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Distribution of Indoor Radon Concentrations

and

Elements of a Strategy for Control

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Abstract

Indoor radon concentrations vary widely in the U.S. housing stock, with normal concentrations estimated to cause a significant risk of lung cancer by comparison with environmental exposures normally considered, and high concentrations causing risks that exceed even those from cigarette smoking. The probability distribution, i.e., the number of houses at various concentrations, can be estimated from an analysis of the U.S. indoor radon data accumulated to date. Such an analysis suggests that in about a million houses, occupants are receiving exposures greater than those experienced by uranium miners. The form of the frequency distribution, including not only the average concentration, but also the number of houses with high levels, has substantial influence on strategies for control of indoor radon. Such strategies require three major elements: formulation of control objectives in terms of guidelines for remedial action and for new houses; selection of means for identifying homes with high concentrations; and a framework for deciding what types of control measures are appropriate to particular circumstances and how rapidly they should be employed.

Distribution of Indoor Radon Concentrations and Elements of a Strategy for Control

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Introduction

By the early 1980s, sufficient information on radon concentrations in U.S. homes had been acquired to indicate that radon decay products contributed significant radiation exposure for the U.S. population, both in terms of average concentrations and in terms of the frequent appearance of houses with high concentrations. However, no consistent analysis of these data had been performed, so that scientists were unable to provide either the general public or interested Federal, state and local agencies an adequate appreciation of the scope of the problem. Furthermore, no large area had been found to have concentrations so high that the local authorities themselves deemed indoor radon to be a serious health hazard. This was true in spite of the fact that a number of ordinary homes around the United States had already been found in the period 1979 to 1983 to have radon concentrations of the order of 100 pCi/l, corresponding to decay product concentrations of about 50 pCi/l, equilibrium-equivalent (0.5 WL potential alpha-energy concentrations).

In the last two years the degree of appreciation of the seriousness of the radon problem has changed rapidly. First, a reasonable examination of the bulk of the U.S. indoor radon data has been performed, leading to a quantitative, albeit tentative, appreciation of the distribution of indoor concentrations in U.S. single family homes. Secondly, the Reading prong has been discovered to be an area in which houses have an unusually high probability of having indoor radon concentrations that must be deemed to be excessive by virtually any standard.

The first development, i.e., a better scientific appreciation of the U.S. radon data, provides a much improved basis for framing a reasonable strategy for controlling indoor radon concentrations. In contrast, it is probable (and ironic) that discovery of large numbers of high-radon houses in the Reading prong area has, to a significant degree, made it more difficult to formulate a reasonable approach. That is, the haste with which authorities at every level feel compelled to deal with the problem can result not only in larger research and action programs, but also in the formulation of interim (or even permanent) guidance without adequate and explicit consideration of the key elements required to formulate a reasonable and effective strategy for control of indoor radon.

The purpose of this paper is, first, to provide - based on an analysis of U.S. indoor radon data performed by the indoor radon group of Lawrence Berkeley Laboratory's (LBL) Indoor Environment Program - a tentative frequency distribution of indoor radon concentrations and, secondly, to indicate the key elements that must be examined as a basis for formulating an adequate overall strategy for the control of indoor radon. These elements include: a proper appreciation of the risk associated with radon and other environmental insults; the adoption of objectives and guidelines for control of indoor radon; the formulation of strategies for finding areas and individual houses that may have excessive radon levels; and, finally, a decision framework for selecting appropriate control measures in view of the standards or guidelines that have been adopted and the results of measurements taken in individual houses.

Frequency Distribution of Indoor Radon Concentrations in U.S. Single-Family Houses

A substantial number of local or regional monitoring efforts have been undertaken to determine concentrations of radon-222 or its decay products in U.S. homes. These efforts suggest that typical radon concentrations in U.S. homes are about 1 pCi/l, with a range of a factor of 3 or 4 in either direction sufficient to include 90% of U.S. homes. However, a significant number of homes have been found with concentrations exceeding 10 pCi/l and even ranging above 100 pCi/l. This has raised concern not only about the average concentration of indoor radon and decay products, but about the frequency of occurrence of houses with very large concentrations, in some cases causing exposures exceeding the occupational limits for underground uranium miners.

Unfortunately, no survey effort to date has included monitoring in a statistical sample of the U.S. housing stock. Nonetheless, the total amount of data available from the United States has been quite substantial, suggesting the value of a systematic evaluation of this data. Such an analysis, described in more detail in Nero et al (1986), included data from published papers and reports as well as from recently completed studies not yet reported in the literature. In all, 38 data sets were utilized in the LBL analysis. In virtually no case were the results derived from a study based on an explicit statistical design intended to capture a representative sample. Furthermore, the various studies used differing monitoring techniques and protocols, and - finally - in a significant number of studies monitoring was undertaken because there was some reason to expect higher-than-average indoor radon concentrations.

In the course of this analysis, an explicit distinction was made between studies with a prior expectation of high concentration and those for which there was not apparently such an expectation. Of the 38 data sets, 16 had an such an explicit expectation, while the other 22 data sets arose, for the most part, in the course of efforts to establish baseline concentrations in connection with programs to save energy in homes. In these 22 sets, homes were typically selected on a volunteer basis, either by taking employees of a particular institution or by selecting from participants in some kind of energy conservation program.

The analysis also considered differing monitoring techniques and, more especially, protocols. In particular, a large number of the data available from U.S. studies were obtained with samplers or instruments placed in homes for a very limited portion of the year, most often during the heating season. Because the exposure of interest is actually the annual-average, we have utilized four studies which took both winter and summer measurements as a basis for calculating transformation factors to estimate annual-average concentrations from results obtained only during the heating season. The ratio of annual-average to winter arithmetic mean concentrations from these four data sets ranged from 0.65 to 0.84, averaging 0.72; this normalization factor was applied to data sets from heating season measurements to obtain "annual-average" arithmetic means. A similar approach was used for other parameters of the distribution.

Although aggregations were performed either using the entire 38 data sets or the subset of 22 "unbiased" data sets, and either using the data taken directly from the studies or normalizing all the data to annual-average concentrations, the primary results of the study are from the analyses of the 22 data sets normalized to annual average concentrations. For even this primary aggregation, two other variations in how the analyses were performed must be distinguished. First, three different kinds of weightings were applied in utilizing the individual data sets to construct a nominal U.S. aggregation. These weightings included 1) the equivalent of direct aggregation of the data, i.e., weighting by the number of houses;, 2) equal weighting of the various data sets, effectively giving each area equal weight, and 3) population weighting, i.e., assigning a weight corresponding to the population either in the state or, in the case of cities or towns, within fifty miles. As it turns out, the results from these three different weighting schemes are essentially indistinguishable, which gives us some confidence in the robustness of the analysis.

In addition, two basic approaches were taken in representing the data. First, because the results from reasonably large samples of houses are almost invariably represented well by a lognormal distribution, the individual data sets were characterized in terms of their lognormal parameters, i.e., a geometric mean (GM) and geometric standard deviation (GSD), as was the aggregate distribution. To indicate the seemliness of this approach, Figure 1 shows the frequency distribution derived from a direct aggregation of 19 of the 22 data sets (without winter normalization). The indicated lognormal distribution, whose parameters are calculated directly from the data, appears to fit the data quite well.

Therefore, in one analytical approach, lognormal parameters of the aggregate distribution were calculated from such parameters for the individual distributions. The results of this analysis can be characterized basically as follows: that the geometric mean annual average indoor radon concentration is approximately 0.9 pCi/l, with a GSD of about 2.8, or that the arithmetic mean is 1.5 pCi/l and the percentage of houses with concentrations exceeding 8 pCi/l is between

1 and 3 percent. There are therefore approximately one million houses with annual exposures to radon decay products exceeding those typical of underground uranium miners.

A parallel analysis was done without utilizing lognormal parameterization. First, the arithmetic mean of the distribution was calculated directly from the arithmetic means of the individual data sets, again, using the three different weightings of the data, and in any case, yielding an aggregate arithmetic mean close to 1.5 pCi/l. A comparable number for the fraction above 8 pCi/l was obtained by examining directly the total of 24 data points in the primary 22 data sets that actually exceeded 8 pCi/l. The weighted and normalized number resulting from this analysis, again, was in the vicinity of 2%. Hence, in either case, the analysis yielded an average concentration of 1.5 pCi/l and about 2% of houses exceeding 8 pCi/l.

This analysis gives relatively little information about the frequency of appearance of houses with levels that far exceed the range of observations, i.e., between about 0.1 and 50 pCi/l in the 22-data-set aggregation. However, if the lognormal function found to fit the data available for this aggregation is assumed to be an adequate representation of the U.S. distribution, even to high concentrations, then direct estimates of the frequency of appearance of high (and even very high) concentrations can be made. These suggest the total number of U.S. homes exceeding 20 pCi/l to be on the order of 10^5, the number above 100 pCi/l (0.5 WL) to be of the order of 10^3, and very few homes exceeding 1000 pCi/l (5 WL). However, it must be recognized that development or utilization of such a distribution for predicting the frequency of occurrence of these extremely high concentrations will always be extremely unreliable, since the small number of homes at very high concentrations - say 5 WL - can be dominated by a single, or a few areas, and hence cannot be analyzed in a statistically effective fashion. On the other hand, this is not as true of levels in the vicinity of 0.5 or 1 WL: the data available to us before the Reading prong discoveries made clear that houses in this range would be found, and the question was effectively, "Where and how many?".

Elements of a Strategy for Control of Indoor Radon

Considerable progress has been made in the last decade in understanding indoor concentrations and the basic factors affecting them. This provides a reasonable basis for control techniques designed either to prevent excessive concentrations in new homes or to reduce high concentrations in existing homes. However, although such control techniques are an essential component in a strategy for controlling indoor radon, such a strategy also includes other basic elements. These include, 1) the delineation of objectives, guidelines, and responsibilities for controlling indoor radon concentrations, 2) methods for identifying housing classes in need of action, and 3) a framework for selecting control techniques appropriate to different houses or circumstances. Underlying this control strategy is necessarily some perspective on the importance of the exposures found inside homes. A final consideration is, of course, the question of how to communicate effectively the current understanding of the importance of indoor radon and of whether, when, or how to do anything about it. The objective of any control strategy is to encourage effective action, not to induce panic.

Estimated Health Risk as a Basis for Action

The use of estimated health risk as a basis for environmental control is complicated by a number of factors, including uncertainties in exposures and uncertainties in the dose-response factor based on epidemiological or other studies. However, this is not the main difficulty in formulating a perspective on to the degree and manner, to which indoor radon ought to be controlled. In this case, the primary difficulty is in establishing a reasonable perspective for control in the indoor setting, in contrast to other settings in which regulatory actions (or personal choices) related to risk are taken.

By way of illustration, it is useful to consider the levels of risk that receive serious consideration in other contexts:

risk level of concern for other contexts
(given as added individual lifetime risk of premature death)

environmental exposures	10^{-5}, 10^{-6}?
occupational risk	10^{-3}, 10^{-2}?
personal choices	10^{-2}, 10^{-1}

indoor radon risks

average exposure	0.3×10^{-2}
million U.S. houses	2×10^{-2}
significant number	10^{-1} or more

In the case of environmental exposures, responsible agencies seriously consider action if the exposures being considered cause the average individual to incur an added lifetime risk of premature death in the range of 10^{-5} or even 10^{-6}, i.e., exceeding one chance in a million. Note that these risks tend to be risks that are not voluntarily received, i.e., they are associated with presence in, or utilization of, the general environment. They are typically risks from which the individual exposed derives little direct benefit. In contrast, the risks from exposures specifically associated with various industrial processes are often in the range of 10^{-3} lifetime risk of premature death or, in some cases (such as that of underground uranium miners), even 10^{-2}, i.e., 1% or more. However, the workers who incur these "occupational" risks, often substantially larger than typical "environmental" risks, derive a direct benefit - i.e., salary - from suffering these risks and are, at least in principle, aware of the risks. Finally, individuals often make personal choices involving risks that are substantially larger than even occupational risks, ranging from 10^{-2} associated with use of an automobile to levels exceeding 10^{-1}, i.e., 10%, in the case of smoking. These risks are voluntary, at least in principal, and known, at least in a general sense, to those who suffer them.

In considering, even superficially, where the case of indoor pollution fits into this scheme, it quickly becomes evident that such exposures do not fit, either theoretically or practically, into these three categories. Indoor exposures and attendant risks are not "environmental" in the general sense: they are associated directly with use of a specific object, a home; they are voluntary in that we choose to live in homes to receive a number of benefits, including health, comfort, and convenience; and, as we will see below, the attendant risks are many orders of magnitude higher than those associated with environmental exposures. In fact, the risks are quite comparable to occupational risks, in some cases reaching levels that are ordinarily associated only with personal choices like driving a car or smoking.

Based on current risk estimates, the average radon decay-product exposure of the U.S. population - that associated with an average radon concentration somewhat greater than 1 pCi/l - entails a lifetime risk of premature death due to lung cancer of the order of 0.3%. This exceeds by three orders of magnitude the risk typically associated with environmental exposures to regulated pollutants. Furthermore, based on the estimates made above, in perhaps a million houses people receive exposures with risks exceeding 2%, assuming that they live most of their lives in those houses. In a significant number of homes, the risks associated with extended occupancy are in the range of 10^{-1} or more, entirely comparable to that in smoking, but usually experienced unknowingly. Effectively, indoor radon poses a new kind of problem for consideration and is one whose solution cannot be found by single-minded or simplistic application of previous experience. Nonetheless, a consideration of previous experience and of the risk associated with different settings, such as that just indicated, can provide some perspective on the question of reducing risks due to indoor radon exposures.

Guidelines for Controlling Indoor Radon Concentrations

An indoor radon control strategy and the associated guidelines must have clearly defined objectives. Considering the distribution found for indoor radon concentrations even superficially, it is evident that two classes of objectives might be sought. One is a limitation or reduction of the average population exposure, and the second is the protection of individuals who otherwise might be exposed to unusually high concentrations. In many contexts, and rightfully so, it is the second objective that is given the most attention. However, certain aspects of a radon control strategy would significantly affect the first objective, i.e., the potential limitation of average exposures.

There is already substantial background for control of indoor radon exposures in the form of regulatory or advisory guidelines, including two categories of guidance. One has to do with indoor exposures associated with some type of contamination of lands or buildings, and the second has to do with ordinary buildings, the dominant problem and the one with which we are primarily concerned.

The history of dealing with industrial contamination leading to elevated indoor radon concentrations consists largely of three experiences: 1) that associated with uranium or radium mill tailings, 2) the use of reclaimed phosphate-mined lands, and 3) radium residues left from industrial activities in various parts of the United States (as well as other countries). Each of these cases has a long and complex history which it is not useful to describe here. In fact, perhaps the most important point to be made is that the very fact that associated elevated concentrations could be attributed to a responsible activity or party led to a strict interpretation of the extent of remedial action necessary, or conversely, of the concentration requiring remedial action in buildings affected. In a case where an external agent causes the problem, the tendency is naturally to try to achieve a risk level similar to that in the general environmental setting, rather than to risks associated with settings in which the individual occupant has some personal interest or benefit.

The problem of indoor radon in ordinary buildings is far more important than the case of contaminated lands or buildings simply because the number of homes involved is far greater. On the other hand, radon occurs in these homes - whether at ordinary or high levels - simply because of the fact that we choose to build homes on the ground: no individual or industry is responsible. In such a case, it appears appropriate, in fact essential, that guidance for control of indoor radon be developed within a perspective that considers the indoor setting in its own right.

Over the last several years, considerable guidance on radon in ordinary homes has already been developed, although typically in a context that is not as complete as it might be, e.g., on the part of organizations that deal narrowly with the problem of "radiation protection". The efforts of such organizations, including the International Commission on Radiation Protection and the National Council on Radiation Protection and Measurements, have already led to recommendations intended as guidance for remedial actions in homes and, in some cases, as guidance for limitation of levels in future houses, which may very well be different. The guidance already developed by international and national organizations, and also by some countries, is summarized in Table 1. There it will be seen that the level above which remedial action is recommended is in the range of 200 - 400 Bq/m^3, equilibrium-equivalent decay-product concentration. The higher number corresponds approximately to 25 pCi/l of radon. The risk associated with this number - for lifelong residents - is of the order of 5%. Just by way of comparison, the loss of life resulting from such a risk of lung cancer is roughly comparable to the average loss of life due to use of automobiles, i.e., a probability of premature death of 1-2% times a <u>portion</u> of life lost that is considerably larger than that due to lung cancer.

In contrast to this, many authorities in the United States have already begun using 4 pCi/l of radon as an effective radon standard, even though this is far lower than the levels recommended by international organizations and in spite of the fact that the associated risk, while considerable compared with "environmental" risks, is not larger than even average risks ordinarily incurred by members of the public. Utilization of a 4 pCi/l standard would, based on the distribution discussed above and presumably on any distribution coming out of a national survey, entail application of remedial action to about 10 percent of the U.S. housing stock, i.e., many millions of homes.

Applying a stricter limit than 20 pCi/l or so to future houses may have a significant effect on the average population exposure. As areas of the country are defined that tend to have difficulties with radon, i.e., a higher than average frequency of high concentrations, guidance can be implemented in these areas in the form of building codes that require relatively inexpensive construction features, resulting in substantially reduced indoor radon concentrations in those areas. As a result, a significant change can be made in the number of houses in the tail of the frequency distribution. Thus not only relatively high houses would be affected by a control strategy: even homes in the mid-range, i.e., roughly 4 to 20 pCi/l range, can effectively be moved down to low radon concentrations at relatively little cost. This is an effective approach for altering this portion of the frequency distribution, permitting near-term efforts to be focussed on houses at higher concentrations, where individuals are receiving excessive risks. In this way, current attention would be directed to homes and people who need it, while tending to avoid a sense of panic in the areas affected.

Identifying Areas and Homes with Excessive Concentrations

The ultimate objective of any control strategy will be to locate houses above some level of concern and apply appropriate measures. Short of monitoring every house in the country, some means must be devised of identifying areas in which the high concentration houses are most likely to occur. The efficacy of such an approach is, in fact, indicated by the distributional analysis discussed above. As indicated in Figure 2, it was found that the (geometric) means of the (annual-average) concentrations in the 22 sets used for the primary analysis were themselves lognormally distributed, ranging from about 0.4 pCi/l to 5 pCi/l.

This is an order of magnitude range in mean concentration, even for a relatively small number of data sets, and illustrates the substantial variability in mean concentrations from one part of the country to another. Use of fundamental source-related parameters or of limited surveys to identify the areas that tend to have high concentrations would then permit more intensive investigations and more substantial resources to be devoted to the search for and remediation of houses with excessive concentrations. A substantial part of the research at LBL and elsewhere is devoted to the development of a predictive capability that would use basic information such as radium content, soil permeability, house structure, and local meteorology, to estimate the radon potential as a first step in identifying the areas that actually have radon problems.

In any case, this first step must be followed by monitoring in the individual houses that have potential difficulties. Fortunately, at least two means are already available for effectively performing monitoring, i.e., use of integrating detectors based either on etched-track techniques or on collection with activated charcoal. In either case, these may be supplemented by grab-sample techniques that, in themselves, are not a very useful tool for this purpose.

One must have a precise strategy in mind, even for performance of the measurement or interpretation of the result. Thus, for example, a week-long charcoal measurement giving a radon concentration of 20 pCi/l may not necessarily imply the need for remedial action in that home, since radon concentrations can vary substantially from one time to another. Fortunately, in this case, a concentration of 20 pCi/l does not require quick action, so that the charcoal measurement can be followed up by a year-long etched track measurement without causing the occupants substantial added exposures in the mean time. This would not be the course of action in the event that the charcoal canister measurement gave a result of, say, 500 pCi/l. Regardless of variability, it is highly likely that the average concentration in such a home, assuming that the living space was the area monitored, would be in excess of a guideline of 20 pCi/l.

Even a grab-sample measurement of radon or its decay products can be useful in very limited circumstances, provided it is realized that such measurements must in all cases be followed by an integrated measurement: if the measurement result is high, it must be confirmed by the more reliable integrated measurement; if it is low, but there was some reason to suspect high concentrations, it must still be followed by integrated measurement, since the concentration may have been lower than average at the time of the grab sample. This illustrates, the potential interaction between the major elements of a radon control strategy. That is, depending upon the structure of guidance and the nature of the measurement results, (and, indeed, of the technical control measures available), the course of investigation and action involves an interaction between the major strategic elements: the guidelines, the means for identification, and the control techniques.

Choice of Control Techniques

We turn finally to the method of choosing specific measures for controlling indoor radon concentrations in individual houses or housing classes. The potential utility of various type of controls roughly follows the order of importance of the several factors that affect indoor radon concentrations: the source strength or entry rate, the house ventilation rates, and the more complex question of the behavior of the radon decay products themselves in the indoor environment. It is found, based on a wide range of measurements and experiments, that the primary determinant of whether or not a house has high radon concentrations is the radon entry rate and that a somewhat less important factor is the ventilation rate. The detailed behavior of the radon decay products including their removal - by ventilation systems or interactions with the walls and other surfaces of the indoor environment - has a relatively modest effect on the exposures and, in particular, of the radiation dose to the bronchial epithelium.

The three corresponding types of control have roughly the same order of effectiveness or advisability. First, because the radon entry rate is the major determinant of indoor concentrations, the biggest "handle" one has for controlling excessive levels is reducing the entry rate itself. It has recently been established that the major mechanism for radon entry is the movement of air from the ground into houses, driven by small pressure differences between the indoors and the outdoors. The corresponding technique for reducing radon entry substantially is modification of this pressure differential by using specialized and local ventilation techniques that reduce the flow of radon-bearing air into the home.

In contrast, increased general house ventilation is not very effective for reducing the indoor radon concentration substantially. Consider, for example, the case of a home with 50 or 100 pCi/l where one would then wish to reduce the indoor concentration by about a factor of 10. If the ventilation rate is initially in the normal range, 0.5 to 1 air changes per hour (ach), this would entail raising the ventilation rate to a range of 5 to 10 ach, which would be intolerable from the point of view of either comfort or cost, except possibly as a temporary measure. In contrast, the specialized ventilation techniques that depressurize the soil beneath a basement (or otherwise remove entering radon), or even the active ventilation of a substructure volume such as a crawlspace or a basement, are much more effective at reducing indoor radon concentrations.

Finally, we might consider the potential utility of air cleaning techniques based on filtration, electrostatic precipitation, or other means to remove particles and radon decay products from the air. At first blush, these might be considered to be effective because with some devices the total decay-product concentration, given as equilibrium equivalent or as potential alpha energy concentration, can be reduced substantially. However, this appears to be a highly misleading measure of the dose to the bronchial epithelium in such circumstances, because by reducing the particulate concentration, one can also raise the fraction of decay products that are not attached to pre-existing airborne particles. Unfortunately, the unattached fraction, although small, delivers a large part of the dose to the lung. Thus reducing the total decay-product concentration by air cleaning may have a modest effect, if any, on the dose of concern. Hence, using the decay product concentration as a measure of dose in these circumstances can be highly misleading. (This, and the tradeoff between changes in unattached fraction and total decay-product concentration, for a fixed radon concentration, leads to the possibility that citing guidelines for the indoor environment in terms of radon concentration itself may be a much more desirable and effective approach than citing decay product concentrations.)

Aside from the issue of specific control measures themselves, it is necessary to develop a more complete picture of the effectiveness of these control techniques in various circumstances and to develop a decision framework for choosing which measures to use (and in what order) for the particular circumstances at hand. This need applies to the entire question of a control strategy. That is, the strategy as a whole is effectively a three-dimensional decision framework with objectives and quantitative guidelines being one element, means for identifying areas and individual types being another, and the choice and timing of remedial action being the third dimension. These dimensions interact with one another, together answering the question either globally or in individual cases about whether something should be done, what should be done, and when.

Prospects for the Future

The results and considerations outlined above raise the question of where we proceed from here, both in terms of the potential need for broad surveys of indoor radon (and other pollutants) and also in respect to development of a reasonable control strategy.

Although we now have a reasonable - and even quantitative - appreciation of indoor radon concentrations in U.S. single-family houses, these results are by no means sufficient, both because of the uncertainties associated with their derivation from non-representative surveys, and because they do not provide a sufficient basis for identifying areas of the country that have high radon concentrations. For this reason, some form of survey on a national basis is advisable, partly to validate the tentative frequency distribution found by the analysis discussed above but, more importantly, to examine the potential connection between measured indoor concentrations and various factors that might affect these concentrations, including the source-related factors, building structure types, meteorological conditions and, perhaps patterns of living in and using homes. Such survey information would be an important element in helping to develop a predictive capability for finding high radon areas or even for simply helping to interpret the results of subsequent local, regional, or national surveys. In this connection, it is worth mentioning the importance of local - including statewide - surveys that - which together with basic source related information - will undoubtedly provide the major means of identifying areas of concern from the standpoint of indoor radon.

A sensible control strategy for indoor radon will require a considered examination of the main elements of such strategies, i.e., the formulation of objectives and guidelines, the development of techniques for identifying areas and homes with excessive concentrations, and the formulation of a decision framework for remedial action. This careful consideration and examination of these elements, and the work required to develop them adequately, has not yet occurred. In the mean time, it is important that one proceed apace in locating and assisting people living in houses with excessive concentrations, defined for the time being at levels recommended by international or national radiation protection organizations, e.g., a radon decay-product concentration of 400 Bq/m^3 or a radon concentration of 20 pCi/l. Such an approach would focus attention where it is most needed.

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Table 1. Recommended Limits on ^{222}Rn Decay-Product Concentrations in Buildings.*

Organization	Existing Buildings		Future Buildings
	Ordinary	Contaminated	
ICRP	200 Bq/m^3 (0.055 WL) (higher for severe actions)		100 Bq/m^3 (0.27 WL)
NCRP	185 Bq/m^3 (0.055 WL)[a]		
WHO	400 Bq/m^3 (0.11 WL)[b] (100 Bq/m^3 if simple measures)		100 Bq/m^3 (0.027 WL)
ASHRAE			37 Bq/m^3 (0.01 WL)[c]
U.S. Agencies		37-185 Bq/m^3 (0.01-0.05 WL)	
Canada		74 Bq/m^3 (0.02 WL)	
Sweden	400 Bq/m^3 (0.11 WL)		100 Bq/m^3 (0.027 WL)

[a] Recommended limit is 340 WL-h per year, equivalent to 0.05WL for 80% occupancy.

[b] Remedial action to be performed before added exposure exceeds 2000 Bq m^{-3} y (27 WLM).

[c] Likely to be raised.

* from: A.V. Nero, "Elements of a Strategy for Control of Indoor Radon," in preparation.

References for ICRP, NCRP, WHO, and ASHRAE recommendations are given in the list of references.

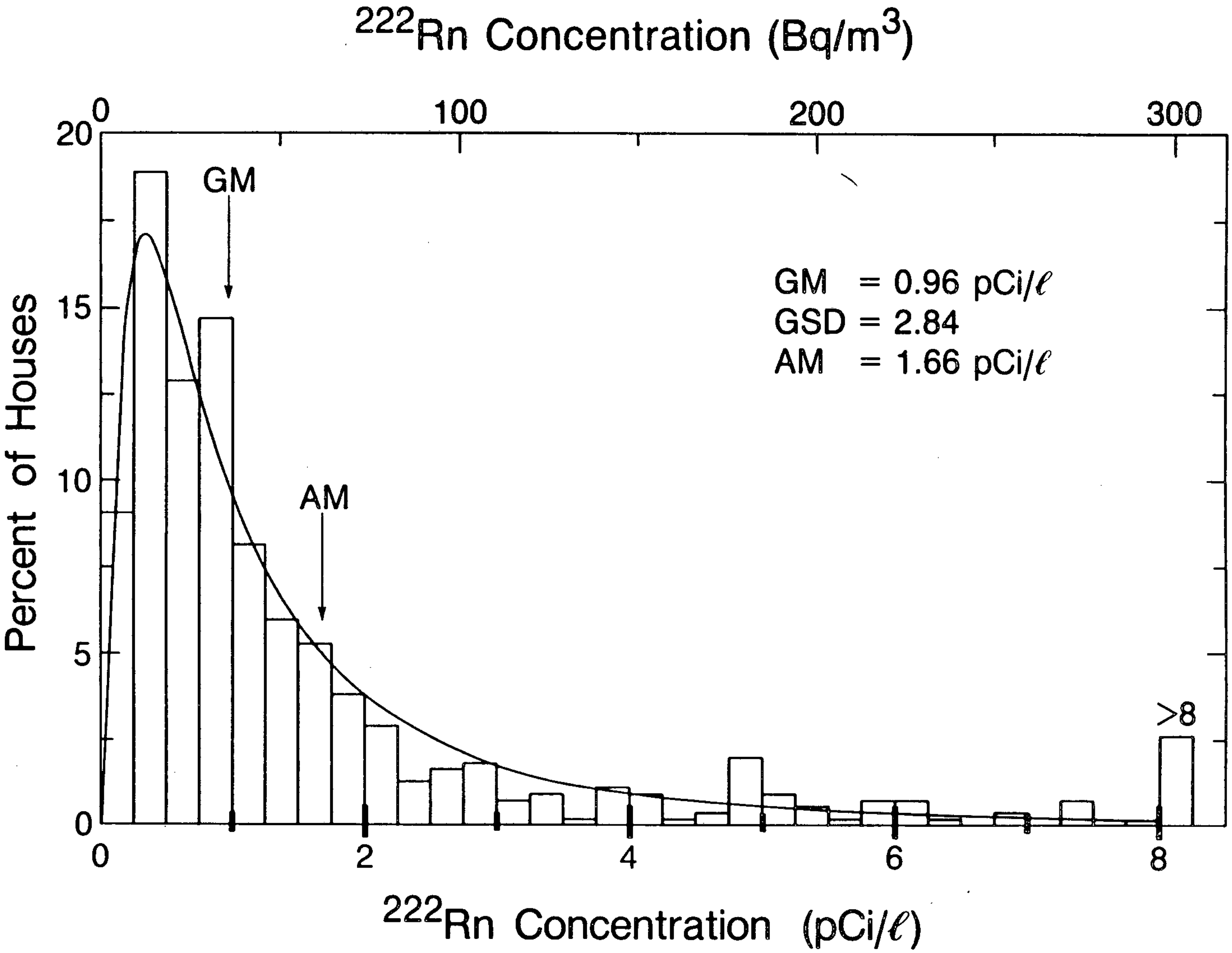

Figure 1. Histogram of radon concentrations from direct aggregation of 552 individual data in 19 data sets from U.S. surveys. The smooth curve is a lognormal function corresponding to the indicated geometric mean (GM) and geometric standard deviation (GSD), calculated directly from the data.

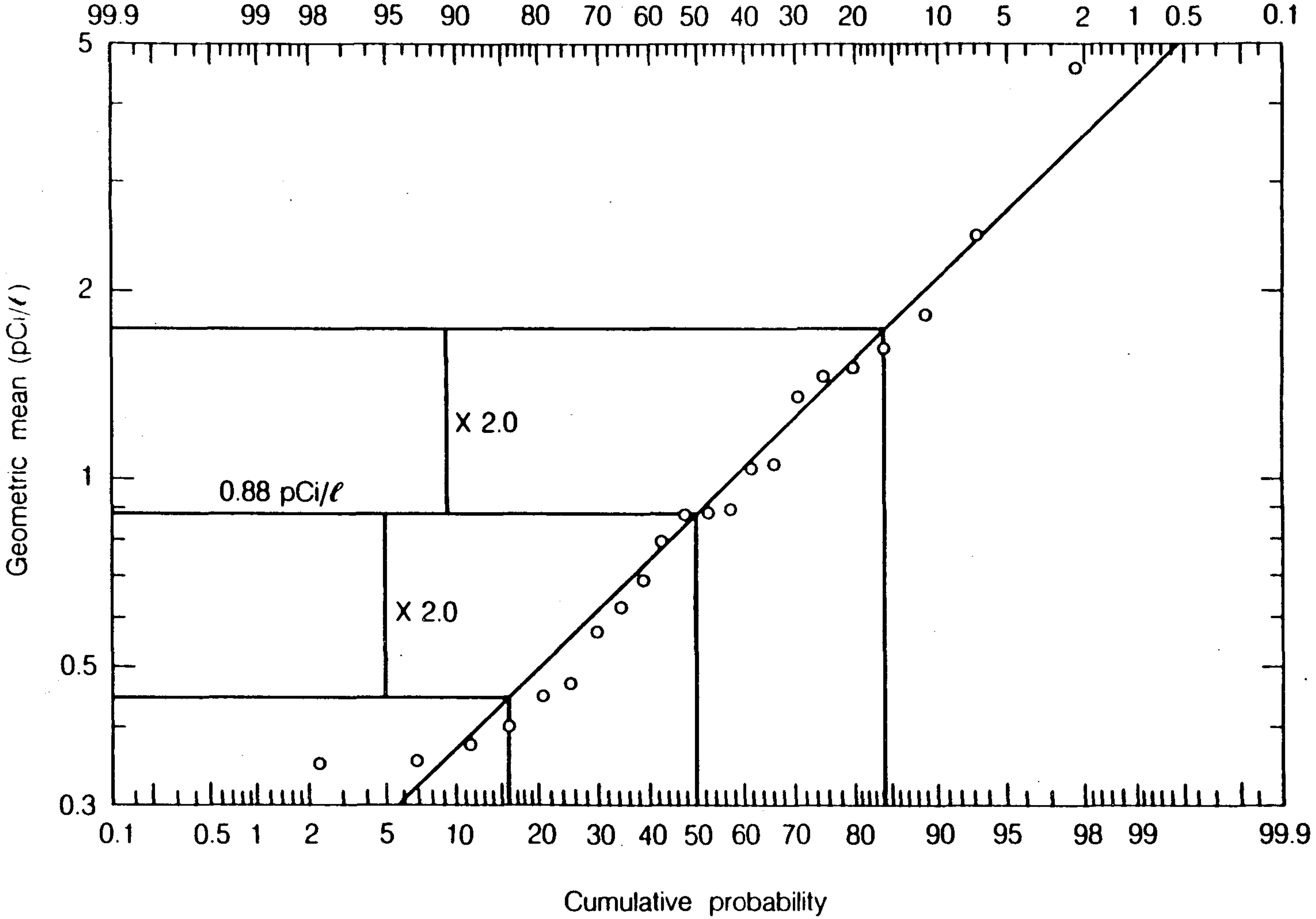

Figure 2. Distribution of annual average GMs for 22 sets of indoor radon data from various areas in the U.S.

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