Study of the Atmospheric Chemistry of Radon Progeny in Laboratory and Real Indoor Atmospheres

Final Project Report

Philip K. Hopke
Department of Chemistry
Clarkson University
Potsdam, N.Y. 13699-5810

MASTER

HH
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

September 31, 1996

Prepared for

THE U.S. DEPARTMENT OF ENERGY
UNDER AGREEMENT NO. DE-FG02-90ER61029

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ABSTRACT

This report completes Clarkson University's study of the chemical and physical behavior of the ^{218}Po atom immediately following its formation by the alpha decay of radon. Because small changes in size for activity in the sub-10 nm size range result in large changes in the delivered dose per unit exposure, this behavior must be understood if the exposure to radon progeny and its dose to the cells in the respiratory tract are to be fully assessed. In order to pursue this general goal, two areas of radon progeny behavior are being pursued; laboratory studies under controlled conditions to better understand the fundamental physical and chemical processes that affect the progeny's atmospheric behavior and studies in actual indoor environments to develop a better assessment of the exposure of the occupants of that space to the size and concentration of the indoor radioactive aerosol. Thus, two sets of specific goals have been established for this project.

The specific tasks of the controlled laboratory studies are 1.) Determine the formation rates of $\cdot\text{OH}$ radicals formed by the radiolysis of air following radon decay, 2.) Examine the formation of particles by the radiolytic oxidation of substances like SO_2 , ethylene, and H_2S to lower vapor pressure compounds and determine the role of gas phase additives such as H_2O and NH_3 in determining the particle size, 3.) Measure the rate of ion-induced nucleation using a thermal diffusion cloud chamber, and 4.) Measure the neutralization rate of $^{218}\text{PoO}_x^+$ in O_2 at low radon concentrations.

The specific tasks of the exposure studies in occupied indoor spaces are 1.) Initiate measurements of the activity size distributions in actual homes with occupants present so that the variability of the indoor activity size distributions can be assessed with respect to indoor aerosol sources and general lifestyle variations of the occupants, 2.) Initiate a prospective study of the utility of measurement of deposited ^{210}Pb embedded in glass surfaces as a measure of the long-term, integrated exposure of the population to radon, and 3.) Develop the methodology to determine the hygroscopicity of the indoor aerosol so that the changes in deposition efficiency of the radioactive indoor aerosol with hygroscopic growth in the respiratory tract can be assessed.

This report describes the results obtained in achieving these objectives.

ACKNOWLEDGEMENTS

I would like to acknowledge the hard work and dedication of the graduate student and post-doctoral associates who have worked on this project. Without their dedication and effort, the work reported here and in the numerous journal publications would not have been possible. We had a number of valuable collaborators including Earl Knutson, Andy George, Carl Gogolak, and Keng Tu of the Environmental Measurements Laboratory; Richard Sextro, Joan Daisey, Mindi Xu, and Matty Nematollahi; Pentti Paatero of the University of Helsinki; Bill Marlow of Texas A&M University; Yung-Sung Cheng and Hsu-Chi Yeh of ITRI; Al. Cavallo, Ken Gatsby, and Rob. Socolow of Princeton University; and David Swift of Johns Hopkins University. These interactions permitted us to do additional interesting studies. We also would like to thank the people who permitted us to come into their homes to make measurements of activity weighted size distributions. We would like to thank the Office of Health and Environmental Research of the U.S. Department of Energy, its Radon Research Program headed by Dr. Susan Rose and our project officer, Dr. Matesh Varma for the opportunity to develop these techniques and to make the measurements we have been able to do over the 6 years of this project and in the earlier DOE Radon Program Projects.

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
LABORATORY STUDIES	1
•OH Radical Production Rate	1
Ion-Induced Nucleation	2
Neutralization Rates	4
Characterization of $^{218}\text{Po}^+$ Ion Clusters	5
Circular Electrical Mobility Spectrometer	5
Hypersonic Impaction of Radon Progeny	10
REAL INDOOR ATMOSPHERE STUDIES	10
Exposure Assessments in Occupied Houses	11
Measurement Method Development	11
Prospective Study of ^{210}Po in Glass	12
Hygroscopic Growth of Particles	13
SUMMARY	13
REFERENCES	14
CURRENT PROJECT PERSONNEL	17
PUBLICATIONS ARISING FROM THIS CONTRACT	17
PRESENTATIONS OF RESULTS OF THIS CONTRACT	20

INTRODUCTION

The health effects of the radon decay products are strongly dependent upon their behavior in the indoor atmosphere. Particularly for ^{218}Po , the partitioning between the "unattached" state and the "attached" forms, combined with the preexisting aerosol particles, has a significant impact on the calculation of the dose to the lung resulting from a given decay product concentration. Thus, the chemical and physical behavior of the ^{218}Po atom immediately following its formation by the alpha decay of radon must be considered if its health implications are to be fully assessed. This report completes the project to investigate the chemical and physical behavior of radon progeny.

LABORATORY STUDIES

The principal areas of the laboratory studies during the current period have been 1.) Determination of the formation rates of $\cdot\text{OH}$ radicals formed by the radiolysis of air following radon decay, and 2.) Measurement of the rate of ion-induced nucleation using a thermal diffusion cloud chamber, 3.) Measurement of the small ion recombination neutralization rate of $^{218}\text{Po}^+$ in pure O_2 , and 4.) Development and application of systems to measure the ion-cluster behavior of the $^{218}\text{Po}^+$ in the presence of a variety of typical indoor volatile organic compounds.

$\cdot\text{OH}$ Radical Production Rate

We have measured the HO_x radical concentrations produced from radon decay with the chemical amplification system developed by Cantrell *et al.* (1984). In the chemical amplifier system, $\cdot\text{OH}$ radicals produced by ^{222}Rn decay in air participate in a series chain reactions with high concentrations of CO (10%) and NO (ppm), resulting in high concentrations of NO_2 . The product NO_2 is measured by luminol chemiluminescence. These reactant gases as well as radon-laden N_2 is mixed into a stream of purified air. The air then passes through a flow-through detector system based on the gas-surface reaction of NO_2 with a 0.01 M Na_2SO_3 , 0.05% methanol, 0.001M aqueous luminol solution of pH 12 (Maeda *et al.*, 1980). Contaminant NO_2 in the reactant NO gas is removed by passing the gas stream over FeSO_4 . This work has been reported by Ding and Hopke (1993).

Ion-Induced Nucleation

We have used the thermal diffusion cloud chamber developed earlier in this project to measure the critical supersaturations and rates for ion-induced nucleation. The potential for ion-induced nucleation of volatile organic compounds (VOCs) by radon decay in indoor environments was investigated by examining the behavior of series of various types of compounds. The first results of these studies on a series of short chain alcohols has been presented by He and Hopke (1993). To obtain a more detailed understanding of the role of the molecular properties such as orientation and distortion polarization on ion-induced nucleation, the critical supersaturation for both ion-induced nucleation and homogeneous nucleation (without radon added) were determined in a thermal diffusion cloud chamber and relating the trends of observed critical supersaturation values with the molecular polarization, both orientation and distortion, for the different classes of compounds under investigation. These compounds include short chain alcohols, carboxylic acids, aldehydes and ketones, aromatic hydrocarbons compounds and paraffins. The choice of these compounds is based on following consideration. First, they have relatively high concentrations and range from the order of micrograms per cubic meter to more than 100 times higher depending upon indoor VOC sources and ventilation rates (Daisey and Hopke, 1993). Second, a broad range of distortion (from 3.29 to $15.9 \times 10^{-24} \text{ cm}^{-3}$) and orientation polarization (from 0 to 2.88 Debye) is covered. Third, the choice of the compounds was limited to the substances whose boiling points must be much higher than their triple points because the condensing vapor must not be allowed to freeze on the condensation surface and the temperature of the liquid pool must be below its boiling point.

There are two indicators of the catalytic effect of the ion on the nucleation process. First, alpha tracks are visible in the nucleation zone (about 80% chamber height) when observed with the forward scattered light if sufficient vapor molecules nucleate on the ions at supersaturated conditions. The second indicator is the difference in the critical supersaturations between homogeneous and ion-induced nucleation at the same nucleation rate. A lower critical supersaturation is expected for ion-induced nucleation.

The results from a larger set of compounds are reported by He (1994) and He and Hopke (1996). Ion induced nucleation of short chain alcohols, carboxylic acids, aldehydes and ketones, aromatic hydrocarbon compounds, and paraffins was investigated experimentally using a thermal diffusion cloud chamber. The catalytic effect of the ions on nucleation is clearly observed for short chain alcohols, carboxylic acids, aldehydes and ketones, and some aromatic hydrocarbon compounds. A small increase in nucleation rate with radon concentrations was observed for n-nonane. However,

this increase is much smaller than that reported by Katz *et al* (1994). No alpha tracks and measurable critical supersaturation differences between the homogeneous and ion-induced nucleation by radon decay were observed for the C_6 to C_9 paraffins. This indicated that the nonpolar paraffins are not as sensitive to the presence of the ions as the polar substances.

The variation of experimentally determined free energy and free energy barrier as a function of cluster size demonstrate some basic physical features of the ion-induced nucleation. Considerable scattering in the plots of $\Delta(\ln S_{cr})$ against the dielectric constant and total polarization suggests that although Thomson's theory can demonstrate some basic physical features of ion-induced nucleation, it is inefficient to describe the critical supersaturation change between the homogeneous nucleation and ion-induced nucleation.

The second area of ion-induced nucleation study is to study H_2SO_4 - H_2O system with radiolytic formation of H_2SO_4 (He and Hopke, 1995). The chamber is cleaned, and helium, radon, and the mixture of O_2 and SO_2 was passed through a filter and introduced into it. When the water supersaturation reaches about 1.15, a very fine mist was observed inside the chamber. After several minutes, the mist disappeared. The observed mist formation rates as a function of SO_2 concentration and its decay curve were reported in He and Hopke (1995). A higher SO_2 concentration led to a more concentrated mist.

It is important to understand what causes this mist formation. One speculation was that it is the impurities formed chemically after the filters (Mäkelä, 1992). A series of attempts was made to examine this mist formation mechanism. The mixtures of O_2 /He/ SO_2 / N_2 / H_2O /Radon, He/ SO_2 / O_2 / H_2O , He/ SO_2 / N_2 / H_2O , He/ H_2O / N_2 , and He/ H_2O have been tried. It was found that whenever SO_2 was involved in the mixture, the condensed mist can be observed. Without the presence of SO_2 , no mist can be seen. This observed phenomena has two implications. First, impurities are not the cause of the observed mist since the filtering is the same in all cases and there is no reason to believe that impurities only exist in the SO_2 cylinder. Second, besides the binary nucleation of H_2SO_4 and H_2O , the binary nucleation of SO_2 and H_2O also contributed to the droplet formation in thermal diffusion cloud chamber.

Binary nucleation of sulfur dioxide and water vapor was observed and previously reported in cloud chamber experiments (Marvin and Reiss, 1978). It remains a problem to distinguish between SO_2 / H_2O and H_2SO_4 / H_2O nucleation. Therefore, in studying the oxidation of SO_2 and the binary H_2SO_4 - H_2O nucleation, the binary nucleation between SO_2 and H_2O cannot be excluded. Second, the critical supersaturation for rain formation in both cases is much lower than that for homogeneous

nucleation for pure water vapor (about 3.5) at the same temperature. This result indicated that the presence of SO_2 reduced the water vapor supersaturation needed for nucleation to occur. Third, the difference between the rain limits for two situations considered indicated that presence of the radon in gas phase of the chamber promoted the normal nucleation process.

Neutralization Rates

We have collaborated with Dr. Y.S. Cheng and coworkers at ITRI on the neutralization of the $^{212}\text{Pb}^+$ ion formed in the decay of ^{220}Rn . In these studies, we have repeated the type of experiment performed by Goldstein and Hopke (1985), but with ^{220}Rn rather than ^{222}Rn . The results of this study have been published (Cheng *et al.*, 1994).

We have initiated studies of the neutralization in ultrapure O_2 to extend the range of radon concentrations to lower values than was possible in our earlier study (Shi and Hopke, 1991). In order to complete these experiments, we have been collaborating with Professor A.J. Howard of the Department of Physics, Trinity College, Hartford, CT. Professor Howard has developed a system for measuring the neutralization rate for $^{218}\text{Po}^+$ ions under well controlled conditions (Howard and Strange, 1991). He has obtained results in good agreement with our earlier measurements (Shi and Hopke, 1991). We have borrowed his system and made one set of measurements. The results are shown in Figure 1. In this case we can observe the expected increase in neutralization rate with increasing radon concentration up to a point where it appears to plateau. However, we unexpectedly obtained a non-zero intercept and thus, the experiments are being repeated.

Figure 1. Neutralization rate as a function of ^{222}Rn concentration in pure O_2 .

Characterization of $^{218}\text{Po}^+$ Ion Clusters

We have initiated two approaches to the study of the ^{218}Po species formed immediately after their formation from ^{222}Rn decay. These studies involve the use of two different methods to measure the "size" of the $^{218}\text{Po}^+$, a circular electrical mobility spectrometer and a hypersonic impactor.

Circular Electrical Mobility Spectrometer

In our original proposal we have suggested continuing the experiments begun in conjunction with Professor William Marlow and his student that resulted in the work presented in Yoon *et al.* (1992). However, there was a serious problem with the resolution in that system. Although we have borrowed the unit from Prof. Marlow, we have subsequently discovered an alternative system that would appear to have a better potential for providing the resolution needed to examine the electrical mobility of the initial cluster ions. This system is a new form of mobility analyzer, the SMEC (Spectrometre de Mobilité Electrique Circulaire), originally developed at CEA by Pourprix and coworkers (Ooghe *et al.*, 1994) and is shown in Figure 2 (Pourprix, 1989). Filtered air is introduced into the lowest part of the SMEC through an axially mounted tube. It flows to the edges of the disc,

passes through a high efficiency filter and then flows radially from the edge to the center, between the upper plate (1, Figure 2) and the collection plate (6, Figure 2). This air is the sheath air in the SMEC and serves the same function as the sheath air in conventional EMA devices. It exits the SMEC through another axial tube located in the upper part of the device. The filter (8, Figure 2) is used to make sure that the air flow in the selection area is homogeneous and laminar. The aerosol to be analyzed is pulled in through an annular slit located on the upper plate. The particles and the filtered air meet in the selection area. The aerosol flow forms a thin layer close to the upper plate, the filtered air ensures that this layer is well defined. It is important that the aerosol and the filtered air flow together without mixing. When those two flows arrive at the SMEC axis, they leave through the extraction nozzle.

The aerosol is drawn into the slit by the following process. The exit from the SMEC is attached to a vacuum pump, the sheath air flowing in from the bottom is less than the rate at which the vacuum pump is removing gas from the SMEC. To balance this, the aerosol is drawn in through the slit.

Figure 2. Schematic diagram of the CEA circular electrical mobility spectrometer.

The main part of the SMEC is the selection area formed by the upper plate and the collection plate. The distance between these two plates is 4 mm. The collection plate (6, Figure 2) is handled by a crown (7, Figure 2). Both pieces are held at the voltage V . The voltage is delivered at a single point in contact with the pin of a bulkhead mounting SHV connector. They are insulated from the

remaining pieces of the SMEC (1, 2 and 3, Figure 2) that are grounded. The electric field existing in the selection area attracts the charged particles in the SMEC. Particles with high electric mobility will be collected on the collection plate while the others will pass through the extraction nozzle. When they exit, they are counted by an appropriate detector.

The SMEC was modified as follows. At the exit, a filter and detector holder was mounted. A schematic diagram is given in Figure 3. The air flow containing the particles is drawn around at a right angle and the particles are trapped on a Millipore, AA 0.8 μm , filter. The detector mounted directly opposite the filter is an EG&G ORTEC DIAD. This detector is a silicon barrier detector complete with a built-in preamplifier. The signal fed from the DIAD is amplified and connected to a

PC-based multichannel analyzer (MCA). The spectrum recorded by the MCA can be analyzed by the energy of the incident particle to separate only the ^{218}Po emissions. The voltage to the SMEC and the MCA are all controlled by a Power BASIC code which automatically increments the voltage supplied by an interface box and analyzes the spectrum for its ^{218}Po content.

Figure 3. Schematic diagram of the detector system to measure the amount of radioactive nuclei exiting the SMEC.

ions following the radon decay and the remaining 12% are neutral (Wellisch, 1913; Chu and Hopke, 1988). However, a even very small amount of trace gases can subsequently neutralize the charged ^{218}Po and thereby increase the diffusion coefficient. However, it must be remembered that with the proposed system only the charged particles are measured since the neutral ones are not captured by the electrostatic precipitation method. When ^{222}Rn or its decay products, ^{218}Po and ^{214}Po , decay, they produce approximately 167,000 ion-electron pairs by the passage of the α -particle through the medium. The recoiling ^{218}Po and the ^{214}Po atoms will be slowed down by a process called thermalization. The large number of free electrons means that although initially the fraction born charged is large, it can be neutralized quite rapidly. The speed of the neutralization will depend of the radioactive isotopes concentration and on the presence of VOCs of low ionization potential which

A set of experiments were performed to test the capability of this new system to size radioactive nanometric and sub-nanometric particles. It was expected that ^{218}Po produced in a nitrogen radon mixture would not to be chemically bounded to nor form molecular clusters with the nitrogen molecules. If such a mixture was analyzed the size of the clusters detected should correspond to ^{218}Po . Measurements, reported by several authors, give diffusion coefficients ranging from $0.04 - 0.08 \text{ cm}^2\text{s}^{-1}$ for these conditions. These values correspond to the size range 0.6 to 0.9 nm. The range is wide because neutral particles are more diffusive than the charged ones and then the mean diffusion coefficient measured depends on the degree of neutralization (Goldstein and Hopke, 1985). It is well known that 88% of the polonium atoms are created as singly charged

can participate in charge transfer reactions with the Po. Thus, the charged fraction could be much lower than the initially present 88%.

The SMEC transmission curve shown in Figure 4 was obtained by taking samples from a mixture of radon and pure dry nitrogen.

Normalized counts are obtained by dividing the actual counts by the maximum count during the experiment. The data shown was computed from three different sets of experimental results. For each experiment, the sampling time was set to 30 min to get an adequate number of counts; that is a Poisson error of around 3% in the counts. A delay time of 20 min followed each change of voltage, to allow the system to settle down and to remove interference from the short-lived activity accumulated on the filter at

the previous voltage. The value of the cutpoint voltage, V_c , was evaluated from this curve as shown in the theoretical curve that is illustrated in Figure 2. Equation 2 is then used to calculate the corresponding mobility. The value of the mean mobility measured for this case was $2.0 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$. Using the Ramamurthi semi-empirical model, for the diffusion coefficient to size relationship, this mobility corresponded to a mean diameter of 0.75 nm.

This result provides a measurement of the ^{218}Po clusters without any interaction with the surrounding gaseous environment. These results can be compared to those obtained with other techniques. First of all an experiment was performed with dry clean air ($\text{RH} \leq 4\%$) rather than nitrogen as the dilution gas. The air has been filtered to remove all aerosol and passed through molecular sieves to remove all trace VOCs and CO_2 . The results shown in Figure 5 give a shape similar to the one in Figure 4. This step curve suggests single mode cluster size distribution is present. The V_c value is larger than the previous experiment. It is 0.8 V which corresponds to a mobility of $1.25 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$, this mobility corresponds to a cluster sized around 1.0 nm. This larger size is most probably formed by molecules of H_2O clustering around the ^{218}Po ion.

Over 300 types of VOC have been detected in indoor air (Berlund *et al.*, 1986). Daisy and Hopke (1993) evaluated the formation of clusters of indoor VOC around ions, including $^{218}\text{Po}^+$ and

Figure 4. Response of the SMEC/radioactivity detection system to ^{222}Rn in 99.998% N_2 .

ion pairs produced by the passage of the 5.5 MeV α -particles and the recoiling Po nucleus through the air. The formation of clusters around ^{218}Po ions in the presence of butanol and ethanol clusters was investigated in this present.

When the alcohol is present in the radon chamber, our system detects larger particles/clusters (Figures 7 and 8). For both cases, ethanol or butanol, the corresponding SMEC response curves suggest a multi-modal size distribution. The curves show at least two steps and hence, two modes are clearly implied. The first mode is present in both cases and correspond to a size of about 0.75 nm. That is assumed to be the mode of ^{218}Po clusters without alcohol molecules around. The larger clusters mode size is 1.2 nm for ethanol and 2.2 nm for butanol. Due to the resolution of the system modes in between these two cannot be ruled out.

Figure 4. SMEC response for radon-clean air mixture.

Figure 5. SMEC response for radon-nitrogen-ethanol mixture.

Figure 6. SMEC response for radon-nitrogen-butanol mixture.

A modified radial flow electrical mobility analyzer (SMEC) was used to measure the mobility of radioactive particles. The system combines the use of electrostatic precipitation of charged particles together with radioactive particles detection. The system has clearly demonstrated the ability to measure mobilities corresponding to the sub-nanometer to a few nanometer size range. We investigated the case of the radon decay product ^{218}Po . The ^{218}Po clusters/particles are subnanometer (~ 0.75 nm). In an atmosphere containing trace gases, water vapor or VOC, these clusters will increase in size by the addition of molecules around the ^{218}Po ion. In the case of an atmosphere containing alcohols particles/clusters as large as 1.2 nm for ethanol and 2.2 nm for butanol were detected. This device can measure the physical diameter of the cluster; another device available, a Hypersonic Impactor, measures the aerodynamic diameter.

Hypersonic Impaction of Radon Progeny.

The ultimate aim of this project is to determine the size of radon progeny as a function of the prevalent gas composition in order to have a better understanding of the behavioral pattern of radon progeny in indoor atmosphere, and to better assess the exposure of the radon progeny and its dose to the cells in the respiratory tract. The SMEC provides information on the ion mobility of the ^{218}Po . Although we can relate the mobility to a diffusion coefficient and then to size, we cannot directly obtain a molecular weight. If we can use inertial separation of the Po species, then we can obtain an aerodynamic diameter that will include the particle density. Thus, from the diffusion diameter and the aerodynamic diameter, we can estimate the density and the molecular weight. This ability will permit us to finally determine the nature of the Po species in the presence and absence of O_2 , estimate the number of water vapor molecules that cluster around the $^{218}\text{Po}^+$ as a function of relative humidity, and a number of other problems that have previously been intractable.

To achieve this objective, a hypersonic impactor based on the work of Prof. Juan de la Mora of Yale University (de la Mora *et al.*, 1990 a&b; de la Mora and Schmidt-Ott, 1993) has been designed using plans provided to us by Prof. de la Mora and built. This impactor has been described by Olawoyin *et al.* (1995).

REAL INDOOR ATMOSPHERE STUDIES

The specific tasks of the exposure studies in occupied indoor spaces are 1.) Initiate measurements of the activity size distributions in actual homes with occupants present so that the variability of the indoor activity size distributions can be assessed with respect to indoor aerosol

sources and general lifestyle variations of the occupants, 2.) Initiate a prospective study of the utility of measurement of deposited ^{210}Pb embedded in glass surfaces as a measure of the long-term, integrated exposure of the population to radon, and 3.) Develop the methodology to determine the hygroscopicity of the indoor aerosol so that the changes in deposition efficiency of the radioactive indoor aerosol with hygroscopic growth in the respiratory tract can be assessed.

Exposure Assessments in Occupied Houses

The measurement of activity-weighted size distributions in normally occupied homes are made using the automated, semi-continuous, graded screen array system described by Ramamurthi and Hopke (1991). The individual studies were published previously (Li and Hopke, 1991a&b; Hopke *et al.*, 1993a; Wasiolek *et al.*, 1993; Hopke *et al.*, 1994). We have reanalyzed all of these results and presented them in Hopke *et al.* (1995).

Measurement Method Development

We are continuing to study the various approaches (Hopke and Paatero, 1994) to the deconvolutions of the activity-weighted size distributions in order to understand the nature of the differences that have been seen in our intercomparisons with others who can make such measurements. We have run another intercomparison experiment in the Twilight Mine, Uravan, CO in May 1994 with EML and the US Bureau of Mines. There are again differences in the amounts of activity in the 3 to 15 nm size range which have important dosimetric implications. After attending the Indoor Air Workshop in Gold Coast, Australia, Prof. Hopke visited Dr. Stephen Solomon and the Australian Radiation Laboratory (ARL) as did Prof. J. Porstendörfer of the University of Göttingen and John Strong of AEA Technologies, U.K. and a discussion of the differences that have been observed in activity-weighted size distribution measurements in homes were discussed. The Göttingen group has not seen the ultrafine peak while the ARL measurements had observed such a peak. At this time, it is not clear why these differences exist and which results are correct.

Prospective Study of ^{210}Po in Glass

Prior studies by Dr. R. Lively of the Minnesota Geological Survey (Lively and Ney, 1987) and Christer Samuelsson of Lund University, Sweden (Samuelsson, 1988) on the relationship between measured ^{210}Po embedded in glass and ambient radon concentrations. When ^{214}Pb or ^{214}Bi is deposited on a surface in a room, they will adsorb to the surface. When the resulting ^{214}Po emits its α particle, the ^{210}Pb nucleus recoils with sufficient energy to embed it about 40 nm into the surface. Thus, it is thus below the surface and is not removed by cleaning, but it is close enough to the surface that the 5.3 MeV α from ^{210}Po can be observed.

All of the previous work has been done using existing glass surface in the house and a year of α measurements. Lively and Steck (1991) has demonstrated the kind of wide variability that can occur even in the annual average radon concentration. Also people are not always certain when the particular piece of glass was placed into its current environment. Thus, some uncertainty exists in the value of the calibration constant. Furthermore, there has not been a study of the variations that might exist within a room or between rooms in the same house. These are the questions our study hopes to address.

Our study plan was to place 150 pairs of 8" x 10" pictures into houses. We placed 144 pair of pictures into homes from California to New York. Another 20 pictures in groups of ten have been placed into two schools (one in Maine and the other in South Dakota). In 50 houses, the pictures are placed in the most lived in room of the house (living or family room). In 50 houses, the pair of pictures go in the master bedroom and in the remaining 50 houses, the pair are split between the two rooms. Within each group of 50 placed in the same room, we have split them into two groups. In the one case, both pictures are placed on an inside wall and in the other, the pair are split between inside wall and outside wall. For the 50 split between two rooms, half have both pictures on inside walls and half have both on outside walls. The pictures are being placed for 18 months. With each picture, there is at least one etched track detector. For 50 individual pictures chosen at random, there are 2 detectors as a QA check. We also have storage blanks and spiked samples. All of these detectors have been analyzed by the vendor.

We have retrieved the exposed pictures. Each picture was individually wrapped in aluminum foil to prevent any inadvertent further exposure in the laboratory. We have counted the activity in the glass with pulse ionization chambers for a sufficiently length of time to provide better than 10% counting statistics. We are currently preparing a manuscript for publication

Hygroscopic Growth of Particles

The final task of this portion of the project was the development of the tandem differential mobility analyzer (TDMA) system to measure the hygroscopic growth of the indoor aerosol when it encounters $> 99\%$ relative humidity within the respiratory tract. The system has been developed that does permit the measurements to be made (Li *et al.*, 1992??). The system has been used to perform a series of measurements on several types of indoor particle sources. Growth studies have been conducted on particles present in cigarette smoke (mainstream and sidestream), incense smoke, and produced by candles, natural gas and propane flames. These results were presented by Li and Hopke (1993). Additional studies of consumer products including hair spray, aerosol cleaning products, and pesticides have been performed and the results of these studies was presented in Li's Ph.D. thesis (1993), at the Indoor Air '93 conference in Helsinki in July 1993 (Hopke *et al.*, 1993b) and has now been published (Li and Hopke, 1994). This work is continuing with support from the Center for Indoor Air Research. The effect of hygroscopic growth on dose has reported by Dua and Hopke (1996)

SUMMARY

We made considerable progress with the support of the OHER Radon Research Program. A number of new and innovative experimental systems have been developed and are now on-line. It is regrettable that it will not be possible to characterize the radon decay products as we are now capable of doing. Substantial data characterizing the behavior of the radon progeny both in the laboratory and in the real world has been produced, but a number of scientifically interesting details must be left for future investigations.

REFERENCES

- Berlund, B., Berlund, U. and Lindvall, T. (1986) Managing indoor air for health and energy conservation. In Proceedings IAQ'86, ASHRAE, Atlanta, GA, pp. 138-149.
- Cantrell, C.A., Stedman, D.H., and Wendel, G.J. (1984) Measurement of Atmospheric Peroxy Radicals by Chemical Amplification, *Anal. Chem.* 56:1496-1502.
- Cheng, Y.S., Yu, C.C., Tung, C.J., and Hopke, P.K. (1994) Neutralization of Thoron Progeny in Gases, *Health Phys.* 67:155-161.
- Chu, K.D. and Hopke, P.K. (1988) Neutralization Kinetics for Polonium-218, *Environ. Sci. Technol.* 22:711-717.
- Daisey, J.M. and Hopke, P.K. (1993) Potential for Forming Ultrafine Aerosols from Indoor Organic Vapors by Radon Decay Radiolysis-Induced Reactions, *Aerosol Sci. Technol.* 19:80-93.
- de la Mora, J.F., S.V. Hering, N. Rao, and P.H. McMurry (1990a) Hypersonic Impaction of Ultrafine Particles, *J. Aerosol Sci.* 21:169-187.
- de la Mora, J.F., Rao, N., and McMurry, P.H. (1990b) Inertial Impaction of Fine Particles at Moderate Reynolds Numbers and in the Transonic Regime with a Thin-Plate Orifice Nozzle, *J. Aerosol Sci.* 21:889-909.
- de la Mora, J.F. and Schmidt-Ott, A. (1993) Performance of a Hypersonic Impactor with Silver Particles in the 2 nm Range, *J. Aerosol Sci.* 24:409-415.
- Ding, H. and Hopke, P.K. (1993) OH Production Due to Radon Decay in Air, *J. Atmos. Chem.* 17:375-390.
- Dua, S.K. and P.K. Hopke, Hygroscopicity of Indoor Aerosols and Their Influence on the Deposition of Inhaled Radon Decay Products, *Environ. Int.* (in press, 1996).
- Goldstein, S.D. and Hopke, P.K. (1985) Environmental Neutralization of Po-218, *Environ. Sci. Technol.* 19:146-150.
- He, F. (1994) *Experimental Study of the Ion-Induced Nucleation by Radon Decay*, Chemical Engineering, Clarkson University, October 1994, Department of Energy Report No. DE/ER61029-17.
- He, F. and P.K. Hopke (1993) Experimental Study of Ion-Induced Nucleation by Radon Decay, *J. Chem. Phys.* 99:9972-9978.
- He, F. and P.K. Hopke (1995) SO₂ Oxidation and H₂O-H₂SO₄ Binary Nucleation by Radon Decay, *Aerosol Sci. Technol.* ??
- He, F. and P.K. Hopke (1996) Experimental Study of Ion-Induced Nucleation of Volatile Organic Compounds by Radon Decay, in *Nucleation and Atmospheric Aerosols 1996*, ed by M. Kulmala and P.E. Wagner, Elsevier Science Ltd, Oxford, U.K. 50-53.
- Hopke, P.K. and P. Paatero (1994) Extreme Value Estimation Applied to Aerosol Size Distributions and Related Environmental Problems, *J. Res. NIST* 99:361-367.
- Hopke, P.K., N. Montassier, and P. Wasiolek (1993a) Evaluation of the Effectiveness of Several Air Cleaners for Reducing the Hazard from Indoor Radon Progeny, *Aerosol Sci. Technol.* 19:268-278.
- Hopke, P.K., W. Li, and S.K. Dua (1993b) Hygroscopic Growth of Particles from Indoor Sources, presented at the Sixth International Conference on Indoor Air Quality and Climate, Helsinki, Finland, July 4-8, 1993.
- Hopke, P.K., B. Jensen, and N. Montassier (1994) Evaluation of Several Air Cleaners for Reducing Indoor Radon Progeny, *J. Aerosol Sci.* 25:395-405.
- Hopke, P.K., B. Jensen, C.S. Li, N. Montassier, P. Wasiolek, A. Cavallo, K. Gatsby, R. Socolow, and A.C. James (1995) Assessment of the Exposure to and Dose from Radon Decay Products in Normally Occupied Homes, *Environ. Sci. Technol.* 29:1359-1364.

- Howard, A.J. and W.P. Strange (1991) Measurement of $^{218}\text{Po}^+$ Neutralization Rates in Gases, *Nucl. Instrum. Methods* A311:378-385.
- Katz, J., J. Fisk, M. Chakarov (1994) Condensation of a Supersaturated Vapor IX: Nucleation on Ions, *J. Chem. Phys.* 101, 2309-2318.
- Li, C.S. and P.K. Hopke (1991a) The Efficacy of Air Cleaners in Controlling Indoor Radon Decay Products, *Health Phys.* 61:785-797.
- Li, C.S. and P.K. Hopke (1991b) Characterization of Radon Decay Products in a Domestic Environment, *Indoor Air* 1:539-561.
- Li, W. (1993) *Hygroscopicity of Indoor Aerosol Particles*, Chemistry, Clarkson University, Potsdam, NY, July 1993, Department of Energy Report DE/ER/61029-14.
- Li, W. and P.K. Hopke (1993) Initial Size Distributions and Hygroscopicity of Indoor Combustion Aerosol Particles, *Aerosol Sci. Technol.* 19:305-316.
- Li, W. and P.K. Hopke (1994) Hygroscopicity of Consumer Spray Product Aerosol Particles, *J. Aerosol Sci.* 25: 1342-1351.
- Li, W., N. Montassier and P.K. Hopke (1992) A System to Measure the Hygroscopicity of Aerosol Particles, *Aerosol Sci. Technol.* 17:25-35.
- Lively, R. and E.P. Ney (1987) Surface Radioactivity Resulting from the Deposition of ^{222}Rn Daughter Products, *Health Phys.* 52:411-415.
- Lively, R. and D. Steck (1991) Current Status of Glass as a Retrospective Radon Monitor, in the Proceedings of the 1991 Symposium on Radon and Radon Reduction Technology, U.S. Environmental Protection Agency, Research Triangle Park, NC.
- Maeda, Y.K., K. Aoki, and M. Munemori (1980) Chemiluminescence Method for the Determination of Nitrogen Dioxide, *Anal. Chem.* 52:307-311.
- Mäkelä, J. (1992) Studies on Irradiation Induced Aerosol Particle Formation Processes in Air Containing Sulfur Dioxide, *Acta Polytechnica Scandinavica*, Applied Physics Series No. 182. Helsinki, Finland.
- Marvin, D.C., and H. Reiss, H. (1978) Cloud Chamber Study of the Gas Phase Photooxidation of Sulfur Dioxide, *J. Chem. Phys.* 69:1897-1916.
- Olawayin, O.O., T. M. Raunemaa, and P. K. Hopke (1995) A System for Aerodynamically Sizing Ultrafine Radioactive Particles, *Aerosol Sci. Technol.* 23:121-130.
- Ooghe, M., B. Mesbah, M. Pourprix, and D. Boulaud (1994) Radial Flow Mobility Analyzer (RF-DMA), *Proceedings of the Fourth International Aerosol Conference*, American Association for Aerosol Research, Cincinnati, OH, 463-466.
- Pourprix, M. (1989) Capteur Electrostatique de Particules d'Aerosol. Brevet Francais 89 08400.
- Ramamurthi, M. and P.K. Hopke (1991) An Automated, Semi-Continuous System for Measuring Indoor Radon Progeny Activity-Weighted Size Distributions, d_p : 0.5-500 nm, *Aerosol Sci. Technol.* 14:82-92.
- Samuelsson, C. (1988) Retrospective Determination of Radon in Houses, *Nature* 334:338-340
- Shi, B. and P.K. Hopke, (1991) The Study of Neutralization of Po-218 Ions by Small Ion - Recombination in O_2 , Ar and N_2 , *Health Phys.* 61:209-214.
- Wasiolek, P., N. Montassier, P.K. Hopke, R. Abrams (1993) Analysis of the Performance of a Radon Mitigation System Based on Charcoal Beds, *Environmental Technology Letters* 14:401-412.
- Wellisch, E.M. (1913) The Distribution of the Active Deposit of Radium in an Electric Field- II., *Phil. Mag* [6] xxvi:623-635.
- Yoon, S.C., W.H. Marlow and P.K. Hopke (1992) Measurement of the Effect of SO_2 on the Polonium-218 Ion Mobility Spectrum by Alpha-Track Detection, *Health Physics* 62:51-57.

PROJECT PERSONNEL

Principle Investigator

Philip K. Hopke, Robert A. Plane Professor of Chemistry

Other Professionals

Piotr Wasiolek, Research Associate, March 1, 1990 - July 1, 1991
 Nathalie Montassier, Research Associate, August 1, 1990 - July 31, 1992
 Taisto Raunemaa, Visiting Research Professor, August 1, 1993 to August 31, 1994.
 Vandana Dayte, Research Associate, October 1, 1994 to March 31, 1995.
 Brian Fitzgerald, Research Associate, October 1, 1994 to June 30, 1996
 Boualem Mesbah, Research Associate, June 15, 1995 - July 15, 1996

Graduate Research Assistants

Kim Karpen-Hayes, Teaching Assistant, August 1, 1989 - June 30, 1991.
 Yefei Wu, Research Assistant, July 1, 1990 - June 30, 1991.
 Huiling Ding, Research Assistant, July 1, 1990 - August 31, 1993
 Wei Li, Research Assistant, July 1, 1990 - July 31, 1993
 Feng He, Research Assistant, August 15, 1991 - October 15, 1994.
 O.O. Olawoyin, Research Assistant, July 1, 1993 - September 1, 1995
 Lin Fei, Research Assistant, August 16, 1993 - June 30, 1995

PUBLICATIONS ARISING FROM THIS CONTRACT

Measurement of the Size Distributions of Radon Progeny in Indoor Air, P.K. Hopke, M. Ramamurthi, and C.S. Li, in *Aerosols: Science, Industry, Health, and Environment*, S. Masuda and K. Takahashi, eds, Vol. 2, Pergamon Press, Ltd, Oxford, 842-847 (1990).

The Effect of Air Cleaning on the Size of the Radioactive Indoor Aerosol, P.K. Hopke, C.S. Li, and M. Ramamurthi, in *Aerosols: Science, Industry, Health, and Environment*, S. Masuda and K. Takahashi, eds, Vol. 2, Pergamon Press, Ltd, Oxford, 827-832 (1990).

Field Evaluation and Health Assessment of Air Cleaners in Removing Radon Decay Products in Domestic Environments, C.S. Li, Ph.D. thesis, University of Illinois at Urbana-Champaign, Urbana, IL, Department of Energy Report No. DOE ER61029-2, (1990).

Radon and Radon Progeny Measurements, P.K. Hopke and P. Wasiolek, *Trends Anal. Chem.* 10:243-249 (1991).

Intercomparison of Activity Size Distribution Measurements with Manual and Automated Diffusion Batteries - Field Test, P.K. Hopke, P. Wasiolek, E.O. Knutson, C. Gogolak, A. Cavallo, K. Gadsby and D. Van Cleef, in the Proceedings of the 1991 International Symposium on Radon and Radon Reduction Technology, Philadelphia, PA, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1991.

Analysis of the Performance of the Radon Mitigation System Based on Charcoal Bed, P. Wasiolek, N. Montassier, P.K. Hopke and R. Abrams, in the Proceedings of the 1991 International Symposium on Radon and Radon Reduction Technology, Philadelphia, PA, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1991.

The Field Measurements of the Activity-Weighted Size Distribution of Radon Decay Products, P. Wasiolek, P.K. Hopke, N. Montassier, A. Cavallo and K. Gadsby, in *Measurement of Toxic and Related Air Pollutants*, B. Gay and R.K.M. Jayanty, eds., Air & Waste Management Association, Pittsburgh, PA, 128-133, 1991.

The Effects of Air Cleaners on the Indoor Radon Hazard, C.S. Li, and P.K. Hopke, Paper No. 91-63.2, Air & Waste Management Association, Pittsburgh, PA, 1991.

Using the Thermal Diffusion Cloud Chamber to Study the Ion-Induced Nucleation by Radon Decay, Y. Wu, MS Thesis, DOE Report No. DE/ER/61029-7 (1991).

The Production of Sulfate Particles Through the Radiolytic Oxidation of Sulfur Dioxide, K. Karpen-Hayes, MS Thesis, DOE Report No. DE/ER/61029-8 (1991).

The Study of Neutralization of Po-218 Ions by Small Ion Recombination in O₂, Ar and N₂, B. Shi and P.K. Hopke, *Health Physics* 61:209-214 (1991).

The Efficacy of Air Cleaning Systems in Controlling Indoor Radon Decay Products, C.S. Li and P.K. Hopke, *Health Physics* 61:785-797 (1991).

Measurement of Size Distributions of Indoor Radioactive Aerosol, C.S. Li and P.K. Hopke, in *Indoor Radon and Lung Cancer: Myth or Reality*, Battelle Memorial Press, Columbus, OH, 113-128 (1992).

Air Cleaning and Radon Decay Product Mitigation, P.K. Hopke, C.S. Li, and M. Ramamurthi, in *Indoor Radon and Lung Cancer: Myth or Reality*, Battelle Memorial Press, Columbus, OH, 479-491 (1992).

Some Thoughts on the "Unattached" Fraction of Radon Decay Products, P.K. Hopke, *Health Phys.* 63 2:209-212 (1992).

Measurement of the Effect of SO₂ on the Polonium-218 Ion Mobility Spectrum by Alpha-Track Detection, S.C. Yoon, W.H. Marlow and P.K. Hopke, *Health Physics* 62:51-57 (1992).

Characterization of Radon Decay Products in the Domestic Environment, C.S. Li and P.K. Hopke, *Indoor Air* 4:539-561 (1992).

Inconsistency in the Length of a Working Month, P.K. Hopke and N. Montassier, *Health Phys.* 63:466-467 (1992).

Inspiratory Deposition of Ultrafine Particles in Human Nasal Replicate Models, D.L. Swift, N. Montassier, P.K. Hopke, K. Karpen-Hayes, Y.-S. Cheng, Y.F. Su, H.C. Yeh and J.C. Strong, *J. Aerosol Science* 23:65-72 (1992).

A System to Measure the Hygroscopicity of Aerosol Particles, W. Li, N. Montassier and P.K. Hopke, *Aerosol Sci. Technol.* 17:25-35 (1992).

Assessment of Exposure to Radon Decay Products in Realistic Living Conditions, P.T. Wasiolek, P.K. Hopke and A.C. James, *J. Exposure Anal. Environ. Epidemiology* 2:309-322 (1992).

The Measurement of Activity-Weighted Size Distribution of Radon Progeny: Methods and Laboratory Intercomparison Studies, P.K. Hopke, M. Ramamurthi, E.O. Knutson, K.W. Tu, P. Scofield, R.F. Holub, Y.S. Cheng, Y.F. Su, W. Winklmayr, J.C. Strong, S. Solomon, and A. Reineking, *Health Phys.* 63 5:560-570 (1992).

Penetration of Ultrafine Particles of ^{218}Po Through Human Nasal and Oral Cast Models, N. Montassier, K. Karpen-Hayes, P.K. Hopke and D.L. Swift, *Rad. Prot. Dosim.* 45:665-667 (1992).

Measurement of Activity-Weighted Size Distributions of Radon Decay Products in Normally Occupied Homes, P.K. Hopke, P. Wasiolek, N. Montassier, A. Cavallo, K. Gadsby and R. Socolow, *Rad. Prot. Dosim.* 45:329-332 (1992).

Nanometer and Ultrafine Aerosols from Radon Radiolysis, M. Ramamurthi, R. Strydom and P.K. Hopke, *J. Aerosol Sci.* 24:393-407 (1993).

Potential for Ion-Induced Nucleation of Volatile Organic Compounds by Radon Decay in Indoor Environments, J.M. Daisey and P.K. Hopke, *Aerosol Sci. Technol.* 19:80-93 (1993).

Analysis of the Performance of a Radon Mitigation System Based on Charcoal Beds, P. Wasiolek, N. Montassier, P.K. Hopke, R. Abrams, *Environmental Technology Letters* 14:401-412 (1993).

Wei Li, *Hygroscopicity of Indoor Aerosol Particles*, Chemistry, Clarkson University, Potsdam, NY, July 1993, Department of Energy Report DE/ER/61029-14 (1993).

Huiling Ding, *Measurement of HO_x Production Rate Due to Radon Decay in Air*, Chemistry, Clarkson University, Potsdam, NY, August 1993, Department of Energy Report DE/ER/61029-15 (1993).

Initial Size Distributions and Hygroscopicity of Indoor Combustion Aerosol Particles, W. Li and P.K. Hopke, *Aerosol Sci. Technol.* 19:305-316 (1993).

Evaluation of the Effectiveness of Several Air Cleaners for Reducing the Hazard from Indoor Radon Progeny, P.K. Hopke, N. Montassier, and P. Wasiolek, *Aerosol Sci. Technol.* 19:268-278 (1993).

Editorial: "Harmonization of Radon Jargon and Units", P.K. Hopke, *Health Physics* 64:459 (1993).

HO_x Production Due to Radon Decay in Air, H. Ding and P.K. Hopke, *J. Atmos. Chem.* 17:375-390 (1993).

Experimental Study of Ion-Induced Nucleation by Radon Decay, F. He, and P.K. Hopke, *J. Chem. Phys.* 99:9972-9978 (1993).

Evaluation of Several Air Cleaners for Reducing Indoor Radon Progeny, P.K. Hopke, B. Jensen, and N. Montassier, *J. Aerosol Sci.* 25:395-405 (1994).

Extreme Value Estimation Applied to Aerosol Size Distributions and Related Environmental Problems, P.K. Hopke and P. Paatero, *NIST J. Res.* 99:361-367 (1994).

He, Feng, *Experimental Study of the Ion-Induced Nucleation by Radon Decay*, Chemical Engineering, Clarkson University, October 1994, Department of Energy Report No. DE/ER61029-17.

Neutralization of Thoron Progeny in Gases, Y.S. Cheng, C.C. Yu, C.J. Tung, and P.K. Hopke, *Health Phys.* 67:155-161 (1994).

Hygroscopicity of Consumer Spray Product Aerosol Particles, W. Li and P.K. Hopke, *J. Aerosol Sci.* 25:1342-1351 (1994).

Electret Method for Continuous Measurement of the Concentration of Radon in Water, S.K. Dua, P.K. Hopke and P. Kotrappa, *Health Phys.* 68:110-114 (1994).

Evaluation of Room Air Cleaners for the Reduction of Exposure and Dose to Indoor Radon Progeny, P.K. Hopke, B. Jensen, N. Montassier, and P. Wasiolek, *Rad. Prot. Dosim.* 56:55-59 (1994).

A System for Aerodynamically Sizing Ultrafine Radioactive Particles. O.O. Olawoyin, T.M. Raunemaa and P.K. Hopke, *Aerosol Sci. Technol.* 23:121-130 (1995).

Assessment of Exposure to Radon and Its Decay Products From Showering in Radon-Laden Water, P.K. Hopke, T. Raunemaa, V. Datye, K. Kuusalo, and B. Jensen, *Indoor Air An Integrated Approach*, 107-110 (1995)

Evaluation of an Electrostatic Air Cleaner for Particle and Radon-Decay Product Removal From Indoor Air, P.K. Hopke, B. Jensen, R. Sextro, M. Xu, and M. Nematollahi, *Indoor Air An Integrated Approach*, 351-354 (1995).

Assessment of the Exposure to and Dose from Radon Decay Products in Normally Occupied Homes, P.K. Hopke, B. Jensen, C.S. Li, N. Montassier, P. Wasiolek, A.J. Cavallo, K. Gatsby, and R.H. Socolow, *Environ. Sci. Technol.* 29:1359-1364 (1995).

SO₂ Oxidation and H₂O-H₂SO₄ Binary Nucleation by Radon Decay, F. He and P.K. Hopke, *Aerosol Sci. Technol.* 23:411-421 (1995).

Hygroscopicity of Indoor Aerosols and Their Influence on the Deposition of Inhaled Radon Decay Products, S.K. Dua and P.K. Hopke, *Environ. Int.* (in press, 1996).

The Initial Atmospheric Behavior of Radon Decay Products, P.K. Hopke, *J. Radioanal. Nucl. Chem.*, 203:353-375 (1996).

Experimental Study of Ion-Induced Nucleation of Volatile Organic Compounds by Radon Decay, F. He and P.K. Hopke, in *Nucleation and Atmospheric Aerosols 1996*, ed by M. Kulmala and P.E. Wagner, Elsevier Science Ltd, Oxford, U.K. 50-53 (1996).

PRESENTATIONS OF RESULTS OF THIS CONTRACT

Measurement of the Size Distributions of Radon Progeny in Indoor Air, P.K. Hopke, M. Ramamurthi and C.S. Li, presented at Third International Aerosol Conference, Kyoto, Japan, September 1990.

The Effect of Air Cleaning on the Size of the Indoor Radioactive Aerosol, P.K. Hopke, C.S. Li, and M. Ramamurthi, presented at Third International Aerosol Conference, Kyoto, Japan, September 1990.

Air Cleaning and Radon Decay Product Mitigation, P.K. Hopke, C.S. Li, and M. Ramamurthi, presented to the 29th Hanford Symposium on Health and the Environment, Richland, WA, October 1990.

Measurement of Size Distributions of Indoor Radioactive Aerosols, C.S. Li and P.K. Hopke, presented to the 29th Hanford Symposium on Health and the Environment, Richland, WA, October 1990.

Intercomparison of Activity Size Distribution Measurements with Manual and Automated Diffusion Batteries - Field Test, P.K. Hopke, P. Wasiolek, E.O. Knutson, C. Gogolak, A. Cavallo, K. Gadsby and D. Van Cleef, presented to the 1991 International Symposium on Radon and Radon Reduction Technology, Philadelphia, PA, 1991.

Analysis of the Performance of the Radon Mitigation System Based on Charcoal Bed, P. Wasiolek, N. Montassier, P.K. Hopke and R. Abrams, presented to the 1991 International Symposium on Radon and Radon Reduction Technology, Philadelphia, PA, 1991.

The Field Measurements of the Activity-Weighted Size Distributions of Radon Decay Products, P. Wasiolek, N. Montassier and P.K. Hopke, presented to the EPA/AWMA International Symposium on Measurement of Toxic and Related Air Pollutants, May 1991.

Penetration of Ultrafine Particles of ^{218}Po Through Human Nasal and Oral Cast Models, N. Montassier, K. Karpen-Hayes, P.K. Hopke, and D.L. Swift, presented at the Fifth International Symposium on the Natural Radiation Environment, Salzburg, September, 1991.

Measurement of Activity-Weighted Size Distributions of Radon Decay Products in Normally Occupied Homes, P.K. Hopke, P. Wasiolek, N. Montassier, A. Cavallo, K. Gadsby and R. Socolow, presented at the Fifth International Symposium on the Natural Radiation Environment, Salzburg, September, 1991.

Size Distributions of Radon Decay Products in Domestic Environments, P.K. Hopke and P. Wasiolek, presented at American Association for Aerosol Research, Traverse City, Michigan, October, 1991.

The Development and Testing of A System for the Determination of the Hygroscopic Growth of Aerosols, N. Montassier, W. Li and P.K. Hopke, presented at American Association for Aerosol Research, Traverse City, Michigan, October, 1991.

Evaluation of The Effectiveness of Several Types of Air Cleaners in Reducing the Hazards of Indoor Radon Decay Products, N. Montassier, P.K. Hopke, Y. Shi, P. Wasiolek, and B. McCallum,

presented at the 1992 International Symposium on Measurement of Toxic Related Pollutants, Durham, NC, May 1992.

Evaluation of The Effectiveness of Several Types of Air Cleaners in Reducing the Hazards of Indoor Radon Decay Products, N. Montassier, P.K. Hopke, Y. Shi, P. Wasiolek, and B. McCallum, presented at International Radiation Protection Association, Montreal, Canada, May 1992.

Measurement of Concentration and Size Distribution of Radon Decay Products in Homes using Air Cleaners, N. Montassier, P. Wasiolek, P.K. Hopke, and B. McCallum, presented at the Air and Waste Management Association Annual Meeting, Kansas City, MO, June 1992.

Extreme Value Estimation Applied to Aerosol Size Distributions and Related Environmental Problems, P.K. Hopke, invited presentation to Conference on Extreme Value Theory and its Applications, National Institute of Standards and Technology, Gaithersburg, MD, May 1993.

Evaluation of Room Air Cleaners for the Reduction of Exposure and Dose to Indoor Radon Progeny, presented at the First International Workshop on Indoor Radon Remediation, Rimini, Italy, June 27 to July 2, 1993.

Hygroscopic Growth of Particles from Indoor Sources, P.K. Hopke, W. Li, and S.K. Dua, presented at the Sixth International Conference on Indoor Air Quality and Climate, Helsinki, Finland, July 4-8, 1993.

Particle Size and Charge Neutralization of Thoron Progeny, Y.S. Cheng, C.C. Yu, and P.K. Hopke, presented to the 1993 Annual Meeting of the American Association for Aerosol Research, Oak Brook, IL, October 1993.

Experimental Study of Ion-Induced Nucleation Using a Thermal Diffusion Cloud Chamber, F. He and P. Hopke, presented to the 1993 Annual Meeting of the American Association for Aerosol Research, Oak Brook, IL, October 1993.

Measurement of Hygroscopicity of Consumer Product Aerosols, S.K. Dua, P.K. Hopke, and W. Li, presented to the 1993 Annual Meeting of the American Association for Aerosol Research, Oak Brook, IL, October 1993.

Determination of Room Model Parameters of the Behavior of Radon Progeny In Indoor Air Based on Experimental Data, B. Jensen, and P.K. Hopke, presented to the 1993 Annual Meeting of the American Association for Aerosol Research, Oak Brook, IL, October 1993.

The Measurement of Ultrafine Aerosol Size (< 10 nm) using Wire Screens, P.K. Hopke, invited presentation to International Conference on Aerosol Science and Technology, Taichung, Taiwan, October 1993.

Hygroscopic Growth of Consumer Spray Products, S. K. Dua, P. K. Hopke and T. Raunemaa, presented at the Fourth International Aerosol Conference, Los Angeles, CA August 29-September 2, 1994.

A System for Sizing, Aerodynamically, Aerosol Particles in the 0.5 nm Range, O. O. Olawoyin, T. M. Raunemaa and P. K. Hopke, presented at the Fourth International Aerosol Conference, Los Angeles, CA August 29-September 2, 1994.

Dynamic Model for the Size Distribution of Airborne Radon Progeny in a Shower Stall, Vandana K. Dante, Bent Jensen and P. K. Hopke, presented at the Fourth International Aerosol Conference, Los Angeles, CA August 29-September 2, 1994.

Modelling the Behavior of Air Cleaners on Radon Progeny in Controlled Indoor Air, Bent Jensen, P. K. Hopke, Richard Sextro, Mindi Xu and Matty Nematollahi, presented at the Fourth International Aerosol Conference, Los Angeles, CA August 29-September 2, 1994.

In-Home and Laboratory Experiments for Short Term Dose from Radon and Radon Progeny in Showering, P. K. Hopke and T. M. Raunemaa, presented at the Fourth International Aerosol Conference, Los Angeles, CA August 29-September 2, 1994.

Study of Ion-Induced Binary Nucleation of $\text{H}_2\text{O}-\text{H}_2\text{SO}_4$ with Radiolysis Formation of H_2SO_4 in Thermal Diffusion Cloud Chamber (TDCC), F. He and P. K. Hopke, presented at the Fourth International Aerosol Conference, Los Angeles, CA August 29-September 2, 1994.

Evaluation of An Electrostatic Air Cleaner For Particle and Radon-Decay Product Removal from Indoor Air, P. K. Hopke, B. Jensen, R. Sextro, M. Xu and M. Nematollahi, presented at the International Workshop, Indoor Air - An Integrated Approach, Gold Coast, Queensland, Australia November 27-December 1, 1994.

Assessment of Exposure to Radon and It's Decay Products From Showering in Radon-Laden Water, P. K. Hopke, T. M. Raunemaa, V. Datye, K. Kuuspalo and B. Jensen, presented at the International Workshop, Indoor Air - An Integrated Approach, Gold Coast, Queensland, Australia November 27-December 1, 1994.

Effects of Volatile Organic Compound (VOC) and Water Vapor on the $^{212}\text{Po}^+$ Cluster Aerodynamic Size Distribution, O. O. Olawoyin, P. K. Hopke, presented at the NRE-VI Symposium, Montreal, June 5-9, 1995.

Hygroscopicity of Indoor Aerosols and Their Influence on the Deposition of Inhaled Radon Decay Products, S. K. Dua, P. K. Hopke, presented at the NRE-VI Symposium, Montreal, June 5-9, 1995.

Exposure Assessment for Showering with ^{222}Rn Bearing Water Based on a Dynamic Model for the Airborne Activity Size Distribution, V. K. Datye, P. K. Hopke, T. Raunemaa, K. Kuuspalo, & B. Jensen, presented at the NRE-VI Symposium, Montreal, June 5-9, 1995.

A System Used for Size Determination of Radioactive Aerosol Particles, L. Fei and P. K. Hopke, presented at the NRE-VI Symposium, Montreal, June 5-9, 1995.

Estimate of Radon Progeny Exposure and Dose in Dry Mines Using Diesel Equipment, P. K. Hopke, K. Kuuspalo and T. Raunemaa, presented at NRE-VI Symposium, Montreal, June 5-9, 1995.