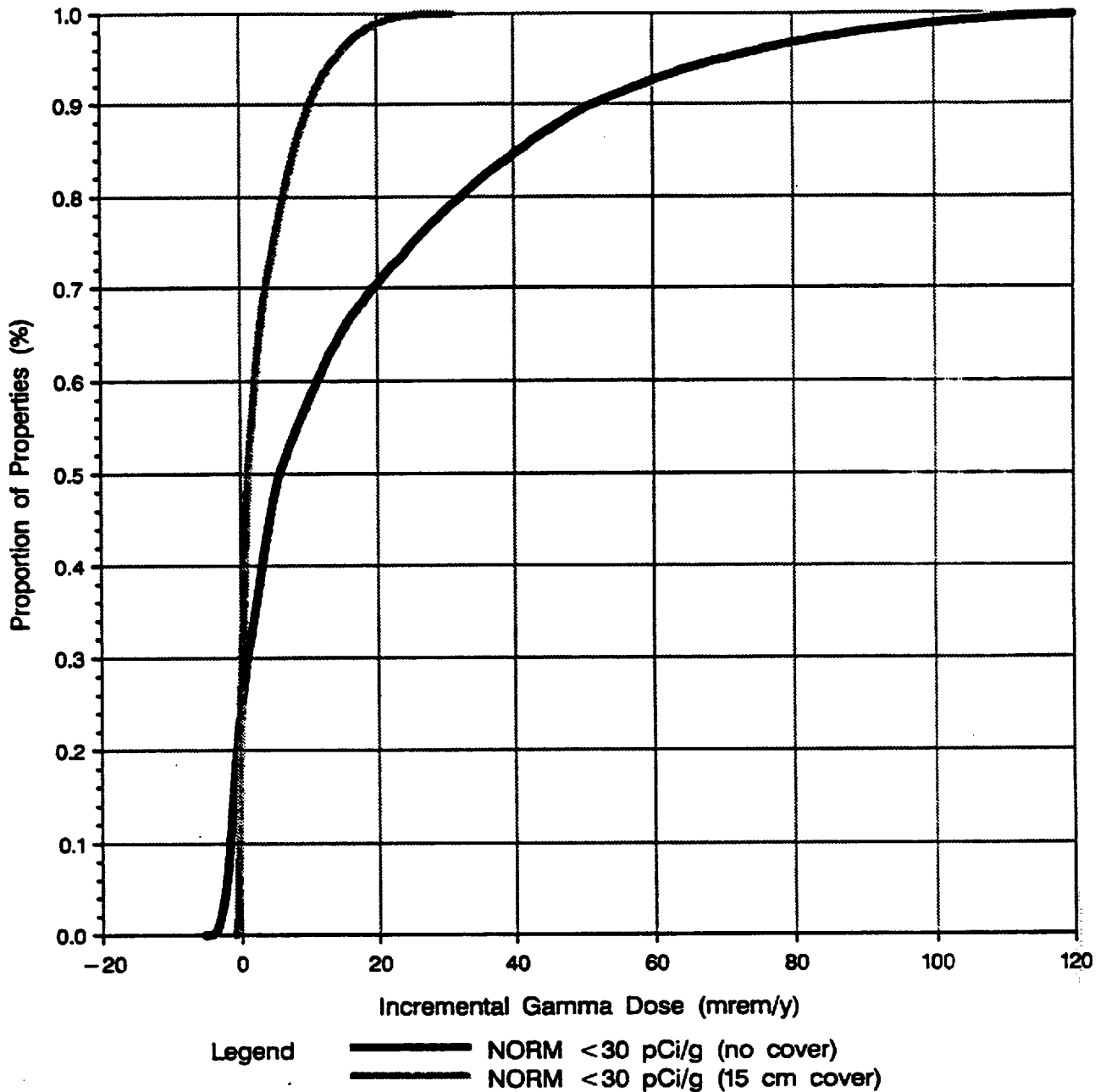
Figure 4.1 shows the distributions of predicted incremental gamma radiation doses for the remediated pit scenario where Ra-226 concentrations are distributed according to the truncated (<30 pCi/g) Otto data. Distributions are shown for scenarios where there is no cover material over the remediated site and a scenario where there is 15 cm (6 in) of cover. The variation arises from the variability in duration spent on the site and the shielding provided by the structure. Fifteen centimeters (15 cm) of cover results in incremental gamma radiation doses that are about 80% lower than doses estimated with no cover. For either scenario, there is low probability that the incremental gamma radiation dose will exceed 100 mrem/y.

A proportion of properties have estimated incremental gamma radiation doses that are negative values. This arises because the modeled Ra-226 concentration in some pits is predicted to be lower than the 1.1 pCi/g background concentration.

Table 4.2 shows selected summary statistics for predicted incremental gamma radiation doses for the

Figure 4.1

**Distribution of Predicted Incremental Gamma Radiation Doses (mrem/y)
From Remediated Pit Scenario**



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scenario where Ra-226 concentration throughout the NORM are at 30 pCi/g. Predicted median doses range from 22 to 110 mrem/y with the highest doses attributable to uncovered remediated pits. Doses to 5% of the people living on uncovered remediated pits were predicted to exceed 160 mrem/y, and doses to 58% of the people were predicted to exceed 100 mrem/y. This scenario is conservative in that it assumes that no cover is present and that the remediated pit covers the entire property.

4.2.2 Land Farming Scenario

Figure 4.2 shows the distribution of predicted incremental gamma radiation doses for the land farming scenario where Ra-226 concentrations are distributed according to the truncated (<30 pCi/g) Otto data. These incremental doses are relatively more variable than doses for the remediated pit scenario because of the variability in source thickness and the mixing with native soils modeled for this scenario. Incremental doses are low; however, a small fraction, <0.1%, are predicted to exceed 100 mrem/y (Table 4.1).

The distribution of predicted incremental gamma doses to residents on remediated land farms to which was added NORM containing Ra-226 at 30 pCi/g (Table 4.2) are significantly higher than corresponding predicted doses to residents when the added NORM contained a distribution of Ra-226 concentrations truncated at 30 pCi/g (Table 4.1). When all of the NORM contained Ra-226 at 30 pCi/g, the doses to approximately 5% of the population were predicted to exceed 100 mrem/y.

Table 4.2
SUMMARY OF PREDICTED INCREMENTAL GAMMA RADIATION DOSES (mrem/y)
FOR NORM CONCENTRATION EQUAL TO 30 pCi/g

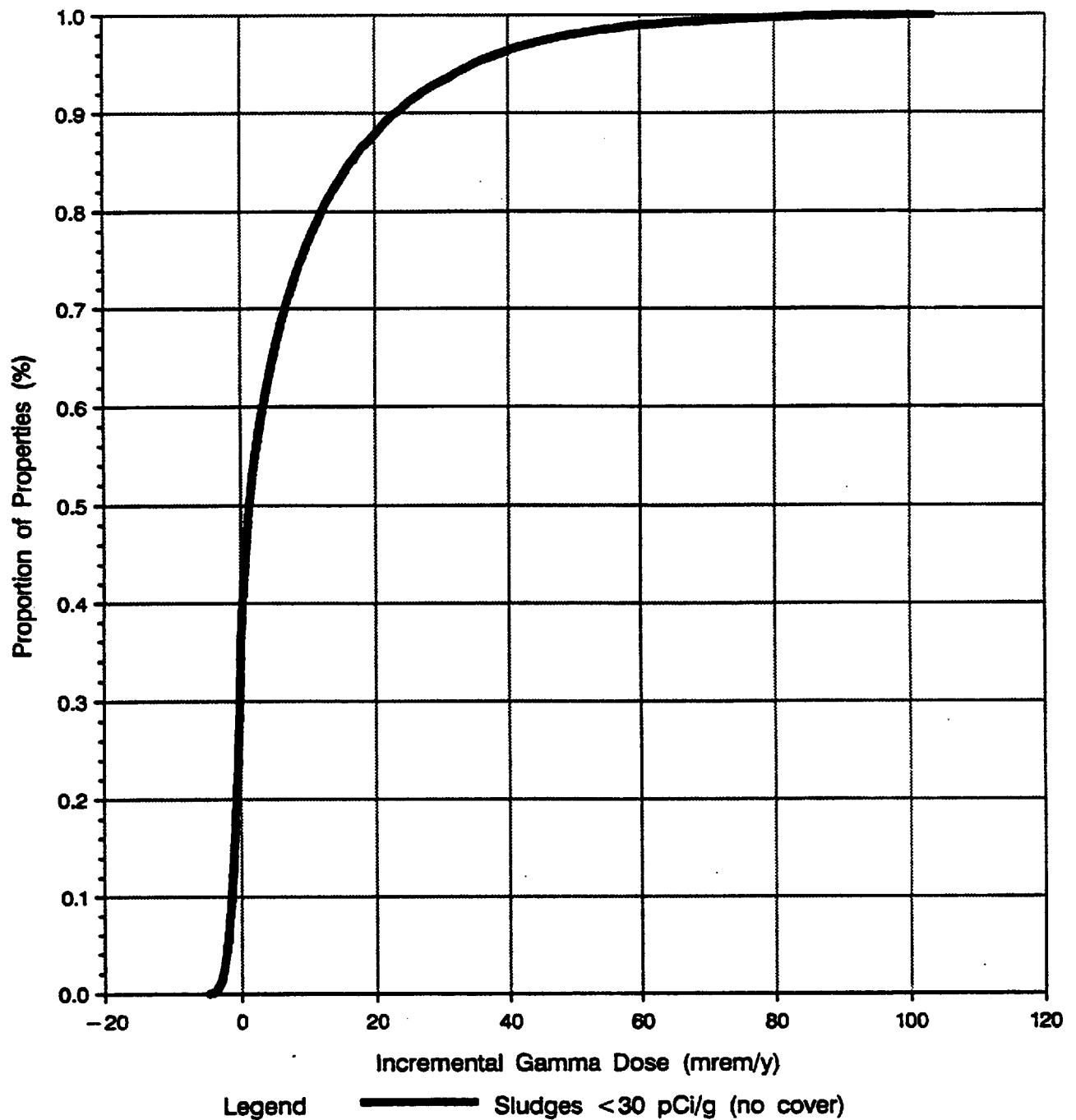
	Summary Statistics			
	Mean	Median	95 th Percentile	Percent over 100 mrem/y
Remediated Pit Exposure Scenario^{a)}				
Combined Scales and Sludges ^a (with cover)	22	22	31	<0.1
Without cover	110	110	160	58
Land Farming Exposure Scenario^{ab}				
Sludges	48	44	100	5.3

Notes:

- a) infinitely thick NORM covering entire property below 15 cm of soil cover;
- b) surface layer of mixed soil and NORM covering entire property.

Figure 4.2

**Distribution of Predicted Incremental Gamma Radiation Doses (mrem/y)
From Land Farming Scenario**



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4.3 INDOOR RADON EXPOSURES

Table 4.3 shows summary statistics of indoor radon levels predicted for the scenarios where Ra-226 concentrations are distributed according to the truncated (<30 pCi/g) Otto data. Median indoor radon levels vary between 0.60 and 0.78 pCi/L depending on the NORM scenario. The distribution of indoor radon levels for U.S. homes that physically contact the soil is also summarized. It is interesting to note that the median indoor radon levels for the scenarios are less than the median background level. This is attributable to the lower radon emanation fractions that have been measured in oil field NORM than in typical soil. Distributions of indoor radon level for individual scenarios are discussed in the following section.

Table 4.3
SUMMARY OF INDOOR RADON LEVELS (pCi/L)
FOR DISTRIBUTION OF NORM EQUAL TO OR BELOW 30 pCi/g

	Summary Statistics			
	Mean	Median	95 th Percentile	Percent over 4 pCi/L
Remediated Pit Exposure Scenario^a				
Distribution of Combined Scales and Sludges ^c	1.4	0.60	4.6	5.9
Land Farming Exposure Scenario^b				
Distribution of Sludges ^c	1.4	0.78	4.0	5.1
Natural Background Levels				
1.1 pCi/g	1.3	0.81	3.9	4.7

Notes:

- a) infinitely thick NORM covering entire property.
- b) surface layer of mixed soil and NORM covering entire property.
- c) excluding NORM greater than 30 pCi/g.

Table 4.4 shows selected summary statistics for predicted indoor radon levels for the scenarios where Ra-226 concentrations throughout the NORM are at 30 pCi/g. Predicted indoor radon concentrations were greater than for the scenarios where Ra-226 concentrations were distributed according to the truncated Otto data.

Table 4.4
SUMMARY OF INDOOR RADON LEVELS (pCi/L)
FOR NORM CONCENTRATION EQUAL TO 30 pCi/g .

	Summary Statistics			
	Mean	Median	95 th Percentile	Percent over 4 pCi/L
Remediated Pit Exposure Scenario^{a)}				
Combined Scales and Sludges	6.1	2.6	21	36
Land Farming Exposure Scenario^{b)}				
Sludges	2.5	1.2	8.4	15

Notes:

- a) infinitely thick NORM covering entire property.
- b) surface layer of mixed soil and NORM covering entire property.

4.3.1 Remediated Pit Scenario

Figure 4.3 shows the distribution of predicted indoor radon levels for the remediated pit scenario where the distribution of Ra-226 concentrations in NORM was based on Otto's truncated (<30 pCi/g) data. The distribution of indoor radon levels for the distribution of concentrations in remediated pits is almost indistinguishable from the distribution of background indoor radon levels. Selected summary statistics for these scenarios are compared in Table 4.3. For both of these scenarios, most (95%) of the predicted indoor radon levels were less than 4.0 pCi/L (the level at which EPA recommends remedial action).

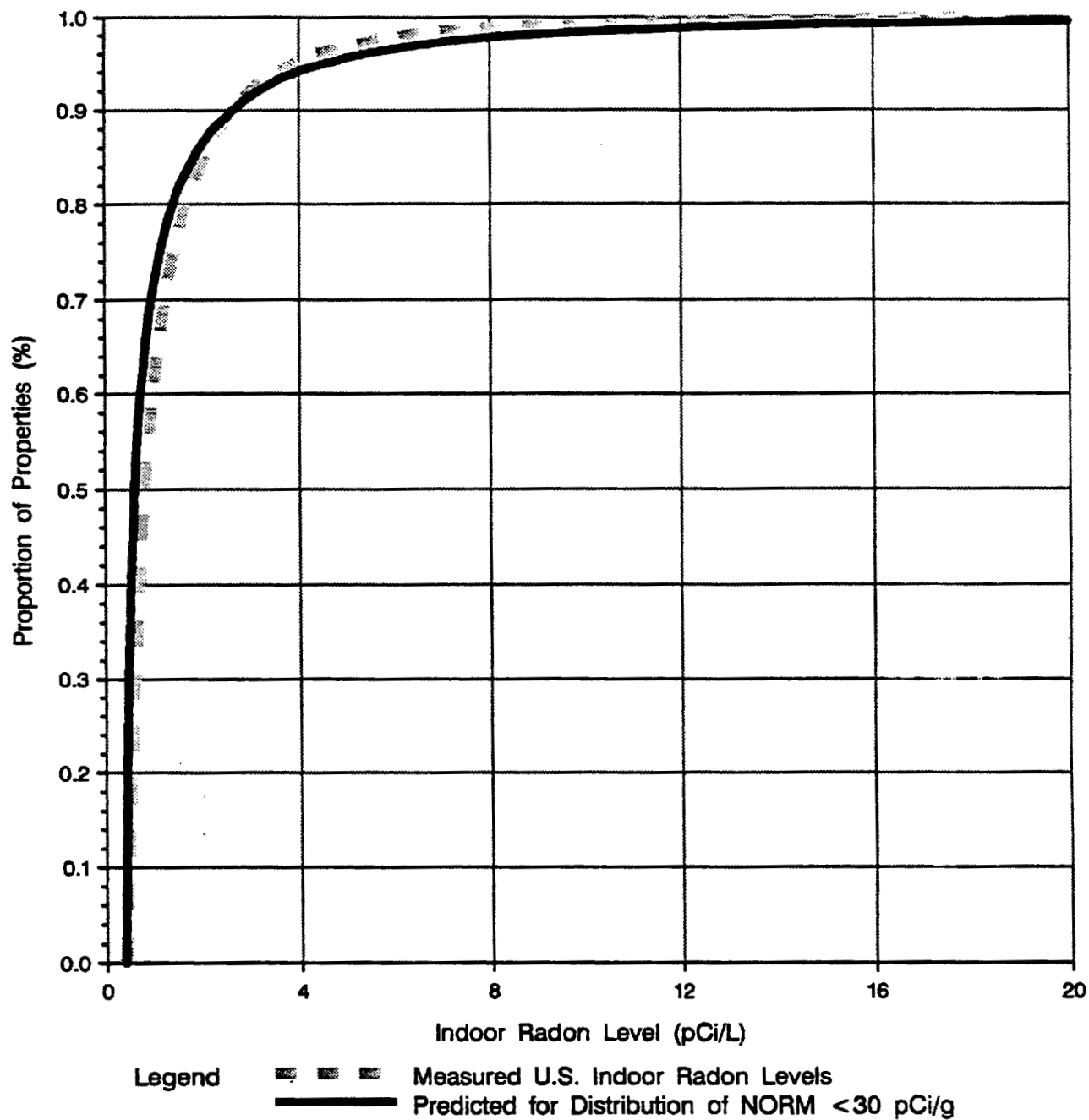
Summary statistics for the distribution of indoor radon concentrations predicted in homes built on remediated pits in which the Ra-226 concentration in NORM was uniformly 30 pCi/g throughout are provided in Table 4.4. The concentrations are higher than from natural background, and the indoor radon concentrations in approximately 36% of the homes were predicted to exceed 4 pCi/L.

4.3.2 Land Farming Scenario

Figure 4.4 shows the distribution of predicted indoor radon levels for the land farming scenario where the distribution of Ra-226 concentrations in NORM was based on Otto's truncated (<30 pCi/g) data. Table 4.3 shows summary statistics for this scenario. Predicted radon levels for the distribution of Ra-226 concentrations and source thickness for this scenario are nearly

Figure 4.3

**Distribution of Predicted Indoor Radon Levels (pCi/L)
From Remediated Pit Scenario**



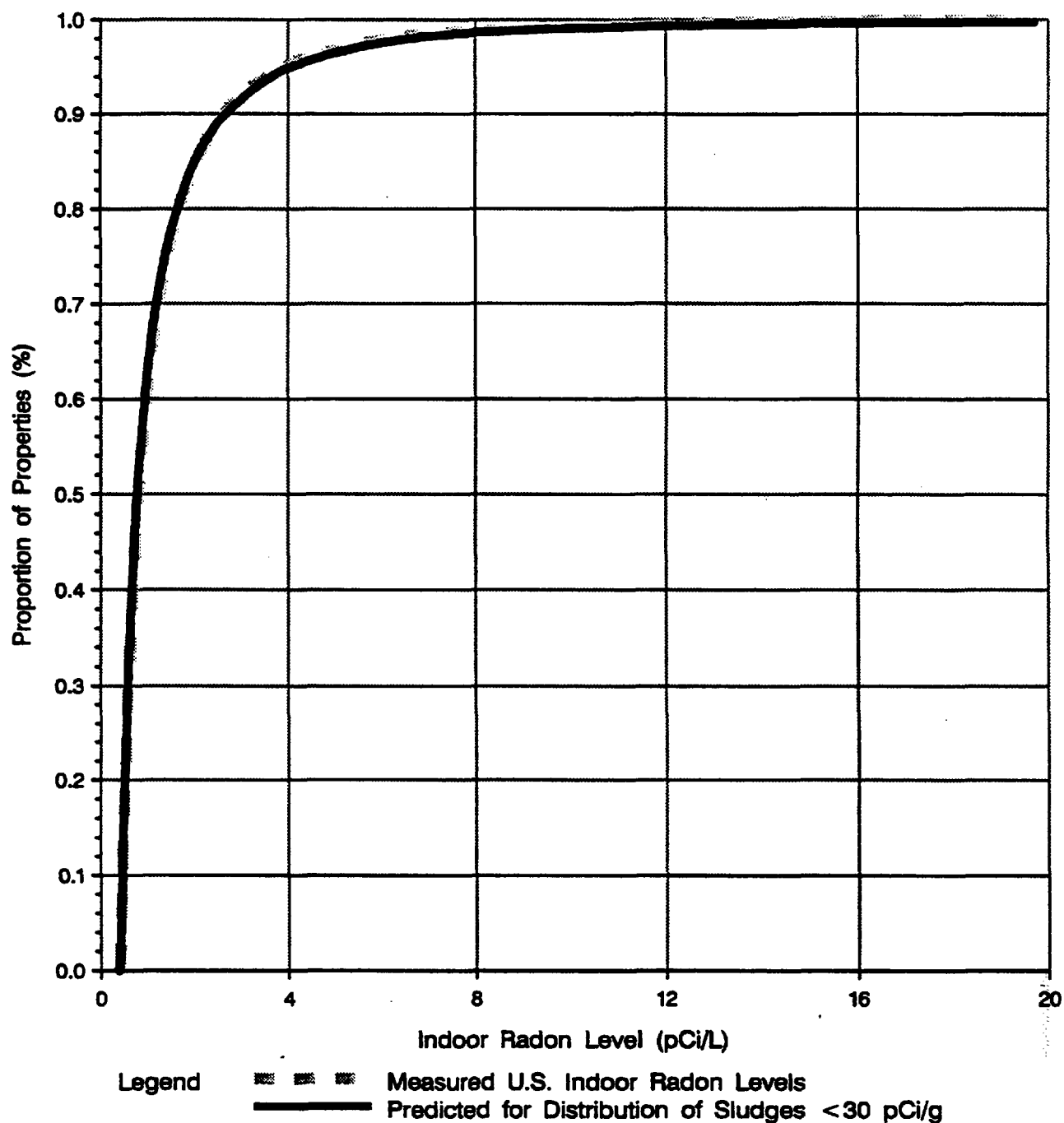
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Figure 4.4

Distribution of Predicted Indoor Radon Levels (pCi/L) From Land Farming Scenario



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