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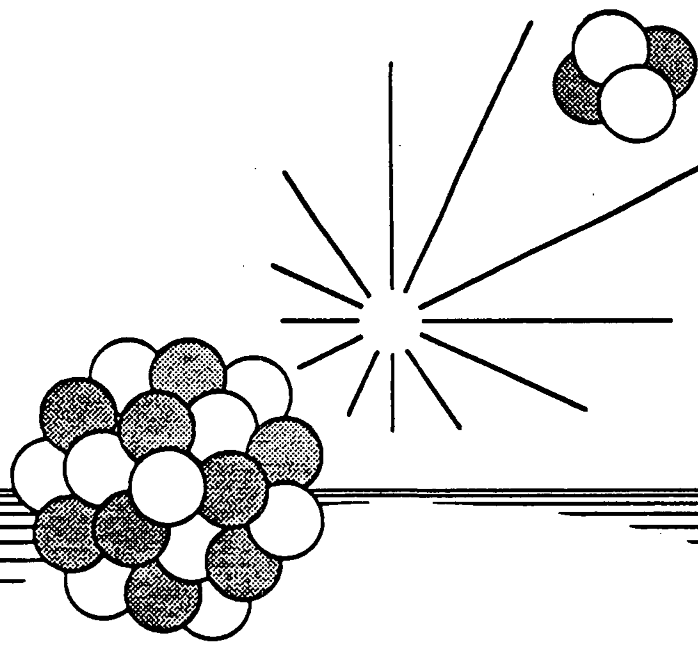

Report of EPA/DOE Roundtable Discussion of Radon Research Needs

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Introduction

Expanded research programs into the potential impacts on public health by naturally occurring radon and its decay products are being developed in the United States. This increased effort is in part a response to the discovery of unusually high levels of indoor airborne radioactivity found in houses in the Reading Prong area of Pennsylvania and New Jersey. In several houses in this region, the radon decay product concentrations were substantially above values that are permitted to be present in active uranium mines. Other surveys in the U.S. and elsewhere are discovering that many houses have higher than anticipated radon and decay product concentrations although generally not to the extremes seen in the Reading Prong region. Thus, the possibility exists that a significant fraction of the United States population is being exposed to concentrations of radon and decay products that are currently considered to pose an increased health risk.

During the past several years, there have been a number of research efforts to determine the concentration of radioactivity in indoor air, to relate that activity to the properties of the structure and its geological setting, to determine the fundamental physical and chemical properties of radon and its decay products, and their impacts on human health as well as determining ways to mitigate against the exposure of persons living in houses with initially high radon levels. A major symposium during which the results of a number of these research efforts were presented was held on April 14-16, 1986 at the 191st National Meeting of the American Chemical Society. Since a large fraction of the researchers in the area of radon and its decay products were presenting the results of their studies at this meeting, a roundtable discussion was organized at the Department of Energy's Environmental Measurements Laboratory to review the status of our understanding of the properties and effects of radon and its progeny and to review the scope and directions of the research programs being planned by the U.S. Environmental Protection Agency and the U.S. Department of Energy. The purpose of this report is to summarize those discussions.

Current Research Areas

This report cannot fully document the full state of knowledge regarding radon and its decay products. The volume to be published containing the ACS Symposium papers (1) will provide considerable information as will the forthcoming book edited by Nazaroff and Nero (2). The proceedings of a symposium held in Maastricht, the Netherlands in March 1985 have recently been published (3) as have the proceedings of a specialty conference on indoor radon organized by the Air Pollution Control Association in February 1986 (4). The objective here is to examine a limited number of topics related to the occurrence of high levels of radon in indoor air, the chemical and physical properties of radon and its decay products, the health effects of this airborne radioactivity, and the adequacy of the currently planned research programs to resolve the unknown or uncertain areas of knowledge critical to evaluating the health risks to the general population.

Occurrence of Elevated Radon Concentrations

It is now generally agreed that the principal source of indoor radon is the soil under a structure. The radon in the soil gas flows into the building because of a pressure differential between the inside of the building and the soil. In particular locations, there may be increased indoor radon from radon dissolved in the potable water brought into the house. There is also a small contribution from building materials although in the case of certain materials such as phosphogypsum, there can be a substantial contribution to the indoor radon levels. However, the most common source of indoor radon is the soil gas under the structure. The input of radon to the building depends in part on the radium concentration in the soil, the permeability of the soil and the total volume of soil gas that can flow into the house. The ability to predict where high levels of indoor radon are likely to occur would permit the focussing of monitoring and mitigation efforts on only those areas that pose a substantial threat to the inhabitants. Thus, the first topic of discussion was the status of our ability to make such predictions based on geological or geographical considerations. A number of surveys have been made in Europe, Canada, Japan, and to a limited extent in the United States. Thus, the question is how well we can utilize the results of these surveys to predict the incidence of elevated indoor radon levels.

The factors that govern the observed levels are related to the structural properties of the building as well as the soil characteristics. Thus, it is important to consider the understanding of both the physical properties of the building and the soil that drive the radon infiltration process. The recent work by the Indoor Air Quality and Ventilation Program at Lawrence Berkeley Laboratory mapping pressure fields and investigating migration rates using inert tracers is starting to build our knowledge of the process. During the past several years, there has been the development of a qualitative appreciation of the factors that contribute to radon in the soil and to ingress of radon into houses. However, we are now just beginning to be able to put that understanding into a framework that may lead to a predictive capability. This understanding is being developed through the use of experimental houses that allow the development of improved building science. These kinds of studies of the relationships between design, construction and infiltration rates need to be continued.

Similarly there are similar research needs in soil science. Although it is known that radium content and soil permeability are important factors for radon availability, it is not possible on a large scale such as the United States as a whole to dependably predict where the high concentrations are likely to be found. It may be possible to predict regions of higher potential radium content or soil permeability based on information such as the NURE maps or from data from the Soil Conservation Service, and thus identify areas that might be suspect as potential higher radon areas. There is a need to test whether the available data are sufficient to make such predictions. The recent study of Spokane, WA, reported at the Symposium (5) has found high indoor radon in this area of high permeability soil. Thus, in some areas the surficial geology may be sufficiently homogeneous that a lognormal distribution of radon values could be expected. However, other areas are so geologically heterogeneous that it would be impossible to predict that the distribution of values would conform to a single distribution. Other tests of the ability to identify high risk areas based on soil properties are needed and appropriate in order to test hypotheses regarding the geological properties and housing characteristics that might be expected to result in high radon levels.

From the results to date from a variety of surveys, it appears unlikely that it will possible to make predictions for any particular building since nominally similar buildings on nominally similar soils have indoor radon concentrations differing by orders of magnitude. It may be that further research into both building and soil science will reduce the uncertainty of prediction, but such improvements are not likely in the immediate future to provide building by building predictions.

The results of surveys generally report lognormal distributions and a variety of summary statistics including the median, the geometric standard deviation and the arithmetic mean. However, different groups of building may result in quite different distributions. For example, the national survey in the United Kingdom resulted in one distribution while a local survey in Cornwall resulted in another lognormal distribution but at a substantially higher median value. The discussion suggested that reporting the parameters of a lognormal distribution appears to be the best representation of the findings in terms of a continuous probability distribution function to estimate the number of buildings with radon exceeding a given level. It was suggested that for exposure considerations, it is the arithmetic mean that is the critical parameter since the population-weighted average exposure will be the arithmetic mean. Thus, an arithmetic mean is required for any risk assessment even though the geometric mean and geometric standard deviation are reasonable to characterize the distribution.

Another source of indoor radon is radon in water and a point of discussion was the current level of understanding on the contribution of water to airborne radon concentrations for a given radon concentration in solution. Calculations have been completed at LBL which included the amount of water use, the actual release efficiency for radon from water, the volume of houses and the distribution of ventilation rates. Distributions of values were estimated for each of these factors and then they were combined to yield a distribution of indoor radon values per unit water use resulting from radon in water. The arithmetic average of this distribution is quite close to the 10^{-4} ratio of airborne to waterborne radon that has been observed by a number of investigators. The geometric standard deviation for the distribution is of the order of 2 resulting from the distribution of ventilation rates. Applying this distribution to the distribution of waterborne radon that has been measured, the estimated contribution to radon concentrations can be estimated.

For those houses using public water supplies derived from surface water, there is essentially no contribution to indoor radon. For houses using public supplies derived from wells, the average contribution to indoor radon is approximately 3%. For private wells the values may be much higher and not generally known. In some circumstances the contribution from well water may be comparable to the radon present due to soil. There have been some building materials used in Europe and the United States that yield high indoor radon levels such as the Grand Junction tailings concrete. The consensus was that normal building materials are important contributors to the average radon levels particularly when soil gas radon concentrations are low, but generally are not responsible for high indoor radon levels. Building materials may also be more important in multilevel, multifamily housing where the upper floors are relatively isolated from soil gas influences.

In order to assess the population exposure, it will be necessary to make measurements in individual houses since it is not currently possible to predict the indoor radon concentrations. There have been a variety of prior survey programs. There arises a sampling strategy question of whether the measurements should assess the average dose to the general population or find the high radon houses where a more acute threat to the residents may exist. These objectives require different survey designs. At the present time, it is not certain how to identify the high radon level houses. As previously discussed, there exist areas where it might be expected that high radon level houses exist and sampling strategies are being developed. With the effort that has been made to determine areas of near-surface uranium deposits, it is likely that any potential Reading Prong area can be identified from such data. Areas of high soil permeability may also be identifiable from soil maps, but it may prove to be much more difficult to be certain in these cases. However, there is now a need to test these concepts to determine their efficacy in making predictions regarding the likelihood of elevated radon and hence a greater need for monitoring in that region of high indoor radon potential.

Properties of Radon and Progeny in Indoor Air

Several parameters are needed to describe the concentrations of radon decay products, their relationship to the radon concentration and the amount of activity attached to the ambient particulate matter. These parameters include the working level, WL, or the potential alpha energy concentration, PAEC, the equilibrium factor, F, and the "unattached" fraction, f, or the "unattached" fraction of alpha potential energy, f_{pot}. In the reports presented at the symposium, a variety of values were presented for F in contrast to the use of 0.50 as the typical F value. For example, the average value in the U.K. assessment was 0.35 (6) while in Norway, a value of 0.50 was used (7). In Germany a value of 0.30 has recently been reported (8). Since most of the large scale monitoring efforts only measure radon, the exposure to the decay products is estimated from the F value and higher or lower values result in larger or smaller WL or PAEC values. One of the key factors that affects the F value is the particle concentration since the F value increases as the particle concentration increases.

The typical indoor environment in the United States generally includes smokers and about half of the U.S. homes cook with gas stoves. There are then major indoor particle sources in the normal U.S. indoor environment. The apparently decreasing values seen in some of these recent European studies may result from decreasing indoor particle concentrations. It may also come from measurements in the bedroom where length of occupancy is large and there are relatively lower particle levels. As the particle concentrations decrease, the amount of "unattached" activity increases. Since some of the dose models put increased weight on this activity in terms of dose deposited in the lungs, the effects of increasing f and decreasing F may counterbalance one another. Vanmarcke (9) presents dose calculations based on measured F and f values and the dose model of James and Birchall (10) indicating just such a result. Thus, in effect, the radon concentration becomes a sufficient measure of exposure to permit dose calculations.

However, we are then in effect adopting as certain the validity and accuracy of this particular dosimetric model. There are others for which this result does not hold. For example the NCRP (11) developed a guideline based on a particular F value and changes in the value would directly affect that guideline value. It is likely that we will discover later that none of the now existing dose models fully account for all of the important phenomena. Thus, although it is attractive to think that only an integrated radon measurement is needed to assess exposure, it would seem wiser to find an appropriate long term integrating measurement of the decay product concentrations and the size distributions of the activity. Then, as health effects are identified in the population, the exposure/dose/effects relationships can be evaluated both from the radon concentration and the decay product levels. McLaughlin (12) has reported an effort to develop such a monitoring system for PAEC, and it would appear that a system that yielded long term integrated measurement of both radon and PAEC levels would be a valuable addition to our monitoring techniques.

Physical and Chemical Properties of the Radon Progeny

Reports presented during the Symposium (13-15) have shown new techniques for measuring the properties of the radon decay products particularly the activity size distribution of the "unattached" fraction and for interpreting the ultrafine particle size activity in terms of classical cluster formation theory. There is interest in these highly diffusional particles from the viewpoint of understanding the atmospheric chemistry of the radioactivity immediately following the radon decay. They may also be important in the dose models depending on whether the dose to a specific portion of the bronchial tree is being assessed. All of these ultrafine particles will deposit in the bronchial region. If the dose models only consider the average dose to the bronchi, then where they specifically deposit is irrelevant. However, if the dose to a particular generation is being considered, then there will be a considerable difference in deposition between 1 and 5 nm particles. Thus, there is a critical need for measurements of the activity size distributions for chemical investigations of the indoor atmosphere and such measurements may be important for assessing the dose depending on which dosimetric model is employed.

The improvements in the measurement of the ultrafine fraction and the initial results of classical cluster formation theory suggest that significant improvements in our understanding of the physical and chemical behavior of the radon progeny are possible and that careful experimental and theoretical studies of these problems have a high probability of success. It is not too early to begin to consider the development of an indoor air quality model involving a variety of reactions initiated by radiolysis, photolysis and combustion processes. In addition to the chemistry, it will be necessary to include the airflow, ventilation, and infiltration patterns within a building. It will take a substantial effort to add the additional knowledge that will be necessary before such a model becomes a useful tool in understanding indoor air quality, but it would be worthwhile to begin such an effort as part of the overall research program on radon and its decay products. It will also be important for this effort to move forward in conjunction with those researchers who are studying the variety of other indoor air quality questions. Radon and its decay products will interact with the other materials present in the indoor air and examining the radon-related questions in isolation from the other pollutants will fail to produce the needed level of understanding of indoor air quality.

There is agreement that the generally used measurement methods for "unattached" activity are quite crude. Although there are differences in the different dose models, all of them give additional importance to this highly diffusional mode and the ability to better define precisely what is meant by the "unattached" activity was considered to be a useful goal for additional study. It is not yet clear what specific size value would best represent the upper limit of the "unattached" activity. However, the reporting of specific size cut-offs (50% collection points) is strongly encouraged for all "unattached" fraction measurements.

In houses where air cleaning measures are in use, the effect of such cleaning will be the reduction in the radon progeny concentrations. However, the particle concentration will also be reduced leading to a substantial increase in the "unattached" fraction. Since this activity contributes much more dose per unit concentration than the attached activity, reduction in the decay product level may not lead to much reduction in the dose to the occupants. In these cases, it is important to measure the radon and estimate the exposure using the much larger f_{pot} value.

Dose Models

The objective of dose models is to relate the measured or estimated concentration of radon and/or its decay products to the energy actually deposited in the tissue of the respiratory tract. There are thus a number of issues that have been discussed that are deeply interrelated to the dose models including the equilibrium fraction and the amount and size distribution of the "unattached" fraction. Dr. B.S. Cohen (16) presented new results on the deposition of particles down to 0.04 μm diameter in lung casts that indicate that the predictive model previously employed to estimate the deposition underestimates the deposition velocities by a factor of 2. The results do show that a diffusional framework is generally correct. However, at the Reynolds numbers typical of respiratory tract flow which are in neither the laminar nor the turbulent flow regimes, further theoretical and experimental studies of the details of the depositional processes are needed.

There are distinct differences in the incorporation of the bronchial deposition in the dose models. As previously discussed, the James-Birchall model assumes an average dose to the bronchial region. The Jacobi-Eisfeld model (10) and NCRP (17) consider the differential dose to the segmental bronchi that depends on the preferential deposition of the unattached activity in the early generations. In these later models, the dose is dependent on both F and f_{pot}, while in the James-Birchall, the dose is relatively insensitive to these almost compensating factors. The results of these differences yield different doses depending on the particle size distribution and the amount of airborne particulate matter present. There are also problems in assessing the dose because of the changing size distributions of hygroscopic particles. This effect is not as critical to dose estimation for accumulation mode particles nor in the average dose approaches, but can cause factor of 2 changes in the segmental bronchial dose for a factor of 3 increase in size of a 1 nm particle. Thus, it is important to also have an understanding of the behavior of radon daughter-bearing particles under high humidity conditions.

To then examine the risk from the deposited activity with any model, it is necessary to know the "unattached" fraction, the activity median diameter, and a weighting factor for dose equivalent to bronchial tissue. For the James-Birchall model and a choice of f_{pot} of 5%, a median diameter of 0.12 μm, and a weighting factor of 0.06, the effective dose equivalent is about 15 mSv per WLM which is a factor of 3 higher than NEA (10) recommends or other corganizations have incorporated in their estimation of the fraction of total radiation dose that an average person receives from radon decay product exposure. If the particle size doubles because of its hygroscopic nature, this dose equivalent reduces to 10 mSv/WLM. However, there is experimental evidence that the hygroscopic increase in size is actually closer to a factor of 4 than 2. Thus, it may be important to distinguish hygroscopic from hydrophobic particles although it would be difficult to incorporate such differences into the models on a generalized basis. It was suggested that in spite of all these considerations, there is really a fair degree of uniformity to the calculated dose and that it only varies by a factor of 2 over the various lung generations unless there is an extremely high "unattached" fraction.

A question was raised as to the use of microdosimetric methods over the commonly applied absorbed dose calculational models. Microdosimetry says that at low doses, the absorbed dose is not meaningful in determining the biological effects. It is necessary to know the number of cells that are hit and the probability that a hit will induce a change in the cell leading to cancer induction. Most cells will not be affected but those that are may receive 50 to 60 rads. It thus may be more useful for the estimation of risk factors to consider microdosimetric methods. However, the dose-response functions that we use are a function of the type of dosimetry used to obtain them. It is important not to use microdosimetry to estimate the dosage to a given cell and then use dose-response curves developed on the basis of uniform dose to estimate the risk of malignancy development. It was generally felt that the traditional dosimetric approaches will yield reasonable estimates of the risks since consistent dose-response curves have been developed within this framework.

In evaluating the effects of radon decay products, it is not yet clear whether a relative risk or an absolute risk model applies. Some data seem to favor an absolute risk while other results support a relative risk approach. However, any of the models have to consider such factors as latency interval, age at which cancer appears, etc. Recent unpublished results on U.S. uranium miners (smokers and nonsmokers) seem to suggest that the risk of cancer induction decreases with time after leaving the high exposure mining environment. Thus, neither absolute and relative risk models apply directly and both have to be modified in order to match the available data on radon decay product induced effects.

There was general agreement that current measurement programs to quantify health risks should focus on radon and not the decay products since reliable monitors, calibration, and quality control procedures are not yet available for long term, integrated measurements of the decay products as are the available track-etch detectors for radon. Until there is an inexpensive, efficient and logistically manageable method for decay product measurements integrated over periods of up to a year, radon measurements must be used to assess exposure. The decay product level cannot be high unless there is high radon present so the use of radon monitoring will identify the population at greatest risk. The details of the actual exposure of the individuals to the daughters can now only be estimated. Thus, an integrating potential alpha energy concentration detector would be an extremely useful development for assessing population exposure in epidemiological studies and in testing dosimetric models.

A monitoring question that has not been fully addressed is that of thoron and its decay products. It has been common to assume that because its short half-life results in a sufficiently short diffusion length, thoron does not penetrate into houses in any significant amount. However, a recent report by Schery (18) suggests that thoron may contribute a significant amount in terms of potential alpha energy concentration, and more long-term monitoring of the impact of thoron and thoron decay products will be necessary in order to fully assess exposure to airborne radioactivity.

DOE/OHER Radon Research Plans

The objective of the discussion was to review the general directions that the Office of Health and Environmental Research of the U.S. Department of Energy has developed for radon research over the next five years. The overview of these plans has been presented by Lowder (19). The goal of the program is to develop the quantitative data and principles that will allow accurate assessment of radon exposure and associated lung cancer risk under environmental conditions. OHER has a particular concern with regard to public health risk associated with possible future trends in indoor radon exposure related to the application of advanced energy conservation technology in new housing. Thus, a comprehensive research program addressing a variety of basic physical, chemical and biological processes is needed to provide the basis for the needed risk assessments.

Radon Availability and Transport within Houses

The first goal of the research program is the development of a model for radon availability and transport into the indoor environment. Such a model would permit the identification of areas where houses would have a high risk of having elevated radon levels and the evaluation of potential control technologies for reducing the radon entry rates. It would be desirable to develop a set of variables that can be readily measured in a house and using those values, be able to predict the radon levels in that particular structure. These diagnostic tools would also permit the development of a cost-effective mitigation strategy for high exposure situations. The question would then be what are the key areas of research that are needed to move forward toward this goal.

There is a need to develop a standardized field measurement procedure to assess radon availability in soil gas so that inexpensive and easily used methods could be used and compared to a standard condition of known radon potential. Laboratory studies may be needed to help determine the critical variables to measure and how best to control the field conditions to obtain reproducible measurements of the critical parameters. To understand the transport of the radon into structures, it is necessary to consider that transport both in undisturbed and disturbed soils. The construction of a house does have an impact on the soil structure that must be explicitly considered and understood. By measuring the radon transport in soil where a house is to be built and then performing subsequent studies after construction, it may be possible to develop a model for the effects of various construction methods and housing designs on the transport processes in the soil around the structure.

However, at this time the state of knowledge is such that all of the critical variables may not yet have been identified or the measurement methods used to quantify those variables may not be providing sufficiently accurate and/or precise data to permit a full understanding of the problem. It is currently possible to make a series of detailed measurements on a few "representative" units of the housing stock. At that point it becomes necessary to generalize those measurements to a much larger number of housing units and thus good physical models are needed to provide a framework for making such extrapolations. It is likely that a number of such models will be needed to cover the range of buildings that are present in the available housing stock.

In developing and testing such mathematical models, the availability of "research houses" where various parameters can be controlled and measured will be invaluable to the testing and validation of the mathematical models. In order to examine the variety of interactions between design, construction practices, geography, geology, and climate, it will be necessary to have a large number of such houses available and to examine the radon levels and infiltration rates over the full range of indoor environmental conditions. However, the way in which the occupants use the house will affect its behavior. Thus, the pattern of heating, cooling, window and door openings may have a profound effect on the radon infiltration and somehow these kinds of factors must be included in the development of the physical and mathematical models if good predictive ability is to be achieved. These models can then be used to develop a cost-effective mitigation strategy that will reduce the radon exposure with limited penalties in energy utilization and occupant comfort.

A point was made in the discussion of these indoor radon questions that radon is not the sole indoor air quality problem and that it is necessary to consider it in the context of a broader range of pollutants including smoke, cooking residues, combustion by-products, materials off-gases, etc. Particularly when considering methods to mitigate against radon entry or reduce existing radon concentrations, the effects on the levels of the other airborne contaminants should be considered. However, the problem is that the only solutions that address both radon and these other pollutants are increased general ventilation and air cleaning. Increased ventilation for high radon houses will probably not work. Air cleaning will perform well for removing cigarette smoke, pollen, combustion products, etc., as well as radon progeny. However, as has been noted before, the increased "unattached" fraction that would be obtained from air cleaning may result in the same dose even though the airborne radioactivity level has been reduced. The report by Jonassen (20) addresses this question of how much dose reduction is obtained relative to the reduction in potential alpha energy concentration. The problem of effects of air cleaning on dose requires further study and deserves inclusion in future research plans.

Radon Exposure and Health Risk Assessment

The dose to the critical cells in the respiratory tract are strongly dependent on the deposition pattern of the inhaled radioactive particles, which in turn depends on the particle size and charge as well as factors associated with the individual breathing pattern and respiratory tract morphology. The accurate estimation of the long-term dose to these cells requires a full understanding of how the environmental factors not only affect the concentrations of radon progeny in the air, but also the physical properties (charge, size, rate of growth, rate of neutralization, coagulation rates, etc.) of the radon decay products. As discussed extensively above, a number of developments in instrumentation have recently led to new information on the behavior of the newly formed Po-218 some of which was reported at the ACS Symposium (21,22). New data are now available on the deposition of particles in the bronchial region over a wider range of particle sizes than had been previously available (16). There have also been continuing modifications to the models for estimating the dose (23,24). However, considerable uncertainties exist and there are clearly different points of view on the risk factors for radon decay product health effects (25,26). Thus, the accurate assessment of the amount and nature of airborne radioactivity, its deposition in the respiratory tract, the long-term dose that the radioactivity deposits in the tissue, and the dose-disease relationships still require considerable additional research and represent important research goals for the DOE/OHER program.

The development of a comprehensive research program then needs to support both basic and applied studies that examine the fundamental physics and chemistry of the decay products, the formation of radiolytic nuclei, the attachment of such nuclei to the preexisting aerosol, and the effects of the radon decay on the other components of the indoor atmosphere such as through the production of free radicals that can react with the gaseous constituents. At this time there are really only a very few measurements of the properties of the indoor aerosol and it is not yet possible to generalize these results to a wider range of homes. Additional measurements are needed to be certain that the full range of possible indoor conditions have been examined.

The previously discussed results of the work by Schery (18) suggest there is also a need for further measurements of thoron and its decay products. Thoron progeny may play a larger role in indoor exposure than has been considered to date. The other potential problem from thoron is its interference on measurements of radon and radon decay products. Thus, there is reason to make additional thoron measurements to determine if and where thoron problems may exist. Thus, there are a variety of additional measurements that are needed to better characterize the indoor airborne radioactivity. In conjunction with the need for more measurements, there must also be the continued development, testing, and validation of measurement methods for radon, the decay products, and the full range of properties of the particles to which the decay products are attached. DOE has held a leadership role in such method developments and needs to continue to do so.

Although the total picture is not yet clear, it appears that the components are now coming together that may make it feasible to start the development of indoor air chemistry models analogous to those that have already been developed for photochemical smog in the outdoor air. However, this effort will require the integration of a number of diverse studies to determine the critical gaps in our knowledge and identify the critical path toward obtaining the missing information. The benefits of having an integrated indoor air chemistry model that would include radon, its decay products along with the other components of indoor air could be a valuable tool in unraveling the complex patterns of health effects caused by indoor air.

A clear problem in terms of applying any air chemistry model developed to the U.S. housing stock is the lack of any model of that housing stock. It is necessary to have good representation of the gross characteristics and contents, energy-related or otherwise, of the U.S. housing stock. Thus, even if we could adequately model the atmosphere inside a home with a given set of characteristics, we cannot extrapolate that understanding to the population as a whole because of this lack of housing stock data. This problem is important to a variety of needs besides assessment of radon impacts and is badly needed for a variety of uses related to indoor air quality, energy utilization, and their interactions.

There are also research needs for better data on deposition of fine particles in the nasal region. There is very little literature on submicron particle deposition in this area of the respiratory tract. The work on bronchial deposition should be extended to even smaller particle sizes. There is a need for a better deposition model to bring the predictions into line with the new submicron data. With these results it will be possible to more fully predict the behavior of the ultrafine particle mode and thus better understand the role of the "unattached" fraction in dose deposition.

Another problem is the determination of the level of long-term exposure to radon decay products. There have been suggestions of measuring the Pb-210 concentrations in the skeleton as such an indicator. There was substantial criticism of this approach at the workshop on the basis that only a small fraction of the Pb-210 in the body comes from inhalation of radon decay products. There will also be considerable intake of this radionuclide in drinking water and food and thus it becomes very difficult to determine the effects of airborne radon relative to dietary intakes. There is also inadvertent ingestion of Pb-210 because of its accumulation on environmental surfaces resulting in hand contamination. Eating hand-held food may thus enhance the dietary intake to an unknown extent. There is also an indication that the detection systems for the Pb-210 may not be sensitive enough to accurately quantify typical exposure levels and may only be useful for high level exposures comparable to uranium miner levels. There was a report of using urinary levels of Pb-210 as an exposure indicator. Such measurements in conjunction with dietary monitoring might provide a useful measure of past exposure and may deserve further study. Also, Pb-210 deposited in dusts in poorly ventilated areas of a house may be useful as a measure of past radon levels and this concept also needs to be examined further. Although there is a real need for assessing past exposure and there has been some positive evidence for detecting radon exposure by Pb-210 in laboratory animals, there were very strong reservations expressed regarding the use of skeletal Pb-210 levels as an integrating monitor of past radon exposure.

Assessment of Health Risks by Epidemiological Studies

Current estimates of the lung cancer risks from inhalation of radon decay products are derived from epidemiological studies of underground miners, primarily uranium miners, in Colorado, Czechoslovakia, Sweden, and Canada. Current OHER research is limited to case control studies of uranium miners in New Mexico where dosimetric, medical, and lifestyle information are superior to previous miner studies, and a study of female lung cancer cases in Pennsylvania being initiated in October 1986. It is anticipated that these studies will provide much more reliable data on the lung cancer risk from radon exposure than prior studies.

It is important to plan epidemiological studies such that they can answer the critical questions that are being addressed. It is thus essential to be able to assess both the dose and the response in a sufficiently well characterized manner so that the resulting statistical analysis will be valid. It is not always possible with retrospective studies to be able to choose a representative population, to accurately assess the exposure of that population to the agent of interest, or to be able to sufficiently document the potential confounding factors. Thus, a case-controlled study of lung cancer in women in Pennsylvania outside of the major urban centers is being initiated in order to assess the risk from radon in a more typical population and at radon levels to which the general public may be exposed.

This study will also be able to provide information on confounding factors such as active and passive smoking. The study will measure the radon levels in houses in which the lung cancer patient lived. Year-long track etch detectors will be used in each house with a pair of detectors to determine the radon and thoron concentrations. The population in this area is quite stable and past experience by the Argonne National Laboratory on radium dial painters in this region suggests that they will be able to follow the population back in time long enough to provide useful results.

There are other epidemiological studies on-going in Canada and in Sweden as well as related studies in the U.S. Other populations that might be considered for studies are workers and/or patients at spa and natural hot springs where high radon levels are found. There are significant numbers of individuals involved at fewer locations to be monitored.

Quantitative Model of Lung Cancer Induction

A major emphasis of OHER radiation research program has been the investigation of the mechanisms of cancer induction following radiation exposure. The understanding of these mechanisms are necessary for the determination of the dose-response relationships over the range of radiation exposure encountered in the environment and the workplace. The current radon risk estimates are derived from the high exposure level of miners and the extrapolation to lower doses. In the absence of a well defined dose-response relationship, the extrapolation leads to considerable uncertainty in the resulting risk estimates.

The planned program will involve studies at both the cellular and subcellular level including searches for cellular markers and oncogenes, kinetic studies of tissue repair processes that lead to metaplasia and neoplasia, and other efforts to connect the effects of the passage of the alpha particle to the physico-chemical changes that ultimately manifest themselves as cancer. Experimental animal studies are needed, particularly to help elucidate the relationship between radon and smoking in lung cancer induction. There is some evidence that radon decay products primarily initiate the carcinogenic process while smoking promotes the cancer growth. Such a difference in function between these factors may significantly affect the risk estimates. Additional animal studies can help clarify this distinction as well as provide additional information on the transport, deposition and clearance of radioactive particles in the respiratory tract. Another important aspect of animal studies is that the effects of the radiation exposure rate as well as the total cumulative dose can be studied. Rate dependent effects are difficult to identify in epidemiological studies. There was an extended discussion of the difficulty in finding an adequate animal model for such studies and in extrapolating the results of controlled exposure of animals to the uncontrolled exposure of humans to complex mixtures of environmental toxins. Thus, although models have their place in elucidating mechanisms, the results of such studies may not directly result in better estimates of the risk of cancer from radon exposure.

The development of a detailed model of lung cancer induction caused by radiation exposure is a very major task, and this goal thus will potentially represent a very large effort with the required commitment of substantial resources. There are other agencies such as the National Cancer Institute who also have a mission in this area of cancer initiation and it will be important to coordinate OHER-sponsored studies to avoid duplication of effort being sponsored by the variety of interested agencies. It may be well for OHER to establish more formal links to other such agencies interested in this problem to provide the necessary program coordination.

EPA/ORP Radon Action Program

The Environmental Protection Agency has a radon-related program that involves both research and operational aspects. In addition to conducting the necessary research studies, a primary goal of the program is the dissemination of technical information to a variety of interested parties including state and local agencies dealing with public health and/or environmental issues, industries such as home building and construction, and individuals so that they can take informed action to accurately measure the radon levels and take appropriate actions to protect public health.

The EPA Radon Action Plan is conceived as a five year program with yearly review and updating. The primary goal is to reduce and prevent exposure to radon decay products in order to reduce the risk of lung cancer to the general population. The plan is striving to achieve this goal in the context of a non-regulatory program. There is currently no statutory authority for radon regulation in homes. The program is thus aimed at developing information and making that information available in such a manner as to provide the motivation and technical knowledge to alleviate the problem. The initial activities involve the implementation of national and state surveys to obtain data on the patterns of radon levels in homes and to evaluate methods for the prediction of areas where housing is at risk of having high radon levels, the development of standardized sampling and analysis protocols for radon and decay product concentrations, the development, demonstration, and evaluation of mitigation methods for reducing the radon levels in existing homes, and the development of new housing construction practices that would reduce the risk of the radon problems occurring.

Exposure Assessment

The plans for the EPA efforts in the area of exposure assessment have been described in detail by Magno and Guimond (27). This report outlines the objectives and planning considerations for the national survey of indoor radon concentrations to be conducted in the near-term future as well as EPA's program of quality assurance including measurement protocols and the measurement proficiency program. The design of the national survey is currently being planned and will be subjected to review before its implementation.

The stated objective of the survey program is to determine the frequency distribution of radon in houses on a national basis. A major question in the development of the survey design is that of how large a population of houses will need to be examined in order to provide the necessary information. In Table 1 reproduced here from Magno and Guimond (27), the number of units to be sampled is presented as a function of the point in the distribution of indoor radon concentrations to be determined and the precision with which that determination is to be made. Thus, to determine with 5% relative standard error, the point in the distribution where the radon concentration is only exceeded in 0.1% of the housing stock of the United States, it will be necessary to survey 800,000 houses. This analysis assumes a lognormal distribution with a geometric mean of 33 Bq/m^3 and a geometric standard deviation of 2.8 (28). In the discussion of this question, there was general agreement that there was little justification for determining the distributional value to better than 20% relative standard error and that the point in the distribution to be determined should be in the range from 0.1% to 1%.

There are several large data sets on radon in houses collected by the Terradex Corporation for the track-etch detectors they have sold to various agencies and individuals. Similarly, B.L. Cohen (29) in his symposium paper reported on a large number of samples that he has measured using charcoal canisters. However, in both these data bases, the samples are not accumulated on a planned design basis and in many cases, there is poor or misleading documentation of the location of the detector in terms of where the house is and where in the house the detector was placed. Thus, although there are many data points, it is extremely difficult to extract meaningful information regarding the distribution of radon in the entire U.S. housing population. Cohen (30) has recently published a more systematic survey of 453 houses using 1-yr track-etch detectors that yielded a lognormal distribution with a geometric mean of 38 Bq/m^3 and a geometric standard deviation of 2.36, quite similar to the Nero _et al._ (29) results. These distributions probably serve as the best starting points for the development of a larger survey design.

In the survey, there is consideration of stratifying the survey on the basis of 7 to 8 geographical regions and between single and multi-family housing with a bias toward oversampling single family houses and

Table 1

Number of Sampling Units for Various Population Percentages

Population Percentages (P)	Sample Size (No. of Units)		
	5% RSE	10% RSE	20% RSE
0.1	800,000	200,000	50,000
1	80,000	20,000	5,000
5	15,000	4,000	1,000

P = Percentage of housing units exceeding known radon concentration

RSE = relative standard error

undersampling multi-family housing. The sampling would still be fully random with the potential for additional oversampling in areas where the geology/radon relationships are being explored.

In the previous discussion, the problem of the lack of a survey of the U.S. housing stock was raised. In part the national radon survey will provide some additional information on the houses that are surveyed for radon. However, in light of the 1990 Census that will be undertaken, it may be more useful to enlist the cooperation of the Bureau of the Census to include some critical questions on the buildings in which people live to provide a more comprehensive data base on the housing stock.

There may be a problem with obtaining cooperation of the individual dwelling residents and various approaches have been employed to enlist people in various survey programs. It may be necessary to offer inducements to people to join the survey. How to approach the individual homeowner may be critical in obtaining a sufficient level of participation as to avoid biasing the sample. Mail solicitations have generally been less effective than direct personal contact. Random digit dialing may be an intermediate cost approach that will lead to an acceptable participation level.

New York State has used this approach in its survey of owner-occupied single family houses and initially had poor participation levels. They have reported better responses recently, but there is still a question of the efficacy of telephone solicitation relative to the door-to-door approach. In any case, it will be important to make a careful review of the survey as it is taken to insure that it is not being biased through uneven participation amongst the various strata in the design.

Another consideration in the survey is whether the occupant and/or owner should necessarily be given the results of the radon measurement. There may be legal problems in selling a home where the owner knows there is a radon problem, but does not disclose it to the potential buyer. In the Argonne study of Pennsylvania, they are allowing the occupant to request that he/she not be informed of the results. Offering this option may also help to improve the participation level.

While planning is ongoing for the national survey, an immediate problem is the identification of high risk areas. This problem is being approached in two ways: 1) by encouraging and providing assistance for state surveys to identify high risk areas, and 2) through the development of predictive methodologies to identify such areas. The EPA will assist the states with radon analyses with charcoal canisters, with assistance in survey design and sample selection, and with assistance in data analysis, management, and interpretation. It is hoped that approximately 15 to 20 states per year could be cooperatively surveyed with the goal of identifying those areas of high radon level potential.

In the longer term, the EPA is trying to develop a land assessment program that would provide a general idea of the hazard potential throughout the United States as well as develop both macro- and microscale models to evaluate regional areas down to individual sites for their potential radon hazard. In order to accomplish this objective, EPA is working with the U.S. Geological Survey to develop predictive models relating the geological setting of a dwelling with its potential for elevated radon levels. During field studies of mitigation methods as described in the next section, there will also be opportunities to gather critical data on soil characteristics and the effects of housing construction practice on the levels of radon in the resulting structures.

It is of great interest to the home construction industry to develop an inexpensive and simple method for evaluating a particular parcel of land for the potential radon in the house to be constructed and to develop an inexpensive and simple method to treat the soil during the construction to minimize the radon in the finished home. These are clearly difficult tasks and there are not obvious approaches to providing these methods.

Mitigation Methods

The mitigation demonstration program is being conducted by the EPA Office of Research and Development (ORD). The program is aimed at development of cost-effective mitigation methods. The initial work has focussed on 18 homes in the Reading Prong area of Pennsylvania and initial results of that work has recently been reported (31). The study is being expanded to some additional 30 to 40 homes in Pennsylvania and additional studies are to be conducted in New York and New Jersey on 50 and 30 homes, respectively. The program is a joint EPA/state venture, and it is hoped that results of the studies can be extrapolated to problems in other areas of the country. The initial step for each house is to identify the radon source, soil or water. If soil is the source, then understanding of the house dynamics becomes important and collaborative studies are being conducted with personnel from Lawrence Berkeley Laboratory to make measurements similar to those they have made elsewhere (5). Various mitigation methods from crack sealing to air-to-air heat exchangers can be tested and evaluated for cost and effectiveness in radon control and related to the building and soil properties. It is hoped that within a few years there will be several hundred homes that have had mitigation methods applied to them so that the experience with a variety of methods in a number of settings will be available.

A house evaluation program is also planned. This program would be to identify high radon level houses where the homeowner is participant in the evaluation and mitigation efforts in conjunction with the EPA and state government. In this way additional houses could be evaluated, mitigation methods evaluated and the understanding of the control methods improved.

Another part of the program is the evaluation of design and construction practices that would provide new housing construction with a greater level of protection against high indoor radon levels. This program is being developed jointly with the Department of Housing and Urban Development and various states. One other aspect of this design development is the desire on the part of builders and others to have a prescription or alternative prescriptions for the construction in the building code so that as long as the house conforms to the code, it can be sold regardless of the actual levels of radon found. Ericson (32) reported a series of designs for high radon potential areas that appeared to provide sufficient protection against radon entry. He also suggested that the house be designed and built with provision for subsequent radon reduction modifications to be made if needed at relatively low cost. Some doubts were expressed that there would be sufficient understanding of the radon entry problem to permit the development of designs that would provide absolute protection against future radon problems. However, the concept of incorporating provision for easy and low cost mitigation was strongly supported.

It was reported that in Sweden, there is a long term plan by the national government for reducing the general population exposure over the next century by a factor of 2. They plan to accomplish this reduction by insuring that as the housing stock is replaced, the newly constructed houses are radon resistant and easily mitigated. However, achievement of this goal does require the cooperation of the local building authorities to insure that construction practices adhere to this goal.

Finally, the EPA is currently confronted with whether they should encourage or discourage the use in high radon houses of air cleaning devices (electrostatic precipitators, HEPA filters, etc.) to remove the decay products relative to structural fixes to reduce the radon levels. The air cleaning systems will reduce the working level but increase the unattached fraction. Jonassen (20) has shown that you can reduce the overall dose by electrostatic filtration based on particular dose models. Although these devices do provide some limited improvement in the dose, they are not the best solutions to the indoor radon problem and their use may discourage the owner from taking the steps necessary to provide more effective and more permanent solutions to the problem.

Other Research

The EPA is also supporting one epidemiological study. The study focusses on lung cancer in women living in Maine and New Hampshire and with the University of Maine performing the study. This study is on-going and it will also be some time before results are available.

Public Information

Another of EPA's strong interests is in providing the public with clear and understandable information regarding the nature of radon and its risks. It wants to provide motivation for the public to cooperate in their own protection by having measurements made and then mitigating the problem if one is found to exist. The agency has released pamphlets entitled "A Citizen's Guide to Radon" and "Radon Reduction Methods". One of the major problems has been to find an effective way to express the comparative risk from radon in terms that the general public can understand. The brochure makes comparisons to cigarette smoking and medical x-ray exposures. It was pointed out that the brochure does not make clear that only the lung cancer risks are being compared since there are other disease risks associated with cigarette smoking. As an alternative, it was suggested that it may be useful to put the rates into perspective relative to causes of death other than cancer, for example, fatal accidents in the home or automobile-related fatality risks.

The point was made that the level of risk that the EPA is using is at the high end of the range of risk estimates and results in a remedial action guideline level (4 pCi/l) that is too restrictive and that will overly alarm the public. Levels previously recommended by health physics organizations such as the NCRP or the ICRP have been substantially higher (8 to 10 pCi/l). However, the need for public health protection suggests that a level should be set at a very conservative value that would then serve as a goal.

An alternative approach might be to introduce the ALARA concept with the associated costs and risks so that the individual who must make expenditure decisions can see the trade-offs between costs and risk reductions. However, it is going to be necessary to express those risks in comprehensible terms. Risks quoted as 1 in 100 or 1 in 1000 are not easily understood by the general public while $1500 for a ventilation system is immediately understood.

A strongly supported suggestion for all forthcoming documents is to present the radon concentrations in Bq/m^3 rather than starting the general public on the archaic unit of pCi/l. It would be best to begin the widespread dissemination of information on radon with the proper standard units rather than having to reeducate them later. Another suggestion for improving dissemination of radon information particularly in rural areas is to enlist the aid of the Agricultural Extension Service. The Ag Extension Advisors in each county could serve as a repository of pamphlets and efforts could be made to train some of the statewide extension advisors in radon related matters to provide consulting services to the county advisors in informing the public of the problem and ways to deal with it.

Conclusions

It was the consensus of the roundtable discussion that the research programs outlined and discussed did address the critical scientific issues related to radon and its decay products. During the past decade there has been a substantial improvement in our understanding of the behaviour and effects of indoor radon. However, there remain critical uncertainties that must be resolved with regard to the occurrence and causes of elevated radon concentrations in houses, the behaviour of the decay products and their relationship to indoor air quality, the effects of the decay products on public health, and the most effective methods for mitigating against high concentrations and human exposure. There appears to be excellent coordination and cooperation between the Department of Energy and the Environmental Protection Agency in developing the various aspects of the research and development programs. The goals and objectives of the plans presented covered the range of problems that our current state of knowledge reveal and the types of studies proposed represent a scientifically valid approach to resolving the existing questions.

Recommendations

As a result of these discussions, the following recommendations were made with regards to the critical areas of research and development related to indoor radon that need to be addressed in the near term future.

- Studies of the relationships between design and construction of houses and infiltration rates need to be continued. Such studies should include both existing housing and research houses.
- Studies are needed to test whether the available data on high potential radium content or soil permeability based on information such as the NURE maps or from data from the Soil Conservation Service are sufficient to make predictions of areas that might be high radon areas.
- From the results of such studies, a land assessment program should be developed that would provide a general idea of the hazard potential throughout the United States as well as develop both macro- and microscale models to evaluate regional areas down to individual sites for their potential radon hazard.
- A standardized field measurement procedure to assess radon availability in soil gas is needed. Laboratory studies are needed to determine the critical variables to measure and how best to control the field conditions to obtain reproducible measurements.
- Physical models are needed that would be able to predict the radon levels in a particular structure for a given radon availability and could evaluate potential construction or control technologies for reducing the radon entry rates.
- Studies are needed to find an appropriate, long-term, integrating measurement of the radon decay product concentrations and the size distributions of the activity so that from the health effects found in a population, the complete exposure/dose/effects relationships can be evaluated.
- There is a critical need for measurements of the activity size distributions for chemical investigations of the indoor atmosphere. Such measurements may also be important for assessing the dose depending on which dosimetric model is employed. Improvements in the methods for determining activity size distributions particularly for particles with diameters below 10 nm are needed.

- Basic and applied studies are needed to examine the fundamental physics and chemistry of the decay products, the formation of radiolytic nuclei, the attachment of such nuclei to the preexisting aerosol, and the effects of the radon decay on the other components of the indoor atmosphere such as through the production of free radicals that can react with the gaseous constituents. The results of such studies can then be incorporated into a comprehensive indoor air quality model.

- Measurements of thoron and its decay products are needed to determine if thoron progeny are more significant in indoor exposure than has been considered to date.

- Further theoretical and experimental studies of particle deposition at the Reynolds numbers typical of respiratory tract flow are needed. There are specific needs for better data on deposition of fine particles in the nasal region.

- Experimental animal studies are needed to help elucidate the relationship between radon and smoking in lung cancer induction, provide information on the transport, deposition and clearance of radioactive particles in the respiratory tract, and examine the effects of the radiation exposure rate as well as the total cumulative dose.

- Epidemiological studies are required that can assess the exposure/dose/respose in a human population in a sufficiently well characterized manner so that the resulting statistical analysis will be valid.

- Investigation of the basic biochemical mechanisms of cancer induction following radiation exposure is needed for the determination of the dose-response relationships over the range of radiation exposure encountered in the environment and the workplace.

- There is a need for a national survey to determine the frequency distribution of radon in houses on a national basis with sufficient precision as to be able to assess the public health threat posed by radon and the number of houses in the upper portion of the distribution that require immediate and effective mitigation efforts.

- Further studies are needed in the development of cost-effective mitigation methods for high radon houses.

- Additional work is needed to improve design and construction practices so that new houses would provide a greater level of protection against high indoor radon levels.

- There is a continuing need to provide the public with clear and understandable information regarding the nature of radon and its risks as well as the motivation for the public to cooperate in their own protection by having measurements made and then mitigating the problems that are found to exist.

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