NUREG/CR-2082
ORNL/HASRD-95

Monitoring for Compliance With Decommissioning Termination Survey Criteria

Prepared by C. F. Holoway, J. P. Witherspoon, H. W. Dickson,
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Prepared for
U.S. Nuclear Regulatory
Commission

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Springfield, Virginia 22161

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Manuscript Completed: March 1981
Date Published: June 1981

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Washington, D.C. 20555
NRC FIN A9085

ABSTRACT

This document was prepared as part of the requirement for considering changes in regulations on decommissioning of commercial nucle facilities. Specifically, it addresses the final steps needed to ensu that a site which has been decontaminated can be released for unrestri use. Consideration is given to preliminary and termination (certifica survey designs and procedures which might be used for licensed nuclear fuel cycle and non-fuel cycle facilities. In addition, information on instrumentation, evaluation and interpretation of monitoring data, and cost-effectiveness of monitoring is given.

This guide was designed to be a general purpose document both for licensees and regulatory agency inspectors who are concerned with spec fications of a monitoring program, complete with checks and audits, wh can be used to verify compliance with decommissioning criteria. Moreo much of the information and methodology presented here furnishes part the data base being established by the U.S. Nuclear Regulatory Commiss in its reappraisal of regulations for decommissioning of licensed facilities.

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BY
NUCLEAR REGULATORY COMMISSION STAFF

The NRC staff is reappraising its regulatory position relative to the decommissioning of nuclear facilities.[1] As a part of this activity, the NRC has initiated series of studies through technical assistance contracts. These contracts are being undertaken to develop information to support the preparation of new standards covering decommissioning.

The basic series of studies will cover the technology, safety, and costs of decommissioning reference nuclear facilities. Light water reactors and fuel cycle and non-fuel-cycle facilities are included. Facilities of current design on typical sites are selected for the studies. Separate reports will be prepared as the studies of the various facilities are completed.

The first report in this series was published in FY 1977 and covered a fuel reprocessing plant;[2] the second was published in FY 1978 and covered a pressurized water reactor;[3] the third of the series was published in FY 1979 and dealt with a small mixed oxide fuel fabrication plant.[4] An addendum to the pressurized water reactor report,[5] which examined the relationship between reactor size and decommissioning cost, the cost of entombment, and the sensitivity of cost to radiation levels, contractual arrangements, and disposal site charges, was issued during FY 1979. The fifth report in this series dealt with a low-level waste burial ground.[6] The sixth report dealt with a large boiling water reactor power station.[7] The seventh report provided information on the technology, safety, and costs of decommissioning a uranium fuel fabrication plant.[8] The eighth report in the series covers the decommissioning of non-fuel-cycle nuclear facilities.[9]

Additional topics will be reported on the tentative schedule as follows:

FY 1981 • Multiple Reactor Facilities

FY 1981 • Research/Test Reactors

FY 1981 • UF_6 Conversion Plant

FY 1982 • Independent Spent Fuel Storage Installations

The second series of studies covers supporting information on the decommissioning of nuclear facilities. Three reports have been issued in the second series. The first consists of an annotated bibliography on the decommissioning of nuclear facilities.[10] The second is a review and analysis of current decommissioning regulations.[11] The third covers the facilitation of the decommissioning of light water reactors,[12] identifying modifications or design changes to facilities, equipment, and procedures that will improve safety and/or reduce costs.

The following report, fourth in the series, covers establishment of an information base concerning monitoring for compliance with decommissioning survey criteria. A fifth report on this same theme is intended for FY 1981 entitled Technology and Cost of Termination Surveys Associated With Decommissioning of nuclear facilities.

The information provided in this report on decommissioning survey on compliance monitoring, including any comments, will be included in the record for consideration by the Commission in establishing criteria and new standards for decommissioning. Comments on this report should be mailed to:

Chief
Chemical Engineering Branch
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

for technical implementation.

REFERENCES

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3. Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, June 1978.

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8. Technology, Safety and Costs of Decommissioning a Reference Uranium Fuel Fabrication Plant, NUREG/CR-1266, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, October 1980.

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1.0 INTRODUCTION

This guide is designed as a general purpose document for those with concern for the final steps needed to ensure that a former radiological site has been decontaminated to the point that it is safe to release that site for unrestricted public use. It is especially designed for two parties: (a) the licensee who wants to dispose of the site, and (b) the regulatory agency inspector who wants to be sure that the site is (or is not) safe to release.

1.1 Background to the Subject

To make the decision that a given site is or is not "safe" to release, the Nuclear Regulatory Commission (NRC), hereinafter identified or personified by the term "inspector," compares the results of a final survey by the licensee with existing standards and regulations governing or relating to such a decision. To check the validity of the licensee's final survey, the inspector must perform a verification inspection. It would be possible, especially for a small licensee lacking sufficient expert staff or consultants, to make a final survey with inadequate equipment, inappropriate procedures, and uninterpretable conclusions. Therefore, it is the purpose of this guide to give guidance and direction on how the licensee shall carry out a final survey, such that its design, procedures, results and interpretations can be compared with existing standards with validity.

This is not a trivial task for licensee or inspector. Judgment is involved at several steps in the process of adapting general procedures to specific site situations. As part of any regulatory process in the public interest, an inspector must deal with the licensee "at arm's length" to avoid any suggestion of "collusion." This cannot be true of the licensee's data and conclusions, which latter being referred to hereinafter as a portion of the available "prior information" on the site. Since the inspector's verification survey is of necessity much less comprehensive (small sample sizes, etc.) than the licensee's final survey, the former final survey needs to make optimal use of previous surveys carried out during the operational period of the site and the post-operational stage (i.e., initial decontamination, demolishment, cleanup, and final decontamination.

While this guide is generally applicable to all sites, the level of effort will vary depending upon the type and complexity of the site involved.

Generalities tend to foster ambiguity or fail to give enough specific guidance. Appendices are included to lend more specificity, at least to the extent of presenting the application of the procedures to two types of sites, a power reactor and an uranium mill.

Guidance for compliance with decommissioning criteria requires, or is facilitated by a variety of aids such as check lists, flow sheets, tables, figures, formulas which are used as needed (see Table of Figures and Index). Guidance must also offer some philosophy of design, monitoring, interpretation, especially with respect to state-of-the-art limitations, assumptions underlying models such as those which relate soil nuclide concentrations or air gamma readings to human dose commitment. Guidance must be realistic relative to the above philosophy as it relates to financial burden on the licensee, potential hazard to the public, limited inspection staff, real versus perceived risk, and application of the ALARA (as-low-as-reasonably-achievable) philosophy.

Though some guidance on philosophy is given as background, the primary purpose of the present guide is to outline the procedures for generating a final licensee's site survey report and for an audit of same for generating an inspectors verification survey report.

Specific objectives include: a) identification of the monitoring requirements; b) general specifications for an adequate monitoring program; c) application of a system of checks and audits; and d) application of the general monitoring program to two generic sites. As licensee and inspector work through their respective tasks, certain monitoring requirements become obvious. A check list minimizes chances of overlooking the obvious as well as less obvious.

Some of the monitoring specifications include:

1. Site characteristics and dividing the site into survey blocks,

2. Specifying the media to be sampled, and why in light of prior information.
3. How the media are to be sampled for laboratory analyses.
4. What instrumentation is suitable for gamma or beta/gamma radiation readings in the air, above ground level readings on site.
5. What limitations exist for the instrumentation used.
6. What limitations exist on laboratory analysis of media taken from the site.
7. How data shall be taken, collated, processed, analyzed, stored, retrieved, used, and interpreted.
8. What quality control is exerted over the data and its interpretation.
9. What temporary and permanent documentation is required.

1.1.1 Existing standards

Regulatory Guide 1.86, "Termination of Operating Licenses for Nuclear Reactors," (June 1974), in process of revision, specifies that the site from which a reactor has been removed must be decontaminated, as necessary, and inspected to determine whether unrestricted access can be approved. Acceptable surface contamination levels cannot exceed those listed in Table I-1 of Appendix I.

It should be noted that though manual wiping with filter paper (commonly Whatman No. 50) is inexpensive and simple, it is not very accurate since applied pressure as well as the surface area wiped are variable. Where cost-effective, standardized pressure and standardized surface area should be used. One such standard system is an IBM smear card in a device with a constant pressure pad and a 2.5-in wheel, one revolution of which moves the IBM card exactly 100 cm^2 across the surface to be wiped, producing a smear card suitable for counting and data processing without cross contamination.[2] There is at least one commercial supplier of an automated system for taking, collating, measuring, and analyzing standardized smears, or any portion of the system thereof, as might be desired by a licensee.[3]

Guidelines leading to unrestricted use of nuclear facility sites in general were published in November 1976 by the Nuclear Regulatory Commission[4] as presented in Appendix I. The same surface contamination limits are given as in Appendix I.

Smears are used on building and equipment surfaces, but not on soil surfaces and water volumes. Radioactivity for soil and water are usually measured in milliBecquerels (picocuries) per gram of soil or per liter of water, and occasionally in megaBq/km^2 (mCi/km^2). Federal limits for these media in these units (e.g., pCi/g of soil) have not been set for most radionuclides of concern.

Federal government regulations relating to potential decommissioning criteria can be found in a relatively small number of sections of the Code of Federal Regulations (CFR). Pertinent Title 10 regulations of CFR include Part 20, which deals with standards for protection against radiation, and Part 712, which contains the Grand Junction Remedial Action Criteria. Other sections of Title 10, which have a minor bearing on decommissioning criteria are Parts 30, 40, 49, 50, and 70. Title 40 deals with environmental regulations which fall in the domain of the Environmental Protection Agency (EPA). In particular, 40CFR190 deals with environmental protection standards for uranium mill tailings,[5] for the exact working of which see Appendix II. Decommissioned uranium mill tailing sites involve naturally occurring radionuclides. To the extent that other decommissioned types of nuclear facilities involve naturally occurring radionuclides, the residual ^{226}Ra requirements of 40CFR190 should be applicable. Some of the requirements are:

1. that for 1000 years following disposal, the average annual release of ^{222}Rn from the residual radioactive materials to the atmosphere shall not exceed 2 pCi/m^2-s;
2. that the average concentration of ^{226}Ra in a 5-cm or smaller thickness of soil or other materials shall not exceed 5 pCi/g after completion of the remedial action, except that this shall not apply to soil or other materials for which residual radioactive materials appear to play no role in causing the average concentration of ^{226}Ra to be greater than 5 pCi/g;

3. That combined ^{226}Ra and ^{228}Ra in dissolved form shall not exceed 5 pCi/L in water at a distance of 1 km from the site.

The NRC Uranium Mill licensing requirements have been published in the Federal Register, Volume 45, No. 194, Pages 65521-65538, October 3, 1980. An earth cover of 3 m or more, sufficient to reduce radon exhalation to not more than 2 pCi/m^2-s above natural background, is required. Provision is made for state monitoring of ^{228}Ra, only when local conditions indicate the necessity, to keep sampling costs down.[6]

The Safe Drinking Water Act of 1974 (Public Law 93-523) sets the standard for radioactivity in drinking water as developed by EPA. In addition, the Resource Conservation and Recovery Act of 1976 (Public Law 94-530) provides for development of criteria to define hazardous radioactive waste, which EPA has set at 5 pCi/g or more of ^{226}Ra. The EPA has proposed also radiation dose limits for exposure from soil contaminated with plutonium.[7]

1.1.2 Regulatory Guidance

Regulatory standards promulgated by EPA and NRC and entered into the Federal Code of Regulations, to implement Congressional legislation, have strong legal compulsion with penalties for failure to comply. For this reason, regulatory agencies are reluctant to publish standards that are not based upon "solid facts," which are extremely difficult to come by and which can move no faster than "the state-of-the-art." In the absence of specific standards for general or specific situations, regulatory agencies are still responsible for the public welfare in their mandated areas, and try to meet this obligation in the form of regulatory guides. These in turn are adapted from recommendations of acknowledged authoritative bodies such as International Commission on Radiological Protection (ICRP), National Council on Radiation Protection and Measurements (NCRP), International Atomic Energy Agency (IAEA), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), U.S. National Academy of Sciences/National Research Council

Advisory Committee on the Biological Effects of Ionizing Radiation (BEIR), American National Standards Institute (ANSI), and others. The authoritative bodies in turn base their recommendations upon published works of research investigators, including themselves. Reports from UNSCEAR[8] and from BEIR[9] provide information on the level of risk associated with radiation exposure. Relating human exposure to environmental contamination requires validated pathway models. Again, validation is a state-of-the-art problem which includes sufficient reliable and pertinent data necessary to confirm theoretical and semi-empirical models.

In the absence of firm solid limit figures for nuclides of cleanup significance, due to the variability of many factors, unofficial guidance in the published works of responsible investigators is sometimes of value, though without legal standing. In its earlier recommendations, the ICRP published, maximum permissible concentrations of radionuclides in air $(MPC)_a$, and, maximum permissible concentrations of radionuclides in water $(MPC)_w$, but no maximum permissible concentrations of radionuclides in soil values $(MPC)_s$. Healy[10] has recommended some soil limits for a few nuclides as given in Table 1.1. The inhalation values for ^{90}Sr and ^{137}Cs in Table 1.1 may seem relatively large. However, "real world" values for air resuspension of respirable size soil particles generally range from 10^{-6} m^{-1} (ref. 11). This would reduce actual inhalation of radionuclide-containing soil particles to 2 pCi of ^{90}Sr per gram of resuspended soil (74 mBq/g) and to 7 pCi of ^{137}Cs per gram (259 mBq/g). The resuspension default value for calculating residual soil activity inhalation corresponding to a given exposure rate in mrem/y (Sieverts/y) by the 1980 NRC model[12] is 10^{-8} per meter. Healy has published two other significant papers on soil contamination, relating to plutonium.[13-14] Schiager addressed the question of the risk from radium-bearing waste,[15] and Goldsmith the problem of uranium tailings cleanup.[16] Criteria for radioactive cleanup in Canada have been suggested.[17]

Where specific national and state regulatory standards do not yet exist, the licensee should look to national and state regulatory guidance. Other guidance sources include NCRP, ICRP, IAEA, and journal literature such as the above. Licensees are advised to maintain a current set of NRC, EPA, and state regulations, and to watch the Federal Register.

Table 1.1. Recommended soil limits in pCi/g for home gardeners[a]

Nuclide	Inhalation	Ingestion	External	All pathways
^{231}Pa	50	150	250	40
^{227}Ac	2,000	1,000	300	250
^{232}Th	45	140	40	20
^{228}Th	1,000	7,800	55	50
^{230}Th[b]	300	940	36,000	280
^{238}U-^{234}U	750	8	6,000	40
^{90}Sr	2,000,000	19	--	100
^{137}Cs	7,000,000	1	90	80

[a]Reference 10.

[b]No daughters.

The NRC is re-evaluating its policy on decommissioning with respect to (a) what residual radioactivity levels would be related to a particular dose level, (b) which of the various exposure pathways are significant, and (c) which nuclides associated with a facility are significant dose contributors.[18] For light-water reactor decommissioning, ^{60}Co, ^{137}Cs, and ^{134}Cs, and external irradiation from deposited nuclides have been identified as special problems.

A review of current regulations on decommissioning nuclear facilities by Schilling et al.[19] is available.

As residual soil levels of radionuclides need to be related to dose rates, so the latter need to be related to pathological (health) effects upon human populations. The prime concern of cleanup crews and radiation surveyors in the field is with meeting residual soil limit requirements, rather than with calculating dose rates or estimating health effects. Residual soil limits similar to that promulgated by EPA for ^{226}Ra (ref. 5) are needed for other important nuclides such as ^{60}Co, ^{137}Cs, and ^{90}Sr.

An intermediate step between recommending bodies such as ICRP and promulgating bodies such as EPA and NRC, is the ANSI. An ANSI committee with Health Physics Society representation proposed in 1980 an American national standard[20] (Appendix III) on control of radioactive surface contamination. As with the 1976 NRC guidelines (Appendix I), limits were given in dpm/100 cm^2 for building and equipment surfaces, but none in mBq/g for soil surfaces. Quality assurance requirements for nuclear power plants published in 1979 (ref. 21) do not give specific standards for decommissioning surveys. In conjunction with the American Society for Quality Control, ANSI published a draft[22] for non-nuclear facilities, and with the American Institute of Chemical Engineers one for nuclear processing plants, N46.2, which is identical with the old N45.2 (ref. 23).

Thus, societies and federal and state agencies tend to march in lock-step fashion which favors conservatism but which needs to give timely guidance now on soil limits for decommissioning cleanup and survey work. As demand increases for soil limits approaching those of background, the problem then becomes one of better data on background variability and ability to distinguish in the field contamination due to man's activities from activity due to natural soil and fallout backgrounds.

1.2 Definitions

AUDIT: Any off-site inspection of a site by examination of any or all records, or other documentation, generated by the licensee and by the NRC for the purpose of determining the suitability of that site for a verification survey and possible unrestricted release to the public domain.

BACKGROUND: Natural unenhanced background (terrestrial + cosmic rays) varies with such factors as snow cover, earth faults, proximity of phosphate or uranium ore bodies, altitude. Technologically enhanced background results from global weapons testing fallout, emissions from nuclear facilities, mining and other human activities. Gamma background 1 meter aboveground commonly varies from 30 to 160 nanoGrays/h (3 to 16 μR/h) (Table 4.3) with an average of perhaps 80 nGy/h, depending on how large an area is averaged and upon spatiotemporal factors. Each radionuclide has its typical mean background, e.g., 26 milliBecquerels/g (0.7 pCi/g) of U, 26 mBq/q of ^{226}Ra and 44 mBq/g (1.2 pCi/g) of ^{210}Pb in soil dust, respectively (ref. 24).

BIASED SAMPLING: A deficiency in the selection method which causes each item in the population not to have an equal chance of being selected.

CENTRAL LIMIT THEOREM: The central limit theorem states that if all samples of size n are selected from a population with a finite mean, u, and a standard deviation, σ, that the distribution of sample means, $\bar{x}$'s, will tend toward a normal distribution with a mean which is the same as the population mean, u, and a standard deviation that is equal to $\sigma/\sqrt{n}$, called the standard error of the mean. The sample means will be normally distributed even though the population from which samplings are made may not be normally distributed, provided the sample size is large enough, namely over 30.

CONFIDENCE LEVEL (OR INTERVAL): Range within which a mean value falls with a given probability, say of 95%.

CONTINUOUS RANDOM VARIABLE: A random variable is continuous if, over a range, it may assume any numerical value in the range.

DECOMMISSIONING: The process of post-operationally decontaminating, demolishing, and decontaminating to levels approaching background for anticipated unrestricted release - or for restricted release at higher levels. A verification survey will ensure that the decommissioned site condition is suitable for unrestricted release.

DISCRETE RANDOM VARIABLE: A random variable which may assume a countable or limited number of quantitative values.

GRIDPOINT: Intersection of two lines at 90°, resulting from a land survey and staking of the site. Four adjacent gridpoints define a rectangle or square and a survey block. In special circumstance, a gridpoint might be defined by polar rather than rectangular coordinates. Soil, air or water sampling and instrumental air readings are made at such grid points or within defined points of the survey block created by such gridpoints.

HAZARDOUS NUCLIDE: A long-lived nuclide (see same) in large enough quantity, improperly contained, as to constitute a somatic or genetic risk in excess of the national rate (ref. 25).

INSTRUMENTAL GAMMA OR BETA/GAMMA DOSE RATE READINGS: Usually referring to gamma readings taken 100 cm above soil surface, or to beta and gamma readings taken 1 cm above the soil surface, or other surfaces, such as interior walls of a building which is to remain for unrestricted use. In general, any portable or fixed instrument that measures radioactivity in the air or from a surface or object emitting detectable radiation such as alpha, beta, gamma, bremstrahlung or neutron emission.

KURTOSIS: A measure of peakedness in distribution, normal being 3, flattened or platykurtotic being less than 3, with more sharply peaked than normal or leptokurtotic being greater than 3. The average of the 4th power deviations from the mean is called the fourth moment.

LOGNORMAL DISTRIBUTION: The density function of a variable, f(x), whose logarithm follows the normal probability law. The mean will be greater than the median which in turn is greater than the mode. The lognormal curve can be described in terms of skewness and kurtosis and has multiplicative instead of additive properties.

LONG-LIVED NUCLIDE: Arbitrarily taken to be a nuclide of radiological half-life greater than 1 year, e.g., ^{60}Co whose half-life is about 5 years.

LOWER LIMITS OF DETECTION (LLD): Defined in the HASL Procedures Manual, HASL-300 (Suppl. 2), August 1974, as that activity which has a 100% 2σ counting error. See also EG&G ORTEC technical publication "LLD versus MDA," PSD No. 14, by W. H. Zimmer, March 1980, defining LLD as that activity detected with 95% probability, with only 5% probability of falsely concluding that a blank observation represents a "real" signal. See also NRC Regulatory Guides 4.8 and 4.12.

MEAN: Average of two or more values.

MODEL (DOSE): Procedure, including mathematical, for converting field readings or laboratory analyses (e.g., pCi of ^{90}Sr per gram of soil) into population dose estimates (e.g., mrem per year) assuming certain environmental transport and dosimetric values.

MONITORING: Instrumental evaluation of a site using portable rate or cumulative count meters while on-site. Media to be monitored are usually surfaces or hollow interiors such as ducts, pipes, core holes, air or water filled cavities. Units of measurement or flux are commonly μR/hr, $n/cm^2/min.$ for a neutron emitter such as ^{252}Cf, and the equivalent SI units such as Grays (1 rad = 0.01 Gray).

NORMAL DISTRIBUTION: Sometimes referred to as the Gaussian curve, completely defined by two parameters, the mean and the variance. The normal curve is symmetrical, with a skewness of 0 and a kurtosis of 3. The standardized normal curve (i.e., values given in terms of z-scores as shown in Eq. 5.2), has a mean of zero, with about 95% of its area falling between -2σ and $+2\sigma$ (Fig. 5.1).

OBSERVATION: A number or matched set of numbers such as a gamma reading at 100 cm, a beta reading at 1 cm, a ^{226}Ra value in pCi/g of soil and an ^{227}Ac value in pCi/g of soil, all taken at the same gridpoint constituting a matched set of numbers.

POPULATION: Closely allied to the question of stratification. Statistically, a population is the total number of units to be sampled and is either finite or essentially infinite. One may define a population: a) as the finite number of survey blocks into which a site is divided; b) the essentially infinite number of air gamma readings that could be taken on the site; c) the essentially infinite number of atoms of a key radionuclide (total inventory) heterogeneously distributed over the site. For the case of naturally occurring radionuclides such as ^{226}Ra or of global fallout such as ^{238}Pu, there is need to differentiate two populations of the same nuclide, namely: a) by on-site activities; b) that concentration of the same nuclide that was on-site preoperationally or which is represented by unenhanced off-site concentration postoperationally. (See Background.)

PRELIMINARY SURVEY: A survey, usually smaller than the main survey, by licensee or inspector, for the purpose of designing a final survey plan to establish whether or not a site is decontaminated sufficiently to warrant unrestricted release according to federal and/or state standards. From the preliminary survey, decisions are then made such as grid size and layout, whether to use a simple random, stratified random or systematic sampling, total sample size, manpower and equipment needed, and probable cost of the final survey. In some cases, where independence of the inspector's final survey is not in danger of compromise, the final survey of the licensee can serve as the preliminary survey of the inspector.

QUALITY ASSURANCE: The planned, systematic actions necessary to provide adequate confidence that a material, component, system, facility, or experiment will perform satisfactorily in service to give a satisfactory result.

QUALITY ASSURANCE AUDIT: A documented activity performed in accordance with written procedures or check lists to verify, by examination and evaluation of objective evidence, that applicable elements of the QA program have been developed, documented and effectively implemented in accordance with specified requirements (Cf.ANSI N45.2.12).

RANDOM NUMBER: A number selected blindly from a table of random numbers that have been tested thoroughly for complete randomness. To draw numbered survey blocks at random for sampling, each block number is selected from a random number table.

RANDOM VARIABLE: A variable whose value is determined by the chance outcome of an experiment. Random variables usually arise from sampling, and may be discrete or continuous.

SAMPLE: Two types are referred to in this guide: 1) A single analytical sample such as a soil sample that has been analyzed in the laboratory for one or more radionuclide concentrations, expressed commonly in pCi of nuclide per gram of wet or dry weight soil, or in μG in the case of total uranium or thorium; and 2) a statistical sample consisting of two or more observations, but preferably of 30 or more observations so that the central limit theorem may be used, and other statistical measures applied with confidence.

SAMPLING: Taking of soil, water, air, vegetation, etc. samples as needed for transport to a field or more distant laboratory for wet and/or dry analysis. Points of sampling shall be identified by reference to a) physical on-site markers, b) grid points and survey blocks on a suitable site map. Sample containers shall not cause addition to, nor detraction from the radioactivity of the sample due to the parents and daughters contained therein, and shall be properly labeled.

SAMPLING DESIGN: Of several possible sampling procedures, such as simple random sampling, stratified random sampling, systematic sampling, cluster sampling, the particular procedure to select and follow will depend upon prior information available about the site characteristics.

SAMPLING DISTRIBUTION: The probability distribution of a statistic such as the sample mean or the sample variance. For sample sizes equal or greater than 30, the sampling distribution is approximately normal with a mean, $\bar{x}$, which approximates that of the population mean, u, and with a sample standard error of $\sigma/\sqrt{n}$. (See Central Limit Theorem.)

SITE CHARACTERISTICS: Meteorology such as wind and rain patterns; soil retention properties; surface and underground water drainage; stratigraphy and other geologic characteristics; manmade waste drainage structures such as interior pipes and ducts, drainage ditches, lagoons; location of former security fence and of former process buildings and areas; quantities of radioactive materials entering, leaving and remaining on-site and the long-lived nuclides of potential significance for that site after unrestricted release; background for the site; etc.

SKEWNESS: A measure of distribution symmetry, ±0 to 0.5, being con-considered symmetrical, ±0.5 to 1 moderately skewed and greater than ±1.0, being highly skewed. Lognormal distributions are skewed to the right, in which case the mode is less than the median which is less than the mean (Fig. 5.1). Derived from the average of the cubed deviations from the mean, it is called the third moment about the mean. See also Kurtosis.

STANDARD DEVIATION: The positive square root of the variance. The standard deviation of the population is denoted by the symbol σ, while the standard deviation of a sample (set of observations) taken from the population is denoted by the symbol s.

STANDARD ERROR: The standard deviation of a sampling distribution, or in the case of the standard error of the sample mean: $\sigma/\sqrt{n}$.

STATISTICAL DESIGN: Design of sampling procedures and other aspects of the site survey, such that generally accepted statistical procedures may be applied to ensure a given degree of confidence in the survey results as part of quality assurance.

STRATUM: Division of a site into two or more groupings by: a) geography; b) survey blocks; c) homogeneity of beta or gamma variance; d) homogeneity of soil nuclides variance; e) operational or processing areas; f) areas of decreasing hazard potential; or a combination of same, for convenience of the surveyor or of the statistican, or both. Appropriate stratification of a site for sampling can be one of the more difficult aspects of statistical design for large and complex sites.

SURVEY: Any overall inspection of a site, with or without instrumental measurements and samplings of media on-site and immediately off-site, for the purpose of radiological assessment of the site prior to and/or at the time of survey.

SURVEY BLOCK: Square or rectangle defined by interaction of grid lines (stakes, chalk points, etc.), laid out systematically upon an exterior or interior surface with sufficient permanency to give reproducible reference points until unrestricted release of the site has been effected. (See also Gridpoint.)

TERMINATION SURVEY: Survey by the licensee of the site after it has been decontaminated and believed ready for unrestricted release. This survey will be carried out in accordance with NRC guidelines which are based on the present guide. The survey will be audited and will serve as a basis for the verification inspection.

TYPE I ERROR: Declaring a site clean when it is actually contaminated (H_o). This is a more serious error and should be given more weight than a Type II Error.

TYPE II ERROR: Declaring a site contaminated when it is actually clean (H_a); the alternate hypothesis to the original hypothesis (H_o).

VARIANCE: The sum of the squares of the deviations from the mean divided by the degrees of freedom, which is commonly n-1, where n = sample size.

VERIFICATION INSPECTION OR CERTIFICATION: Inspection by an NRC inspector of the site to confirm the licensee's final survey data and conclusions. Spot readings and soil samples to check licensee's instrumental air readings and soil analysis results shall be made. In addition, the inspector has discretionary power to take additional observations, such as sampling in spot areas not specifically sampled by the licensee.

Z-SCORE: The z-score corresponding to a measured value, x, is the number of standard deviations that x is from the population mean, μ. It is a means by which any normal curve can be compared with any other normal curve, though expressed in different units, by converting the normal curves to be compared into a standardized normal curve, for which z-tables are then readily available.

1.3 Scope

This guide is structured around the following objectives and procedures.

1.3.1 Identification of monitoring requirements

Before a monitoring program to confirm compliance with decommissioning criteria can be written or applied, all significant elements pertinent to the site in question must be identified. This guide gives general guidance, but it is also the responsibility of licensee and of inspector to adapt, amplify or abbreviate the generalized procedures to meet site specifics. Protection of the public health on a cost-effective basis in conformity with standards existing when the final clearance procedures begin can be a difficult task whose dimensions the present guide attempts to circumscribe. Monitoring experience from the Department of Energy Formerly Utilized Sites - Remedial Action Program (FUSRAP) is used in this guide as a basis for the identification and utilization of pertinent methods and techniques for an adequate monitoring program. This includes instrumentation and their use. Monitoring requirements are restricted to post-operational sites that involved storage, processing and/or use of radioactive materials - sites being considered as candidates for unrestricted release to the public domain. Final monitoring of the site by the licensee or his designated representative, and the audit and verification survey by an inspector for the NRC, are an integral and final part of the decommissioning process. Monitoring by the licensee and the inspector with standardized procedures and equipment is necessary to ensure compatability and interpretability of data. Identification of monitoring requirements is a first step in such standardization.

1.3.2 General specifications for a monitoring program to ensure and confirm compliance

Having identified the essential site-specific elements of an adequate monitoring program, using the generic elements of the present report, the licensee or the inspector as the case may be then needs to work out a detailed plan of action. A generalized reactor site and mill site are given in Appendices I and II, respectively, which are to aid in the process (see Section 1.3.4 below). Specifications must include: 1) a survey plan; 2) instrumentation used for the survey; 3) media sampling methods; 4) protecting the integrity of data through proper storage and documentation; 5) ensuring quality of the data through standard quality assurance procedures; and 6) appropriate data analysis by generally accepted practices, including standard descriptive and inferential statistics, and comparison with existing regulations and guidelines.

1.3.3 Development of a system of checks and audits

Though intended primarily for the inspector, this aspect of a monitoring program can and should be used also by the licensee, especially when large and complex operations, including the post-operational cleanup phase, are involved. Checks and internal audits are common sense aspects of good housekeeping and quality control.

Check lists are a somewhat specialized form of checks and audits. They are sometimes used in the form of worksheets, as illustrated in the Ernst and Whinney workbook[26] or other standard texts and workbooks on the subject. See Section 6.1.2 for information on checklists.

1.3.4 Application of the monitoring program

This guide is intended to present not only generalities but enough specificity that licensee and inspector can set up and carry out a monitoring program for compliance and verification, confidence in the results of which will be sufficient to ensure that the released site will not constitute a significant future radiological hazard as the direct result of licensee's former use of radioactive material on the site.

The reactor site and uranium mill site examples (Appendix IV and V), though based upon real sites are generalized in order to smooth out specifics that would not necessarily be applicable for all sites. The generalized monitoring program presented here, which may be called a Generic Monitoring Program, is a combination of real data experiences encountered in the Formerly Utilized Sites Remedial Action Program coupled with a Reference Reactor Site composited from real data by Battelle Northwest Laboratory.[27]

The reactor and mill site examples are intended to entail essentially all of the types of monitoring activities that would be involved in the decommissioning monitoring of a complex nuclear facility.

1.4 General Approach

The general approach to a Reference Radiological Monitoring Program (RRMP) which could be used to demonstrate that a candidate site for decommissioning meets all applicable radiological criteria prior to its release for unrestricted use has already been implied and to some extent spelled out by 1) the Index, 2) the Introduction, and 3) the Scope in the preceding pages of this guide.

The inspector will be thinking in terms of several sites as his responsibility; the licensee usually in terms of his own specific site.

The <u>first step</u> in a general approach by the inspector or licensee is to consider a specific monitoring program for a specific site in relation to the Reference Radiological Monitoring Program presented herein (Fig. 1.1).

The <u>second step</u> is to be sure that all applicable regulations, guidelines, standards for decommissioning and verification of suitability for unrestricted release are at hand. A check of the *Federal Register*, Nuclear Regulatory Guides, NRC and EPA reports, correspondence with regulatory offices, consultation with specialists, subscription to private service, and so forth are ways of obtaining the latest updating.

The <u>third step</u> is to state clearly the objective if or to the extent that it differs from that expressed in the first paragraph of this Sect. 1.4.

The <u>fourth step</u> involves the formulation of a survey design and procedures to accomplish the objective in terms of specific site peculiarities or history. Design and procedures for indoor areas tend to differ in some respects from those for outdoor and are usually formulated separately.

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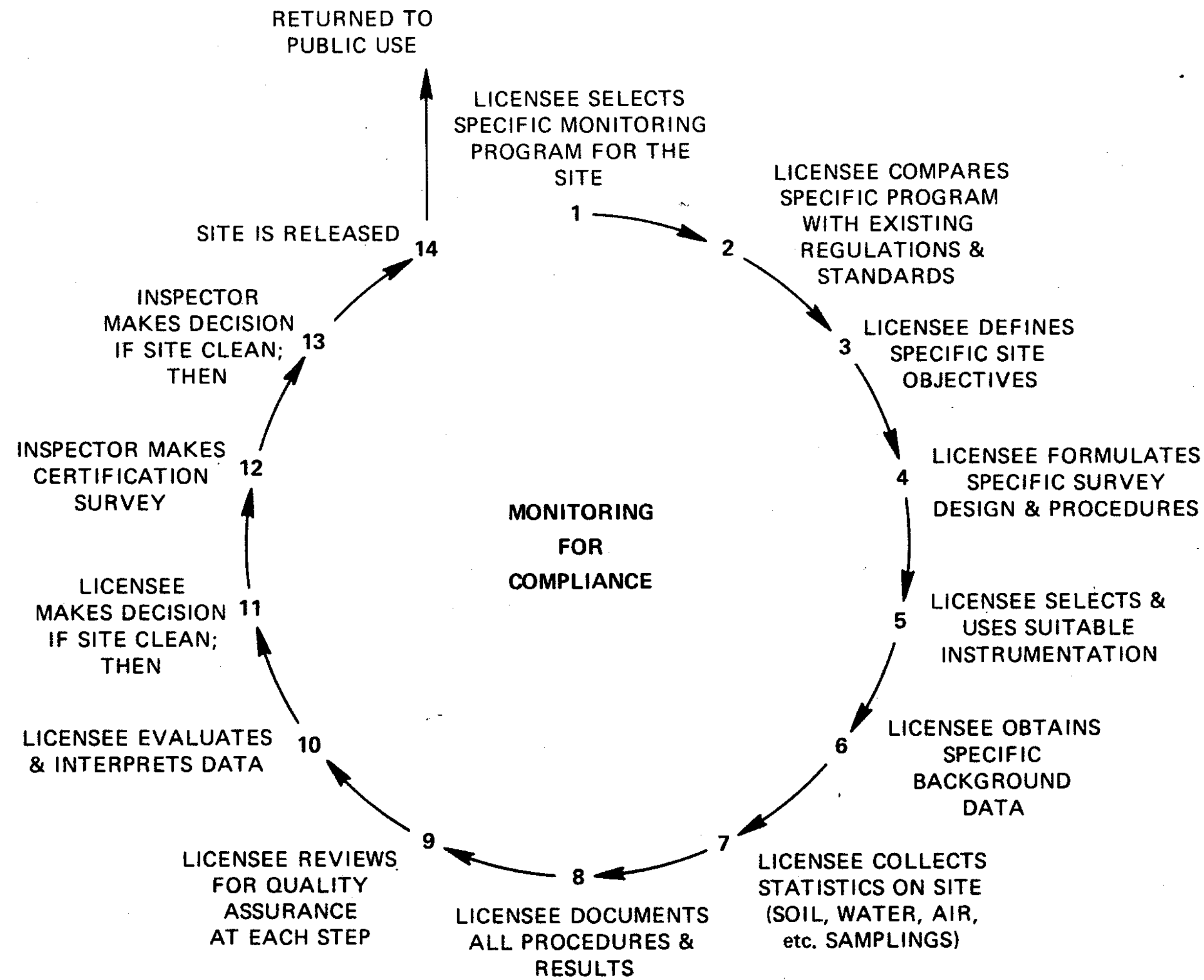

Fig. 1.1. Flowsheet for general approach to monitoring for compliance with decommissioning criteria

The fifth step is selection, calibration, and use of suitable equipment for the job, unless contracted out to someone who supplies the necessary hardware and software. Small licensees with fewer than 5 or 10 employees, small radiological operations and sites not much more than perhaps 0.01 km^2 (2.47 acres or 1 hectare) will not need as much automated equipment as large and complex operational sites.

The sixth step requires a good characterization of the natural background surrounding the site area, preoperationally if possible; otherwise from operational and postoperational surveys.

The seventh step is collection of postoperational statistics on the site: results of soil, water, air, and other media field readings and laboratory analyses for radiation and emitters responsible for the radiation fields. Similar statistics taken during the operational phase of the site help to extrapolate from higher to near-background levels. A preliminary radiological survey and/or sufficient prior information is needed for a statistical design that will optimize confidence in the results and minimize the likelihood of overlooking significant amounts of radioactivity that could be interpreted as a future hazard potential. For old or abandoned sites prior information may be scanty. New sites will have better documentation.

The eighth step requires good documentation of all procedures and results, including the first seven steps above, and should result in lower final survey costs.

The ninth step reviews for quality assurance purposes all preceding (and successive) steps to ensure confidence in the data to be evaluated and interpreted.

The tenth step by the licensee is that of data evaluation and interpretation relative to regulatory guides and standards to assess radiological status of the post-operational site ready to be certified for unrestricted (or restricted) release.

The eleventh step is decision by the licensee that the site is clean and ready for the certification survey by NRC. At this point, work of the licensee is essentially complete.

The twelfth step is then a certification survey by the NRC inspector, after having reviewed all of the steps taken by the licensee to ensure that the site is clean.

The thirteenth step is decision by the inspector that the site is indeed clean and ready for unrestricted use, or in rare cases that more cleanup is needed, or that the site should have restricted release, for purposes to be specified in the deed for the site.

The fourteenth and final step is release by the inspecting agency for the stated purpose, such as unrestricted release.

The first eleven steps are common to both the licensee's final survey and the inspector's final (certification) survey. The major difference between the two lies primarily in the larger sample sizes of licensees. The inspector's province is that of auditing the licensee's data, analysis and interpretation, and of comparing and confirming licensee results against the inspection survey, which not only confirms existing grid results reported by licensee, but may also sample at other locations. If agreement is statistically sound for data taken at the same locations by licensee and by inspector in the same manner, and if there is no evidence (at the same or different grid points and/or survey blocks) that above-background activity exists at a level sufficient to be of future concern, then the main potential obstacle to release of the site will have been eliminated.

Quality assurance on the entire monitoring cycle, Fig. 3.9, including the inspector's report, resides finally with the Commission or responsible department head.

The preceding steps of the monitoring cycle are summarized in flowsheet form in Fig. 1.1.

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*Available for purchase from the NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission, Washington, DC 20555, and/or the National Technical Information Service, Springfield, VA 22161.

**Available free upon written request to the Division of Technical Information and Document Control, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

2.0 OBJECTIVES OF THE MONITORING PROGRAM

This manual is concerned with (1) a Verification or Certification Inspection, and (2) a licensee's Termination Survey as defined in Section 1.2. The NRC inspector's audit of the site history up to and including the licensee's final survey generates the prior information needed by the inspector to plan, carry out, and interpret his verification inspection. The NRC inspectyor then does an inspection which will include, in all probqbility a minor survey but will consist largely of verifying the licensee's survey and inspecting other items for clearance. If the site was cleaned up to specifications for unrestricted release, as demonstrated by a properly executed final monitoring survey of the site by its licensee, then an independent field sampling check on the licensee's results by the inspector should confirm this, and the site can then be released. However, if any inconsistencies are found, then one or several options must be invoked: (1) discrepancies must be shown to fall within expected statistical sampling variability; (2) an accidental or systematic error at one or more steps of the quality assurance cycle must be identified which would explain the discrepancy; (3) additional sampling may be needed by the licensee and/or inspector; (4) additional information on the site's entire operational history may be needed if available and not previously utilized; and (5) the survey design chosen and implemented may have been inadequate and is in need of reassessment.

More specific objectives are covered in Sections 1.1, 1.3, and 1.4.

3.0 SURVEY DESIGN AND PROCEDURES

3.1 Preliminary Survey

It is important to conduct a relatively brief preliminary study of the site, at some time before the formal survey, in order to formulate plans for an efficient, comprehensive survey. During the preliminary survey, decisions are made concerning logical divisions of the site into separate survey units or strata. A survey unit may consist of a tract of land, one story of a building, a roof, a loading dock, or any area naturally distinguishable from the remainder of the site. Since some minimum number of measurements are to be made in each unit, the site should not be divided into a prohibitively large number of units. In particular, several adjoining rooms could be combined as one unit. If possible each unit should cover an area of at least 30 m^2. Dimensions of the survey units are obtained so that a scaled drawing of each unit can be prepared prior to the formal survey.

During the preliminary study of the site, each survey unit is given a brief beta-gamma and gamma survey. For indoor areas, direct alpha measurements are also made. Individual measurements are made at roughly uniformly spaced points. Then the averages $\bar{x}(\alpha)$, $\bar{x}(\beta\text{-}\gamma)$, and $\bar{x}(\gamma)$ and the corresponding sample standard deviations $s(\alpha)$, $s(\beta\text{-}\gamma)$, and $s(\gamma)$ are computed for the alpha, beta-gamma, and gamma measurements, respectively. For indoor areas, the maximum (M) of the set $s(\alpha)/\bar{x}(\alpha)$, $s(\beta\text{-}\upsilon)/\bar{x}(\beta\text{-}\gamma)$, $s(\gamma)/\bar{x}(\gamma)$, 0.82 is found. If all measurements are at background, set maximum M = 0.82; the quantity 0.82 will lead to at least 30 measurements. The maximum number of survey blocks needed in the survey will be given by

$$N - 45\ M^2 \ . \tag{3.1}$$

This statistical approach was used in the FUSRAP surveys and is documented in refs. 1 and 2. For outdoor areas, the variance of the preliminary measurements can be used to establish strata boundaries which will be the survey units for the formal survey. A more detailed discussion of stratified random sampling can be found in Section 3.5.

During the preliminary survey, samples of contaminated soil, water, and building material (if any are found) are collected and returned to the laboratory for determination of the types of contamination. The design of the formal survey requires some knowledge of the type of contaminant on the site.

A preliminary survey is essential for old sites, such as operated in World War I or II, where accountable licensees or their records are inadequate or no longer available. For newer sites of the 1970's and 1980's under NRC regulations and guidance, prior information from licensees and in NRC files may in some cases be adequate to dispense with a preliminary inspection survey. The final survey by the licensee or its designated representative probably will have available prior surveys before, during and after decommissioning steps to use as preliminary surveys for the final one. One basic purpose of a preliminary or prior survey post-operationally, is to perform a land survey for the purpose of dividing the site into survey blocks using suitable grid point markers such as wood stakes, small flags, or other marking devices, so that readings and samples can be referenced properly. The FUSRAP surveys tended to use a site grid for systematic sampling, which can be expensive if the site is large and survey block sizes small. From a preliminary survey or from prior surveys before the final licensee and inspector surveys, stratification of the site for random instead of, or in conjunction with, systematic sampling can be designed, depending upon how much information is known about the site (see also Section 3.2.3). The principle of systematic or of stratified random sampling can be used indoors, but with smaller survey block sizes.

3.2 Survey Design

The preliminary survey must be an integral part of the overall survey design if the final certification survey is to be no more than a sampling of the licensee's final survey. For newer sites, the licensee's final survey could well be the inspector's preliminary survey. For older sites with little prior information and no active licensee available, the inspector will then need to make a preliminary survey. For a licensee, the preliminary survey will usually mean a survey taken immediately before the licensee's final survey. A preliminary survey ensures the presence of grid markers on the site for defining survey block numbers and locations, and a grid map of the site for locating and recording preliminary air beta and gamma readings, and the analytical results on a few randomly selected soil samples to confirm any prior information about the sites radiological conditions during or after decommissioning steps have been taken. The preliminary survey aids in deciding how to sample the site, that is, whether by random sampling, stratified random sampling, systematic sampling, some combination, and so forth. If little is known about the sites radiological condition, then an expensive systematic sampling, block by block, may be indicated. If it is known that only certain areas of the site have potential for significant contamination, then a stratification approach may be in order. If contamination originates from a central source as from a tailings pile, burial spot, underground test explosion, etc., a simple random sampling assuming exponential falloff modified by wind or water patterns might be considered.

While a monitoring program specifically designed to verify compliance with decommissioning criteria has certain unique features, it also has many principles in common with other radiological surveillance programs.[2] Many sampling and measurement techniques or procedures are applicable to environmental surveillance in general. Much of the material on quality assurance and data, including statistical, analysis would generally apply.

3.2.1 General approach

Elements of a survey design include (1) sampling techniques, (2) external radiation measurement, (3) soil sampling, (4) water sampling, (5) air sampling, and (6) measurement techniques. Statistical design is covered in Section 3.5. A good general approach to elements of a survey design can be found in ref. 4.

3.2.1.1 Sampling techniques. Substantial information has been published on sample collection procedures. Only a few points covering elements of accepted practice are discussed here. The key to correct assessment of the radiological status of a given site is the procurement of representative samples and, consequently, data of the environmental media of interest.

Sampling locations are best selected randomly in order to describe the site without bias. Occasionally, this results in the selection of an inaccessible or otherwise undesirable site such as a large rock where a soil sample is to be taken. Provision must be made beforehand to cope with such conditions. In general, this can be handled by having surplus randomly selected locations which replace the problematic location. In practice, this can be done by picking 10% more random coordinates than necessary (i.e., 10% more than the requisite number of samples) and using the coordinates in the order generated until an "impossible" location is encountered. This location may be skipped and the next pair of coordinates used. This procedure continues until the requisite number of samples are acquired.

Consistency in taking samples requires careful attention to detail in sampling procedures. The procedures must be written clearly and concisely, but with sufficient detail that there can be no unacceptable alternative that has not been precluded by specification. For example, care must be exercised to prevent contamination of a sample. It is easy for samples to get cross-contaminated in the field. A sampling tool should not be used on two consecutive samples without cleaning. Samples must be separated and packaged promptly to avoid mixing or confusing with other samples. Field labeling with identifying marks such as coordinates of location, data, and other pertinent data or remark, is critical to the production of uncontaminated and usable samples.

One common difficulty in sampling is the loss of radionuclides to apparatus and/or container surfaces through chemical, physical, and/or biological action. Selection of relatively nonreactive and nonretentive materials and the minimization of areas of sample contact and of sample storage time are of value, as is flushing of containers with the sample stream before final collection of grab samples. Perishable samples which must be preserved for later analysis should be refrigerated or chemically preserved[5] with proper caution not to affect any radiochemical analysis which may be required later.

3.2.1.1.1 External radiation. In most cases, gamma tends to be the main source of external radiation exposure because of its more penetrating nature than alpha or beta, especially with ^{60}Co and ^{137}Cs. Where strong beta emission is present, the monitoring program needs to be correspondingly more responsive. At sites where dose rate is about 5 microrads/h, assuming 0.956 rad/R, in situ gamma spectrometry may provide sufficient discrimination[6] to distinguish an annual incremental dose equivalent of 5 millirems, but many of the EG&G reports (Table 4.3) give background gamma levels as high as 12 μR/h. The range of natural background variability at a given site determines whether a dose equivalent of 5 to 10 millirems/y is feasible and cost-effective. Statistical methods in Sects. 3.4, 3.5, and 5.3 provide some help. The ability to differentiate artificial enhancement from natural background needs further study, especially for external gamma due to nuclides which also occur naturally.

Integrating dosimeters include thermoluminescent dosimeters (TLD), film, and ionization chambers; however, TLD is the dosimeter of choice based on demonstrated sensitivity, reproducibility, reliability and stability.[7] An American National Standards Institute (ANSI) standard[8] gives performance, testing, and procedural specifications for TLD's in environmental application. Corrections must be made for transient exposures. Specific survey techniques and their sensitivies are covered in Section 4.2.

3.2.1.1.2 Soil sampling. For termination surveys of land areas, soil sampling will constitute one of the most significant parts of the total survey. In many cases, assessment of both surface and subsurface radionuclide concentrations is required. Surface sampling can be used to assess the amount of deposition of radioactive material from an effluent stream. Alternatively, special procedures have been developed for assessing surface contamination by direct instrument measurements. For example, a portable phoswich[9] detector has been developed to survey large surface areas for possible plutonium contamination. The use of soil sampling for the same kind of assessment is provided by the NRC.[10] This guideline calls for surface samples of 5 cm depth, which may not be generally applicable since others have used depths of 1-10 cm.

In general, coring will be necessary for an assessment of subsurface contamination. This technique consists of the use of a special tool to sample soil as a function of depth. Care must be exercised to keep samples from different depths uncontaminated and identifiable. The specific coring techniques will depend on the composition and consistency of the soil to be sampled. Some coring procedures are described in an NRC guideline[10] and elsewhere.[11] For certain radionuclides, it is possible to determine subsurface concentrations by a logging procedure. In this procedure a detector is lowered down into a penetration in the soil and the radiation level is related to the concentration of radionuclide as a function of position (depth). Details of coring and logging are provided in Section 3.3.2.1.

3.2.1.1.3 Water sampling. Sampling of water should include surface and groundwater sources as well as the potable water supply. Standardized sampling procedures are covered in several manuals.[5,12,13] A major concern is that of obtaining a representative sample, especially in view of the fact that most of the samples for a decommissioning survey will be grab samples. If possible, a continuous proportional sampling device should be used for streams, rivers or other continuous liquid effluent pathways. This sampling could continue at least for the duration of the the site survey.

Water should be sampled from every accessible source on the site. In addition, groundwater that seeps into core holes should be sampled. Primary drainage pathways should be sampled upstream from the site (if applicable), on the site, and downstream from the site.

The size of an individual sample to be taken will depend on the analytical techniques used; however, a 3.5 liter sample is generally recommended. Larger samples are needed when sample splitting for replicate analysis is anticipated.

Care should be exercised to prevent extraneous material such as sediment, floating debris, well casing corrosion, etc. from entering the sample. An alternative is to consider filtration of the water sample immediately after collection, saving any natural sediment of the original environment.

Under some circumstances, it will be necessary to preserve the sample by addition of chemicals. Appropriate references[5,10-13] should be consulted for specific cases since this problem can be exceedingly complex. For example, acids added as biocides can oxidize iodide to iodine, resulting in volatilization loss.

3.2.1.1.4 Air sampling. Radioactivity in air may be composed of a large variety of different radionuclides in several physical states. In general, air contaminants can be divided into two broad classes: (1) gases and (2) particulates (and occasionally liquid aerosols). Since the physical and chemical behavior of radioactive gases and particulates do not differ significantly from those of nonradioactive gases and particulates, the same properties and characteristics are used for sampling.

Three methods of air sampling which find common application are grab sampling, continuous sampling, and integrated sampling. Grab sampling refers to the collection of an air sample at a point in time and space. Grab sampling provides only a single concentration measurement with an averaging time that is equal to the duration of the sampling. An advantage of grab sampling is that samples can be taken from many locations simultaneously and analyzed afterward.[8] Continuous sampling produces a profile of the pollution concentration as a function of time governed by the response time of the instrument and the readout cycle of the system. Continuous sampling provides information on short-term fluctuations in airborne concentrations. Integrated sampling provides for "long-term" averaging of radionuclide levels. Integration periods can run from hours to months.

Several techniques exist for sampling radioactive gases each with its own advantages and disadvantages that should be recognized and compensated for. Instantaneous or grab samples are collected with evacuated flasks or by water displacement. Continuous or integral sampling makes use of techniques such as adsorption, absorption, and freeze-out. The adsorption technique commonly is used for iodine and a few other radioactive gases such as those containing ^{14}C (notably CO_2, CH_4). The freeze-out technique has been successfully applied to noble gases (such as radon), carbon dioxide and tritium as water vapor.

Other techniques exist for particulate sampling. These include sedimentation, inertial devices, electrostatic precipitation, and filtration. Inertial devices include the centrifugal collectors such as cyclones, impingers, and impactors. Filtration is versatile and requires a minimum of specialized equipment. A variety of filters are available to sample particulate media with various physical and chemical characteristics.

3.2.1.2 Measurement techniques. A large variety of measurement techniques are available for determining the radioactivity in samples which have been taken from a site which is to be decommissioned. The measurement techniques of choice will depend on the media being sampled, the type of radiation or radioactive contamination, the number of samples to be analyzed, the required sensitivity, accuracy and precision, and the rapidity with which results are needed. Some general guidance is provided below for the measurement of external radiation and of soil, water, and air contamination.

3.2.1.2.1 External radiation. A portable survey meter using a NaI scintillation probe may be used to measure low-level gamma radiation exposure. One acceptable scintillation probe is a 3.2 cm-diam × 3.8 cm-long NaI crystal coupled to a photomultiplier tube. This probe may be connected to a suitable ratemeter or scaler to compose a unit capable of measuring radiation levels from a few to several hundred microroentgens per hour. Typical calibration factors are of the order of 500 cpm/μR hr^{-1}. The required sensitivity for an instrument to measure external gamma radiation exposure rates is of the order of a few microroentgens per hour with the capability of detecting variations of ±1 μR/hr. However, background itself may vary spatially and temporally ±5 μR/hr, as in the vicinity of ground faults or with diurnal variation in radon.

3.2.1.2.2 Soil analysis. Samples of soil may be analyzed using radiochemical methods.[11,14] These methods are radionuclide specific and sometimes involve long, tedious extractions or fusion. The advantages of radiochemical analysis are high specificity and high sensitivity.

One can frequently avoid the pitfalls of chemical methods by employing direct gamma-ray analysis of soil samples, provided, of course, that the radioisotope(s) of concern emit gamma rays. Many different gamma rays can be analyzed simultaneously provided their energies are sufficiently far apart to be resolved by the detection system.

Soil samples collected on-site are packed in plastic bags and returned to the laboratory where they are dried, typically for 24 hr at 110°C and then pulverized to a particle size no greater than 500 μm in diam (~35 mesh). Next, aliquots from each sample are transferred to appropriate containers, weighed, and counted using a NaI(Tl) or Ge(Li) detector[15] and a multichannel analyzer. Using a 50 cm^3 Ge(Li) detector in a graded shield and a 300 cm^3 sample, it is possible to measure 1 pCi/g (0.037 Bq) of ^{226}Ra (or ^{232}Th) with an error of ±10% or less and ^{227}Ac with an error of ±30%.[16]

Neutron activation analysis of uranium by delayed neutron counting[17] has been applied on a routine basis to a great variety of samples with considerable success, although of limited usefulness in routine termination surveys.

3.2.1.2.3 Water analysis. The analytical method used for the determination of radionuclide concentration in water will depend on the type of radiation, the chemical characteristics, the anticipated level of activity, and the quality of the water. Water that contains few dissolved solids or salts is amenable to volume reduction by evaporation to increase the radionuclide concentration provided the isotopes of interest are not volatile. In contrast, water from the vicinity of uranium mill tailings piles, highly alkaline and brackish sources, and sea water do not tolerate evaporation because of near saturation conditions.

In many cases concentration of the radionuclide is a prerequisite for measurement and some method[18] such as precipitation or adsorption is required. Ion exchange techniques are commonly employed as a means of removing interfering ions.

Direct measurement of radioactivity in water is an alternative to chemical separations in cases where sensitivity and specificity is not a problem. Water volumes of up to several liters may be placed in a Marinelli beaker[19] and counted with either a NaI(Tl) or Ge(Li) detector; the former detector would have superior sensitivity, but a Ge(Li) detector would have superior resolution. A number of gamma-ray emitters may be analyzed conveniently and quickly using this method.

3.2.1.2.4 Air sample analysis. When one is dealing with complicated mixtures of radionuclides such as are found in environmental air samples, instrumental techniques for identification become extremely difficult, if not impossible. As a result, for positive determination of the type and quantity of radionuclides present, chemical analysis of air samples must be undertaken. A number of variations in analytical procedures are available; however, all procedures have two characteristics in common: (1) the high specificity of the procedures for the nuclide of concern, and (2) the high purity of the recovered product. The chemical analysis of air filters or other samples is a very tedious and difficult operation under the best of conditions. The problems of analysis are increased greatly when a large number of radionuclides are to be determined at low concentrations. Thus, radiochemical analysis of air samples should be performed only when other simpler methods of analysis will not provide the desired information.

The gross beta activity of air is composed of both natural and man-made beta emitters. Thus, if one wants to determine the extent of man-made contamination, the activity due to artificial radionuclides must be distinguished from that due to natural radioactive materials. The natural radioactivity in air is primarily a mixture of ^{220}Rn (radon) and ^{222}Rn (thoron) and their associated daughter products. Filtration collects only the particulate daughter products which have relatively short half-lives (0.5 hours for ^{214}Pb and 10.6 hours for ^{212}Pb). By judicious selection of counting times the problems associated with natural emitters can be minimized. Sample counting for beta emitters is frequently done with an internal proportional counter.

In some cases (e.g., uranium mill tailings sites and radium contaminated sites), the analysis of radon and radon daughter products themselves will be of primary concern. Further details on radon and radon daughter measurements are contained in Sections 3.3.2.3 and 4.2.2 of this report.

Weak beta emitters such as ^{3}H or ^{14}C are assayed by either gas counting or liquid scintillation counting. The beta emitter is actually incorporated into the counting gas in ionization chambers, proportional counters, or Geiger-Mueller counters.

Some gamma emitters may be analyzed by direct counting of the sampling canister using a NaI crystal.

Alpha emitters on filter media may be counted directly with scintillators such as ZnS or with surface barrier detectors which provide excellent energy resolution to identify specific alpha emitters. If the sample is from a dusty environment, the analysis may not proceed directly due to excessive self-absorption. In that case, separation of the pure alpha emitter before analysis may be needed.

3.2.1.3 Sampling and measurement of surface contamination. Surface contamination refers to radioactive material which is lying on, attached to, or embedded in surfaces of equipment, materials, and facilities. Surface contamination may be either removable (i.e., lying on or loosely attached to surfaces) or nonremovable (i.e., firmly attached to or embedded in material).

Both alpha and beta surface contamination usually can be detected by direct monitoring methods. In some cases (such as where high background radiation levels prevail, or available instrumentation lacks the required sensitivity, or where lack of accessibility prevents instrumental monitoring), an indirect or smear method may be used. Both methods should be applied where possible to give a complete assessment of surface contamination. The direct monitoring method gives an estimation of the total contamination (both removable and nonremovable) whereas the indirect method gives a measure of the removable contamination.

Direct monitoring of a surface is done by making sequential measurements at the surface with a survey meter. In practice for beta monitoring the detector is slowly swept over the surface while for alpha monitoring, the detector is held stationary for a period of time sufficient to give a statistically significant measurement. Aural indicators of instrument response should be used while monitoring.

The indirect monitoring method involves the smearing or wiping of a surface with soft absorbent material, such as filter paper, to partially remove radioactive contamination from a surface. The large variability in fraction of radioactivity removed causes quantitative estimation of surface contamination by this method to be uncertain. The smear sample is taken to a remote radiation detector for counting and assessment of contamination.

More specific guidance on the sampling and measurement of surface contamination is provided by ANSI.[20] The ANSI document discusses alpha and beta monitoring procedures and makes recommendations on proper instrumentation.

3.2.2 Indoor areas

The survey design of an indoor area represents a concentrated effort in a smaller space. Like an outdoor survey, horizontal walking surfaces are monitored, namely, floors and roof. In addition, vertical walls, ceilings, support beams, equipment, and air and sewage ducts complicate the survey somewhat. It may be convenient to consider all walking surfaces as one stratum, non-walking surfaces as another stratum. Smear sampling of soil surfaces is not a common outdoor procedure, but is very common indoors, especially where alphas and weak betas are involved. Consideration needs to be given to smear or other type sampling of duct and drain pipe inside surfaces, especially where sharp angles and constrictions occur. Since indoor areas to be covered are generally smaller than outdoor areas, at least for sites with significant acreage, the survey block dimensions marked out can be and indeed need to be smaller, commonly 1 m × 1 m. The potential for residual radioactivity indoors tends to be higher because the potential for extensive dispersal is limited by containment within the buildings. Relatively inaccessible horizontal surfaces such as overhead beams need special consideration when designing a smear or dust collection program. Air convection patterns in the building may help in deciding where to do extra sampling. Additional factors to consider in designing an indoor survey are presented in Section 3.3.1.

3.2.3 Outdoor areas

An important part of an outdoor survey design is the statistical basis. Where practical (significant site heterogeneity of the key nuclide(s) distribution), stratified random sampling should be tried. The stratification approach by geography is covered in Section 3.5.

Another important aspect of survey design is the total sample size (air readings, soil nuclides) for the entire site, since it has an important bearing not only on statistical confidence but cost. When the site is stratified, the total sample size is subdivided (allocated) among the various strata according to hazard potential of the stratum.

The total sample size required (for example, the number of soil samples required for ^{90}Sr analysis, or the number of beta, gamma air readings needed), is controlled by the variance. Sometimes it is more convenient to work with the square root of the variance, or the standard deviation, which may be defined as:

$$s = \frac{\Sigma(x-\bar{x})^2}{n-1} \tag{3.2}$$

where

s = sample standard deviation;

n = sample size;

$\bar{x}$ = sample mean; and

x = individual value.

The required sample size (n) for a given sample standard deviation(s) depends upon the required confidence level, and the allowable error on that confidence level. Walpole and Meyers[21] express sample size in terms of standard deviation, confidence level, and allowable error as follows:

$$n = \frac{z_{a/2}(\sigma)}{e}^{2} \tag{3.3}$$

where

n = required sample size,

$z_{a/2}$ = confidence tails in terms of z-score,

s = unknown true population standard deviation which is estimated by the sample standard deviation(s), and

e = error allowed on the standard deviation.

Using this equation, a table (such as Table 3.1 illustrated) can be constructed. As the allowable error decreases, sample size must increase for a given standard deviation and stratum. For example, given three strata (1, 2, and 3) with respective standard deviations of 0.3, 0.6, and 0.9, the sample size for stratum 1 should be 35; for stratum 2, 138; and for stratum 3, 311; if the required confidence level is to be 95% with an allowable error of 10% in each case. Using a formula such as the preceding Eq. 3.3, gives a statistical basis for selecting sample sizes that will maintain a high confidence level and yet give a sample size that is not prohibitive. This can only be accomplished if the standard deviation is not too large. If it is, then an attempt should be made to redraw stratum boundaries to minimize within stratum standard deviation or variance. If this cannot be done, then one must live with larger sample sizes, or consider additional site cleanup to reduce the variance.

When systematic sampling of the entire site is to be used, as would likely be the case for a site about which little is known, sizes of the survey blocks will control the total sample size, where the same number of samples are to be taken per block regardless of block size. Block size, then, is determined from whatever limited prior information is available upon which to assign block sizes. For example, not more than 5 × 5 m for areas behind the former security fence, and between 1 and 3 m for inside areas, etc. The more prior information known about the site the lower the sample cost possible, subject to the above restrictions and other factors such as radiological half-life, radiotoxicity, and ease

Table 3.1. Sample size vs standard deviation at the 95% confidence level[a]

Allowable error (%)	Standard deviation of sample vs. sample size		
	0.3	0.6	0.9
50	2	6	12
25	6	22	50
20	9	35	78
10	35	138	311
5	138	553	1245
2	863	3453	7770

[a]($z_{a/2}$ = 1.96).

of environmental transport to man which are built into the standards and models approved by EPA, NRC, and other regulatory agencies.[22-24]

Whereas the licensee is likely to choose stratified random sampling as the basic design for outdoor sampling because of its potential for holding sample costs down on a statistically sound basis, the inspector whose sampling program can be much more modest (verification of an already established clean situation) is likely to use a simple random sampling over the entire site. At his discretion, however, he may decide to do extra sampling in an area of which he has reason for concern. Professional judgment is an essential adjunct to any statistical design.

Additional information on outdoor areas is presented in Section 3.3.2.

3.3 Survey Procedures

3.3.1 Indoor survey

For the final survey by licensee or the verification survey by the inspector, each indoor survey unit is divided into two subunits: (1) lower surfaces, comprised of floor surfaces, wall surfaces, up to a height of 2 m, and any other surface easily accessible to a surveyor standing on the floor; and (2) overhead surfaces, comprised of ceiling surfaces, wall surfaces more than 2 m above the floor, and all other surfaces not described in (1).

The floors and lower walls are divided by a rectangular grid system such as that shown in Fig. 3.1. The smaller blocks formed in this manner are referred to as "survey blocks," and the corners of the survey blocks are called "grid points." The choice of the particular grid system is guided by the following rules:

(a) No survey block should measure less than 1 m on a side. Survey blocks of less than 1 m on a side would require an impractically large number of measurements in the buildings.

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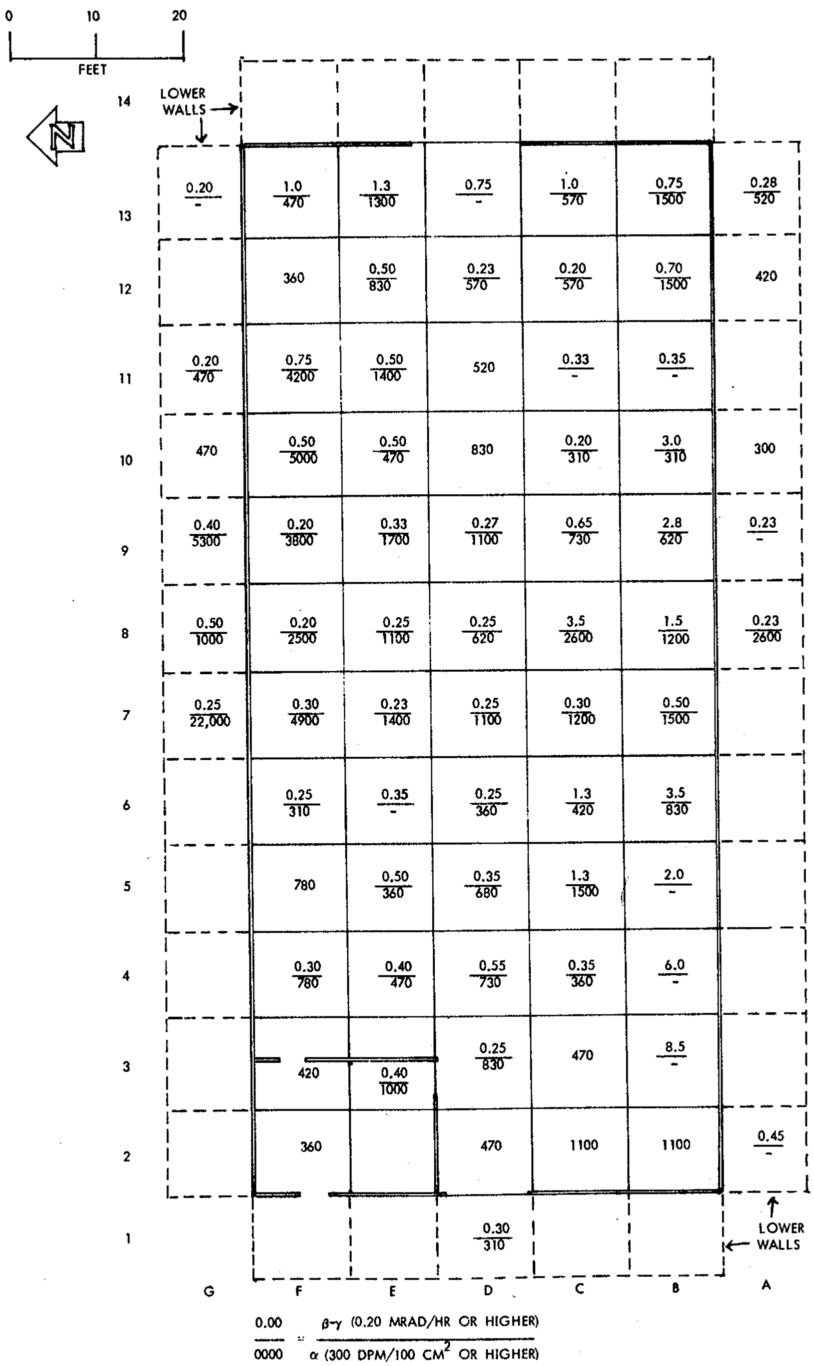

Fig. 3.1. Measurements made in a typical survey block.

(b) No survey block should measure more than 3 m on a side. Survey blocks larger than 3 m on a side could lead to large uncertainties as to the precise location of the contamination.

(c) There should be at least N survey blocks in the population (N defined in Eq. 3.1), unless this violates Rule (a). (Note that $N \geqq 30$.)

The radiological conditions to be characterized on the lower surfaces include alpha contamination levels (by direct reading), beta-gamma dose rates at 1 cm above the surface, external gamma radiation levels at 1 m above the floor, and removable alpha and beta contamination levels. Clearly, these radiological conditions are not independent, and best results are obtained by using a unified approach for the selection of survey points.

At 1 m above the center of each survey block, the external gamma radiation level is measured. At the surface in each survey block, five direct measurements each of alpha contamination levels, beta-gamma dose rates, and gamma radiation levels are made at uniformly spaced points in 1 m^2 area in the center of the survey blocks as shown in Fig. 3.2. (If the entire survey block has an area of approximately 1 m^2, then the "corner" measurements shown in the 1 m^2 area in Fig. 3.2 are moved 30 cm toward the center of the block.) For each type of measurement, the average value and the local varability in this 1 m^2 area can be estimated. For an area of only 1 m^2, it appears that five alpha or beta-gamma measurements will usually yield a good estimate of the average in that area. This is also in line with previous guidelines (see refs. 1 and 4 of Section 1) which required a knowledge of the average alpha or beta-gamma level. See Regulatory Guide 1.86 (Table I.1). For soil cleanup purposes, it is also necessary to specify soil limits in millibecquerels per gram (mBq/g) of soil, or picocuries per gram, as they can be related to total human dose rates (Sieverts/y or millirems/y) through validated and realistic pathway analysis. By "realistic", it is meant experimentally determined rather than theoretically calculated or assumed model parameters. As mentioned earlier (Section 1.1.2 on Regulatory Guidance),

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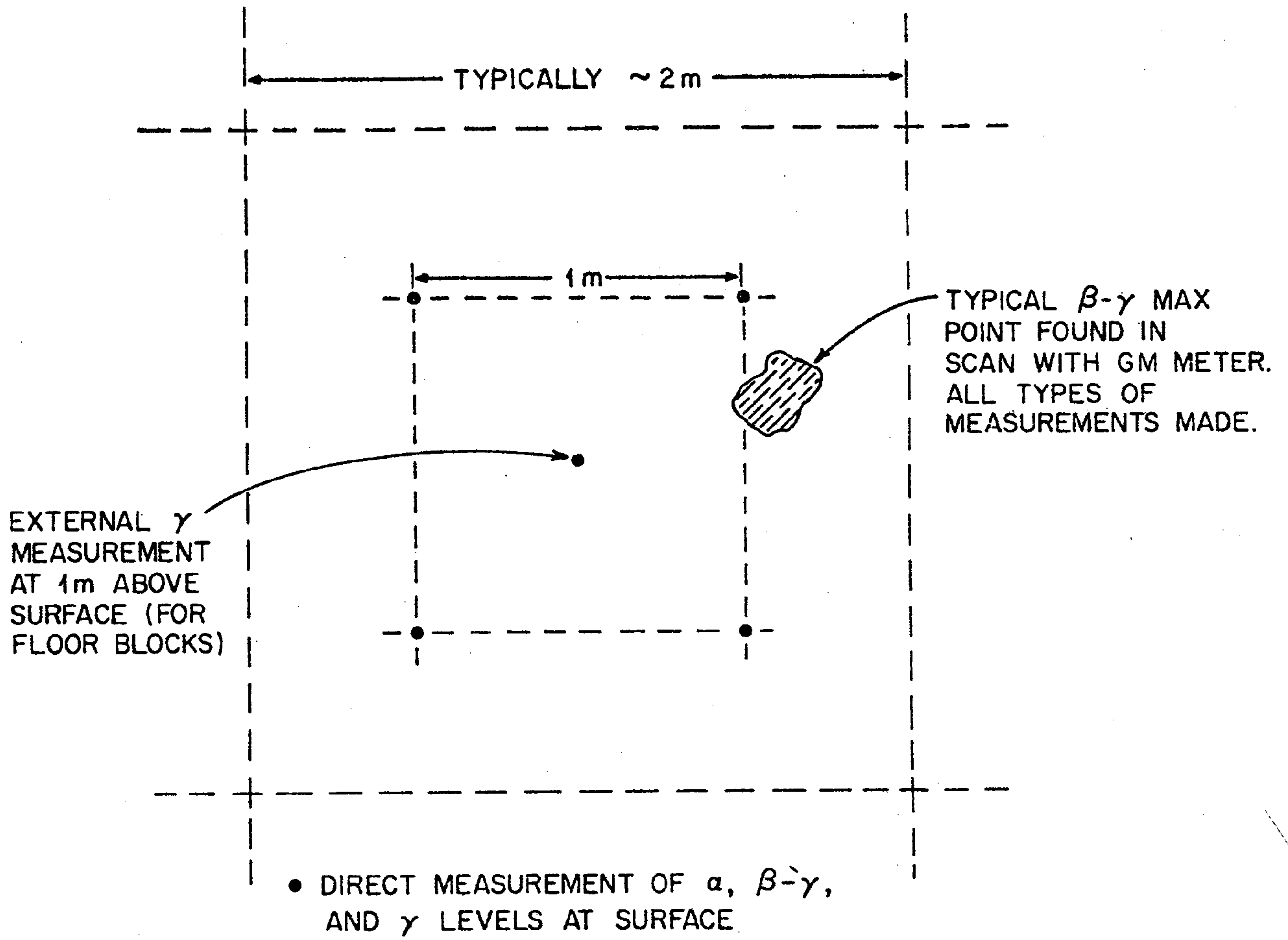

Fig. 3.2. Maximum observed beta-gamma dose rates and direct alpha measurements in survey blocks in a building contaminated with uranium ore raffinates.

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soil limit values are needed for all nuclides significant to nuclear facilities before this procedure can be implemented fully.

The survey block is next scanned with a G-M meter (open-window), the point showing the maximum reading (if any) is located, and each type of measurement (including smear samples of measurements of transferable alpha and beta contamination levels) is made at this "beta-gamma maximum point." Because of the interdependence of the conditions being considered, these measurements are likely candidates for the maximum or near-maximum of each radiological condition.

Although the surveyor records all measurements, some of the data should be reduced before results are reported. In particular, the average of five measurements of each type in each block should be reported as an "unbiased" measurement for that block, and the measurements at the "beta-gamma maximum point" should be reported as "biased" measurements. Smear or dust samples should be taken at some of the beta-gamma maximum points for correlation study or to utilize former correlation formulas.

Horizontal and vertical overhead surfaces usually show somewhat uniform contamination, but the horizontal surfaces often show higher contamination levels than do the vertical surfaces. The apparent reason for this situation is that contamination on overhead surfaces (unlike floor and lower wall surfaces) generally results from the settling out of contaminated dust particles in the air. A sufficient characterization of alpha and beta-gamma levels (both directly measured and removable) on overhead surfaces usually can be accomplished with 30 measurements of each type on vertical surfaces and 30 measurements of each type on horizontal surfaces, provided the points of measurements are uniformly spaced and spread over the upper surfaces.

Because smear and dust samples are more expensive to analyze than corresponding (matched) beta-gamma maximum readings, the ratio of beta-gamma maximum readings to smear or dust samples needs to be more than one. Sample size for smear or dust is similar to that for soil sampling, and is discussed in Sections 3.2.3 and 3.5 on Outdoor Areas.

A typical floor plan for an indoor survey is illustrated by Fig. 3.3, taken from an actual intermediate survey of a site. Since this was not the final verification survey of a completely cleaned up site, actual readings shown should not be taken as typical of a final survey. The figure also represents systematic sampling rather than simple random or stratified random sampling since the site was contaminated and in need of a thorough survey. The manner of data recording for an indoor survey is illustrated by Table 3.2. The following minimum data are needed:

1. Survey block numbers, identifiable on a scale drawing, and
   a) the building name or number;
   b) the building floor number;
   c) the surfaces surveyed; and
   d) types of measurements and the units (dpm/100 cm^2, millirad/h, and/or μR/h; mGy/h and microGy/h).

2. Name of surveyor taking measurements, date of survey, location data such as township, building location relative to the outdoor grid coordinates for the site as a whole, logbook pages for original data.

3. Surface smears, plaster chips, etc., taken, and the indoor block number from where they may have been taken, the container number, and whether matched to any air readings.

4. Type, model number, calibration data, sensitivity limit, and any other information needed about the portable survey instruments to interpret the data obtained with these instruments, and to ensure quality control on the data so obtained.

5. When a block surveyed is below the sentivitity of the instrument, the fact that such a measurement was made should be included as a significant datum.

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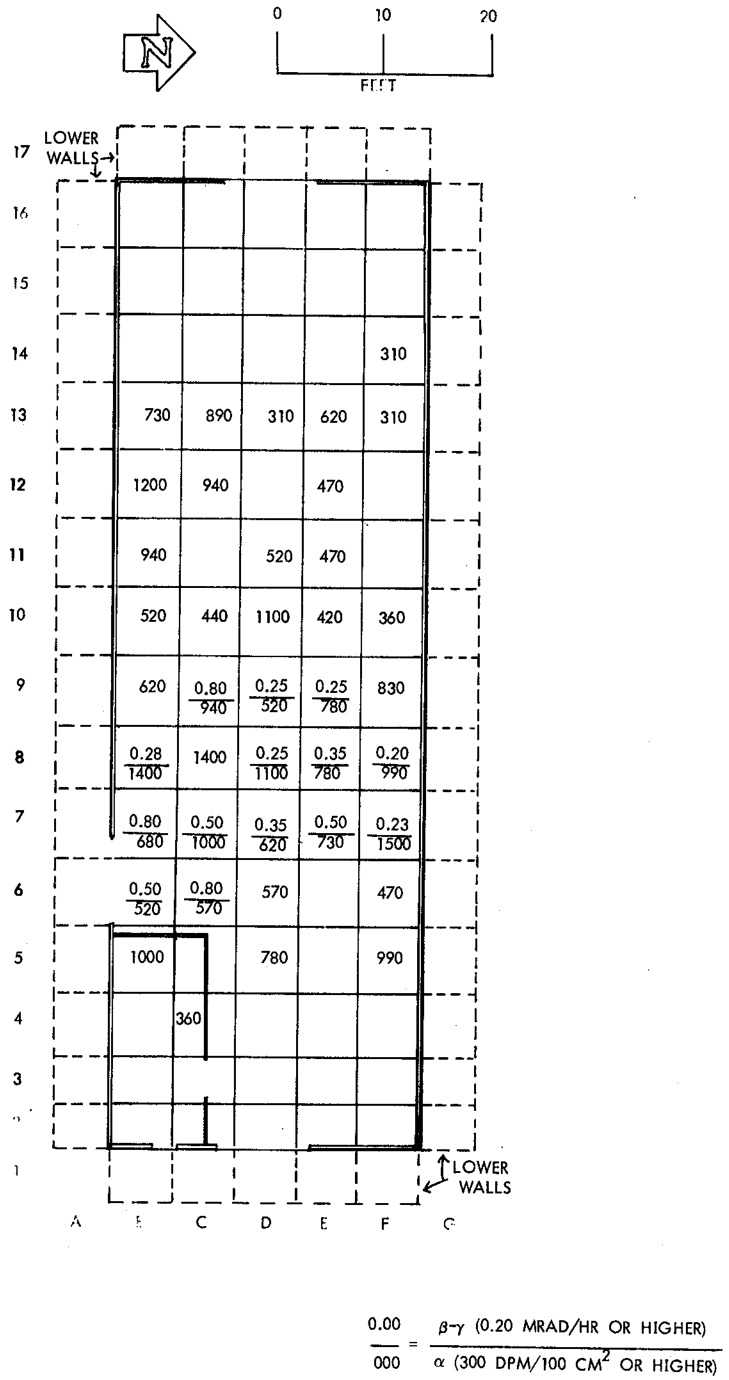

Fig. 3.3. Sample floor plan for an indoor survey showing which areas exceed applicable standards.

Table 3.2. Alpha, beta-gamma and external gamma radiation levels in Building 7, including floor and lower wall surfaces

Survey block	Directly measured contamination at center of block: Alpha (dpm/100 cm^2)	Directly measured contamination at center of block: Beta-gamma dose rate at 1 cm (millirad/hr)	Directly measured contamination surface at maximum beta-gamma point: Alpha (dpm/100 cm^2)	Directly measured contamination surface at maximum beta-gamma point: Beta-gamma dose rate at 1 cm (millirad/hr)	External gamma radiation level 1 m above floor (μR/hr)
A 2	100	0.05	100	0.45	NA[a]
3	100	0.08	NR[b]	0.08	NA
4	200	0.13	NR	0.13	NA
5	210	0.13	NR	0.13	NA
6	50	0.13	NR	0.13	NA
7	160	0.05	NR	0.10	NA
8	2100	0.15	2600	0.23	NA
9	100	0.15	210	0.23	NA
10	310	0.15	NR	0.15	NA
11	100	0.15	NR	0.15	NA
12	420	0.15	NR	0.15	NA
13	520	0.28	520	0.28	NA
B 1	210	0.05	NR	0.05	NA
2	620	0.10	1100	0.10	40
3	160	0.10	160	8.5	35
4	220	0.18	260	6.0	45
5	260	1.8	160	2.0	40
6	210	0.10	830	3.5	50
7	1500	0.35	940	0.50	75
8	880	0.25	1200	1.5	70
9	620	0.30	620	2.8	100
10	310	0.25	260	3.0	130
11	260	0.25	210	0.35	120
12	1500	0.20	1100	0.70	130
13	990	0.60	1500	0.75	220
14	160	0.15	NR	0.15	NA
C 1	50	0.05	NR	0.05	NA
2	1100	0.09	NR	0.09	35
3	470	0.08	NR	0.15	40
4	310	0.13	360	0.35	60
5	420	0.15	1500	1.3	80
6	420	0.13	310	1.3	75
7	1170	0.13	620	0.30	70
8	620	0.30	2600	3.5	50
9	260	0.08	730	0.65	55
10	310	0.11	310	0.20	55
11	210	0.15	260	0.33	90
12	570	0.15	100	0.20	85
13	570	0.40	210	1.0	170

[a]NA = not applicable.
[b]NR = no reading taken.

These data needs are also generally applicable to outdoor surveys. Additional illustrations are presented in Appendix IV, including approximate times needed for indoor surveys (Table IV-10), useful for cost estimation.

3.3.2 Outdoor survey

Many small outdoor areas, such as roofs, loading docks, or concrete pads, may be surveyed using the approach described for indoor surveying. Surveys of large tracts of land (e.g., greater than 3000 m^2) require a somewhat different survey procedure.

First the land is divided by a rectangular grid system such as that shown in Fig. 3.4.[16] This figure also shows that the site was divided into three geographic parcels (A, B, and C) or strata for sampling purposes. In this case, a common survey baseline was used. The choice of the particular grid system is guided by the following set of rules:

(a) No survey block should measure less than 5 m on a side.
(b) No survey block should measure more than 15 m on a side.
(c) There should be at least N grid points (N defined by Eq. 3.1, unless this violates Rule (a). (Note that $N \geqq 30$.)

At each grid point, beta-gamma measurements are made within 1 cm of the surface and a second gamma measurement is made at 1 m above the surface. These grid-point measurements are considered "unbiased" and are used to estimate average gross gamma and beta-gamma radiation levels on the tract of land. On most sites, each outdoor survey block can be quickly scanned with a gamma scintillation survey meter. However, if soil samples collected independently of the gamma and beta-gamma readings during the preliminary survey have indicated that the contamination consists largely of beta-emitting nuclides such as ^{238}U with its short-lived daughters, the survey block should be scanned with a G-M meter, with the open-window probe held no more than a few centimeters from the surface. If a maximum gamma (or beta-gamma) point in the survey block is found during the scan, gamma measurements at the surface and at a 1 m and a beta-gamma measurement at the surface are recorded for this

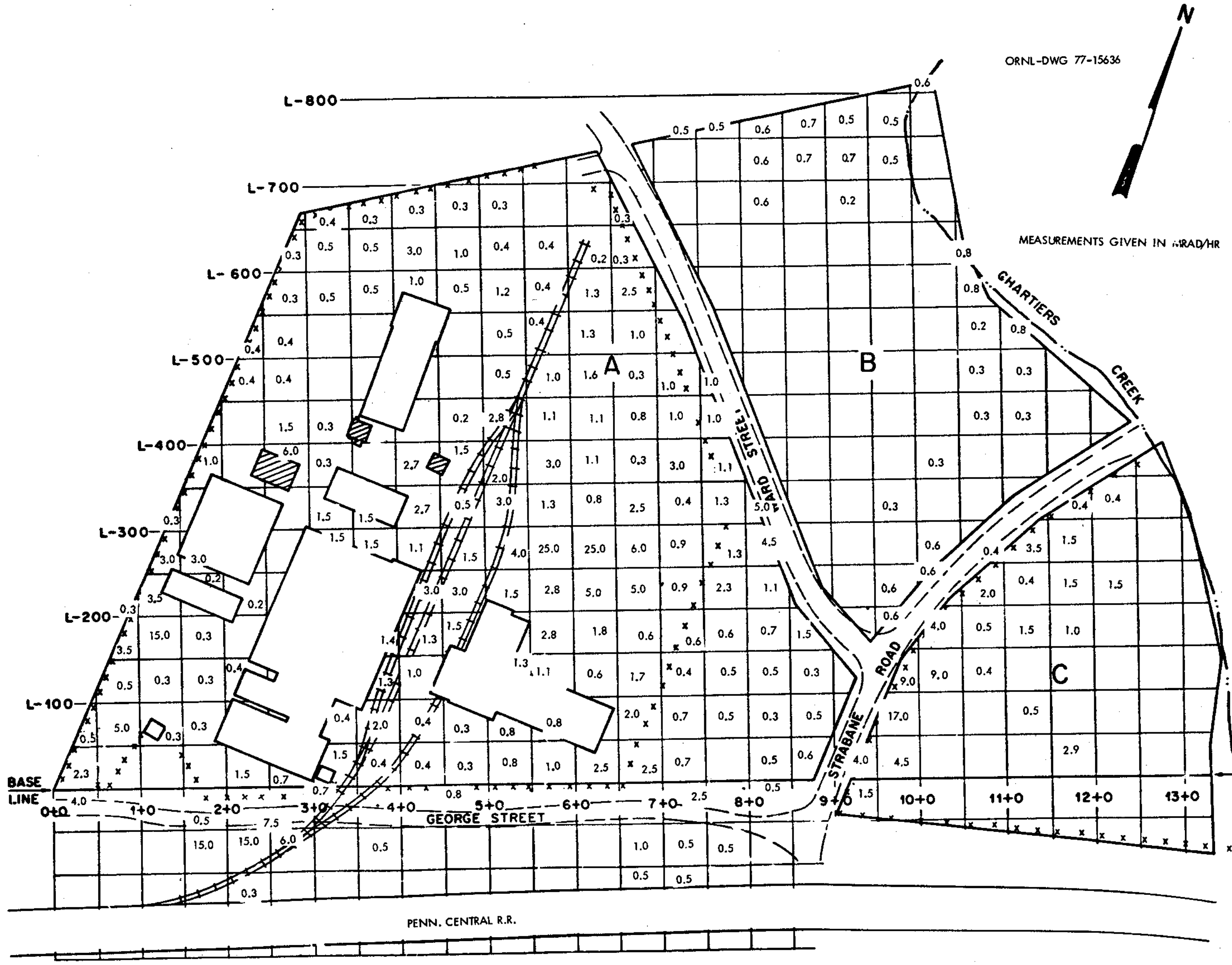

Fig. 3.4. Presentation of data showing which grid blocks exceeded applicable standard (0.2 mrad/h in this case).

point. These latter measurements are estimates of the local maxima of the radiological conditions under study.

The outdoor survey generally includes collections of surface soil samples for determination of radionuclide concentrations. These samples are taken in the upper 5 to 15 cm of soil. Maximum concentrations of radionuclides in surface soil are estimated from samples collected at points showing highest gamma or beta-gamma radiation levels. Average radionuclides concentrations are estimated from "unbiased" samples taken at randomly selected points within each strata. The selection of these sample points is discussed further in Section 3.5.

The general approach to monitoring procedure is essentially the same whether indoor or outdoor; (1) to divide the surface into survey blocks and (2) to take systematic readings at all blocks, or to select randomly a subset of the blocks for readings. Outdoor sampling involves surface soil samples scooped or dug from the first 0 to 15 cm of soil depth. In addition, water and air samples are taken, and in some cases plant and animal biota sampling to define radionuclides present or movement on- or off-site. Core drillings are also involved in outdoor work.

The entire site have been divided into survey blocks, commonly 10 m × 10 m, these blocks in turn can be subdivided into smaller blocks if prior information indicates the need. By transit survey, the entire site is staked out with markers (grid points) and a scale drawing made. Next, if stratification seems warranted in terms of local site heterogeneities, subdivision into three or more large survey units or strata on the scale drawing is made. Stratum 1 represents the highest potential hazard area from prior information on the site documented during the operational phase of the facility. This scale drawing can then be used for various recording and collating purposes.

Figure 3.4 shows one such application, namely, identification of survey blocks where beta-gamma readings exceeded an arbitrarily predetermined value. For the figure cited, this was 0.2 mrad/h for a partially cleaned up site, with residual contamination still so high and lack of prior information such as to require a systematic survey of all blocks. A cleaned up site presumably ready for a final certification survey by an NRC inspector would more likely be something like 0.05 mrad/h, assuming a background range of 0.01 to 0.1 mrad/h normally distributed, with an instrument lower sensitivity limit of 0.02 mrad/h. A beta-gamma instrument typically reads 30 to 40 c/m, with a calibration factor of 2000 c/m = 1 mrad/h, for uranium in equilibrium with its daughters (personal communications from H. W. Dickson, W. D. Cottrell, and T. E. Myrick at ORNL). It is assumed that the instrument sensitivity limit of 0.01 to 0.02 mrad/h represents background, with readings of 80 c/m or 0.04 mrad/h taken to indicate above background, with readings of 80 c/m or 0.04 mrad/h taken to indicate above background. There are several variables, location, depth, nuclide mix, and so forth, which affect beta-gamma readings. A statistical analysis of beta-gamma data from FUSRAP and other sources is needed. The FUSRAP data in general involve the naturally occurring nuclides and not those of reactor site interest.

Figure 3.5 illustrates the use of a survey unit (parcel) C for showing gamma gradients prior to complete decontamination, where over 50% of the C stratum was contaminated from 5 to over 50 times normal gamma background taken 100 cm above ground level, and assuming normal gamma for the area to be 10 μR/h. Such information prior to final cleanup and final licensee survey can be helpful to the NRC inspector in planning his or her certification survey.

Figure 3.6 presents a third application of the gridded map, namely to identify drill hoes for subsurface sampling.

Examples of data collected relative to map coordinates and marked locations are shown in Tables 3.3 and 3.4. The first table tabulates instrumental air readings of gamma at 100 cm and beta-gamma at 1 cm; the second table soil nuclide concentrations at various core drilling depths. Values shown are indicative of a contaminated site before final cleanup, and should be taken as representative of a methodology that has been applied in the field, and not of values that an NRC inspector or licensee would expect to find in a final site survey. Figures, tables, and data taken from a real site survey[16] were systematically surveyed for land parcels A, B, and C, representing convenient administrative subdivision rather than stratification. Prior information on

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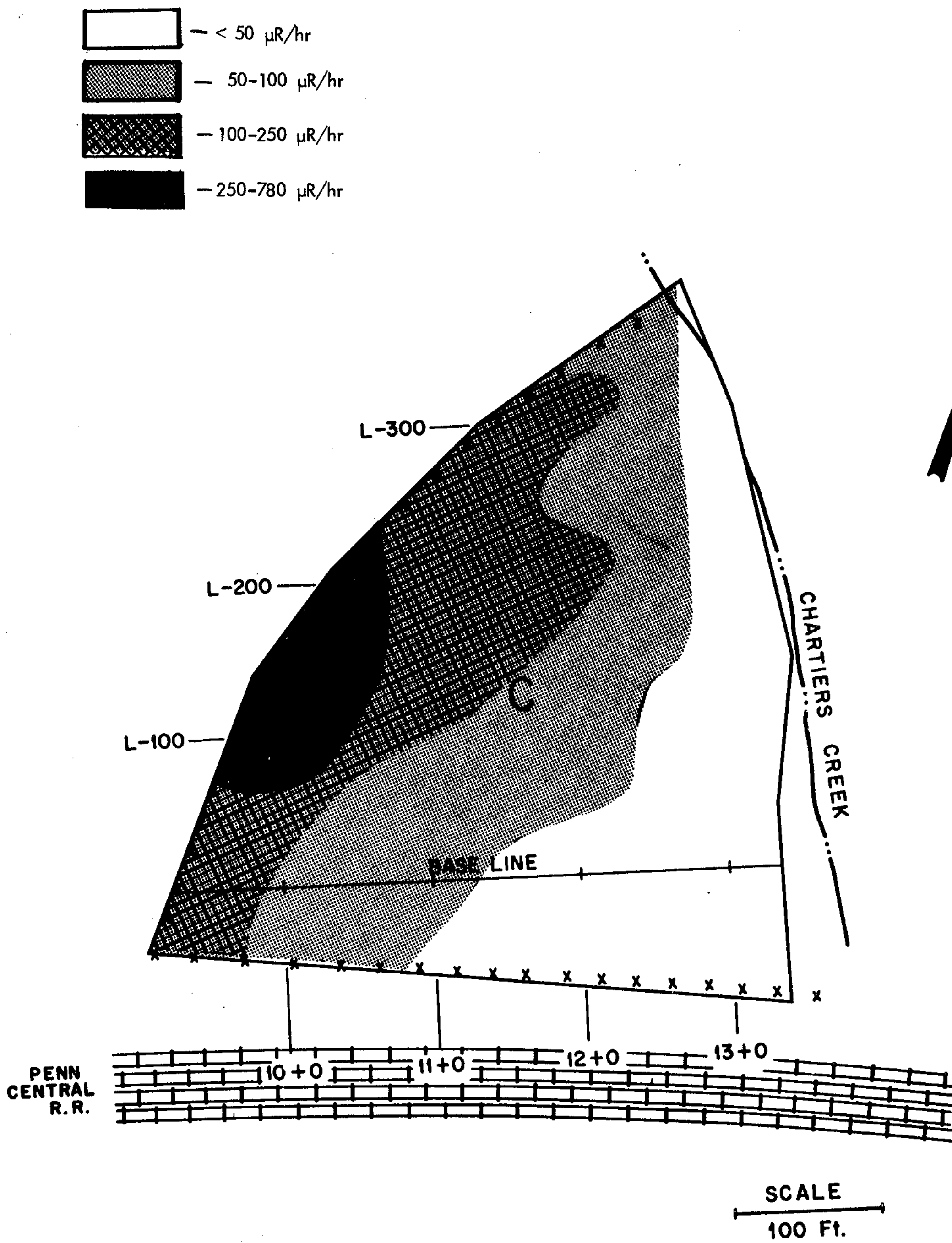

Fig. 3.5. Example of the presentation of radiation profiles which in this case gives the gamma exposure rates at 1 m above the surface.

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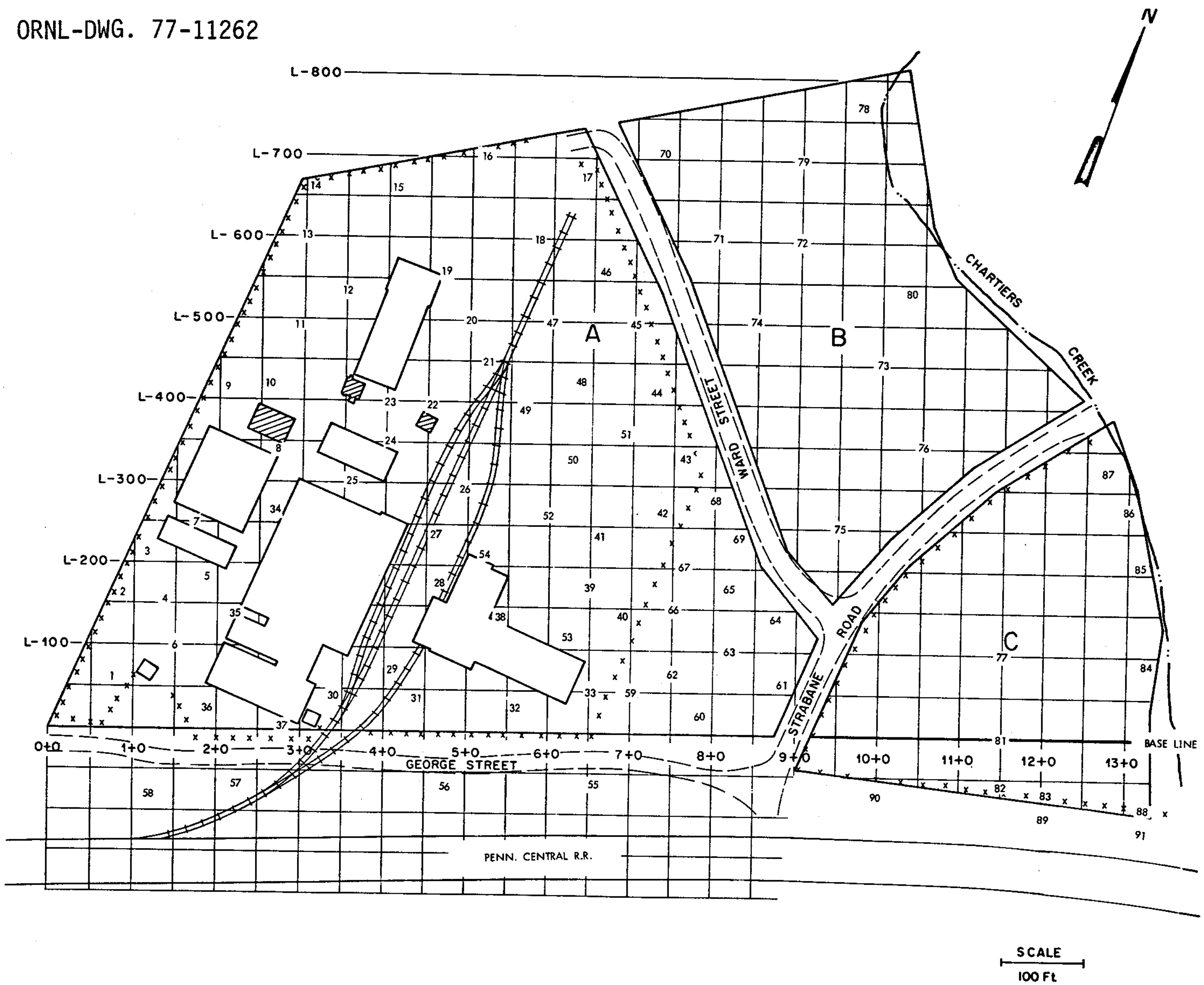

Fig. 3.6. Illustration of how to locate drilling locations for subsurface soil sampling.

Table 3.3. Beta-gamma dose rates at 1 cm and external gamma radiation levels at 1 m above grid points, outdoors on the site

Coordinates shown in Fig. 3.4 and 3.6		Beta-gamma dose rate at 1 cm above surfaces (millirad/hr)	External gamma radiation level at 1 m above surface (μR/hr)
Base line	Left (L) or right (R)		
0 + 0	0	0.30	140
0 + 50	0	0.13	90
0 + 50	L 50	0.16	110
0 + 50	L 100	0.50	130
1 + 0	0	0.25	130
1 + 0	L 50	0.15	80
1 + 0	L 100	0.10	90
1 + 0	L 150	0.18	120
1 + 0	L 200	0.28	120
1 + 50	0	0.15	150
1 + 50	L 50	0.14	100
1 + 50	L 100	0.28	140
1 + 50	L 150	0.13	110
1 + 50	L 200	0.30	160
1 + 50	L 300	0.34	130
2 + 0	0	0.08	95
2 + 0	L 100	0.30	80
2 + 0	L 150	0.06	65
2 + 0	L 195	0.15	85
2 + 0	L 250	0.21	65
2 + 0	L 400	0.13	95
2 + 0	L 450	0.04	35
2 + 50	0	0.35	330
2 + 50	L 200	0.10	60
2 + 50	L 250	0.14	100
2 + 50	L 350	0.18	100
2 + 50	L 400	0.08	85
2 + 50	L 450	0.15	110
2 + 50	L 500	0.40	190
2 + 50	L 550	0.05	50
3 + 0	L 0	0.70	280
3 + 0	L 350	0.23	140
3 + 0	L 400	0.29	170
3 + 0	L 450	0.17	110
3 + 0	L 500	0.09	65
3 + 0	L 550	0.09	80
3 + 0	L 600	0.25	140
3 + 0	L 650	0.08	60
3 + 50	0	0.16	140
3 + 50	L 50	0.40	210
3 + 50	L 300	0.35	180
3 + 50	L 400	0.11	95

Table 3.4. Concentrations of ^{226}Ra, ^{238}U, and ^{227}Ac in soil samples taken from core holes outdoors

Location	Depth (ft)	^{226}Ra (pCi/g)	^{238}U (pCi/g)	^{227}Ac (pCi/g)
1	0-0.5	24	ND[a]	ND
	0.5-1.0	19	105	ND
	1.0-1.5	100	1200	ND
	1.5-2.0	95	120	ND
	2.0-3.0	2.3	5.3	ND
	3.0-4.0	2.0	8.6	ND
	4.0-5.0	1.8	3.4	ND
	5.0-6.0	1.3	2.0	ND
	6.0-7.5	1.2	1.5	ND
10	0-0.5	48	104	14
	0.5-1.0	5.7	7.0	1.9
	1.0-1.5	630	420	46
	2.5-3.5	850	190	ND
	3.5-4.5	78	450	5.0
	4.5-5.5	480	200	36
	5.5-6.5	110	230	ND
12	0-0.5	4.8	5.9	ND
	1.0-2.0	72	45	ND
	2.0-3.0	150	200	18
	3.0-4.0	130	260	17
	4.0-5.0	7.0	46	0.73
	5.0-6.0	1.8	47	0.83
17	0-1.0	43	31	11
	1.0-2.0	15	35	4.0
	2.0-3.0	14	12	ND
	3.0-4.0	2.0	2.4	ND
	4.0-5.0	1.1	1.3	ND
	5.0-5.5	1.0	1.0	ND
22	0-0.5	7.2	12.0	1.2
	0.5-1.0	ND	5.1	ND
	1.0-1.5	53	42	ND
	1.5-2.0	630	280	86
	2.0-2.5	2600	180	400
	2.5-3.0	11	68	ND
	3.0-3.5	5.1	54	ND
	3.5-4.0	ND	8.0	ND
	4.0-5.0	3.8	4.1	ND
	5.0-5.5	14.0	17.0	ND
	5.5-6.5	2.6	4.3	ND
30	0-1.0	120	240	ND
	1.0-2.0	1900	3400	210
	5.5-6.5	39	160	ND

[a]ND indicates not detectable.

the site indicated widespread contamination because of extensive earth movements carried out at the site during its previous post-operational history. The general methodology of summarizing and documenting data on grid maps for decision-making, however, is applicable to final licensee and NRC survey results.

Surface and subsurface soil costs affect final survey design. Deposition limits for farming use are 8×10^{-5} Ci/m^2 for ^{137}Cs and 2×10^{-4} Ci/m^2 for ^{90}Sr.[24] The cost of reducing soil levels to this or any other specified concentration will depend upon the method used, such as: (a) removing top soil, (b) waiting for decay, (c) leaching the top soil, (d) covering the top soil (with clean soil, asphalt, etc.), or (e) diluting the top soil by plowing and disking. Cost figures for these operations are charged to cleanup, but can influence final survey charges and should be costed from this viewpoint. For example, in (a) sampling is needed where (1) top soil removal was obviously missed, (2) top soil permeability suggests likelihood of downward migration of nuclides below top soil removal zone, (3) top soil was spilled along removal route. In (b), waiting for decay (applicable only to short-lived isotopes) there may be lost opportunity cost of land while waiting, minus some cost recovery by restricted (controlled) use of the land, which may or may not need to be charged in part to final survey cost.

Soil concentration of fallout or aged releases of radionuclides is sometimes taken to decrease exponentially with depth. This could be used as a cutoff point in deciding how deep to sample. Daily rental rates for a simple drilling rig are in the range of \$400 to \$500 in 1979, plus \$4 to \$10 per foot. It would require a 100 ft depth sampling for the per foot charge to equal the initial rental charge for one core drilling, 10 ft for 10 core drillings, 1 ft for 100 core drillings. A cost formula with two terms: (1) fixed daily rental + (2) variable cost as a function of total linear feet of depth drilling and average drilling time per foot yields a cost approximation that will be a function of (a) the number of samples (core drillings) required and (b) laboratory analysis cost on the samples. At Savannah, 10% of the plutonium was detectable at a depth of 15 cm, with 84% within the first 5 cm[25] and at Hanford, trench-discharged solutions of ^{239}Pu, totaling 30 kg of plutonium in about 1 million L of waste solutions over a 2 y period, gave a concentration of about 50,000 μCi of ^{239}Pu/L of sediment 50 cm below trench bottom, decreasing to 10 μCi/L at a depth of 9 m.[25] Where the problem of downward soil leaching may become a future threat to underlying aquifers, but the need exists to keep core drilling costs down, consideration might be given to predicting nuclide depth penetration from a field knowledge of the underlying geology coupled with laboratory study of nuclide percolation through columns of core samples representative of the site. Core drilling locations and depths might then be selected according to likelihood of eventual contact with underground water.

3.3.2.1 Subsurface soil sampling. If there is any reason to suspect (from records or measurements or nature of the operations conducted on the site) subsurface contamination in the outdoor areas to be surveyed or under buildings, a subsurface soil sampling plan should be implemented. In the area of suspected contamination, holes should be drilled with a motorized rig equipped with an 30-cm-diam auger to a depth of approximately 5 m. After casing the auger hole with a 10-cm-diam plastic pipe, a collimated NaI scintillation probe can be lowered inside the pipe to measure the gamma radiation intensities resulting from contamination within small fractions of the hole depth.

Measurements are usually made at 15 to 30 cm intervals, depending on the variation of gamma radiation as a function of depth beneath the surface. This "logging" of the core holes is done as a first step in determining the extent of subsurface contamination at each location. Log gamma readings are related to soil concentrations by empired formulas. For example, the empirical formula for relating ^{226}Ra concentrations in pCi/g (Y) to logging meter readings in thousand cpm (X) was given as Y = 7.3 (x-z) for the Pennsylvania Railroad Landfill site (see ref. 12 of Table 3.9). From each of approximately half of the auger holes, a soil sample should be taken at the point showing the highest gamma radiation level. These samples are analyzed for whatever radionuclides are suspected for the site.

The auger hole loggings are used to select outdoor locations where further soil sampling would be useful. At points as close as practical to selected auger holes, a split-spoon sampler is used to collect soil samples at 15 to 30 cm intervals throughout the contaminated zone. The concentrations of radionuclides of interest are determined for these samples. If it is suspected that the elevated gamma in the auger hole may represent migration, additional soil samples should be taken around the hole (e.g., on a 10 m radius). If gamma emitters on a given site are known to be accompanied by alpha and/or beta emitters, then the additional soil samples sould be analyzed for alpha and beta, as well.

3.3.2.2. Water sampling. Water samples should be taken from each source of potable, surface and ground water on the site. Also, water samples should be taken from each auger hole in which water is found. These samples should be analyzed for any radionuclides suspected of being present in significant quantity.

When liquid effluents are released to streams, rivers, lakes or impounded water, samples of these waters should be taken. Groundwater may accumulate detectable activity from liquid effluent discharges to surface bodies of water. Drinking water supplied from any source (surface or ground water) should be sampled as a possible source of radiation dose to man. The sampling of sediment from streams or ponds can provide a measure of the undissolved radionuclides which may lead to exposure to man through aquatic species, through aqueous resuspension, or as an external source of radiation.

A possible sampling scheme is to take weekly grab samples of surface water composited for a month and daily grab samples of drinking water composited for either a week or perhaps a month. Periodic grab sampling is also the method of choice for groundwater. The composite sample for analysis should total 3.5 to 4 L.

Samples of sediment can be collected by hand. These samples should be oven dried and analyzed much like a soil sample, reporting the activity per gram dry weight (pCi/g).

3.3.2.3 Air sampling. Since air is a primary pathway to man for many radionuclides, air sampling is a critical part of the monitoring program. Two categories of airborne radionuclides normally require measurement: particulates and gaseous products. For sites contaminated with ^{226}Ra, the short-lived daughters of ^{222}Rn are of particular concern since most of the dose to the human respiratory tract comes from the daughter products. Some recommended general guides to air sampling are available.[26,27]

Long-lived alpha emitters may be collected using a high-volume air sampler with glass fiber filters having an efficiency of nearly 100% for 0.3 μm particles. A sample should be collected for 8 h or longer at an average flow rate of at least 10 cfm.

Radon-222 and radon daughter concentrations at both indoor and outdoor locations may be determined using any of several continuous or integrating measurement methods.[28-37] It has been found that the level of radon in the atmosphere in any given location is time dependent, exhibiting diurnal and seasonal variations. Sampling must be conducted over a suitable period of time to obtain a representative average concentration. One recommended procedure[38] is to average the results of 6 air samples, each of at least 100 h duration, and taken at a minimum of 4 week intervals throughout the year. At least one such integrated measurement should be made in each structure on the site being surveyed. The location of this measurement should be in the occupied area having the highest radon level or in other suspect areas as determined by a grab sample technique.[32-34,37]

Since decontamination criteria[38,39] frequently specify limits on radon daughter concentrations in terms of working level (WL), it will be necessary to either measure the equilibrium ratios for radon daughter products so the radon concentrations can be converted to WL or measure radon daughter concentrations directly over the requisite period of time. One method for the measurement of radon daughter concentrations in air is to sample air for approximately 10 min at 10 to 15 L/min through a membrane filter with maximum pore size of 0.4 μm. The filter is counted with a surface-barrier detector and the daughter concentrations determined by an alpha spectroscopy technique.[33,34]

3.3.3 Areas of limited accessibility

Limited accessibility to sampling was discussed briefly in Section 3.2.1.1 on Sampling Techniques, where it was pointed out that provision must be made beforehand to cope with the situation of a large rock covering soil beneath that randomly selected for sampling. Another situation may be a paved area covering the desired soil sample area. This latter is likely to be more of a problem than the natural rock obstacle, since it could represent a temporary solution to a below-surface contamination problem prior to restrictions on such practice. Before incurring the expense of core drilling through the pavement, effort should be made to evaluate the area paved from prior information, in terms of former use and of intended future use, unless air readings taken at the pavement surface give values well above natural background. If readings are unacceptably high, core drilling is indicated automatically. Buildings rehabitated for use may have been replastered, or otherwise resurfaced to reduce radiation levels to background. Again it is important to know the prior use of that building, and in case of doubt to take subsurface samples at locations where visual damage will not be visible or too obvious, as with a staff lunchroom. Contaminated soil may have been covered with a foot or more of clean soil as part of an old decontamination program.

Limited accessibility areas are more likely to be a problem of older sites, and accentuate the importance of an inspection survey before backfilling of excavated areas. Old covered up drainage ditches from areas involving former radionuclide operations are to be strongly suspect. These can often be located on site maps filed with the AEC subsequent to initiation of the docket file system in 1957 or thereabouts. Earlier records become increasingly spotty. A few sites were engaged in radium extraction and other activities as early as 1910, about which little is now known. When the government began to restrict its guaranteed purchases of uranium, some operations were forced out of business prematurely. Any licensees who purchased land used by previous owners for radiological operations should be aware of the possible complications this may engender. Fortunately, these situations are probably few.

One of the surest ways to solve a building potential-contamination problem is to demolish it down to and including the foundation earth beneath. If this constitutes an unacceptable expense, and if radiological operations were formerly carried out in the building, then constrictions, sharp turns, etc. in air and sewage duct systems servicing the building must be sampled even though not readily accessible, and in some cases removed entirely, depending on radionuclide half-life and potential quantities that could have built up.

3.4 Determination of Background Radiation Levels

Since decommissioning criteria frequently are written to indicate acceptable levels of radioactivity above site background, the importance of reliable background data cannot be overemphasized. Those features known to contribute to good background data are (1) survey design to provide representative, unbiased sampling, (2) proper allocation of sampling, (3) selection of area least likely to have been affected by facility activity (such as upwind or upper side of sloping terrain), (4) high sensitivity, calibrated and stable instrumentation, and (5) quality assured analysis. Equally critical is the selection of a sampling area which closely resembles the site in question, yet, for all intents and purposes, has not been affected by site activity.

The wide variety of decommissioned sites and future candidates for decommissioning makes it difficult to use the same approach for all background measurement. This will require a judgmental decision on the part of the surveyor as to the proper approach to the problem. The best answer for new sites in the future will be to use a preoperational survey of the candidate site, properly executed with sufficient detail. The problem of designing a generic background survey is suggested by the following types of sites which may be encountered:

1. Nuclear reactor (power and research).
2. Fuel fabrication plant.
3. Fuel reprocessing plant.
4. Uranium and thorium mill.
5. UF_6 conversion plant.

6. Radiochemical laboratory.
7. Radioactive disposal site.

One sampling scheme for background is the concept of a wheel with its emanating spokes or concentric circles drawn around the site with varying radii which may be adopted for the sake of survey planning. Before a decision has been reached as to the survey units to be included, consideration should be given to the elimination of those segments of the "pie" represented as downwind, downstream and the lower slope of the site since these locations may be influenced by contamination from the site. However, rectangular grids eliminate need for polar coordinates, thus simplifying data treatment. From the boundries of the site, background readings or samples may be taken at distances of 0.50, 1.5, and 3.0 km in the various compass directions. There should be at least 30 (and preferably many more depending on site size, terrain homogeneity, etc.) background measurements of each of the following:

1. concentration of suspected radionuclides in surface soil, water, and other environmental media of concern;
2. concentration of ^{222}Rn daughters and long-lived alpha emitters in air within structures;
3. external gamma radiation levels at 1 m above the surface, both indoors and outdoors; and
4. beta-gamma radiation levels at 1 cm from building and ground surfaces.

As the easiest and least expensive samples, many air gamma readings should be taken. If gamma logging of auger holes is included in the site survey, background subsurface gamma radiation levels should be measured at various depths in at least three auger holes drilled at background locations. Concentrations of radionuclides should be determined in background water samples taken near the site, but from sources which could not receive water originating at the site or from any other nearby nuclear operations.

Background measurements may vary considerably from point to point. However, for each type of measurement, there is the need to determine a "background level," B, above which an on-site measurement may be interpreted as reflecting contamination. The definition of a "background level" is based on the assumption that the distribution of background data are lognormally distributed (i.e., their logarithms fit a normal [Gaussian] distribution).

The fit of the data to the lognormal distribution may be tested with statistical tests, but is usually estimated by "eyeballing" the data and the line through it. From a log-probability plot of the data it is possible to determine whether the data represent the distribution of a single or mixed lognormal population. The linear data plot, whose geometric standard deviation is generally around 2, describes the distribution of the background population while other constituents of higher value are due to contaminating sources. This conceivably might be used as an identifying test for background levels in the environment in which a small number of samples ($\leqq 10$) are measured.

For a given radiological condition, it is desired to determine a background level such that all future measurements less than or equal to B will be considered background and all measurements greater than B will be interpreted as reflecting contamination. We have elected to determine B so that the probability that x (the random variable for the given radiological condition) is less than or equal to B is 90%, or symbolically, probability $(x \leqq B) = 0.9$. Some measurements less than B could be due to slight contamination, but there are background measurements at the same levels. However, future measurements that are above B will have a small likelihood of being background measurements or, conversely, a large likelihood of reflecting contamination.

It is desirable to have a large number ($n \geqq 30$) of background measurements. Statistical interpretation becomes less precise with smaller numbers of measurements.

Once the n sample background measurements $x_1, x_2, \ldots x_n$ are made, the natural logarithms $\log x_1, \log x_2, \ldots \log x_n$ are found, and the sample mean $(\overline{\log x})$ and sample standard deviation s, are computed:

$$(\overline{\log x}) = (\sum_{k=1}^{n} \log x_k)/n \tag{3.4}$$

$$s = \sqrt{\frac{\sum_{i=1}^{n} ((\overline{\log x}) - \log x_i)^2}{n-1}} \tag{3.5}$$

It can be shown that the "maximum likelihood" estimate of log B is then

$$\log B = (\overline{\log x} + 1.28 \sqrt{\frac{n-1}{n}}\, s) \ , \tag{3.6}$$

so that B can be estimated from the formula

$$B = \exp\ [(\overline{\log x} + 1.28 \quad \frac{n-1}{n}\ s] \quad \text{(ref. 1)} \tag{3.7}$$

The preceding equation, therefore, is used to obtain an estimate of the background level B for each radiological condition of interest.

Hickey[40] has asked what is meant by "natural background." Should 20 pCi of ^{226}Ra/L of well water be classed as "natural background," some waters from sandstone sources running this high or more. Soil ^{226}Ra ranges from about 0.1 to 4 pCi/g.[41] Florida sands and soils may contain up to 9 pCi/g.[42] A preoperational survey of soil radium in the vicinity of the Maine Yankee Atomic Power plant at Wiscaset[43] ranged from less than 0.02 to over 3 pCi/g. Healy[44] suggested some permissible limits on soil radium in order to limit radon daughters in indoor air, as shown in Table 3.5.

Thus, the variability of background nuclides from state to state, from site to site and even within a site requires adequate sampling to

Table 3.5. Permissible radium levels in soils to limit radon daughters in homes (ref. 44)

Depth of contaminated soil (cm)	Soil type	
	Sand (pCi/g)	Loam (pCi/g)
1	150	150
10	15	15
100	2	3
1000	1	2.7

obtain average and maximum background values against which to assess slight to significant residual contamination that can be attributable to former radiological operations at the site in question. The EPA limit of 5 pCi of ^{226}Ra/g of soil after completion of cleanup (Section 1.1.2) is thus a conservative standard to apply to other than uranium mill tailings sites for which it is specifically designed.[45]

Since natural radiation exposures in the United States range from about 50 to 150 mrem/y,[46] (terrestrial and cosmic) a variation of perhaps 25 mrem/y (one-fourth of natural background) would suggest a verifiable figure of 25 mrem/y, increasingly difficult to justify in progressing from 25 to 10 to 5 mrem/y when trying to establish a realistic cleanup value for soil (Table IV-4 of Appendix IV). More data is needed to establish firm values for natural radiation exposure, county by county, after which a value such as 10 or 25 mrem/y will have to be established by legislation, as was done for the Grand Junction remedial action program.[38]

3.5 Statistical Basis for Survey Design

The basic goal in conducting a radiological survey is to obtain an accurate characterization of the radiological condition of the site. In the interest of performing a creditable survey, provided adequate instrumentation is available, one is obligated to obtain sufficient data to satisfy a predetermined level of confidence in the results. In order to avoid biasing the data, a statistically sound plan for surveying and obtaining data must be devised prior to the survey. Sampling points whether they be for smears, direct readings, or soil samples should be governed by random sampling or stratified random sampling or systematic sampling based on a grid arrangement. Judgmental sampling offers too much opportunity for bias; furthermore, it is difficult, if not impossible, for the regulatory inspector to verify the results of such termination surveys by accepted statistical procedures. To fulfill these requirements, it is necessary to determine the number of data points or survey readings required to yield data with the desired level of confidence.

3.5.1 Selecting the sample size for estimating population mean

In order to compare measurements with applicable numerical guidelines, it is generally necessary to estimate the average and worst case (maximum) conditions in relatively small areas. Furthermore, comparison with existing guidelines[22-24,45] often requires a knowledge of the variability of conditions including natural background in small subregions. In the following paragraphs, the basic principles[45] involved in estimating the average value and variability of a radiological condition in a relatively small region (stratum) are described. The survey approach also deals with the problem of estimating the maximum of a radiological condition.

All possible measurements of a radiological condition may be considered to be a statistical population, that is, a set of quantifiable data. The frequency distributions of the populations encountered in surveying are usually not familiar statistical distributions; for example, the distributions are rarely normal. The Central Limit Theorem states that if repeated random samples of a size n are drawn from any population (not necessarily normal) that has mean μ and standard deviation σ, the frequency distribution of the sample mean $\bar{x}$ in repeated random samples of size n tends to become normal as n increases.

The Central Limit Theorem suggests that the population mean (μ) of a radiological condition, along with associated confidence intervals, can be estimated from a random sample of size n, where n is small compared with the size of the population. The values $\bar{x}$ and s (sample mean and sample standard deviation) from the sample population are usually used to estimate μ and σ, respectively, of the parent population. It is suggested in many statistics texts that n = 30 is usually adequate when making use of the Central Limit Theorem. However, a considerably larger sample may be desirable for estimating the mean of some populations encountered in radiological surveying.

To check whether the average of a radiological condition has been adequately approximated with n measurements, the following test is applied: the sample mean $\bar{x}$ and sample standard deviation s of the n measurements are calculated, and the approximation of the population mean is considered adequate if and only if

$$t(n)s\sqrt{n} < 0.25\ \bar{x} \qquad (3.8)$$

Here t(n) is the distribution number associated with the number of measurements, n, and the 90% confidence interval. For large n (say n > 30), t(n) is approximately 1.7. Hence, for n ≧ 30, inequality (3.8) reduces to

$$s/\sqrt{n} < 0.15\ \bar{x}. \quad \text{(ref. 1 and 2)} \qquad (3.9)$$

This test means that the population mean is adequately approximated whenever it is known with less than a 25% error at the 90% confidence level. The value 0.15 in equality (Eq. 3.9) was, in a sense, empirically determined. It has been observed, based on actual measurements of various radiological conditions (alpha contamination levels, beta-gamma dose rates, external gamma radiation levels, concentrations of radionuclides in soil, etc.) at several sites,[16,47,48] that the satisfaction of inequality (Eq. 3.9) (with n > 30) is generally a reasonably attainable goal. Inequality (Eq. 3.9) can be used to estimate the number of measurements needed in a population in order to allow an efficient yet thorough survey.

Before detailed alpha, beta-gamma, and gamma measurements are made in an area, several (perhaps 30) quick measurements of each type should be taken at randonly chosen points over the area. The average and standard deviation, determined from this quick survey for each type of instrument, are inserted into inequality (Eq. 3.9), which is then "solved" for n:

$$n \geqq 45\ \frac{s^2}{\bar{x}^2} \qquad (3.10)$$

Inequality (Eq. 3.10) provides a first estimate of the number of measurements of each type needed. If the right hand of inequality (Eq. 3.10) is less than 30, the inspector should still make at least 30 air measurements per stratum. The number of air radiation measurements needed by the licensee will be much greater. Soil samples for laboratory analysis of nuclides must be taken more sparingly because of higher cost, for example, one soil sample for every hundred air radiation readings. The higher the correlation between air readings and soil nuclide concentrations, the fewer the number of soil samples needed per 1000 air radiation readings, with a minimum of 30 for statistical confidence.

If the entire site is divided into an equal number of equal-sized survey blocks, say 1000 blocks, each and every one measuring 50' × 50' as illustrated in Fig. 3.7, the survey designer must then decide from results of the preliminary survey and/or other prior information whether to specify (1) systematic, (2) simple random and/or (3) stratified random sampling of the survey blocks.

For a very thorough instrumental survey of a site, about which little is known, every block might be measured for beta and gamma readings for a minimum of 1000 × 5 = 5000 beta-gamma readings if the four corners of each block were to be measured (grid points) plus a reading in the center, or a maximum reading wherever found in each block. This would constitute a maximum systematic instrumental sampling (observations). Sampling of every fifth or nth block would be a partial systematic sampling. The question of sample size is also covered in Section 5.1 on Statistics. For an uncomplicated uranium mill site in which beta and/or gamma readings might fall out exponentially with distance from the tailings pile periphery, simple random instrumental sampling along spoke lines radiating out from the pile perimeter might be employed, in that case using polar rather than rectangular coordinates. For a site reasonably well-defined from prior surveys as will be the case for new sites not yet decommissioned, stratified random sampling may be the most cost-effective. Where prior information on a cleaned-up site indicates variation in instrument readings and/or soil analyses by a factor of three or more, stratification may be indicated as a likely means of reducing sampling costs. Stratification of a site may be effected in one or more of several ways. To avoid possible confusion, the method or methods of stratification must be clearly stated. In addition to dividing a site into survey blocks, a site may be stratified (a) geographically, (b) by gamma readings (in μR/h), (c) by key

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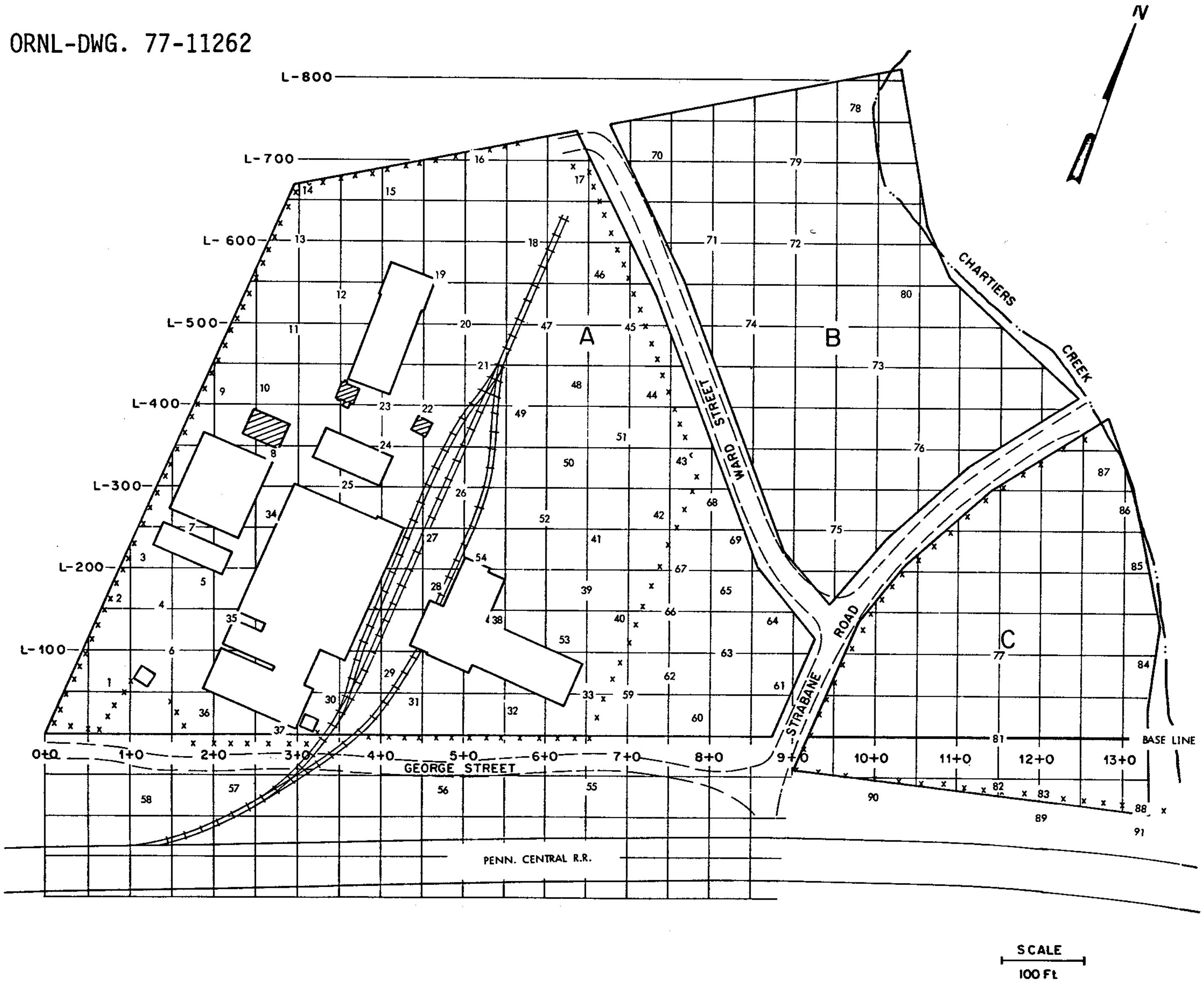

Fig. 3.7. Example of a grid system which can be used for outdoor surveys.

soil nuclide values (in pCi/g of soil), (d) substratified by variance of mean gamma readings for selected numbers of survey blocks (e) sub-stratified by variance of mean key soil nuclide values, and (f) any combination of the preceding. In contrast to simple random sampling such as a 1% or 10% sampling of the 1000 survey blocks, stratified random sampling divides the site (or survey blocks) into two or more survey units. Site size and complexity of former operations or movements of nuclides on the site affect choice of survey design for any specific site. The following is the generic recommended approach.

For a very large site (more than 1000 acres), start with a reference site and scale down or up according to: (1) site size, (2) actual building sizes, and (3) former processing areas, usually behind the old security fence, in accordance with Tables 3.6 and 3.7.

Each stratum is defined simultaneously by: (a) geographic areas for the convenience of the surveyors and in terms of probable hazard potential, and (b) by the survey blocks into which the geographic areas and the site as a whole have been divided. In the past it has been customary in the United States to work in terms of English units such as 30 ft, but even numbers in metric units will now be more appropriate. Thus, assuming the entire site is to be divided into 10 m × 10 m survey blocks, those blocks defining (former) buildings should in turn be subdivided into 1 m × 1 m blocks. Table 3.7 presents some latitude in block size according to the estimated hazard potential, consistent with recommended block sizes specified in Sections 3.3.1 and 3.3.2. Areas near site boundaries (Stratum 4 of Fig. 3.7) where hazard potential from prior information is low, and which could constitute as much as 99% of the total site unless a significant portion is known or suspected of being highly or moderately contaminated, could have grid size up to 20 m. Off-site survey block sizes can be even larger, especially upwind and uphill, from which to sample.

To avoid confusion, "population" as used must be defined, especially when used in more than one sense (see Section 1.2 on Definitions). In the mathematical derivations which follow, the population under consideration is the total number of survey blocks (N) into which the entire site is subdivided. The subpopulations, N_1, N_2 + ..., are the strata,

Table 3.6. Stratification of a reference site[a]

Stratum no.	Stratum	Area (m^2)
1	Process buildings/areas	2,745
2	Fenced area exclusive of 1	12,000
3[b]	Sewage lagoons and drainage routes	2,000
4[b]	Remaining site	4,700,000
5	Off-site background (upwind, upstream, etc.)	12,000

[a]Reference site: 4.8 km^2 (1200 acres). Fenced area: 0.1 km^2 (25 acres).

[b]Modified as needed to include or exclude hazardous areas such as burial, incineration or former storage sites.

Table 3.7. Stratified sampling of a reference site

Stratum	Grid size (m)	Region	Hazard potential
1	1-3	fenced	highest[a]
2	1-5	fenced	next highest
3	5-15	outside	moderate
4	10-20	outside	low
5	$\geq$20	off site	background

[a]Process buildings and/or areas (10 m grid = 1000 ft^2 $\approx$ area of a small future residence).

those blocks composing each stratum as defined in Fig. 3.2 and 3.3. At this point the survey designer for the site must make a decision: (a) that each stratum shall be subject to simple random sampling, or (b) that an attempt will be made to minimize variance for statistical reasons (primarily to reduce total sample size and cost for the entire site) by subdividing each stratum in such a manner as to minimize variance within substrata and maximizing variance between substrata. One way to subdivide each stratum is to arrange survey blocks according to their decreasing average gamma readings, or to arrange the gamma readings themselves without regard to block numbers in which they occur. Having arranged gamma readings (or soil concentrations) by decreasing values, sharp breaks between readings may suggest where to break into substrata. Kinnison and Jarvis[49] use a cumulative normal probability plot of soil nuclide values such as ^{134}Cs to look for breaks, for deciding whether they are dealing with more than one population of ^{134}Cs values on a site, as shown in Fig. 3.8. The frequency distribution of air gamma or beta, and/or soil nuclide concentrations is not necessarily normal. It may be lognormal or exponential. A single straightline on cumulative lognormal probability plot suggests one lognormally distributed population.

Sampling every survey block on a small site or stratum, say less than 0.1 km^2, might be feasible costwise for survey blocks considerably larger than 1 m^2, but certainly not for large sites with survey blocks on the smaller side. Accordingly, all survey blocks are numbered consecutively, and a subset of them, such as 1%, randomly selected for soil sampling, using a random number table to select the numbers. The total number of sampling units, N, survey blocks in this case, having been determined by Eq. (3.1) of Section 3.1 for the entire site (simple random sampling) or for one stratum of the site (stratified random sampling), allocation of samples by substrata must then be decided according to one or more criteria such as cost per stratum or variance between substrata. These factors are considered below, more detail on which is available from Schaeffer et al.[50]

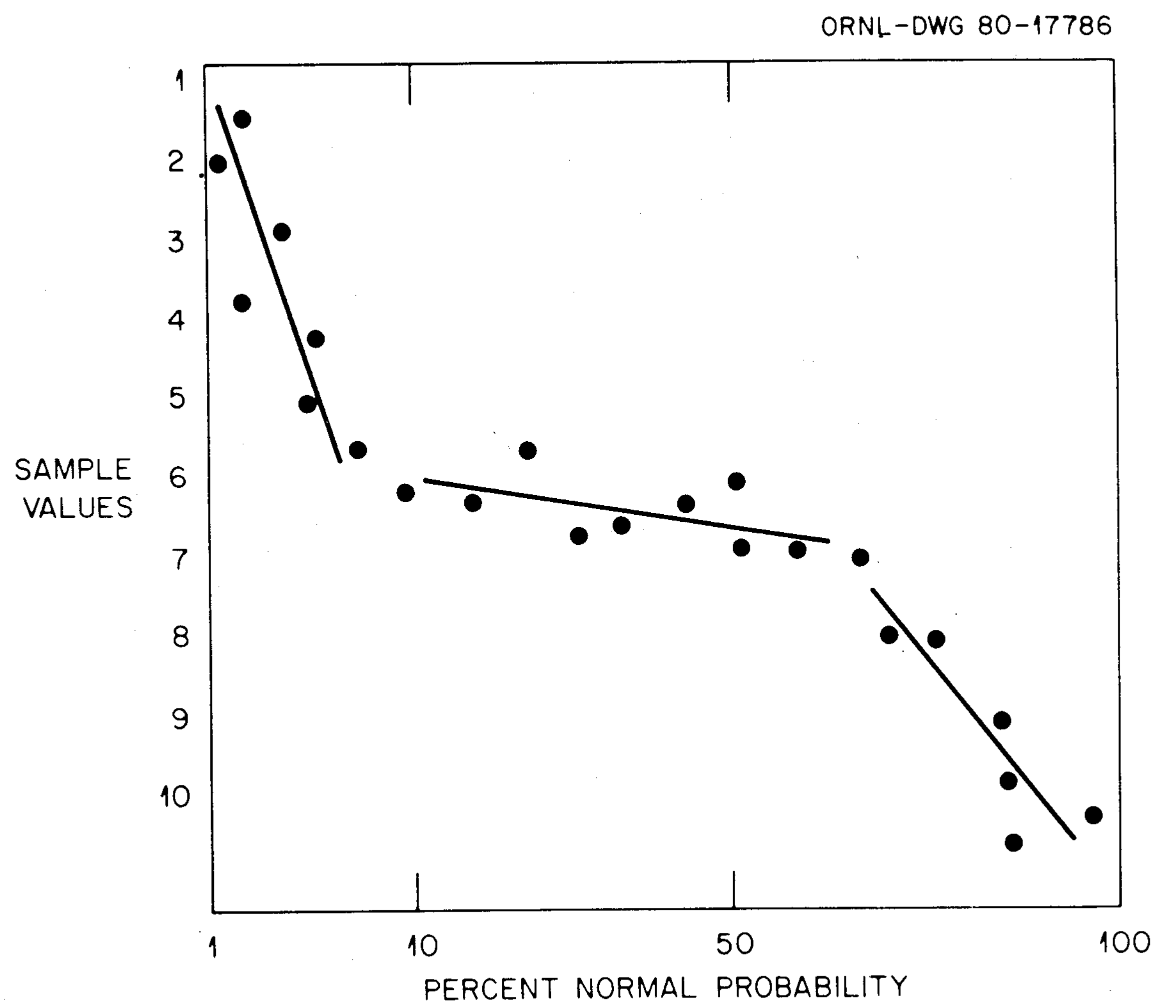

Fig. 3.8. Defining substratum populations by sharp breaks in a probability plot of sample values, such as soil ^{226}Ra or air beta readings.

With stratified random sampling the population (radiological survey area) of N units (grid blocks) is divided into subpopulations of N_1, N_2, ... N_4 units (grid blocks), respectively. These subpopulations or subgrid areas, differentiated by markedly different levels of radioactivity yet fairly homogeneous within a subgrid area are nonoverlapping, and together they comprise the whole of the survey grid units, so that,

$$N_1 + N_2 + \ldots . N_L = N .$$

The subgrid areas are called strata. To obtain the full benefit from stratification, the values of the N_h (total number of units) must be known. When the strata have been determined, a sample is drawn from each, the drawings being made independently in different strata. The sample sizes within the strata are denoted by N_1, N_2, ... N_L, respectively.

If a simple random sample is taken in each stratum, the whole procedure is described as stratified random sampling.

If strata are constructed in such a manner as to make the units within each stratum homogeneous compared to the variation between the stratum means, the stratified random sample will have greater precision than the simple random sample. The basis for making effective stratification of a radiological condition may be related to different levels of activity (perhaps an order of magnitude), previous knowledge about the distribution of radioactivity processing activity, building floors versus ceilings and walls or outside storage areas, and surrounding terrain. Any prior information or information derived from preliminary random sampling which will aid in making homogenous groups of units of the population can be used.

In general, the more stratification, the greater then increase in precision. Precision increases at a decreasing rate as strata are divided into smaller units until a point is reached where no further gain in precision is obtained. The additional strata also complicate the analysis so that the gain in precision must be considered in relation to the cost to obtain it.

The total number of sampling units, N, is usually allocated to the strata proportionally (e.g., if a stratum contains 20% of the population then 20% of the sampling units will be taken from that stratum). This allocation is not optimum in the sense that the variance of the mean will be a minimum; however, unless the variation within the strata differs markedly from stratum to stratum it will be nearly as good an allocation as is possible. Optimum allocation with unequal costs per unit in different strata is discussed later.

The estimate of the mean overall strata, Yst (st for stratified), and the variance for this mean, $\hat{V}(\overline{Y}st)$, are given by

$$\overline{Y}st = \frac{1}{N} \pm N_1 \overline{Y}_1 + N_2 \overline{Y}_2 + \ldots N_L Y_L 1 = \frac{1}{N} \sum_{i=1}^{L} N_i \overline{Y}_i \tag{3.11}$$

$$\hat{V}(\overline{Y}st) = \frac{1}{N^2} \sum_{i=1}^{L} N^2 \left(\frac{N_i - n_i}{N_i}\right) \frac{s_i^2}{n_i}, \quad i = 1, 2, 3 \tag{3.12}$$

where N_i is the total number of units (grid blocks) in the i<u>th</u> stratum, L is the total number of strata, N is the total number of units in all strata, and

$$\frac{s_i^2}{N_i} = \hat{V}(\overline{Y}_i) \; . \tag{3.13}$$

$\hat{V}(\overline{Y}_i)$ is the variance of the mean, $\overline{Y}_i$, of the i<u>th</u> sampling unit as shown below

$$\overline{Y} \; \left(\sum_{i=1}^{N_i} Y_i\right)/N_i \; , \tag{3.14}$$

$$\hat{V}(\overline{Y}) = \sum_{i=1}^{N_i} (Y_i - \overline{Y})^2 / N_i (N_i - 1) = s_i^2 / N_i \; , \tag{3.15}$$

and s_i^2 is the sample variance for ith stratum. s_i^2 estimates the corresponding true variance σ_i^2.

3.5.1 Selecting the sample size for estimating population mean

The amount of information in a sample depends on the sample size n, since $V(\overline{Y}st)$ decreases as n decreases. A method for choosing the sample size to obtain a fixed amount of information for estimating a population parameter follows. Where the survey specifies that the estimate, $\overline{Y}st$, should lie within B units of the activity level mean, with probability approximately equal to 0.95, the variance will be estimated by

$$V(\overline{Y}st) = D \frac{1}{N^2} \sum_{i=1}^{L} N_i^2 \left(\frac{N_i - nw_i}{N_i}\right) \frac{\sigma_i^2}{nw_i} \tag{3.16}$$

by substituting $n_i = nw_i$ in Eq. (3.12)

$$n = \frac{\sum_{i=1}^{L} \frac{N^2 i \quad \sigma^2 i}{w_i}}{N^2 D + \sum_{i=1}^{L} N_i \sigma_i^2} \tag{3.17}$$

We must obtain approximation of the activity variances σ_1^2, σ_2^2, ..., σ_L^2 before we can use the above formula. One method of obtaining these approximations is to note the range of activity levels within each stratum from preliminary surveys.

Methods of choosing the fractions w_1, w_2, ..., w_L are given below.

3.5.2 Allocation of the samples

The objective of the sample survey design is to provide estimation with small variances at the lowest possible cost. After the sample size, n, is chosen, there are several ways to divide n into the individual stratum sample sizes, n_1, n_2, ... n_L. Each division may result in a different variance for the sample mean. The objective is to use an allocation which gives a specified amount of information at minimum cost.

The best allocation scheme is affected by the following three factors:

1. the total number of elements in each stratum,
2. the variability of observation with each stratum, and
3. the cost of obtaining an observation from each stratum, as expressed in the following equation.[50]

$$B = \sqrt{V(Yst)} = 2\sqrt{\frac{1}{N_2} \sum_{i=1}^{L} N_i^2 \left(\frac{N_1 - n_i}{N_i}\right) \frac{\sigma^2}{n_i}} . \tag{3.18}$$

The multiplier (2) above represents two standard divisions (s), the equivalent to 95% probability of error of variance.

The equation (3.18) may be expressed as

$$B = 2\sqrt{V(\bar{Y}st)} \tag{3.19}$$

or,

$V(\bar{Y}st) = \frac{B^2}{4}$, which contains the actual activity variance of $\bar{Y}st$ rather than the estimated variance.

Although we set $V(\bar{Y}st)$ equal to $\frac{B^2}{4}$, we cannot solve for n unless we know something about the relationships among n_1, n_2, ... n_L and n. There are many ways of allocating a sample of size n among the various strata. In each case, however, the number of observations n_i allocated to the ith stratum is some fraction of the total sample size n. We denote this fraction by w_i. Hence, we can write

$$n_i = n\, w_i,\ i = 1, 2 \ldots L.$$

Using this equation, we can set $V(\bar{Y}st)$ equal to $\frac{B^2}{4}$ and solve for n.

$D = \frac{B^2}{4}$ when estimating the activity mean (μ).

The number of elements in each stratum affects the quantity of information in the sample, therefore, large sample sizes should be assigned to strata containing large numbers of elements.

3.5.3 Cost aspect of sample allocation

Variability must be considered, because a larger sample is needed to obtain a good estimate of an activity parameter when the measurements are less homogeneous.

If the cost of making a measurement varies from stratum to stratum, one may take fewer samples from strata with high costs. This would be done because one objective is to keep costs at a minimum.

The approximate allocation which minimizes cost for a fixed value of $V(\bar{Y}st)$ or minimizes $V(\bar{Y}st)$ for a fixed cost:[50]

$$n_i = n \frac{N_i \ \sigma_i/\sqrt{C_L}}{N_1 \ \sigma_1/\sqrt{C_1} + N_2 \ \sigma_2/\sqrt{C_2} + \ldots + N_L \ \sigma_L/\sqrt{C_L}} , \qquad (3.20)$$

$$n_i = n \frac{N_i \ \sigma_i/\sqrt{C_i}}{\sum_{i=1}^{L} N_i \ \sigma_i/\sqrt{C_i}} \qquad (3.21)$$

where N_i denotes the size of the ith stratum, σ_i^2 denotes the measurement variance for the ith stratum, and C_i denotes the cost of obtaining a single measurement from the ith stratum.

Statistical design to minimize cost may increase the probability of missing a hot spot (Section 5.3.1). However, if prior information on the site has been reasonably accurate and is in agreement with the preliminary site stratification suggested by Fig. 3.3, then cost reduction and hot spot identification are not likely to be incompatible goals.

The less dependence upon good prior information by the licensee, the higher the final survey cost must be. Similarly, for the inspector, the less dependence on raw data generated by the licensee, the more elaborate must be his verification survey. In the extreme case of no available prior information from licensee and from NRC files, as might be the case of a pre-World War I site before the Atomic Energy Act of 1954, the inspector, or a designated survey team, would need to make a full-scale survey of the site for any or all possible radionuclides at any or all areas and depths of the site. The situation for a current licensee would be more complicated if a candidate site for release were on a pre-World War I or II site operated by a different organization than the current licensee.

For further discussion of Survey Cost Estimation, see Appendix VI.

3.6 Documentation

Proper documentation of every aspect of the program is necessary for future references to the decommissioning survey. Without firm documentation it would be impossible for a regulatory inspector to verify the results obtained by the licensee or a contractor. One of the most basic requirements of the licensee should be that an accurate mapping of the survey site with its relationship to the surrounding area be provided.

Instrumental measurements and analytical results should be reported in the following manner:

1. Location of the measurement or sample.
2. Date or dates of measurements or sample collection.
3. The measured concentration of the specific nuclides in pCi or mBq/m^3 for air samples, pCi or mBq/L for water samples, pCi or mBq/g for soil or sediment samples and mBq/kg for vegetation or food samples.
4. Measurements of radiation sources should be reported as follows: alpha in dpm/100 cm^2, beta-gamma dose rate at 1 cm in μR/h, and gamma at 1 m above surface in μR/h.

5. The analytical error at 95% confidence level should be reported for all analyses.
6. Name of surveyor, sampler, or analyst.
7. Analysis date.
8. Instrument specifications and calibration data.
9. Confidence level, standard error, etc. attached to analytical results.
10. Name of person verifying results.

The actual net measured values (including negative values) and their associated errors should be reported. For values lower than the lower limit of detection (LLD) as defined in ref. 51, the term "not detected" and less than values or zeros shall not be used. Values lower than the LLD should be reported in the following manner: 11.1 ± 18.5 pCi or mBq/L or 7.4 ± 18.5 pCi or mBq/g. The LLD question is discussed in more detail by ref. 4.

The following supplemental information should be included:

1. description of survey and sampling equipment;
2. survey and sampling procedures, including sampling times, rates, and volumes;
3. analytical procedures;
4. calculational methods;
5. calculation of the lower limit of detection;
6. calibration procedures; and
7. discussion of the program for ensuring the quality of results.

A survey conducted in the manner previously described (see Section 3.5) will produce a large quantity of data for even relatively small sites. It is important that the data be presented in such a manner that: (1) the radiological condition of the site is completely and accurately depicted; (2) the inspector can ascertain the radiological condition of the site without further analysis and manipulation of the data; and (3) the inspector can readily ascertain types and locations of conditions exceeding guidelines. In order that these goals can be met, the radiological survey report is written on two levels. The first level consists of an overview of the radiological condition of the site given in the text with figures illustrating specific radiological conditions, such as the gamma radiation levels at 1 m above the surface on a tract of land. The second level consists of a detailed presentation of data in the form of tables or figures.

Examples of methods of data presentation, taken from ref. 16, are shown in Figs. 3.3, 3.4, and 3.5. It should be pointed out that, while the radiological survey described in this reference was conducted using methods similar to those described in the preceding sections of this document, the methods were in some cases not refined to the point described in this article. Hence, there are discrepencies in some cases between measurements suggested here and measurements presented in the tables and figures taken from the referenced report.

A scaled drawing of the site, together with the grid system used for the outdoor survey, is shown in Fig. 3.7. There are three outdoor survey units, parcels A, B, and C, shown in the figure. The grid system for all three survey units was referenced to a common baseline.

The beta-gamma dose rates at 1 cm and surface alpha radiation shown in Fig. 3.3 were reported in tabular form, superimposed on a grid map. In addition, an overview of outdoor radiation levels on the site is given in figures. For example, Fig. 3.5 provides a profile of gamma radiation levels at 1 m above the surface on parcel C. The division of gamma radiation levels at 50, 100, and 250 μR/h in Fig. 3.5 was somewhat arbitrary, but provided a simple profile. This profile was based on grid point gamma measurements together with information jotted on a scaled drawing of parcel C during a gamma scan of individual survey blocks. Such a profile is meaningful for gamma radiation levels at 1 m because of the relatively continuous spatial changes of that parameter.

A different kind of overview for beta-gamma dose rates at 1 cm above the ground on the site is given in Fig. 3.4. This figure shows those survey blocks where the applicable guideline[20] (in this case, 2 μGy/h averaged over any area of no more than 1 m^2) was exceeded. In each block where the guideline was exceeded, the highest beta-gamma dose rate in that block was shown. The type of profile shown in Fig. 3.5 is not appropriate for beta-gamma dose rates at 1 cm or other conditions which typically show large variation over relatively small areas.

Descriptions of some radiological conditions may be treated using figures showing measurement locations together with tables of data taken at those locations. This may be the case, if the data describe a condition in more than two dimensions, such as subsurface contamination levels in some tracts of land. As an illustration, Fig. 3.6 shows drilling locations on a site, and Table 3.4 gives concentrations of ^{226}Ra, ^{238}U, and ^{227}Ac in subsurface soil samples taken from selected locations shown in Fig. 3.6.

As another example, consider methods of reporting measurements made on the lower surfaces of a building interior. An overview of conditions exceeding guidelines can be given by figure. For example, Fig. 3.3 shows maximum measurements of beta-gamma dose rates at 1 cm and sample alpha contamination levels in the survey blocks. Entries are made only in blocks where guidelines were exceeded. Hence, the reader can readily ascertain where guidelines are exceeded. More complete information concerning contamination and radiation levels must be given in tables, (for example, Table 3.2), so that intermediate data compilation and final conclusions can be checked if needed.

Original data as illustrated by Tables 3.2, 3.3, and 3.4 need not be stored on computer tape nor as a report, but must be available in some form such as the original field logbooks which are numbered and stored such as to be readily accessible. An unbroken trail should exist from raw data to condensed (histograms, etc.) to fitted equations (with appropriate measures and tests such as correlation coefficients to estimated, potential human exposure under realistic environmental conditions, and the degree of confidence that can be expected at each stage, of which the overall confidence will be a composite.

The simplest standards to follow are maximum soil limits for nuclide concentrations, such as 185 mBq (5 pCi) of ^{226}Ra per gram of dry weight soil. As models for conversion of soil limits to human exposure rates become validated for realistic parameters, cleanup to some exposure limit such as 0.1 mrem/y or 10 mSv/y will probably replace or supplement soil limits.* See Tables IV-3, IV-4, and IV-5 of Appendix I for documentation in terms of human exposure rates.

Since documentation is closely associated with quality assurance, Sect. 3.7 should be consulted for general guidance on documentation procedures. Additional guidance in the form of general and specific checklists can be found in Sections 1.1., 1.3, 1.4, 3.2., 3.3, and 6.1.

3.7 Quality Assurance

One definition of "Quality Assurance" has been given by the American National Standards Institute.[52] Quality assurance comprises those planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service. Quality assurance has been given added emphasis by AEC, EPA, DOE, and NRC during the past decade. Any reputable organization or professional person has always practiced quality assurance to a degree, but the increasing complexities of large engineering programs such as space and energy have required that nothing be left to chance except statistics. The objective of a quality assurance program on monitoring for compliance with decommissioning criteria is to ensure confidence in the sampling, analysis, interpretation and use of data generated for this purpose, on a cost effective basis that will not compromise the public health. Such quality assurance must start with the original program design and be maintained at each significant step to final decision on whether to release the site totally, or in part, for unrestricted or restricted use. A good proportion of common sense aided by a manual of standard procedures and confirmed by a final survey will meet the objective.

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*For example, if soil resuspension factor of 10^{-6} m^{-1} can be taken as more realistic than 10^{-8} (Section 1, ref. 11) and if natural background mean and standard deviation can be defined more precisely for a given site or county (Section 3.2.1.1.1, Table 4.3), then soil and exposure limits for cleanup can be defined more realistically in terms of actual health hazard and decommissioning costs.

A basic document for the nuclear field has been Appendix B of 10CFR50 (ref. 53) in which 18 basic criteria are identified as composing an adequate quality assurance (QA) program. The American National Standards Institute has taken Appendix B and made minor modifications,[54] for a total of 19 categories.

Of the 19 QA categories given by ANSI[54] the present manual has adapted 12 and added two (9 and 14) as given in Table 3.8.

3.7.1 An identifiable quality assurance program

Depending on the size of the company or its nuclear operations, responsibility for QA of company activities and products should rest in one man or office with direct access to higher management. In addition, a very large organization might have one person concerned at least part-time with QA for his building, department, or plant. No single set of QA requirements can be entirely applicable to every specific site or program. Field variables have different components than laboratory or office variables, even though each may find all 14 of the above categories applicable in one respect or another. The intensity of QA effort should be commensurate with the seriousness of breakdown in quality of a given step. Many elaborate QA manuals are in use by large organizations of the nuclear industry, and a QA program leading to eventual or immediate decommissioning of a nuclear facility should be an integral part of any larger QA program. For example, DOE contractors and subcontractors are subject to DOE QA procedures, and NRC licensees attempt to conform not only to NRC regulations, but to EPA and state regulations - all of which should be compatible for simplicity and cost-effectiveness. A QA coordinating office or officer is needed.

3.7.2 Design control of the monitoring program

The specifics of design are covered in other sections. Concern in this section is with QA designs, for whatever purposes. To a considerable extent, QA steps parallel the monitoring steps that the program QA is intended to monitor. The monitoring steps must be differentiated at all times from the QA steps.

Table 3.8. Essential elements of a quality assurance program on monitoring for compliance with decommissioning criteria

1. An identifiable Quality Assurance Program.
2. Design control of the monitoring program.
3. Instructions, procedures, drawings, computer files, etc.
4. Document control.
5. Identification and control of component parts of the monitoring system.[a]
6. Control of special processes (e.g., sampling procedures, statistical models).[a]
7. Control of measuring and test equipment.[a]
8. Handling, storage and shipment of field samples, records, (and preservation).[a]
9. Timeliness.
10. Quality assurance records (as controls on other records).
11. Audits.
12. Nonconforming items (samples, sample analyses).[a]
13. Corrective action.[a]
14. Health and safety quality assurance for decommissioning personnel.

[a]To the extent that monitoring requires hardware (analysis equipment, calibration standards, supplies, etc.) as contrasted with services (computer programming, data storage and analysis routines, interpretation, etc.) the footnoted items (5, 6, 7, 8, 12, and 13) may not apply to the extent that physical aspects of the monitoring program are contracted out to a specialized company with the hardware. Quality assurance of these categories then becomes the primary responsibility of the contractor or subcontractor. However, the site owner is jointly responsible for QA on the final results, namely compliance with the decommissioning criteria.

Quality assurance of survey design prior to actual instrumental survey of the site is intended to ensure that sampling design is based upon sound statistics with respect to statistical procedures used (not selected), and implementation (not selection) of the sampling design chosen. Selection, rationale, use and interpretation of designs are to be found in the corresponding sections. As generalists, QA staff are not expected to be specialists in accounting, statistics, nuclear physics, economics, computer science, graphic arts, etc., but in procedures for ensuring and coordinating quality assurance in and between all specialties required to accomplish the job. In particular, QA should identify oversights, gaps and errors that would compromise significantly the validity of the final decision (verification of compliance with decommissioning criteria).

3.7.2.1 Survey design. A pilot study of the site by licensee and by an NRC inspector should be made from the specific viewpoint of final site survey preparatory to decommissioning. At this time, company records are essential to furnish maps, identify buildings where radioactive materials were handled, offer results and summaries of soil and other analyses, identify subsoil hydrogeology characteristics, prevailing wind direction and other meteorological characteristics, preoperational radioactivity background levels on- and off-site, production losses, and so forth. In addition to this paper study, on- and off-site spot field samples should be taken of soil, water, air, vegetation with deep roots, and possibly a core drilling should be taken. Each sample and reading must be identified on a survey grid map when taken, by whom, for what purpose, and with what precautions. From the pilot samples a survey design can be constructed making better use of the main sampling program.

Quality assurance on the company records used and the pilot samples taken is a first step toward QA on the survey design that will be based on the pilot sampling. Where radioactivity levels differ significantly from area to area, each of those areas may need to be treated separately (see Section 3.5 on stratification) in order to reduce variability and therefore number of samples needed, thus, keeping sampling costs down without sacrificing statistical validity.

3.7.2.2 Sampling design. Actual design of the sampling program is a problem for the technical staff, but ensuring that the selected design and steps for sampling are within specified standards can be a joint responsibility with QA staff. In a sense, this is how health physics came into being as an identifiable discipline for radiation control of experiments designed by physicists.

Although sampling design is a recognized field[55-58] of research and application, there is no single recognized standard or guideline for sampling. Practical experience in the FUSRAP Program[59] has led to a standardized procedure[1] for that program which can serve as a guide for sampling design. Accepting this as a general guide, QA steps can then be taken to ensure adherence to such a design in order to optimize the procedure. For example, the use of layout maps, field data entry sheets, use of instruments, etc. can be standardized and dove-tailed with more generalized procedures for document control. Table 3.9 lists the earlier FUSRAP reports. Since sampling design is heavily dependent upon statistical design, the technical aspects is covered in the appropriate section on statistics.

3.7.3 Statistical design

In this section, how QA is selected or formulated remains the issue, technical aspects being covered in another section. As with sampling design, of which statistical design is a more general aspect, QA steps begin when the design to be followed is selected. Statistical design for monitoring begins with a map of the site – how, where, and why to sample various subsections of the site with a minimum number of samples to keep cost down and an optimum number of samples to ensure statistical reliability. Once the manner in which the site is to be subdivided has been selected, the manner in which samplings are to be taken, preserved, stored, shipped, analyzed, and the resulting data recorded, stored, processed, analyzed and used, all become subject to quality control. Inadequate control on any of these steps could compromise the validity of a careful statistical design. Quality assurance at each step will be considered as each step is covered. For example,

Table 3.9. Formerly utilized MED/AEC sites — remedial action program

	Report No.	Title
1.	DOE/EV-0005/1	*Radiological Survey of the Middlesex Sampling Plant, Middlesex, New Jersey*
2.	DOE/EV-0005/2	*Radiological Survey of the Hooker Chemical Company, Niagara Falls, New York*
3.	DOE/EV-0005/3	*Radiological Survey of the Former VITRO Rare Metals Plant, Canonsburg, Pennsylvania*
4.	DOE/EV-0005/4	*Radiological Survey of the Ashland Oil Company, Tonawanda, New York*
5.	DOE/EV-0005/5	*Radiological Survey of the Former Linde Uranium Refinery, Tonawanda, New York*
6.	DOE/EV-0005/6	*Radiological Survey of the Seaway Industrial Park, Tonawanda, New York*
7.	DOE/EV-0005/7	*Radiological Survey of Site A, Palos Park Forest Preserve, Chicago, Illinois*
8.	DOE/EV-0005/8	*Radiological Survey of the E. I. DuPont deNemours and Company, Deepwater, New Jersey*
9.	DOE/EV-0005/9	*Radiological Survey of the Former GSA 39th Street Warehouse, 1716 Pershing Road, Chicago, Illinois*
10.	DOE/EV-0005/10	*Radiological Survey of the Former Horizons, Inc., Metal Handling Facility, Cleveland, Ohio*
11.	DOE/EV-0005/11	*Radiological Survey of the Seneca Army Depot, Romulus, New York*
12.	DOE/EV-0005/12	*Radiological Survey of the Pennsylvania Railroad Landfill Site, Burrell Township, Pennsylvania*
13.	DOE/EV-0005/13	*Radiological Survey of the Museum of Science and Industry, 57th Street and Lakeshore Drive, Chicago, Illinois*
14.	DOE/EV-0005/14	*Radiological Survey of a Contaminated Industrial Waste Line, Los Alamos, New Mexico*
15.	DOE/EV-0005/16	*Radiological Survey of the St. Louis Airport Storage Site, St. Louis, Missouri*
16.	DOE/EV-0005/17	*Radiological Survey of the Former Simonds Saw and Steel Company, Lockport, New York*
17.	DOE/EV-0005/18	*Radiological Survey of the Former Virginia-Carolina Chemical Corporation Uranium Recovery Pilot Plant, Nichols, Florida*
18.	DOE/EV-0005/19	*Radiological Survey of the Building Site 421, United States Watertown Arsenal, Watertown, Massachusetts*

cost effectiveness of the monitoring program is significantly affected by the number of samples required, the degree of sensitivity required, and the natural background variability. The role of statistical design in optimizing parameters will be considered in those sections where statistical design is particularly important to the intermediate or end result, and therefore, in need of QA.

3.7.4 Procedures, forms, records, and special paperwork

It is in the areas involving flow of information via paper (memos, laboratory procedures, maps, blueprints, computer programming, printout formats, etc.) that QA can be particularly helpful. Thousands of measurements in field and laboratory, and conversion to computer files, are best handled by forms designed for the purpose. Existing standards for blueprints, maps, drawings, etc. can be used with little or no special adaptation to a monitoring program. The NRC Regulatory Guides listed in Table 3.10 all give some guidance on means of assuring quality of measurements of radioactive materials in effluents and in the environment.

3.7.5 Document control

Since document control permeates all or many steps of a program as the major tool of QA, the licensee organization with the aid of its QA officer should visualize via a flow sheet or other form each step of the final monitoring program for verifying compliance so that this final step can be executed in a timely manner to minimize labor, equipment, and other costs incurred. A generalized flow sheet will include the elements in Fig. 3.9. As the licensee works through the steps in this diagram, QA can be regarded as a moving pointer, focusing on each step. Many of these steps, of course, will be in progress simultaneously, which results in a managerial QA function. Most, if not all, of these steps require documentation as part of the QA program.

Table 3.10. NRC guides relating to quality assurance of monitoring measurements and reporting

Regulatory Guide	Subject
1.21	Measuring, Evaluating and Reporting Radioactivity in Solid Wastes and Releases of Radioactive Materials in Liquid and Gaseous Effluents from Light-Water-Cooled Nuclear Power Plants
4.1	Programs for Monitoring Radioactivity in the Environs of Nuclear Power Plants
4.8	Environmental Technical Specifications for Nuclear Power Plants
4.14	Measuring, Evaluating and Reporting Radioactivity in Releases of Radioactive Materials in Liquid and Airborne Effluents from Uranium Mills

ORNL-DWG. 80-14052

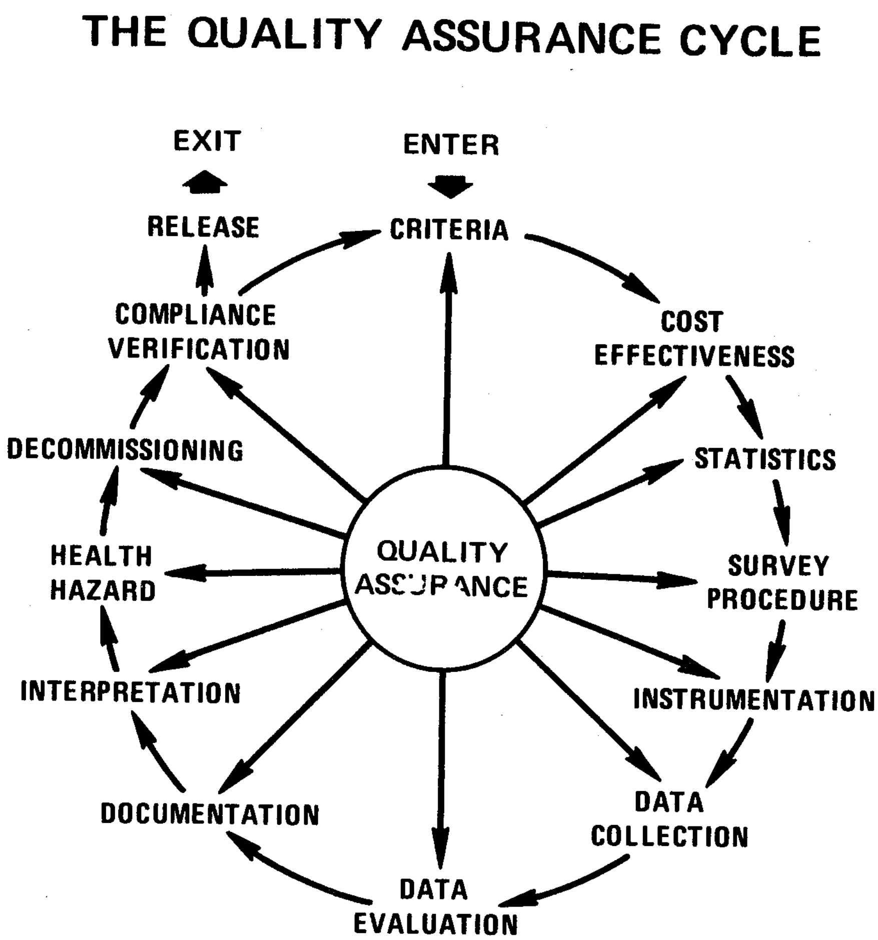

Fig. 3.9. Quality assurance for monitoring aspects of decommissioning compliance.

3.7.6 Control of special processes

This adapted ANSI category cuts across several operations, depending on how "special processes" is defined. For the present purpose, special sampling processes, special statistical procedures, special equipment, etc. would refer to processes not generally used by survey teams, established analytical laboratories, or statisticians for routine problems. Such processes are less likely to come under routine control as a result, and for that reason may require special attention or handling to ensure quality of product or performance. An example would be a delicate radiation measuring instrument not commerically available. In general, special processes (equipment or procedures) are to be avoided unless unusual circumstances exist. When a circumstance becomes "unusual" it requires definition. This may be defined as a circumstance that cannot be handled by existing regulations, standards, guides, criteria, or recommendations of governmental agencies, recognized scientific organizations or professional societies. Where official standards are lacking, it becomes necessary to fall back on publications of professional societies and organizations. If quasi-official guidance or concensus is lacking, in critical cases, a ruling may be required – the Surgeon General's promulgation of radon criteria for indoor air of schools and dwellings at Grand Junction being a case in point.

3.7.7 Control of measuring and test equipment

In general terms, ANSI Category 13 on Control of Measuring and Test Equipment[54] and NRC Category 12 on the same topic[53] specify that a test program be established to assure that the item will perform satisfactorily in service. Equipment shall be tested in accordance with written test procedures which incorporate or reference the requirements and acceptance limits contained in applicable design documents. Prerequisites include such items as calibrated instrumentation, appropriate equipment, trained personnel, condition of test equipment and provisions for data acquisition. Test results shall be documented and evaluated by responsible authority to assure that test requirements have been met. Measures shall be established and documented that tools, gauges, instruments and other inspection, measuring and testing equipment and devices used in activities affecting quality are of the proper range, type and accuracy to verify conformance to established requirements. To assure accuracy, inspection, measuring and test equipment shall be controlled, calibrated, adjusted and maintained at prescribed intervals or prior to use, against certified equipment having known valid relationships to nationally recognized standards.

There are no specific QA standards to apply in deciding on the purchase of equipment for quantitative measurement of radioactivity; however, for a given instrument there are isotope standards available from the National Bureau of Standards, EPA,[60] and elsewhere by which the instrument can be calibrated within the limits of its sensitivity for a given radionuclide. The detection limit problem is discussed in Section 4.2.

Within the limitations of the given piece of available equipment, the generalized ANSI standards can be implemented, such as periodic maintenance by a trained electronics service person, documentation of the test results, etc. Another overall control on measuring equipment is participation in intercomparison studies between laboratories. Such intercomparisons are available through EPA,[61,62] DOE,[63] and other organizations,[64] and should be part of any significant monitoring program.

3.7.8 Handling, shipment, storage, and preservation of samples and records

Quality assurance procedures for manual handling of samples and records can be obtained from NRC, DOE, and EPA. The IAEA[65] is also active in this area. Shipping low volume, low radioactivity samples from field to laboratory and elsewhere comes under existing transportation and interstate commerce regulations. An important question that always comes up is that of deciding when to clean out old files, to destroy original records. Preservation needs for records may vary from a day to the facility's lifetime of 40 years or more. Likewise, the value of stable samples such as soil or core drillings may increase with time as reference standards for the site, even after return to the public domain. General guidance is given by the General Services Administration[66] and by ANSI.[54]

As a relatively new storage and print-on-demand type of record, the handling, storage and preservation of computer programs and records has not received as much QA attention. Recognizing the need for QA standards on computer programs, Sicilian and Pryor published an informal report[67] for the NRC which may be considered a forerunner of QA standards for computer programs and data storage. To the extent applicable, licensees using or contemplating use of computerized records as part of the decommissioning compliance procedure should be aware of the need for QA for computerized data and other record storage.

3.7.9 Quality assurance records

An auxiliary set of QA records complement the basic operational records as a result of QA work on the monitoring program (Fig. 3.9). These ensure the quality of each step from survey design to data interpretation and final decision on whether or not decommissioning criteria have been met. Large organizations with established QA offices will usually have rather elaborate programs, compactly summarized as one or more QA manuals. A typical manual would include not only sample record forms but procedures and explanations, organized in major categories. As an example, the QA manual would also include QA guide sheets such as illustrated in Table 3.11.

In anticipation of final site decommissioning, the QA program should incorporate decommissioning steps. If the site is already inactive, or on standby basis, checklists for the monitoring program will become a primary tool, and QA on same may not have the luxury of control by an existing QA office or officer. The present guide covers general aspects of quality assurance for design planning, data generation and interpretation, in line with the NRC plan for reevaluation of its policy on decommissioning nuclear facilities.[68] Sufficient records of suitable quality are required to stand up in court or elsewhere as reasonable proof that the monitored site meets decommissioning criteria.

Table 3.11. Sample contents of a typical QA manual

QA Guide No.	Topic	Issuance date
QA-P-001	Quality assurance program	xx-xx-xx
QA-P-002	QA planning	xx-xx-xx
QA-P-003	QA assessment	xx-xx-xx
QA-P-004	QA procedures	xx-xx-xx
QA-P-005	QA operations	xx-xx-xx
QA-P-006	Document and record control	xx-xx-xx
QA-P-007	Project technical review - general	xx-xx-xx
QA-P-007A	Project technical review - monitoring	xx-xx-xx
QA-P-008	Instrumentation control and calibration	xx-xx-xx
QA-P-009	Quality deficiency	xx-xx-xx
QA-P-010	Identification and control of nonconforming items	xx-xx-xx
QA-P-011	Deviation approval	xx-xx-xx
QA-P-012	Corrective action	xx-xx-xx
QA-P-013	QA audits	xx-xx-xx
Etc.		

3.7.10 Audits

Abandoned sites will become a thing of the past after the present backlog has been inventoried, inspected and decommissioned. Audits for abandoned sites may consist only of a final check on the procedures of a government-sponsored monitoring team. In such cases, only the site can be in compliance. More typically, an ongoing licensee program will be in progress, though frequently in a stage approaching decommissioning. In such a case, previous audits will be available, and corrective actions and orderly planning for final decommissioning will have been instituted with guidance from a QA company officer or consultant. Such audits, along with radionuclide inventories, operational locations etc., will offer a firm base on which to design and carry out the necessary monitoring program. From the audits one should be able to obtain the following information:

1. Areas audited.
2. Area operations.
3. Area inventories.
4. Available records on area.
5. Quality assurance on area records.

Of the total number of samples taken by the licensee in replicate, 0.1 to 10% should be reserved for analysis by an independent laboratory as part of a quality assurance audit, depending on site size and complexity of nuclear operations.

3.7.11 Nonconforming items

The nonconforming items of ANSI[54] (termed corrective action by NRC[53]) applied to the monitoring program could range from incorrect calibration of a measuring instrument, or a Type 2 statistical error in deciding whether above-background levels of radioactivity exist in the monitored area, to the final decision that site status is not in compliance with decommissioning criteria. Procedures are then needed to ensure that the necessary corrective action is taken. This may be a simple or a complex procedure. To remain cost effective, prompt action is needed, control of which should be ensured by a good QA program.

The QA procedures themselves should not be a hindrance and should be based on good technical theory and practice. Practical and theoretical treatment of the above and other potentially nonconforming items are discussed in the various sections of this manual.

3.7.12 Corrective action

If corrective action is involved, then a sequential checklist or other courses of action may be indicated. Nonconformance of an item may be due to an undetected error or condition at one or more steps prior to the nonconforming item. The immediate and original causes of item nonconformance must first be identified. Cause of nonconformance may have originated in the original survey design, statistical procedures, instrument calibration, etc. Review of the QA steps taken at each stage of the program (Fig. 3.9) may, in a majority of the cases, locate the step where an original error developed which led to the nonconforming item, and perhaps one or more additional dependent or independent errors or inadequate measures contributing to the nonconformance. If noncompliance is confirmed, then further cleanup, restriction of the area, or other steps beyond the scope of the monitoring program may be necessary.

3.7.13 Health and safety quality assurance for monitoring personnel

An examination[69] of incidents at Sandia Corporation, Albuquerque suggested that proven principles and techniques of QA can be used or modified to support health and safety programs. Concern for decommissioning and monitoring personnel should be as great as for the general public since such personnel are more likely to encounter a higher radiation background before final cleanup, or while in the process of locating areas in need of cleanup. The concern for such personnel is of course short term and such personnel generally are protected (respirators, etc.). Quality assurance in health for both workers and the public is built into the entire nuclear program in a generalized way, attempts to isolate it specifically from a QA viewpoint being more recent. The Health Effects Research Laboratory at Research Triangle Park, North Carolina, is developing this approach for the EPA.[70,71]

Documentation of personnel exposure records (film badges, pocket dosimeters, etc.) is a long-standing practice in the nuclear industry, and reporting procedures for over-exposure well established. This aspect of health and safety QA is covered by ANSI Category 7 on Document Control.[54] Quality assurance on exposure-measuring devices comes under Category 13 on Control of Measuring and Test Equipment.

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4.0 INSTRUMENTATION

Analytical instrumentation used to generate data is of two types: (1) portable in the field, and (2) fixed in the laboratory. The licensee whose radiological operations are small may not be able to afford investment in the second type. Some cost figures for instrumentation are listed in Appendix VI. In the latter case, samples are sent out for analysis. At the other extreme, large licensees such as chemical corporations maintain their own radiological laboratories for soil and related analyses.

4.1 Instrument Selection

Perhaps the best approach for a small (less than five employees) licensee is to talk with sales representatives of instrument manufacturers, study their literature, visit a radiological laboratory, figure cost estimates, and otherwise become familiar with the problem, before deciding on whether to invest in equipment and its use. For the winding down of a small-scale radiological operation, the services of a commercial surveying group known to the field as reputable is likely to be the preferred route.

The large licensee who has been in operation for some years will have accumulated the necessary basic instrumentation, and will be more interessted in such questions as expected sensitivity for his surveys, including the final one. Some of the basic instrumentation used is referred to in Section 4.2.

4.2 Survey Techniques and Sensitivities

A critical element of a monitoring program designed to verify compliance with decommissioning criteria is the selection of sufficiently sensitive radiation detection techniques. In general it is desirable to use those techniques which provide all the advantages in terms of cost, time, ease of measurement, etc., and at the same time provide sufficient sensitivity. Unfortunately, it is not always possible to enjoy this ideal situation. Frequently, trade-offs are necessary to select the optimum detection techniques. Three general types of monitoring can be readily identified. These are:

1. Environmental sample analysis.
2. Real-time environmental measurements.
3. Direct surveys with portable instruments.

In the interest of time and expense, it would be advantageous if termination surveys consisted largely of the latter type, supplemented as necessary by environmental sampling and in situ measurements.

A search of the literature along with experience gained in the environmental monitoring and off-site measurements programs at the Oak Ridge National Laboratory have provided approximate sensitivities for the various types of radiation detection techniques.

4.2.1. Environmental sample analysis

In many cases it may be necessary to take samples of soil, water, or some other environmental medium and perform laboratory analyses in order to obtain the necessary sensitivity when portable survey instruments cannot give the necessary sensitivity and/or specificity. The required sensitivity will be dictated by the decommissioning criteria which are applicable. Environmental monitoring with laboratory analysis is the most expensive and time consuming type of monitoring, yet provides the best sensitivity and specificity.

Frequently, in performing termination surveys it will be necessary to determine the isotopic composition of contaminants. In some instances, adequate information on the nature of the contaminants will be available from previous site documentation. In general, this will require spectroscopic analysis of various media, including smears on surfaces. This would represent the minimum need for environmental sample analysis. In complex surveys, it may be necessary to determine radionuclide distributions in subsurface soil. Cost considerations may necessitate simultaneous monitoring for nonradioactive contaminants. Consequently, the sampling program could be rather extensive.

From experience with environmental sample analysis at ORNL and information available in the literature,[1-6] Table 4.1 has been prepared to give an estimation of the approximate sensitivities for various radioisotopes. Required minimum sensitivities for nonradioactive contaminants are listed in Table A of the EPA Proposed Standards given in Appendix II.

4.2.2 Real-time environmental measurements

Like environmental sample analysis, real-time environmental measurements are both expensive and time-consuming. Most detector systems used for these real-time measurements require a large initial investment. The cost may be amortized over the useful lifetime of such systems provided they can be used repeatedly in termination surveys or the licensee may opt to subcontract the survey. Real-time environmental measurements may be prohibitively expensive for those having a one-time-only application. Another drawback is that most of these systems require fixed placement for lengths of time running from a few minutes to many hours. Then one obtains a measurement which is characteristic of the point of measurement rather than the whole site. To take many such measurements would require a prohibitively long period of time. This type of monitoring would be useful for spot inspection of a site to certify its compliance with the applicable guidelines.

In situ Ge(Li) detector systems[7,9] are capable of measuring gamma ray emitters from the natural decay chains (U, Th) and from ^{40}K at levels of 1 pCi/g or less. Fallout nuclides such as ^{137}Cs and ^{60}Co may be measured at levels of a few pCi/cm^2. Direct measurement of uranium in soil also may be done with a high resolution Ge(Li) spectrometer[10] at the parts per million level.*

*Only by spectral analysis can one "see" the small incremental contribution to background due to the small residual levels allowed for unrestricted release.

Table 4.1. Detection sensitivities for environmental sample analysis

Analysis	Sensitivity[a]	
	Water (pCi/L)	Soil (pCi/g)[b,c]
^{40}K		0.05
^{54}Mn	15	0.05
^{59}Fe	30	0.10
^{60}Co	15	0.05
^{65}Zn	30	0.10
^{90}Sr[d]	2	0.05
^{95}Zr-Nb	10	0.10
^{137}Cs	15	0.05
^{226}Ra	2	0.5 (0.03)[e]
^{232}Th		0.04
^{238}U[c]	2	0.04
^{239}Pu	0.01	0.004
^{241}Am		0.004

[a]Sensitivity is taken to mean the limit of detection.

[b]Gamma emitters may be counted with NaI(Tl) or Ge(Li) detectors depending on the complexity of the sample spectrum. Sensitivity depends on the number of interfering radionuclides. The actual sample size may vary but be of the order of several hundred grams. Alpha and beta emitters require special treatment.

[c]37 mBq = 1 pCi.

[d]Requires prior chemical separation followed by alpha or beta counting as appropriate.

[e]By ^{222}Rn emanation technique.

Pressurized ionization chambers[11] have been used to measure environmental exposure rates of a few μR/h.*

Some radon and radon daughter measurements may also be included in this type of monitoring. The sensitivities of several monitoring techniques[12-16] for radon and radon daughters are listed in Table 4.2.

4.2.3 Direct surveys with portable instruments

A great deal of the actual monitoring necessary in a termination survey will have to be conducted with portable instrumentation. Due to the difficult accessibility of many areas that will have to be monitored and the need to have thorough coverage of all areas, portable instruments will be needed for most of the measurements to be taken in a termination survey. Also of practical consideration is the length of time to complete a termination survey. Here again portable instruments provide the most expedient measurements.

Geiger-Mueller (G-M) and scintillation survey instruments are also recommended for contamination monitoring. Several factors, however, need to be considered in evaluating instrument sensitivity including wall thickness, scanning speed and beta energy.

Beta emitters can be measured with a glass or aluminum-walled 30 mg/cm^2 G-M tube or with a thin-window 1 to 2 mg/cm^2 probe. Thin-window probes can measure beta particles down to 0.16 MeV (^{14}C) and energetic alpha particles. It should be noted that it will not be possible to detect tritium contamination with a survey meter (0.0186 MeV Beta). Sampling following by liquid scintillation counting must be used for tritium measurements. A 30 mg/cm^2 wall tube can measure beta

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*For several years EG&G has been generating aerial gamma isopleth maps of active sites. Reference 17 is a typical report, showing that, except for an area centered on the plant, natural radiation background levels over the western half of the site were generally 6 to 8 μR/h (60 to 80 nGrays/h), and over the more rugged eastern half 6 to 17 μR/h (60 to 170 nGrays/h), calculated for 1 m above ground level, actual helicopter altitude being 90 m above ground level. From typical EG&G data shown in Table 4.3, it can be assumed that 1 m gamma readings exceeding 12 μR/h (120 nanoGray/h) are likely to represent man-made contamination.

Table 4.2. Detection sensitivities for radon and radon daughter measurements

Method	Detection technique	Sensitivity
Radon-air (grab sample)	ZnS scintillation flask	0.1 - 0.3 pCi/liter
Radon-air (integrating)	Thermoluminescent dosimeter	15 pCi/hr/liter
Radon-air (continuous)	Wrenn Chamber	0.01 pCi/liter
Radon daughter (grab sample)	Alpha spectroscopy count of filter sample	0.0005 WL
Radon daughter (integrating)	Thermoluminescent dosimeter	0.1 WL/h

Table 4.3 Variability in gamma background at 1 m above ground level, according to some EG&G aerial surveys, 1972-1980

State	City	Site	μR/h	Survey Date	Report No. EGG-1183-
California	Clay Station	Rancho Seco Nuclear Power Plant	6-16	Jan 1980	1761
Minnesota	Monticello, Elk River	Monticello & Elk River Power Plants	8-10	May 1972	1659
Missouri	St. Louis	Mallinkrodt Nuclear, Maryland Height	8-11	Oct 1977	1721
Wisconsin	Genoa	LaCrosse Boiling Water Reactor Site	7-10	Oct 1977	1720
Illinois	Morris	Dresden Nuclear Power Plant	8-10	Jun 1978	1657
	Sheffield	Nuclear Engineering Company (NECO)	8-11	Sep 1979	1772
Ohio	West Jefferson	Battelle Nuclear Science Facility	9-13.5	May 1979	1739
	Miamisburg	Mound Facility	7-11	Mar 1978	1722
	Portsmouth	Portsmouth Gaseous Diffusion Plant	6-8	Jul 1976	1719
Pennsylvania	Goldsboro	Three Mile Island Nuclear Plant	3-10	Aug 1976	1710
Michigan	Big Rock Point	Big Rock Point Nuclear Power Plant	7-11	Apr 1978	1701
Kentucky	Paducah	Paducah Gaseous Diffusion Plant	7-11	Apr 1978	1727
Tennessee	Daisy	Sequoyah Nuclear Power Plant	3-5	Nov 1977	1755
	Erwin	Nuclear Fuel Services Facility	9-12	May 1979	1748
Alabama	Dothan	Joseph M. Farley Nuclear Power Plant	6-10	Nov 1978	1734
Florida	Red Level	Crystal River Nuclear Power Plant	4-6.5	Jun 1979	1746
Georgia	Baxley	Edwin I. Hatch Nuclear Power Plant	6-10	Nov 1978	1726
S. Carolina	Seneca	Oconee Nuclear Power Plant	7-10	Apr 1977	1648
New York	Scriba	Nine Mile Point Nuclear Power Plant	4-8	Sep 1972	1656
	Ontario	Robert Emma Ginna Power Plant	4-10	Feb 1978	1658
Rhode Island	Wood River Junction	UNC Recovery Systems Facility	3-4	Aug 1979	1756
Massachusetts	Billerica	New England Nuclear Corp. Facility	3-4	Aug 1979	1753

According to the above EG&G reports, U. S. background (including cosmic ray contribution) varies in general from 3 to 16 μR/h (30 to 160 nanoGray/h), roughly by a factor of 5. Examination of the above upper values will suggest that gamma readings exceeding 12 μR/h (120 nGy/h) are likely to represent man-made contamination or contribution to natural unenhanced gamma background 1 m above ground level, barring natural ore bodies such as phosphate or uranium, or volcanic extrusions. Gamma readings exceeding 120 nGy/h are likely to represent above-background levels anywhere in the United States. For very low background areas such as 40 nGy/h, readings above 80 nGy/h might be suggestive of slight contamination. More extensive background data by counties is needed, where present or past nuclear operations have been absent.

emitters with energies down to about 0.3 MeV. It is recommended that the scanning speed shall be slow enough to ensure a source detection probability of 50%.[18] A scanning speed of 5 cm/s was shown to be adequate to detect a source of 200 betas/min with a 50% detection frequency.[18] Beta contamination below 200 dpm/100 cm^2 would be very difficult to detect. Investigations by Sommers[19] showed that at more realistic survey velocities, 10 to 15 cm/s, it takes a source of 10,000 to 15,000 betas/min to provide a detection frequency of 90%. The above observations were made in an area producing a background count rate of 120 counts/min. If higher backgrounds are encountered, the probability of detection will be lower.

Minimum detection levels for direct surveys with G-M type instruments are generally limited to the equivalent of background reading at the survey location (e.g., a detection level of 100 counts/min above a background level of 100 counts/min.

Floor monitors utilizing an array of G-M tubes with an active length of 18 inches and a wall thickness of 30 mg/cm^2 are available that provide lead shielding which will lower the background. These are useful for smooth floor surfaces and can be modified to survey walls. A sensitivity similar to a hand-held G-M probe is attaintable. Another mode of beta monitoring is with a walking stick using a G-M probe at the end and a count-rate meter carried from a shoulder strap.

A summary of beta-gamma contamination monitoring instrumentation is given in Table 4.4.

Because of the short range of alpha particles, direct field measurements with portable survey instruments is a tedious, time-consuming process. On rough surfaces like soil, the sensitivity and reproducibility of these measurements is reduced tremendously. Even a layer of dew over alpha emitters can result in the activity being shielded from detection. It is recommended that the distance of the probe window to surface not exceed 0.5 cm.[18] When monitoring for the more hazardous alpha emitters, the scanning speed should not exceed in cm/s one-third the numerical value of the detector window dimension (in centimeters) in the direction of the scan. This is a very slow scanning speed; a

Table 4.4. Instrumentation and methods for beta-gamma contamination monitoring

Instrument or method	Nuclide	Application	Sensitivity
GM thin-walled probe	Gross beta	Surveying by hand or with walking stick	2000-3000 dpm/100 cm^2
GM end window or pancake	Gross beta	Hand surveying for beta contamination	1500 dpm/ 100 cm^2
GM floor monitor	Gross beta	Surveying smooth surfaces	2000 dpm/ 100 cm^2
Phoswich	Beta and low energy gamma	Special phoswich for ^{90}Sr surveying	1 nCi/g in 4 pCi/cm^2
Intrinsic Germanium	^{90}Sr	Used for well logging and soil measurement	30 pCi/g
In situ GeLi or NaI	Gamma emitter	Site evaluation move-able by net for survey	<50 nCi/m^2
NaI or GeLi counting	Gamma emitters	Counting samples	100 pCi/sample
Gross beta counting	Gross beta	Counting swipes or soil	20 pCi/sample
Liquid scintillation	^3H, ^{14}C	Counting ^{3} or ^{14}C	200 pCi/ℓ of water
Radiochemistry	Beta gamma emitters	Measurement at low levels	Variable

detector with a window that is 20 cm long in the direction of the scan should traverse only 40 cm in one minute.

For hard nonporous surfaces such as floors, walls, and smooth equipment, direct alpha monitoring can be used. If surfaces are to be scanned in search of activity, the scanning speed is slow as mentioned above. If measurements are made at fixed points on a grid, an activity of 200 d/m per detector area can be measured (~20 nCi/m^2). If measurements are made in a scanning mode, the level that can be expected to be measured is 50 to 100 nCi/m^2. Again, it should be emphasized that these levels are under ideal conditions with the alpha activity in a thin layer on a smooth surface.

One of the most viable means of field measurement for plutonium, americium or other alpha emitters that emit low energy X or gamma rays is the FIDLER (Field Instrument for Detecting Low Energy Radiation) instrument. The FIDLER uses a thin NaI or CaF_2 crystal and photon pulse height discrimination to detect 17-KeV x-rays from the progeny of plutonium, or the 60-KeV photon of ^{241}Am. Although the sensitivity of the FIDLER instrument, ideally about 130 nCi/m^2, is about two orders of magnitude above ambient background levels of plutonium (nominally 1 to 2 nCi/m^2 of ^{239}Pu) it provides significantly greater utility for contamination surveys than alpha detection survey instruments.[20]

Although the minimum sensitivity of the FIDLER is indicated as 130 nCi/m^2 for ^{239}Pu, this relates to only 75 cpm above minimum background values of 200 cpm. Given the variability of background with values up to 400 cpm, or more, extreme care should be exercised to accurately access net contamination at 200 or even 500 nCi/m^2. Without an accurate knowledge of background, values at these levels would have uncertainties approaching 50 to 100 percent.

The Los Alamos Scientific Laboratory (LASL) has adapted a phoswich detector for use as a field survey instrument.[21,22] This semiportable instrument has a background which is two to three times lower than an FIDLER probe. This instrument utilizes standard NIM electronics carried in a truck with a 30 m umbilical cord attached to the probe. The electronics are operated by a power inverter from the vehicle battery.

With a 500 cpm background, the detection limit is considered 1200 pCi/g for a signal equal to background. This instrument is now commercially available in a portable model.

Finally, lower sensitivities can be reached for alpha emitters with Enewetak or Princeton Gamma Tech (PGT) instruments by making integral counts over Petri dishes containing soil. Minimum sensitivities below 1 pCi/g can be achieved with these instruments. The additional survey time and costs associated with these detection devices may be necessary in certain situations.

Table 4.5 lists instrumentation and methods for alpha contamination monitoring.

For monitoring contamination levels on surfaces and in soil, it is expected that portable survey meters backed up by some sampling and laboratory analysis will be used. Laboratory analysis can provide data that may allow "index isotopes" to be selected which are more readily measured with survey instruments and allowing other nuclide concentrations to be estimated by use of ratios. Examples of such ratios are $^{137}Cs/^{90}Sr$ or $^{241}Am/^{239}Pu$.

Table 4.5. Instrumentation and methods for alpha contamination monitoring

Instrument or method	Nuclide	Application	Sensitivity pCi/g soil	Sensitivity dpm/100 cm
Alpha survey (scint. prop)	Gross alpha	Smooth surfaces		200
FIDLER	Pu ^{241}Am	Surface or soil-count rate made	2000	
Phoswich	^{239}Pu ^{241}AM	Soil-count rate made	1000 100	
Phoswich	^{239}Pu ^{241}Am	Soil-integrate mode	20 2	
Zn S Scint.	Gross alpha	Soil or swipes	25	
Intrinsic germanium[a]	^{239}Pu ^{241}Am	Soil, petri dish sample	4 0.5	
Enewetak - Proportional	Gross alpha	Petri soil - integrate mode (5-10 min)	5	
Enewetak - IMP	^{241}Am	In situ soil - integrate mode (15 min)	0.5	
Radiochemistry	^{239}Pu ^{241}Am ^{226}Ra	Low-level measurements for specific nuclides	0.002 0.002 0.1	

[a] Princeton Gamma Tech (PGT-IGe) minimum sensitivity with 240 min count is 0.04 pCi ^{241}Am/g soil and 5 pCi ^{239}Pu/g soil.

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5.0 EVALUATION AND INTERPRETATION OF MONITORING DATA

5.1 Statistics

In Section 3.5 the importance of the Central Limit Theorem was stressed, with the need for sample sizes to be no less than 30 for significant univariate (one-variable) statistics and comparisons. By the Eq. (3.18) test, the unknown population mean, of which the average of sample means is an approximation, was considered adequately approximated whenever the former mean was known with less than 25% error at the 90% confidence level. In stratified random sampling, the population of survey blocks into which the entire site was further subdivided (stratified), and a subset of blocks randomly selected from each stratum for air measurements and soil sampling. An alternative procedure for small sites or for a controversial site, and potentially more expensive as a survey procedure, was systematic sampling of every survey block. A site requiring measurements on every block might be one of high hazard potential in a high-density population area for which inadequate prior information exists. The block dimensions might be 1 m × 1 m for indoor high hazard potential areas to 10 m × 10 m or higher for outdoor moderate to low hazard potential. If a rough prior estimate of hazard potential is not available, then smaller block sizes would be required. For newer sites, a rough estimate of hazard potential will probably be available in terms of such prior information as (1) nuclides involved, (2) their radiological half-lives, (3) quantities (throughput) involved during the operational lifetime of the site, (4) unidentified losses during the operational period, (5) on-site burial of contaminated rubble, (6) indications from the licensee's final survey that the site has been cleaned up to existing standards. Adequate prior information of this type allows for selection of larger block sizes for simple random or stratified random sampling, and hence lower survey costs. A common procedure is to take 5 to 10 radiation readings per block, more if readings suggested a hot spot in that block, obtaining both average and maximum readings for each block. In addition, soil samples are taken from some blocks, the higher the correlation between soil nuclide concentration and readings the fewer the soil samples needed per 100 radiation readings. This requires some matched "observations," as defined in Section 1.2 to evaluate the correlation or lack of it. In Section 3.5 questions of total sample size for the entire site and how to allocate samples between strata relate to variance and cost were presented.

In Section 5.3 the paramount question of distinguishing between natural or unenhanced background variability (distribution) and enhanced background distribution specifically due to radiological operations formerly carried out on that site by the application of statistical tests (inferential statistics) is addressed. In this section, some characteristics of the normal distribution (Gaussian) curve and the question of non-normality are considered briefly.

Two parameters, the mean and the standard deviation completely define the normal curve, with a skewness of zero and a kurtosis of three. The skewness statistic is useful if more than 200 measurements are available, kurtosis if 1000 measurements are available.[1] Unlike the normal curve, the lognormal curve mode, median and mean do not coincide (see Fig. 5.1). Soil nuclide distribution is likely to be lognormally distributed, in which case transformation to normal distribution by taking logs can be effected. A straight-line plot on normal probability paper indicates normality, while a straight-line plot on lognormal probability paper indicates lognormality. Assuming erroneously that a distribution is normal can result in (1) overestimating the mean and values near the mean, and (2) underestimating values far from the mean.[2] Outdoor plutonium has been reported to be lognormally distributed.[3] At Livermore, radioactivity has been reported to be lognormally distributed in all types of samples (soil, water, air, sewage, vegetation) with a geometric standard deviation of about two.[4] On the other hand, to assume that all measurements are lognormally distributed can result in erroneous conclusions too, according to Ong and LeClare.[5] It is convenient to assume normal or parametric statistics, an alternative being to use nonparametric statistics which is relatively distribution-free but less informative for small sample sizes.

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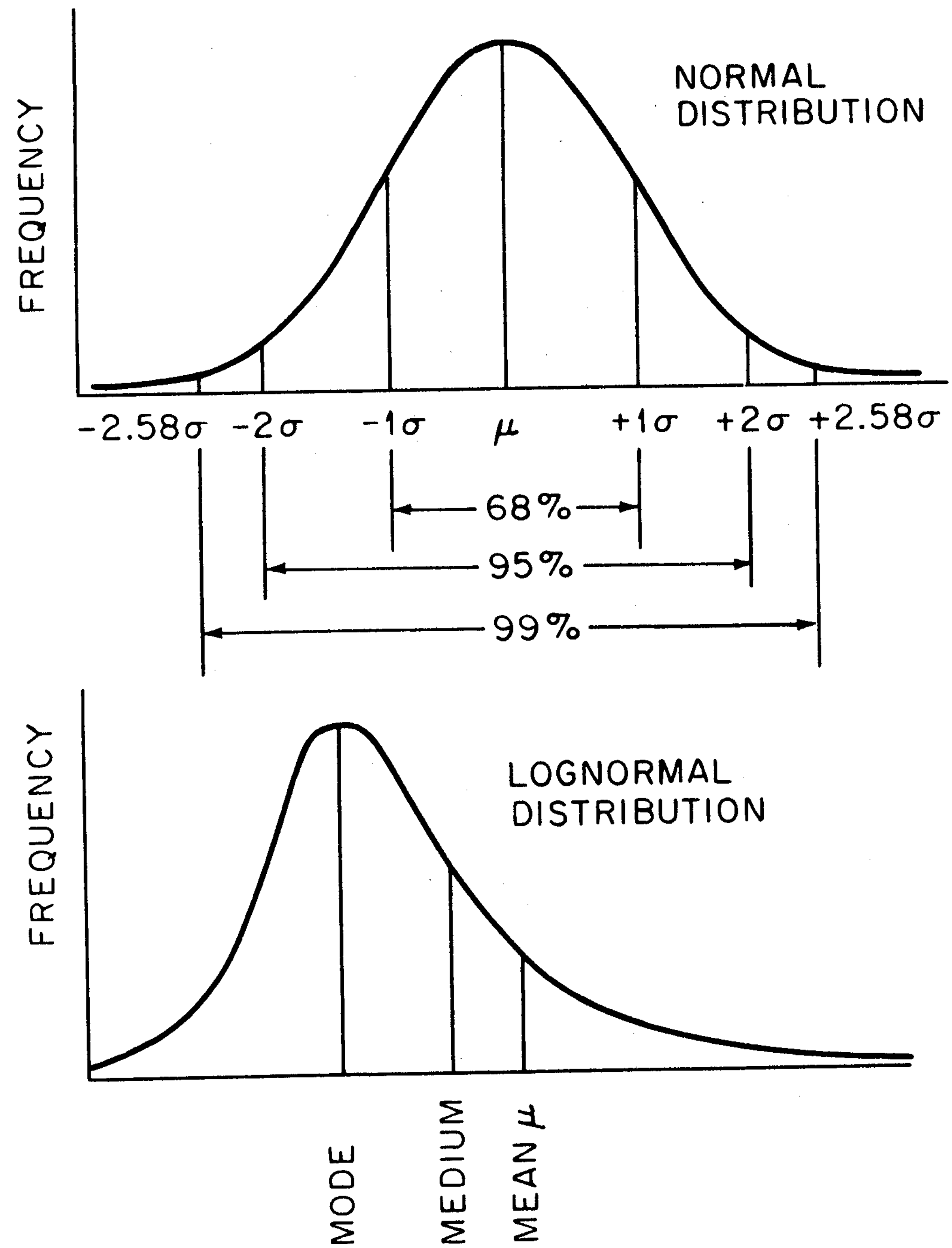

Fig. 5.1. Normal and lognormal distributions.

According to the Central Limit Theorem, if a series of means ($\bar{x}$'s) of samples taken from the unknown population is large enough ($n \geqq 30$ for each sample), then their distribution will be normal (even though the population thus sampled may not be), and the Grand Mean ($\bar{X}$) of these means ($\bar{x}$'s) will be an unbiased estimate of the unknown population mean (μ). A bar over the x indicates a mean or average value of several x's. The standard deviation of the sampling distribution of $\bar{x}$'s is known as the standard error of the mean ($\sigma_{\bar{x}}$) and the relation

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}} \tag{5.1}$$

is used to answer in Section 5.3 the question: Does sample x come from the same population as Sample B (B for Background)? This question becomes increasingly significant as the condition of the cleaned-up site approaches that of background characteristic for the site area, and the sample distribution curves begin to overlap. Given a specific population such as background values of ^{226}Ra in pCi/g of soil, an average of 30 values taken on one day will probably differ from an average of 30 values sampled the next day, and so forth, until a distribution of averages is obtained whose grand mean is the most probably background mean. If the residual ^{226}Ra contamination of the site from former ^{226}Ra operations on that site is only slightly higher in terms of the mean and standard deviation than for background ^{226}Ra, then the acceptability or non-acceptability of the site for unrestricted release depends upon how rigid the standard and how confident one can be about the results. Using the EPA standard that the average concentration of ^{226}Ra in the 5 cm or smaller thickness of soil shall not exceed 5 pCi/g after completion of the remedial actions (Section 1.1.2), it remains to be decided at what confidence level and with what allowable error on that confidence level the ^{226}Ra is conceded to be about 5 pCi/g. This depends in part on the state-of-the-art (detection limit of ^{226}Ra). It is possible to measure 1 pCi/g of ^{226}Ra with an error of ±10% using a 300 cm^3 soil sample and a 50 cm^3 Ge(Li) detector in a graded shield. On- and off-site natural background heterogeneity of ^{226}Ra concentration is another factor. To the extent that beta and gamma air readings reflect soil concentrations of beta and gamma emitting nuclides, the same problem exists for distinguishing natural background air gamma readings from air gamma readings due to the former use of gamma emitters on that site. The question of differentiating near-background contamination from unenhanced background is treated in Section 5.3.

In order to facilitate comparison of non-standard normal curves with the standard normal curve, values such as μR/hr or pCi/g are converted to z values or z scores as follows:

$$\text{z score} = \frac{x-\mu}{\sigma}, \tag{5.2}$$

where

μ = population (or sample) mean, and

σ = population (or sample) standard deviation.

When it becomes necessary to differentiate population mean from sample mean, most texts will use $\bar{x}$ for the latter. To differentiate population standard deviation from sample standard deviation, it is common to use either $\sigma\bar{x}$ or s to signify the latter.

In other words, a z score expresses the deviation from the mean in standard deviation units (i.e., how many standard deviations away from the mean is x. Having converted raw scores into z scores, the mean is now zero and the standard deviation is one. According to the theorem of Tchebysheff (Chebyshev), the range of a normal distribution is roughly 4 to 6 standard deviations. Stated another way by Tchebycheff's inequality: the probability that a standardized score drawn at random from a distribution has an absolute magnitude greater than or equal to some positive number, k, is always less than or equal to $1/k^2$. For example, the probability of a standardized score (z score) of three or more is no more than 1/9. One rough test of an "outlier," that is a value that does not belong to the population under consideration, is whether that value is more than 4 standard deviations from the mean of that population. If stratification is to be made on the basis of minimizing variance (square of the standard deviation) within the strata while maximizing the difference between strata, then a rough test for stratification by populations is helpful.

A surveyor in the field tends to favor stratification by geography (grouping contiguous survey blocks together), while a statistician tends to favor stratification by variance regardless of where the survey blocks lie. Where feasible a combination of the two has some merit. It is important to keep in mind when the population under consideration is the total number of survey blocks (from which readings and soil samples are taken) and when the population is taken to mean the total number of air gamma readings or soil samples taken. In stratified random sampling, air readings and soil samples are taken from a randomly selected subset of numbered survey blocks constituting the stratum. Sampling from one stratum can be considered simple random sampling. In systematic sampling of air readings over the entire site, readings are taken on every survey block. The sampling statistics given in Section 3.5 can be used to determine sample size for simple random or stratified random sampling.

5.1.1 Field measurements

For each variable measured in the field, at least 30 measurements should be taken for each stratum in the licensee's final survey. Since the inspector's final survey is only confirmatory, he may take only 30 measurements for the entire site. Measurements on each variable (air, gamma, soil, ^{226}Ra, etc.) should be averaged, the standard deviation calculated, and measurements converted to z scores. Confidence levels or limits should be set on the averages obtained. Finally, the field measurements should be compared against existing standards and guidelines.

An important aspect of field measurements are the points chosen for the instrumental readings and soil samplings. Points chosen are in reference to randomly selected survey blocks. Number the blocks consecutively, starting in the upper left corner of the grided site map, numbering horizontally, ending in the lower right. In theory each block number could be written on a piece of paper, all pieces thoroughly mixed, and pieces removed randomly until the calculated sample size is reached. A simpler procedure is to use a published random number table from which to select the calculated subset of survey block numbers to be measured. Calculation of sample size is covered in Section 3.5.

5.1.2 Laboratory measurements

Laboratory analyses of field samples have long been under quality control. Small licensees will send their samples out for radiochemical analysis. Large licenses will have their own analytical laboratories. Those desiring detailed information on statistical aspects of laboratory analysis should consult standard references. One such statistical reference might be that of Kolthoff and Elving,[6] especially Part I, Volume 1, Chapter 4 by L. A. Currie on "Sources of Error and the Approach to Accuracy in Analytical Chemistry" and Chapter 5 by J. Mandel on "Accuracy and Precision: Evaluation and Interpretation of Analytical Results."

5.2 Analysis of Data

Each of the 87 Department of Energy sites declared surplus before October of 1976 and to be decommissioned over the next 20 years,[7] will have its own special site characteristics. The public is concerned about the few large sites, but the NRC must also concern itself with literally thousands of small by-product licensees. Analysis of data may range, therefore, from complex to simple. General principles of statistical analysis presented below may be scaled up or down according to the licensee's scale of operation.

In the course of data reduction, univariate (one-variable) raw data will have been sumamrized in terms of range, mean, median, standard deviation, variance, a frequency histogram, skewness, kurtosis, and other sample statistics as needed to use in estimating population parameters (total site contamination if any). Bivariate comparisons and perhaps multivariate correlations may have been made to see if or to what extent one variable such as air gamma readings might or might not serve as a useful predictor for another variable such as ^{226}Ra or

^{137}Cs. Normal distribution statistics can be used with greater confidence if sample sizes are larger than 30 each, according to the Central Limit Theorem. If a discrete histogram is skewed, as illustrated by the smoothed curve shown in Fig. 5.1, a lognormal (Eq. 3.4) or exponential transformation may convert the data to a normal distribution so that normal statistics can be used. If the sample size of concern is less than 30, or if the distribution cannot be defined as or transformed to normality, then nonparametric statistics[8] can be used at the expense of some information loss.

Sample means are commonly used as the least biased estimate of the unknown population mean. For example, air gamma or soil nuclide mean for the entire site. The confidence limits to be set upon such a sample mean are needed to assess the significance or degree of confidence one can place in such a value. The use of the standard error of the mean (Eq. 5.1) to set confidence limits can be illustrated by an example. Assume a 50-acre (0.2 km^2) site was given a final systematic gamma survey by the licensee (no alpha or beta emitters involved at the site). One thousand, three hundred and sixty gamma readings were taken at 0.2 m above the surface with an instrument having a minimum detection capability of 1 μR/h at this distance. Readings have been grouped into 6 class intervals, and columns set up for calculating the sample standard deviation ($\sigma\bar{x}$) as shown in Table 5.1, in μR/h. To convert to μGy/h, use the conversion factor, 1 μR/h = 0.01 μGy/h.

Table 5.1. Setting confidence limits on a mean for a given standard error

Class interval (μR/hr)	Midpoint	No. of air gamma readings	Product of frequency	$(x-\bar{x})^2$	$f(x-\bar{x})^{2a}$
0-1.99	1	118	118 × 1 = 118	$(1-5.03)^2$	118 × 16.24 = 1916.4
2-3.99	3	237	237 × 3 = 711	$(3-5.03)^2$	237 × 4.12 = 976.4
4-5.99	5	680	680 × 5 = 3400	$(5-5.03)^2$	680 × 0.001 = 0.07
6-7.99	7	195	195 × 7 = 1365	$(7-5.03)^2$	195 × 3.88 = 756.6
8-9.99	9	92	92 × 9 = 828	$(9-5.03)^2$	92 × 15.76 = 1449.9
10-11.99	11	38	38 × 11 = 418	$(11-5.03)^2$	38 × 35.64 = 1354.3
Totals		1360	6840		6454.3

[a]Standard deviation of the mean = $\sigma_{\bar{x}} = \frac{f(x-\bar{x})^2}{N} = \frac{6454.3}{1360} = 2.18$.

Completing the analysis, the

$$\text{standard error of the mean} = \frac{\sigma}{\sqrt{N}} = \frac{2.18}{\sqrt{1360}} = 0.06,$$

mean of the readings = $5.03 \pm 0.06 = \bar{x}$; and

the 99% confidence level = 2.57. (From Table 5.2.)

Therefore, the confidence limits for a standard error of

$0.06 = \bar{x} \pm (2.57 \times 0.06) = 5.03 \pm 0.15 = 4.88$ to 5.18 μR/h,

or 0.049 to 0.052 μGy/h.

We can be 99% confident that the population mean lies between 4.88 and 5.18 μR/h for the 0.2 km^2 site surveyed. If natural background for the area were 5 μR/h, then the site would be clean. No situation would be this ideal. Natural background itself exhibits variability, perhaps as high as 10 μR/h or more. Since the minimum detection capability of the instrument used was stated to be 1 μR/h with no variability range given, at best it could not be less than ±0.1 μR/h, since class intervals were given to ±0.01 to avoid overlap of class values.

If a set of analytical values is normally distributed, then 68% of the values will fall within ±1σ (one standard deviation) of the standardized mean. Values above and below the mean that cover a given percentage of the normal curve are known as confidence limits, some of the most commonly used of which are given in Table 5.2.

The most commonly used confidence levels are the 90%, 95%, and 99%, corresponding to z-scores of 1.64, 1.96, and 2.57, respectively. Most statistics texts will have a table of z-scores versus normal curve areas, but it is important to check before using to see if the areas are (1) from $-z$ to $+z$ as in Table 5.2, (2) for the area (α) in the two tails, (3) for the area ($\alpha/2$) in one tail (Table 5.3), (4) for the area from mean to z, or (5) for the area excluding one tail. For a z-score of 2.0, the corresponding values are 0.9544, 0.0456, 0.0228, 0.4772, and 0.9772. The total area under the normal curve (Fig. 5.1) is 1.0.

Table 5.3 refers to a one-tail α-level of 0.05, the z-score for which is 1.645.

5.3 Statistical Interpretation

A site sufficiently cleaned up as to be a candidate for unrestricted release will be close to the unknown natural background characteristic for that area. The problem then is one of deciding whether one or more sets of means differ sufficiently from the accepted natural background mean as to be the result of slight residual contamination due to operational or post-operational activities on the site. It is to be expected that several sets of 30 observations, each will not give the same mean each time. Rather, they will form a normal, lognormal, exponential, or other distribution of sample means, centering around the hypothetical (unknown) population mean representing the contaminated population of data readings. This is also true for the single sample value mean taken to be representative of the unknown natural background population. Systematic surface survey of the entire site and surroundings for gamma may be possible by aerial survey, but is expensive. This is not true for below-surface soil analysis for specific radionuclides, nor for the state-of-the-art field analysis for two or more nuclides in surface

Table 5.2. Some useful confidence limits

Percent of normal curve area	$\pm\sigma$
99.73	3.0
99.0	2.57
98.0	2.33
97.00	2.17
95.44	2.00
95	1.96
90	1.64
80	1.28
75	1.15
68.27	1.0
50	0.67

Table 5.3. Standard normal probability, one-tail, α

z	Second decimal place of z									
	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641
0.1	0.4602	0.4562	0.4522	0.4483	0.4443	0.4404	0.4364	0.4325	0.4286	0.4247
0.2	0.4207	0.4168	0.4129	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859
0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3594	0.3557	0.3520	0.3483
0.4	0.3446	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121
0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776
0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451
0.7	0.2420	0.2389	0.2358	0.2327	0.2296	0.2266	0.2236	0.2206	0.2177	0.2148
0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867
0.9	0.1841	0.1814	0.1788	0.1762	0.1736	0.1711	0.1685	0.1660	0.1635	0.1611
1.0	0.1587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379
1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170
1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1038	0.1020	0.1003	0.0985
1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0869	0.0853	0.0838	0.0823
1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0722	0.0708	0.0694	0.0681
1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559
1.6	0.0548	0.0537	0.0526	0.0516	0.0505	0.0495	0.0485	0.0475	0.0465	0.0455
1.7	0.0446	0.0436	0.0427	0.0418	0.0409	0.0401	0.0392	0.0384	0.0375	0.0367
1.8	0.0359	0.0352	0.0344	0.0336	0.0329	0.0322	0.0314	0.0307	0.0301	0.0294
1.9	0.0287	0.0281	0.0274	0.0268	0.0262	0.0256	0.0250	0.0244	0.0239	0.0233
2.0	0.0228	0.0222	0.0217	0.0212	0.0207	0.0202	0.0197	0.0192	0.0188	0.0183
2.1	0.0179	0.0174	0.0170	0.0166	0.0162	0.0158	0.0154	0.0150	0.0146	0.0143
2.2	0.0139	0.0136	0.0132	0.0129	0.0125	0.0122	0.0119	0.0116	0.0113	0.0110
2.3	0.0107	0.0104	0.0102	0.0099	0.0096	0.0094	0.0091	0.0089	0.0087	0.0084
2.4	0.0082	0.0080	0.0078	0.0075	0.0073	0.0071	0.0069	0.0068	0.0066	0.0064
2.5	0.0062	0.0060	0.0059	0.0057	0.0055	0.0054	0.0052	0.0051	0.0049	0.0048
2.6	0.0047	0.0045	0.0044	0.0043	0.0041	0.0040	0.0039	0.0038	0.0037	0.0036
2.7	0.0035	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026
2.8	0.0026	0.0025	0.0024	0.0023	0.0023	0.0022	0.0021	0.0021	0.0020	0.0019
2.9	0.0019	0.0018	0.0017	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014

soil (0 to 5 cm depth). Laboratory analysis of soil versus instrumental field readings is expensive, especially when using heavy soil-drilling equipment for subsurface samplings (see Table III-1 of Appendix III on Cost-Effectiveness of Monitoring). The worst case is unpredictable variation in the ratios of radionuclide mixes. Where ratios are reasonably constant, the concentration on one (unmeasured) nuclide can sometimes be estimated from the measured concentration of another. The greater the site disturbance by earth movements, the less predictable one nuclide by another is likely to become, except for daughter nuclides which have not been subject to differential leaching action by physical or biological agents, or for unpredictable spatial separation of previously associated nuclides as a result of processing at the site during the operational phase of the facility. A specific example will serve to illustrate a statistical approach to the problem of differentiating near-background artificial contamination from natural background contamination.

A background sample (mean of 30 observations) of gamma readings in air taken 100 cm above the surface soil level gave a value of 10 μR/h, designated as Sample B. This sample was taken sufficiently far from the site (upwind, uphill, etc.) as to give reasonable assurance that unenhanced (natural) background air gamma was being measured. An on-site stratum sample (mean of 50 observations) of air gamma readings taken 100 cm above the soil surface gave a value of 14 μR/h, designated as Sample X. The problem is: Does Sample X come from the same population as Sample B? Or is it perhaps on the extreme edge of even higher readings nearby that might otherwise be missed? In other words, if the standard deviation of Sample B is small enough, and the stakes are potentially high (from prior information) for this particular stratum, then we want to be very sure that the Sample X mean of 14 μR/h is from the same population (unenhanced background) as the Sample B mean of 10 μR/h. We want to be sure to the 95% confidence level. This example is the most severe test that will be encountered (less than twice background), and illustrates the following tests and procedures:

1. Setting up null and alternate hypotheses.
2. Calculating standard deviation and standard error.
3. Accepting or rejecting the null hypothesis (H_0).
4. Use of z score versus significance level (α) table to accept or reject H_0 at the 95% confidence level.
5. Probability of making a Type II error.

The use of standard statistical tests such as these not only makes the licensee's conclusions more objective (testable) if brought into question, but facilitates work of the inspector.

The Null Hypothesis is to prove that the on-site stratum sample having a mean of 14 μR/h is actually 10 μR/h; in other words, that there is no contamination on the site. It should be noted that we have assumed the off-site sample mean of 10 μR/h to be identical with the unknown population of unenhanced background readings. This is not probable, since another unenhanced background sample might average 8, 9, or 11. Hence, additional unehanced background samples should be measured (or taken from other published data available for the area) and all of the available means averaged to get a grand mean. For simplicity we shall assume that the grand mean did turn out to be 10 μR/h for technologically unenhanced background.

Null hypothesis (H_0): Sample X mean = 10 μR/h = background.

Alternate hypothesis (H_a): Sample X mean is greater than 10 μR/h ≠ background.

We wish to test at an alpha level (α) = 0.05, 1-tail since we do not care if Sample X mean is less than background (10 μR/h). A 2-tail test would be $\alpha/2$. H_0 will be rejected if the Sample mean ($\bar{x}$) is more than 1.645 standard errors above the population mean of 10 μR/h:

$$\text{Reject } H_0 \text{ if } \bar{x} > 10 + 1.645\ \sigma_{\bar{x}}\ ,$$

where 1.645 corresponds to an alpha level = 0.05 by Table 5.1 (extrapolated value between α = 0.0495 and 0.0505). The standard error ($\sigma_{\bar{x}}$) is

$$\frac{\sigma}{\sqrt{n}} = \frac{14}{\sqrt{50}} = 2.0, \text{ when } n \geqq 30.$$

where σ will have been determined from the relation:

$$\sigma = \frac{(x_i - \bar{x})^2}{n-1} ,$$

where

n = sample size of 50,

$\bar{x}$ = the mean of 50 gamma readings, and

x_i = each individual gamma reading entered in the field logbook.

Thus, H_o is rejected if $\bar{x} > 10 + 1.645 \times 2 > 13.3$, and is not rejected if $\bar{x} \leqq 13.3$. For a normal sampling distribution with a mean of 14 and a standard error of 2.0, an $\bar{x}$ value of 13.3 corresponds to a z score of:

$$z = \frac{13.3 - 13}{2.0} = -0.35 \tag{5.3}$$

The absolute value, 0.35, from Table 5.3 has a probability (α level) of 0.3632.

The left hand tail probability below 13.3 for the normal distribution having a mean of 14 is 0.3632 for a sample size of 50. This means that for a sample size of 50 there is a 0.3632 probability of not rejecting H_o: mean = 10, if in fact the mean = 14. If the actual value of the mean is 14, and not 10, then the probability of committing a Type II error is the probability that $\bar{x}$ is less than 13.3, where a Type II error is defined as below:

Type I Error: When H_0 is rejected, even though it is true. In the example, the null hypothesis (H_0) is that the on-site stratum sample with a found mean of 14 μR/h is actually 10 μR/h, the latter being off-site unenhanced background.

Type II Error: When H_0 is not rejected even though it is false. It is more serious to think that on-site stratum sample X is a part of unenhanced background when in fact it is not.

The probability of making a Type II error for the alternative hypothesis (H_a) is 0.3632. Consult standard statistics books such as Agresti[9] for more detail. The probability of a Type II error is a function of the sample size, and can be reduced by increasing the sample size.[10] It is also a function of the extent to which the null hypothesis (H_0) is false. It is common to think of the decision to accept H_0 as being a weak conclusion unless it is known that beta is acceptably small. The probability of a Type II error = P (accept $H_0 | H_0$ is false) = β. The vertical bar (|) is interpreted to mean "given that." The four types of decisions are:

	H_0 true	H_0 false
Accept H_0	No error	Type II error
Reject H_0	Type I error	No error

Rejection of H_0 is always a strong conclusion when the probability of wrongly rejection H_0 can be controlled by the decision maker. The example given above to illustrate some statistical tests can be summarized by Fig. 5.2 as adapted from Agresti.[9]

A = Normal distribution of unenhanced background (Population A), the null hypothesis (H_0) being true;

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THE PROBABILITY OF A TYPE II ERROR AT AN ALPHA LEVEL OF 0.05.

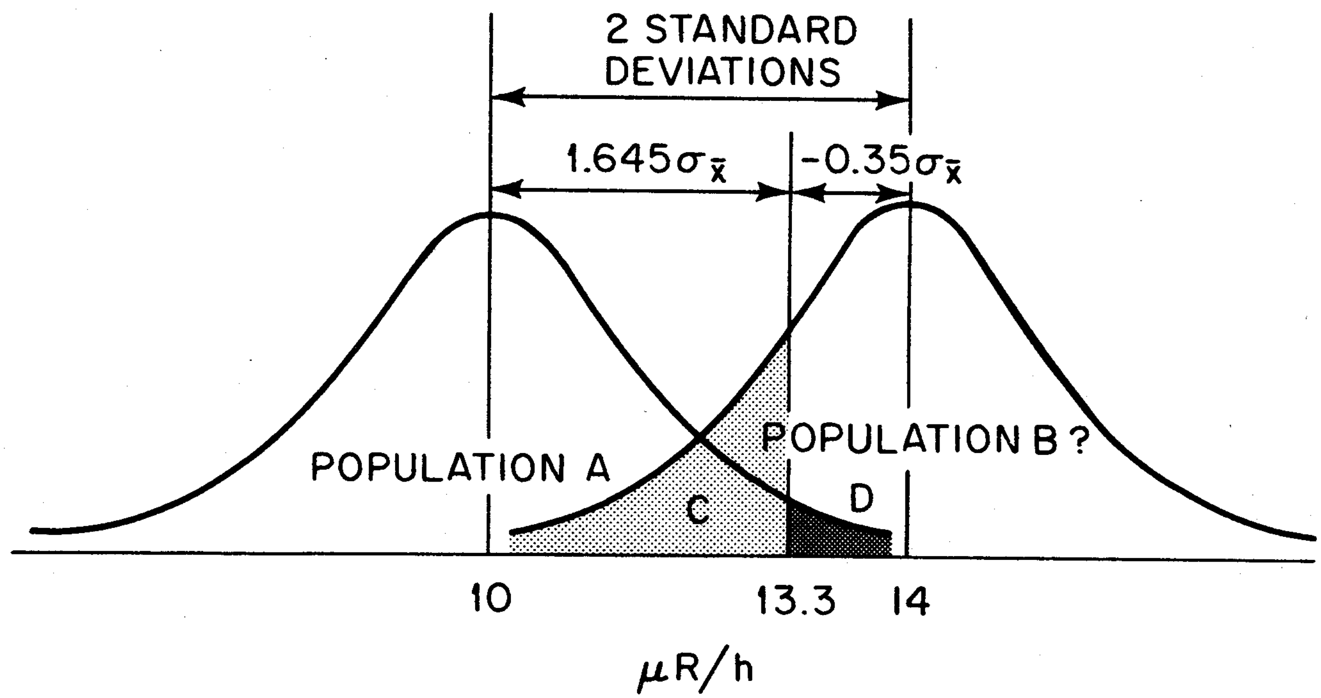

Fig. 5.2. Testing the null hypothesis that Population B is the same as Population A versus the alternate hypothesis that it is not.

B = Normal distribution of sample means ($\bar{x}$'s), the null hypothesis being false;

C = Light-shaded area representing the probability that H_o will not be rejected when the sample mean is 14, the null hypothesis being false.

D = Dark-shaded area representing a one-tail alpha level of 0.05, corresponding to a 95% confidence level.

H_o = Null hypothesis that the sample mean is the same as unenhanced background = 10 μR/h;

H_a = Alternate hypothesis that the sample mean is greater than 10 μR/h;

$\sigma\bar{x}$ = Standard deviation of the sample mean = the standard error = 2.0;

1.645 = z-score corresponding to a one-tail alpha level of 0.05;

-0.35 = (13.3-14)/2.0.

H_o is rejected if the sample mean (Population B) is more than 1.645 standard errors above the natural background (Population A) mean of 10 μR/h, namely, more than 13.3 μR/h.

In summary, the standard error for the on-site sample of 50 gamma readings having a mean of 14 μR/h was $14/\sqrt{50} = 2.0$ for the illustration given. A one-tail alpha level of 0.05 (corresponding to a 95% confidence level) has a corresponding z-score of 1.645. $10 + 1.645 \times 2 = 13.3$. A mean ($\bar{x}$) of 13.3 corresponds to a z-score of -0.35. Since the on-site stratum sample of 50 observations (gamma readings) had a mean of 14, which exceeds 13.3, it is concluded (H_a) that the stratum sample does not represent a normal variability value of unenhanced background (which had a grand mean of off-site samples equal to 10 μR/h). Therefore, this on-site stratum sample is slightly contaminated because its mean is about two standard deviations (1.64 + 0.35 = 1.99) from the unenhanced mean of 10 μR/h. Since prior information was postulated to have led us to believe that any contamination at all in this particular stratum might be potentially serious, an additional set of gamma readings would probably be taken – unless it could be shown that unenhanced background variability for that area varied by more than two standard deviations (swamping effect). Information on the control of Type I (alpha) and Type II (beta) errors can be found in Wolf.[11] If a Type II error is considered more serious than a Type I error, then the probability of a Type II should be decreased, even though it automatically means an increased probability of a Type I error.

5.3.1 Probability of not detecting significant highly localized contamination

When all is said and done, licensee having done his best to clean up his site to specifications and inspector feeling reasonably certain that the site is indeed clean, there will always remain some shadow of doubt. Since the site was not given a 100% area survey at all depths down to, say, 10 m (32.8 ft) for all nuclides in all media (soil, water, vegetation, etc.) with instruments of complete specificity and infinite sensitivity, what is the probability that a one or more significant hot spots may have been missed?

It is necessary first to define a "hot spot." It might be defined for a gamma emitter for example as a sufficient quantity of radioactivity of high enough energy (>50 keV) confined in a limited volume (e.g., 1 kg of soil weight, or less than 1 m^2 of soil surface) to measure more than an order of magnitude above the average unenhanced background characteristic for the site and immediate surrounding area at a distance of 1 m or less in any straight line direction from the essentially point-source material.

This definition does not address the problem of alpha, beta, or weak gamma emitters buried more than a few centimeters below the surface, which are below instrument detection limits, and which might conceivably constitute a potential health effect under most unfavorable conditions. This situation must be handled from prior information about type and magnitude of long-lived isotope quantities formerly used at the site, where and how used within the site, the results of core drillings, instrumental checks or excavations before backfills, and so forth.

The probability of missing a hot spot is a function of, or is dependent upon a number of factors, including:

1. Type of radiation
2. Radiation energy spectrum and percentage of each decay event
3. Area covered by the hot spot relative to survey block dimensions, survey paths taken, number of blocks sampled.
4. Depth of hot spot.
5. Detection limits of the field instrument.
6. Survey conditions, e.g., whether all or some measurements were made at 1000 m (aerial survey), 1 m, 0.01 m, or other distances.
7. Acceptable confidence level and error in ability to differentiate from unenhanced background normal for that site and immediate area.

The probability statistics for missing hot spots on a decontaminated site is still developmental, and so specific guidance cannot be offered at this time. Some indication on how the question may be approached is given in Appendix VII.

Section 5.0. References

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10. W. W. Hines and D. C. Montgomery, *Probability and Statistics in Engineering and Management Science*, pp. 269-71, Wiley, New York (1980).

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6.0 VERIFICATION INSPECTION

6.1 Auditing the Termination Survey Report from a Licensee

The auditing inspector should find the task relatively easy if the licensee has written his final report along the lines of this manual, specifically:

1. Introduction,
2. Objectives,
3. Survey design and procedures,
4. Instrumentation, and
5. Evaluation and interpretation of monitoring data,

as expanded in accordance with the index for this manual. The inspector may wish to check in some detail the quality assurance steps taken by the licensee with respect to instrumentation and record handling. Normally, the inspector's audit should precede his own verification survey in order to take maximum advantage of the licensee's prior information for planning the verification survey. The licensee's final survey should be checked against all docket folder information on the site which may be available in regional files or at the central repository, taking special care to check whether radiological operations were carried out at the site by other than the present licensee, and including users of the site prior to creation of the AEC docket file system in the 1950's. Planning the verification survey will in itself create needs for certain information, automatically ensuring examination of the licensee's final survey from such viewpoints. For example, the existence, and design of survey maps including survey block dimensions used and survey results by blocks will need to be checked relative to field verification by sampling.

Checklists, both general and specific, useful for planning the audit, are given in Sections 1.1, 1.3, 1.4, 3.2, 3.3, and 6.1 as was mentioned under Section 3.6 on Documentation.

The inspector's audit will be a technical one. In addition, the Commission may wish to consider a standard CPA audit of both licensee and inspector reports in special circumstances.

Since the agency must assume final responsibility for unrestricted clearance of a site, the inspector's verification survey report with its recommendations may also be audited by the Commission. Normally, it would be expected that at least one inspector is assigned to a given site during and after decommissioning and until he has made his final verification survey and turned in the completed report. The inspector would be expected to make at least one quality assurance audit of the site during or following the licensee's decommissioning steps to establish a baseline and prior information for the final verification survey. For a small operation, the audit would normally be straight forward, and more involved for a large and complex operation with high potential for future population hazard.

Much of what is presented in the next few paragraphs is taken from Ernst and Whinney.[1]

The 1972-73 Report of the Committee on Auditing of the American Accounting Association suggests that basic auditing should give significant attention to statistical inference because the audit evidence obtained in many situations can best be evaluated by statistical techniques.

The Committee on Auditing Procedure of the American Institute of Certified Public Accountants in Section 320B.04 of "Statement on Auditing Standards No. 1" has stated that statistical sampling should: "be used only by auditors who have adequate statistical knowledge to (a) decide when statistical audit samples may be appropriate, (b) design and select a valid sample, (c) evaluate the audit evidence from the sample, and (d) apply the evaluation in the overall context of the audit."

Some basic auditing issues include: (a) defining ultimate risk; (b) identifying how sampling is to be used in the audit process; (c) describing the two common types of audit risks (alpha and beta risks) and their causes; and (d) the pros and cons of judgmental vs. statistical sampling.

The objective of an audit is an unqualified opinion, the opinion paragraph summarizing the conclusions of detailed audit procedures. The auditor's opinion concludes that: (a) lack of potential hazard to the public is fairly presented, and (b) is in confirmity with generally accepted accounting principles applied on a consistent basis.

The term "fairly presented" includes: (a) acceptability of the accounting procedures applied, (b) adequacy of disclosures, and (c) freedom from material errors.

The Commission inspector is more likely to have a science or engineering degree than an accounting degree, but should acquaint himself or herself with acceptable accounting procedures if that person is to audit licensee's operations and records for regulatory and prior information purposes. The final audit by the Commission should probably be done by a certified public accountant under contract to the NRC.

An examination of the licensee's decommissioning activities begins with a familiarization with the licensee's operations, including accounting procedures, which leads to the identification of risks of material errors in the accounting records.

Statements on Auditing Standards (SAS), Section 320A by the Committee on Auditing Procedures of the American Institute of Certified Public Accountants states that:

> ".14... The ultimate risk against which the auditor and those who rely on his opinion require reasonable protection is a combination of two separate risks. The first of these is that material errors will occur in the accounting process by which the financial statements are developed. The second is that any material errors that occur will not be detected in the auditor's examination.
>
> .15... The auditor relies on internal control to reduce the first risk and on his tests of details and his other auditing procedures to reduce the second.
>
> .19... The second standard of fieldwork recognizes that the extent of tests required to constitute sufficient evidential matter under the third standard should vary inversely with the auditor's reliance on internal control and on his auditing procedures should provide a reasonable basis for his opinion

in all cases, although the portion of reliance derived from the respective sources may properly vary between cases."

The above are intended only to introduce the need for standard audit procedures. The original reference[1] and others should be consulted for more detail.

To determine sample size for an audit, according to acceptable accounting procedures, the following should be specified:

(a) desired reliability (confidence limit);
(b) desired upper precision limit; and
(c) expected occurrence rate.

In other words, the technical monitor and/or his statistical advisor and/or the accountant who makes the final audit of licensee and/or inspector final survey reports should be aware of the need of compatability.

6.1.1 Technical points for an inspector's audit of licensee's records

Every site will have its special aspects and special check needs. The following list is suggestive only and a specific site checklist will need to be formulated for each site.

A. Operational history of the site

Types and quantities of long-lived (more than 1 yr radiological half-life) radionuclides entering, leaving, and remaining on-site from start to finish.

All previous owners of the site.

Buried waste (including building rubble, etc.) on the site.

Waste removed from the site (type and amounts).

B. Monitoring history of site

Results of all known radiological surveys of the site by licensee, AEC, NRC, EPA, state, and any other regulatory or consulting agency.

Instruments used, their calibration, sensitivity specificity, model numbers, etc.

Radiological procedures used, including sample sizes, areas of site surveyed, sampling procedures, site conditions before, during, after surveys, etc.

C. Characteristics of the site

Meteorology (including rainfall, average wind direction); water drainage patterns (both surface and subsurface); soil retention properties; technologically unenhanced background microheterogeneity (less than 1 m^2) and macroheterogeneity (more than 1 km^2) averaged on- and off-site. Location of former security fence, buildings, etc.

D. Decommissioning procedures for the site

Which structures were demolished and why, including extent of radioactive contamination and disposition of rubble and other contaminated materials (both on- and off-site disposition). Pathways taken by trucks and other moving vehicles to move contaminated materials for disposition. Extent of soil transfer and coverage (including depth of coverage, and original and final locations of soil loads transferred). Extent of dust raising, settling, and resuspension during demolishing and physical decontaminating procedures. Types (e.g., water, organic solvents, chelating agents, etc.) and amounts of decontaminating agents used, their movement and disposition.

E. Names of responsible licensee staff persons, contractors, consultants who could be contacted in potentially serious or significant situations or operations for corroborative or additional information needed to assess an operation, procedure, or condition of consequence.

F. Survey design and procedures followed by licensee

Deviations from the general design and procedures given as guidelines and reasons. Transit survey and staking of the post-operational site. Gridding and stratification of the site. Survey block sizes according to potential hazard and magnitude of area. Method(s) of taking observations (air instrumental readings, and media sampling for laboratory analyses. Selection and definition of "population(s)" to be sampled.

Modes of sampling.

Recording of data.

Processing of data.

Storage of analyzed data.

Quality Assurance on recording, processing, analyzing, storing, interpretating, etc.

Interpreting analyzed data (including comparison with regulations, guidelines, and decision among available options – unrestricted release, restricted release, second round of decontamination or cleanup, re-examination of prior information, or independent radiological survey, etc.).

Six major areas (A-F) broken down into approximately 100 major and minor points have been enumerated above. This listing could be numbered in more detail and expanded (or contracted) according to the magnitude and hazard potential of a particular licensee's operation. For example, the use of a single short-lived isotope in small quantities would not constitute a potential long-term hazard to the public if such a site were approved for unrestricted release. Accordingly, many of the above points could be eliminated or given minimum consideration. For the case of a site using a single short-lived isotope, some of the main points to confirm would be: (1) that no previous long-lived radionuclides have been used by another licensee on that same site which is a candidate for unrestricted release; (2) that the site not be released for 10 half-lives or until the single nuclide involved had decayed to not more than three times unenhanced background typical for that area whichever gives a smaller value; (3) that unenhanced background has been reasonably well defined for the site and/or its immediate surrounding area; (4) that records are complete, accurate and adequate for the site as to ensure that no known storage or processing of radioactive materials occurred at the site since 1900, prior to the current licensee with one or a few short-lived nuclides, or that survey design and procedures were adequate to include all previous storage or processing operations.

6.1.2 Standardized checklists

Variety in purpose, form and detail for checklists is so great that a single generalized form is not practical. The index for this guide could constitute a generalized checklist. As an illustration of a more detailed checklist that could be expanded into minute detail, and probably unnecessarily so unless a computerized data base for a large organization is contemplated, see Table 6.1. Here each number could signify a checklist. For example, checklist 263 (Table 6.1) would represent documentation aspects of data collection, beginning with field notebooks and how they could be formated to facilitate data collection on-site, including such information as survey block number, type, size and location of sample collected for laboratory analysis, of beta and gamma readings taken 1 cm above soil surface, etc. The checklist 266 might include such quality assurance aspects of documentation as types of documents to check (e.g., laboratory reports) frequency of checking, how sampled, by whom, for what purpose, how verified, etc. A three-man licensee operation would have little need for some checklists that would be essential to a large corporation.

Checklists as a methodology for control and decision-making have been reviewed by Canter.[2] For example, the U.S. Department of Transportation has devised a checklist similar to a computerized interaction matrix. The problem, such as monitoring, is divided into X areas and subdivided into Y parameters.[3] The U.S. Soil Conservation Service has developed a scaling checklist.[4] For additional information on scaling-weighting and other types of checklists, see Canter.[2]

The chief caution is to make checklists no more elaborate than necessary, to facilitate auditing, recordkeeping, quality control, legal requirements and to hold costs down, consistent with the overall objective and moral responsibility of protecting the public health from adverse effects of previous operations by the licensee.

There is no fine line of distinction between checklists and some types of recordkeeping forms which are a form of checking. One such form is illustrated in Fig. 6-1.

Table 6.1 Example of elaborate checklist system

	Survey design	Locations	Instrumentation	DATA: Collection	DATA: Analysis	DATA: Interpretation	Quality assurance	Cost effectness
Survey design	000	001	002	003	004	005	006	007
Air	010	011	012	013	014	015	016	017
Soil	020	021	022	023	024	025	026	027
Water	030	031	032	033	034	035	036	037
Vegetation	040	041	042	043	044	045	046	047
Real estate	050	051	052	053	054	055	056	057
Locations	060	061	062	063	064	065	066	067
Outdoor	070	071	072	073	074	075	076	077
Grid No.	080	081	082	083	084	085	086	087
Surface	090	091	092	093	094	095	096	097
Volume	100	101	102	103	104	105	106	107
Indoor	110	111	112	113	114	115	116	117
Grid No.	120	121	122	123	124	125	126	127
Instrumentation	130	131	132	133	134	135	136	137
Selection	140	141	142	143	144	145	146	147
Calibration	150	151	152	153	154	155	156	157
Sensitivity	160	161	162	163	164	165	166	167
Specificity	170	171	172	173	174	175	176	177
Durability	180	181	182	183	184	185	186	187
Cost	190	191	192	193	194	195	196	197
Data	200	201	202	203	204	205	206	207
Collection/Format	210	211	212	213	214	215	216	217
Analysis	220	221	222	223	224	225	226	227
Interpretation	230	231	232	233	234	235	236	237
Comparison	240	241	242	243	244	245	246	247
Computerization	250	251	252	253	254	255	256	257
Documentation	260	261	262	263	264	265	266	267
Standards	270	271	272	273	274	275	276	277
Compliance	280	281	282	283	284	285	286	287

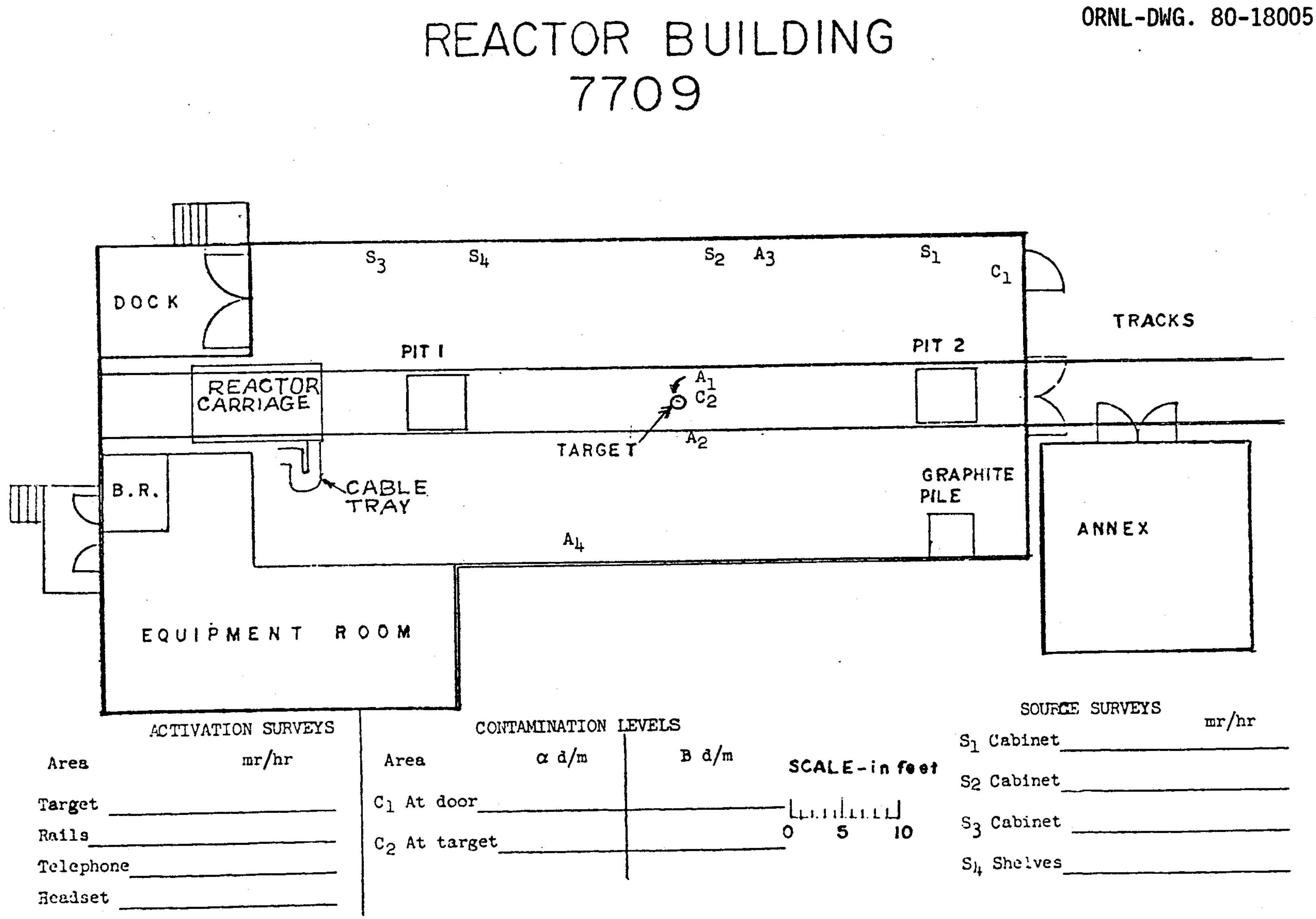

Fig. 6.1. Monthly check on background in a reactor building.

6.2 Inspection Survey

In essence, this is a manual of design and procedures for a verification survey, except that it has a dual function since it serves the same purposes for the licensee's final survey. The two surveys are inextricably linked from an inspection viewpoint in that the verification survey can only be an independent sampling of the licensee's more elaborate survey, and not a complete duplication. Where the licensee may have taken, for example, thousands of air gamma readings, the inspector will take only a few hundred. As a rough guide, the inspector's survey efforts may be a 1 to 10% sampling of licensee's results, using the same survey block system staked or otherwise marked out. For a small, simple, straightforward site of relatively low hazard potential in terms of quantities and radiological half-lives, a 0.1% sampling might suffice. Because of the wide variety of sites, hard and fast rules cannot be stated before the fact.

As with the licensee, the inspection survey starts with some prior information on which to base a survey design (Section 3.2) and procedures to follow (Section 3.3), tailored to the specific site in question. Background for the site area must be well-defined, the design and procedures should be statistically defensible such as sample size selection, all aspects of planning and implementation properly documented and subjected to standard quality control procedures, including proper instrumentation and use, and correct evaluation and interpretation of results made in terms of existing standards and regulations. These aspects of the inspection survey plan and implementation are treated in the respective sections, as shown in the index.

Specific aids for conducting the inspection or verification survey are ennumerated in Appendix IV under Inspection for Certification.

6.2.1 Field measurements and sampling by inspector

Having studied all available prior information on the specific site to be visited for the verification survey, including especially the licensee's final survey, the inspector is now ready to go on-site for three reasons:

(1) to take radiation readings (beta, gamma and/or alpha according to the site),

(2) to take soil and other media samples as projected from his plan, and

(3) to select split samples held in reserve by the licensee, or designated representative, if not picked up at an earlier date, at the designated repository. (In some cases no buildings will be left on the site and the licensee will not be in residence.)

Verification survey must be made while stakes, flags, or other temporary markers still define the survey blocks used by the licensee for his final survey. If the inspector has made an earlier visit to survey excavated areas before backfilling with clean fill, these results should be considered part of the verification survey.

Radiation readings will be taken according to plan, and if while being taken there is indication or desire to take additional readings not included in the plan, the inspector should exercise this option. Air sampling is covered in Section 3.2.1.1.4, soil in 3.2.1.1.2, and water in 3.2.1.1.3. In many cases a simple random sampling at known grid points or within survey blocks selected at random may suffice. For more complex situations, a simple stratification into inside and outside operational areas, allocating more measurements and samples within, may suffice. For high-hazard potential sites, a sampling scheme approaching that of the licensee's may be required. In view of the fact that a site may range from a one-man to a thousand-man operation and more, hard and fast rules cannot be given before the specific facts are known and studied.

See Appendix V for some specific recommendations that the inspector needs to consider. Although Appendices IV and V are meant to be generic applications of the manual design and procedures to reactor and mill sites in general, they are sufficiently general to be applicable to other former nuclear operations sites.

6.2.2 Split and replicate sampling

In the trade, several types of samples may be used:

1. Split sample. A large sample taken from a coordinate point is divided into two or more smaller samples and given to two or more parties. Results of independent analyses by the two or more parties may differ significantly, to the extent that each party subjects each sample to differing degrees of drying, grinding and/or mixing. To be a good split sample, drying, grinding, and mixing should be done under standard conditions before splitting into two or more samples for two or more parties.

2. Replicate sample. When more than one sample is taken from the same spot, the samples are known as replicate samples. Technically speaking, once a soil sample has been removed, a hole remains which cannot be sampled again. A second adjacent sample to the hole could be somewhat different. A sample taken after a rain would have a higher water content than one taken in the same area before the rain, which might or might not be significant. A split sample is to be preferred to a replicate sample when available.

3. Grab sample. A random sample, not taken from a grid.

4. Biased sample. Taking a sample where at least trace contamination is known or believed to exist.

5. Composite sample. Two or more samples combined into a larger one.

If as part of the survey plan filed by the licensee it was stated that all or some proportion of samples taken during the final licensee survey would be split and held in reserve, then the inspector has available to him such samples from which to select and send out for analysis as an independent check on licensee's reported results. If split sampling had not been agreed upon between licensee and the license-issuing agency beforehand, then split samples are not likely to be available. In this case, or in addition, the inspector must select his own biased and/or unbiased samples at the site. The advantage of taking some biased samples lies in the fact that measurable readings in air can be taken at the soil sampling spot for generating correlation curves between readings and soil concentrations. Where correlations are sufficient to be usable, more air readings and fewer soil samples can be taken. To cut down on bagging and tagging, several scattered samples of soil may be combined in one bag in an area where contamination potential is known to be low, such as background areas, provided a minimum of 30 separate soil samples are taken for separate analyses in an area where background has not been thoroughly defined, especially for the licensee. A 10% background sampling by the inspector in such a case would mean a minimum of 3 soil bags properly tagged for contents.

6.3 Duplicate Sample Analysis Comparison by an NRC or Independent Laboratory

For legal validity there must be an unbroken chain defining the sample from the moment it is removed from its resident spot on the site, bagged, tagged, dried, ground, mixed, split, stored, shipped, analyzed, and recorded. Results of analysis on several split soil samples that were also analyzed by the licensee are averaged, the standard deviation and confidence interval for the true mean calculated at the 95% confidence level and compared with results obtained by the inspector. The usual precautions must be taken, such as use of NBS standard samples where available, the same standardized procedure (such as an ASTM method) as was used by the licensee. It is important that the sample used for analysis be of adequate size, not less than 0.2 gram. Occasional intercomparisons between laboratories by analysis of common standards should be an integral part of quality assurance. The EPA, NRC, and other regulatory agencies will be requiring such documentation to ensure the validity of duplicate sample analyses by licensees and licensors. Detailed considerations on sample analysis can be found in Kolthoff and Elving.[5]

Section 6.0. References

1. Ernst and Whinney, *Audit Sampling*, pp. 203-31, E&W No. 56246 (1979).

2. L. W. Canter, *Environmental Impact Assessment*, pp. 199-218, McGraw-Hill, New York (1977).

3. A. D. Little, Inc., *Transportation and Environment: Synthesis for Action: Impact of National Environmental Policy Act of 1969 on the Department of Transportation*, 3 volumes (July 1971).

4. U.S. Department of Agriculture, *Environmental Assessment Procedure*, Soil Conservation Service, Washington, D.C. (1974).

5. I. M. Kolthoff and P. J. Elving, *Treatise on Analytical Chemistry*, Wiley and Sons, New York (1978).

7.0 FUTURE RESEARCH AND EFFORT

Areas that should be investigated or stressed relative to final surveys by licensees, and certification surveys by the NRC inspectors, for unrestricted release of sites include the following:

1. More extensive information on natural radiation background variability in the United States, county by county.
2. More extensive information on technological enhancement of radiation background due to fallout from weapons testing, from operating nuclear facilities, and other man-made sources of increased radiation background.
3. Continued development of low-cost, rugged, high sensitivity/specificity instrumentation for field use, for both measurement and data processing of the measurements.
4. Establishment of usable correlations where feasible between air radiation readings and soil nuclide concentrations to decrease soil sampling costs.
5. Increased use of statistical quality control on cleanups and surveys to help hold costs down.
6. Increased use of inter-laboratory comparisons of instruments, and of standard soil and core samples.
7. More extensive documentation of published experimental data for statistical analysis.
8. Residual soil limit standards for all radionuclides produced in significant quantities by nuclear facilities, to facilitate cleanup and survey operations.
9. Further investigation into the probability and consequences of missing significant hot spots in the final certification survey.
10. Realistic pathway parameters, based on new experimental results to verify and improve existing models.

11. Improved dose calculations based upon more experimental data designed specifically for ICRP and NCRP.
12. Realistic correlation between dose calculations and pathological effects of low-level radiation upon human populations.

APPENDIX I

GUIDELINES FOR DECONTAMINATION OF FACILITIES AND EQUIPMENT PRIOR TO RELEASE FOR UNRESTRICTED USE OR TERMINATION OF LICENSES FOR BYPRODUCT, SOURCE, OR SPECIAL NUCLEAR MATERIAL

U. S. Nuclear Regulatory Commission
Division of Fuel Cycle
and Material Safety
Washington, D. C. 20555

November 1976

The instructions in this guide in conjunction with Table 1.1 specify the radioactivity and radiation exposure rate limits which should be used in accomplishing the decontamination and survey of surfaces or premises and equipment prior to abandonment or release for unrestricted use. The limits in Table I.1 do not apply to premises, equipment, or scrap containing induced radioactivity for which the radiological considerations pertinent to their use may be different. The release of such facilities or items from regulatory control will be considered on a case-by-case basis.

1. The licensee shall make a reasonable effort to eliminate residual contamination.
2. Radioactivity on equipment or surfaces shall not be covered by paint, plating, or other covering material unless contamination levels, as determined by a survey and documented, are below the limits specified in Table I.1 prior to applying the covering. A reasonable effort must be made to minimize the contamination prior to use of any covering.
3. The radioactivity on the interior surfaces of pipes, drain lines, or ductwork shall be determined by making measurements at all traps, and other appropriate access points, provided that contamination at these locations is likely to be representative of contamination on the interior of the pipes, drain lines, or ductwork. Surfaces of premises, equipment, or scrap which are likely to be contaminated but are of such size, construction, or location as to make the surface inaccessible for purposes of measurement shall be presumed to be contaminated in excess of the limits.
4. Upon request, the Commission may authorize a licensee to relinquish possession or control of premises, equipment, or scrap having surfaces contaminated with materials in excess of the limits specified. This may include, but

Table I-1. Acceptable surface contamination levels

Nuclides[a]	Average[b,c,f]	Maximum[b,d,f]	Removable[b,e,f]
U-nat, U-235, U-238, and associated decay products	5,000 dpm α/100 cm^2	15,000 dpm α/100 cm^2	1,000 dpm α/100 cm^2
Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	100 dpm/100 cm^2	300 dpm/100 cm^2	20 dpm/100 cm^2
Th-nat, Th-232, Sr-90 Ra-223, Ra-224, U-232, I-126, I-131, I-133	1,000 dpm/100 cm^2	3,000 dpm/100 cm^2	200 dpm/100 cm^2
Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and other noted above.	5,000 dpm $\beta\gamma$/100 cm^2	15,000 dpm $\beta\gamma$/100 cm^2	1,000 dpm $\beta\gamma$/100 cm^2

[a] Where surface contamination by both alpha- and beta-gamma-emitting nuclides exists, the limits established for alpha- and beta-gamma-emitting nuclides should apply independently.

[b] As used in this table, dpm (disintegrations per minute) means the rate of emission by radioactive material as determined by correcting the counts per minute observed by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.

[c] Measurements of average contaminant should not be averaged over more than 1 square meter. For objects of less surface area, the average should be derived for each such object.

[d] The maximum contamination level applies to an area of not more than 100 cm^2.

[e] The amount of removable radioactive material per 100 cm^2 of surface area should be determined by wiping that area with dry filter or soft absorbent paper, applying moderate pressure, and assessing the amount of radioactive material on the wipe with an appropriate instrument of known efficiency. When removable contamination on objects of less surface area is determined, the pertinent levels should be reduced proportionally and the entire surface should be wiped.

[f] The average and maximum radiation levels associated with surface contamination resulting from beta-gamma emitters should not exceed 0.2 mrad/hr at 1 cm and 1.0 mrad/hr at 1 cm, respectively, measured through not more than 7 milligrams per square centimeter of total absorber.

would not be limited to, special circumstances such as razing of buildings, transfer or premises to another organization continuing work with radioactive materials, or conversion of facilities to a long-term storage or standby status. Such request must:

a. Provide detailed, specific information describing the premises, equipment or scrap, radioactive contaminants, and the nature, extent, and degree of residual surface contamination.

b. Provide a detailed health and safety analysis which reflects that the residual amounts of materials on surface areas, together with other considerations such as prospective use of the premises, equipment or scrap, are unlikely to result in an unreasonable risk to the health and safety of the public.

5. Prior to release of premises for unrestricted use, the licensee shall make a comprehensive radiation survey which establishes that contamination is within the limits specified in Table I.1. A copy of the survey report shall be filed with the Division of Fuel Cycle and Material Safety, USNRC, Washington, D.C. 20555, and also the Director of the Regional Office of the Office of Inspection and Enforcement, USNRC, having jurisdiction. The report should be filed at least 30 days prior to the planned date of abandonment. The survey report shall:

   a. Identify the premises.

   b. Show that reasonable effort has been made to eliminate residual contamination.

   c. Describe the scope of the survey and general procedures followed.

   d. State the findings of the survey in units specified in the instruction.

Following review of the report, the NRC will consider visiting the facilities to confirm the survey.

APPENDIX II

PROPOSED STANDARDS

The Administrator of the EPA hereby proposes to add a Part 192 to Title 40 of the Code of Federal Regulations as follows:

Part 192 - ENVIRONMENTAL PROTECTION STANDARDS FOR URANIUM MILL TAILINGS

Subpart A -- Environmental Standards for the Disposal of Uranium Mill Tailings from Inactive Sites

Sec.

192.01 Applicability

192.02 Definitions

193.03 Standards

Subpart B -- Environmental Standards for Remedial Action for Open Lands and Buildings Contaminated due to Uranium Mill Tailings from Inactive Processing Sites

Sec.

192.10 Applicability

192.11 Definitions

192.12 Standards

Subpart C -- Variances

Sec.

192.20 Application for granting of a variance

(Authority: Section 275 of the Atomic Energy Act of 1954, 42 U.S.C. 2022, as amended by the Uranium Mill Tailings Radiation Control Act of 1978, PL 95-604.)

Subpart A -- Environmental Standards for Disposal of Uranium Mill Tailings from Inactive Processing Sites

192.01 Applicability

This subpart applies to the disposal of residual radioactive material at any designated processing site or depository site as part of any remedial action conducted under Title I of the Uranium Mill Tailings Radiation Control Act of 1978 (PL 95-604).

192.02 Definitions

(a) Unless otherwise indicated in this subpart, all terms shall have the same meaning as that provided by Title I of the Uranium Mill Tailings Radiation Control Act of 1978.

(b) Remedial action means any action performed under Section 108 of the Uranium Mill Tailings Radiation Control Act of 1978.

(c) Disposal means any remedial action intended to assure the safe and environmentally sound stabilization of residual radioactive materials on a long-term basis.

(d) Disposal site means the region within the smallest practical boundaries around residual radioactive material following completion of disposal.

(e) Depository site means a site selected under Section 104(b) or 105(b) of the Uranium Mill Tailings Radiation Control Act of 1978.

(f) Aquifer means a geologic formation, group of formations, or portion of a formation capable of yielding usable quantities of groundwater to wells or springs.

(g) Contaminate means to introduce a substance that would cause:

(1) the concentration of that substance in an aquifer to exceed the maximum level specified in Table A, or

(2) an increase in the concentration of that substance in an aquifer, when the existing concentration of that substance exceeds the maximum level specified in Table A.

(h) Groundwater means water below the land surface in the zone of saturation.

(i) Underground drinking water source means:

(1) an aquifer supplying drinking water for human consumption, or

(2) an aquifer in which the groundwater contains less than 10,000 mg/P total dissolved solids.

(j) Curie (Ci) means that quantity of a radioactive material which produces 37 billion nuclear transformations per second. (One picocurie (pCi) = 10^{-12} Ci.)

192.03 Standards

(a) The disposal of residual radioactive materials shall be conducted in a way that provides reasonable assurance that for one thousand years following the disposal:

(1) The average annual release of ^{222}Rn from the residual radioactive materials to the atmosphere shall not exceed 2 pCi/m^{222}-sec, and

(2) No underground drinking water source shall be contaminated by substances released from the residual radioactive materials.

(3) Releases from the residual radioactive material to surface waters shall not cause a violation of any promulgated and approved standards under Section 303 of the Clean Water Act, PL 95-217.

(b) The values in Table A shall apply to the dissolved portion of any listed substance at a distance of

(1) 1.0 kilometer from the disposal site if the disposal site is part of an inactive processing site, or

(2) 0.1 kilometers from the disposal site if the disposal site is a depository site.

Subpart B -- Environmental Standards for Remedial Actions for Open Lands and Buildings Contaminated due to Uranium Mill Tailings from Inactive Processing Sites

192.10 Applicability

This subpart applies to open lands and buildings which are part of any designated processing site.

192.11 Definitions

(a) Unless otherwise indicated in this subpart, all terms shall have the same meaning as that provided by Title I of the Uranium Mill Tailings Radiation Control Act of 1978, or by subpart A of this part.

(b) Open land means any land (surface and subsurface) not covered by a building, which is part of a designated processing site, but which is not a disposal site.

(c) Working level (WL) means any combination of short-lived radon daughters in one liter of air that will result in the ultimate emission of alpha rays with a total energy of 1.3×10^5 million electron volts.

(d) Dose equivalent means the product of absorbed dose and appropriate factors to account for differences in biological effectiveness due to the quality of radiation and its spatial distribution in the body. The unit of dose equivalent is the "rem."

192.12 Standards

(a) The average concentration of ^{226}Ra in a 5 centimeter or smaller thickness of soil or other materials shall not exceed 5 pCi/gm after the completion of remedial actions.

(b) Section (a) of this subpart shall not apply to soil or other materials for which residual radioactive materials appear to play no role in causing the average concentration of ^{226}Ra to be greater than 5 pCi/gm.

(c) The levels of radioactivity in any occupied or occupiable building at any designated processing site shall not exceed the values specified in Table B after the completion of remedial action at that site, except where residual radioactive materials appear to play no role in causing the values in Table B to be exceeded.

(d) The cumulative lifetime radiation dose equivalent to any organ of the body of a maximally exposed person due to radionuclides other than ^{226}Ra and its daughters, resulting from the presence of residual radioactive materials, shall not exceed the maximum doses which could occur from ^{226}Ra and its daughters under paragraphs (a), (b), and (c) of this section.

Subpart C -- Variances

192.20 Application for granting of a variance

The Administrator of the EPA may waive or reduce the requirements of Sections 192.03 and 192.12 upon application by the implementing authorities. Any such application shall be a public record stating the specific conditions and reasons for which the exception is requested.

Table A

Arsenic	0.05 mg/g
Barium	1.0 mg/P
Cadmium	0.01 mg/P
Cobalt	0.05 mg/P
Chromium	0.05 mg/P
Lead	0.05 mg/P
Mercury	0.002 mg/P
Molybdenum	1.0 mg/P
Nickel	0.2 mg/P
Selenium	0.01 mg/P
Silver	0.05 mg/P
Combined ^{226}Ra and ^{228}Ra	5.0 pCi/P
Gross alpha particle activity (including ^{226}Ra, but excluding radon and uranium)	15.0 pCi/P

Table B

Average Annual Radon Daughter Concentration (above average background)	0.005 WL
External Gamma Radiation (above background)	0.010 mR/h

APPENDIX III

Excerpts from
Proposed
ANSI N328-197

Proposed American National Standard

Control of Radioactive Surface Contamination on Materials, Equipment, and Facilities to be Released for Uncontrolled Use

Secretariat

Health Physics Society

Property shall not be released for uncontrolled use unless documented measurements show the total and removable contamination levels to be no greater than the values in Table III-1 or Table III-2. (Table III-2 is easier to apply when the contaminants cannot be individually identified.)

Where potentially contaminated surfaces are not accessible for measurement (as in some pipes, drains, and ductwork), such property shall not be released pursuant to this standard, but made the subject of case-by-case evaluation. Credit shall not be taken for coatings over contamination.

Table III-1

Surface Contamination Limits

The levels may be averaged[a] over the 1 m^2 provided the maximum activity in any area of 100 cm^2 is less than 3 times the limit value.

Nuclide	Limit (activity) dpm/100 cm^2 Total	Removable
Group 1: Nuclides for which the nonoccupational MPC_a[b] is 2×10^{-13} Ci/m^3 or less or for which the nonoccupational MPC_w[c] is 2×10^{-7} Ci/m^3 or less; includes Ac-227; Am-241; -242m, -243; Cf-249; -250, -251, -252; Cm-243, -244, -245, -246, -247, -248; I-125, -129; Np-237; Pa-231; Pb-210; Pu-238, -239, -240, -242, -244; Ra-226, -228; Th-228, -238.[d]	100	20
Group 2: Those nuclides not in Group 1 for which the nonoccupational MPC_a[b] is 1×10^{-12} Ci/m^3 or less or for which the nonoccupational MPC_w[c] is 1×10^{-6} Ci/m^3 or less; includes Es-254; Fm-256; I-126, -131, -133; Po-210; Ra-223; Sr-90; Th-232; U-232.[d]	1000	200
Group 3: Those nuclides not in Group 1 or Group 2.	5000	1000

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[a] See note following table on applications of limits.

[b] MPC_a: Maximum Permissible Concentration in Air applicable to continuous exposure of members of the public as published by or derived from an authoritative source such as NCRP, ICRP, or NRC (10 CFR 20, Appendix B, Table 2, Column 1).

[c] MPC_w: Maximum Permissible Concentration in Water applicable to members of the public.

[d] Values presented here are obtained from 10 CFR Part 20. The most limiting of all given MPC values (e.g., soluble vs. insoluble) are to be used. In the event of the occurrence of a mixture of radionuclides, the fraction contributed by each constituent of its own limit shall be determined and the sum of the fractions must be less than one.

Table III-2

Alternate Surface Contamination Limits

(All alpha emitters, except U-nat and Th-nat are considered as a group.) The levels may be averaged over 1 m^2 [a] provided the maximum activity in any area of 100 cm^2 is less than 3 times the limit value.

Nuclide	Limit (activity) dpm/100 cm^2 Total	Removable
If the contaminant cannot be identified; or if alpha emitters other than U-nat and Th-nat are present; or if the beta emitters comprise Ac-227, Ra-226, Ra-228, I-125, and I-129.	100	20
If it is known that all alpha emitters are generated from U-nat and Th-nat; and beta emitters are present which, while not identified, do not include Ac-227, I-125, I-129, Ra-226, and Ra-228.	1000	200
If it is known that alpha emitters are generated only from U-nat and Th-nat; and the beta emitters, while not identified, do not include Ac-227, I-125, I-129, Sr-90, Ra-223, Ra-228, I-126, I-131, and I-133.	5000	1000

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[a] Note on application of Tables 2 and 3 to isolated spots or activity: For purposes of averaging, any m^2 of surface shall be considered to be contaminated above the limit, L, applicable to 100 cm^2 if:

a. From measurements of a representative number, n, of sections, it is determined that $1/n \sum_n Si > L$, where Si is the dpm/100 cm^2 determined from measurement of section i; or

b. On surfaces less than 1 m^2, it is determined that $1/n \sum_n Si \geqq AL$, where A is the area of the surface in units of m^2; or

c. It is determined that the activity of all isolated spots or particles in any area less than 100 cm^2 exceeds 3L.

APPENDIX IV

APPLICATION OF A REFERENCE MONITORING SURVEY TO A REFERENCE REACTOR SITE

APPLICATION OF A REFERENCE MONITORING SURVEY TO A REFERENCE REACTOR SITE

This appendix deals with the application of the termination survey monitoring methodology described in the body of this report. The particular application involves a reference light-water reactor site which has been used previously[1] for determination of decommissioning costs. While the reference site bears close resemblance to an existing pressurized water reactor, the site description is generic enough to apply to the decommissioning of power reactors in general. A few changes would be in order for the survey of a boiling water reactor but would not represent extensive modification of the survey design discussed in this appendix.

The reactor site is generally located in a rural area with characteristics similar to those found in midwestern or south mideastern United States. A power reactor may occupy an area of 4.7 km^2 (1160 acres) in a rectangular shape (2 km × 2.35 km) with a moderate size river running by one corner of the site. The plant facilities are located inside a much smaller fenced in portion of the site ($\sim$0.1 km^2) (see Fig. IV-1 and Table 3.6).

The site occupies a low bluff that forms a bank of the river running through one corner. Several flat alluvial terraces comprise the main topographic features of the property. These terraces lie at average elevations of 280 to 284 m above sea level and slope away from the river at grades of 2 to 3%. The river is used for disposal of acceptable liquid effluents from the reactor facility.

The major structures on the reference site include the reactor building, turbine building, auxiliary building, fuel building, control building, condensate demineralizer building, chlorine building, administration building, cooling tower and the shop and warehouse.

The reactor building, designed to house the primary nuclear system, is in the shape of a right circular cylinder. It has a hemispherical dome and a flat base slab with a central cavity and instrumentation tunnel. The building is constructed of reinforced concrete prestressed by post-tensioned tendons in the cylinder walls and dome. The interior

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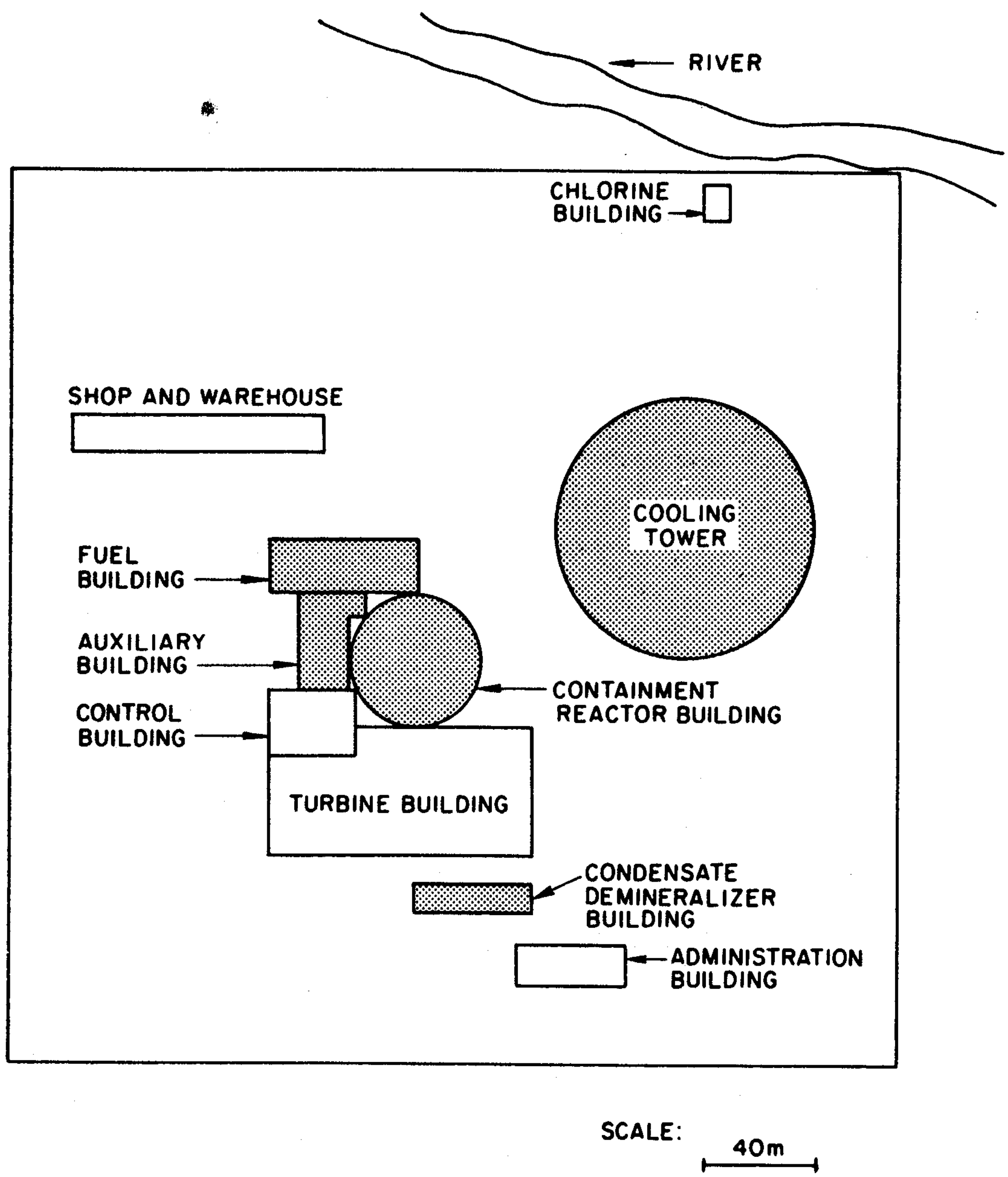

Fig. IV-1. Reference reactor site used for illustrating termination survey application. Shaded structures are assumed to be removed during decontamination. Actual structures retained will depend upon the specific site.

is lined with steel plates welded to form a leak-tight barrier. It consists of essentially two structures on a common foundation. The primary function of the outer structure is to provide a leak-tight vessel and biological shielding for normal and accident situations. The interior structure, constructed of reinforced concrete, provides biological shielding around the nuclear steam supply system and consists of the reactor cavity, biological shield, steam generator and pressurizer compartments, and the refueling pool.

The reactor site has the potential for contamination with a greater number of radionuclides than any other prospective decommissioned site with the exception of a spent fuel processing facility. Because of their functions, the auxiliary and fuel buildings have a potential for contamination approaching that of the reactor building. Part of the contaminating radionuclides are derived from neutron induced reactions on reactor components, exclusive of fuel, and structural materials, concrete and reinforcing steel. Also, contaminating fission-derived radionuclides may have escaped through a rupture in the fuel cladding, generally, in the gaseous phase, and, therefore, tending to diffuse off the site. Another aspect to be considered in the planning process of a decommissioning survey is the fact that the half-lives of most of the contaminants are in excess of one year of which approximately 25%, exclusive of the fuel related radionuclides, are solely beta or beta-gamma emitters. This is evident from a review of Table IV-1 which lists many of the possible contaminants according to their origin, half-life, and particle energy.

Of the radionuclides listed in Table IV-1, exclusive of the fuel sources, there is no single identifying feature other than the fact that all, except one, can be measured with an open mica window (1.5 to 2.5 mg/cm^2) Geiger-Mueller (G-M) probe. Since the beta radiation energy threshold for this probe is approximately 40 KeV, tritium is the only potential surface contaminant not detectable with this instrument. Therefore, the surveyor is encouraged to use this type of instrument for beta-gamma measurements for preliminary and formal surface surveys. Although surface beta-gamma measurements will entail more time than the

Table IV-1. Partial listing of reactor site radionuclides

Source and radionuclide	Half-life	Energy of major emissions: Gamma (MeV)	Beta (MeV)	Alpha (MeV)
Activation products				
^{3}H	12.3y		0.018	
^{14}C	5730y		0.156	
^{54}Mn	312d	0.835		
^{55}Fe	2.74y	0.25		
^{57}Co	270d	0.122		
^{60}Co	5.26y	1.17, 1.33	0.31	
^{63}Ni	100y			
^{65}Zn	245d	1.11	0.327	
^{93}Mo	$3 \times 10^{3}y$	1.03		
^{108m}Ag	5y	0.614		
^{110m}Ag	253d	0.658	0.039	
Fission products				
^{90}Sr-^{90}Y	27.7y		0.546, 2.27	
^{93}Zr	$9.5 \times 10^{5}y$	0.030	0.063	
^{103}Ru	39.5d	0.497	0.70	
^{106}Ru	369y	0.511	0.0394	
^{129}I	$1.59 \times 10^{7}y$	0.040	0.15	
^{125}Sb	2.73y	0.41	0.61	
^{134}Cs	2.06y	0.605	0.662	
^{137}Cs	30.1y	0.662	0.512	
^{144}Ce	284d	0.134	0.31, 2.99	
Fuel				
^{235}U	$7.1 \times 10^{8}y$	0.185		4.58
^{238}U	$4.5 \times 10^{9}y$	0.063		4.20
^{237}Np	$2.14 \times 10^{6}y$	0.086		4.78
^{239}Pu	$2.44 \times 10^{4}y$	0.052		5.16

1 m air gamma measurements, they will better characterize the heterogeneous conditions likely to exist at a reactor site. Beta measurements are determined by the difference between open- and closed-window readings taken with a G-M probe at 1 cm from the surface. NaI crystals are more sensitive than G-M probes.

Dose Assessment Methodology

To place in perspective the residual radioactivity levels for the spectra of radionuclides associated with the operation of the reference reactor site, numerical estimates of radiation dose to man were developed.[2,3] These estimates provide insight into: a) what residual radioactivity level would not exceed a given dose limit; b) which of the various exposure pathways are significant; and c) which radionuclides are significant for the reference reactor site. Calculations of the relative contribution of the radionuclides[4] on the reference reactor site are presented in Table IV-2. The doses from the major radionuclides were calculated[5,6] for various pathways to man and the results given in Table IV-3.

In these calculations, it was assumed that the reactor was decommissioned four years after shutdown and that wooden frame houses were constructed on the site for residential use at six years following shutdown. Residence in wooden houses reasonably represents the most restrictive use of the decommissioned site. It was further assumed that surface activity levels at six years following shutdown[1] represented soil contamination to a depth of 15 cm. The resulting total contamination levels (pCi/g) to produce annual doses of 1, 5 and 25 mrem are given in Table IV-4. In Table IV-3 it can be seen that three radionuclides contribute more than 99% to the total dose from all pathways; those being ^{60}Co, ^{90}Sr, and ^{137}Cs. These are the contamination levels that should be measured in the soil to verify compliance with decommissioning criteria. Due to its longer half-life, ^{137}Cs will become a major contributor ten years or more after shutdown.

If only the direct and inhalation exposure pathways are operative, as is the case for contaminated building surfaces, the total limiting surface contamination level can be determined as given in Table IV-5.

Table IV-2. Calculated isotopic composition of radioactive surface contamination on the reference reactor site

Radionuclide	Half-life	Fractional contamination at decay time		
		0	4 y	10 y
^{54}Mn	312d	2.4E-2	1.2E-3	1.2E-5
^{58}Co	71d	8.6E-3	*b*	*b*
^{60}Co	5.26y	3.0E-1	2.4E-1	1.4E-1
^{59}Fe	45.6d	3.6E-4	*b*	*b*
^{89}Sr	50.3d	4.3E-4	*b*	*b*
^{90}Sr	27.7y	5.1E-2	6.1E-2	6.8E-2
^{90}Y	64h (27.7y)[c]	5.1E-2	6.1E-2	6.8E-2
^{131}I	8.08d	1.6E-3	*b*	*b*
^{133}I	20.3h	1.6E-4	*b*	*b*
^{134}Cs	2.06y	3.0E-2	1.0E-2	1.7E-3
^{137}Cs	30.1y	5.3E-1	6.3E-1	7.2E-1
		1.0E0	1.0E0	1.0E0

[a]Composition of residual radioactive contamination taken from ref. 4, *Final Generic Environmental Statement on the Use of Recycled Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors*, NUREG-0002, Vol. 3 (August 1976).

[b]Values less than 1.0E-6.

[c]Daughter isotope seemingly decays with half-life of parent if not chemically separated.

Table IV-3. Dose from pathways considered for the reference reactor site

Radionuclide	Concentration (pCi/g)[a]	Dose (mrem/y)[b]				
		Direct[c]	Inhalation[d]	Ingestion[e]	Submersion[f]	Total
^{54}Mn	1.2E-5	7.4E-5	6.1E-14	6.2E-8	5.2E-15	7.4E-5
^{60}Co	1.0E-2	1.8E-1	1.2E-9	2.2E-3	1.4E-11	1.8E-1
^{90}Sr	3.3E-3	0	3.4E-9	7.8E-3	0	7.8E-3
^{90}Y	3.3E-3	1.3E-8	2.1E-11	9.8E-6	1.7E-19	9.8E-6
^{134}Cs	3.0E-4	3.8E-3	1.1E-11	3.7E-5	2.4E-13	3.8E-3
^{137}Cs	3.4E-2	1.5E-1	9.0E-10	2.9E-3	1.2E-11	1.5E-1
Total						3.4E-1

[a]Concentraction in soil at 6 years after shutdown (ref. 1).

[b]Total body dose equivalent (ICRP26).

[c]Individual resides in a wooden frame house (shielding factor 0.4). Home occupancy 6062 hr/y, outdoor occupancy 130 hr/y.

[d]Individual on site 6192 hr/y, resuspended radioactivity is 10^{-11} of the top cm of surface soil.

[e]One-third of diet is from home garden.

[f]Same as for inhalation pathway.

Table IV-4. Concentrations of radionuclides in soil on reference reactor site which produces specified doses

Radionuclide	Combined[a] concentration in pCi/g to produce dose of		
	1 mrem/y	5 mrem/y	25 mrem/y
^{54}Mn	3.5E-5	1.8E-4	8.8E-4
^{60}Co	2.9E-2	1.5E-1	7.3E-1
^{90}Sr	9.7E-3	4.9E-2	2.4E-1
^{90}Y	9.7E-3	4.9E-2	2.4E-1
^{134}Cs	8.8E-4	4.4E-3	2.2E-2
^{137}Cs	1.0E-1	5.0E-1	2.5E+0

[a] The sum of the radionuclide concentrations in a given column will produce the anual dose given at the heat of that column.

Table IV-5. Limiting surface contamination levels to produce specific dose limit

Radionuclide	Combined[a] surface contamination[b] (pCi/m^2) to produce		
	1 mrem/y	5 mrem/y	25 mrem/y
^{54}Mn	6.7E+1	3.4E+2	1.7E+3
^{60}Co	4.1E+3	2.1E+4	1.0E+5
^{90}Sr, ^{90}Y	2.3E+4	1.1E+5	5.6E+5
^{134}Cs	2.4E+2	1.2E+3	6.0E+3
^{137}Cs	4.4E+4	2.2E+5	1.1E+6

[a] The sum of the radionuclide concentrations in a given column will produce the anual dose given at the heat of that column.

[b] Surface contamination in a 10 × 10 × 3 m room. Individual is exposed to direct radiation and inhalation of 10^{-6} resuspended surface activity for 2000 h/y.

Surface contamination is of concern only in the buildings remaining on the site. A slightly different isotopic composition was assumed for contamination inside buildings[1] as compared to contamination spread over the site itself. A comparison indicates that the contamination level at the proposed 5 mrem/y is compatible with other regulatory guidance.[7] The total contamination level of 3.5×10^5 pCi/m^2 corresponds to 7,770 dpm/100 cm^2 and present regulatory guidance specifies a maximum residual contamination of 15,000 dpm/100 cm^2. Nevertheless, it is prudent to examine termination surveys which could be conducted over a range of dose limits from 1 mrem/y (0.01 mSv/y) to 25 mrem/y (0.25 mSv/y) since this criterion has not been established.

Reactor Site Conditions before Termination Survey

It is anticipated that a reactor site ready for a termination survey has been restored, in the opinion of the licensee, to its pre-operational radiological condition within defined statistical certainty limits. The termination survey, confirms or documents that desired condition. In the process of preparing for the survey, a vigorous dismantling and decontaminating program has been conducted in which equipment and buildings have been decontaminated and some or all removed. The reactor and related equipment have been removed to another and approved burial or storage site. (Alternatively, the reactor may remain intact or stabilized in concrete, in place.) If the reactor has been removed, all structural materials subjected to neutron induced contamination have also been removed down to and including basic foundation earth. Equipment and buildings supportive of the reactor operation have also been dismantled and removed, typically.* In particular, the reactor

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*The number and type of buildings actually demolished will depend upon the specific site. This appendix is illustrative of the application of a methodology. Should one encounter a different set of buildings in an actual survey, the same procedures would be extended to cover all existing structures.

building, fuel building, auxiliary building, condensate demineralizer building and cooling tower could be demolished and removed. However, removal of radioactive decontamination, and not of structures is the primary aim of site decommissioning, and is the basis of an ORNL report[8] on technology versus cost where it is assumed that all buildings can be decontaminated, and none demolished (see also ref. 1). Other buildings on the site may be decontaminated successfully and released for unrestricted use. Contaminated surface soil and soil adjacent to the reactor activated by neutron induction have also been removed. It has been assumed that planning for decommissioning and decontamination phases have occurred in the first four years after shutdown.

Planning the Termination Survey

The designer of the termination survey, whether licensee or agent, should be thoroughly familiar with the dismantling and decontaminating process. It would help if the designer could observe and/or participate in the total decommissioning activity, because surveys prior to, during and after decommissioning operations are an essential planning aid for the final survey.

For purposes of the final site survey, the following elements of the site should be considered:

1. Ground areas of the site including soil-covered and paved areas and the cavity (not backfilled before final inspection survey) once occupied by the reactor, fuel and any other buildings having a potential for elevated residual activity.
2. Residual contamination on and in buildings, other structures and environment (soil, water, air, biota) remaining on the site after decontamination.
3. Sites of demolished buildings or outside dismantled equipment where radioactive material may have been stored or processed.

4. Paved, painted or otherwise covered areas suspected of shielding radioactive deposits.
5. Surface and ground water within or adjacent to the reactor site, and drainage systems.
6. Air sampling for the purpose of identifying airborne radioactivity indicative of soil or building contamination.
7. The stream bed adjacent to or in close proximity to the steam turbine building and drainage systems.

Termination Survey Procedure

The licensee or his agent should plan to take the following course of action to fulfill the monitoring requirements for decommissioning a reactor or other type of site:

1. Evaluation of natural radiation background levels for the site and immediate environs.

For large sites of many square kilometers, an aerial survey at 50 to 150 m altitude is one possible option, with data processing equipment in the plane of on the ground in a mobile van. Gamma signals from NAI(Tl) detectors mounted on the plane or helicopter are summed and routed through an analog-to-digital converter and pulse-height analyzer and recorded on tape, along with altitude, map coordinates, and so forth (see for example Table 4.3). For small sites less than a square kilometer, and for alpha and beta measurements, surveys on foot are needed. For sufficiently energetic betas and gammas, detectors mounted under a moving vehicle are an alternative to foot surveys. Upwind, upstream, uphill, and off-site are normal requirements for background readings, with no other nuclear facilities in the general area. Otherwise, both facilities need to be analyzed in common. Distances of 1 but no more than 5 km from the site boundary should be suitable for background measurements. At greater distances, background may be significantly different from the local site unenhanced background. For decommissioned reactor sites, preoperational survey for reactor-oriented nuclides such as ^{60}Co, ^{137}Cs, ^{134}Cs, and ^{54}Mn would be optimum, but for older sites may not be available in detail. If not, their determination in surface and subsurface soil and in water is required. At least 30 background soil samples should be taken, documenting that background soil has the same general characteristics as site soil where for the latter the likelihood of contamination is significant.

2. Evaluation of on-site radiation background levels where there is more likelihood that some areas and buildings may still have residual contamination.

Where prior information indicates or suggests contaminated spots to be more likely, stratification accordingly may be a way of allocating sampling to keep within reasonable size the total number of samples needed for the entire site. Where there is indication that the site is more or less homogeneously contaminated, stratification may be unnecessary. Where operational environmental monitoring data are incomplete or insufficient, a preliminary post-operational survey will be necessary to plan the final survey.

3. Evaluation of background levels within buildings where there is greatest likelihood of residual contamination.

Since buildings where radionuclide activities were involved tend to confine the activity, they frequently require more detailed survey in the form of smear samples of surfaces for residual contamination due to insufficient cleanup or measurement. Effluent routes (air, water) from buildings to outside environment not removed by cleanup need particular survey attention for possible residual contamination.

Preliminary Survey

In preparation for a preliminary survey, establish the limits of each survey unit along the following lines:

1. Floors, walls extending 2 m from the floor, and roofs of decontaminated buildings (Stratum 1 of Table 3.6).
2. Upper walls (extending above 2 m from the floor), ceilings and overhead structures in decontaminated buildings (Stratum 1 of Table 3.6).
3. Excavated areas prior to backfill (Stratum 1 of Table 3.6).
4. Dismantled building sites (Stratum 1 of Table 3.6).
5. Outdoor areas within 10 m of buildings (Stratum 1 of Table 3.6).
6. Outdoor controlled areas beyond 10 m but within the main plant facilities area (typically 100-200 m radius around reactor building) (Stratum 2 of Table 3.6).
7. Utility property beyond main plant area (typically 3-5 km^2) (Stratum 4 of Table 3.6).
8. Any other logical geographic area or localized area of contamination (such as Stratum 3 of Table 3.6).

Make at least 30 beta-gamma measurements with an open-window Geiger-Mueller probe 1 cm above the surface, at roughly uniformly spaced points in each survey unit, to determine optimum number of grid or survey blocks required for each survey unit. Use Eq. (3.1) and Table 3.7 with appropriate limitations to determine the grid structure. Once the survey unit sizes have been decided upon, layout a grid for dimensioned indoor and outdoor areas of each survey unit as indicated by the prior determination.

For indoor surveys, measure at 1 cm above the surface with an open- and closed-window G-M probe for beta-gamma and gamma activity levels at a minimum of five points in the survey block. Scan the survey block with the open-window G-M probe to locate the maximum. At the beta-gamma maximum point, each type of measurement is taken, including smear samples for measurement of transferable alpha and beta contamination.

The five-measurement average of beta-gamma and gamma, and the gamma measurement at 1 m above the center of the block are reported.

For outside area surveys, measurements will be made at grid points with both open- and closed-window G-M probe at 1 cm from the surface and with a gamma scintillator at 1 m above the surface. Scan each survey block a few centimeters from the surface with the open-window probe for the location of a maximum reading. After a maximum point is found, record the 1 cm surface beta-gamma and 1 m gamma reading.

Use of Preliminary Survey Data

Having determined the average and maximum beta-gamma measurements for each survey block within the "unit." Decide whether simple or stratified random sampling (see Section 3.5) of surface and subsurface soil would best characterize the radionuclide level, and whether soil samples should be taken at: (1) same points where beta, gamma readings were taken, or (2) at different points from where beta, gamma readings were taken, or (3) both (matched vs. unmatched observations).

Except where specified otherwise, "unit" should be taken to mean stratum. "Stratum" is defined in one of the following ways:

1. By variance – Collecting all values of observations falling within 1, 2, or 3 standard deviations of a selected mean (i.e., grouping observations into 2 or more strata. Disadvantage: though preferred by statisticans, stratification by variance destroys geographic relations of observations for surveyor's convenience.
2. By geography – Collecting all values of observations taken on former processing building sites, and/or inside former security fence area, etc.
3. By geography and variance (e.g., two or more substrata by variance within fenced area, main stratum). There can be, or may have to be more than one stratification or substratification scheme [(1) one stratification by beta, gamma readings 1 cm above soil surface, and (2) a second

stratification of the site by a key nuclide whose geographic distribution pattern of soil concentration does not coincide with the geographic distribution pattern of air beta, gamma readings (because the latter air readings include radiation from other beta and/or gamma emitters than the key nuclide in question, and/or because the key nuclide is not a beta and/or gamma emitter)].

To avoid two or more stratification schemes, one tries to resort to a combined single stratification compromise scheme, (e.g., by using a weighted sample allocation formula according to variance of each variable (beta, gamma vs. nuclide A vs. nuclide B variances); the variable with the greater variance getting the larger sample size (at least between nuclide A and nuclide B since beta, gamma readings can and should be large because of the low cost per observation (reading). Consider stratified random sampling if beta-gamma readings seem to exceed background in portions of the site. (See Section 3.3.2 on Outdoor Survey.)

Based on the hypothesis that a more or less direct relationship exists between the open-window G-M measurements at 1 cm from the soil surface and the radionuclide level in the topmost centimeters of soil, it is possible to optimize the number of soil samples required to characterize the survey unit. To find the number of soil samples, n, required by simple random sampling to estimate the mean of the soil radionuclide concentration with a bound B on the error of the estimation of 10% at the 95% level of confidence, use equation:

$$n = \frac{N\,\sigma^2}{(N-1)D+\sigma^2}\,, \quad \text{(ref. 9)} \tag{1}$$

where

n = number of soil samples for the survey unit,

N = number of survey blocks in the survey unit ("unit" defined as stratum),

$$D = \frac{(\bar{y}B)^2}{4} ,$$

$\bar{y}$ = mean beta-gamma dose rate,

B = error expressed as a decimal, and

σ^2 = population variance.

In practice, the population variance is unknown. A sample variance, s^2, is available from the beta-gamma measurements from which we can obtain an approximate sample size by replacing σ^2 with s^2 in the above equation.

$$s^2 = \sum_{i=1}^{j} \frac{(y_i - \bar{y})^2}{j-1} \tag{2}$$

where

y_i = the ith beta-gamma measurement, and

$\bar{y}$ = mean beta-gamma measurement.

As an example of a situation at a reactor site ready for a decommissioning survey, consider the application of the above approach to a survey unit of 100 grid blocks. Choosing to sample beta-gamma readings 1 cm above soil samples at 30 random grid blocks (hypothetical measurements given in Table IV-6), we obtain a sample variance from the mean to estimate the number of soil samples required to furnish a radionuclide mean within prescribed limits.

The calculation of sample size, n, is based upon beta-gamma variance for 30 hypothetical survey blocks. Wherever possible, decision and calculations should be based upon a minimum of 30 observations for statistical reasons.

Table IV-6. Beta-gamma (open-window) G-M survey measurements 1 cm above soil surface of hypothetical reactor site

Grid block	mrad/hr[a]	Grid block	mrad/hr[a]	Grid block	mrad/hr[a]
1	0.07	11	0.10	21	0.16
2	0.06	12	0.09	22	0.07
3	0.09	13	0.04	23	0.07
4	0.15	14	0.07	24	0.08
5	0.11	15	0.12	25	0.11
6	0.10	16	0.14	26	0.10
7	0.21	17	0.08	27	0.09
8	0.09	18	0.10	28	0.12
9	0.08	19	0.11	29	0.10
10	0.12	20	0.07	30	0.10

[a]To convert mrad/h to mGray/h, multiply by 0.01.

$\bar{y}$ = 0.102,

s^2 = 1.164E-3,

B = 0.10,

D = 2.60E-5, and

N = 100.

$$n = \frac{N\ s^2}{(N-1)D + \sigma^2} = \frac{(100)(1.164E-3)}{(99)(2.6E-5) + 1.164E-3} = 31\ .$$

A sensitivity analysis has been performed for sampling with Eq. (1) and the results are given in Table IV-7. The number of samples to be taken from a survey unit having a fixed total site number (N) of grid blocks will depend on the sample standard deviation, the acceptable error, and the confidence level (see Table 3.1).

Table IV-7. Sensitivity analysis for sampling equation[a]

Population (grid blocks) N	Error bound B	Sample standard deviation s	Samples required n
29	0.025	0.03412	6
100	0.025	0.03412	7
5000	0.025	0.03412	7
29	0.010	0.03412	18
100	0.010	0.03412	32
5000	0.010	0.03412	46
29	0.005	0.03412	25
100	0.005	0.03412	65
5000	0.005	0.03412	180
29	0.025	0.01706	2
100	0.025	0.01706	2
5000	0.025	0.01706	2
29	0.010	0.01706	9
100	0.010	0.01706	11
5000	0.010	0.01706	12
29	0.005	0.01706	18
100	0.005	0.01706	32
5000	0.005	0.01706	46
29	0.025	0.06824	15
100	0.025	0.06824	23
5000	0.025	0.06824	30
29	0.010	0.06824	25
100	0.010	0.06824	65
5000	0.010	0.06824	180
29	0.005	0.06824	28
100	0.005	0.06824	88
5000	0.005	0.06824	649
29	0.001	0.03412	29
100	0.001	0.03412	98
5000	0.001	0.03412	2411

[a]Conditions: Mean of 29 samples = 0.100 mrad/h (0.001 Gy/h); B = 0.025 corresponds to 25% error, etc. Standard deviation of actual data was 0.03412. Use of Mendenhall equation:

$$n = \frac{N\,\sigma^2}{(N-1)\,\frac{B^2}{4} + \sigma^2}$$

where the sample standard deviation s has been substituted for σ, the population standard deviation which is unknown.

Final Survey Sampling

Surface soil samples should be taken to a depth of 5 to 15 cm in an amount sufficient to provide 1 km of dried soil. Outside areas known to have been disturbed or suspected of subsurface contamination should be augered for gamma monitoring and sampling.

Surface measurements will be made with a G-M meter, using the open- and closed-window modes. External gamma radiation levels will be measured with a NaI scintillation survey meter or any other instrument of comparable sensitivity. A survey for removable contamination will be conducted, where appropriate, using a standard smear technique. If preliminary measurements indicate the presence of alpha contamination, alpha measurements should be made with an alpha scintillation survey meter or another equally sensitive and discriminatory instrument.

Subsurface soil sampling should be done at reactor and fuel building sites and any other areas having a high potential for reactor oriented radionuclides. Samples should be taken from any remaining reactor building foundation concrete and reinforcing steel prior to back-filling for reactor induced radionuclide analysis. The number of samples and location will be determined by the configuration and extent of the foundation but the total area sampled should be at least 1% of the foundation area. If paved areas examined by direct survey indicate a measurement in excess of background, penetrate the pavement and remove a subsurface soil sample for analysis.

Soil samples will be analyzed qualitatively and quantitatively with a pulse height gamma spectrometer. Gross beta measurements of all soil samples will be made with a gas flow proportional counter or other appropriate detector. Ground and river water and river sediment samples will be taken for analysis for reactor-originated radionuclides. All measurement and sampling locations should be properly documented. Soil and water samples should be sufficiently large enough for triplicate analysis.

Survey of the Reference Reactor Site

The reference reactor site is assumed to be a plant facilities area which is approximately 0.1 km^2 (~26 acres) inside a much larger (4.7 km^2) largely unoccupied piece of property. The buildings on site are shown in Fig. IV-1 and the dimensions of each are summarized in Table IV-8. Actual building dimensions for the specific site should be substituted. In addition, a cooling tower which has a typical base diam of 119 m and is 152 m tall would be located on the plant facilities area. Several of the buildings may be contaminated to such an extent that demolition is the appropriate decommissioning action and this has been so indicated in Table IV-8. Buildings and equipment not residually contaminated, or capable of being decontaminated on a cost-effective basis, need not be demolished.[1,8]

A termination survey is assumed to proceed along the general design already discussed. The buildings remaining on site after decontamination should be surveyed according to the survey procedures given in Section 3.3.1. In this survey, it is assumed from prior information that the critical radionuclides are the ones identified in Table IV-3 and thus an alpha survey is not required. However, if alpha contamination has been observed on preliminary (or cleanup) surveys, alpha measurements would be called for in the termination survey. Likewise, any beta or gamma found significant for the specific site and reactor type other than those identified in Table IV-5 should be added if sufficient in potential quantity and half-life. The area adjacent to buildings in the main plant area should be surveyed with an intensity approaching that of the buildings themselves. It is proposed at the 5 mrem/y level that the buildings be surveyed on a 2 m grid and the adjacent land be surveyed on a 3 m grid out to approximately 10 m from existing and previously existing structures. Beyond the 10 m distance the remainder of the plant facilities area is surveyed on a 10 m grid. This survey design is illustrated in Fig. IV-2. At the 1 mrem/y level the grid dimension would have to remain at 3 m for the entire survey. At the 25 mrem/y level, the grid dimension may be relaxed but it is not

Table IV-8. Buildings on reference reactor site

Building	Dimensions of base	No. of floors	Disposition in decommissiong action
Reactor containment	22.5 m diam.	--	Demolished
Auxiliary	19 m × 35 m	6	Demolished
Fuel	19 m × 54 m	4	Demolished
Condensate dimineralizer	10 m × 43 m	3	Demolished
Cooling tower	119 m diam	--	Demolished
Turbine	49 m × 95 m	2	Decontaminated
Control	24 m × 31 m	4	Decontaminated
Chlorine	10 m × 15 m	1	Decontaminated
Administration	13 m × 27 m	2	Decontaminated
Shop and warehouse	13 m × 90 m	1	Decontaminated

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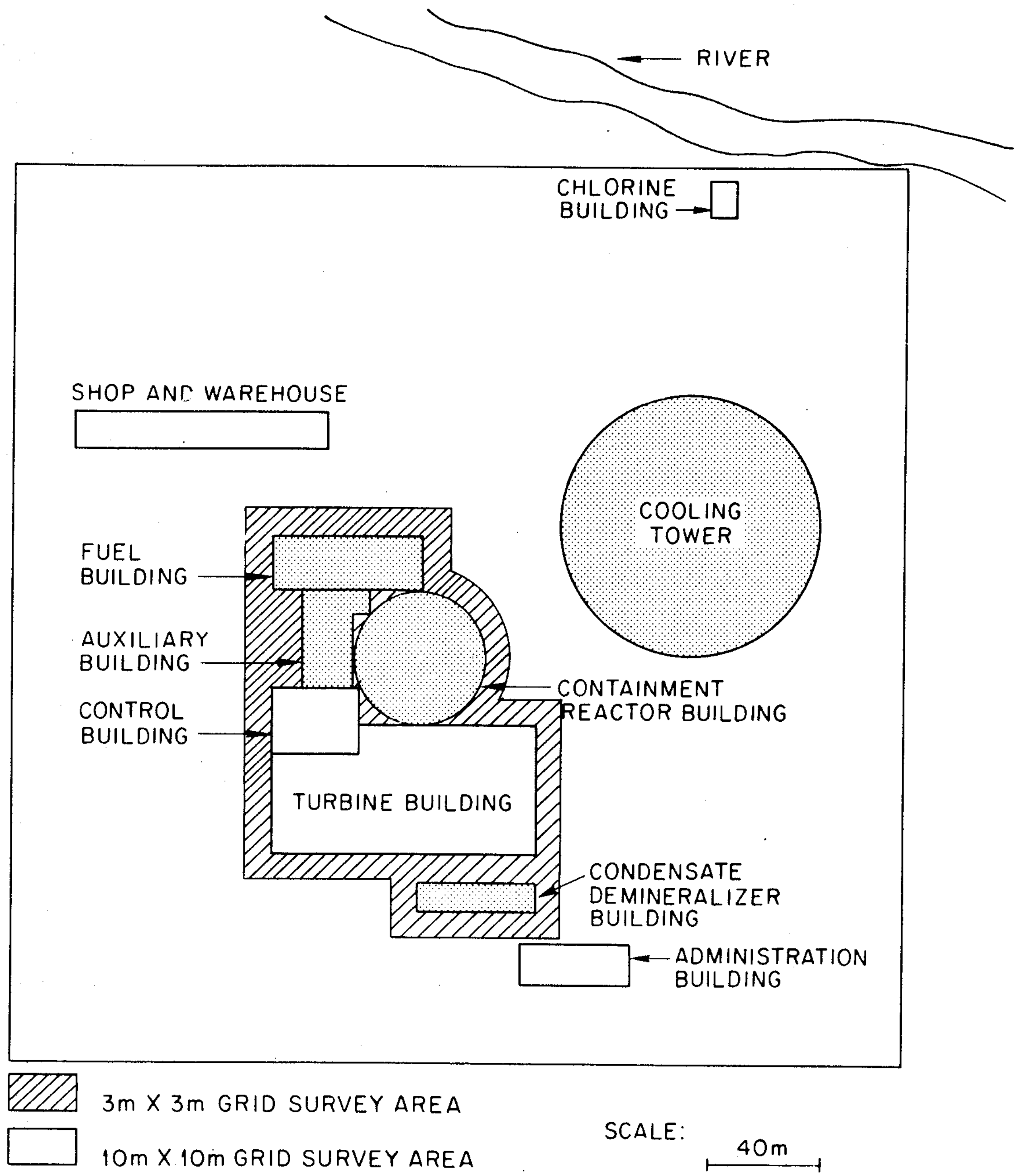

Fig. IV-2. Several major survey units for the reference reactor site are shown. These survey units are (1) separate buildings, (2) area adjacent to buildings (cross hatched), and (3) remainder of plant facilities area.

recommended since a survey on a 10 m grid is within reason per the as-low-as-reasonably-achievable philosophy.

Survey of structures

For the purposes of a termination survey, building wall areas are divided into upper and lower areas with the lower (2 m) area to be surveyed in the same manner as floors or roofs. The upper walls, ceilings and overhead structures are all treated similarly. The building survey measurements are indicated in Table IV-9 and summarized in Table IV-10. The average time required to take an individual measurement is approximately 30 s for β-γ, γ measurements and smears. On this basis it will require approximately 672 person hours to survey the buildings remaining on the site and determine the average contamination levels. This does not include time for data processing. In addition, each survey block must be scanned for potential hot spots and the maximum point in each block identified and characterized. The time to scan a block is estimated at five minutes and characterization of the maximum point in each block requires an additional two minutes (i.e., three measurements and a smear). Given 6431 survey blocks, an additional 750 h are required to complete these measurements and take the necessary smears. Once taken, the smears are taken to the counting laboratory for analysis, where each smear is counted for a minimum of 1 min. to determine removable β-γ contamination levels. The counting time should be doubled if alpha counting is also required. The time required to analyze the smear samples is summarized in Table IV-11, which indicates approximately 225 h are required to perform this part of the survey.

Outdoor survey

The outdoor survey includes three major components (see Fig. IV-2).

1. An intensive survey in the area of demolished buildings and extending 10 m beyond building foundations (existing or demolished). (Stratum 1 of Tables 3.6 and 3.7)
2. A thorough survey of the plant facilities area (0.1 km^2) outside the intensive survey area.

Table I-9. Survey measurements performed in a termination survey of the reference reactor site

Building	Survey unit[a] (No.)	Area (m^2)	No. of survey blocks	No. of instrument readings: β-γ	No. of instrument readings: surface γ	No. of instrument readings: γ at 1 m	No. of smears
Turbine	Floor (2)	9310	2328	11640	11640	2328	2328
	Lower wall (3)	1728	432	2160	2160	432	432
	Upper wall (3)	15552	--	90	90	90	90
	Ceiling (2)	9310	--	60	60	60	60
	Roof (1)	4655	1164	5870	5820	1164	1164
			3924	19770	19770	4074	4074
Control	Floor (4)	2976	774	3720	3720	744	744
	Lower wall (5)	1100	275	1375	1375	275	275
	Upper wall (5)	2860	--	150	150	150	150
	Ceiling (4)	2976	--	120	120	120	120
	Roof (1)	744	186	930	930	186	186
			1205	6295	6295	1475	1475
Shop and warehouse	Floor (1)	1170	293	1465	1465	293	293
	Lower wall (2)	824	206	1030	1030	206	206
	Upper wall (2)	4944	--	60	60	60	60
	Ceiling (1)	1170	--	30	30	30	30
	Roof (1)	1170	293	1465	1465	293	293
			792	4050	4050	882	882
Chlorine	Floor (1)	150	38	190	190	38	38
	Lower wall (2)	200	50	250	250	50	50
	Upper wall (2)	300	--	60	60	60	60
	Ceiling (1)	150		30	30	30	30
	Roof (1)	150	38	190	190	38	38
			126	720	720	216	216
Adminis-tration	Floor (2)	702	176	880	880	176	176
	Lower wall (3)	480	120	600	600	120	120
	Upper wall (3)	1120	--	90	90	90	90
	Ceiling (2)	702	--	60	60	60	60
	Roof (1)	351	88	440	440	88	88
			384	2070	2070	534	534

[a] A building may be considered a population, and the survey units tabulated as "strata."

Table IV-10. Summary of building survey measurements

Building	No. of blocks	No. of measurements	Time expended (hrs)
Turbine	3924	47688	400
Control	1205	15540	130
Shop/warehouse	792	9864	82
Chlorine	126	1872	16
Administration	384	5208	44
	6431	80172	672

Table IV-11. Analysis of smear samples

Building	No. of smears		Total counting time (hrs)
	Routine	Maximum point	
Turbine	4074	3924	133
Control	1475	1205	45
Shop/warehouse	882	792	28
Chlorine	216	126	6
Administration	534	384	15
Totals	7181	6431	227

3. A cursory survey over the remainder of the site with thorough coverage in any areas found to contain contamination above twice background. (Stratum 4 of Tables 3.6 and 3.7.)

An intensive survey should be conducted on grid dimensions not to exceed 3 m and should be performed on that area formerly occupied by the dismantled fuel, auxiliary, condensate-demineralizer and reactor buildings and the cooling tower as well as a 10 m perimeter strip around the major buildings (see Fig. IV-2). The total area represented is 29,569 m^2 which will form 3285 grid blocks. The survey should proceed much as an indoor survey would with five beta-gamma and gamma measurements at the surface in each block, one gamma measurement at 1 m over the center of each block, a scan of the block and finally a characterization of the maximum point in each block (one beta-gamma and one gamma at the surface and one gamma measurement at 1 m over the point). The time to perform these measurements is summarized in Table IV-12. Smear samples are not appropriate for radiological surveys over land surfaces. Soil samples are taken instead and the procedure for determining the number and location of these is discussed later in this section.

The remaining area (62,971 m^2) in the plant facilities area should be surveyed on a 10 m grid (at the 5 or 25 mrem/y level) as an outdoor parcel (see Section 3.3.2). This area will constitute approximately 630 grid blocks. A minimum of three measurements is required at each grid intersection, one open-window and one closed-window G-M reading near the surface and one gamma reading at 1 m above the surface. Because these readings will be taken and recorded in the field where instruments and clipboards must be carried, required time per measurement has been estimated at one minute rather than one-half minute as used in the more convenient environment in and around buildings. The time required for this part of the survey is approximately 30 h.

In addition, the blocks should be scanned with an open-window G-M probe for hot spots. This would require approximately 10 minutes per block or about 105 h. Any hot spots that are found should be characterized by taking open- and closed-window G-M readings near the surface

Table IV-12. Summary of time required to survey area formerly occupied by buildings and area in close proximity to remaining buildings

Survey technique	Time (hrs)
Block average	301
Block scan	274
Characterize maximum point	110
	685

and a gamma reading at 1 m above the location. In addition, a soil sample should be taken at the hot spot. If the site has been properly decontaminated, there should be very few hot spots (<10) so this procedure would not add much to the overall effort of the survey.

The remainder of the site may be surveyed on a larger grid since activities involving radioactivity presumably were not conducted on this area. If the records indicate to the contrary, those areas where radioactivity was handled should be treated as separate survey units and a more intensive survey conducted. The area involved in this survey unit is quite large (~4,600,000 m^2) but should be relatively uncontaminated so a grid dimension of 30 m is proposed for the 5 or 25 mrem/y level (10 m for the 1 mrem/y level). This would produce 511 survey blocks. The survey procedure is otherwise the same as the preceding one for the plant facilities area. Scanning time is increased to 20 minutes per block owing to the increased size of the blocks. The time to conduct this part of the survey would include 25 h for grid point measurements, 1703 h for scanning, and an undetermined but presumably small amount of time for characterizing hot spots, if found. The outdoor survey measurements have been summarized in Table IV-13.

Soil sampling

The beta-gamma measurements taken for the three major outdoor survey units are used to determine the number of surface soil samples to take in each unit. For illustrative purposes, assume the parameters given in Table IV-14 where survey unit 1 is the area around buildings, survey unit 2 is the main plant area exclusive of survey unit 1 behind the former security fence, and survey unit 3 is the remainder of the site. The innermost area is likely to have a higher average radiation level and be more variable than the other areas. Using Eq. (1), the number of randomly located soil samples required to characterize these survey units to within 10% at the 95% level of confidence are 64, 36, and 14 for survey units 1, 2, and 3, respectively. Surface soil samples are taken to a depth of 5–15 cm by a method that is convenient and standardized for the type of soil encountered. Surface soil samples

Table IV-13. Outdoor survey at reference reactor site at the 5 to 25 mrem/y (0.05 to 0.25 mSv/y) level

Survey unit	Area (m^2)	Survey blocks	Instrument measurements		
			β-γ	Surface γ	γ at 1 m
Former building sites and close proximity to buildings	29,569	3,285	16,425	16,425	3,285
Plant facilities area exclusive of area adjacent to buildings	62,971	630	630	630	630
Remainder of site	4,600,000	5,111	5,111	5,111	5,111
Total	4,700,000	9,026	26,166	22,166	22,166

Table IV-14. Hypothetical parameters for determining number of soil samples on reference reactor site

Parameters	Survey unit		
	1	2	3
Survey blocks (N)	3285	630	5111
Standard deviation of β-γ measurements	0.06	0.03	0.015
Average β-γ measurement	0.15 mrad/h	0.10 mrad/h	0.08 mrad/h
Error bound	±10%	±10%	±10%
Number of soil samples required	64	36	14

indicate contamination that could be involved in dose to man via the pathways previously discussed (see Table IV-3).

In addition to the random samples, soil samples are to be taken at all "hot spots" located during the scanning survey. This may consist of up to 10 samples per survey unit or 30 total hot spot samples.

It is assumed that 144 total surface soil samples will be required for the hypothetical case just outlined. Assuming that it requires 10 minutes each to locate the random sampling locations and an additional 15 minutes each to collect a sample, the time to perform surface soil sampling will amount to 60 h.

Should soil sample analysis reveal that the number of soil samples taken do not give the requisite accuracy and precision, additional soil samples may be required. Since the number of samples was based on the surface β-γ dose rate and the correlation between surface dose rate and soil concentration is less than perfect, it is reasonable to expect that desired soil characterization may not be achieved from the first sampling.

In general, subsurface soil samples should be taken to verify that significant contamination does not exist at greater depths. While contamination at greater depths would not be encountered normally by members of the public, future excavation or construction on the site could bring this contamination to the surface and in contact with man. In addition, radioactivity could be leached from subsurface deposits and end up in drinking water supplies. Surveys of sites with known burial of radioactive material should emphasize subsurface soil sampling while surveys of sites not suspected of having subsurface contamination should only strive to confirm that presumption.

For the reference reactor site under consideration, subsurface soil should be sampled in the area of survey unit 1 to the depth of excavation for structures on the site, perhaps 10 m. Soil samples can be taken with a split-spoon sampler at regular intervals of 30 cm, along the depth of the sample hole. While the number of corings is somewhat arbitrary, randomly coring about 1% of available survey blocks will result in at least 30 core holes. Either samples may be taken at regular intervals along the depth of the core hole or the radioactivity may be measured in situ by means of a collimated detector. Assuming that 10% of the available samples (~900) are taken for comparison with in situ radiation measurements, that means about 90 soil samples will require analysis. The most practical means to accomplish this subsurface sampling program is to auger 27 of the 30 holes at a cost of approximately \$15.00 per m and core the remainder at a cost of approximately \$30.00 per m. As a result of the proposed sampling program (outlined in Table IV-15), 90 soil samples would be taken that would require subsequent analysis and 810 in situ measurements would be made that require an average of 3 min each to make, or about 40 h total. The 90 soil samples would require about 22.5 h to collect.

Water sampling

Water samples should be taken from each and every source of water on the site. While the primary source is the river which provided service water, several other sources may be present. One should not overlook standing surface water. This portion of the survey is not expected to be a major part of the overall effort.

Table IV-15. Subsurface sampling of soil at reference reactor site

Type	No. sample locations	Depth	Samples or measurements
Auger	27	10 m	810
Core	3	10 m	90
	30		900

INSPECTION FOR CERTIFICATION

Introduction

Though this guide considers the needs of both licensee and inspector for design of their respective final surveys, the somewhat divergent objectives of each should be kept in mind and not confused when text switches from one viewpoint to the other. The two have not been separated because one is an integral part of the other insofar as the licensee's final information is input to the inspector's final survey design for verification of the licensee's compliance. This premise is predicated on a Bayesian approach[10] to the problems addressed. The licensee's final survey is prior information (but not the only prior information) to be used by the inspector for design of his verification survey. It is also premised in this guide that the inspector's final recommendation is based not only upon an audit of the licensee's final survey report and other records, and upon a third party analysis of duplicate samples held in reserve, but also upon an actual field survey involving instrumental air measurements and environmental samplings taken on-site at the same time to be analyzed by a third or fourth party. Accordingly, the inspector's final report is partially dependent on the licensee's data and interpretations as carried out by a survey design agreed upon by licensee and the regulatory agency.

In general terms, Bayes' theorem takes into account prior information to supplement or interpret the otherwise theoretical probability approach to survey design. When B (licensee's survey) and A (inspector's survey) are independent, then:

$$P\,(A/B) = P(A)\,\frac{P(B/A)}{P(B)}\ ,$$

where

P = probability of the right decision by the agency,

$P(A)$ = encoding of the agency's state of knowledge before knowing the priority probability B, P(A/B) = encoding of state of knowledge by B after learning about the posteriority probability A, and

P(B/A)/(P(B)) = the measure of relevance (when this ratio = 1, information A is not relevant to B, any other number larger or smaller than 1 indicates relevancy and is reflected by the assignment of a new value to the probability of B (i.e., $P(A/B) \neq P(A)$.

This equation gives in principle a procedure for updating our state of knowledge in the presence of new information. To utilize this approach quantitatively on the problem at hand (whether or not to clear a site for unrestricted use) is not a trivial problem. A major use of prior information in the present situation is to relate theoretical statistics (which can be performed on any set of observations whether they be generated from the real world or created from an imaginary situation) and models to actual data obtained from specific sites. More specifically, prior information is essential to a reasonable interpretation of degrees of correlation obtained between two or more soil nuclide concentrations and between these soil nuclides and air gamma or beta, gamma readings taken above the soil samples in-situ before removal to the laboratory for analysis. Correlation, or lack of it, is controlled by a number of factors, including instrumental specificity and sensitivity (detection limit), the particular mixture of beta and/or gamma emitting nuclides in the soil, air distance of instrument from the soil surface, extent of soil disturbance/mixing, especially of two or more distinctly different types of operations, or of the same operation at different times which permit differential environmental transport of nuclide mixtures, thus changing ratios and correlations (see also Appendix VII).

The survey plan prepared by the licensee (or his radiological contractor) should be reviewed by the certification inspector prior to initiation of the licensee's final survey plan. For small licensees, in particular, who are decommissioning a site for the first time, the certification inspector should emphasize review of the analytical techniques, quality assurance measures, and statistical bases for sampling.

The licensee (or his radiological contractor) should carefully consider the incorporation of comments offered by the certification inspector. This early agreement should minimize the need for a completely independent radiological survey by the certification inspector.[11]

Following the NRC protocol will ensure that the licensee collects the appropriate number of duplicate samples. The certification inspector will be concerned with samples obtained on a random basis from a reproducible grid system. Samples taken from biased areas such as "hot" spots indicated by field instrumentation will also be of interest as maxima. The requisite number of sample splits, replicate analyses of identical samples, and other details should be defined in the survey plans of the licensee. It should be noted that state and local agencies may also be interested in analyzing split samples or conducting similar nondestructive analyses on the same sample.

Results which are much less than ideal may result from failure to seek approval of the certification inspector at an early stage. Results obtained by the certification inspector will, of course, determine whether or not the remedial action was successful. Consequently, the licensee should seek advice from the certification inspector when major changes in the survey plan are caused by discoveries during the decontamination process (e.g., a "hidden" subsurface layer of an expected radionuclide).

When the licensee has completed the cleanup and documented the radiological condition of the site, the inspector is ready for the verification process. As an aide in conducting this verification phase, the following areas should be addressed:

1. Determine conditions under which background alpha, beta, beta-gamma, and gamma measurements were made. Were calibrated instruments of adequate sensitivity used in the measurements? Were the locations of measurements documented so that verification of the measurements could be made by the inspector if he desires?

2. Determine if a grid layout of the reactor site was used for the preliminary survey, commensurate with the contamination probability of the various areas.
3. Determine if a sufficient number of soil samples were taken to give the required confidence level in the results.
4. Within buildings on the reactor site used for storage of radioactive material, if positive results were obtained by direct survey or the survey for removable contamination, were samples of the suspect area taken for quantitative and qualitative examination?
5. Determine if smears and/or samples of removable debris were taken from systems within buildings used for the storage or processing of radioactive materials.
6. Were subsurface soil samples taken in all areas of disturbed soil or paved areas reading above background?
7. Have sediment samples been taken from beds of bodies of water on the site?
8. If measurements or soil sample analysis from an area are more than background but less than twice background, verify 1% of all soil samples by repeating measurement or analysis of replicate samples. For areas showing twice background or above, repeat analysis 10% of all soil samples for verification.

   The inspector should be guided by the acceptable limits mentioned earlier for surface radiation rates and soil radionuclide levels and any subsequent decommissioning criteria which may be developed.

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APPENDIX V

APPLICATION OF MONITORING PROGRAM TO URANIUM MILL SITE

INTRODUCTION

The typical mill site is located in the western United States, and in an arid region with low rolling hills and occasional steep ridges and mesas. Occasionally mill sites are adjacent to populated areas but as a rule are separated by several miles. A nearby stream serves as a process water source or/and a means of disposal for treated process liquids. Except for irrigated areas, the site and surrounding land areas support only sparse vegetation so the unprotected soil is subject to wind erosion. Generally, the site controlled area consists of several hundred acres with 10 to 20% of it devoted to milling process and service buildings, ore storage dumps, liquid waste retention ponds and mill tailings piles.

Characteristically, the site is identifiable by the mill tailings pile, the solid ore refining waste, containing tens to hundreds of curies of ^{226}Ra and other daughters of the ^{238}U, ^{235}U, and ^{232}Th decay chains. The pile could represent thousands of tons of solid waste accumulated over a 5 to 15 year operational period. Some piles contain only a fraction of the daughters since the mill slimes, enriched in uranium and daughters may have been transferred to another mill to complete the refinement. They may have served as dumps for wastes from some other process remote from source material refining. Contaminated soil from around buildings, ore storage, and process areas may have been incorporated in the pile. Although the authors are not aware of any tailings pile of any magnitude having been removed from the mill site, there may be an isolated case. Unfortunately, there are instances in which some sand-like material has been removed for use as construction material and as fill dirt. In some cases the pile has been sparsely covered while in others the pile has been covered with several feet of clean soil, sufficient to trap the gaseous daughters of ^{226}Ra from entering the atmosphere. If vegetation was not shortly established on the soil covering, spot exposure and subsequent transfer off-pile of the tailings material may be anticipated downwind.

The tailings pond, an integral part of every mill, served as the repository for mill liquid raffinate and pile drainage. At an inactive uranium mill site it may be dried out and/or filled with clean soil.

PLANNING FOR THE DECOMMISSIONING SURVEY

After the licensee or his agent has completed a program of decontaminating, dismantling, and general cleanup accompanied by spot radiological surveys, he is in a position to plan for the decommissioning survey.

The planner needs to consider the site overall in terms of geographic divisions, natural barriers, underground geological structure, water table, drainage conditions, slope, prevailing wind direction, and the sites' relation to populated areas. He may view the site as being composed of five identifiable regions from the standpoint of survey treatment: (1) the mill tailings pile and pond, (2) intact buildings, (3) process sites, (4) stream, and (5) the remaining controlled outdoor area. With the exception of the pile and pond, the remaining areas may potentially be contaminated at different levels, yet be within NRC guidelines for release for unrestricted use.

As might be expected, the radionuclides within the boundaries of the uranium mill site, exclusive of the tailings pile will be nonuniformly distributed. The ore storage area will have a distribution equivalent to the natural form while the indoor and process area will range from natural to all stages of refinement. Since most of the uranium chain daughters are characterized by hard gammas, this allows their detection by gamma instrumentation. Because of this correlation it is possible to use the air gamma measurements as a guide in estimating the number of surface and subsurface soil samples required to adequately assess the radiological condition of the survey unit.

The principle radionuclides, in order of appearance in decay chain, likely to be found in the mill tailings pile are ^{230}Th, ^{226}Ra, ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, and ^{210}Pb. Also to be found, but of lesser significance, is natural thorium (^{232}Th) and daughters. In mill site areas removed from the tailings pile, one will probably find a distribution (1) similar to natural ore, (2) blended with tailings, or (3) equivalent to tailings due to atmospheric transport.

The planner and/or surveyor is referred to Section 3.0 of the main body of this report for instruction as to the proper survey design and procedure to be used in indoor surveys. He should be further guided by the criteria for the total and removable activity level[1] and air radionuclide concentration[2] for the release of indoor facilities for unrestricted use. Should the air external gamma survey indicate isolated hot spots under floors, or paved areas, in drains, crevices, and painted surfaces, they should be penetrated for sampling and laboratory analysis. Sampling of the indoor air for ^{222}Rn and radon daughter determination should be done by one of several continuous or integrating measurement methods (Section 2).

The outdoor area should initially be divided by a selected grid system as a guide in making a preliminary external gamma survey. Based on recorded gamma readings made at each grid line intersection, the planner is equipped to make a decision as to what areas should be further divided into smaller units or grids for additional measurements. Where maximum gamma measurements are greater than twice the background, those areas should be divided into smaller units to assure a more accurate assessment. By increasing the grid density of those questionable areas, the likelihood of missing hot spots is minimized.

Further activities which the licensee must engage in to prepare for the compliance inspection are the following:

1. Preoperational background of beta-gamma dose rates and external air gamma 1 m above the surface would be optimum; however, in lieu of this measurement, measurements 1 km downwind of the site may be used for a background survey.
2. Preoperational site background for ^{238}U, ^{232}Th, ^{230}Th, ^{226}Ra, ^{220}Ra, and ^{210}Pb is preferred; however, if such is not available their determination in surface and subsurface soil and water samples taken 1 km from the process site is required.

3. Divide the outdoor area, exclusive of the retention pond and tailings pile, by a 30 m grid with an established baseline for reference.
4. Measure beta-gamma dose-rates within 1 cm of the surface with an open-window (30-40 mg/cm^2) G-M survey meter and gamma exposure rates at 1 m above the surface. Record the reading and location. Those grid point measurements are used to estimate average gross gamma and beta-gamma radiation levels on the tract of land.
5. Should further reduction in area of the survey block be indicated by initial beta-gamma maxima readings, divide those areas with a 10 m grid and repeat the measurements for the new grid intersections. Those areas most likely to require grid reduction are ore storage sites, building sites, areas adjacent to buildings, process sites, burial sites, and tailings pile site following removal.
6. Scan each grid block with a gamma scintillation survey meter. If a maximum point in the block is found, measure beta-gamma at the surface and gamma 1 m above the surface, recording the location.
7. If the beta-gamma and gamma measurements within a selected grid of no less than 50 survey blocks are homogeneous, determine the number n of surface soil samples (to 5-15 cm depth) selected by simple random sampling to adequately quantify the nuclides in the soil.
8. The number of samples needed to estimate the soil radionuclide mean m with a bound on the error of estimation of magnitude B at a 95% confidence level is found by setting two standard deviations of the estimator, y, (average beta-gamma) equal to B and solve for n.[8] [See also Appendix IV, Eq. (1).]
9. Should the variance of the measurements within a chosen survey unit be such as to demand a large number of soil samples by virtue of extensive and intensive variabilities

in nuclide concentrations over the site and environment, then stratified random sampling should be considered.

10. Intact tailings piles should be beta-gamma and gamma surveyed at 30 m intervals on 90° transaxial lines crossing the pile.
11. Subsurface soil and water sampling should be done in areas indicated by licensee records as having served as ore storage, refined source material storage, process, solid or liquid raffinate storage and burial sites.
12. Take several ^{222}Rn measurements not less than 1.5 km, 30° apart, downwind and also upwind from the mill site for comparison with the off-site integrated background measurements.
13. Water and sediment samples should be taken upstream, within or adjacent to the site and downstream from a stream suspected of receiving drainage from the site.

Table V-1. Grid block external gamma survey measurements at 1 m above the surface (in μR/h)[a]

17	12	12	34	22
11	17	4	17	12
11	13	40	21	
16	19	7	13	
16	16	12	8	
10	12	12	10	
11	10	10	17	
15	8	13	7	
15	10	30	17	
18	8	6	25	

[a]To convert μR/h to μGy/h, multiply by 0.01.

14. Water samples should be taken from wells within, adjacent to and remote from the site to determine if lateral transfer of radionuclides has occurred.
15. The location of all measurements and sampling sites should be adequately documented. The quantity of all samples taken should be sufficient to allow for triplicate analysis.

NRC Inspection of Mill Site for Decommissioning Compliance

As a preliminary to any action taken, the compliance inspector needs to become fully versed in the site's history, process, topography, its relation to the uncontrolled adjacent areas, equipment site location, decontamination and dismantling procedures and locations of areas with a high probability of contamination. A briefing on the mill's history should bring into focus events which may have a bearing on probable locations of contaminated areas (i.e., leaks, burial sites, settling basins, retention dam breaks and spills). An understanding of the nature of the soil underlying the site and of differential movement of nuclides through the type soil involved (e.g., sand, clay, loam) would indicate the probability for prior movement of radionuclides into the subsurface water supply. If, in the process of decontaminating and dismantling buildings and equipment, the contaminated material is buried on site at a depth not detectable by the surveyor, then the inspector should be in a position to address the situation. Knowledge of the area drainage profile and the prevailing wind direction should point out possible contaminated areas beyond the site boundaries. Since some of the mill sites were engaged, prior to and after milling source materials, in other types of materials, in other types of milling activities, the inspector needs advised to consider them also in his overview. Operational surveys and environmental monitoring reports developed when the mill was active is a source of excellent background information.

There is a possibility that one of two situations may exist at a decommissioned mill site, either the tailings pile has been moved to a remote pit or ravine for burial, or the tailings pile has been stabilized in place with a layer of uncontaminated earth, subject to restricted use. Also, the decontaminated buildings may have been removed or left intact. If the stabilized pile remains then the inspector does not need to be concerned with it since its use will be restricted.

The survey plan prepared by the licensee (or his radiological contractor) should be reviewed by the certification inspector and approved by his agency prior to the initiation of remedial action in the final stages of cleanup, and in few cases, after necessary reiteration of the process, where standards may not have been met. The certification inspector should emphasize review of the analytical techniques, quality assurance measures, and statistical bases for sampling. The licensee (or his radiological contractor) should incorporate comments and recommendations of the certification instructor to minimize the need for a completely independent radiological survey by the certification inspector.[4]

Prior agreements between the licensee and certification inspector can also reduce the need for an excessive number of duplicate or triplicate samples. The certification inspector will be concerned with samples obtained on a random basis from a reproducible grid system. Samples taken from biased areas such as "hot" spots indicated by field instrumentation or soil sampling for nuclides not detectable by field instrumentation will also be of interest as maxima to supplement average conditions. The certification inspector may need to observe field and laboratory techniques employed by the licensee or their contractor. Agreements about sample splits, replicate analyses of identical samples, and other details should be settled in advance of the remedial measure. It should be noted that state and local agencies may also be interested in analyzing split samples or of conducting non-destructive analyses on the same sample.

The certification inspector must retain his independence and integrity of results. This independence can be preserved without disrupting the schedule for backfilling excavated areas and without interfacing with the time schedule for completing remedial action, if the proper preliminary surveys are undertaken prior to beginning remedial action.

Otherwise, expensive subsurfaces sampling may become necessary if sampling is not done before filling in the excavation.

Relationships less than ideal may result from failure to incorporate the ideas of the certification inspector at an early stage. Results obtained by the certification inspector will determine whether or not the remedial action was successful. Consequently, the licensee should seek advice from the certification inspector when major changes in the survey plan are caused by discoveries during the decontamination process (e.g., a "hidden" subsurface layer of an unexpected radionuclide).

In evaluating the survey design to be followed in the decommissioning survey, the inspector should determine if the grid layout employed in measuring and sampling is of sufficient fineness to minimize the probability of missing "hot spots" of significance. Assessment surveys in the past[5-7] have adopted 30-50 m grids for outdoor areas known to be uniformly contaminated with the same distribution pattern of radionuclides. Other outdoor areas with a history of high contamination and nonuniform distribution such as building or process sites and areas adjacent to buildings would qualify for a grid structure of 3-10 m. In areas of marked nonuniformity (i.e., an order of magnitude difference) the measurement and sampling data should be treated on a stratified random sampling basis). See Section 6.1 for a realistic variance of the data from the mean of the surveyed area. Floors and walls within buildings may be treated on a 1 m grid basis, paying close attention to possible deposits of contaminants in drains and floor cracks, under floors, and on the top surface of overhead structural material.

The inspector, after having been satisfied that the survey design which was used by the surveyor provides the framework for a comprehensive survey, is then in a position to (1) address the appropiateness, the proper documentation, the adequacy of number and sensitivity of the measurements, and (2) to plan his own survey strategy. Since gamma measurements with a portable calibrated gamma scintillation survey instrument held 1 m above the outside surface can be made rapidly, and therefore cheaply, it is presumed all grid points were measured. They should be reported as μR/h. This preliminary survey is a means by which the licensee refined his plans for final sampling and beta-gamma measurements (alpha in the case of alpha emitters, unless correlation can be established for use of gamma as an indirect measurement of alpha, e.g., ^{241}Am for ^{239}Pu).

The inspector needs to evaluate the appropriateness of the instrument used to make the measurement in terms of type of activity, energy, interfering factors and instrument stability. The manner in which the measurement is made and the sample taken and prepared are factors that should be considered. One needs to ask, does the measurement or sample truly represent the condition at that point and surrounding location? The sensitivity of the instrument must be such as to cover the guideline values established for the particular radiological condition. In addition, the techniques and conditions for calibration of the instruments should be clearly identified and documented for the inspector's evaluation.

It is particularily important in evaluating the adequacy of the data to compare its form with that expressed in the decommissioning criteria. Should that not be possible, the inspector needs to determine if a pathway analysis has been properly addressed.

In keeping with the exercise of quality assurance throughout the licensee's decommissioning survey, the inspector is obligated to determine if the required level of confidence in the reported error has been adhered to in sampling statistics. When reporting laboratory analytical data, the need to express it in terms of range of variability and degree of confidence is self-evident. It is suggested that at least 10% of the samples be subjected to quality assurance audit.

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APPENDIX VI

COST-EFFECTIVENESS OF MONITORING

INTRODUCTION

Cost of Termination Survey

The cost of a termination survey is highly variable depending upon the number of measurements required and the number of samples requiring analysis. The cost of conducting a survey of a large, complex site will greatly exceed the cost for a survey of a small site which handled small quantities of a limited number of isotopes. Quoting an average or range of costs would not be very helpful for anyone contemplating a termination survey for a specific site. Consequently, this guide attempts to provide basic cost information which will allow calculation of the approximate total survey cost. Most of the cost information has been derived from FUSRAP experience[1] with sites that have not been cleaned up to ALARA (As-Low-as-Reasonably-Achievable) levels.

Major costs can be attributed to labor and materials. Additionally, one should plan for services such as analytical measurements, drilling and coring, land surveying, etc. For an offsite contractor, travel expenses could constitute a significant portion of the total costs.

The effort required to survey a one acre site without buildings is in the range of 3-6 person-weeks. A site of the same size with structures may require twice as much effort, particularly if alpha measurements are required.

Materials

Materials that will be required for performing a decommissioning survey, analyzing samples, interpreting the data and preparing a report include such things as sampling tools, sample containers, plastic bags, signs, labels, photographic film, protective clothing, etc. It is difficult to estimate the costs for a typical survey since costs are very dependent on the number and kind of samples, but it would be reasonable to assume $750–1000 (1980 dollars) for such materials. Other costs will far overshadow the costs of materials, thus an error in estimating material cost will have little bearing on the total estimated cost of the survey.

Instrumentation and equipment

Should it be necessary to acquire the instrumentation for performing a radiological survey and analyzing samples, additional large capital outlays would be required.

For a large, complex site such as a nuclear power plant, the following instrumentation and equipment may be required.

Portable survey instruments	$12,000
Laboratory detectors and electronics	7,500
Sample analysis systems	55,000
Sample preparation equipment	2,500
Miscellaneous supplies and equipment	3,000
	$85,000

Experience with FUSRAP[1] suggests that a mobile laboratory would be useful if not essential for surveying remote sites. Such a laboratory would cost a minimum of $25,000, assuming that it was supplied with instrumentation and equipment from the list above. If the mobile laboratory is to be instrumented independently, additional capital outlay could exceed $50,000.

Soil samples

The cost for obtaining surface soil samples is largely determined by labor cost. A relatively minor investment of a few hundred dollars will cover the cost of sampling tools for this type of sample. Obtaining subsurface soil samples requires additional effort and expenditures. Generally, this involves the procurement of a motorized drilling rig on some sort of contractural basis.

Drilling services are available on one of two general types of contractual arrangements:

1. Daily rate for rent of a rig and crew.
2. Footage rate for augering or coring.

Both types of contracts may call for a one time mobilization charge of $200–400. Daily rental rates for a simple drilling rig are $400–500. The cost for augering a hole in earth is generally in the range of $3.75–5.00 per ft while the cost of coring with a split-spoon sampler is $7.00–10.00 per ft. Costs are highly variable depending on the location and the figures mentioned are only for purposes of rough estimating. One should contact a local driller for specific costs.

Occasionally it is necessary to drill through asphalt, concrete, or some other barrier to reach the soil that needs to be sampled. Because such drilling requires specialized equipment, the costs are considerably higher than for soil sampling alone. In addition, it will generally be necessary to patch holes drilled in such barriers so as to restore the surface. This service may cost $25.00 per hole but is somewhat dependent on the number of holes requiring patching.

Analytical costs

Analytical costs are subject to a great deal of variability depending on the type of analysis that must be done, the number of samples requiring analysis, and the level of radioactivity to be assayed. Analysis of a sample for a single radionuclide may present little difficulty while analysis of the same sample for a large number of radionuclides would be difficult and, consequently, expensive. Also, some isotope quantifications are much easier (and cheaper) than others. The sample medium makes some difference (e.g., water samples can generally be analyzed with less cost than soil samples for the same radionuclides).

It will not be possible to present costs for all analytical services for all types of samples. Instead, this report lists a few representative analyses for the types of samples generally encountered in radiological surveys. Table VI-1 gives estimates of sample analysis costs for sample lots of ten each. A smaller number of samples of any type would result in higher per sample costs. Similarly, a significantly larger number of samples may lead to some economy of scale.

The actual number of samples will be dictated by the statistical accuracy and confidence limits required.

Land surveying

A minimum land survey would consist of surveying the site boundaries and establishing a baseline for locating sampling sites. Based on a 20-acre site, the fee for such a survey would be approximately $3,000. If the location of core holes needed to be documented by additional

Table VI-1. Estimate of sample analytical costs

Sample type	Analysis	Cost/$ sample (1980)
Water	Total uranium, ^{227}Th, ^{230}Th, ^{210}Po, ^{226}Ra	300
Sediment	Dissolved uranium, ^{230}Th, ^{226}Ra	125
	Uranium, ^{226}Ra, ^{230}Th, ^{210}Pb	250
Soil	Total uranium, ^{227}Th, ^{230}Th, ^{210}Po, ^{210}Pb, ^{226}Ra	350
	^{226}Ra only	75
Air	Radon (^{222}Rn)	50
	Uranium, ^{230}Th, ^{210}Pb, ^{226}Ra	250

survey work, the cost for the same size site could escalate to $6,000–8,000 depending on the number of core holes that needed to be located. Land survey work generally costs $40–50 per hour.

Report preparation

After the site has been surveyed, samples collected and analyzed, the data must be evaluated and presented in a report which documents the findings of the survey. Details of what goes in the report and how the data may be presented are contained in Section 3.6 on Documentation.

The labor associated with report preparation can be broken down as follows:

	Person-weeks
Engineer	4
Graphic arts	1
Technical writer/editor	3
Clerical	2
	10

Costs for these services vary, but for the purpose of estimating, may be assumed as shown in Table VI-2.

In addition to the cost of labor, the cost of materials, such as paper and film, and services, such as printing or copying, must be added.

Dependence on Specific Decommissioning Criteria

In general, standards for acceptable levels of residual contamination of radioactive material have not been established for nuclear sites which are to be decommissioned and released for unrestricted use. Any standard finally established should be applicable to all nuclear fuel cycle sites. Since facilities to be decommissioned have differing radionuclide spectra, it will be necessary to establish a standard in terms of a value which is not radionuclide dependent. However, once the radionuclide spectrum has been determined qualitatively and quantitatively through environmental sampling, radiological surveying or by experience with specific facility types, it should be possible to ascertain whether compliance with the standard has been achieved.

Table VI-2. Labor costs for preparation of survey report

Labor category	Time (hrs)	Rate ($/hr)	Amount[a]
Engineer	160	18.75	$3,000
Graphic artist	40	10	400
Technical editor/writer	120	10	1,200
Clerical	80	5	400
Total	400		$5,000

[a]1980 dollars.

Note: Costs in this appendix are illustrative only, since exact figures depend on variable factors such as inflation rate and local labor conditions.

A standard that meets the characteristics proposed above is one that specifies an annual dose equivalent limit. Then a facility and site or portions thereof may be deemed acceptable for unrestricted use if the exposure from all significant pathways to a realistically exposed individual does not exceed this limit.

While there is some disagreement over the exact dose limit which should and can be imposed, suggested values seem to lie in the range of 1-25 mrem/y. For a number of radionuclides and pathways to man, this dose range is close to that which can be measured with currently available instrumentation and monitoring procedures.

The choice of a termination survey depends on the choice of specific decommissioning criteria; in particular, that of dose limit to be used. The costs for performing a survey at three different levels: 1 mrem/y, 5 mrem/y, and 25 mrem/y have been estimated. In general, the costs increase with decreasing dose limits and the cost can be very high for a survey near the state-of-the-art detection limits at high confidence levels. There will exist a dose limit so low, that no expenditure is sufficient to produce a satisfactory confirmation that the residual levels of radioactive contamination would result in a dose of the prescribed magnitude or less. Counting longer using a more sensitive and discriminating detector, or taking more samples all have theoretical limits individually and in combination relative to the ability for distinguishing between background and near background levels of residual radioactivity.

Detection sensitivities listed in Table 4.1 reflect the capabilities of national laboratories and some of the better equipped commercial analytical laboratories for routine measurement. Regulatory Guide 4.8 lists the following detection limits in terms of lower limit of detection (LLD) for nuclides of reactor site interest (Table VI-3). Detection sensitivities for these and additional nuclides can be furnished by commercial radioanalytical laboratories. From the sparse data given, it would seem that a more intensive compilation and critique of detection sensitivities is needed.

Table VI-3. Detection sensitivities (lower limits of detection) for environmental sample analysis

Nuclide	Soil pCi/g dry wt	Soil milliBq/g dry wt	Water pCi/liter	Water milliBq/liter
^{134}Cs, ^{137}Cs	0.15	5.55	15	555
^{58}Co, ^{60}Cs	--	--	15	555
^{90}Sr	0.15	5.55	2	74
^{54}Mn	--	--	15	555

Table VI-4. Critical radionuclides at selected nuclear fuel cycle facilities

Facility	Critical radionuclides
Light water reactor	^{54}Mn, ^{60}Co, ^{90}Sr, ^{134}Cs, ^{137}Cs
Mixed oxide fuel fabrication	^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am
UO_2 fuel fabrication	^{234}U, ^{235}U, ^{236}U, ^{238}U
Low level waste burial	^{54}Mn, ^{60}Co, ^{134}Cs, ^{137}Cs

Fortunately, for many nuclear facilities the really critical nuclides can be narrowed down to very few which result in the largest percentage (>75%) of potential individual exposures occurring via the important pathways. Table VI-4 identifies such nuclides for several types of facilities. Monitoring is then reducible in scope to a consideration of the few critical nuclides. Although these few critical nuclides can be identified by operational quantities involved, radiological half-lives, holdup times according to soil characteristics, resuspension potential, etc., confirmatory qualitative and quantitative spectral analysis on preliminary soil and water samples are needed before launching into the final survey. For reactor sites, the background problem is primarily one of differentiating reactor-generated long-lived nuclides from those same nuclides deposited on the site from global weapons testing fallout. Natural background from ^{40}K and the uranium/thorium decay series can be differentiated and compensated for by standard stripping technique and application of correction factors to gross gamma and beta observations.

Survey Cost for the Reference Reactor Site

Radiological survey

A termination survey was described in Appendix IV for the reference reactor site. The major elements of a radiological survey consist of instrumental surveys of buildings and land areas and collection of appropriate samples (soil, air, water, etc.). The land (or site) survey is further broken down into three or more distinct survey units with different degrees of measurement intensity. Much of the cost associated with these efforts is labor. Several competent radiation surveyors would be employed to take the instrument readings, and collect the samples. Estimated labor is summarized in Table VI-5. The methods of determining average and maximum contamination levels are discussed in Appendix IV. A scan consists of essentially 100% coverage of the respective survey unit at least in high probability areas and for small sites (<10 acres). Logging was placed under sampling but is meant to cover instrument readings made in augered holes on the site.

Table VI-5. Labor involved in radiological survey of reference reactor site

Activity	Labor purpose	Hours	
		1 mrem/y[a]	5-25 mrem/y[a]
Building survey	Average	672	672
	Scan/maximum	750	750
	Smears	227	
Survey unit 1	Average	301	301
	Scan/maximum	384	384
Survey unit 2	Average	641	30
	Scan/maximum	816	105
Survey unit 3	Average	2,300	256
	Scan/maximum	7,667	1,703
Sampling	Surface soil	60	60
	Subsurface soil	22.5	22.5
	Logging	40	40
	Air, water, etc.	10.5	10.5
		17,363[b]	5,701[b]

[a]To convert from mrem/y to mSv/y multiply by 0.01.

[b]A 25% contingency is added.

In addition to survey labor, costs will include fringe benefits, administration (including supervision) and overhead. It has been assumed that the licensee or an on-site contractor performed the radiological survey. Should an off-site contractor be used, travel and per diem costs would have to be added. A 25% contingency can be added to labor cost estimates to cover unknowns.

Materials

Materials are not generally a major cost item in a termination survey. Materials are required in the field to take samples, and in the laboratory to prepare and store samples. Other traditional radiation protection materials and supplies will be required. In the preparation of the documentation, photographic and stationary supplies will be required. An estimate of the cost of total materials is $2000 for the termination survey at the reference reactor site.

Services

Several different kinds of services will be required to complete the termination survey. The most significant costwise are:

1. Drilling, including augering, coring, and land restoration.
2. Land surveying, including location of property boundaries, layout of grid network, and location of core holes and other sampling points.

Report Preparation

About 10 man-weeks of labor will be required to prepare a report documenting the results of the termination survey of a reference reactor site.

Sample Preparation

In some cases, observations (instrument readings) are taken in the field while in other cases considerable off-site preparation must be done. Smear samples generally are counted with no special preparation.

Water and air samples may require special preparation. Soil samples almost always require preparation prior to analysis.

Soil generally is dried, ground, and sieved as a minimum amount of preparation. This usually involves handling the soil several times and results in labor costs. Depending on the type of analysis that follows, additional preparation may be required. As a minimum, the sample must be placed in an appropriate container for counting. On the average, it is anticipated that soil sample preparation will require 30 min/sample at a cost approximately $25 per sample. For the total 234 soil samples (144 surface samples and 90 subsurface samples) taken at the reference reactor site, the cost for sample preparation would be approximately $5,850.

Sample Analysis

Soil, water, air, and smear samples that were collected during the termination survey, will require laboratory analysis. The cost for analytical work will depend on the number of samples and the level of radioactivity in each sample. As the level of radioactivity approaches the minimum detection limits (MDL), the cost goes up and the precision of the measurement goes down (see Table VI-6). It would appear that the practical MDL for competent commercial analytical laboratories precludes the measurement of all but ^{137}Cs at the residual levels predicted to lead to 1 mrem/y (see Table VI-6). The costs for analysis of the critical radionuclides in the reactor site soil samples are given in Table VI-6.

From the previous section, it was determined that approximately 144 surface soil samples and 90 subsurface soil samples would be required based on assumed site characteristics. It would be appropriate at the 5 mrem/y (0.05 mSv/y) level to assume that these samples could be counted at above the MDL at a cost of about $53 each or a total of $12,400. Should the decommissioning criteria be relaxed to 25 mrem/y, the analytical costs would be approximately $9,360.

Table VI-6. Cost of soil sample analysis

Concentration in soil (pCi/g)[a]	Nuclides	Cost/sample (1980 dollars)
5E-2[b]	^{60}Co, ^{90}Sr, ^{137}Cs	80-100
1E-1[c]	^{60}Co, ^{90}Sr, ^{137}Cs	45-60
1E0[d]	^{60}Co, ^{90}Sr, ^{137}Cs	35-45

[a] To convert from pCi/g to mBq/g, multiply the former by 37.

[b] Considered minimum detection limit (giving ±100% error) for competent commercial analytical laboratories using standard procedures.

[c] This concentration should be measurable with a ±50% error.

[d] This concentration should be measurable with a ±10-20% error.

Summary of Costs

Cost elements include labor for surveys (based on $10/hr), fringe benefits, administration and overhead on the labor, materials and services. These costs are summarized in Table VI-7. The value of $10/hr in 1980 dollars may be low by a factor of at least two, depending on local labor and related costs of travel, lodging and meals.

Table VI-7. Summary of costs in 1980 dollars for termination survey of reference reactor site

Element of cost	Cost		
	1 mrem/y	5 mrem/y	25 mrem/y
Labor			
Radiological survey	173,630	57,010	57,010
Report preparation	5,000	5,000	5,000
Fringe benefits @25%	44,657	15,502	15,502
Administration @15%	26,794	9,301	9,301
Overhead @31%	55,375	19,223	19,223
Materials[a]	2,000	2,000	2,000
Services			
Drilling (auger, coring, restoration)	6,100	6,100	6,100
Land surveying	10,000	8,000	8,000
Analytical	26,910	18,250	15,210
Total	$350,466	$140,386	$137,346

[a]Exclusive of instruments and equipment.

REFERENCES FOR APPENDIX VI

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APPENDIX VII

ON THE PROBABILITY OF MISSING HOT SPOTS IN A PRELIMINARY, FINAL, OR CERTIFICATION SURVEY

STATEMENT OF THE PROBLEM

Given an 0.08 km^2 site (20 acres) which has been declared clear of radioactive materials by the licensee, assume a radiological survey will be conducted to verify that the site is indeed "clean" or "safe." The site is partitioned into square blocks (e.g., 3 m × 3 m). The number of blocks on the site, denoted by N, is known. The area surrounding a site is referred to as background. For the background, a single number is compiled, which is the number of microRoentgens per hour (μR/h) for the background. Denote this number by "B," for Background.

Definition of "hot spot"

The ith block on the site will be called a hot spot if the maximum number of μR/h for the ith block exceeds kB where k is a constant to be defined by 10CFR, for example, the value 2. The number of hot spots for the site is denoted by H. The expectation is to identify all hot spots and to eliminate them. This could be done by checking each and every block (systematic sampling). Such a complete survey would be expensive and time-consuming. If sampling, n, of block, N, is to be used, the problems becomes one of estimating the number of hot spots. A 10% or 20% sample, for example, would be less expensive and results can be obtained more rapidly. With sampling, only a fraction of the site is surveyed and there is the potential for missing some hot spots. In the next section, a Bayesian model is presented for measuring the probability of missing hot spots.

Model for determining the probability of missing hot spots

Assume a finite population of size N and a Bayesian approach. The population contains an unknown number of hot spots, H. Then, H is taken to be a random variable with some prior distribution which it is assumed a statistician can specify after discussion with the survey designer. The surveyor and/or designer gives the statistician a subjective evaluation on possible values of H. A convenient family of "prior" distributions for H[1-3] is the beta-binomial distribution. This family is convenient because it permits a wide variety of shapes for the distribution of H and also because the mathematics is tractable. The general beta-binomial distribution can be given by

$$f_1(H|\alpha,\beta,N) = \binom{N}{H} \frac{B(H + \alpha,\ N - H + \beta)}{B(\alpha,\ \beta)} \quad \text{for } H = 0,\ 1,\ \ldots,N \tag{1}$$

where $B(\alpha,\ \beta) = \int_0^1 t^{\alpha-1}\ (1-t)^{\beta-1}dt$ for $\alpha > 0$ and $\beta > 0$.

The values of α and β are chosen to represent the state of prior knowlege about H. Three examples are treated in the following section.

With $f_1(H|\alpha,\beta,N)$ as the prior distribution, a random sample of size n is taken and h, the number of hot spots in the sample, is determined. The parameter h has the hypergeometric distribution given by

$$f_2(h|H) = \frac{\binom{H}{h}\binom{N-H}{n-h}}{\binom{N}{n}} \quad \text{for } h = 0,\ 1,\ \ldots,n \tag{2}$$

(Note that the distribution of h is dependent on H.)

The next step is to find $f_3(H|h)$ which is the "posterior" distribution of H. That is, $f_3(H|h)$ utilizes subjective experience about the distribution of H after obtaining the sample information. It can be shown[3] that $f_3(H|h)$ is given by

$$f_3(H|h) = \binom{N-n}{H-h} \frac{B(H + \alpha,\ N - H + \beta)}{B(h + \alpha,\ n - h + \beta)} \tag{3}$$

for $H = h,\ h + 1,\ldots,\ N - n + h$. The probability distribution given in Eq. (3) can be used to help one determine the probability of missing a specific number of hot spots in the unsampled population.

Assume that the random sample of size n contains $h = h_0$ hot spots. Having observed h_0 hot spots, there are at least h_0 hot spots on the entire site and no more than $N - (n-h_0)$. Thus, given that h_0 hot spots have been observed in the random sample of size n, the probability that there are exactly H_L hot spots left in the unsampled population is:

P (missing exactly H_L hot spots given $h = h_o$)

$$= P(H = H_L + h_o | h = h_o)$$

$$= f_3(H_L + h_o | h_o)$$

$$= \binom{N-n}{H_L} \frac{B(H_L + h_o + \alpha, N - H_L - h_o + \beta}{B(h_o + \alpha, n - h_o + \beta} \qquad (4)$$

Also

P (missing more than H_{L_o} hot spots given $h = h_o$)

$$= P(H > H_{L_o} + h_o | h = h_o)$$

$$= \sum_{H_L = H_{L_o} + 1}^{N-n} f_3(H_L + h_o | h_o) \qquad (5)$$

Numerical examples

Three examples will illustrate the content of the previous section. In all three cases, assume that the site to be verified contains N = 1000 blocks. The three different prior distributions for H to be considered are $f_1(H|1,1,1000)$; $f_1(H|1,500,1000)$; and $f_1(H|1,1000,1000)$. Their histograms are given in Figs. VII-1, VII-2, and VII-3.

The prior distribution in example I is a uniform prior distribution. This prior distribution is often used[4] by Bayesian statisticians as that prior distribution which is appropriate when one does not know the values of H, i.e., there is no strong (or weak) evidence to indicate that the probability of any one particular value of H is greater than another. The prior distribution in example II suggests an initial feeling, or

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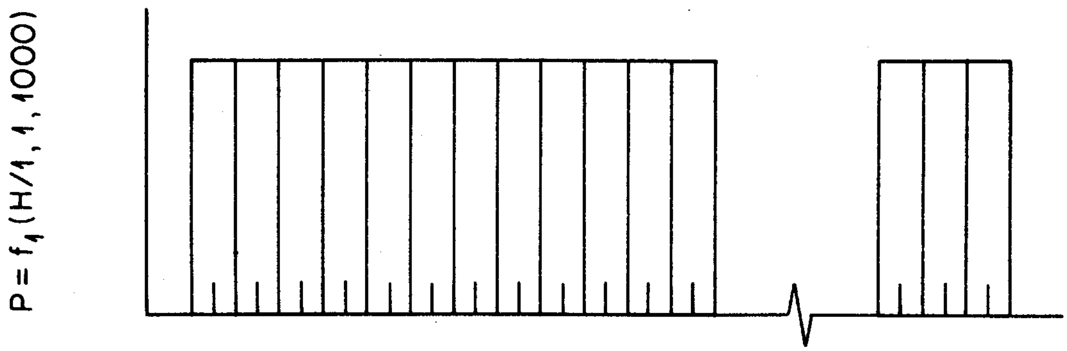

Fig. VII-1. Example I (Uniform Prior Distribution)
N = 1,000 survey blocks
H = Number of hot spots - completely unknown

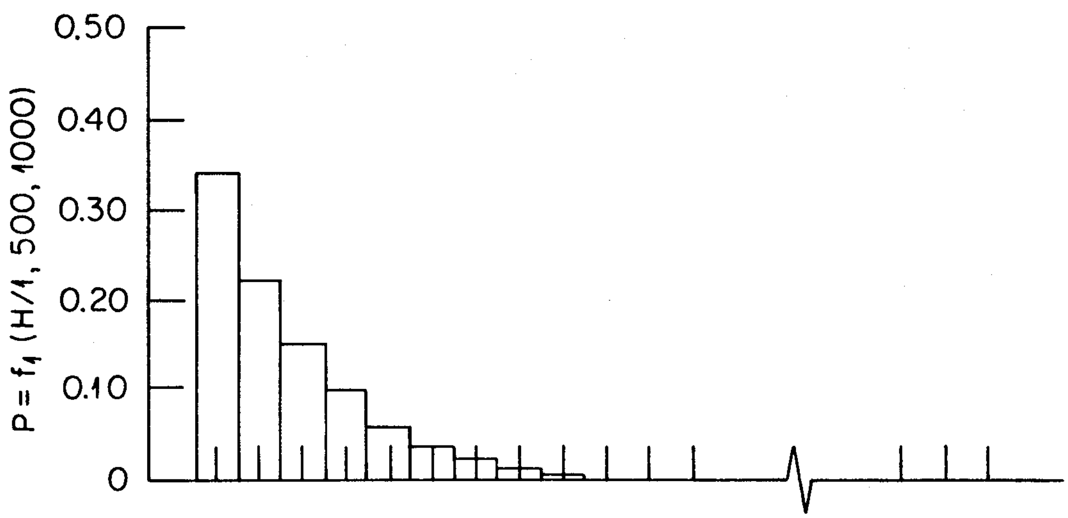

Fig. VII-2. Example II (Skewed Prior Distribution)
N = 1,000 survey blocks
H = Number of hot spots probably less than 9 from prior information

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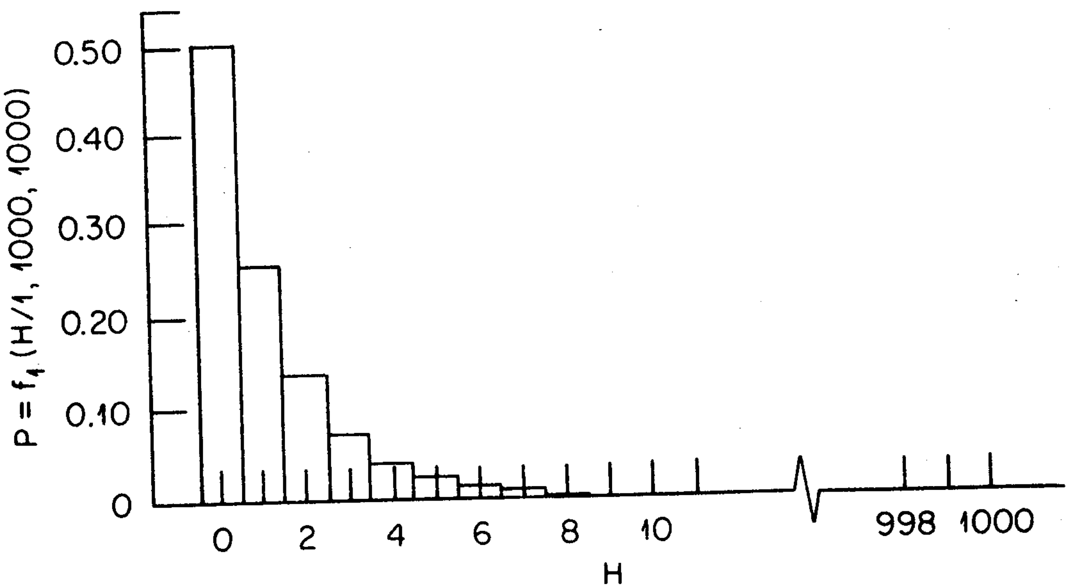

Fig. VII-3. Example III (Skewed Prior Distribution)
N = 1,000 survey blocks
H = Number of hot spots definitely less than 9 from prior information

reason to believe, that H is a small (less than 9) number. The prior distribution in example III suggests an even stronger initial feeling that H is a small number.

Tables on the probability of missing more than H_L hot spots given h_0 in the sample are shown in Tables VII-1 through VII-9 for the three examples. The corresponding graphs are given in Figs. VII-4 through VII-12.

Concluding remarks

The use of sampling techniques in the decommissioning of sites should be encouraged because of reduced cost, greater speed, greater scope, and greater accuracy.[5] However caution should be taken because by sampling there is the finite chance of missing some hot spots, especially for weaker gamma emitters in the soil, or where attenuated by shielding.

The purpose of this Appendix VII has been to present a model for determining the probability of missing hot spots. The model should not be viewed as a final result or "the answer," but as a first step toward the consideration of this important issue. Further research is needed, and the following related questions need addressing:

1. Are there other models which are applicable?
2. How does one determine the prior distribution, and what information is needed if the Bayesian model presented here is used?
3. How does a change in blocksize affect the probability of missing hot spots?
4. What is an appropriate sample size?
5. What about the stratification issue?
6. Can one use techniques which would make use of sample surveys and censuses?[6]

Of equal importance to the probability of missing one or more long-lived hot spots on a cleaned-up site is the potential hazard significance of missing such hot spot(s) after some of the radioactive atoms have passed through the food chain to man.

Table VII-1. The probability of missing more than three hot spots given h_o hot spots in a sample size n (Example I)

h_o / n	0	1	2	3
10	0.9566993	0.9989208	0.9999806	0.9999997
20	0.9185696	0.9959616	0.9998468	0.9999952
50	0.8109947	0.9769355	0.9977614	0.9998126
100	0.6530416	0.9176643	0.9840857	0.9973032
150	0.5193687	0.8340113	0.9524762	0.9879561
200	0.4073501	0.7358451	0.9007523	0.9667151
300	0.2385247	0.5265725	0.7434760	0.8738361
400	0.1285652	0.3354043	0.5430741	0.7096274
500	0.0618765	0.1862503	0.3423419	0.4989041

Table VII-2. The probability of missing more than five hot spots given h_o Hot spots in a sample size n (Example I)

h_o / n	0	1	2	3
10	0.9356946	0.9977608	0.9999462	0.9999990
20	0.8802621	0.9917325	0.9995825	0.9999831
50	0.7301069	0.9546423	0.9941732	0.9993750
100	0.5273724	0.8485661	0.9616625	0.9917304
150	0.3738939	0.7143440	0.8941592	0.9661094
200	0.2595934	0.5742362	0.7958156	0.9142293
300	0.1161911	0.3270867	0.5498637	0.7287435
400	0.0459126	0.1569335	0.3133010	0.4808488
500	0.0152988	0.0615183	0.1428905	0.2519331

Table VII-3. The probability of missing more than seven hot spots given h_o hot spots in a sample size n (Example I)

$n \backslash h_o$	0	1	2	3
10	0.9151099	0.9962073	0.9998861	0.9999975
20	0.8434791	0.9661826	0.9991294	0.9999569
50	0.6571442	0.9271491	0.9883901	0.9984837
100	0.4256934	0.7720784	0.9292087	0.9815326
150	0.2689731	0.5961831	0.8188311	0.9304172
200	0.1652638	0.4328814	0.6756796	0.8381984
300	0.0565010	0.1935145	0.3799744	0.5675005
400	0.0163517	0.0691779	0.1650318	0.2936753
500	0.0037672	0.0189728	0.0534611	0.1113477

Table VII-4. The probability of missing more than three hot spots given h_o hot spots in a sample size n (Example II)

$n \backslash h_o$	0	1	2	3
10	0.1893560	0.4475687	0.6673518	0.8168161
20	0.1818091	0.4345919	0.6539802	0.8061130
50	0.1605172	0.3965719	0.6132844	0.7722649
100	0.1292541	0.3366137	0.5443201	0.7105964
150	0.1027967	0.2814542	0.4753483	0.6435456
200	0.0806253	0.2315283	0.4079183	0.5727377
300	0.0472103	0.1481949	0.2831226	0.4272621
400	0.0254464	0.0866812	0.1787381	0.2894036
500	0.0122470	0.0449930	0.0996974	0.1727831

Table VII-5. The probability of missing more than five hot spots given h_o hot spots in a sample size n (Example II)

h_o / n	0	1	2	3
10	0.0822279	0.2506466	0.4516097	0.6340749
20	0.0773566	0.2389045	0.4354562	0.6174291
50	0.0641611	0.2058824	0.3882786	0.5669257
100	0.0463450	0.1580196	0.3148354	0.4824419
150	0.0328574	0.1186299	0.2491269	0.4002655
200	0.0228128	0.0869452	0.1920356	0.3231403
300	0.0102108	0.0430164	0.1044639	0.1921047
400	0.0040348	0.0186182	0.0493529	0.0986822
500	0.0013444	0.0067438	0.0193888	0.0419441

Table VII-6. The probability of missing more than seven hot spots given h_o hot spots in a sample size n (Example II)

h_o / n	0	1	2	3
10	0.0356580	0.1331680	0.2829645	0.4532030
20	0.0328669	0.1245065	0.2680506	0.4343949
50	0.0256062	0.1011204	0.2262432	0.3796374
100	0.0165875	0.0699522	0.1664273	0.2954925
150	0.0104808	0.0470089	0.1185585	0.2222815
200	0.0064396	0.0306099	0.0816009	0.1612244
300	0.0022016	0.0116455	0.0344192	0.0750756
400	0.0006372	0.0037119	0.0120546	0.0288147
500	0.0001468	0.0009339	0.0033071	0.0086055

Table VII-7. The probability of missing more than three hot spots given h_o hot spots in a sample size n (Example III)

n \ h_o	0	1	2	3
10	0.0598534	0.1809997	0.3341784	0.4890471
20	0.0574680	0.1749376	0.3249395	0.4781009
50	0.0507378	0.1575008	0.2978445	0.4453674
100	0.0408559	0.1309190	0.2549532	0.3915526
150	0.0324930	0.1073766	0.2151977	0.3393489
200	0.0254848	0.0867710	0.1788538	0.2895010
300	0.0149227	0.0537994	0.1170838	0.1994740
400	0.0080433	0.0306099	0.0701720	0.1256463
500	0.0038712	0.0155079	0.0373668	0.0702101

Table VII-8. The probability of missing more than five hot spots given h_o hot spots in a sample size n (Example III)

n \ h_o	0	1	2	3
10	0.0145982	0.0589638	0.1375775	0.2436587
20	0.0137334	0.0558839	0.1313128	0.2341062
50	0.0113907	0.0473795	0.1136778	0.2066908
100	0.0082278	0.0354611	0.0880216	0.1652792
150	0.0058333	0.0260187	0.0667490	0.1293439
200	0.0040500	0.0186740	0.0494666	0.0988501
300	0.0018127	0.0089037	0.0250800	0.0531880
400	0.0007163	0.0037338	0.0111474	0.0250219
500	0.0002387	0.0013160	0.0041520	0.0098391

Table VII-9. The probability of missing more than seven hot spots given h_o hot spots in a sample size n (Example III)

h_o / n	0	1	2	3
10	0.0035532	0.0179656	0.0508333	0.1063286
20	0.0032750	0.0166909	0.0475890	0.1002763
50	0.0025515	0.0133111	0.0388210	0.0836022
100	0.0016529	0.0089547	0.0270919	0.0604499
150	0.0010444	0.0058677	0.0183937	0.0424804
200	0.0006417	0.0037341	0.0121145	0.0289313
300	0.0002194	0.0013647	0.0047275	0.0120387
400	0.0000635	0.0004205	0.0015492	0.0041924
500	0.0000146	0.0001027	0.0004013	0.0011504

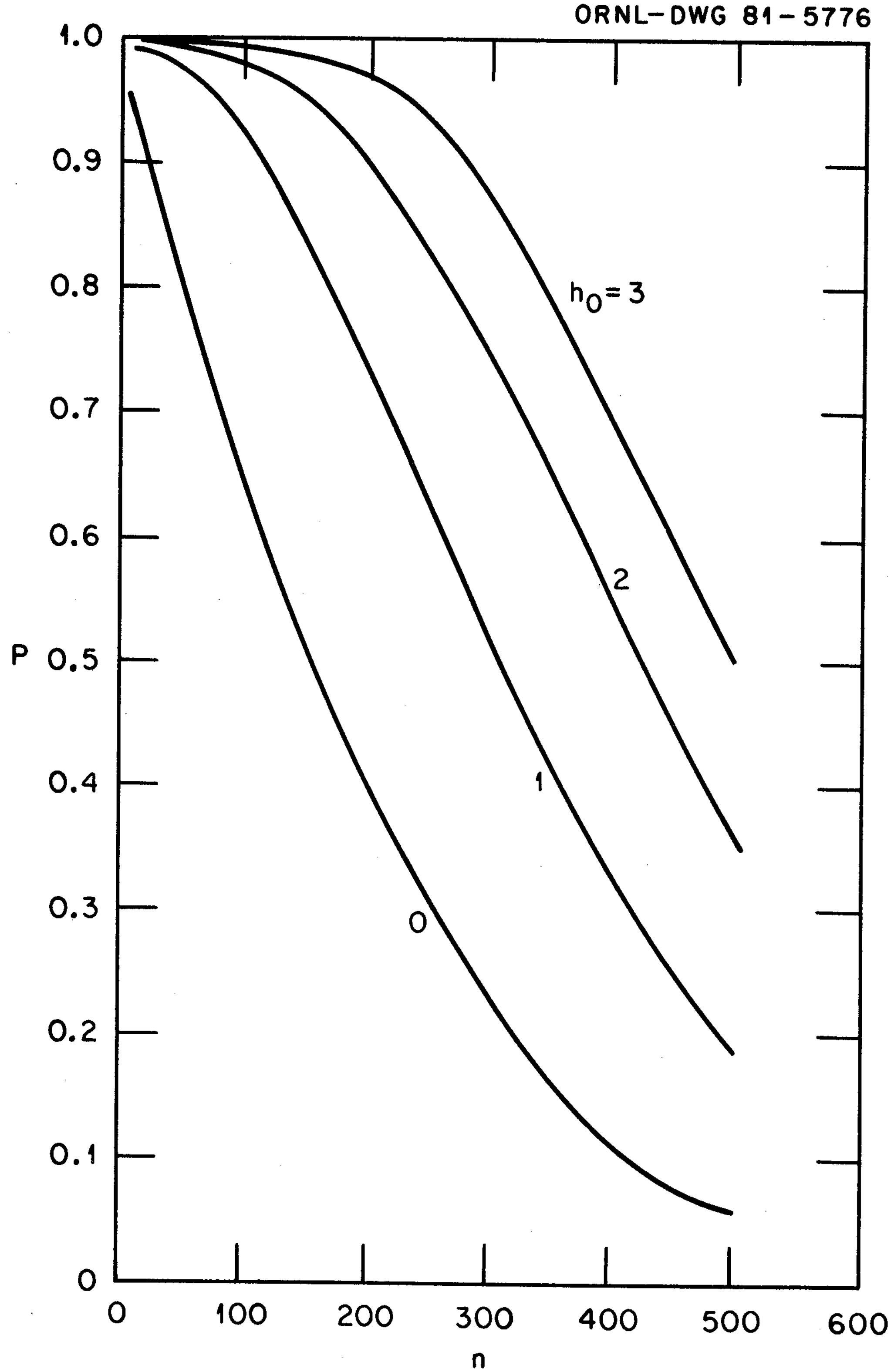

Fig. VII-4. The Probability (P) of Missing More than Three Hot Spots on a "Cleaned-Up" Site, Given h_o Hot Spots Found in a Sample Size n (see Fig. 1).

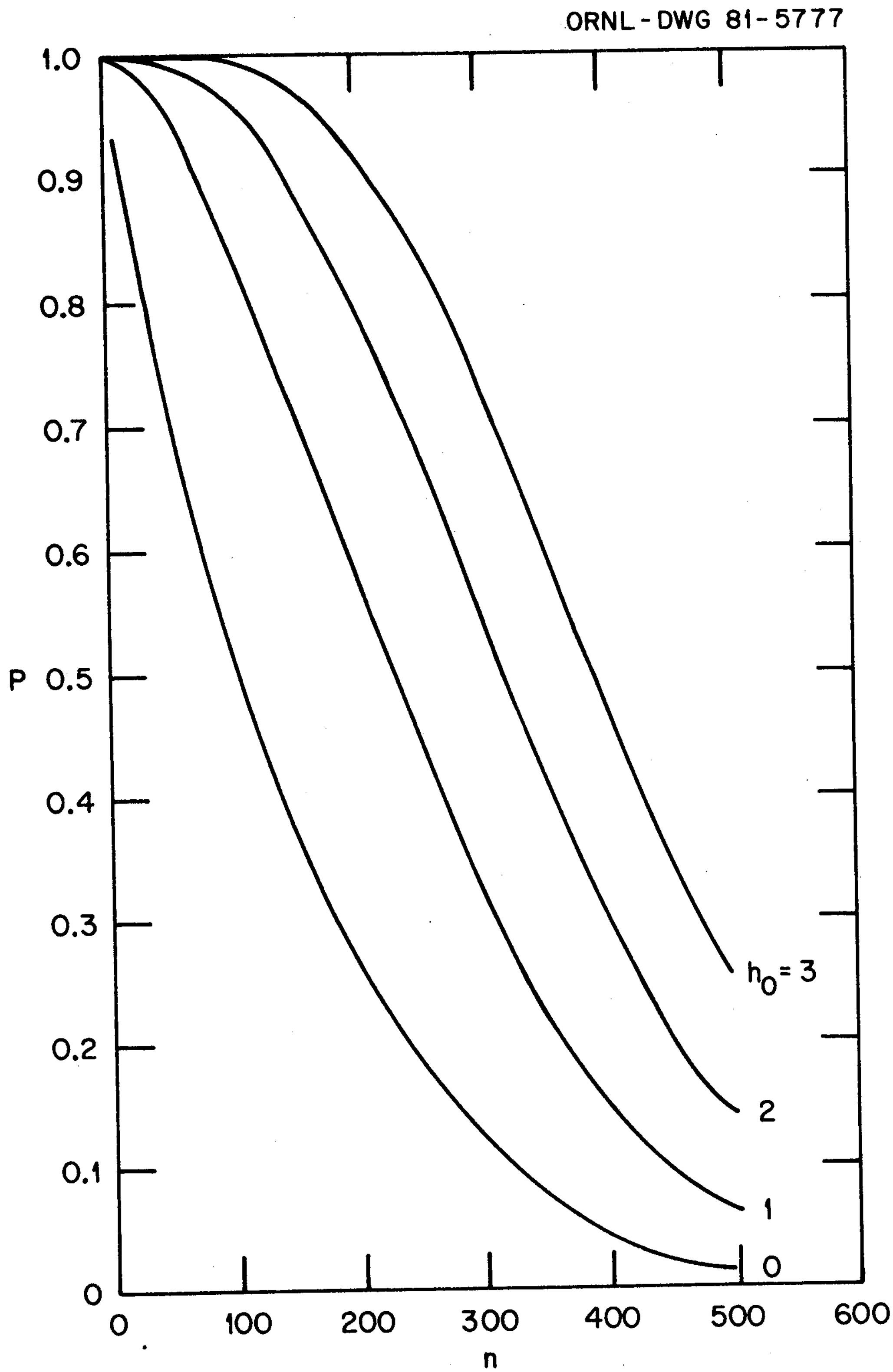

Fig. VII-5. The Probability (P) of Missing More than Five Hot Spots on a "Cleaned UP" Site, Given h_0 Hot Spots Found in a Sample Size n (see Fig. 1).

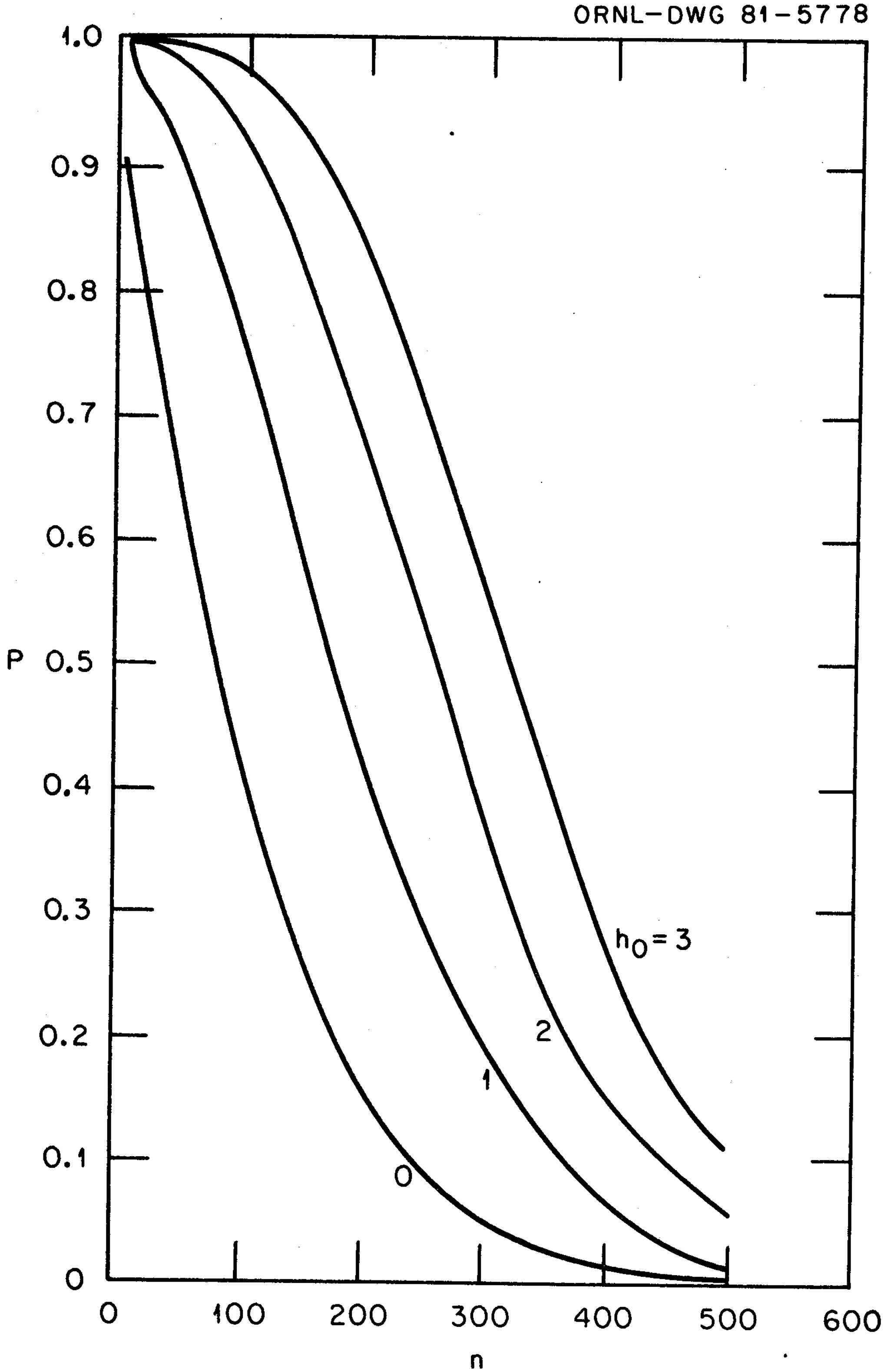

Fig. VII-6. The Probability (P) of Missing More than Seven Hot Spots on a "Cleaned-UP" Site, Given h_o Hot Spots Found in a Sample Size n (see Fig. 1).

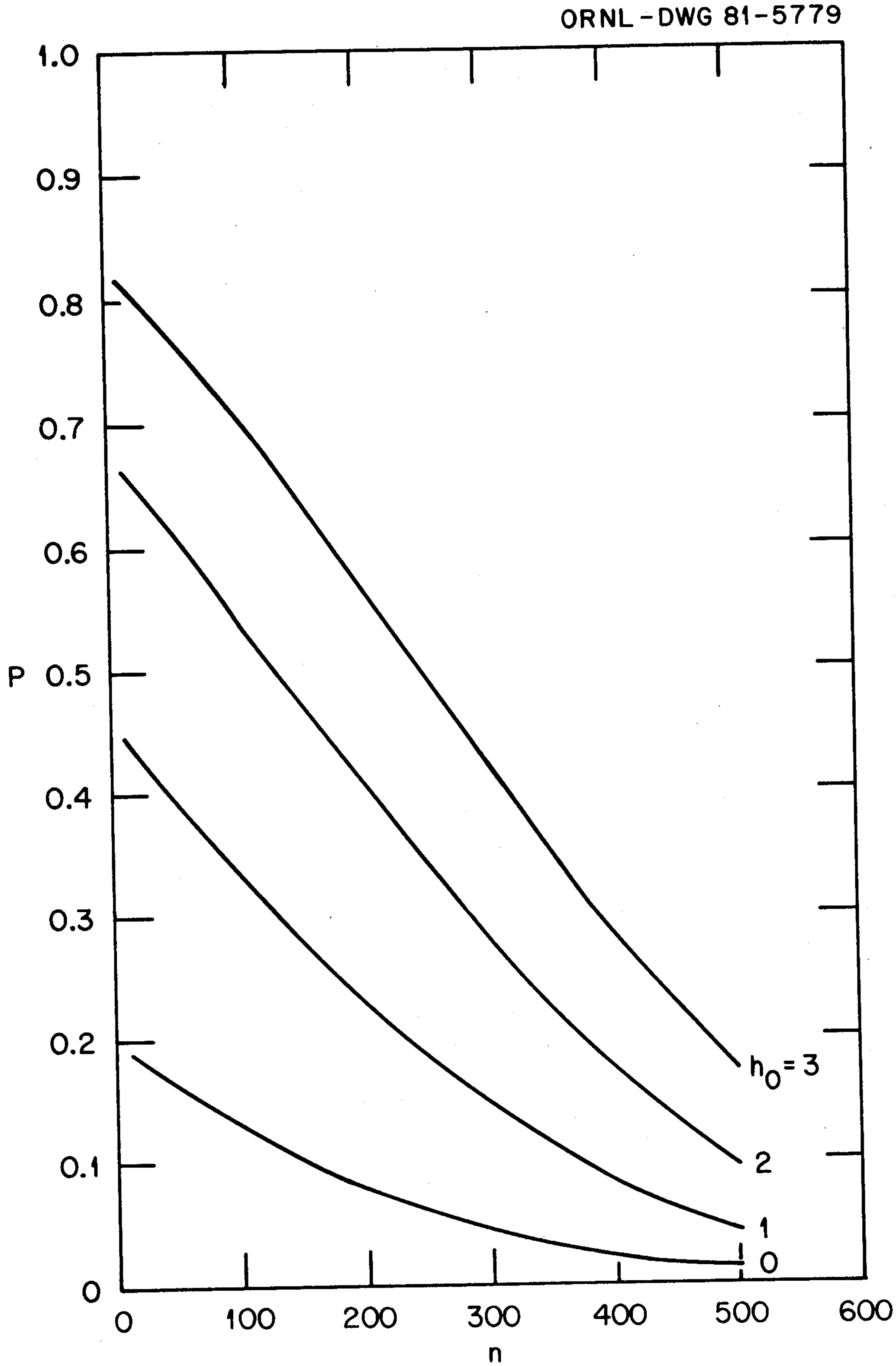

Fig. VII-7. The Probability (P) of Missing More than Three Hot Spots on a "Cleaned-Up Site, Given h_0 Hot Spots Found in a Sample Size n (see Fig. 2).

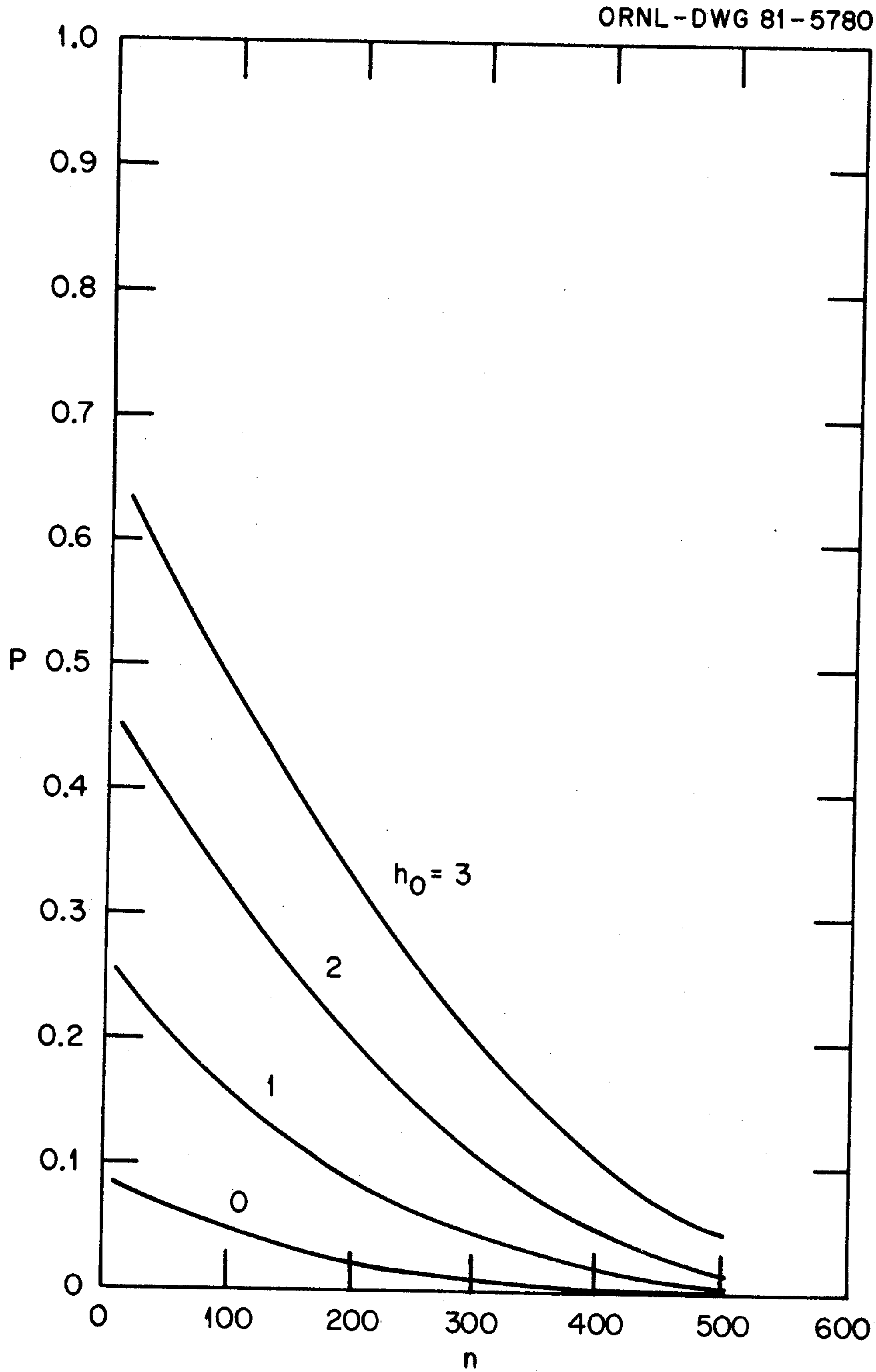

Fig. VII-8. The Probability (P) of Missing More than Five Hot Spots on a "Cleaned-Up" Site, Given h_o Hot Spots Found in a Sample Size n (see Fig. 2).

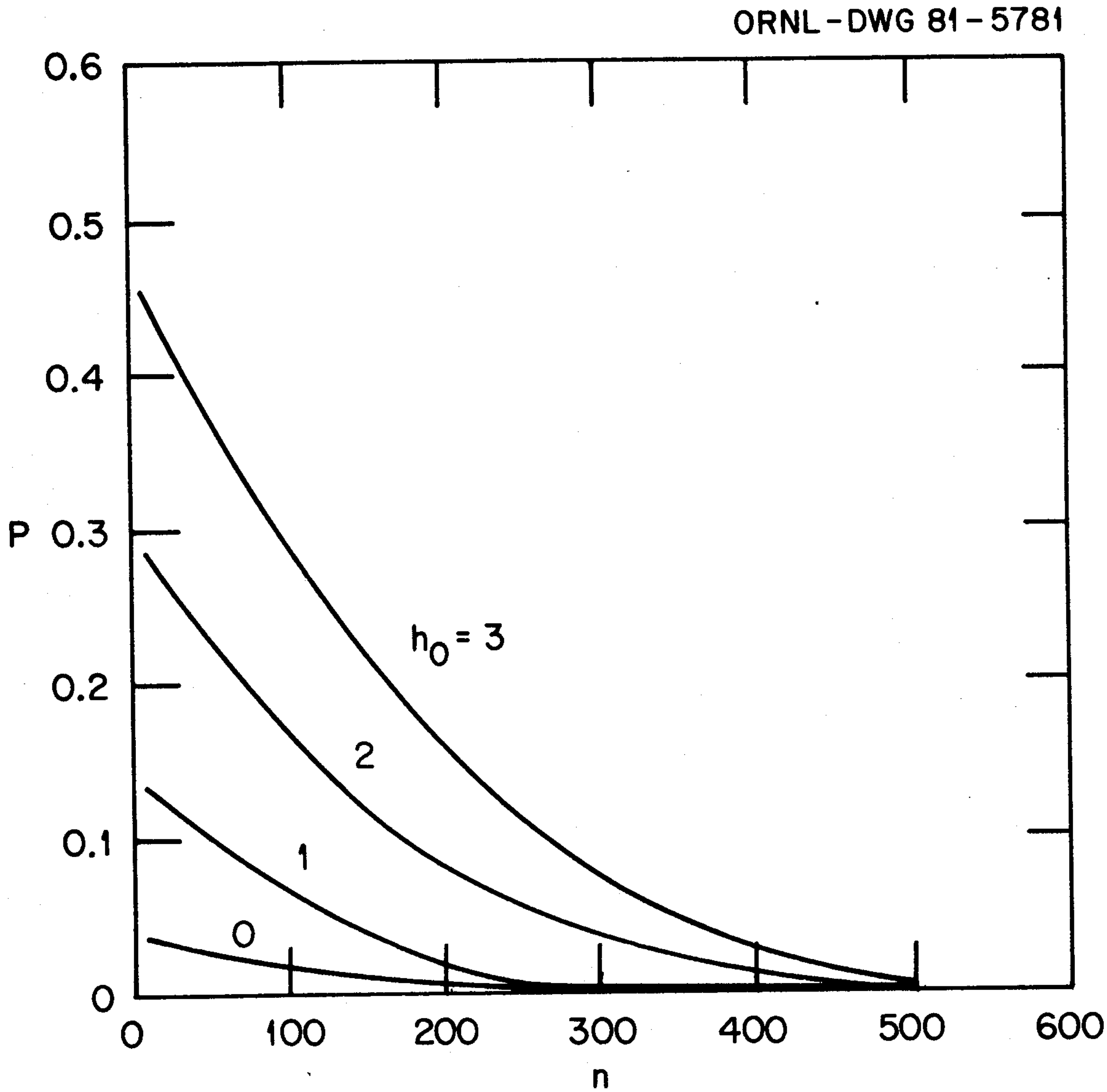

Fig. VII-9. The Probability (P) of Missing More than Seven Hot Spots on a "Cleaned-Up" Site, Given h_0 Hot Spots Found in a Sample Size n (see Fig. 2).

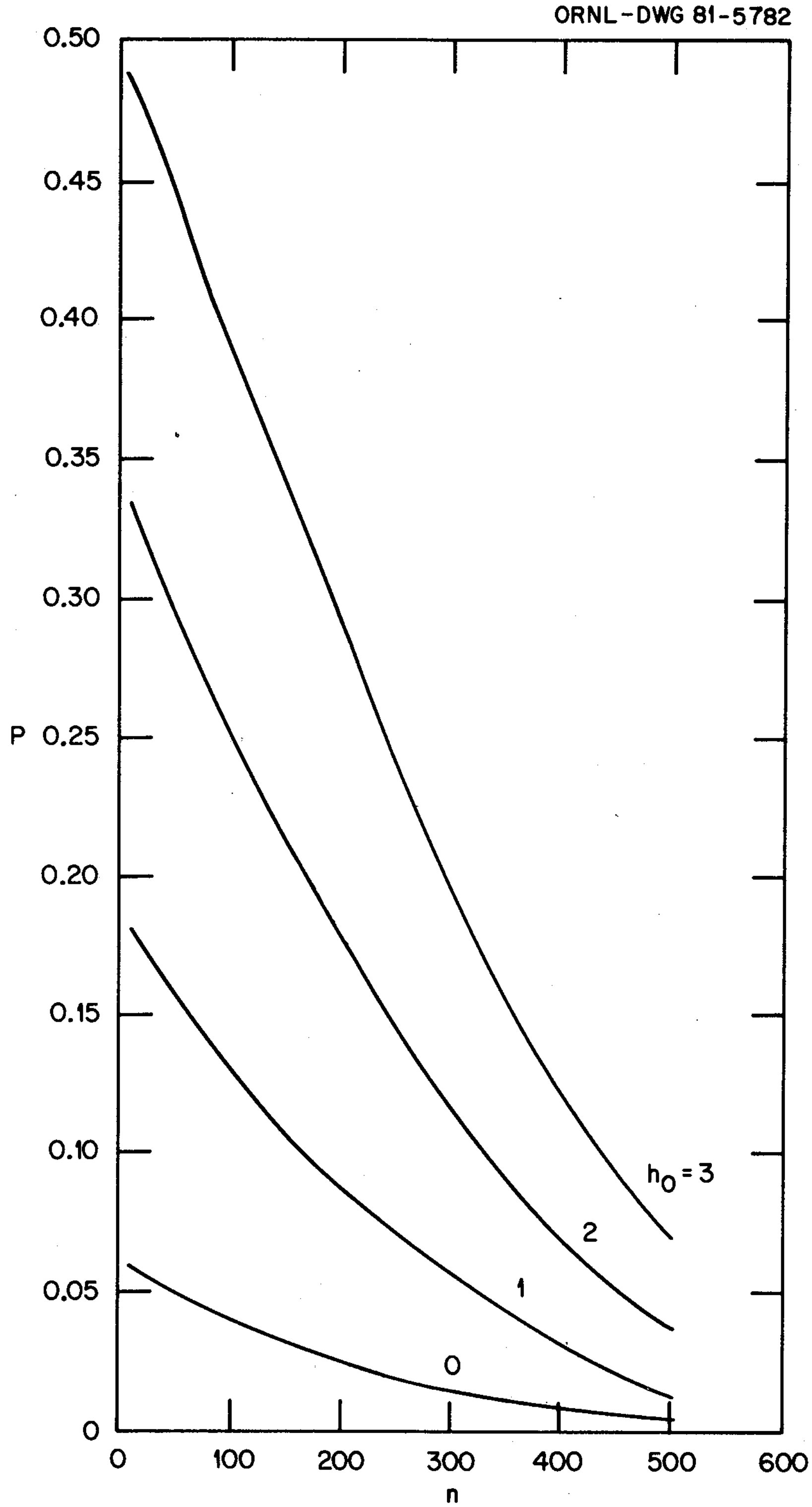

Fig. VII-10. The Probability (P) of Missing More than Three Hot Spots on a "Cleaned-Up" Site, Given h_0 Hot Spots Found in a Sample Size n (see Fig. 3).

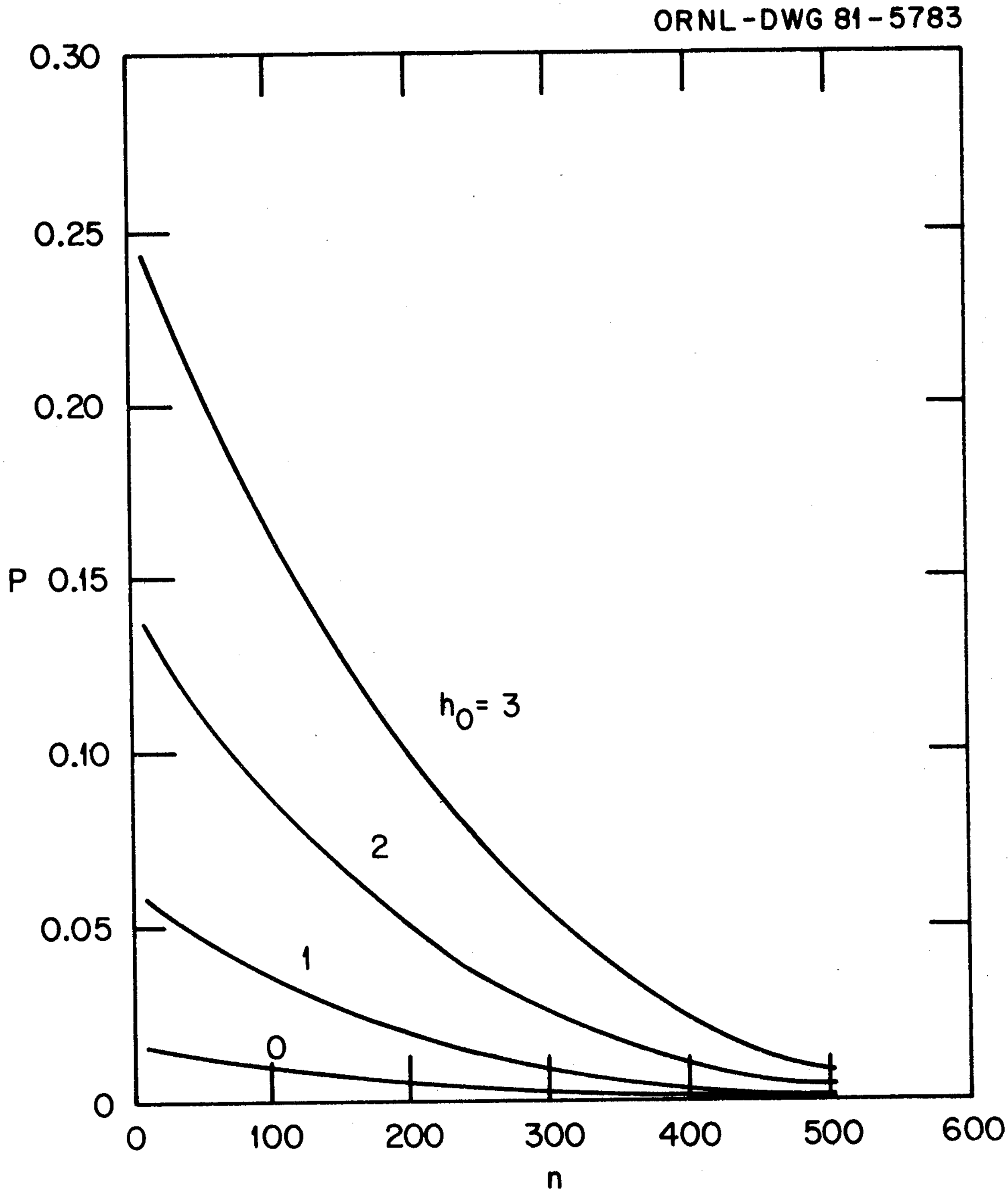

Fig. VII-11. The Probability (P) of Missing More than Five Hot Spots on a "Cleaned-Up" Site, Given h_o Hot Spots Found in a Sample Size n (see Fig. 3).

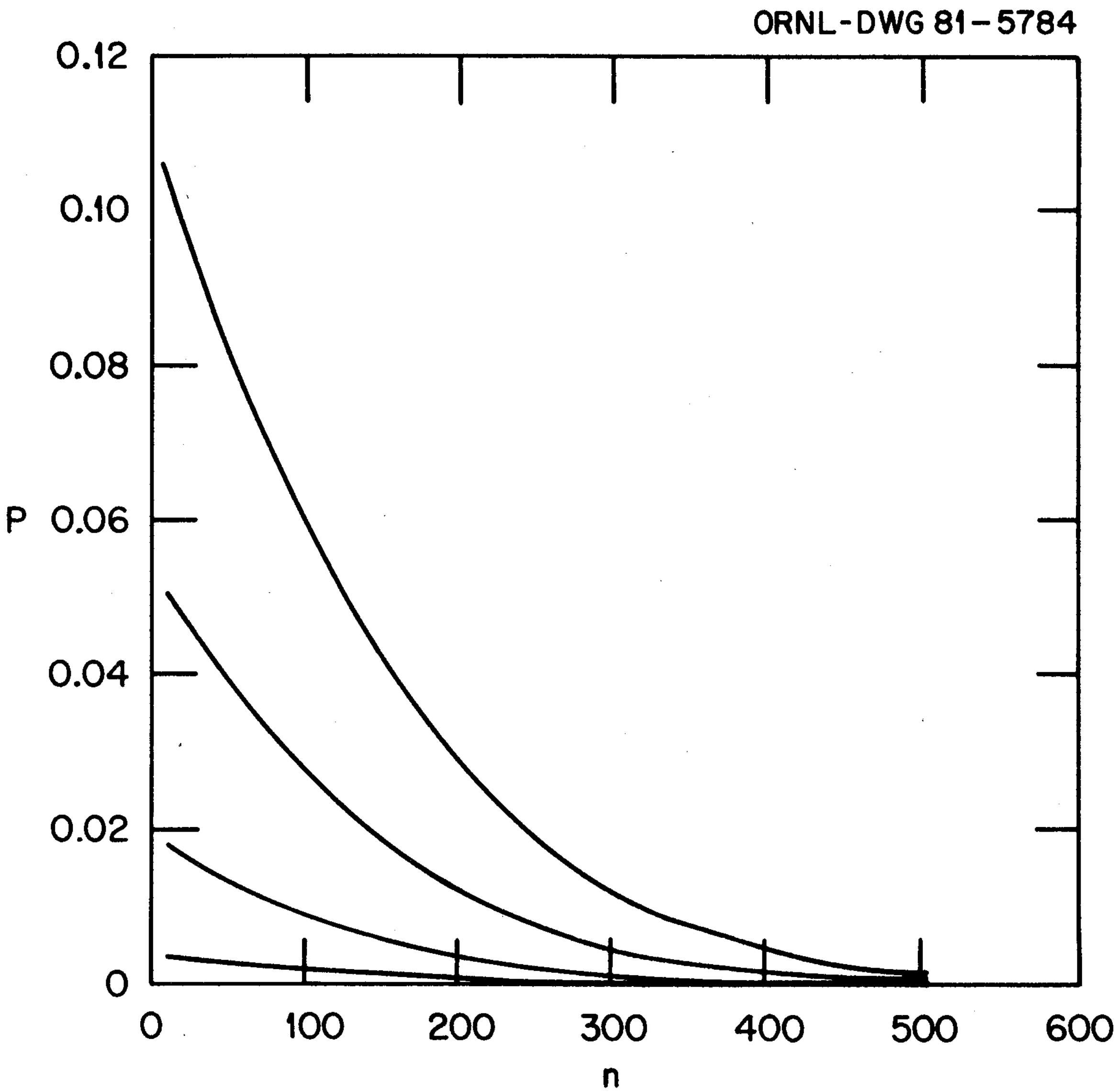

Fig. VII-12. The Probability (P) of Missing More than Seven Hot Spots on a "Cleaned-Up" Site, Given h_o Hot Spots Found in a Sample Size n (see Fig. 3).

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4. TITLE AND SUBTITLE (Add Volume No., if appropriate) Monitoring for Compliance with Termination Survey Criteria	2. (Leave blank)
	3. RECIPIENT'S ACCESSION NO.
7. AUTHOR(S) C. F. Holoway, J.P. Witherspoon, H.W. Dickson, P.M. Lantz, T. Wright	5. DATE REPORT COMPLETED MONTH: March YEAR: 1981
9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Oak Ridge National Laboratory Oak Ridge, TN 37830	DATE REPORT ISSUED MONTH: June YEAR: 1981
	6. (Leave blank)
	8. (Leave blank)
12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Division of Engineering Technology Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission Washington, D.C. 20555	10. PROJECT/TASK/WORK UNIT NO.
	11. CONTRACT NO. FIN A9042
13. TYPE OF REPORT Technical data base	PERIOD COVERED (Inclusive dates)
15. SUPPLEMENTARY NOTES	14. (Leave blank)

16. ABSTRACT (200 words or less)

This document was prepared as part of the requirement for considering changes in regulations on decommissioning of commercial nuclear facilities. Specifically, it addresses the final steps needed to ensure that a site which has been decontaminated can be released for unrestricted use. Consideration is given to preliminary and termination (certification) survey designs and procedures which might be used for licensed nuclear fuel cycle and non-fuel cycle facilities. In addition, information on instrumentation, evaluation and interpretation of monitoring data, and cost-effectiveness of monitoring is given.

17. KEY WORDS AND DOCUMENT ANALYSIS	17a. DESCRIPTORS
17b. IDENTIFIERS/OPEN-ENDED TERMS	

18. AVAILABILITY STATEMENT	19. SECURITY CLASS (This report)	21. NO. OF PAGES
Unlimited	Unclassified	
	20. SECURITY CLASS (This page) Unclassified	22. PRICE $

NRC FORM 335 (7-77)

☆U.S. GOVERNMENT PRINTING OFFICE: 1981—341-742:1149