WORLD HISTORY OF RADON RESEARCH AND MEASUREMENT FROM THE EARLY 1900'S TO TODAY

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Abstract:

In 1900, Dorn discovered the emanation in the uranium series that eventually became the well-known gas ^{222}Rn. From 1900 through 1908, it was demonstrated that ^{222}Rn is a radioactive gas found in tap water, highly condensable at low temperatures with a half-life of approximately 3.7 days and can be collected on charcoal by adsorption. Although, radon was discovered in 1900, the effects of prolonged exposure had been suspected and noted 300 years earlier among underground miners who developed lung cancer. During the period from 1924-1932, it was suggested that radon was the cause of high lung cancer incidence. In 1951, researchers at the university of Rochester N.Y. pointed out that the lung cancer health hazard was from the alpha radiation dose delivered by the radon decay products that deposited in the respiratory tract. The findings of the BEIR Committee Report VI, which was based on epidemiological studies in different groups of mines in the 1950's and 1960's and on laboratory studies, showed that from 60,000 miners over 2,600 developed lung cancer where only 750 were expected.
Since 1998, the epidemiological study conducted in Iowa US, showed beyond any reasonable doubt that radon decay products cause lung cancer among women who lived at least twenty years in their homes. This paper will cover early radon measurements in soil, building material, ground water and in different air environments such as in the atmosphere, caves spas, underground mines and in residential indoor air environment. Radon measurements were conducted in many areas for diagnostic purposes. Radon was used as natural tracer to study air masses, vertical diffusion, and atmospheric studies, in earthquake prediction, and as a geological indicator for radium and uranium. In the early radon measurements, electroscopes, electrometers and primitive ionization chambers were used for many years. In the 1940's fast pulse ionization chambers replaced total ionization chambers. From the mid 1950's onwards a variety of radon measuring instruments were developed to assess the radon and radon decay product exposure to underground miners, workers at contaminated sites with uranium and radium tailings and to the general public in residential buildings. In the last twenty years, new instruments and methods were developed to measure radon by using grab, integrating and continuous modes of sampling. The most common are scintillation cell monitors, activated carbon collectors, electret ionization chambers, alpha track detectors, pulse and current ionization chambers and solid-state alpha detectors.

1. Introduction

Radon is a radioactive noble gas, having three naturally – occurring radioactive isotopes ^{219}Rn (Actinon, a by-product of the Actinium Series), ^{220}Rn (Thoron, a by-product of the Thorium Series) and ^{222}Rn (Radon, a by-product of the Uranium Series). Radon-222, being the most important radon isotope in terms of radiation exposure, is measured in different environments to determine its contribution to human radiation exposure. Rn-222 contributes about 55% of the annual radiation dose to the general population from all sources and 70% from natural radiation sources.

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In 1900, Frederick Dorn a German scientist found that radium-226 was giving off a gas which he called "radium emanation" known today as Rn-222. In 1908, Ramsey and Whytlow-Gray, isolated enough of the gas to study its physical properties and named it Niton (the shining one). In 1904, Mache [1,2], introduced the first unit for radon activity concentration and called it Mache-Enheit that was replaced in 1910 with the Curie. Mache used a galvanometer similar to the one used by Curie to measure the ionization current. One Mache (ME), corresponds to 13.5 Bq/L (364 pCi/L) and 37 Bq/M^3 or (1 pCi/L) = 0.0028 ME

In 1901, Rutherford and Brooks [3] demonstrated that radon is a radioactive gas. Rutherford, in the same year discovered the active deposits of thorium and the Curies discovered the active deposits of radium. In 1902, Rutheford and Soddy characterized alpha particles when they worked on thorium compounds [4,5].

The Radon Health Effects of Underground Workers:

Although, radon was discovered in 1900, the effects of prolonged exposure had been noted about 300 years earlier. Georgius Agricola, a German physician and geologist (1494-1555), noted a high frequency of fatal lung diseases occurring among local miners. Paracelsus a Swiss physician and scientist (1493-1541) studied the diseases of underground miners in the Erz Mountains of Eastern Europe and found that many miners died from lung disease, concluding that dust and gases present in the mines were the cause of it. In 1879, two physicians Harting and Hesse, found that the mortality rate of uranium miners who worked in Germany and Czechoslovakia to be near 75% [6]. The German miners who worked more than 10 years developed the Erz Mountain disease which was later identified as lung cancer. In 1921, Margaret Uhlig, was the first to suggest that the radium emanation might well be the cause of lung cancer [7].

Three years later in 1924, Ludewig and Lorenser suggested that the lung cancers of these miners might be caused by the radon gas in the mines [8]. During 1924-1932, the finding of high concentrations of radon in the region and in the nearby mines of Joachimstal in Chechoslovakia and in radium mines of Schneeberg Germany, suggested that radon was the cause of the high lung cancer incidence. In 1932, Pirchan and Sikl, concluded that the radium emanation causes lung tumors among the miners at Jachymov. Over half the deaths were from lung cancer and most occurred among miners before they reached the age of 50.

The Findings of the Radon Health Effects of Underground Miners in the Last Fifty Years:

Research on radium and radon exposure began to shift to the other side of the Atlantic. Work on factory workers, medical patients, radium dial painters and the military. In 1944, Lorenz pointed out that radon itself, contributed a small percentage of the radiation Bale in (1951) [9] and Harley in (1952), were the first to point out that the lung cancer hazard was from the alpha dose delivered by the radon decay products when deposited in the respiratory tract. In 1956, Bale and Shapiro calculated the dose to the lungs from inhaled and deposited radon decay products making radon decay product concentration Measurements very important.

The hypothesis that radon decay products caused lung cancer was not accepted by some, until the findings of epidemiological studies of underground miners in the 1950's and 1960's. The findings of the BEIR Report VI, which was based on underground mine data and laboratory studies showed that from 60,000 miners who worked between 1941-1990, in different groups of mines in 8 countries, over 2,600 developed lung cancer where only 750 were expected [10]. From 20 epidemiological studies of underground miners, eleven studies provided quantitative information on the exposure response relationship between radon and lung cancer risk (Lubin et al.) [11-13]. In the past 5 years, the epidemiological study in Iowa US in particular, showed a high incidence of lung cancer among women exposed to high radon levels in residential buildings [14]. As a result of these studies, both in the underground mines and in residential studies support very strongly the characterization of radon concentration levels and the assessment of the radiation dose from radon found in different environments.

To calculate the radiation dose from radon and radon decay products, we must have knowledge of their concentration, particle size, respiratory deposition and clearance of the radon decay products and other factors such as lung morphometry and breathing characteristics. The exposure of underground miners was estimated using data of radon and radon decay product concentrations obtained in several US mines in Colorado, New Mexico. (Breslin et al.[15], George [16], George et.al.[17], and Knutson and George [18].and BEIR VI [10]).
Knowing the concentration of radon in most cases is adequate to estimate an upper limit for radiation exposure. From thousands of simultaneous measurements of radon and radon decay products in residential buildings the average equilibrium ratios were found to range between 0.4 to 0.5 a value that can be used to estimate exposure to radon and radon decay products. In the past 25 years, emphasis is on radon concentration measurements because of the simplicity, convenience and the cost effectiveness of radon measuring instruments and methods. More measurements of radon were done than of any other radioactive pollutant because measurements are easy and simple and there is a health concern and a market for it. In the past 20 years in the U.S alone, about 1 million indoor measurements of radon concentration are conducted on an annual basis

Before I begin to describe the radon measurement methods and techniques used in different applications and environments starting from 1900 to the present, I will highlight the history of radon in some chronological sequence. Some of the best research in natural radiation, was conducted in the early 1900's, by eminent scientific investigators who were worthy of a Nobel Prize in Physics or Chemistry. I consider that time, the classical era of scientific research with limited available resources.

Chronological History, Related to Radon Research and Measurement:

1597 Agricola first noted the high incidence of lung disease
1879. Harting and Hess. Described the autopsy findings on underground miners.
1898 The Curies and Schmidt discover radioactivity of thorium and the elements radium and polonium
1898 Rutherford discovers alpha and beta particles.
1899 Thomson and Rutherford demonstrate that radioactivity causes ionization.
1900 Dorn discovers the emanation (Radon), in the uranium series
1901 Rutherford and Brooks demonstrate that radon is a radioactive gas.
1902 Rutherford and Soddy discover transmutation.
1902 Elster and Geitel, made qualitative measurements of radon decay products on charged wire screens
1902 Thomson, discovers radon in tap water
1903 Rutherford and Soddy, noted that radon is highly condensable at low temperatures.
1903 Rutherford and Soddy measured the half-life of the radium emanation as 3.7 days, not too far from the 3.82 days, used today
1906 Rutherford, suggested the adsorption of radioactive emanations by charcoal.
1907 Eve, used charcoal to collect radon to measure in an electroscope.
1908 William Ramsey and R.W, Whytlaw-Gray, isolated enough radium emanation to study its properties and called "Nitens", meaning "the shining one".
1909 Satterly, used charcoal to collect and measure the concentration of radium emanation in the atmosphere.
1908 Ashman, used charcoal to determine the quantitative radium emanation in the atmosphere
1909 Regener, built a scintillation system and counted ^{210}Po
1913 Arnstein, identified squamous carcinoma of the lung in autopsy of a miner
1913 Rutherford, described the properties of the emanations and that they only emit alpha particles, they condense around –150^{o}C and are strongly adsorbed by coconut charcoal. .
1914 First use of radon for medical purposes
1925 First mention of radon in the literature. The name radon and symbol "Rn" was adapted for all isotopes of element 86.
1932 Evans, determined small quantities of radon and thoron using two ionization chambers
1943 Hess, wrote a paper on the radon content of the atmosphere and the radium content of river-water
1940's Casual link shown between radon and lung cancer.

Early Radon Measurements:

In general, in the early 1890's scientists had two basic instruments with which to detect the ions created from uranium and other radioactive materials. The earliest measurements of radon were made with various home-made electrometers which were nothing but ion chambers. They were the quadrant electrometer and the electroscope. They were primitive ion chambers that operated in a closed vessel filled with the sample to be tested. The next generation of ion chambers included electrometer tubes, dc amplifier and recorder. In 1902, Elster and Geitel, were the first to make measurements of radon decay products by collecting them on a charged wire [19]. By 1914 the quadrant electrometer became obsolete and the electroscope remained as the best instrument for many years. In 1908, Rutherford and Geiger using this type of instrument proved that the alpha particle was a helium nucleus. The method that Geiger developed for this work is the prelude to the so-called Geiger counter. Ionization chambers were commonly used until World War II. .

In 1909, Regener built a counting system for the alpha particles emitted by Po-210. He used ZnS medium as the detector and counted the alpha particles through an optical microscope. Robley Evans [20] developed a two-chamber system that allowed subtraction of background by having one chamber filled with sealed air that responded to external gamma radiation

In 1943, Curtis and Davis [21], measured total ion current in a single chamber..
At the beginning of World War II, the most common methods available for the detection of alpha and beta radiation, were scintillation electroscopes and ionization chambers.
At the start of the Manhattan Project, the standard for protecting workers against radium and radon were set at 0.1 μCi and 370 Bq/M3, respectively.

By 1947, Davis [22] and the Health and Safety Laboratory (HASL) of the U.S. Atomic Energy Commission and later Fisenne and Keller [23], opted for fast pulse ionization chambers rather than total ionization. With the latest HASL version with a 2 liter electropolished stainless steel instead of brass chamber, the method could measure 2 Bq for an overnight count. The HASL, pulse ionization chambers were used extensively to measure very low concentrations of radon in different environments such as in the troposphere and stratosphere. From 1981-1996, the HASL pulse ionization chambers became the Standards Instruments for low concentrations of radon and served the calibration and intercomparison needs of the International community.

Since the mid 1950's many measurement methods and techniques for measuring radon were developed to meet the needs of research scientists and of those who made measurements in underground, occupational and indoor and outdoor environments. Today, there is a variety of instruments and techniques for making radon measurements using the grab sampling, integrating and continuous methods. Emphasis will be directed on the most commonly used instruments that serve today's needs.

Application of Radon and Radon Decay Product Measurements:

The major source of radon in the atmosphere is the normal emanation from the radium-226 in the earth's surface. The global emanation from soil is estimated at about 2 billion curies per year. The ground water potential is about 500 million curies per year (Harley and (NCRP Report No. 97) [24],[25] and [26]

Radon measurements were conducted in many areas and they were essential for diagnostic purposes such as sources of radon emanation rate from soil, building materials and ground water. In 1974, Clements and Wilkening [27] measured the effects of atmospheric pressure on radon transport across the earth air interface. Kojima [28], measured the exhalation of radon from soil to surface using a flow-through accumulator and an ionization chamber. Choubey [29], measured radon in soil and in spring water using scintillation cell detectors. The most popular method for measuring radon in water today is the liquid scintillation technique described by Pritchard [30] where the alpha particles from Po-218 and Po-214 interact with the scintillating material in an organic cocktail to produce photons that can be detected by a photomultiplier tube. Radon flux measurements were made by Wilkening [31] using the accumulation method and by Countess [32] using activated carbon accumulators. Hutter and Knuton [33], measured radon exhalation in soil gas by transferring the soil gas into scintillation cells.
Radon in building materials was measured in many countries by placing intact or crushed building materials into accumulators and then transferring the emanated radon into scintillation cells for counting.

T. Gesell [34], did an extensive review of the background atmospheric radon concentrations outdoors and indoors by examining the sources, variation with time of the day, time of the year, altitude and geographic location. At areas with low concentrations of radon, usually radon was collected in chilled activated carbon collectors and subsequently the radon was transferred into scintillation cells or into very sensitive fast pulse ionization chambers such as the electropolished HASL chambers described by Fisenne and Keller [23]. Another method was to use high air flow through a large two-filter tube system and count continuously the alpha activity from Po-218 and Po-214 collected on the second (exit) filter [35]. Smaller two-filter tubes were used to obtain grab samples in uranium mines where the concentrations of radon were higher. The second filter was removed and was counted on a scintillation or solid-state alpha detector.
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Radon and radon decay product measurements were made near Geothermal plants using integrating devices employing thermoluminescence detectors [36].
The radiation doses from radon in natural gas from combustion during heating and cooking were assessed from measurements conducted in different countries with concentrations ranging from 40-54,000 Bq m^{-3}. The highest concentration range was measured in Texas, US, [37].

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Radon was measured in the prediction of earthquakes. Radon monitoring in groundwater, soil and atmosphere near seismic areas of the world are being used to predict earthquakes and active-fault sites [38]. Temporal anomalies were observed before and after the 1995 Kobe earthquake. The observed anomalies are presumably caused by changes due to micro fracturing in rock or migration of water from different sources. Also, co-seismic changes may be caused by seismic shaking and regional stress. The experience acquired in the past 25 years indicates that changes in ground water radon do occur prior to major earthquakes [39]. A continuous radon monitoring system with a solid-state detector is used to record data in the Chuko fault zone in Taiwan for earthquake prediction.

Many measurements of radon were made using it as a natural tracer for the study of air masses and vertical diffusion as a function of altitude ranging from near the ground to hundreds of meters and several kilometers. Hess and Schmidt were the first to calculate the vertical distribution of radon assuming vertical diffusion coefficients [40]. In more recent studies radon was used as a tracer to study vertical diffusion in the lower atmosphere [41]. Fisenne and others [42] measured radon in the stratosphere (4-20 km) in three North American locations using chilled activated charcoal traps. The trapped radon was flushed with formic gas into the 2-liter fast pulse ionization chambers for counting. Iida, [43], measured the vertical distribution of radon up to 5 km in the atmosphere in central Japan using grab samples in a 32 liter cylindrical vessel. The positively charged ^{218}Po was collected electrostatically on the electrode of an aluminized Mylar coated with ZnS(Ag) phosphor. The scintillations are detected by a photomultiplier tube.
Radon decay products were used in the study of small radioactive ions in the atmosphere and in other times were converted to radon concentrations assuming equilibrium conditions between them.

In other applications radon was measured in caves, spas, geothermal sites. Radon concentrations were also measured as a geological indicator for radium and uranium. To estimate the radium body burden, radon was measured in exhaled breath.

A few studies of radon and radon decay products were mainly conducted in indoor environments in different countries. Hultqvist, probably was the first to make radon daughter concentration measurements in Sweden[44]. Steinhausler et al., [45] and George [46] made indoor radon daughter measurements in 1975 in Austria and the U.S. respectively. George and Breslin, made indoor radon and radon daughter measurements in the Metropolitan area of New York City during a three year period from 1975-1978, [47]. Stranden [48] and Swedjemark [49] conducted radon daughter measurements in dwellings in Norway and Sweden respectively. These small surveys were conducted to estimate the radiation exposure of the general population to radon and radon decay products. Since 1984, when high radon levels were found in Pennsylvania, millions of short-term measurements were conducted throughout the US alone. In Europe and other countries usually long-term measurements with alpha track detectors were made to characterize the indoor air radon environment.

Besides the world radon programs administered by various government agencies, a radon measurement and mitigation industry was established in the U.S. to address the health risk from radon and radon decay products.
The US EPA, in a national radon survey found that more than 6% of the US homes have radon levels above150 Bq m^{-3} . More recent measurements by radon inspectors and by the radon industry professionals indicate that perhaps 10% of the homes in the US, have radon greater than 150 Bq/M^3.

Several methods for measuring radon decay products were developed to characterize underground, outdoor and indoor environments. All methods are based on the collection of radon decay products on high efficiency filter media. The radioactivity collected on the filters is determined by gross alpha counting or by alpha spectrometry. The Kusnetz method [50] and the Rolle method [51] were very popular in underground mines. They provide the potential alpha energy concentration (PAEC) or the working level(WL) only. The concentration of the individual radon decay products and the associated PAEC are measured with more sophisticated methods [52-58].

Methods for the Measurement of Radon Decay Product Size Distribution

The size of the radon decay products is important because it affects the amount and site of deposition in the respiratory tract. The activity size distribution of radon decay products is a complex and difficult measurement. Measurements are undertaken by research groups and the availability of data is scarce. Today, there are two basic types of size classifying instruments developed in universities and in some governmental laboratories.. They are the diffusion battery system and the micro-orifice uniform deposit impactor (MOUDI). Diffusion batteries consist of the collimated disc type [59] and the wire screen system [60]. Both systems cover the range between 0.5-500 nanometers. Their resolution above 500 nm, is poor. The MOUDI system [61] measures sizes between 50-5000 nm. Since it does not provide information on the ultra-fine particles that are <50 nm, a graded screen array system is simultaneously used to complement the MOUDI data and cover the whole range from 0.5-5000 nm.

Radon Measurements in the Last Twenty Five Years

Today, emphasis is on radon gas measurements rather than radon decay products. Radon measurements are simpler more convenient and practical, providing a good estimate of the radiation exposure of the general public in timely fashion. The special relationship between the parent radon and its decay products expressed by the equilibrium ratio (ER), makes radon gas measurements more desirable. With the development of more sensitive measurement techniques, short-term radon measurements (2-7 days long) have become very popular in the U.S. The US EPA found that about 85%-90% of the short-term radon measurements are in close agreement with the long-term measurements. Short-term measurements are very practical and have become very useful in identifying the areas with elevated radon levels.

According to US EPA radon survey, which was conducted in the early 1990s, about 7% of the homes in the US have radon levels >150 Bq/m^3 (4.0 pCi/L). Today, US home inspectors and radon professionals estimate that the number of homes with elevated radon is probably close to 10%. Moreover, most of the radon measurements in the US are driven by real estate transactions and relocations making short-term radon measurements even more desirable. In Europe, Asia and other countries most tests for radon are conducted with long-term alpha track detectors for the assessment of the annual average radon concentration. The selection of the appropriate measurement method and technique depends on the sensitivity of the method, cost and how fast results can be obtained. The most commonly used instruments for the characterization of the indoor radon environment since the mid 1970's till today, consist of the following two categories.

I. Passive integrating radon measurements:

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1. Activated carbon collectors of the open face (OF) or diffusion barrier type (DB) are used for 2-7 day-exposures. The canister type uses the gamma counting technique. The liquid scintillation vials (L/S) type, uses alpha and beta counting. About 70% of the radon measurements in the US, use passive open face or diffusion barrier activated carbon collectors [62]-[64].

2. Electret ion chambers used for 2-7 day-exposures measure the voltage reduction on the electret being proportional to the radon concentration. About 10-15% of the radon measurements in the US, use this detector technique [65]

3. Alpha track detectors are more appropriate for long-term radon measurements. They are used infrequently in the US. However, they are very popular everywhere else [66]. They were used in national surveys throughout Europe and Asia.

II. **Passive or Active Continuous radon measurements:**

1. Scintillation cell monitors mostly of the flow through type.
2. Current and pulse ionization chambers (mostly passive).
3. Solid State, passive or active if they use a pump to move air through the sensitive volume of the monitor.

The sensitivity and accuracy of the most recent developed radon measuring instruments and methods is summarized in table 1. In this report, I tried to emphasize instruments that are portable and practical to use in the field. Instruments developed for research purposes and those that I had no information about them were not included. Along with the sensitivities of the different instruments listed are the principle of detection and cost.

The cost of continuous radon monitors ranges from $1,000-$8,000, with the most popular, from $1,000-$4,500. The cost of individual passive radon collectors or detectors analyzed by private laboratories is about $25.00.

The sensitivities of the different activated carbon collectors was determined from a 2-day radon exposures at 150 Bq M^{-3} (4 pCi/L). Analysis was performed 3 days after exposure. Activated carbon canisters were analyzed using gamma counting and the Liquid Scintillation LS vials using the alpha counting method. The sensitivities of different continuous radon monitors, alpha track detectors and the calibration factors of electret ion chambers were given by the manufacturer or cited from published literature. Instruments or methods with high sensitivity can achiee results with greater certainty.
Table 1, shows that activated carbon collectors are the most sensitive and precise devices for measuring environmental radon for periods from 2-7 days, even if the radon concentration varies by as much as a factor of 10, and the humidity ranges from 25%-80% during the measurement [62, [63] and [64]. These collectors must be calibrated initially at different conditions of exposure duration, temperature and humidity to obtain the calibration factor. At environmental levels of radon, activated carbon collectors when analyzed yield the highest net counting rate at 150 Bq M^{-3} (4 pCi/L). Activated carbon collectors come in different configurations and sizes. When properly calibrated under different conditions of exposure, they can become a powerful tool in short-term radon measurements. The sensitivity of activated carbon collectors that use the gamma counting technique is roughly proportional to the mass of carbon in the collector. Their high sensitivity is due to the accumulation of radon in the collector, which is decreasing by the decay of radon only until counted. In contrast, continuous radon monitors detect radon that enters the sensitive volume of the monitor without the advantage of accumulation. Table 1, shows that activated carbon collectors at radon levels of 150 Bq m^{-3} are 15-50 times more sensitive than the most frequently used continuous radon monitors. For this reason, continuous radon monitors use the cumulative hourly counts instead of the minute counting intervals to improve counting statistics.

TABLE 1. RADIOSENSITIVITY AND ACCURACY OF RADON MEASURING INSTRUMENTS AND METHODS

Instruments	Principle of Detection	Sensitivity dps/150 Bq m-3	Sensitivity cpm/4 pCi/L	Cost of Device Cost/exposure
RTCA, 50g, DB canister	Gamma	1.50	90.0	$25.00 *
RTCA, 90g, DB canister	Gamma	2.40	145.0	$25.00 *
RTCA, 2g DB (LS)	Alpha	0.90	54.0	$25.00 *
RTCA, 90g OF canister	Gamma	4.20	250.0	$25.00 *
PA, DER, 75g DB canister	Gamma	1.00	60.0	$25.00 *
US EPA, 75g DB canister	Gamma	0.80	48.0	$25.00 *
Sun Nuclear 1028, CRM	Solid-State	0.0030	0.18	($700-1,500)
Sun Nuclear 1029, CRM	Solid –State	0.0060	0.36	$1,000.00
Rad Star RS500, CRM	Solid-State	0.0050	0.30	$2,000.00
Radon Scout, CRM	Solid-State	0.0055	0.33	$1,000.00
Durridge Rad7, CRM	Solid State	0.0470	2.80	$5,800.00
Femto CRM-510 LP	Pulse Ioniz.	0.0200	1.20	$4,500.00
RTCA E-Smart CRM	Current Ioniz.	0.0200	1.20	$2,250.00
Radalink Aircat	Pulse ioniz.	0.0280	1.70	----------
Alpha Guard, CRM	Pulse Ioniz.	0.0470	2.80	$6,000.00
Active, Atmos 12D	Pulse Ioniz.	0.0500	3.00	$5,000.00
Active Pylon CRM, AB-5	Scint. Cell	0.0950	5.70	$3,500.00
Active DOE, CRM	Scint. Cell	0.1400	8.40	$3,000.00
Active Eberline , CRM	Scint. Cell	0.4000	24.00	$6,000.00

* Cost per test

In Table 2 and Table 3 listed are the sensitivities of alpha track detectors and the calibration factors for electret ion chambers respectively. Although these latter two types of radon detectors cannot be compared directly with the devices listed in Table 1 in terms of counts per150 Bq m^{-3}, the number of tracks per cm^2 per unit time and the calibration factors are useful in selecting the appropriate device for a specific measurement application. Information on these techniques for radon testing was obtained from the literature and from private communications with the developers and users of some of these devices. Alpha track detectors with larger sensitive volumes exhibit the highest sensitivity.

At this time, I was able to locate two manufacturers of electret ion chambers (both in the US) for short-term and long-term radon exposures. The two types of electret ion chambers have similar sensitivities and can be used for short-term or long-term exposures depending on the thickness of the electret.

TABLE 2. SENSITIVITES OF ALPHA TRACK DETECTORS AND ELECTRET ION CHAMBERS

Device Id. and Type	Sensitivity –Tracks cm^{-2} per 150 Bq m^{-3} h^{-1}	per 4 pCi L^{-1} d^{-1}
Landauer CR-39 (closed)	0.07	1.70
Germany Makrofol (closed)	0.15	3.60
Japanese Makrofol (closed)	0.19	4.50
RSSI CR-39 (closed)	0.23	5.60
Swedish Cr-39 (closed)	0.39	9.40
NYU CR-39 (closed)	0.48	11.50
French LR-115 (open)	(0.20-0.60)	(4.80-14.40)
Gamma Data CR-39 (closed)	(0.33-0.66)	(7.90-15.80)
Italian LR-115 (closed)	0.92	22.00
Slovenia CR-39 (closed)	0.97	23.40

TABLE 3. THE SENSITIVITIES OF ELECTRET ION CHAMBERS

Device Id	Volume (ml)	Calibration Factor Volts per 150 Bq M^{-3} h^{-1}	4 pCi L^{-1} d^{-1}
Rad Electret (short-term)	200.0	0.330	8.0
Rad Electret (long-term)	200.0	0.029	0.7
RTCA Radome (long-term)	65.0	0.029	0.7

CONCLUSIONS:

Radon research and measurement from the early 1900's to the present has come a long way. Some of the best research in natural radiation and specifically of radon was conducted in the early 1900's in European research laboratories by eminent scientific investigators such as the Curies, Dorn, Rutherford, Soddy, Thomson, Elster and Geitel. I consider that time, as the classical era of scientific research with limited resources.

The suggestion in 1924-1932, that radon was the cause of high incidence of lung cancer in European underground miners intensified the research and study of radon throughout the world to be subsequently interrupted by the Second World War. In the meantime, in 1951 across the Atlantic at the university of Rochester NY, researchers pointed out that the lung cancer in underground miners was due to the alpha radiation dose delivered by the radon decay products. The findings of the epidemiological studies in different groups of mines (1950's-1960's) conducted and cited in the BEIR Committee Report VI, solidified the evidence that from 60,000 miners over 2,600 developed lung cancer where only 750 were expected. Since 1998, the epidemiological study conducted in the State of Iowa, US, showed beyond any reasonable doubt that radon and radon decay products cause lung cancer to the general public in residential buildings.

While studies were conducted to assess the health risk from radon and radon decay products, radon research and measurements were conducted to characterize different environments such as radon in soil, building materials, ground water, the atmosphere, caves, spas underground mines and in the residential environment. Radon measurements were used to study air masses vertical diffusion, atmospheric studies, earthquake prediction and in geological studies.

Measurements of radon in the early years were conducted with electrometers, electroscopes and ionization chambers. By 1947, fast pulse ionization chambers begun to replace total ionization chambers that could measure as low as 2 Bq for a 16-hour count. Beginning with the mid 1960's many measurement methods for radon and radon decay product concentrations their inhalation and particle size distribution were made in The US and Canada, Austria, France, Germany, Norway, Sweden, Australia and Japan.
In the last twenty-five years, several instruments and methods for measuring radon rather than radon decay products were developed to characterize the indoor radon environment. Today's, most commonly used instruments for radon measurements are passive integrating devices such as activated carbon collectors and electret ionization chambers (for 2-7 day exposure) and alpha track detectors (for 90 days or longer). The measurement application of any of these devices is a function of sensitivity providing the average radon concentration during the measurement period.
In the last twenty years, several passive or active continuous electronic devices have been developed that produce hourly measurements and the average value during the test period. They are represented by scintillation cell, current and pulse ionization chambers and by solid-state detector monitors. Tables 1 and 2 compare the sensitivity and cost of each device making it easier to select the appropriate one for a specific measurement application.

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