American
Petroleum
Institute

STEP
Strategies for Today's Environmental Partnership

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

Exploration and Production Department
API Publication 7105
November, 1997

STEP
Strategies for Today's Environmental Partnership

One of the most significant long-term trends affecting the future vitality of the petroleum industry is the public's concerns about the environment, health and safety. Recognizing this trend, API member companies have developed a positive, forward-looking strategy called STEP: Strategies for Today's Environmental Partnership. This initiative aims to build understanding and credibility with stakeholders by continually improving our industry's environmental, health and safety performance; documenting performance; and communicating with the public.

API ENVIRONMENTAL, HEALTH AND SAFETY MISSION AND GUIDING PRINCIPLES

The members of the American Petroleum Institute are dedicated to continuous efforts to improve the compatibility of our operations with the environment while economically developing energy resources and supplying high quality products and services to consumers. We recognize our responsibility to work with the public, the government, and others to develop and to use natural resources in an environmentally sound manner while protecting the health and safety of our employees and the public. To meet these responsibilities, API members pledge to manage our businesses according to the following principles using sound science to prioritize risks and to implement cost-effective management practices:

- To recognize and to respond to community concerns about our raw materials, products and operations.
- To operate our plants and facilities, and to handle our raw materials and products in a manner that protects the environment, and the safety and health of our employees and the public.
- To make safety, health and environmental considerations a priority in our planning, and our development of new products and processes.
- To advise promptly, appropriate officials, employees, customers and the public of information on significant industry-related safety, health and environmental hazards, and to recommend protective measures.
- To counsel customers, transporters and others in the safe use, transportation and disposal of our raw materials, products and waste materials.
- To economically develop and produce natural resources and to conserve those resources by using energy efficiently.
- To extend knowledge by conducting or supporting research on the safety, health and environmental effects of our raw materials, products, processes and waste materials.
- To commit to reduce overall emission and waste generation.
- To work with others to resolve problems created by handling and disposal of hazardous substances from our operations.
- To participate with government and others in creating responsible laws, regulations and standards to safeguard the community, workplace and environment.
- To promote these principles and practices by sharing experiences and offering assistance to others who produce, handle, use, transport or dispose of similar raw materials, petroleum products and wastes.

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

Exploration and Production Department

API PUBLICATION 7105

PREPARED BY:

SENES Consultants Limited, June 1997
for the API NORM Issue Group

NOVEMBER 1997

American Petroleum Institute

FOREWORD

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to assure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use or for the violation of any federal, state, or municipal regulation with which this publication may conflict.

Suggested revisions are invited and should be submitted to the director of the Manufacturing, Distribution and Marketing Department, American Petroleum Institute, 1220 L Street, N.W., Washington, D.C. 20005.

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:

	Incremental External Gamma Dose, mrem/y from Ra-226 only		Indoor Radon Concentration (total), pCi/L	
Remediated Site	Mean	95th Percentile	Mean	95th 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

	External Gamma Dose, mrem/y from Ra-226 only		Indoor Radon Concentration, pCi/L	
Remediated Site	Mean	95th Percentile	Mean	95th 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.

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 m^2 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.

TABLE OF CONTENTS

Page Nº

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES

LIST OF TABLES

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, pCi m^{-2} 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, pCi m^{-2} s^{-1} per 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 forseeable 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 (95^{th} 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

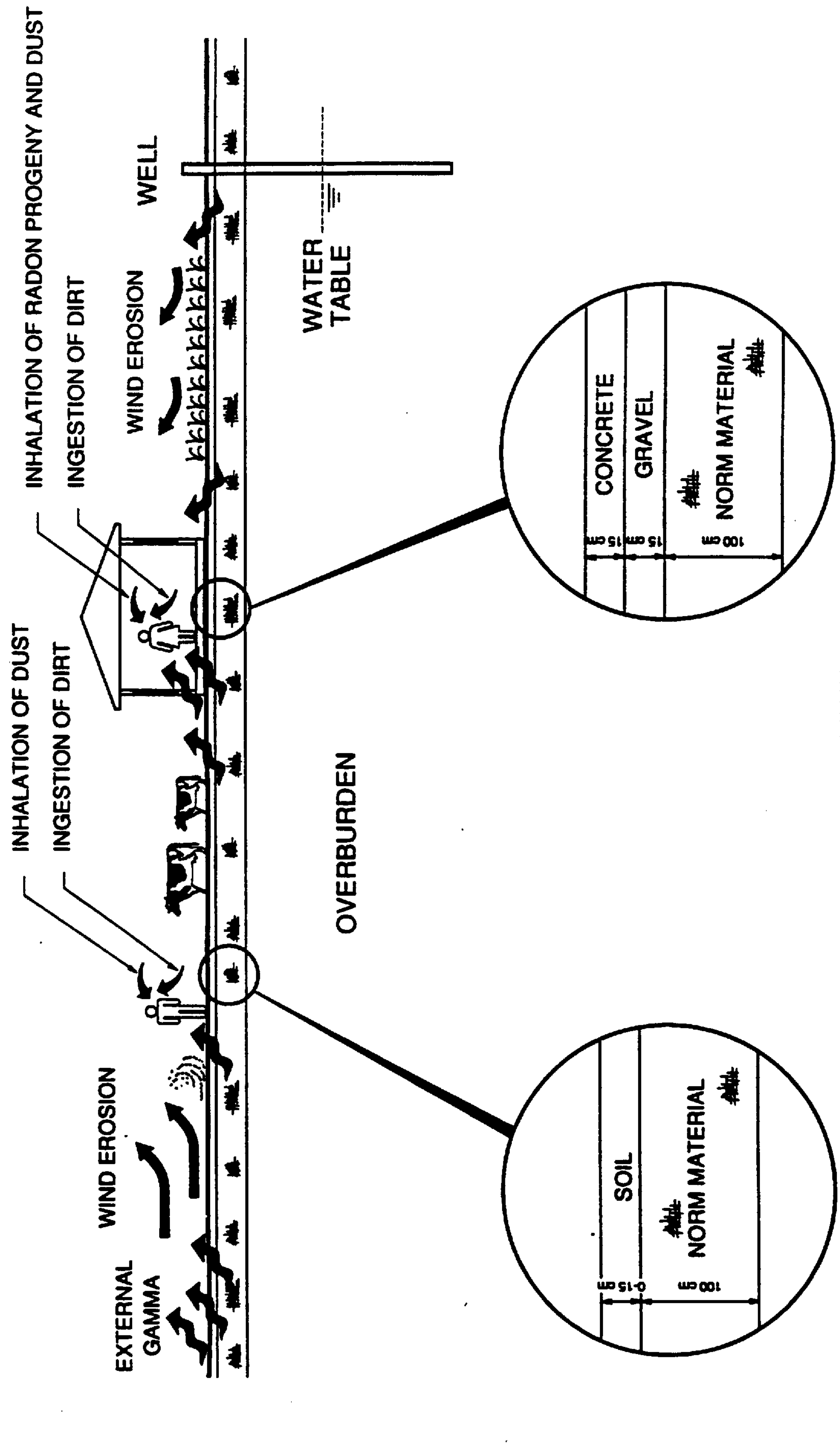
The potential doses to users of remediated sites are critically dependent upon the exposure frequency and duration. Therefore, the potential doses to residents living in homes built on remediated oil field sites would exceed corresponding doses from any other forseeable use. The largest contributors 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



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	95th 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

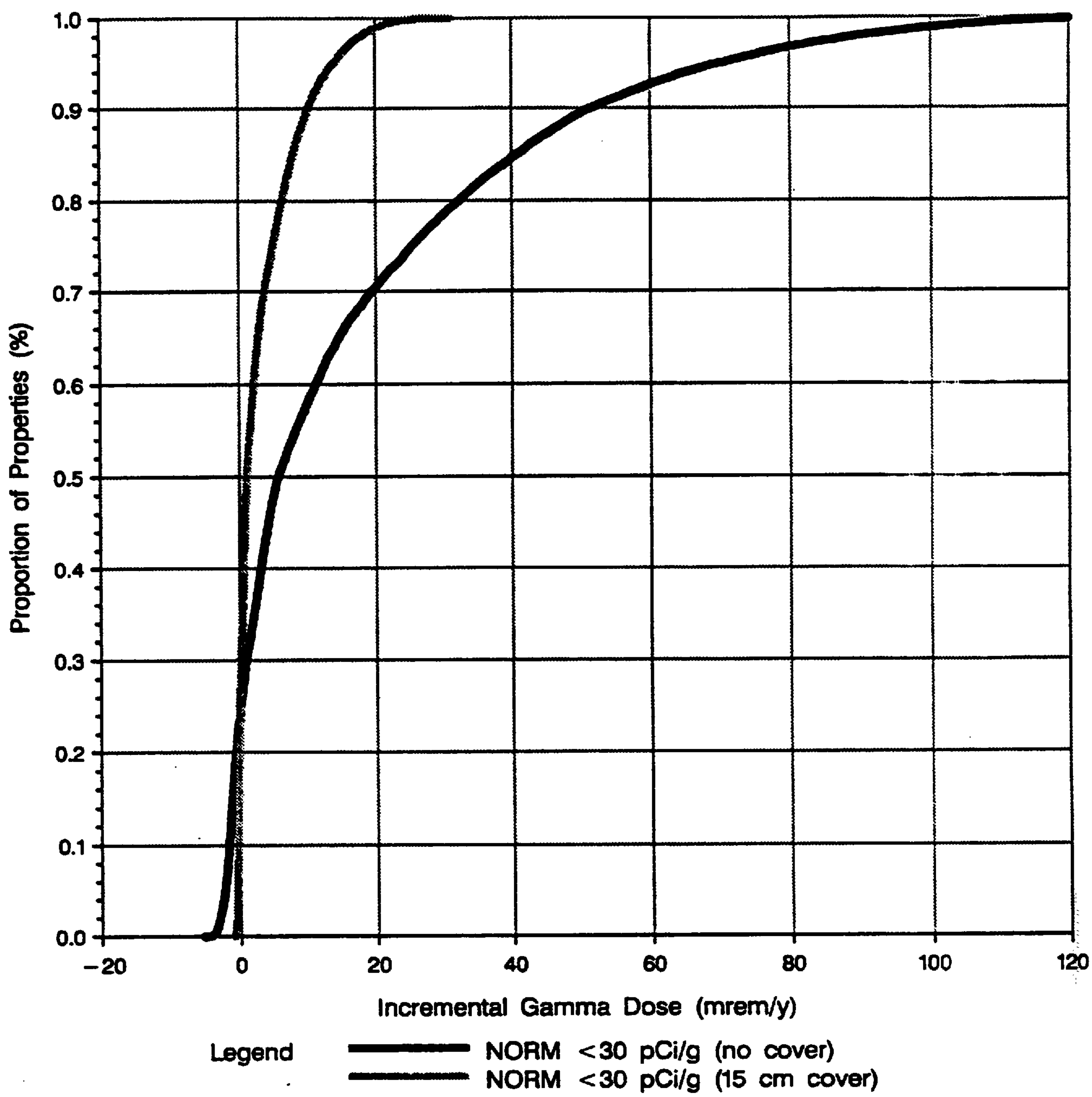
Figure 4.1 shows the distributions of predicted incremental gamma radiation doses for the remediated pit scenario where Ra-226 concentrations are distributed according to the truncated (<30 pCi/g) Otto data. Distributions are shown for scenarios where there is no cover material over the remediated site 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



d:\32105\progs\figures\f4gamplY.sas – 6 June 1997 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.

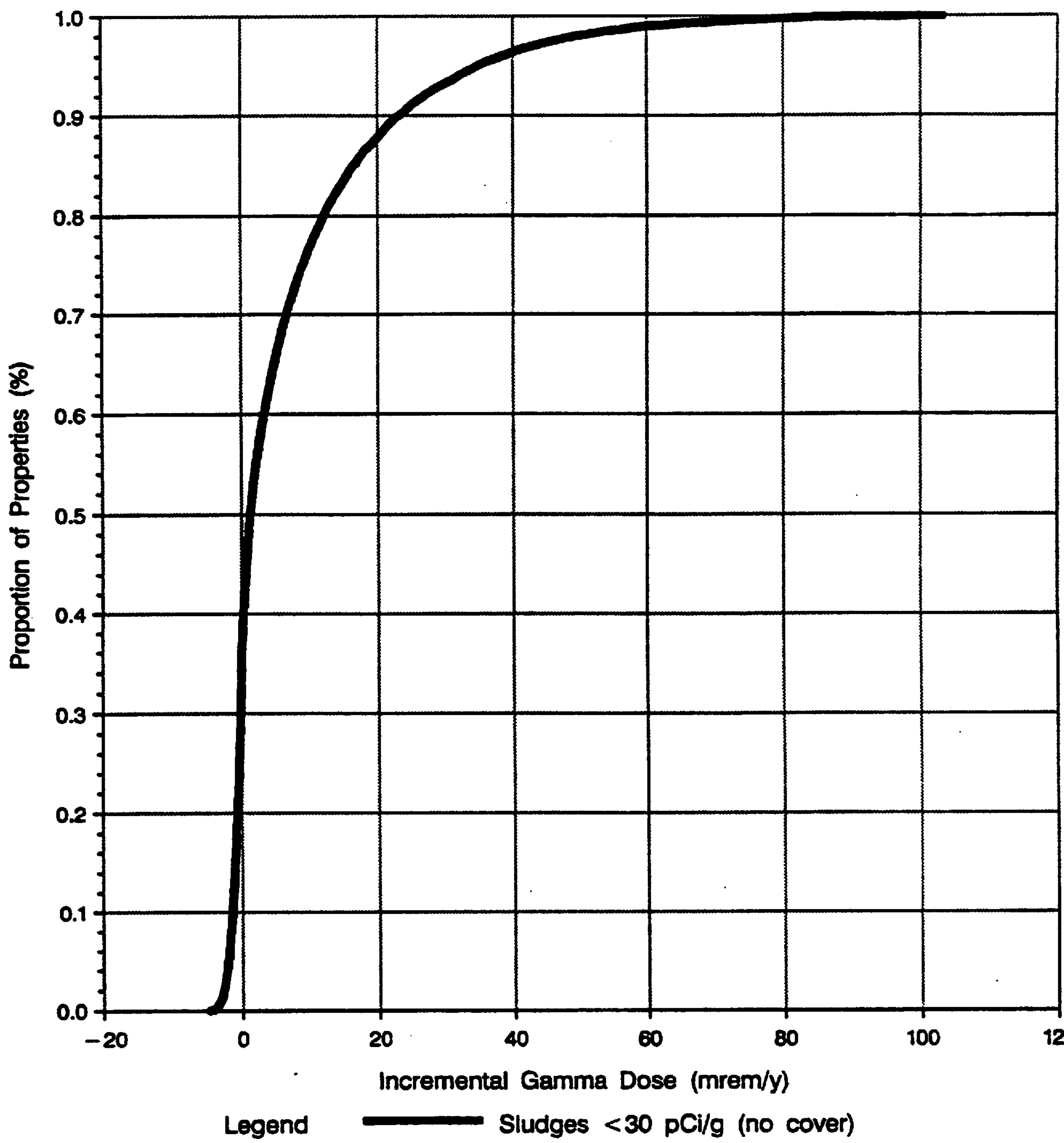
Table 4.2
SUMMARY OF PREDICTED INCREMENTAL GAMMA RADIATION DOSES (mrem/y) FOR NORM CONCENTRATION EQUAL TO 30 pCi/g

	Summary Statistics			
	Mean	Median	95th 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[a,b]				
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



d:\32105\progs\figures\f4gamfry.sas – 6 June 1997

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	95th 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	95th 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).

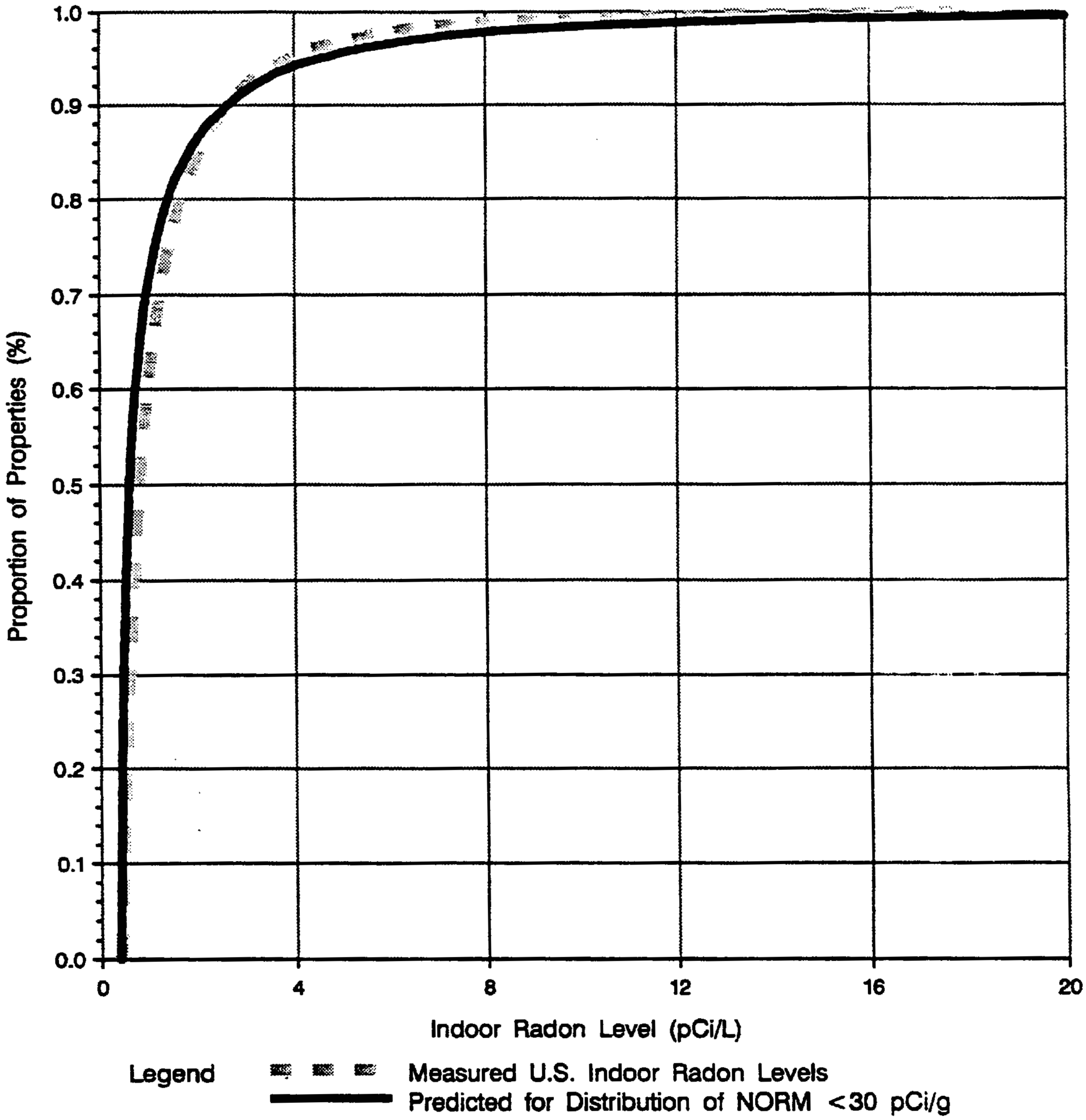
Summary statistics for the distribution of indoor radon concentrations predicted in homes built on remediated pits in which the Ra-226 concentration in NORM was uniformly 30 pCi/g throughout are provided in Table 4.4. The concentrations are higher than from natural background, and the indoor radon concentrations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

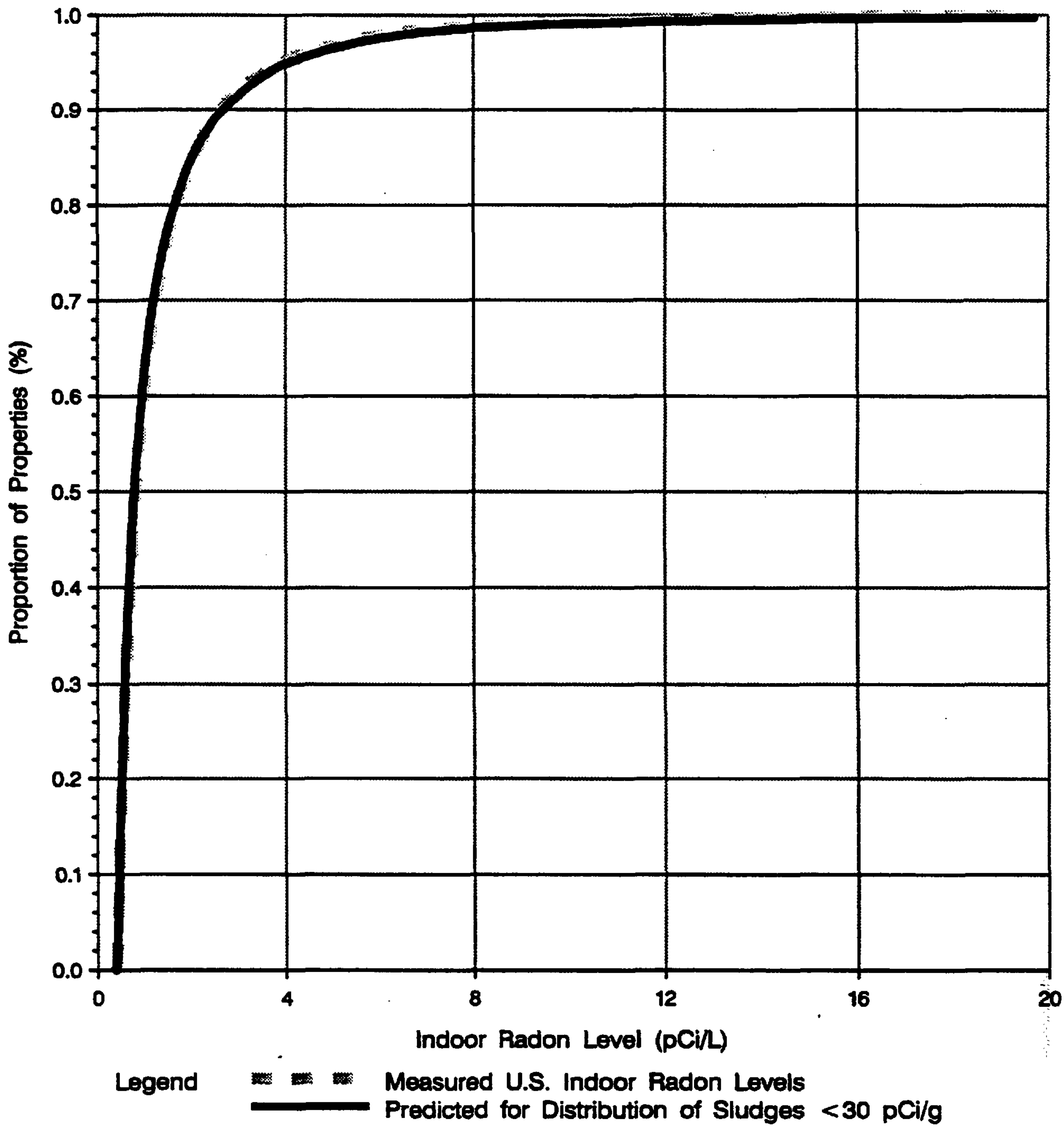
Distribution of Predicted Indoor Radon Levels (pCi/L) From Remediated Pit Scenario



d:\32105\progs\figures\fradpiY.sas – 6 June 1997

Figure 4.4

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



d:\32105\progs\figures\f4radfrY.sas – 9 June 1997 indistinguishable from natural background.

Summary statistics for the distribution of indoor radon concentrations predicted in homes built on remediated land farms in which Ra-226 concentration in NORM was uniformly 30 pCi/g throughout are shown in Table 4.4. The concentrations are higher than natural background, and the indoor radon concentrations in approximately 15% of the homes were predicted to exceed 4 pCi/L.

5.0 DISCUSSION

5.1 PREDICTED LEVELS

5.1.1 Comparison Of Predicted Exposures to Naturally Occurring Exposures

The predicted incremental gamma radiation doses were comparable to the calculated natural background dose of about 4 mrem/y from Ra-226. Therefore, gamma radiation doses from Ra-226 calculated for the oil field NORM exposure scenarios were generally greater than the calculated natural background doses from Ra-226. This arises because the NORM wastes typically had higher Ra-226 levels compared to natural background and the gamma radiation doses are a direct function of Ra-226 level.

Predicted indoor radon levels for the remediation scenarios were similar to, or in many cases lower than, the natural background levels even though Ra-226 levels in the waste are usually higher than levels in natural soils. This pattern arises because the higher Ra-226 concentrations in the waste were counteracted by the relatively low emanation fraction in oil field NORM compared to the emanation fraction in typical soils. Thus the radon flux from oil field NORM was only about 10% to 20% of the radon flux from natural soils with the same Ra-226 concentration.

Predicted doses and indoor radon levels were higher when all the NORM was modelled to have 30 pCi/g concentration.

5.1.2 Comparison to Regulatory Guidelines for Remediated Pit Scenarios

The distribution of predicted indoor radon levels for the distribution of Ra-226 concentrations in remediated pits was nearly indistinguishable from the distribution of indoor radon levels attributable to natural background. In both cases, the radon concentration in approximately 6% of the houses exceeded 4 pCi/L - the level at which EPA recommends that remedial action be taken. Gamma radiation doses were somewhat higher than background but the elevation was dependent on the amount of cover material. Regardless, the NRC limit of 100 mrem/y to members of the public near licensed facilities is rarely exceeded for the distribution of Ra-226 concentration in remediated pits.

5.1.3 Comparison to Guideline Values for the Land Farming Scenario

The distribution of indoor radon levels for the land farming scenario with the distribution of Ra-226 concentration is nearly indistinguishable from the distribution of background levels. Approximately the same percentage of homes had levels exceeding the EPA guideline of 4.0 pCi/L (remedial action recommended) for this scenario as in background homes. Gamma radiation doses were slightly higher than background but the predicted incremental doses were well below the 100 mrem/y guideline.

5.2 SENSITIVITY

Incremental gamma radiation doses were most sensitive to the Ra-226 concentration in the source layer and the amount of cover material. Variability in duration spent indoors and outdoors on the property were of less significance.

Predicted indoor radon levels were most sensitive to house-to-house variations in the relationship between radon flux from the soil and the indoor radon levels.

5.3 UNCERTAINTY

Two assumptions that were used in the analysis tend to overpredict the incremental gamma radiation doses and indoor radon levels. First, the NORM was assumed to cover the entire property. While this may have been reasonable for the land farming scenario, remediated pits may cover only a portion of the property due to their generally smaller size and, hence, the size of the source term may have been overestimated. Second, all radium in the wastes was assumed to have been Ra-226. This results in overprediction of doses from NORM, especially in recently deposited material which may contain substantial amounts of Ra-228 that decays relatively rapidly and, hence, represents less of a health risk.

Predicted indoor radon levels were highly dependent on the radon emanation fraction and limited information on this parameter was found in the literature. The range of emanation fractions for oil field NORM used in this study were from 0.02 to 0.06 which is about ten times lower than the value for natural soils and the typical value for uranium tailings. Radon diffusion coefficients in the NORM were assumed to be similar to the radon diffusion coefficient for soil but also little information was found on this parameter.

Substantial uncertainty existed in the distribution of Ra-226 activity in oil field NORM. Many direct measurements of Ra-226 have been collected and these measurements have demonstrated the high variability in concentrations with a few locations and types of NORM exhibiting levels exceeding 1,000 pCi/g while other sites have Ra-226 levels that may be lower than 1 pCi/g. Unfortunately, the distribution of, or even the average, Ra-226 level and NORM volumes in the U.S. can not be derived from these spot measurements. The Otto data provided the most comprehensive and consistent radiological characterization of oil field NORM.

The distribution of Ra-226 concentrations in sludges and scales was derived by EPA (1993) from surficial gamma radiation measurements collected from a survey that was not statistically designed for this purpose (Otto 1989). Assumptions were required regarding the relationship between the Ra-226 concentration, the volumes for various types of NORM and the overall representativeness of the data. A survey, using a standard statistical sampling design, would provide a better characterization of the distribution of Ra-226 levels in oil field NORM.

5.4 Comparison to Predicted Doses from Other Assessments

Other assessments of potential dose to users of remediated oil field sites have been carried out. Predicted doses vary over a wide range mainly because of differences among the assessments with respect to: 1) the radionuclide concentrations and characteristics in NORM material used as the source; 2) exposure scenarios (home on the remediated site with no cover, home on a site with NORM buried at depth, etc.). A brief summary of selected assessments is provided in Appendix E.

5.5 NORM Survey Procedures by Oil Companies

Many oil companies have prepared NORM guidance manuals (Grice 1997) within the framework of standard operating procedures which specify equipment and land survey protocols, soil sampling procedures, engineering and administrative controls, standard work practices, and other procedures to ensure that appropriate control of oil field NORM is maintained at all times. The survey procedures provide two levels of control: 1) the identification of NORM; and 2) the disposition of NORM in excess of state regulatory or internal corporate criteria. These controls are in place during normal operations, and during remedial activities in preparation for the release of sites for unrestricted access.

Surveying during operations ensures that NORM materials containing radium concentrations in excess of 30 pCi/g will be identified in processing equipment, at tank battery sites and in waste pits. This facilitates proper disposal of the affected material. During remediation, gamma surveys (and soil sampling if necessary) are carried out on all sites to be released to unrestricted access. For example, Texaco performs a survey by delineating the area into a grid with a spacing no greater than

10 meters. In areas with known NORM materials or areas exhibiting scattered elevated levels, the grid spacing does not exceed 3 meters. Measurements are taken at a distance of one meter above the ground. Background radiation levels are determined off-site, and all NORM materials which generate radiation readings in excess of twice the background level receive further investigation. Soil samples are taken in areas of elevated gamma readings and where the average reading of twice the background (or higher) encompasses an area equal to or greater than 100 m^2. Soil areas identified as being above 30 pCi/g, (some state rules require 5 pCi/g as the screening criterion), are removed for disposal at a licensed NORM disposal facility or are disposed of using a state approved disposal practice, such as underground injection.

Chevron also uses a combination of gamma surveys and measurements of activity concentrations in NORM to ensure that the Ra-226 concentration in materials left in remediated sites does not exceed 30 pCi/g. Their methods are specified in standard operating procedures and specify the placement of radiation meters within approximately one inch of NORM material. Any materials which generate radiation levels in excess of 50 μR/h are disposed to licensed NORM disposal facilities or by using another state approved disposal practice.

Through the use of gamma survey and soil sampling protocols specified in standard operating procedures for remediating sites containing NORM, oil companies ensure that the maximum concentration of Ra-226 remaining even in isolated small areas will not exceed 30 pCi/g, and that the average of the site will be significantly less than this value.

5.6 Limitation on Indoor Radon by NORM Survey Procedures

To determine the implications for indoor radon levels in houses built on remediated sites containing a small area of NORM at 30 pCi/g, a probabilistic assessment was carried out. First, the upper limit on the diameter of an area containing Ra-226 at 30 pCi/g that would meet the gamma survey criteria used by the oil companies (described in the previous section) was estimated using probabilistic methods. Second, the indoor radon level in homes built on the area determined to be the upper limit (in the first step) was predicted using the models and probabilistic methods described in previous sections.

Table 5.1 shows summary statistics on the probability that indoor radon levels exceed 4.0 pCi/L for various sizes of 30 pCi/g NORM covered by a 36 m^2 house. For the remediated pit scenario, an area of NORM ranging from 2 m by 2 m to 2.5 by 2.5 m was predicted to result in a 10% chance that the indoor radon level will exceed 4.0 pCi/L. The corresponding size for the land farming scenario is 4 m by 4 m.

Table 5.1

PERCENTAGE OF HOMES EXCEEDING
4.0 pCi/L AS A FUNCTION OF AREA AT 30 pCi/g

Side of a Square, m	Remediated Pit	Land Farming
0.0	4.7	4.7
0.5	5.1	4.8
1.0	5.5	5.0
1.5	7.1	5.2
2.0	9.0	5.6
2.5	11.8	6.4
3.0	15.7	7.3
4.0	22.7	9.5
5.0	30.4	12.2
6.0	37	14.9

Note: Home is 36 m^2 and completely covers the NORM.

The probability of detecting NORM at 30 pCi/g using the established field protocols depends on the area and the local background gamma exposure rate. NCRP (1987) reports that external gamma radiation exposure rates across the U.S. can be divided into three groups with mean values of 3, 6 and 12 μR/h corresponding to coastal, non-coastal and a few elevated regions. The upper limits of external gamma radiation in each of these areas corresponds to 5, 10 and 15 μR/h, respectively. The upper limits were used to evaluate the probability that indoor radon concentrations would exceed 4 pCi/L in a home constructed on a site containing a small area of NORM at 30 pCi/g Ra-226. Table 5.2 shows probabilities for a 3 m x 3 m grid and measurement of gamma exposure rates at a height of 1 m. The table provides a range of background exposure rates and detection probabilities for various sizes of NORM. Incremental exposure rates were calculated using MicroShield (Grove 1995) and included random locations of the NORM material. The table shows that areas of 30 pCi/g material between 2.5 and 4.0 m on a side can be detected with more than 95% probability depending on the local background exposure rate.

Table 5.2

PROBABILITY OF DETECTING A SINGLE HOT SPOT AT 30 pCi/g BY GAMMA MEASUREMENT ON A 3 m GRID SPACING USING A CRITERION OF TWO TIMES BACKGROUND

Side of a Square, m	Background μR/h			
	5	10	15	20
0.5	0.00	0.00	0.00	0.00
1.0	0.18	0.00	0.00	0.00
1.5	0.50	0.18	0.00	0.00
2.0	0.93	0.50	0.25	0.00
2.5	1.00	0.81	0.50	0.25
3.0	1.00	1.00	0.81	0.50
3.5	1.00	1.00	1.00	0.81
4.0	1.00	1.00	1.00	1.00
4.5	1.00	1.00	1.00	1.00
5.0	1.00	1.00	1.00	1.00

The most conservative assumption that houses completely cover the NORM area was used in the above calculations. Therefore, it was concluded that areas of NORM which could result in indoor radon levels exceeding 4 pCi/L in 10% of houses located directly over them can be detected with high probability using the established protocols. It is likely that some of the houses may be positioned so that only part, or none of the NORM is covered; therefore the actual percentage of homes exceeding 4.0 pCi/L will be lower than 10%.

5.7 Conclusions

Although the studies were not statistically designed for the purpose, the concentrations of Ra-226 in oil field NORM have been shown to be predominantly distributed at levels comparable to natural background in soil and relatively small quantities of oil field NORM contain Ra-226 up to 30 pCi/g and higher using method from Rogers et al. (1989) and data from Otto (1989). Experiments have also shown that radon emanation fractions from oil field NORM are significantly lower than from Ra-226 in normal soils.

In this report, it was demonstrated by screening analysis that external gamma doses and exposure to indoor radon are the major exposure pathways to residents on remediated oil field sites released to unrestricted public access.

Potential incremental doses from Ra-226 to residents and total indoor radon concentrations in houses built on remediated oil field sites were estimated by more detailed modelling. All NORM containing Ra-226 concentrations >30 pCi/g was excluded, and the distributions of Ra-226 concentrations below 30 pCi/g were set equal to the distributions developed using methods from Rogers et al. (1989) and data from Otto (1989). Model parameter values were assigned distributions representing natural uncertainty and variability, and the models were calculated probabilistically. The predicted incremental gamma dose rates from Ra-226 (95th percentile was approximately 70 mrem/y) were less than 100 mrem/y, the limit on doses to members of the public set by the NRC on emissions from licensed facilities. The total indoor radon concentrations in houses built on remediated sites were predicted to be almost indistinguishable from the corresponding concentrations attributable to natural background Ra-226 in soil. Total indoor radon concentrations were predicted to exceed 4.6 pCi/L in only 5% of the houses built on remediated sites compared to >3.9 pCi/L in 5% of the houses from natural background. These values are essentially comparable to the criterion of 4 pCi/L at which EPA recommends remedial action. However, an essential feature of the analyses described here was that the distribution of Ra-226 concentrations in oil field NORM was similar to that developed using methods by Rogers et al. (1989) and data from Otto (1989) except that Ra-226 concentrations above 30 pCi/g were excluded.

Finally, it was shown that external gamma and soil survey methodologies used by oil companies during remediation of oil field sites before release to unrestricted public access facilitate compliance with the gamma dose and radon standard described above.

REFERENCES AND BIBLIOGRAPHY

Alvarez, J.L., R. Gedes and J.R. Rice 1995. *Methods of estimating dose to individuals from NORM.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 1: Measurement and Survey. GRI-95/0474.

American Petroleum Institute 1996. Commission on NORM.

Ashland Exploration, Inc. 1994. *Technical support addendum to the Martha reclamation program.* December.

Ashland Exploration, Inc. 1993. *Martha reclamation program.* August.

Auxier & Associates, Inc. 1996. *Leachate analysis of Martha oil field wastes Martha, Kentucky.* Prepared for Ashland Exploration, Inc. Houston, Texas 77218-8330. Revised November 1996.

Auxier & Associates, Inc. 1994. *Basis for reclamation standards. An evaluation prepared in support of the Martha reclamation program.*

Baird, R.D., G.B. Merrell, R.B. Klein, V.C. Rogers and K.K. Nielson 1990. *Management and disposal alternatives for NORM wastes in oil production and gas plant equipment.* May. RAE-8837/2-2. Prepared for the American Petroleum Institute.

Bassignani, A., G. Di Luise, A. Fenzi and P.B. Finazzi 1991. *Radioactive scales in oil and gas production centers.* Presentation at the First International Conference on Health, Safety and Environment held in The Hague, The Netherlands, 10-14 November. SPE 23380.

Bernhardt, D.E., D.H. Owen and V.C. Rogers 1996. *Assessments of NORM in pipe from oil and gas production.* In: Proceedings of the 29th Midyear Topical Meeting: NORM/NARM: Regulation and Risk Assessment. 7-10 January, Scottsdale, Arizona.

Bernhardt, D.E., V.C. Rogers and K.K. Nielson (Rogers & Associates Engineering Corporation) 1996. *Radiological criteria for unrestricted use of sites containing NORM.* Presented at Forty-First Annual Meeting of the Health Physics Society at Seattle Washington, June.

Blanchard, W.P. Jr. 1996. *Surveys, sampling, and field analysis of radium-226 and radium-228 applications to soil remediation and containerized NORM waste.* Energy Week Conference & Exhibition: Incorporating ETCE, January 29-February 2, 1996, George R. Brown Convention Center, Houston, Texas. Houston, Tex: Pennwell Conferences & Exhibitions, 8 v. v.1, p. 135-139.

Blunt, D.L. and K.P. Smith 1995. *Dose assessment for management alternatives for NORM-contaminated equipment within the petroleum industry.* Presentation at Beneficial Reuse '95, Third Annual Conference on the Recycle and Reuse of Radioactive Scrap Metal. 31 July - 3 August, Knoxville, Tennessee.

California Department of Health Services and Department of Conservation 1996. *A study of NORM associated with oil and gas production operations in California.*

Carriker, A.W. and J.G. Albright 1995. *Transportation regulations for LSA NORM.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 2: Regulatory Issues and Activities. GRI-95/0474.

Conference of Radiation Control Program Directors (CRCPD) 1996. *Part N regulation and licensing of naturally occurring radioactive materials (NORM).* June. Draft.

Dehmel, J.C., I. Supernaw and T. McNulty 1996. *Recycling of NORM-contaminated equipment.* Presented at Forty-First Annual Meeting of the Health Physics Society at Seattle Washington, June.

Drummond, I., P. Boucher, B. Bradford, H. Evans, J. McLean, E. Reczek and H. Thunem 1990. *Occurrence of ^{222}Rn and progeny in natural gas processing plants in western Canada.* Health Physics, Vol. 59, No. 1, pp. 133-137.

Finklea, S.L., R.D. Paris, T.C. Cardwell, T.D. Donakowski, K.L. Weaver, E.A. Stetar, J. Eng. and D.E. Hendricks 1992. *Report of the E-4 committee on NORM contamination and decommissioning/decontamination. Report 3.*

Fisher, R.S. 1995. *Geologic, geochemical, and geographic controls on NORM in produced water from Texas oil, gas, and geothermal reservoirs.* Presentation at the SPE/EPA Exploration & Production Environmental Conference held in Houston, TX, USA, 27-29 March. SPE 29709.

Fisher, R.S. 1994. *Hydrogeochemical and production controls on NORM in oil and gas field operations.* DE-AC22-92MT92011.

Flynn, C.R., M.S. Blair and R.R. Highfill 1995. *High density radiological site characterization surveys for NORM sites.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 1: Measurement and Survey. GRI-95/0474.

Ford, W.G.F., L.L. Gadeken, T.J. Callahan and D. Jackson 1995. *Effective removal of NORM scale in the Rycroft field.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 3: NORM Management and Disposal. GRI-95/0474.

Fuller, K.C. 1995. *Technical profile of the Envirocare of Utah, Inc. NORM Disposal Operation.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 3: NORM Management and Disposal. GRI-95/0474.

Gallup, D.L. 1995. *A comparison of NORM scale dissolvers.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 4: NORM Scale Prediction and Control. GRI-95/0474.

Gerbino, A.J., S.J. Saunders and M. Rafal 1995. *Computer aided prediction of NORM associated scale.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 4: NORM Scale Prediction and Control. GRI-95/0474.

Gooden, D.S. 1996. *Naturally occurring radioactive materials in the petroleum and natural gas industries.* In: Proceedings of the 29th Midyear Topical Meeting: NORM/NARM: Regulation and Risk Assessment. 7-10 January, Scottsdale, Arizona.

Gray, P. 1990. *Radioactive materials could pose problems for the gas industry.* Oil & Gas Journal, 25 June, pg. 45.

Greer, C.R. and M.R. Landress 1995. *In-situ radium activity measurements for NORM assessment and remediation.* Presentation at the SPE/EPA Exploration & Production Environmental Conference held on Houston, TX, USA, 27-29 March. SPE 029714.

Grice, K. 1997. Personal communication to SENES Consultants Limited.

Grove Engineering, Inc. 1995. *MicroShield Version 4.2 user's manual.* 15215 Shady Grove Road, Rockville, Maryland 20850, USA.

Hamilton, L.D., A.F. Meinhold and J. Nagy 1991. *Produced water radionuclide hazard/risk assessment - Phase I.* API Publication number 4532. June. Prepared for the American Petroleum Institute.

Hartog, F.A., W.A.I. Knaepen and G. Jonkers 1995. *Radioactive lead: an underestimated NORM issue?* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 1: Measurement and Survey. GRI-95/0474.

Hebert, M.B., L.M. Scott and S.J. Zrake 1995. *A radiological characterization of remediated tank battery sites.* Health Physics, Vol. 68, No. 3, pp. 406-410. March.

Herrera, A.W. 1996. *Poster presentation for the society of environmental Toxicology and chemistry 15th annual meeting.*

Knaepen, W.A.I., W. Bergwerf, P.F.J. Lancée and G. Jonkers 1995. *Determination of naturally occurring radionuclides in samples from the gas and oil industry.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 1: Measurement and Survey. GRI-95/0474.

Kolb, W.A. and M. Wojcik 1985. *Enhanced radioactivity due to natural oil and gas production and related radiological problems.* The Science of the Total Environment, 45, pp. 77-84.

Landa, E.R. and D.F. Reid 1982. *Sorption of radium-226 from oil-production brine by sediments and soils.* Environ. Geol., 5, No. 1, pp. 1-8.

McArthur, A., S. Schroeder and W. Lemons 1995. *Evaluation of NORM site release criteria for unrestricted use.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 1: Measurement and Survey. GRI-95/0474.

McKenzie, M.J., S. He, C. Hinrichsen, J.E. Oddo, A.J. Gerbino, A.T. Kan and M.B. Tomson 1995. *Controlling barium sulfate scale deposition by inhibitor squeeze at the Guerra Well in South Texas: a case study.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 4: NORM Scale Prediction and Control. GRI-95/0474.

Meinhold, A.F., S. Holtzman, and M.P. DePhillips 1996. *Risk assessment for produced water discharges to open bays in Louisiana.* Department of Applied Science Brookhaven National Laboratory, Upton, New York. BNL-62239.

Meinhold, A.F., M.P. DePhillips and S. Holtzman 1996. *Final report: risk assessment for produced water discharges to Louisiana open bays.* 22 March. BNL-62975. Prepared for U.S. DOE.

Meinhold, A.F., S. Holtzman and L.D. Hamilton 1995. *Health risk assessment for radium discharged offshore in produced water.* Presentation At the SPE/EPA Exploration & Production Environmental Conference held in Houston, TX, USA, 27-29 March. SPE 29728.

Michigan Geological Survey Division 1991. *Naturally occurring radioactive material (NORM) briefing paper.*

Michigan Department of Natural Resources 1992. *The need and desirability to issue an order establishing particular requirements for plugging of wells where naturally occurring radioactive material (NORM) may be present.*

Michigan Department of Natural Resources 1992. *Utilization of survey instruments relating to naturally occurring radioactive materials (NORM).*

Michigan Department of Natural Resources and Michigan Department of Public Health 1991. *Naturally occurring radioactive material (NORM) at Michigan oil and gas field sites: preliminary survey results.*

Michigan Department of Public Health 1993. *NORM Guide N.2. Guidance for conducting surveys and sampling for naturally-occurring radioactive material (NORM) to allow release for unrestricted use.*

Michigan Department of Public Health 1992. *NORM Guide N.1. Guidance for conducting screening surveys for naturally-occurring radioactive material (NORM).*

Michigan Department of Public Health 1992. *Interim standards for the control of NORM associated with the oil and gas industry in Michigan.*

Miller, H.T., E.D. Bruce and L.M. Cook 1991. *Environmental, health, and safety decision making for naturally occurring radioactive materials in producing operations using pathway exposure analysis.* Presentation at the First International Conference on Health, Safety and Environment held in The Hague, The Netherlands, 10-14 November.

Miller, H.T., E.D. Bruce and L.M. Cook 1991. *The management of occupational and environmental exposure to naturally occurring radioactive materials (NORM).* Presentation at the 66th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers held in Dallas, TX, 6-9 October.

National Council on Radiation Protection and Measurements (NCRP) 1993. *Limitation of exposure to ionizing radiation.* NCRP Report No. 116.

National Council on Radiation Protection and Measurements (NCRP) 1987. *Exposure of the population in the United States and Canada from natural background radiation.* NCRP Report No. 94.

Nielson, K.K., V.C. Rogers and C.S. Pollard 1988. *BRC disposal alternatives for NORM waste in Texas.*

Oddo, J.E., X. Zhou, J.P. Gamez, S. He and M.B. Tomson 1995. *A laboratory and field study of the mitigation of NORM scale in the gulf coast region of the United States.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 4: NORM Scale Prediction and Control. GRI-95/0474.

Orum, J.D., D. Baudoin and O. Briscoe 1995. *Remediation of normally occurring radioactive material (N.O.R.M.): a field trial.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 4: NORM Scale Prediction and Control. GRI-95/0474.

Otto, G.H. 1989. *The incidence of naturally-occurring radioactive material (NORM) in oil and gas production and processing equipment in the United States.* Proceedings of the Business and Economic Statistics Section of the American Statistical Association.

Otto, G.H. 1989. *A national survey on naturally occurring radioactive materials (NORM) in petroleum producing and as processing facilities.* Prepared for the American Petroleum Institute.

Raabe, O.G. 1996. *Studies of the solubility of naturally-occurring radionuclides in petroleum pipe scale* In: Proceedings of the 29th Midyear Topical Meeting: NORM/NARM: Regulation and Risk Assessment. 7-10 January, Scottsdale, Arizona.

Rajaretnam, G., C. Blasio, K. Lovins and H.B. Spitz 1996. *Effect of leachability on environmental risk assessment for naturally occurring radioactive materials (NORM) in petroleum oil fields* Presented at Forty-First Annual Meeting of the Health Physics Society at Seattle Washington. June.

Rittiger, C.L. and J.G. Yusko 1996. *An overview of NORM data collected in Pennsylvania specific to oil and gas production.* In: Proceedings of the 29th Midyear Topical Meeting: NORM/NARM: Regulation and Risk Assessment. 7-10 January, Scottsdale, Arizona.

Rogers, V. and D.E. Bernhardt 1994. *Radiation criteria for unrestricted release of oil production sites containing NORM in the Martha oil field.* Prepared for Kentucky Department for Health Services.

Rogers & Associates Engineering Corporation 1990. *Management and disposal alternatives for NORM wastes in oil production and gas plant equipment.* RAE-8837/2-2. Prepared for the American Petroleum Institute.

Rogers, V.C., K.K. Nielson and M.K. Bollenbacher 1989. *Methods for measuring naturally-occurring radioactive materials in petroleum production equipment.* December. RAE-8837/1-1. Prepared for the American Petroleum Institute.

Rood, A.S. and D.T. Kendrick 1996. *Measurements of ^{222}Rn flux, ^{222}Rn emanation, and ^{226}Ra concentration from injection well pipe scale.* In: Proceedings of the 29th Midyear Topical Meeting: NORM/NARM: Regulation and Risk Assessment. 7-10 January, Scottsdale, Arizona.

Russo, W. 1993. *A preliminary risk assessment of management and disposal options for oil field wastes and piping contaminated with NORM in the State of Louisiana.*

SC&A, Inc. and Rogers & Associates Engineering Corporation 1993. *Diffuse NORM wastes - waste characterization and preliminary risk assessment.* RAE-9232/1-2. Prepared for U.S. EPA.

SC&A, Inc., Rogers & Associates Engineering Corp and R.F. Weston, Inc. 1991. *Draft - diffuse NORM wastes - waste characterization and risk assessment.* Prepared for U.S. EPA.

Scott, L.M., D.L. Van Gent and M.B. Hebert 1994. *Preliminary assessment of naturally occurring radioactive material at selected production sites Part 1.* Prepared for the American Petroleum Institute.

Scott, L.M. and M.B. Hebert 1993. *Radiological characterization of the Martha, Kentucky, remediated tank battery sites.* July.

SENES Consultants Limited (SENES) 1994. *Review of EPA's final version - diffuse NORM wastes - waste characterization and preliminary risk assessment April 1993.* Prepared for American Mining Congress, Washington, D.C. February.

SENES Consultants Limited (SENES) 1993. Critical review of "*A preliminary risk assessment of management and disposal options for oil field wastes and piping contaminated with NORM in the State of Louisiana - Peer Review Draft.*" Prepared for the American Petroleum Institute. (SENES #31382.)

Shell Development Co. 1993. *Comments on "A preliminary risk assessment of management and disposal options for oil field waste and piping contaminated with NORM in the State of Louisiana".* 21 pgs.

Shuler, P.J., D.A. Baudoin and D.J. Weintritt 1995. *Control of NORM at Eugene Island 341-A.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 4: NORM Scale Prediction and Control. GRI-95/0474.

Smith, G.E., T. Fitzgibbon and S. Karp 1995. *Economic impact of potential NORM regulations.* Presentation at the SPE/EPA Exploration & Production Environmental Conference held in Houston, TX, USA, 27-29 March. SPE 29708.

Smith, K.P., D.L. Blunt, G.P. Williams and C.L. Tebes 1995. *Radiological dose assessment related to management of naturally occurring radioactive materials generated by the petroleum industry.* Prepared for presentation at the SPE/EPA Exploration & Production Environmental Conference held in Houston, TX, 27-29 March.

Smith, K.P. and D.L. Blunt 1995. *Scrap metal management issues associated with naturally occurring radioactive material.* Presented at Beneficial Reuse '95, Knoxville, Tennessee, 31 July-3 August.

Smith, K.P. 1992. *An overview of naturally occurring radioactive materials (NORM) in the petroleum industry.* December. ANL/EAIS-7, DE93 011795.

Smith, A.L. 1987. *Radioactive-scale formation.* Journal of Petroleum Technology, pp. 697. June.

Snavely Jr., E.S. 1989. *Radionuclides in produced water. A literature review.* Prepared for the API Guidelines Steering Committee, 16 August.

Spitz, H., K. Lovins and C. Becker 1997. *Evaluation of residual soil contamination from commercial oil well drilling activities and its impact on the naturally occurring background radiation environment.* Journal of Soil Contamination. January.

Testa, C., D. Desideri, M.A. Meli, C. Roselli, A. Bassignani, G. Colombo and R.F. Fantoni 1994. *Radiation protection and radioactive scales in oil and gas production.* Health Physics, Vol. 67, No. 1, pp. 34-38.

Testa, C., D. Desideri, M.A. Meli, C. Roselli, A. Bassignani and P.B. Finazzi 1992. *The determination of radium, uranium and thorium in low specific activity scales and in waters of some oil and gas production plants.* Presented at Eighth International Congress of the International Radiation Protection Association, Montreal, Canada, 17-22 May.

United States Department of Energy (U.S. DOE) 1993. Comments on "*A preliminary risk assessment of management and disposal options for oil field wastes and piping contaminated with NORM in the State of Louisiana - peer review draft.*"

United States Environmental Protection Agency (U.S. EPA) Science Advisory Board (SAB) 1994. *Review of the office of radiation and indoor air draft document on diffuse naturally-occurring radioactive material (NORM): Waste Characterization and Preliminary Risk Assessment.* EPA-SAB-RAC-94-013. May.

United States Environmental Protection Agency (U.S. EPA) 1993. *A preliminary risk assessment of management and disposal options for oil field wastes and piping contaminated with NORM in the State of Louisiana - peer review draft.*"

United States Environmental Protection Agency (U.S. EPA) 1989. *Exposure factors handbook.*

United States Nuclear Regulatory Commission (U.S. NRC) 1992. *Residual radioactive contamination from decommissioning. Technical basis for translating contamination levels to annual total effective dose equivalent. Final Report.* NUREG/CR-5512, PNL-7994, Volume 1.

United States Nuclear Regulatory Commission (U.S. NRC) 1982. *Calculational models for estimating radiation doses to man from airborne materials resulting from uranium milling operations.* Reg. Guide 3.51.

Western Canadian NORM Committee 1995. *Guidelines for the handling of naturally occurring radioactive materials (NORM) in western Canada.* August.

Williams, T.M. 1995. *Detecting NORM contaminated tubing during pulling operations.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 1: Measurement and Survey. GRI-95/0474.

Williams, G.P., K.P. Smith, D.L. Blunt and C.L. Tebes 1995. *Modeling of NORM injection in a layered geologic system.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 3: NORM Management and Disposal. GRI-95/0474.

Williams, G.P., K.P. Smith, D.L. Blunt and C.L. Tebes 1995. *Modeling and dose assessment of underground injection of naturally occurring radioactive materials (NORM) scenarios.* Presented at The Second International Petroleum Environmental Conference: Environmental Issues and Solutions in Exploration, Production and Refining. SERA/University of Tulsa, New Orleans, LA, September.

Wilson, A.J. and L.M. Scott 1992. *Characterization of radioactive petroleum piping scale with an evaluation of subsequent land contamination.* Health Physics, Vol. 63, No. 6, pp. 681-685.

Woods, S., S. Abernathy and P. Johnson 1995. *Development of a comprehensive NORM program.* In: Proceedings 1995 American Petroleum Institute and Gas Research Institute Naturally Occurring Radioactive Material Conference. Session 2: Regulatory Issues and Activities. GRI-95/0474.

APPENDIX A

CHARACTERISTICS OF OIL-FIELD NORM AND MANAGEMENT PRACTICES

APPENDIX A: CHARACTERISTICS OF OIL FIELD NORM AND MANAGEMENT PRACTICES

This Appendix briefly introduces oil field naturally occurring radioactive materials (NORM) and subsequently focuses on the radiological characterization of three categories of oil field NORM wastes, namely: scales, sludges and produced waters. In particular, the radiological characteristics of oil field NORM-bearing scales, sludges and produced water were estimated on the basis of the most relevant available information from the literature, taking into account, to the extent possible, the large uncertainties associated with these characteristics. In this regard, it is important to emphasize that this assessment was limited by the lack of representativeness of the existing information for characterizing U.S. wide oil field NORM wastes, which in turn reflects the wide geographical distribution of NORM and the wide variation of NORM concentrations at oil production fields.

The disposal of mixed NORM wastes in oil field waste sites can lead to "bulk" radiological characteristics that differ from those of each individual NORM waste. This is addressed in Chapter 4.0 for the three categories of oil field waste disposal sites considered in this assessment, namely: waste pits, tank batteries, and land farming areas.

A.1 INTRODUCTION TO OIL FIELD NORM

Connate water from underground geological formations contains various levels of NORM from the natural uranium (^{238}U) and natural thorium (^{232}Th) series. During oil production, mainly the radium (^{226}Ra, ^{228}Ra and ^{224}Ra) and radon isotopes of the natural uranium and thorium series dissolve in formation water and are transported to the surface with the produced water waste stream[(1)]. This is because radium isotopes are slightly soluble whereas other NORM isotopes are relatively insoluble. (Smith 1992 p.12, Snavely 1989 p.7)[(2)]. Snavely (1989 p.7 and 13) also indicates that radium isotopes alone comprise probably over 90% of the total radioactivity of produced water when radon (^{222}Rn, a radioactive gas) is excluded, and about 60% of the total radioactivity when radon is included. However, in some cases radon concentrations in water greatly exceed radium concentrations.

Over the long term, the presence of long-lived ^{226}Ra with a 1,602 years half-life is particularly important, whereas ^{228}Ra with a 5.8 year half-life is of less concern. In the absence of ^{232}Th (as for

(1) ^{226}Ra is part of the ^{238}U series, and ^{228}Ra and ^{224}Ra are part of the ^{232}Th series.

(2) It is noteworthy that enhanced levels of ^{238}U and ^{232}Th and their progeny up to the radium isotopes have not been detected in oil field NORM (Smith 1992 p.12, Knaepen et al. 1995 p.5, and Hartog et al. 1995 p.59). Furthermore, Snavely (1989 p.7) reports that only trace amounts of non-radium NORM from underground geological formations are found in produced water.

oil field NORM), ^{228}Ra controls the production of ^{224}Ra with a 3.6 day half-life.

When dissolved radium is brought to the surface, it may either remain in solution in produced water, or, under proper conditions, coprecipitate with barium, strontium, or calcium to form either hard sulfate scales or more granular silicate and carbonate sludges. (Coprecipitation can be initiated by chemical changes and reduced pressure and temperature as the fluids are separated and processed). Radium dissolution and precipitation depend on the formation water salinity, pH, temperature, and pressure (Smith 1992 p.2).

NORM scale deposits are found in all types of water handling equipment: e.g. piping, filters, and the components of brine disposal/injection wells. NORM sludge accumulates inside piping, separators, heater/treaters, storage tanks, and other equipment used to handle produced water (Smith 1992 p.2).

Based on a number of NORM characterization surveys, radium concentrations tend to be highest closest to the well head and in more saline waters, and NORM tends to be more prevalent at older production wells because water production usually increases with the age of the well (Smith 1992 p.2).

Geographical areas where the highest external gamma exposure levels from NORM-contaminated oil production equipment were reported in the most comprehensive survey conducted to date in the United States are: the Gulf Coast region from Florida to Texas (including Alabama, Mississippi, and Alabama), northeastern Texas, southeastern Illinois, and southern Kansas. However, oil production fields with above-background exposure levels were found in each of the 20 States surveyed (Otto 1989 p.1 and 15). A more recent survey also reported high NORM concentrations in Michigan (Smith 1992 p.2).

Quantitative estimates of the radiological characteristics of oil field NORM wastes (i.e. scale, sludge and produced water) are discussed in the remainder of this chapter.

A.2 PRODUCED WATER

One of the most comprehensive information sources for NORM in oil field produced water is the Snavely (1989) report. Unless otherwise noted, the data presented below were derived from that report.

A.2.1 Concentration

Selected NORM concentrations in produced water for various U.S. regions summarized by Snavely (p.7, 29-30, Appendix 1: p.79) are listed in the following table:

Location	^{226}Ra (pCi/L)	No. of Wells	^{228}Ra (pCi/L)	No. of Wells	% of Wells Over 50 pCi/L
Oklahoma	10 to 1620	10	75 to 240	4	50
Texas Panhandle	3 to 1560	75	-	-	65
Gulf Coast:					
Oil wells	1.3 to 437	10	204 to 575	6	70
gas wells	0.1 to 1580	18	19 to 1507	14	78
Coastal La	0 to 930	405	0 to 928	405	-
Offshore La*	4 to 584	42	18 to 568	42	-

* Data from Hamilton et al. (1991 p.18).

On this basis, produced water contained 0.1 to 1620 pCi/L of ^{226}Ra and 19 to 1507 pCi/L of ^{228}Ra. Furthermore, 50 to 78% of oil and gas wells exceeded 50 pCi/L. Data for Gulf Coast gas wells also indicated an upper value for total radium (^{226}Ra and ^{228}Ra) of 2,801 pCi/L (Snavely p.7,29, Appendix 1: p.79). However, Smith (1992 p.2) reported that "a recent NORM survey conducted in Michigan indicates that NORM concentrations may be much higher than these reported ranges suggest". Radium concentrations up to 29,000 pCi/L were measured in this survey of produced water. However, such high concentrations were not reported to be a common occurrence.

Snavely's (Appendix 1: p.54) more detailed information on the distribution of ^{226}Ra in brines from 75 Panhandle gas wells (Texas) that ranged from 3 to 1560 pCi/L (second row of the data in the previous table) was:

^{226}Ra (pCi/L)	No. of Wells
less than 10	7
10 to 50	19
50 to 100	9
100 to 200	22
200 to 400	8
400 to 600	5
more than 600	5

The following statistics were estimated from this distribution when mid-values were assumed for each range: a mean of 199 pCi/L ± 62 pCi/L (twice the standard error on the mean i.e. at a 95% confidence level), individual readings ranged from 3 to 1560 pCi/L, 46.7% of the individual readings (i.e. 35/75) were below 100 pCi/L, and the distribution standard deviation was 269 pCi/L.

The U.S. EPA (1993 p.3-21) reported for filtered and unfiltered produced water a range of 16 to 195 pCi/L for ^{226}Ra and a range of 170 to 570 pCi/L for ^{228}Ra.

In comparison with the above radium concentrations for produced water, Snavely (p.21) reported 0 to 81 pCi/L of ^{226}Ra and 0.3 to 32 pCi/L of ^{228}Ra for potable ground water.

- $^{226}Ra/^{228}Ra$ Ratio

A range of $^{226}Ra/^{228}Ra$ ratios from about 0.4 to 1.8 was reported by Snavely (p.31, Appendix 1: p.70-71) based on measurements made in brines at 41 Gulf Coast wells. He also reported (p. 31) that there was no consistent relationship between the levels of ^{226}Ra and ^{228}Ra in produced waters since it depends on the ratio of $^{232}Th/^{238}U$ in the source rock (or underground geological formation).

Shell (1993, Attachment 2, p.2) indicated that "freshly" produced scale tends to have a small $^{226}Ra/^{228}Ra$ ratio, whereas scale that has remained in flow lines or vessels for 10-20 years (a common situation) has a high ratio. Reference made by Shell (1993, Attachment 2, p.2) to Louisiana data on radium in produced water discharges supported a ratio equal to or less than one.

In summary, average concentrations of ^{226}Ra in produced water of 199 ± 62 pCi/L with a $^{226}Ra/^{228}Ra$ ratios ranging from 0.4 to 1.8 were suggested on the basis of the above information.

A.2.2 Distribution Coefficient (K_D)

Based on Snavely (p.49), radium in the environment behaves much like the other alkaline earth elements barium, strontium and calcium. These elements form insoluble sulfates, are strongly absorbed by clays, and tend to concentrate in hard tissues (bone) when metabolized. In discharges to streams, radium partitions to sediments but depends on ionic strength of the water and nature of the sediments. K_Ds for sediment/water interactions with radium range from less than 10 to over 1,500 L/kg. Fine clays, have very high absorption capacities for radium. Very little radium may be absorbed by sediments if waters are saline and sediments are mostly sand.

Humus in soil is also reported (p.49) to have a strong affinity for radium; humus in peat almost completely immobilizes radium from migration. K_Ds range from 1,500 to 2,500 L/kg for peat and from 150 to 200 L/kg for sand.

A.2.3 Leaching

Based on Snavely (p.49), the penetration rate of radium through sediments, below the top 10 cm where bioturbation takes place, is normally controlled by a Fick's diffusion coefficient of about 10^{-8} cm^2/s. When fresh water is the infiltrating medium, about 1,000 years are required for 10% of the surface concentration of radium to diffuse one foot. Similarly, a 10% concentration front would require 2,740 years for radium to diffuse to a depth of 60 cm (p.57). Other references mentioned in the report (p.57-58) indicate the Fick's diffusion coefficient to be 5.8×10^{-6} to 1.1×10^{-8} cm^2/s and that 0.1% of radium would be leached from initial concentrations of 1,500 to 5,000 pCi/g over a 5 year period. The report (p.58 and Appendix 2:p.45-47) also refers to a site in Russia where radium from oil field produced water at 8,000 pCi/L discharged for 30 years has penetrated to only a 30 cm depth in soil. This site was studied 20 years after the discharge ceased and the surface was found to contain about 2,000 pCi/g of ^{226}Ra.

Snavely concluding comments (p.8) about the leaching potential of radium state that "*Radium-containing produced waters discharged at the surface are not a threat to contaminate potable aquifers with radium. The infiltration rate of radium through soils and sediments is only about 1 ft per thousand years. Radium is not mobile in potable water aquifers because of the high absorption capacity of rock for radium in fresh waters*".

A.2.4 Sediment Absorption of ^{226}Ra from Produced Water

Snavely (p.51-52) reported the results of an experiment where dried sediment samples comprised of silt, sand, and clay were stirred with fresh aliquots of produced water containing 90,000 mg/L of total dissolved solid (TDS) and 180 pCi/L of ^{226}Ra. Sediment samples were found to absorb a total of 1.35 pCi/g. This result would correspond to an absorption of 7.5 pCi/g in sediments for water containing 1,000 pCi/L with the same TDS level (90,000 mg/L). This calculation assumes that no precipitates are present in the water. In the presence of precipitates a portion of the radium would be removed from water. Mineral solids carried from the reservoir rock would contain less radium than precipitates with clay absorbing the most and sand absorbing the least. The salinity, or TDS, of produced water can be from brackish (5,000 mg/L) to saturated (300,000 mg/L) (p.11).

- Distribution of ^{226}Ra in Crude Oil

Using the above result and assuming the highest ^{226}Ra found in crude oil of 0.034 pCi/g, 25 ppm of suspended solids and 25 ppm of suspended oil; the report (p.51-53) indicates that the radium distribution in crude oil is 99.98, 0.001 and 0.02% for the water, oil and solid phases, respectively.

A.3 PIPE SCALE

A.3.1 Concentration

In general, radium concentration in most scale ranges from background levels to several thousand pCi/g (Smith 1992 p.14, RAE 1990 p.2-2).

The two following NORM scale-related characterization studies are amongst the most relevant information sources from the literature:

> Wilson and Scott (1992 p.681-685) - Characterization of NORM piping scale at a retired petroleum pipe-reaming field in southern Louisiana. The test field area was 15.2 m x 15.2 m where the majority of the scale was discarded.
>
> Rood and Kendrik (1996 p.139-144) - The analysis of 20 scale-bearing pipes.

Wilson and Scott (1992) reported ^{226}Ra concentrations ranged from 143.1 to 1,681 pCi/g in the upper 7.6 cm layer of soil, and from 6.8 to 1,675 pCi/g in the next 5 cm layer. Rood and

Kendrik (1996) reported ^{226}Ra concentrations ranged from 400 to 2,760 pCi/g with a mean of 1,670 pCi/g and standard deviation of 870 pCi/g. The samples were supplied by oil companies as examples of NORM scale and were not intended to represent the distribution of radioactivity concentrations over all oil field scales.

- ^{226}Ra/^{228}Ra Ratio

With respect to the ^{226}Ra/^{228}Ra ratio of scale, many authors have reported a value of about 3 (e.g. Nielson et al. 1988 p.383, U.S. EPA 1993 p.3-1, RAE 1990 p.3). In comparison to the ratio of 0.4 to 1.8 given earlier for produced water, the higher ratio in scale is likely attributable to lower levels of ^{228}Ra in aged scale. However, "fresh" scale should have a similar ratio to that in produced water.

In summary, the above distribution of ^{226}Ra in scale with ^{226}Ra/^{228}Ra ratios ranging from 0.4 to 3 were recommended. This range of ratios should account for the presence of both fresh and aged scale.

A.3.2 Gamma Exposure Rate

The Wilson and Scott (1992) study on pipe scale NORM at a retired petroleum pipe-reaming field presented in Section A3.1.1 also provided information on gamma exposure rates from the test field where pipe scales had been disposed. Measurements taken over a 7.3 cm thick surface at 0.3 m above ground were plotted on a graph and had a slope of about 1.07 µR/h per pCi/g of ^{226}Ra[(3)]. The report indicated that these measurements were about half of those predicted by a simplified formula (with a 2.4 µR/h per pCi/g of ^{226}Ra slope) at 1 m above ground for an infinite slab 45 cm thick. Non-uniform radium concentrations and non-infinite source thickness are mentioned as an explanation for the difference observed. It should be noted that the influence of ^{228}Ra levels on these results was not discussed. Overall, gamma measurements at the site averaged at 250 µR/h with a peak at 1,800 µR/h and a background at 9 µR/h.

For comparison, the U.S. NCRP (1991 p.69) recommends 1.83 µR/h per pCi/g of ^{238}U and 2.48 µR/h per pCi/g of ^{232}Th for estimating the gamma exposure rate at 1 m above a semi-infinite source with uniform concentrations in radioactive equilibrium. This is comparable with the Scott and Wilson (1992) results since most gamma emitters are associated with ^{226}Ra and ^{228}Ra and their progeny.

---

(3) A correction was made to the graph and published in the official journal of the Health Physics Society (HPS April 1993: Vol.64, No.4, p.443). Conversion factor from nCi/kg/h to µR/h = 3.85. Conversion factor from pCi/kg/s to µR/h = 13.95.

A.3.3 Radon Emanation Fraction

The most relevant information on radon emanation fractions from NORM scale were reported by Rood and Kendrik (1996). For the 20 samples of scale analyzed, the following statistics were estimated: a mean of 0.04 ± 0.005 (twice the standard error on the mean i.e. at a 95% confidence level), individual readings ranged from 0.02 to 0.06, and the distribution standard deviation was 0.01. On the other hand, Scott and Wilson (1992) reported a radon emanation fraction of 0.0067 for one sample of scale. The scale matrix in which radium is trapped explained the low fractions obtained in comparison to those for soil (i.e. an emanation fraction of about 0.2).

A.3.4 Radon Flux

No specific information was found on radon exhalation rate (radioactivity emission rate per unit area per unit time) from pipe scale alone. Only radon release rates from the extremities of scale-bearing pipe sections were reported. However, these data provided only limited information for assessing dose associated with the disposal of pipe scale.

A.3.5 Leaching

Specific information on leach tests performed on three scale samples were reported by Wilson and Scott (1992). The results of this study are reproduced below. SENES derived the equivalent "k_d" values on the basis that 1,600 mL solution was used to perform the leach tests.

Concentration (pCi/g)	Ra-226 in leachate (pCi)	Ra-226 leached (%)	equivalent k_d (cm^3/g)
24.01	0.33	0.01	72,758
78.8	0.00	0.00	∞
62.23	0.21	0.005	296,333

These results appeared consistent with the distribution coefficient for the solid/aqueous phases of radium in scales of 250,000 cm^3/g reported in RAE (1990 p.2-2).

Based on these results, the report concluded that "*radium sulfate, like barium sulfate is difficult to dissolve. Even in more acidic environments, this scale will not dissociate.*"

The potential for leaching radium from scale is limited by the potential for dissolving the barium sulfate matrix into which radium is incorporated. Shell (1993, Attachment 3, p.6) reported a distribution coefficient for barium sulfate of about 390,000 cm^3/g. A simple approach for estimating the leach rate for scale using the distribution coefficient for barium sulfate was given in RAE (1990 p.4-9).

A.3.6 Other Characteristics

RAE (1990 p.2-2) reported bulk dry density for very hard scale between 2 to 3 g/cm^3. Upon removal and disposal, a nominal bulk dry density of about 1.6 g/cm^3 is reported due to the porosity of 0.45 between the broken pieces of scale. Shell (1993, Attachment 3, p.6 and 10) indicated that a much lower porosity value should be used for loose scale: not much higher than 0.26.

A.4 SLUDGE

A.4.1 Concentration

In general, radium concentrations in sludge in production equipment ranged from background levels to several hundred picocuries per gram (pCi/g), although recent Michigan measurements include one sludge sample with 6,600 pCi/g (Smith 1992 p.14, RAE 1990 p.2-2).

- $^{226}Ra/^{228}Ra$ Ratio

As for scale, a range of 0.4 to 3 was recommended for the $^{226}Ra/^{228}Ra$ ratio of NORM sludge.

A.4.2 Gamma Exposure Rate

No specific information was found on gamma exposure rate from sludge alone.

A.4.3 Radon Emanation Fraction

RAE (1990 p.2-1) indicated a typical radon emanation fraction for sludge of 0.22. (The basis for this value was not clear.) This is similar to typical values for soil.

A.4.4 Radon Exhalation Rate

No specific information was found on radon exhalation rate from sludge alone.

A.4.5 Leaching

RAE (1990 p.2-2) indicated a distribution coefficient for the solid/aqueous phases of radium in sludge of 2,500 cm^3/g and of lead in sludge of 5,100 to 20,000 cm^3/g.

A.4.6 Other Characteristics

RAE (1990 p.2-2) reported that typical bulk dry densities in equipment or disposed deposits were about 1.6 g/cm^3 and porosities were about 0.39.

A.5 WASTE PIT DISPOSAL

Based on the summary statistics presented in the U.S. EPA (1993) report on NORM oil field waste pits in Louisiana, the Louisiana Department of Natural Resources (DNR) appeared to have the most comprehensive information on this subject. Unless otherwise mentioned, the data presented below came from this report.

According to U.S. EPA (1993 p.2-6), waste pits have traditionally been the primary disposal method for NORM-contaminated scales, sludges, and some produced water residues. Two types of disposal pits for sludges and scales were mentioned in the report, namely: burn pits and brine pits. Burn pits were described as earthen pits used for storing temporarily and burning periodically non-hazardous oil field waste (excluding produced water) collected from tanks and other facilities. Brine pits were described as produced water pits that are lined, or earthen pits used for storing produced water and other non-hazardous oil field wastes, hydrocarbon storage brine, or mining water.

The following discussions only address brine pits since they represent the large majority of waste pits; U.S. EPA (1993 p.2-8) reported 5,853 brine pits and 435 burn pits for a total of 6,288 pits in Louisiana.

A.5.1 Dimensions

Statistics on brine pit dimensions (U.S. EPA p.2-9) are given in Table A.1. A much higher mean volume than the median volume (about a factor 10) indicated that the pit volume distribution is highly skewed by a small number of very large pits. Indeed, Shell (1993 p.11) suggested that there were probably less than 10 pits in Louisiana that exceed about 1,420 m^3 (or 50,000 ft^3).

Table A.1
BRINE PIT DIMENSIONS

	Brine Pit (m^3)(1)	Estimated Dimensions (see text below)		
		depth (m)	area (m^2)	diameter (m)
Max	2,124	3	708	30
Mean Volume	540	2	270	18.5
Median Volume	55	2	27	6
Min	4	1	4	2.2

One reference (Greer and Landres 1995 p.253-260) reported a former in-situ remediation situation in Louisiana at a larger pit than the maximal pit volume (over three times larger) given in the U.S. EPA report. The pit was located in a shallow estuary environment and had been receiving waste from production facilities over 30 years. The pit dimensions were approximately 70 m in diameter (or 3,848 m^2) and 2 to 3 m deep, with a nominal volume of approximately 7,200 m^3.

On this basis, a waste pit depth of 1 to 3 m appeared reasonable. The brine pit areas and diameters shown in Table A.1 were estimated by assuming circular pits with the deepest depth for larger pits (3 m), intermediate depth (2 m) for mean and median pits, and the lowest depth for small pits (1 m). The resulting pit areas are: all less than 1/5 of an acre (about 810 m^2 = 4,049 $m^2/5$), on average less than 1/15 of an acre (or 270 m^2), and over 50% of them are less than 1/150 of an acre (or 27 m^2) given the skewed pit volume distribution. Only the extreme pit case mentioned earlier approached a size of one acre.

For comparison, circular brine pits shown in the Ashland report (1993, Attachment 2-a to 2-f) were about 3 to 12 m diameters (or 7 to 113 m^2), and thus, were consistent with the equivalent diameter size of median pits (i.e. 6 m).

In summary, circular waste pit areas ranging from 4 to 708 m^2 (less than 1/5 of an acre) with a depth ranging from 1 to 3 m were suggested. For an average waste pit, circular areas ranging from 27 to 270 m^2 with a 2 m depth were suggested.

A.5.2 Radiological Characteristics

- Concentration

Concentrations of ^{226}Ra in mixed scales and sludges disposed at waste pits were estimated by pro-rating the distributions (with and without a 30 pCi/g cut-off) obtained in Section A.3.1 and A.4.1 to the total volume of waste generated by a reference 10 well facility over a 30 year period taking into account the difference between the scale and sludge densities (about 2.5 and 1.6 t/m^3 for scale and sludge, respectively).

Based on the U.S. EPA (1993 p.2-8) report, only 1 of the 10 pits were above 30 pCi/g, 5 were above 15 pCi/g, and all 10 pits were above 5 pCi/g. Statistics on radium concentrations for the 10 representative disposal pits were: a median of 19.2 pCi/g, a mean of 20.7 pCi/g, and a standard deviation of 10.6 pCi/g.

Greer and Landres (1995 p.253-260) reported in their analysis of an old large pit that ^{226}Ra concentrations were found in layers from 0.25 to 1.5 m in thickness and on the pit levee and berm. ^{226}Ra levels ranged from about 5 pCi/g to over 500 pCi/g. ^{228}Ra levels were negligible.

- Gamma Exposure Rate

Greer and Landres (1995 p.253-260) reported that gross gamma measurements at the pit surface ranged from 12 to over 400 μR/h. The pit and surrounding marsh were submerged under 0.2 to 1 m of water except for a narrow protective berm around the pit.

A.6 TANK BATTERIES

The most relevant information sources found on tank batteries all related to the NORM characterization of unreclaimed and reclaimed tank batteries at the Ashland Exploration Inc. (Ashland) Martha oil field in Lawrence and Johnson counties, Kentucky. Three of these studies were:

- Ashland (1993) - A proposed NORM reclamation program for the Martha site.

- Scott and Hebert (1993) - A NORM characterization study of (previously) reclaimed tank batteries in support of Ashland (1993). This paper is enclosed in Ashland (1993 Attachment 3).

- Hebert et al. (1995) - A paper presented in the Journal of the Health Physics Society on the <u>same</u> results that were reported in Scott and Hebert (1995), but excluding the dose estimations. (Not addressed below.)

Based on Ashland (1993): crude oil production activities by various companies (including Ashland) at the Martha oil field began more than 70 years ago. The site included a total of 71 tank battery sites distributed over an area of approximately 6,610 acres (3.7 km * 7.3 km). Each battery site typically included brine pits, flowlines, roads, and the tank battery itself.

Of the 71 battery sites, 43 had been reclaimed and the remaining 28 were in various stages of demobilization and reclamation (p.3). Unreclaimed tank batteries were those sites where production pits had not yet been closed. Production pits typically contained, tank bottoms (basic sediments), a surface skim of hydrocarbons and in some cases NORM. These sites may also have included isolated NORM-containing discharge areas (p.4).

Reclaimed tank batteries were those sites where production pits had been closed under the requirements of the U.S. Administrative Order (which did not appear to address NORM). Some remaining areas that were also NORM-impacted at some of these sites include: tilled, discharge or drainage areas. Reclaimed battery site may have included a land farming area (indicated as "land spread" in the report maps) in place of the tank battery itself.

Ashland (p.7) defined "NORM-impacted" in its proposed NORM reclamation program for the Martha site in terms of a standard for release of land for unrestricted use. This standard is: "*no more than 30 pCi/g of Ra-226 in the top 15 centimeters (cm) of soil averaged over 100 square meters*". An exposure rate of 55 μR/h at 1 m above ground was mentioned as a guideline for on-site verification. This guideline was expanded for readings greater than 250 μR/h to at least one foot below surface for flowlines (p.5).

Other reclamation issues mentioned in the report related to flowline and well sites (p.5-7). Flowlines were used for various purposes including flow of: oil, brine and gas from production wells to tank battery sites; fresh water from the water supply wells to the injection plant and on the injection wells; and the natural gas from the tank battery sites to a compressor station and on to wells used for repressurizing (p.5).

A.6.1 <u>Dimensions</u>

Based on the Ashland report map (1993 Attachment 1), the Martha site was about 6,610 acres (12,000 ft * 24,000 ft) in size. Each tank battery site was about one acre (or 4,049 m^2) in size.

Tank battery sites had rectangular shapes and ranged from about 53 to 594 m^2. Based on the maps provided in the report, a mean size for the five tank batteries is about 337 ± 180 m^2 (two times the error on the mean at a 95% confidence level). As discussed earlier, circular brine pits were about 3 to 12 m in diameter (or about 7 to 113 m^2). Typically, there were about two brine pits per tank battery site.

A.6.2 Radiological Characteristics

- **Ashland (1993)**

Based on this report: all 71 tank battery sites had been characterized in terms of area extent of NORM distribution using a gamma (µR/h) survey meter.

A general statement in the report indicated that NORM at the Martha oil field was typically "*confined to small isolated areas with the minimis activity levels by nuclear standards*". Areas where NORM levels were significantly above background were reported to have a very limited areal extent (usually less than one square yard) and typically located at the production pits associated with the tank battery site (p.2-3). Similarly, the report indicated that NORM-impacted areas "*are confined to the immediate vicinity of unreclaimed production pits or discharge points where scale may have accumulated*" and that other areas with above background NORM, "*are typically limited to the tank battery site proper, and except for the tilled (reclaimed areas), confined to the top few inches of soil*" (p.5).

Fig 2-a and 2-b (report Attachment) represented two unreclaimed tank battery sites where the highest readings (confined to a very small area within each tank battery) were obtained (p.3-4).

Fig 2-c and 2-d (report Attachment) represented two reclaimed tank batteries where the highest readings (confined to a very small area within each tank battery) were obtained (p.4).

Fig. 2-e (unreclaimed site) and 2-f (reclaimed site), were representative of those tank battery sites that have small areas slightly above background.

Other reclamation issues identified in the report included flowlines and well sites.

The detailed radiological study (gamma surveys, ^{226}Ra in soil, radon flux, radon emanation coefficient, and dose estimation) of Scott and Hebert (1993) was referred to in the report. (The results from this study are addressed further below.)

Pathways where deposition was most likely to occur were associated with the primary oil production stream: the equipment associated with production well, production flowlines, separators, tanks and the tank battery site itself which included discharge and drainage areas, and production pits. Unlikely pathways were those that followed the freshwater and gas reinjection streams and pathways secondary to production since up to 90% of the NORM was removed from the produced water stream by co-precipitation (p.13-14). This precipitate was highly insoluble. It was either deposited as a scale on the production equipment, settled out in the tank bottom or discharged into the environment. The report referred to two studies that confirmed the very limited migration potential of NORM from the precipitate (p.14). (These studies were discussed in Section A.2)

Gross alpha levels measured in 70 residential underground drinking water sources in the Martha area ranged from 0 to 25 pCi/L with only 4 sources above 5 pCi/L. ^{226}Ra levels measured in a portion of the 45 aquifer monitoring wells ranged from 0 to 77 pCi/L with only 4 wells above 5 pCi/L (p.16).

- **Scott and Hebert (1993)**

A detailed radiological study (gamma surveys, ^{226}Ra and ^{228}Ra in soil, radon flux, radon emanation coefficient, and dose estimation) were conducted in 1992 for six previously <u>remediated</u> tank battery sites at the Martha oil field. These sites were chosen across the production field to accurately represent the average radon flux by selecting two high, two moderate, and two low gamma activity tank batteries based on previous gamma surveys (p.1-2).

Based on the data summary presented in the report:

Average gamma exposure rates ranged from 35 to 83 μR/h (min=25, max=185, and average background at 14),

Average radon exhalation rates ranged from 0.8 to 5.7 pCi m^{-2} s^{-1} (min=0.5, max=12.6, and average background at 1.6),

Average radon emanation fractions ranged from 0.028 to 0.063 (min=0.024, max=0.062, background at 0.32),

Average ^{226}Ra concentrations ranged from 14.4 to 62.4, 13.3 to 75.3, and 7.4 to 85.6 pCi/g for soil depths of 0 to 5, 15 to 30, and 30 to 51 cm. Soil concentrations in all samples (for all three depth ranges) ranged from 1.7 to

189.3 pCi/g of ^{226}Ra and from 0.4 to 21.1 pCi/g of ^{228}Ra. Average background concentrations of ^{226}Ra and ^{226}Ra were 2.5 and 1.2, respectively.

Two main observations were drawn from these results. Firstly, the radon emanation fractions were much lower than those expected for typical soil or sludge. Indeed, they are very similar to the radon emanation fractions reported by Rood and Kendrik (1992) for scale. Perhaps, Asland's (1993 p.2) statement that typical soils in the region of the Martha oil field have a high clay content can explain this. If this were to be the reason, the application of this result on a U.S. wide basis would be questionable. Secondly, the presence of radium in all layers appears to contradict Asland's statement (p.5) that NORM-impacted areas in the tank battery site proper were typically confined to the <u>top few inches</u> of soil" (except for the tilled of reclaimed areas). Alternatively, a plow depth of 51 cm appeared quite high for a tilled area.

APPENDIX B

DERIVATION OF THE DISTRIBUTIONS OF Ra-226 CONCENTRATIONS IN OIL-FIELD NORM

APPENDIX B: DERIVATION OF THE DISTRIBUTIONS OF Ra-226 CONCENTRATIONS IN OIL-FIELD NORM

The radium concentrations in NORM arising from gas processing and oil production facilities vary significantly among types of equipments and among well fields. NORM has been measured at individual sites but a systematic and scientific survey of NORM concentrations at U.S. facilities has not been conducted. Hence, neither the mean radium concentrations or the variability, or distribution, of these concentrations is well known.

This appendix describes the procedure used to estimate the distribution of radium concentrations in remediated pits and at land farms from a survey of gamma radiation levels measured on gas processing and oil production equipment. The procedure, in all likelihood, overestimated the Ra-226 concentrations due to a bias to high radioactivity in the gamma radiation data set.

Gamma Radiation Data

Gamma exposure rates at the external surfaces of petroleum equipment containing NORM were collected during a survey conducted by the American Petroleum Institute (Otto 1989). The broad purpose of the survey was to identify the geographic areas and types of equipment with higher gamma radiation exposure rates arising from the presence of NORM wastes.

High variability was obvious with over 50% of the gamma radiation measurements indicating no difference from background but some measurements were substantially elevated above background measurements. There were significant differences in gamma radiation levels between the types of equipment and between various geographical locations.

The author assessed the data as *the most comprehensive and consistent set of NORM data available for petroleum operations* but then stated the following caveats:

.., much of the data was collected at sites exhibiting some degree of radioactivity. Hence, the data is not typical of a randomly chosen site and tends to overestimate the magnitude of NORM occurrence.

.... there is no scientific basis for extrapolating the results to unsurveyed areas of petroleum production/gas processing. The number of observations from gas processing and producing equipment may not be proportional to the actual amount of operational equipment in the area.

For the purposes of this review, the Otto data were acquired from API for further statistical analysis. The database contained external gamma radiation exposure rates, background gamma radiation exposure rates, and the net gamma radiation exposure rates. The data also include state, county, a code for the company, equipment type, and facility type (gas processing or producing) for each observation.

Although the original Otto data show gamma radiation measurements to one decimal place, the data provide by API were rounded to the nearest μR/h. Furthermore, data for Texas were not available for inclusion in this report. In general, the Texas gamma radiation levels exhibited substantial variability, but were on average, lower than gamma radiation levels measured in the rest of the country. As a result, statistics of gamma radiation exposure reported by Otto could not be exactly reproduced.

Derivation of Radium Concentration from Gamma Radiation Measurements

Radium and its decay products emit gamma radiation that can be easily measured with hand-held equipment. Gamma radiation levels are highly correlated with radium concentrations when radium (including its decay products) is the predominant gamma emitting radionuclide present but the correlation, or relationship, depends on geometry and shielding factors for different equipment types.

A method for estimating radium concentrations from these gamma radiation measurements was presented by the EPA (1993a). Equipment types containing NORM suitable for downhole exposure were identified (Table 2-1; EPA 1993a). In addition, physical dimensions were provided for the equipment size, wall thickness, and the thickness of scale or sludge inside the equipment. (The Louisiana NORM report did not clearly identify the basis for these data.) Estimates of the volume of NORM from each type of equipment for the 30 year life of a 10 well producing facility were shown.

Based on the definition of equipment containing scale and sludge, a merge with gamma exposure rates for those types of equipment was conducted. The EPA report (Table 3-1; EPA 1993a) shows the matching of equipment classification with the Otto report (1989). Two points require discussion; firstly, production facility equipment classifications in Otto's report (1989) include both gas and oil producing facilities. The table in EPA's report (1993a) assumes that all these measurements are representative of oil well measurements. Secondly, gamma exposure rates of more than one equipment type in EPA's report (1993a) are represented by Otto's equipment categories. For example, Otto's category 'Flowlines to include all lines and elbows' has been used to characterize exposures in the two categories of 'Oil Line Piping' and 'Oil Line Valves' in EPA's report (1993a).

The distributions of radium concentrations in each type of equipment were estimated from the gamma exposures for each equipment type using Equation 3-1 (EPA 1993a). This equation uses the typical dimensions of equipment and scale (or sludge) thickness that were reported in an earlier table (Table 2-1, EPA 1993a) and reproduced in section 3.1 (Table 3-4, EPA 1993a). Factors for correlation parameters and density for NORM wastes were included in the latter table.

The radium has been assumed to be all Ra-226 although a significant fraction (possibly more than 50%) may be Ra-228 especially for newly formed NORM wastes. Ra-228 decays relatively rapidly (a half-life of 5.8 years) so that within 30 years most of this radionuclide has decayed. The assumption that all radium is Ra-226 is conservative with respect to dose in that it overestimates the dose from NORM wastes after the Ra-228 has decayed.

Ra-226 (i.e. total radium) concentrations were calculated for each measurement in the Otto data base using equation 3.1 from the EPA report, the factors from table 3.1 from the same report and the incremental gamma radiation levels. Table B.1 shows a summary of the gamma radiation measurements and estimated radium concentrations by equipment type. It is obvious that radium concentrations in scales are typically much higher than the radium concentrations in scales. For a typical pit containing the scales and sludges from a production facility, the scale contributes more than 90% of the radium activity but only about 10% of the volume.

Variability

The radium concentrations in NORM are known to vary substantially between production facilities and it follows that the radium concentration in waste pits will vary between pits. The Otto data does not provide gamma radiation data for each equipment type at the production facility level; therefore, a hypothetical distribution of NORM has been generated.

Gamma radiation measurements were relatively frequent for oil stock tanks and this equipment type has been chosen as a basis for estimating NORM concentrations. Tank bottoms are similar from facility to facility and gamma radiation measurements are less susceptible to geometric and thickness variations. The following assumptions have been used to estimate the concentrations in individual remediated pits and land farm applications:

i) concentrations in NORM from stock tanks at a given facility are proportional to the concentrations in NORM from the other types of equipment at the given facility.

ii) county level mean concentrations for stock tanks are equal to the mean of the individual estimates.

iii) radium concentrations for stock tanks at individual production facilities are lognormally distributed about the county mean for stock tanks.

Mean and median radium concentrations were calculated by state, county and equipment type and the correlation in county medians levels for the equipment types was determined. Statistically significant positive correlations were present for most combinations of equipment types indicating that when radium concentrations are high in one equipment type then the radium concentrations in other equipment types tend to be high as well. These empirical data are consistent with the assumption that radium concentrations in NORM from oil stock tanks are proportional to concentrations in other types of equipment.

Table B.2 shows the ratio between radium concentrations in various equipment types to the concentration in sludges from oil stock tanks. Ratios were calculated at the county level if there were more than 4 measurements for each equipment type. The overall ratio was weighted by the number of measurements in each county.

A value of 0.5 μR/h was assigned if the measured increment from the Otto database was 0 μR/h. A distribution of concentrations of all stock tank sludges for each county was constructed by selecting the 5th, 15th, 25th and so on up to 95th percentile of the hypothetical distribution of radium concentration in the stock tank sludges for the county. The hypothetical distribution was lognormal with a geometric standard deviation equal to the median measured value and an assumed geometric standard deviation equal to 3.0. Concentrations for other equipment types were estimated by multiplying the stock tank concentration by the ratios in Table B.2.

<u>Remediated Pit Composition</u>

The distribution of Ra-226 concentrations were developed for the following two scenarios:

i) all sludges and scales from a facility were placed in the pit (All NORM); and

ii) only sludges and scales with Ra-226 levels lower than 30 pCi/g from the facility are placed in the pit (<30 pCi/g).

Scales were typically not included in <30 pCi/g pits due to concentrations predicted as above 30 pCi/g for many facilities. For some facilities, the modelled concentrations of all sludges and scales exceeded the 30 pCi/g threshold and, hence, there would be no volume, activity or mass of NORM for that facility.

The mass of NORM for each equipment type was calculated by multiplying the volume of NORM by the specific density (i.e. 2.6 for scale and 1.6 for sludges). The radium activity from each equipment type was estimated by multiplying the radium concentration by the estimated mass. The pit composition and volume were determined by adding the activities and masses for each equipment type NORM that met the scenario criteria. For example, only those activities and masses for equipment NORM lower than 30 pCi/g were added for the <30 pCi/g scenario. All activities and masses were added for the All NORM Scenario.

The mean concentration in the remediated pits was calculated by dividing the total radium activity in the pit by the mass of NORM selected for the pit. Pit volumes were set equal to the sum of volumes of NORM selected for the pit.

The total volume of NORM for each county was assumed to be proportional to the number of gamma radiation measurements (summed over all equipment types) reported for that county in the Otto data. Volumes for each theoretical pit were scaled by the relative number of gamma radiation measurements for the county.

Figure B.1 shows the two distributions of Ra-226 concentration in remediated pits. The distribution based on all NORM is highly skewed with a more than 50% of the pits estimated to contain 40 pCi/g or more. This differs substantially from the distribution of concentrations when NORM greater than 30 pCi/g are excluded. The median value for these pits is less than 5 pCi/g.

Land Farm NORM

Land farm NORM are assumed to arise only from sludges and two distributions were developed:

i) a mixture of all sludges from a facility;
ii) a mixture of sludges with NORM >30 pCi/g excluded.

The procedure was similar to the remediated pit characterization.

Figure B.2 shows the distributions of Ra-226 concentrations for the tank farm scenario. Concentrations for the mixture of all NORM are substantially lower than for the mixture of scales and sludges in the remediated pit scenario. The median level is about 5 pCi/g for the sludge compared to the 40 pCi/g median value predicted for the mixture of sludges and scales. Regardless, the predicted concentrations can be high with 10% of the NORM containing 50 pCi/g or more.

Concentrations are lower in the distribution of NORM after that NORM greater than 30 pCi/g have been removed.

Table B.1
SUMMARY OF RA-226 CONCENTRATIONS ESTIMATED FROM GAMMA RADIATION DATA

a) Scales

EPA Name	Number of Obs	pCi/g per µR/h (inc)	Mean µR/h (inc)	Mean pCi/g	Volume per Facility (ft^3)	Activity (Ci)	Proportion of Activity (%)
Oil Line-Piping	508	37.7	36	1,343.1	414.9	0.41	70.7
Oil Line-Valves	508	21.7	36	775.1	0.8	0.00	0.1
Manifold Piping	809	48.3	41	1,985.8	1.6	0.00	0.4
Headers/Manifold	809	29.4	41	1,206.5	0.8	0.00	0.1
Injection Well Tubing	56	26.4	34	898.1	42.1	0.03	4.8
Water Lines	243	3.7	84	310.5	54.2	0.01	2.1
Water Valves	243	14.4	84	1,205.1	56.7	0.05	8.7
Production Well Tubing	1,160	49.9	15	730.4	1.0	0.00	0.1
Meters, Screens, Filters	243	56.0	1	34.8	1.0	0.00	0.0
Total Scales					573.1	0.50	87.0

Table B.1 (Cont'd)
SUMMARY OF RA-226 CONCENTRATIONS ESTIMATED FROM GAMMA RADIATION DATA

b) Sludges

EPA Name	Number of Obs	pCi/g per µr/h (inc)	Mean µR/h (inc)	Mean pCi/g	Volume per Facility (ft^3)	Activity (Ci)	Proportion of Activity (%)
Test/Production Separators	3,649	2.8	40	112.8	47.1	0.00	0.4
Free Water Knockouts	3,649	3.6	40	143.4	20.9	0.00	0.2
Gun Barrel (Wash Tanks)	3,649	0.9	40	36.8	754.0	0.01	2.2
Oil Stock Tanks	3,947	0.7	13	9.2	4,418.0	0.02	3.2
Heater Treaters	1,878	0.8	52	40.2	125.7	0.00	0.4
Sump Pits	249	2.2	21	46.6	79.2	0.00	0.3
Water Storage Tanks	1,825	0.7	42	28.9	2,827.5	0.04	6.4
Total Sludges					8,272.4	0.08	13.0
Total All Wastes					8,845.5	0.58	100.0

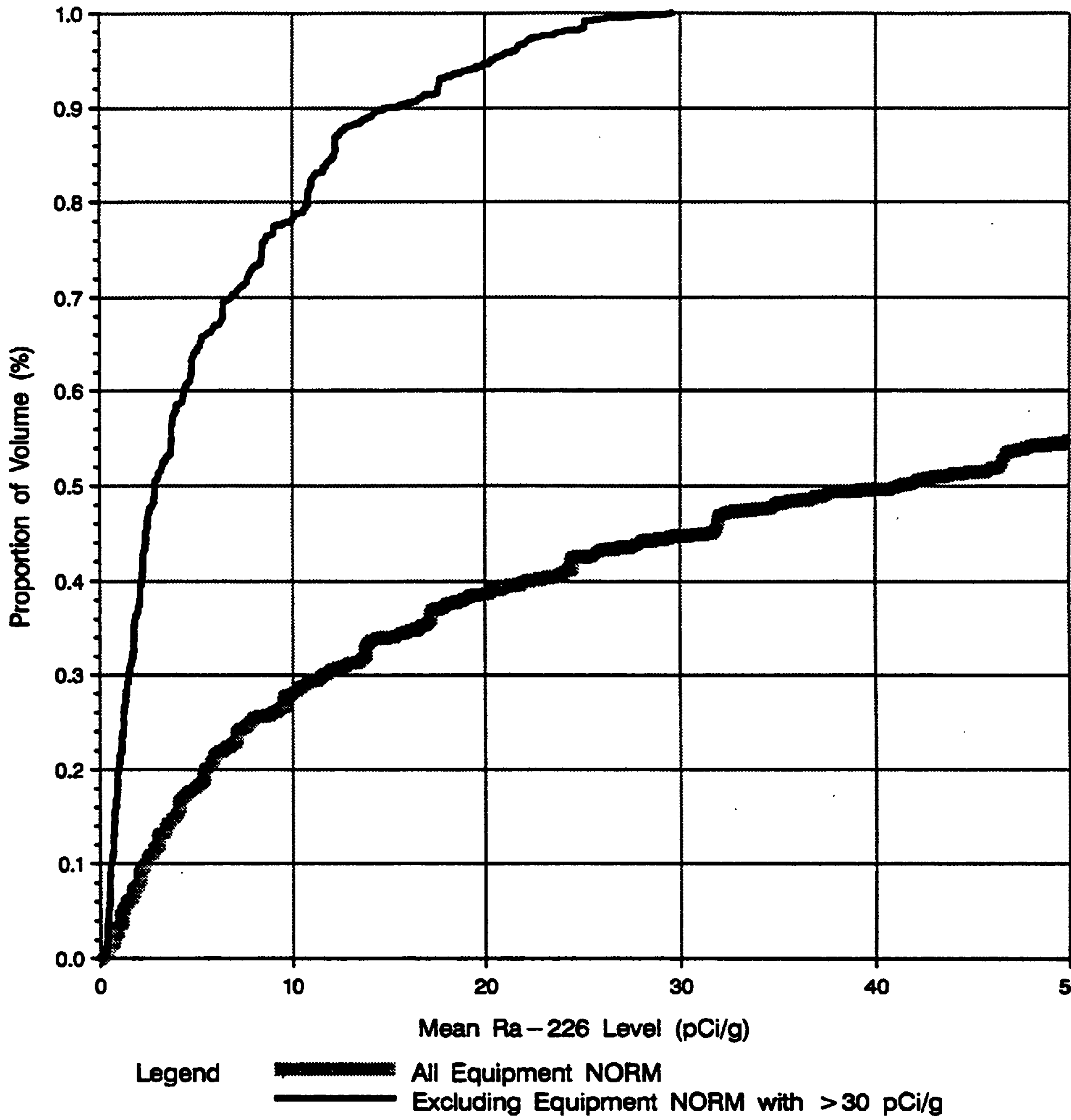
Table B.2

RATIO OF RA-226 CONCENTRATION IN VARIOUS EQUIPMENT TYPES TO THE CONCENTRATION IN SLUDGES FROM OIL STOCK TANKS

Equipment Type	Ratio
Oil Line-Piping	183.0
Oil Line-Valves	105.0
Manifold Piping	47.8
Headers/Manifold	29.0
Injection Well Tubing	23.9
Water Lines	13.6
Production Well Tubing	36.4
Meters, Screens, Filters	11.0
Test/Production Separators	10.9
Free Water Knockouts	13.9
Gun Barrel (Wash Tanks)	3.6
Heater Treaters	5.0
Sump Pits	4.0
Water Storage Tanks	1.6

Figure B.1

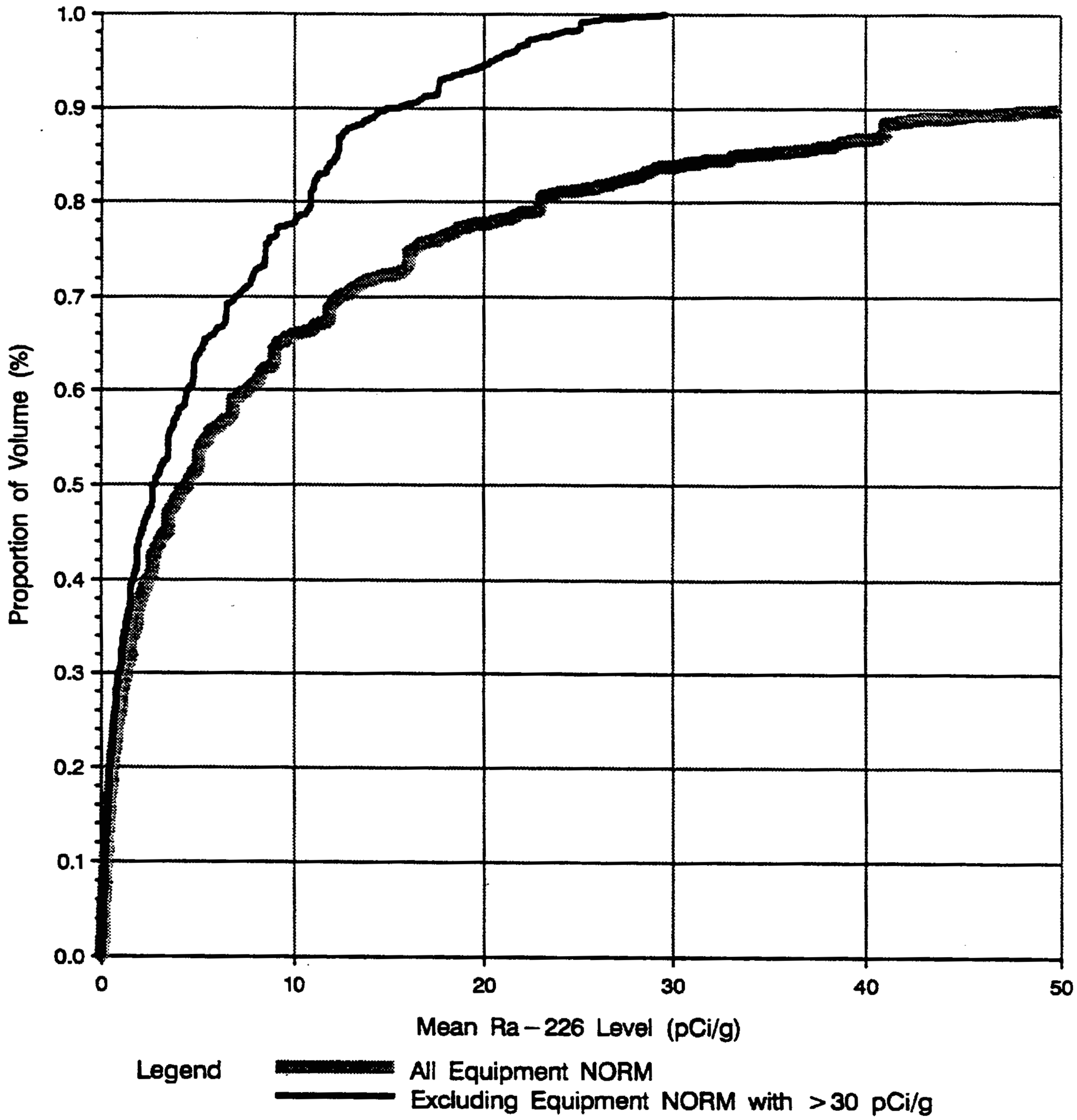
Distribution of Mean Ra – 226 Levels (pCi/g)
in Mixtures of Scales and Sludges from Individual Production Facilities



Based on distribution of county means for stock water tanks
in Ottos data and proportioning to other waste types
County volumes proportional to total number of measurements
d:\32105\progs\good\figures\ottoconx.sas – 10 June 1997

Figure B.2

**Distribution of Mean Ra-226 Levels (pCi/g)
in Mixtures of Sludges from Individual Production Facilites**



Based on distribution of county means for stock water tanks
in Ottos data and proportioning to other waste types
County volumes proportional to total number of measurements
d:\32105\progs\good\figures\ottoconx.sas – 10 June 1997

APPENDIX C

SCREENING PATHWAYS MODELS AND CALCULATIONS

APPENDIX C: SCREENING PATHWAYS MODELS AND CALCULATIONS

Screening level calculations of potential dose to residents living on remediated sites were made by deterministic methods to identify those pathways which contributed the largest dose to the total. The mathematical models used to estimate doses from dust inhalation, dust ingestion, external gamma radiation, well-water ingestion, and ingestion of locally grown vegetables, fruit and animal produce are described. The last section shows printouts of the spreadsheet calculation, parameter values and results.

Inhalation Pathway Model

The annual committed effective dose (D_{hi}) from inhalation of radionuclide i was calculated using the following model:

$$D_{hi} = C_d \times C_i \times 10^{-6} \times I_h \times t_e \times DCF_{hi} \tag{C.1}$$

where:

C_d	=	airborne concentration of dust, $\mu g/m^3$;
C_i	=	concentration of radionuclide i in dust, pCi/g;
10^{-6}	=	units conversion factor, $g/\mu g$;
I_h	=	inhalation rate, m^3/h;
t_e	=	exposure time, h/y; and
DCF_{hi}	=	committed effective dose equivalent factor (inhalation) radionuclide i, μrem/pCi.

Dust Ingestion Pathway Model

The annual committed effective dose (D_{gi}) from ingestion of radionuclide i was calculated using the following model:

$$D_{gi} = I_g \times 10^{-3} \times C_i \times \frac{t_e}{24} \times DCF_{gi} \tag{C.2}$$

where:

I_g	=	ingestion rate of dust, mg/d;
10^{-3}	=	conversion factor, g/mg; and

DCF_{gi} = committed effective dose equivalent factor (ingestion) radionuclide i, μrem/pCi.

External Gamma Pathway Model

The annual effective dose (D_{xi}) from external gamma radiation was calculated using the following model:

$$D_{xi} = C_i \times DCF_{xi} \times C_c \times t_e \qquad (C.3)$$

where:

C_c = dose conversion coefficient, rem/rad (air); and
DCF_{xi} = absorbed (air) dose rate factor, μrad (air) /h per pCi/g.

Well-water Ingestion Model

The annual committed effective dose (D_{wi}) from ingestion of well-water was calculated using the following model:

$$D_{wi} = \frac{C_i}{k_d} \times 10^{-3} \times I_{wg} \times \frac{t_e}{24} \times DCF_{gi} \qquad (C.4)$$

where:

k_d = soil/water distribution coefficient, L/g;
10^{-3} = conversion factor, mrem/μrem; and
I_{wg} = well-water ingestion rate, L/d.

Local Vegetable and Fruit Model

The annual committed effective dose (D_{jif}) from consumption of vegetables and fruit, j, (leafy vegetables, other vegetables, fruit and grain) containing radionuclide i was calculated using the following model:

$$D_{jif} = C_i \times T_{ji} \times f_{wj} \times I_{jf} \times f_{dj} \times 10^3 \times DCF_{gi} \qquad (C.5)$$

where:

T_{ji} = soil-to-vegetable j transfer factor for radionuclide i, g soil (d) / g veg (d);
f_{wj} = dry/wet fraction for vegetable j, g(d) / g(w);
I_{jf} = consumption rate of vegetable j, kg veg (w)/y;
f_{dj} = fraction of diet of vegetable j that is local, unitless; and
10^3 = units conversion factor, g/kg.

Local Animal Produce Model

The annual committed effective dose (D_{kip}) from consumption of animal produce, k, (beef, milk, poultry, and eggs) containing radionuclide i in animal feed j (fresh forage, stored hay and grain) was calculated using the following model:

$$C_{ikf} = C_i \times T_{ji} \times f_{wj} \times I_{kja} \times T_{ki}$$
$$C_{ikw} = \frac{C_i}{k_d} \times I_{kw} \times T_{ki}$$
$$D_{kip} = \left(C_{ikf} + C_{ikw}\right) \times I_{ki} \times f_k \times DCF_{gi}$$

where:

C_{ikjf} = concentration of radionuclide i in animal produce k from consumption of feed j, Bq/g;
I_{kja} = feed j ingestion rate by animal k, kg/d;
T_{ki} = feed-to-animal produce k transfer factor for radionuclide i, d/kg;
C_{ikw} = concentration of radionuclide i in animal produce k from consumption of water, Bq/g;
I_{kw} = water ingestion rate by animal k, L/d;
I_{ki} = annual consumption rate of animal produce k by humans, kg/y; and
f_k = fraction of animal produce k that is local, unitless.

Results

The screening dose calculations were completed for an assumed Ra-226 concentration of 1 pCi/g. The parameter values, references and results are shown on printouts of the spreadsheets which are included at the end of this appendix.

Table C.1 summarizes the screening dose assessment for 1 pCi/g Ra-226 in equilibrium with its decay products. The external gamma radiation dose, 7.25 mrem/y, dominates the doses for these pathways and accounts for 84% of the total dose. The next largest contribution is 0.63 mrem/y for the well water pathway.

Table C.1

SUMMARY OF SCREENING LEVEL DOSES FOR 1 pCi/g Ra-226 CONCENTRATION IN SOIL

	mrem/y	Percent
External Gamma Dose Rate	7.25	84.39
Inhalation of dust	0.04	0.46
Ingestion of soil and dust	0.11	1.28
Consumption of well water	0.63	7.33
Consumption of garden produce	0.53	6.12
Consumption of farm produce	0.04	0.042
	8.59	100.00

32105screening4 5-Dec-96

SCREENING DOSE CALCULATIONS

Parameter	units	name	Ra-226	Pb-210	Po-210	source or equation
Concentration in soil	pCi/g	Cra	1	1	1	assumption
External Gamma Radiation Model						
external dose factor, µrad/h per ;	µrad/h	Dfx	1.58			NCRP #94 p. 69 1987
absorded dose to effective dose	rem/rad	abed	0.7			NCRP #94 p.68 1987
hours per week exposed	h/wk	hpwk	126			NRC NUREG/CR-5512 p. 6.37 1992
week per year exposed	w/y	wpy	52			NRC NUREG/CR-5512 p. 6.37 1992
annual effective dose	mrem/y	Dxg	7.25			'=Cra*Dfx*abed*hpwk*wpy/1000
Inhalation Dose Model						
airborne dust concentration	µg/m3	adc	70	70	70	NRC NUREG/CR-5512 p. 6.37 1992
average inhalation rate	m3/h	dir	1.2	1.2	1.2	NRC NUREG/CR-5512 p. 6.37 1992
inhalation dose factors	µrem/pCi	Dfinh	35	21	16	'=4.3*100/27
						ICRP 71, adult, Slow type, highest dose factors
annual effective dose	mrem/y	Dinh	1.94E-02	1.14E-02	8.77E-03	'=Cra*adc*dir*hpwk*wpy*Dfinh/(1000000*1000)
			3.95E-02			
Ingestion of dust and soil model						
dust and soil ingestion rate	mg/d	dsir	50	50	50	NRC NUREG/CR-5512 p. 6.37 1992
ingestion dose factors	µrem/pCi	Dfing	1.04	2.59	4.44	ICRP67 , adult dose factors
annual effective dose	mrem/y	Ding	0.01	0.04	0.06	'=Cra*dsir*(hpwk/24)*wpy*Dfing/(1000*1000)
			1.10E-01			
Well water ingestion						
radium distribution coefficient	L/g	Radc	2.5	20	7.3	Rogers et al (1990), Sheppard & Thibault (1990)
water ingestion rate	L/d	wingr	2	2	2	NRC NUREG/CR-5512 p. 6.37 1992
annual effective dose	mrem/y	DingwRa	0.226	0.071	0.332	'=wingr*(hpwk/24)*wpy*Cra*Dfing/(Radc*1000)
			0.630			

	mrem/y	Percent
External Gamma Dose Rate	7.25	84.39
Inhalation of dust	0.04	0.46
Ingestion of soil and dust	0.11	1.28
Consumption of well water	0.63	7.33
Consumption of garden produce	0.53	6.12
Consumption of farm produce	0.04	0.42
	8.59	100.00

32105screening2 5-Dec-96

SCREENING DOSE CALCULATIONS (2)

Parameter	units	name	Ra-226	Pb-210	Po-210	source or equation
Concentration in soil	pCi/g	Cra	1	1	1	assumption
VEGETATION						
LEAFY VEGETABLES						
dry/wet fraction	g(d)/g(w)	dwflveg	0.200	0.200	0.200	NRC NUREG/CR-5512 p. 6.28 1992
soil-plant transfer (dry/dry)	g soil/g veg	sptlveg	7.50E-02	5.80E-03	2.50E-03	NRC NUREG/CR-5512 p. 6.26 1992
plant conc't'n	Bq/g(wt)	Clveg	1.50E-02	1.16E-03	5.00E-04	'=Cra*sptlveg*dwflveg
OTHER VEGETABLES						
dry/wet fraction	g(d)/g(w)	dwfoveg	0.25	0.25	0.25	NRC NUREG/CR-5512 p. 6.28 1992
soil-plant transfer (dry/dry)	g soil/g veg	sptoveg	3.20E-03	3.20E-03	9.00E-03	NRC NUREG/CR-5512 p. 6.26 1992
plant conc't'n	Bq/g(wt)	Coveg	8.00E-04	8.00E-04	2.25E-03	'=Cra*sptoveg*dwfoveg
FRUIT						
dry/wet fraction	g(d)/g(w)	dwff	0.180	0.180	0.180	NRC NUREG/CR-5512 p. 6.28 1992
soil-plant transfer (dry/dry)	g soil/g veg	sptf	6.10E-03	9.00E-03	4.00E-04	NRC NUREG/CR-5512 p. 6.26 1992
plant conc't'n	Bq/g(wt)	Cf	1.10E-03	1.62E-03	7.20E-05	'=Cra*sptf*dwff
GRAIN						
dry/wet fraction	g(d)/g(w)	dwfg	0.910	0.910	0.910	NRC NUREG/CR-5512 p. 6.28 1992
soil-plant transfer (dry/dry)	g soil/g veg	sptg	1.20E-03	4.70E-03	4.00E-04	NRC NUREG/CR-5512 p. 6.26 1992
plant conc't'n	Bq/g(wt)	Cg	1.09E-03	4.28E-03	3.64E-04	'=Cra*sptg*dwfg
CONSUMPTION						
leafy vegetables	kg/y	Crlveg	11	11	11	NRC NUREG/CR-5512 p. 6.24 1992
Other vegetables	kg/y	Croveg	51	51	51	NRC NUREG/CR-5512 p. 6.24 1992
Fruit	kg/y	Crf	46	46	46	NRC NUREG/CR-5512 p. 6.24 1992
Grain	kg/y	Crg	69	69	69	NRC NUREG/CR-5512 p. 6.24 1992
Fraction of diet from garden	-	Fdfg	0.25	0.25	0.25	NRC NUREG/CR-5512 p. 6.38 1992
Total activity ingested	pCi/y	Tai	83	106	37	'=(Clveg*Crlveg+Coveg*Croveg '+Cf*Crf+Cg*Crg)*Fdfg*1000
ingestion dose factors	µrem/pCi	Dfing	1.04	2.59	4.44	'=0.28*100/27
annual effective dose	mrem/y	Ding	0.09	0.27	0.17	'=Dfing*Tai/1000
			0.53			

32105screening3 5-Dec-96

SCREENING DOSE CALCULATIONS (3)

Parameter	units	name	Ra-226	Pb-210	Po-210	source or equation
Concentration in soil	pCi/g	Cra	1	1	1	assumption
TRANSFER TO VEGETATION						
FRESH FORAGE						
dry/wet fraction	g(d)/g(w)	dwff	0.220	0.220	0.220	NRC NUREG/CR-5512 p. 6.28 1992
soil-plant transfer (dry/dry)	g soil/g(d) vi	sptff	7.50E-02	5.80E-03	2.50E-03	NRC NUREG/CR-5512 p. 6.26 1992
plant conc't'n	pCi/g(w)	Cff	1.65E-02	1.28E-03	5.50E-04	'=Cra*sptff*dwff
STORED HAY						
dry/wet fraction	g(d)/g(w)	dwfsh	0.220	0.220	0.220	NRC NUREG/CR-5512 p. 6.28 1992
soil-plant transfer (dry/dry)	g soil/g(d) vi	sptsh	7.50E-02	5.80E-03	2.50E-03	NRC NUREG/CR-5512 p. 6.26 1992
plant conc't'n	pCi/g(w)	Csh	1.65E-02	1.28E-03	5.50E-04	'=Cra*sptsh*dwfsh
GRAIN						
dry/wet fraction	g(d)/g(w)	dwfg	0.910	0.910	0.910	NRC NUREG/CR-5512 p. 6.28 1992
soil-plant transfer (dry/dry)	g soil/g(d) vi	sptg	1.20E-03	4.70E-03	4.00E-04	NRC NUREG/CR-5512 p. 6.26 1992
plant conc't'n	pCi/g(w)	Cg	1.09E-03	4.28E-03	3.64E-04	'=Cra*sptg*dwfg
TRANSFER TO BEEF						
Fresh forage - daily intake rate	kg(w)/d	ffdirb	27	27	27	NRC NUREG/CR-5512 p. 6.19 1992
Stored hay - daily intake rate	kg(w)/d	shdirb	14	14	14	NRC NUREG/CR-5512 p. 6.19 1992
Stored grain - daily intake rate	kg(w)/d	sgdirb	3	3	3	NRC NUREG/CR-5512 p. 6.19 1992
Fresh forage - daily intake	pCi/d	ffdib	4.46E+02	3.45E+01	1.49E+01	'=Cff*ffdirb*1000
Stored hay - daily intake	pCi/d	shdib	2.31E+02	1.79E+01	7.70E+00	'=Csh*shdirb*1000
Stored grain - daily intake	pCi/d	sgdib	3.28E+00	1.28E+01	1.09E+00	'=Cg*sgdirb*1000
feed-to-beef transfer factor	d/kg	ftbtf	2.00E-04	3.00E-04	3.00E-04	NRC NUREG/CR-5512 p. 6.30 1992
Concentration in beef	pCi/kg	Cb	1.36E-01	1.95E-02	7.09E-03	'=(ffdib+shdib+sgdib)*ftbtf
TRANSFER TO MILK						
Fresh forage - daily intake rate	kg(w)/d	ffdirm	36	36	36	NRC NUREG/CR-5512 p. 6.19 1992
Stored hay - daily intake rate	kg(w)/d	shdirm	29	29	29	NRC NUREG/CR-5512 p. 6.19 1992
Stored grain - daily intake rate	kg(w)/d	sgdirm	2	2	2	NRC NUREG/CR-5512 p. 6.19 1992
Fresh forage - daily intake	pCi/d	ffdim	5.94E+02	4.59E+01	1.98E+01	'=Cff*ffdirm*1000
Stored hay - daily intake	pCi/d	shdim	4.79E+02	3.70E+01	1.60E+01	'=Csh*shdirm*1000
Stored grain - daily intake	pCi/d	sgdim	2.18E+00	8.55E+00	7.28E-01	'=Cg*sgdirm*1000
feed-to-milk transfer factor	d/kg	ftmtf	4.50E-04	2.50E-04	3.50E-04	NRC NUREG/CR-5512 p. 6.30 1992
Concentration in milk	pCi/kg	Cm	4.84E-01	2.29E-02	1.28E-02	'=(ffdim+shdim+sgdim)*ftmtf
TRANSFER TO POULTRY						
Fresh forage - daily intake rate	kg(w)/d	ffdirp	0.13	0.13	0.13	NRC NUREG/CR-5512 p. 6.19 1992
Stored grain - daily intake rate	kg(w)/d	sgdirp	0.09	0.09	0.09	NRC NUREG/CR-5512 p. 6.19 1992
Fresh forage - daily intake	pCi/d	ffdip	2.15E+00	1.66E-01	7.15E-02	'=Cff*ffdirp*1000
Stored grain - daily intake	pCi/d	sgdip	9.83E-02	3.85E-01	3.28E-02	'=Cg*sgdirp*1000
feed-to-poultry transfer factor	d/kg	ftptf	3.00E-02	2.00E-01	9.00E-01	NRC NUREG/CR-5512 p. 6.30 1992
Concentration in poultry	pCi/kg	Cp	6.73E-02	1.10E-01	9.38E-02	'=(ffdip+sgdip)*ftptf
TRANSFER TO EGGS						
Fresh forage - daily intake rate	kg(w)/d	ffdire	0.13	0.13	0.13	NRC NUREG/CR-5512 p. 6.19 1992
Stored grain - daily intake rate	kg(w)/d	sgdire	0.09	0.09	0.09	NRC NUREG/CR-5512 p. 6.19 1992
Fresh forage - daily intake	pCi/d	ffdie	2.15E+00	1.66E-01	7.15E-02	'=Cff*ffdire*1000
Stored grain - daily intake	pCi/d	sgdie	9.83E-02	3.85E-01	3.28E-02	'=Cg*sgdire*1000
feed-to-eggs transfer factor	d/kg	ftetf	2.00E-05	8.00E-01	7.00E+00	NRC NUREG/CR-5512 p. 6.30 1992
Concentration in eggs	pCi/kg	Ce	4.49E-05	4.41E-01	7.30E-01	'=(ffdie+sgdie)*ftetf

TRANSFER FROM SURFACE WATER TO LIVESTOCK						
soil/water distribution coeff.	L/g	swdc	2.5	20.0	7.3	Rogers et al1990, Sheppard and Thibault 1990
Concentration in water	pCi/L	Cw	4.00E-01	5.00E-02	1.37E-01	'=Cra/swdc
To Beef						
water ingestion rate	L/d	wingrb	5.00E+01	5.00E+01	5.00E+01	NRC NUREG/CR-5512 p. 6.19 1992
concentration in beef	pCi/kg	Cbw	4.00E-03	7.50E-04	2.05E-03	'=Cw*wingrb*ftbtf
To Milk						
water ingestion rate	L/d	wingrm	6.00E+01	6.00E+01	6.00E+01	NRC NUREG/CR-5512 p. 6.19 1992
concentration in milk	pCi/kg	Cmw	1.08E-02	7.50E-04	2.88E-03	'=Cw*wingrm*ftmtf
To Poultry						
water ingestion rate	L/d	wingrp	0.30	0.30	0.30	NRC NUREG/CR-5512 p. 6.19 1992
concentration in poultry	pCi/kg	Cpw	3.60E-03	3.00E-03	3.70E-02	'=Cw*wingrp*ftptf
To eggs						
water ingestion rate	L/d	wingre	0.30	0.30	0.30	NRC NUREG/CR-5512 p. 6.19 1992
concentration in eggs	pCi/kg	Cew	2.40E-06	1.20E-02	2.88E-01	'=Cw*wingre*ftetf
HUMAN CONSUMPTION						
ingestion dose factors	μrem/pCi	Dfing	1.04	2.59	4.44	'=1.2*100/27
Fraction of diet from produce	-	Fdfp	0.25	0.25	0.25	NRC NUREG/CR-5512 p. 6.38 1992
annual beef consumption	kg/y	Crb	59	59	59	NRC NUREG/CR-5512 p. 6.38 1992
Activity from beef	pCi/y	Arb	2.06	0.30	0.13	'=(Cb+Cbw)*Crb*Fdfp
Effective dose from beef	μrem/y	Edb	2.14	0.78	0.60	'=Arb*Dfing
annual milk consumption	kg/y	Crm	100	100	100	NRC NUREG/CR-5512 p. 6.38 1992
Activity from milk	pCi/y	Arm	12.36	0.59	0.39	'=(Cm+Cmw)*Crm*Fdfp
Effective dose from milk	μrem/y	Edm	12.82	1.53	1.74	'=Arm*Dfing
annual poultry consumption	kg/y	Crp	9	9	9	NRC NUREG/CR-5512 p. 6.38 1992
Activity from poultry	pCi/y	Arp	0.16	0.25	0.29	'=(Cp+Cpw)*Crp*Fdfp
Effective dose from poultry	μrem/y	Edp	0.17	0.66	1.31	'=Arp*Dfing
annual egg consumption	kg/y	Cre	10	10	10	NRC NUREG/CR-5512 p. 6.38 1992
Activity from eggs	pCi/y	Are	1.18E-04	1.13E+00	2.54E+00	'=(Ce+Cew)*Cre*Fdfp
Effective dose from eggs	μrem/y	Ede	1.23E-04	2.93	11.31	'=Are*Dfing
Total activity ingested	pCi/y	Taip	14.58	2.28	3.36	'=Arb+Arm+Arp+Are
Total annual effective dose	μrem/y	Ding	15.12	5.90	14.95	'=Dfing*Taip
			35.98			

APPENDIX D

EXTERNAL GAMMA AND RADON PATHWAYS - PROBABILISTIC METHOD

APPENDIX D: EXTERNAL GAMMA AND RADON PATHWAYS - PROBABILISTIC METHOD

This appendix describes the pathways models and probabilistic methods used to predict the distribution of incremental gamma radiation doses and indoor radon levels for the NORM scenarios. Pathways models were based on a residential exposure scenario where a house was built and the occupants spent time indoors and outdoors on the property. Probabilistic modelling has been utilized due to the high variability in source concentrations and the variation in lifestyle and physical aspects from property to property that influence doses or indoor radon levels arising from the NORM. The models include variability in source concentration and source geometry as well as the duration of time spent indoors and outdoors. The variability in indoor radon was modelled using an empirical estimate of the home-to-home variability in annual average indoor radon levels.

SOURCE CHARACTERIZATION

Ra-226 concentrations in the NORM vary from property to property depending on the Ra-226 concentrations in sludges and scales. These concentrations vary considerably from facility to facility with background, or lower, concentrations at many wells. The probabilistic assessment randomly selects Ra-226 concentrations from this distribution and, thereby, reflects the variation in concentrations from property to property. This provides a distribution of concentrations and an arguably more realistic representation of the average concentration than the selection of an arbitrary value for characterizing the concentrations.

Distributions of Ra-226 concentration in NORM were developed based on a previous survey of contact gamma radiation levels on oil-field equipment and a relationship between gamma radiation levels and Ra-226 concentration. NORM concentrations were developed to represent the concentration in disposed NORM after excluding the proportion of NORM with concentrations exceeding 30 pCi/g. This approach models the current management practices. As described in the main text and Appendix B, the distributions of Ra-226 concentrations in NORM were not based on statistically sound data but were taken from the results of studies designed for other purposes. The results were used here for illustration only.

These distributions were sampled for input values of the NORM concentrations and then source concentrations were derived from the randomly selected NORM concentrations. Hypothetical, or reference, scenarios were considered where the NORM concentration was exactly equal to 30 pCi/g.

Remediated Pit Scenario

The Ra-226 concentrations for the remediated pit scenario were randomly selected from the distribution of mixed scales and sludges not including NORM with concentrations greater than 30 pCi/g. This distribution was estimated, in Chapter 2 and Appendix B, using Otto's surface gamma radiation data and an empirical relationship between gamma radiation level and Ra-226 concentration in the NORM.

The distribution of Ra-226 was not modelled by a probability distribution but, rather, was expressed as a file of estimated Ra-226 concentrations and the estimated percentage of the total number of U.S. remediated pits with that concentration. Remediated pit concentrations, C_{NORM}, were randomly selected from this distribution with probability proportional to the percentage of remediated pits with that concentration.

Since there was no mixing of NORM with other material in the remediated pit scenario, the randomly selected Ra-226 concentration, C_{NORM}, was equivalent to the source layer concentration, C_{source}, used in the probabilistic models.

Land Farming Scenario

The source layer for the land farming scenario was assumed to be a mixture of NORM material and native soils; therefore, determining the Ra-226 concentration in the source was a two part process. First, the concentration in the waste was selected and, second, the proportion of waste material to native soil was selected.

Waste concentrations were sampled from the distribution of mixed sludges not including those sludges with Ra-226 concentrations exceeding 30 pCi/g. This distribution was not summarized by a probability distribution but was expressed, similar to the remediated pit distribution, as a file of Ra-226 concentrations and associated percentage of properties. The NORM concentration, C_{NORM}, was randomly selected from the distribution.

The source layer was considered to have varying mass proportion between the NORM and native soil with the NORM material constituting between 0 and 100% of the layer. For each probabilistic trial, a proportion was randomly selected from a uniform distribution ranging from 0 to 100%. The source concentration was then calculated from the mixture of NORM and native soil according to the following formula:

$$C_{source} = P_{NORM} \times C_{NORM} + (1 - P_{NORM}) \times C_{back}$$

where:

- C_{source} was the Ra-226 concentration (pCi/g) in the source layer;
- P_{NORM} was the mass proportion of NORM in the source layer;
- C_{NORM} was the Ra-226 concentration (pCi/g) in the NORM; and,
- C_{back} was the Ra-226 concentration (pCi/g) in background soil and was assumed to be a constant value of 1.1 pCi/g.

The formula was simply a weighted average of Ra-226 concentrations in the NORM and native soil.

Gamma Radiation Modelling

The objective of the gamma radiation model was to estimate incremental doses arising from gamma radiation for various NORM scenarios.

Model Development

The model calculated the incremental Ra-226 concentration in the source layer and multipled this by a factor relating the exposure rate in air (µR/h) to the Ra-226 concentration in the source if the source were an infinite half-plane. This outdoor exposure rate was modified by a geometry factor that reflects the effects of shielding by cover material or reflects the finite thickness of the source layer.

Incremental indoor gamma radiation exposure rates that were attributable to the source were lower than outdoor gamma radiation exposure rates since the building materials act as shield against the gamma radiation emitted from the source layer. An exact calculation of this shielding was mathematically complicated for any single house and the shielding provided by the house varies considerably from house-to-house depending on the building materials used and the physical dimensions of the house. Most risk assessments use factors that relate indoor exposure rate to outdoor exposure. Example values were 0.33 and 0.70 (NRC 1992, NRC 1982).

Annual exposure rates depend on the time spent on the property and, since outdoor exposure rates were different than indoor rates, the breakdown between outdoor and indoor duration on the site was important. Typically, people spend about 75% of the day on the property with most of the time spent indoors; however, there was variability in both the on-site and indoor durations (EPA 1989).

Probabilistic Model

The following equation was the probabilistic model for predicting gamma radiation exposure rates:

$$Exposure_{gamma} = (C_{source} - C_{back}) \times 1.82 \times G_{source} \times (\frac{T_{outdoors}}{7} + G_{housing} \times (T_{total} - \frac{T_{outdoors}}{7})) \times 365$$

where:

$Exposure_{gamma}$	was the annual incremental exposure rate (uR/y) from gamma radiation;
C_{source}	is the Ra-226 concentration (pCi/g) in the source layer;
C_{back}	is the Ra-226 concentration (pCi/g) in background soil that would have been occupied by the source layer if it were not there;
1.82	is the factor relating exposure rate in μR/h to soil concentration in pCi/g in a semi-infinite plan (NCRP 1993)
G_{source}	is a geometry factor that modifies the exposure rate based on the thickness of the source layer and the amount of cover material;
$T_{outdoors}$	is duration (h/week) spent outdoors on the property
7	is the number of days in a week and was used to convert hours per week to hours per day
$G_{housing}$	is a geometry factor that modifies the indoor exposure rate based on the shielding provided by the walls and the floor;
T_{total}	is the total duration (h/day) spent on the property
365	is the number of days in a year and was used to convert daily exposure rates to annual rates.

Incremental doses were calculated by converting units between the annual incremental exposure rate in μR/y and the incremental dose rate in mrem/y according to the following equation.

$$D_{gamma} = 0.6 \times Exposure_{gamma} \times 0.001$$

where:

D_{gamma}	is the incremental gamma radiation dose (mrem/y);
0.6	is the conversion factor (mrem per mR) between exposure and effective dose;
$Exposure_{gamma}$	is the incremental gamma radiation exposure rate (μR/y); and,

0.001 is the conversion factor from μR to mR.

Sampling Distributions

Each probabilistic trial was comprised of selecting a value for each parameter in the model. Some of the parameters were constants while other parameters were variable and were from different distributions depending on the scenario.

i) The Ra-226 concentration in the source layer, C_{source} depended on the NORM scenario and was sampled from the previously described distributions for the remediated pit and land farming scenarios. The background soil concentration, C_{back}, was treated as a constant parameter with a value of 1.1 pCi/g.

ii) The geometry factor for outdoor exposure rate, F_{source} was dependent on the scenario and, for the land farming scenario, was variable depending on the thickness of the source layer. For the remediated pit scenario, a constant value of 1.0 was selected for the no cover scenario and a constant value of 0.2 was selected for the 15 cm cover scenario. These values were taken from a published figure showing the proportion of total gamma radiation as a function of depth (NCRP 1984). The source layer in the land farming scenario was assumed to have a thickness varying between 15 and 23 cm (6 to 9"). The geometry factor varies approximately linear from 0.8 to 0.93 over this depth and, hence, the geometry factor was sampled from a uniform distribution between those values.

iii) The time spent outdoors, $T_{outdoors}$, was distributed uniformly between 0 and 6 h/week based on published data (EPA 1991) and did not depend on the scenario. Total time spent on the property, T_{total}, was also variable and did not depend on the scenario. A triangular distribution ranging between 12 and 24 h/day with a mode of 18 hours per day was the sampling distribution for this parameter (EPA 1991).

iv) The shielding provided by the house, $G_{housing}$ was also considered variable but the distribution did not depend on the scenario. A uniform distribution between 0.33 and 0.70 was chosen for this parameter (NRC 1992, NRC 1982).

Table D.1 summarizes the sampling distributions for modelling incremental gamma radiation doses.

Table D.1

PARAMETER VALUE DISTRIBUTIONS FOR MODELLING INCREMENTAL GAMMA RADIATION DOSES

Parameter	Scenario	
	Remediated Pit	Land Farming
C_{source}	Combined Scales and Sludges[a] (variable)	Combined Sludges[a] (variable) Mixed with Natural Soil
C_{back}	1.1 (constant)	1.1 (constant)
G_{source}	1.0 (constant) for no cover 0.2 (constant) for 15 cm soil cover	Uniform (0.80, 0.93)
$G_{housing}$	Uniform (0.33, 0.70)	Uniform (0.33, 0.70)
$T_{outdoor}$	Uniform (0, 6)	Uniform (0, 6)
T_{total}	Triangular (12, 18, 24)	Triangular (12, 18, 24)

Note:

[a] Predicted source concentration after excluding NORM with Ra-226 concentrations exceeding 30 pCi/g

INDOOR RADON MODELLING

The objective of the indoor radon model was to estimate the distributions of annual average indoor radon gas concentrations in homes on remediated pits or land farming sites. Predictions of indoor radon contributions are difficult for individual homes. The physical (or scientific) relationship between soil radium concentration and the incremental indoor radon level arising from the Ra-226 in the soil is complex. Several theoretical models have been developed but predictions of radon levels in individual homes are difficult due to the large number of parameters required for these models and the uncertainties associated with selecting appropriate parameter values. Furthermore, there was a high variation in the parameter values from home to home; therefore, it was difficult to develop defensible distributions of all the parameter values required for the physical (or scientific) models that predict indoor radon levels. The selected methodology incorporated a simplified (or conceptual) physical model and used empirical data derived from a nationwide survey of radon in homes carried out by the EPA.

Model Development

The sources of indoor radon can be conceptualized as follows:

i) from soil gas (from source material, from natural soil or both) directly entering the structure;
ii) from outdoor air entering the structure;
iii) from building materials used in the structure; and,
iv) exhalation from water containing radon.

The following formula represents this conceptual partitioning among the sources:

$$Rn_{indoor} = (Rn_{NORM} + Rn_{soil}) + Rn_{outdoor} + Rn_{building} + Rn_{water}$$

Building material and water exhalation sources of indoor radon can be significant in a few individual homes; however, they were assumed negligible for this study since these sources are typically small compared to contribution from soil gas and outdoor air entering the structure.

The annual average background concentration of radon in outdoor air (C_{bkgd}) was reported by Hopper (1992) to have an average value of 0.39 pCi/L, ranging from 0.16 to 0.59 pCi/L at sites across the 50 States.

The annual average concentration of radon measured in homes to which the ground-contact population of the US was exposed was reported by EPA (1992). EPA defines the ground-contact population as residents of all single-family units, except those that were 100 percent open underneath (such as unskirted mobile homes), and residences above the first floor in multi-family units. The results of the EPA survey include many types of home construction (e.g. slab-on-grade, basement, etc.) and varying climates and lifestyles.

EPA demonstrated that the distribution of radon concentrations could be approximated by using a lognormal distribution with a geometric mean value of 0.77 pCi/L and a geometric standard deviation of 2.92. This model predicts that 6.18 and 0.83 % of the population would be exposed to radon concentrations in excess of 4 and 10 pCi/L, respectively. These predictions compared well to the observed data in which 6.85 and 0.75 % of the population were exposed to concentrations in excess of 4 and 10 pCi/L, respectively.

The indoor radon contribution from soil gas was related to physical characteristics of the soil, primarily, Ra-226 concentration, the radon emanation factor, and the diffusive characteristics. Myrick et al. (1983) measured Ra-226 concentrations in surface soils at 327 locations across 33 states and reported a mean value of 1.1 pCi/g with a standard deviation of 0.48 pCi/g, ranging from 0.23 to 4.2 pCi/g. The radon emanation fraction from radium in soil has a mean value of 0.2 (NCRP 1987). Radon diffusion coefficients vary from soil to soil with generally higher diffusion coefficients in coarser and dryer soils than in finer and wetter soils.

The distribution of contribution to indoor radon level from soil gas has been determined by estimating the lognormal distribution that was equal to the EPA's distribution of indoor radon level when a mean outdoor radon level of 0.39 pCi/L was added. The estimated geometric mean was 0.408 pCi/L for the contribution of soil gas to indoor radon levels and the geometric standard deviation was 3.837 which indicates a high variability among homes. This empirical distribution of the indoor radon level contribution from soil gas was based on natural conditions and was modified by the Ra-226 concentration in NORM, emanation fractions, and source characteristics.

Probabilistic Model

The following equation was the probabilistic model for predicting indoor radon levels for the waste scenarios:

$$Rn_{indoor} = \frac{C_{source}}{1.1} \times \frac{E_{source}}{0.2} \times F_{source} \times H_{housing} + (1 - F_{source}) \times H_{housing} + Rn_{outdoor}$$

where:

Rn_{indoor}	was the indoor radon level (pCi/L);
C_{source}	was the Ra-226 concentration (pCi/g) in the source layer;
E_{source}	was the radon emanation fraction (unit less) for the source material;
F_{source}	was the geometry correction factor (unit less) for a finite source thickness and was equal to the proportion of radon flux entering the residential structure if the source layer were infinite in thickness and spatial extent; and,

$H_{housing}$ is the housing factor (pCi/L) that describes the distribution of indoor radon levels for actual conditions (includes variations in soil diffusion coefficients, residential construction type, cracks, air changes, and meterological conditions); and

$Rn_{outdoor}$ is the outdoor radon level (pCi/L).

The first line of the equation models the indoor radon contribution from the source layer and modifies the natural indoor radon level by the Ra-226 concentration in the source, the radon emanation factor in the source, and the geometry of the source relative to the waste (e.g. thickness of the layer and amount of cover material). The second line of the equation models the indoor radon from natural soil that covers, or lies below, the source layer. Factors for Ra-226 concentration and emanation fraction were not required for this component because the housing factor (indoor radon levels from natural soils) was based on the distribution of natural soils. The third line models the outdoor air contribution to indoor radon concentration.

Sampling Distributions

Parameter values were probabilistically sampled during each trial; however, the sampling distribution may be dependent on the waste scenario according to the following:

i) The Ra-226 concentration, C_{source} depends on the NORM scenario and was sampled from the previously described distributions for the remediated pit and land farming scenarios.

ii) The radon emanation fraction, E_{source} was dependent on the NORM scenario. The sampling distribution was uniform from 0.02 to 0.06 for the remediated pit but was a weighted average of the emanation for natural soil and wastes in the landfarming scenario.

iii) The geometry correction factor, F_{source} depended on the scenario. A constant value of unity was selected for the remediated pit scenario based on the assumption of infinite thickness. The geometry factor for the land farming scenario was sampled from a uniform distribution between 0.133 and 0.816 in order to reflect the finite thickness of the source layer. The factors were calculated based on the range of fluxes for different soil types and thickness of the source layer. For the background reference scenario, a constant value of 0 was assigned.

iv) The housing factor, $H_{housing}$ was independent of the waste scenario since it was assumed that the house responds in the same way to the radon arising from the NORM layer as it responds to the radon arising from the natural soil. Parameter values were selected from the previously described distribution.

v) The outdoor radon, $Rn_{outdoor}$ was independent of the NORM scenario and has been assigned a constant value of 0.39 pCi/L. The areal extent of the waste sites was relatively small and the minor influence of radon exhaled from local soils on natural background concentrations of radon in outdoor air has been ignored.

Table D.2 summarizes the sampling distributions for each waste scenario.

Table D.2
PARAMETER VALUE DISTRIBUTIONS FOR MODELLING INDOOR RADON LEVELS

Parameter	Scenario		
	Remediated Pit	Land Farming	Background
C_{source}	Mixed Scales and Sludges[a] (variable) or 30 pCi/g (constant)	Mixed Sludges[a] (variable) or 30 pCi/g (constant)	n/a
E_{source}	Uniform (0.02, 0.06)	Uniform (0.02, 0.06)[b]	n/a
F_{source}	1 (constant)	Uniform (0.133, 0.816)	0 (constant)
$H_{housing}$	Ln (0.408, 3.837)	Ln (0.408, 3.837)	Ln (0.408, 3.837)
$Rn_{outdoor}$	0.39 (constant)	0.39 (constant)	0.39 (constant)

Notes:

[a] Predicted source concentration after excluding NORM with Ra-226 concentrations exceeding 30 pCi/g.

[b] modified for landfarming scenario to reflect mixture of NORM and natural soils.

n/a not applicable.

APPENDIX E

BRIEF REVIEW OF SELECTED ASSESSMENTS

APPENDIX E: BRIEF REVIEW OF SELECTED ASSESSMENTS

A listing of selected assessments is given in Table E.1 and the results of some of them are summarized in Table E.2.

E.1 ASSESSMENTS ON OIL FIELD NORM IN MARTHA, KENTUCKY

In 1993, Ashland Exploration Inc. prepared a remedial plan for their oil field at Martha, Kentucky and submitted a proposal to the Commonwealth of Kentucky on remediation criteria which included a supporting pathways assessment (Scott and Hebert 1993). Rogers and Associates (1994) prepared a pathways assessment for the State. Following discussions with the state authorities, Ashland submitted a revised proposal for remediation criteria and supported it with a pathways assessment (Auxier 1994) that included a review of the Rogers and Associates report (1994).

Scott and Hebert (1993) prepared an assessment of the potential incremental exposures to residents living on remediated oil-field sites at Martha, Kentucky using data collected at the site and pathways models. To support the proposed remediation criterion, they characterized the radiation source as a 6 inch layer containing Ra-226 at a concentration of 30 pCi/g. They estimated the annual doses from external gamma radiation in the range 0.7 to 100 mrem/y depending on the home construction type (basement, 6 inch concrete slab, 4 inch concrete slab, crawl space). The annual doses from radon progeny were calculated to be in the range 0.1 to 9 mrem/y (depending on home construction type) using the RESRAD4 model. The RESRAD model described by the reference made by Scott and Hebert does not include radon progeny pathways. The authors of this report did not have access to the RESRAD4 model and could not assess the reasons for the low values of dose that were calculated.

Rogers and Associates (1994) also prepared an assessment of the potential incremental exposures to residents living on remediated oil-field sites at Martha, Kentucky. They characterized the radiation source as an 18 inch layer containing Ra-226 at a concentration of 30 pCi/g. Their estimates of dose rate from external gamma radiation and of radon concentration in indoor air were 260 mrem/y and 2 pCi/L, respectively. Auxier and Associates (1994) commented that Rogers and Associates had overestimated the dose from external gamma radiation, and that the correct estimate of annual dose from external gamma radiation from an even thicker source than used by Rogers and Associates (i.e. infinitely thick) was 82 mrem/y. Auxier and Associates also argued that the predicted indoor radon gas concentration would be <2 pCi/L due to the low radon emanation fractions measured at Martha, Kentucky.

In this assessment, SENES calculated the potential annual dose from external gamma radiation and the predicted indoor radon gas concentration in homes built on remediated oil-field sites. At a Ra-226 concentration (infinite depth) of 30 pCi/g, the predicted annual dose rate from external gamma radiation had a mean value of 110 mrem/y and the 95th percentile was 160 mrem/y if there were no cover material. The corresponding predicted concentrations of total indoor radon had mean and 95th percentile values of 6.1 and 21 pCi/L, respectively.

SENES also calculated the potential annual dose and the predicted indoor radon gas concentration where the Ra-226 concentration was distributed from 0 to 30 pCi/g with a mean value of 5.5 pCi/g. The form of the distribution was developed from the data analysed by Otto (1989) and by Rogers and Associates (1989). The predicted annual dose from external gamma radiation had a mean value of 17 mrem/y and the 95th percentile dose rate was 70 mrem/y. The corresponding predicted concentrations of indoor radon had mean and 95th percentile values of 1.4 and 4.6 pCi/L, respectively.

The predicted annual dose rate from external gamma radiation and the radon concentration in indoor air are comparable to the values predicted by Auxier and Associates (1994) and Rogers and Associates (1994). The differences among the predicted values are attributable to the different models or different parameter values that were selected.

E.2 Assessments on Oil-field NORM by EPA

In 1993, EPA released for peer review a draft assessment of potential doses from disposal of oil-field NORM to members of the public in Louisiana (1993a). SENES (1993) prepared a critical review of this document for API. Also in 1993, EPA released another draft of its Diffuse NORM document which included a section on potential doses from oil-field NORM (1993b).

EPA (1993a) predicted that residents living in a home built in Louisiana on land previously used for land farming would receive 220 mrem/y (p. 10-21) from external gamma radiation, and they would be exposed to an annual average indoor radon gas concentration of 2 pCi/L (p. 10-19). These values were predicted by EPA on the basis that the Ra-226 and Ra-228 concentrations in the 8 inch thick layer of NORM totalled 15 pCi/g (p. 10-6) assuming dilution during land farming.

EPA (1993b) predicted that residents living in a home built on a remediated oil-field pit would receive 1200 mrem/y from external gamma radiation and they would be exposed to an annual average indoor radon gas concentration of 72 pCi/L. SENES back calculated this value by dividing the risk from one year of exposure (3.1 x 10^{-3}) predicted by EPA by the risk factor (4.3 x 10^{-8} per pCi/m^3) reported by EPA. These doses were predicted by EPA on the basis that the Ra-226 and Ra-228 concentrations in the waste were 90 and 30 pCi/g, respectively.

The values predicted by EPA in both of the assessments described above are higher than the corresponding values predicted by SENES in this assessment. EPA's overestimate of gamma radiation dose is attributable to their use of models that overestimate dose as described by Auxier and Associates (1994) and SENES (1993a and b).

Table E.1
LIST OF SELECTED DOSE ASSESSMENTS OF OIL FIELD NORM

Year	Subject	Author
1997	generic sludge and scale	SENES (this study for API)
1994	oil field NORM Martha, Kentucky	Auxier and Associates (for Ashland Exploration Inc.)
1994	oil field NORM Martha, Kentucky	Rogers and Associates (for Commonwealth of Kentucky)
1993	oil field NORM Martha, Kentucky	Scott and Hebert (for Ashland Exploration Inc.)
1994	Review of EPA's Louisiana NORM	SENES (for API)
1993	Louisiana NORM - oil/gas	US EPA
19??	Louisiana oil fields	Scott
1996		Bernhardt
1996		Rajarethan
1995		Smith and Blunt (Argonne National Lab)
1992		Smith (ANL/EAIS-7)
1991		Miller
1990		Baird ? Rogers and Associates RAE8837/2-2
1988		Rogers and Associates

Table E.2
COMPARISON OF RESULTS OF SELECTED DOSE ASSESSMENTS

Study	NORM Thickness	External Gamma mrem/y	Radon pCi/L
Scott & Hebert 1993 for Ashland (Kentucky)	6"	0.7-100	0.1-9 (mrem/y)
Rogers & Associates, 1994 for Kentucky	18"?	260?	2
Auxier & Associates, 1994 for Ashland (Kentucky)	∞	82	<2
Generic Oil-Field NORM (this study 30 pCi/g)	∞	110 160	6.1 (mean) 21 (95th percentile)
Generic Oil-Field NORM (this study <30 pCi/g)	∞	17 70	1.4 (mean) 4.6 (95th percentile)
Natural Background (this study 1.1 pCi/g)	∞	4.2 5.9	1.3 (mean) 3.9 (95th percentile)

Additional copies available from API Publications and Distribution: (202) 682-8375

Information about API Publications, Programs and Services is available on the World Wide Web at: http://www.api.org

American Petroleum Institute
1220 L Street, Northwest
Washington, D.C. 20005-4070
202-682-8000

Order No. G71051