Theremino **System**

A Radon
Ion Chamber

The Ion Chamber

For those who want to know more about ion chambers, the words for searching are: **"Diffusion type Ion Chamber for continuous measurement of radon through counting, according to the EPA CR method"**

This paper discusses the characteristics of ion chambers in general, and the measurement of the activity of radon. For details on the construction of mechanical and electronic engineering, technical specifications and detailed information on radon, please consult the attached documents:

A Radon Ion Chamber (this document in PDF format):
Radon_IonChamber_ITA
Radon_IonChamber_ENG
Radon_IonChamber_JPN
Radon_IonChamber_ESP

Mechanics:
Radon_IonChamberConstruction_ITA
Radon_IonChamberConstruction_ENG
Radon_IonChamberConstruction_JPN

Electronics:
Radon_IonChamberElectronics_ITA
Radon_IonChamberElectronics_ENG
Radon_IonChamberElectronics_JPN

Information on radon:
Radon_Info_ITA
Radon_Info_ENG
Radon_Info_JPN

First of all, why measuring radon?

In recent years it has been found, that radon is much more dangerous than previously believed and that has the same importance as cigarette smoking, as the cause for lung cancer.
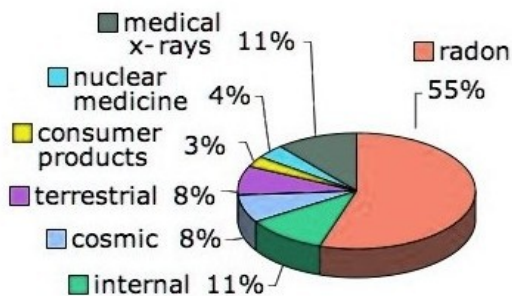
In the past we had a great concern, regarding X-rays (radiography), but these and all other sources of radiation all together, aren't even half the radiation, that we receive on average, everything else is linked to radon.

The danger of radon is due to the fact that it is colorless and odorless, chemically non-reactive, present in all homes almost unnoticed and that it is often very concentrated, up to a hundred times the limit that is considered dangerous.

In a good percentage of homes (one in ten) and in some rooms, (especially on the ground floor) the concentration of radon, can reach 10000 Bq/m3 (400 pCi/l 270 pCi/l). Who lives and smokes all his life in those rooms, (due to the synergic effect of smoking in presence of radon) has a very high chance of getting lung cancer.

Knowing this hazard, solutions exist such as changing living spaces, let circulate air, or let out the radon before it spread into other rooms, with a vacuum in the basement. While continuing to smoke, just removing radon, the risk is not only halved, but reduced by 90%.

Since many years there are studies, neglected by the most, who warn regarding this risk. Just recently statistics on radon multiply and there are no more doubts about its dangers.

- http://www.epa.gov/radon/healthrisks.html#Iowa Study

- http://www.bfs.de/en/ion/radon

- http://www.hse.gov.uk/radiation/ionising/radon.htm

- http://www.wantchinatimes.com/news-subclass-cnt.aspx?id=20111211000031&cid=1105

- http://www.independent.co.uk/life-style/health-and-families/features/radon-gas-the-silent-killer-in-the-countryside-2047987.html

- http://www.washingtonpost.com/wp-dyn/content/article/2007/01/24/AR2007012400505.html

- http://ukradon.org/ern.php

These documents explain the dangers of radon, much better than we can do here. Our contribution will be mainly to facilitate measurements, with a "do it yourself" meter, that can be built with cheap materials, available in any hardware store. A portable device that, once built, will be able to measure not only all the rooms at home, but can also be lent to friends, making possible doing hundreds of tests at no cost. Unfortunately, "official" tests cost pretty much (over 50 Euro each) and are done only in public places such as schools. Just rarely, and only on request, in private homes.

Diagram of the ion chamber
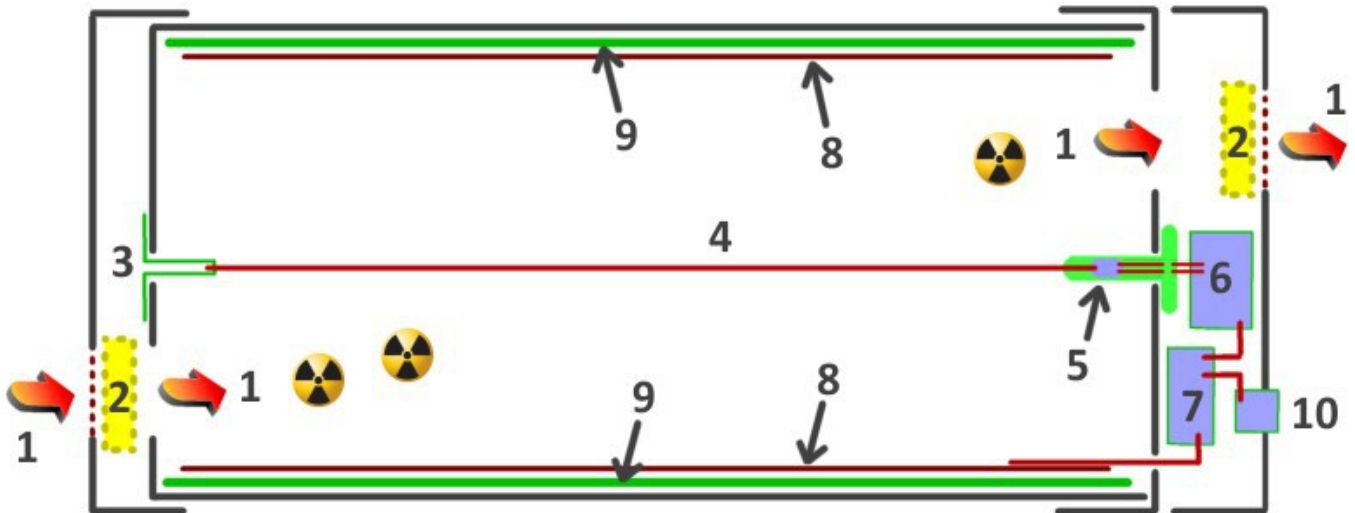
The ion chamber consists of a cylinder, with a diameter of 8 cm and 20 cm in height, with a total volume of one liter, plus three covers, that protect the electronic components from electrical noise and dust. The cylinder and the lids **(Black bars)** are **in tinplate,** they are all connected together electrically and mechanically joined, with copper wires soldered.

Outside air and radioactive isotopes enter the chamber **(1 red arrows)** by diffusion and convection, through two 25 mm holes with brass grilles , insulating from electrical noise and working as dust filters **(2 Yellow)**

The Inside of the cylinder, is lined with an electrode of adhesive aluminum tape (or copper), **(8 red)** isolated from the outer cylinder by means of a sheet of plastic insulator **(9 green),** and loaded with 400 positive Volts, created by a high voltage generator **(7 purple)**

A central electrode **(4 red)** is held taut between the two ends of the chamber, between a nylon tie rod **(3 green)** and a low noise FET (**5 purple**). The FET, which is located to minimize noise, inside the same chamber, provides a robust signal, no longer influenced by electrical noise.

The amplifier and discriminator pulse width, **(6 purple)** isolates the pulses produced by radon and its daughters and outputs rectangular pulses of constant width, strong and easy to count.

The output connector, **(10 purple)** can be connected directly to a Theremino System standard PIN. Normally you use a master module that provides the power for the ion chamber and sends counts via USB, to the software ThereminoGeiger.

A single Master can feed up to six Ion Chambers, with links hundreds of meters, collecting all of the data. A few of the six chambers, may also be replaced with Geiger probes for Alpha, Beta and Gamma rays, or other environmental sensors.
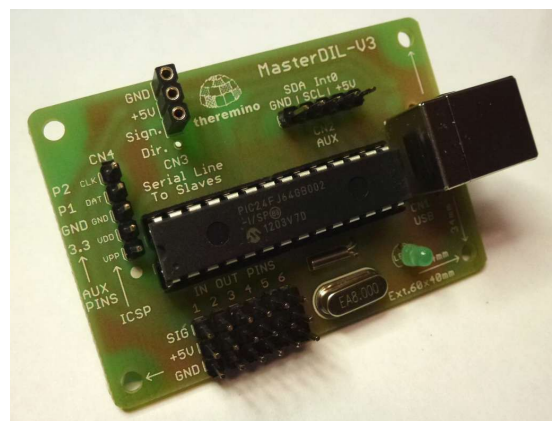
Counting the disintegrations with a Ion Chamber

There are two types of ion chambers, counting chambers and integration chambers. Those normally encountered in the literature are of the integrating type and measure the average current produced by many disintegrations. The integration chambers are extremely dependent on environmental factors such as humidity, temperature and air pressure. So often, you read misleading information on the instability and inaccuracy of ion chambers. These reports are not applicable to our method, that is not based on the measurement of the average current (integration) but on the counting of individual events.

The correct definition of the method we used is "Counting ionization chamber" and its operation, is similar to a Geiger tube, operating on digital counting. For a precise definition of our technology, read the Appendix 1 (at the end of this document) to list all methods classified by EPA (Environmental Protection Agency). Our method is classified as "CR"

Counting the disintegrations in a precise time and in a given volume, the calibration is stable and easily repeatable.

This technology is as simple as the egg of Columbus, but was rarely used because, according to the literature, needs "expensive and delicate electronic circuitry". This was true in the past, now there are very low current noise FETs and operational amplifiers with excellent features. With these components, it is easy to isolate individual events and count them.

Difference between "counting" and "measuring the medium current"

As the data to collect is the number of disintegrations, there's no better way, than count them one by one. The alternative way of trying to calculate their number, by measuring the average current and then dividing by what is assumed to be the current produced by each disintegration, is inaccurate and easily fooled by variables such as humidity, temperature, air pressure and smoke.

Humid air, can produce a greater current, than the one we should measure. Other environmental variables affect a lot as well and just the slightest presence of smoke in the air, can greatly reduce the current measured.

Finally, the number of ionized atoms (and hence the current produced) changes if the disintegration takes place close to a wall, or in the center of the room. It can change depending on the random direction of the beta particles that cause ionization, as well. If the particle appears close to a wall and travels toward the center, develops its energy and produces the maximum number of ionized atoms. If instead, it travels in the opposite direction, immediately collides with the wall of the room and produces few ionized atoms, resulting in a very small electric current. Different events of disintegration can therefore contribute to the average current in a different way, with differences between one event and the another of even ten times.

How is it possible to make precise measurements with chambers integration is a mystery. Joking apart, it's really hard to compensate everything. The eventual presence of smoke should be checked as well (but never is done)

The patents on ion chambers

Fortunately, ion chambers that count the pulses are "prior art" from a long time. The earliest known versions (but not patented) dates back to 1954, there are also Patents 4,827,224 and 4,859,854 by Carl J. Kershner and Edward T. Burgess, from May and August 1989 (being in 2013, it means they expired 4 years ago, already) To check the patents, we recommend the excellent Google Patents. Either in Italy, than in the U.S., patents have a term of 20 years and once expired, the technology is public and no longer patentable. Therefore, ion chambers (both counting and integration chambers) are now freely available.

Is it calibration needed?

Counting do not depend on humidity and air pressure, but only by the actual volume of the active zone, which in turn, depends only on the geometrical dimensions. All these factors, do not change from one unit to the other, an individual calibration is then, not required.

If you respect the exact dimensions given here, it is sufficient to set a calibration coefficient to obtain an accuracy even better than +/- 20%. For major safety, we will declare an accuracy of +/- 50%, limiting the measures on the order of magnitude, as the following table:

```
pCi/liter   Bq/m3    pulse/min   pulses/second    outcome
-----------------------------------------------------------------------
   0.01        0.4       0.02        -             you're in a sealed tank ...
   0.1         3.7       0.2         -             don't worry
   1          37         2           0.03          check often
  10         370        22           0.3           get worried
 100        3700       220           3             do something immediately
1000       37000      2200          33             hard to believe ...
```

It doesn't matter if you measure 0.33 or 1.22, rather than 0.88 pCi/liter. Related to the risk of physical hazard, it doesn't change practically nothing. What we want to be sure, is that it is not 50 pCi/liter or worse than that, 500. Our chamber, can give this security even without calibration. Furthermore, the measurements and the calculation are simple, making difficult to do dangerous errors.

Ion Chamber size

Why making a one liter ion chamber? You could easily do a 4 x 4 cm, 1 cm high chamber that it would be easier to build and less sensitive to vibration. All manufacturers of commercial appliances, with prices lower than $ 2,000, have chambers of a few tens of cubic centimeters. Unfortunately however, measurement accuracy on small chambers is lower and becomes necessary to use, too long times.

Being one or two days, the necessary measuring times, it becomes difficult to measure all of the rooms in a house, experimenting with vacuum or opening windows to see what happens. It would take a month, to make a reasonable number of tests and you would be busy everyday. Otherwise using shorter times, it becomes possible to do many tests on the same day and make changes to the air extraction system, immediately seeing the effect. We have therefore attempted to reduce the measurement time, as much as possible, maximizing the volume.

The sensitivity ratio, between large and small chambers, is greater than the ratio between the two volumes, as in small rooms the active volume percentage is lower. The free path of alpha rays in the air, is about 4 inches and when the chamber comes close to this size, most of its volume is located close to the walls, which prevents disintegrations, from turning all their energy into ions.

The tables on the next page, show the results in terms of performance.

Effects due to the size of the ion chamber

To show the effects related to the size of the chamber, we compared the features with the great tool Rstone, developed at the University of Pisa & INFN, that uses one of the most recent techniques: "revelation solid-state diffusion in the room." , with the popular Safety Siren Pro3.

Characteristics depending on the size of the chamber

	Size of the chamber	Sensitivity (Cpm/pCi/l)	Sensitivity (Counts/hour 100 Bq/m3)	Counts spurious background	Notes
Safety Syren Pro3	20 cm3	0.03	2.5	(Note 1)	In two hours you have a reliable measure for dangerous levels > 400 Bq/m3
Rstone (2)	50 cm3	0.06	5	1.2 Bq/m3 0.03 pCi/l	In one hour you have a reliable measure for dangerous levels > 400 Bq/m3
Theremino Ion Chamber (3)	1000 cm3	2	160	0.4 Bq/m3 0.01 pCi/l	In one hour you have a reliable measure also for the environment < 10 Bq/m3

Time required to obtain a measure reasonably stable (undulations less than 20%)

|	Safety Syren Pro3	Rstone (2)	Theremino Ion Chamber (3)	Notes
10 000 Bq/m3	12 - 24 minutes	6 - 12 minutes	3-6 seconds	Levels never measured in homes
1000 Bq/m3	2 - 4 hours	1 - 2 hours	40 - 80 seconds	These levels are very rare
500 Bq/m3	4 - 8 hours	2 - 4 hours	1 - 2 mins	Only in rare cases
100 Bq/m3	20 - 40 hours	10 - 20 hours	6 - 12 minutes	Levels normally found
10 Bq/m3	8 - 16 days	4 - 8 days	1 - 2 h	Levels normally found

(1) According to the specifications published in the "Safety Siren Pro3 User Manual". The background is not specified in the user manual, nor in the Internet documentation.

(2) According to the Rstone data, published in "Natural radioactivity: current measurement techniques and development prospects (Part III) - G. Batignani, University & INFN Pisa "

(3) The relationship between the sensitivity and then between the times, is much greater than the 20 times that could be expected, from the relationship between the two volumes, as in a small chamber, the active area is proportionally smaller, due to the many ionizations that occur, close to the walls.

What are minimum and maximum values to be measured?

This image shows the data collected by an extensive sampling campaign done in the USA, in a large number of houses, shops and schools (schools are in yellow, kindergartens in green, stores are blue, the houses in brown, red and purple) Many studies around the world have given these same results, but this graph shows, better than the other, the minimum and maximum levels that may be encountered in the measurements.
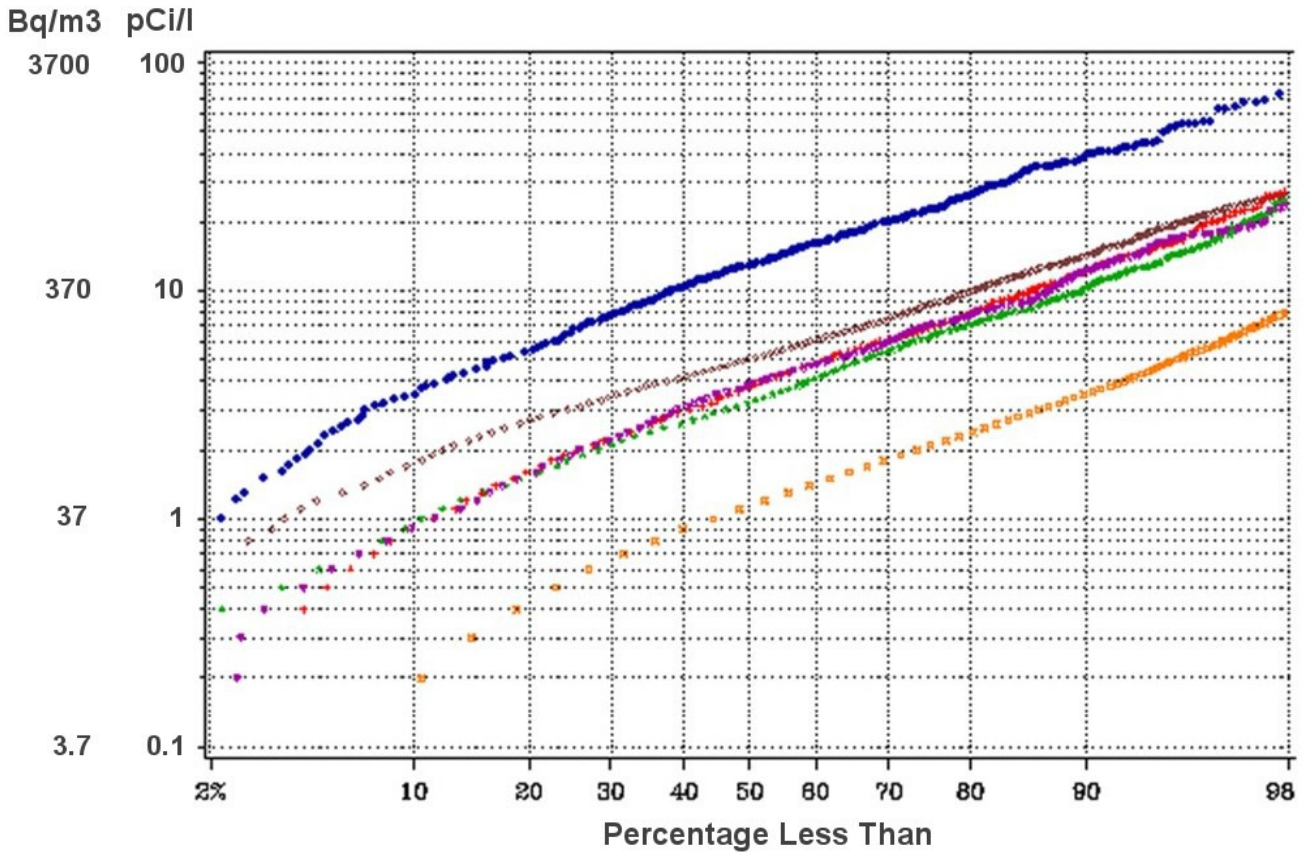
In a sample of thousands of cases, no measurement was lower than the classic 0.2 pCi/liter (8 Bq/m3), that are measured outdoors, or exceeded 70 pCi/liter (2600 Bq/m3)

We can then establish with certainty, that the range of values to be measured, is 0.1 pCi/l (4 Bq/m3) to 100 pCi/l (3700 Bq/m3)

Our Ion Chamber, measures from 0.01 pCi/l (0.4 Bq/m3) to 2800 pCi/l (100,000 Bq/m3), from one-tenth of the minimum requirement, up to about thirty times the maximum.

Check operation and background pulses

A simple functioning test is performed, by placing the ion chamber outdoors or in a well ventilated area. In these conditions, should be measured about 10 Bq/m3 (0.3 pCi/l). This is not a calibration, no matter if the concentration actually measured, is 10.2 or 15.9 or 7 Bq/m3, we just need a curve visibly in place, without jumps caused by interference, in order to check that the electronics count regularly and that the background is low enough, not to influence the measures. The guidelines of EPA, specify that the background, should be less than 40 Bq/m3 (1 pCi/liter), a value pretty easy to obtain. Our chamber outdoor, usually measures around 10 Bq/m3 (about 0.3 pCi/liter).

Background pulses

EPA's guidelines fix the pulses of the background, to be below 40 Bq/m3 (about 1 pCi/liter). This check is also important, to make sure that there are no false counts, caused by mechanical or electrical noise.

To delete the pulses due to radon, the chamber should be sealed, waiting until radon decays within a sufficiently low level. Unfortunately it is very difficult to seal the chamber, as radon passes through almost all materials. You should close your chamber in a big aluminum cylinder, with screw cap in aluminum as well and be particularly careful with the output connector. Even the smallest resin or plastic seal, could let enter radon, within the 15 days or more, it takes to decay enough.

Fortunately, there is another method. Hold a reserve of air in the cylinder of a normal air compressor, without turning it on, for about a month. As radon decays in 3.8 days and that his daughters have a much shorter time, in a month the radioactivity falls to a two hundred and fiftieth of the initial radioactivity, a level almost unmeasurable. EPA on its notes, call this air, "aged air". With this air, is easy to clean the chamber and then keep it in this state, with a wisp of air, all the time of the measurement.

The preliminary tests indicate that with a nicely built chamber, you can get counts lower of one pulse per hour, that means less than 0.4 Bq/m3 (less than a hundredth of a pCi/liter).

Air circulation and radon

The operation of the ionization chamber, is based on the assumption that the air inside the chamber, is a representative sample of the air in the environment that is being monitored. Radon spreads very easily in air, water and even through many solid materials. It enters easily into the chamber for diffusion and soon brings the internal concentration in equilibrium with the external one.

Concentration variations inside, follow with just some delay, the concentration changes of the external environment. In our tests **the delay time is negligible**, just a few tens of minutes, **even though the room had small openings, covered with dust filters**.

A replacement fast enough using diffusion alone, allows to work without an air pump. The pump would bring a variety of problems, the main among them, the rapid build-up of dust in the filters. This, in addition to rise costs of maintenance, prevents automatic measurements for a very long time.

Ions or electrons?

The counting chambers in turn, are divided into two subtypes, depending on what is amplified, electrical pulses products by electrons or ions.

At first, we thought that the choice, between ions and electrons, depended on the polarity, following this reasoning: If the outside is negative, then the center electrode is positive and captures electrons. At the opposite, if it would be negative, it would capture ions. But, as we measure the electrical current as a "difference in potential", at first analysis, you might think that there is no difference between amplifying the ionic current or the electronic one.

A difference should exist: the electrons are very small and travel faster than the large and heavy ions, therefore the electrical pulses, produced by the electrons are short (a few micro-seconds); instead those relative to the ions, are a thousand times longer (a few milliseconds)

For this reason, we equipped ourselves with high voltage generators, with the possibility of switching quickly, between positive and negative polarity, to verify in this manner, strengths and weaknesses of amplifying ion current, or the electronic one.

Consequently, we made an interesting discovery: amplifying current produced by electrons, is very difficult. You must amplify a bandwidth of several MHz (already pretty difficult task). Even worse, electronic components noise, increases with the increase of the bandwidth, making almost impossible to distinguish pulses generated by the electrons, from the background noise of the input circuit (in our case a low-noise FET)

We then limited the bandwidth, to a few hundred Hz and optimized the amplification circuit, to obtain the maximum ratio between signal and noise, for the pulses generated by ions. We have therefore obtained, a signal/noise ratio of about 40dB (100 times), this allows to isolate the pulses produced by the disintegrations from the noise, in an absolute reliable way. The bandwidth, should be 10 MHz for electrons, but ratio would drop to a few dBs, making very difficult to isolate pulses, from the noise.
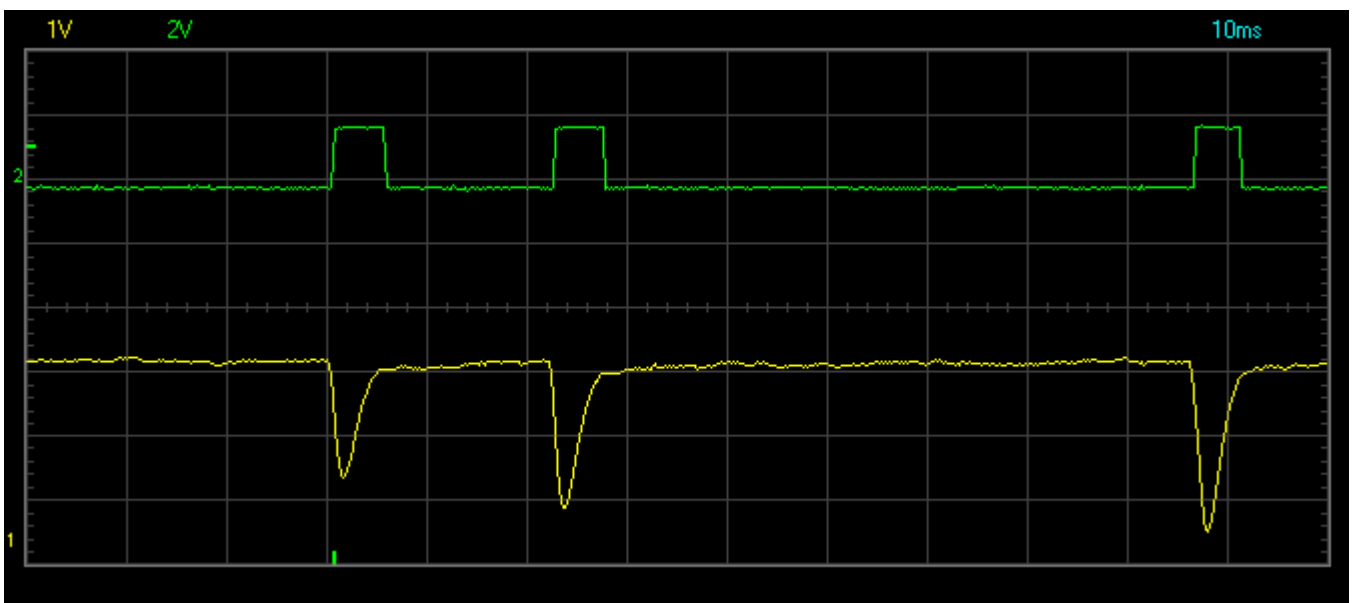
Note the clean yellow pulses, (a few volts) in relation to the background noise (tens of millivolts). The green pulses are the output pulses, squared and normalized to 5 milliseconds, with a Schmitt trigger, to avoid double counting.

Counting ions decreases the maximum count frequency?

This is true. Theoretically, with the electrons, we could arrive to some MHz, reaching **22 million pico Curie** per liter, at the opposite, counting the ions, we can reach **only 100 Hz**, equal to about **2800 pico Curie** per liter (which are about **103600 Becquerel per cubic meter**)

As for Radon measuring, it's enough counting up to 100 pCi/l, having a margin of twenty-eight times.

Approaching the maximum count frequency, the number of pulses lost, gradually increases. This effect, can be compensated by adjusting the parameter "BKG" of the counting software (Theremino_Geiger), that makes a statistical calculation and restores almost perfectly, the linearity of the upper part of the scale.

Polarity of the voltage

Once you have decided to amplify ions current, the theory says that it is better to collect ions on the center electrode, high positive voltage on the outside of the chamber and negative on the central electrode, to attract positive ions.

Being a bit picky ,we wanted to verify ourselves, this brought to another interesting discovery:

If we amplify the ion current with bandwidth optimized for pulses of a few milliseconds, there is no difference between the two polarities (or it is so small, to be irrelevant)

Probably there is no difference, as what we measure is not the current, but the "difference in potential" produced by the current. If someone finds a better explanation, please let us know.

In conclusion: as it is preferred by theoretical considerations and making high positive voltage power is even easier, we decided to **polarize the outer coating with positive voltage**.

A further advantage of using positive voltage, is that the FET is stabilized in a much shorter time, (a few seconds) after having given voltage to the electronics. This is because in positive, the junction limits the gate voltage to less than a volt. With high negative voltage, at the opposite, being no limitation, the gate drops to 30 negative volts and over, taking almost a minute before the current loss, brings it back to zero voltage.

Energy discrimination

In our implementation the amplification circuit contains a timed Schmitt trigger that, in addition to preventing double counting caused by noise, sets a minimum voltage threshold below which, the pulses are not counted.
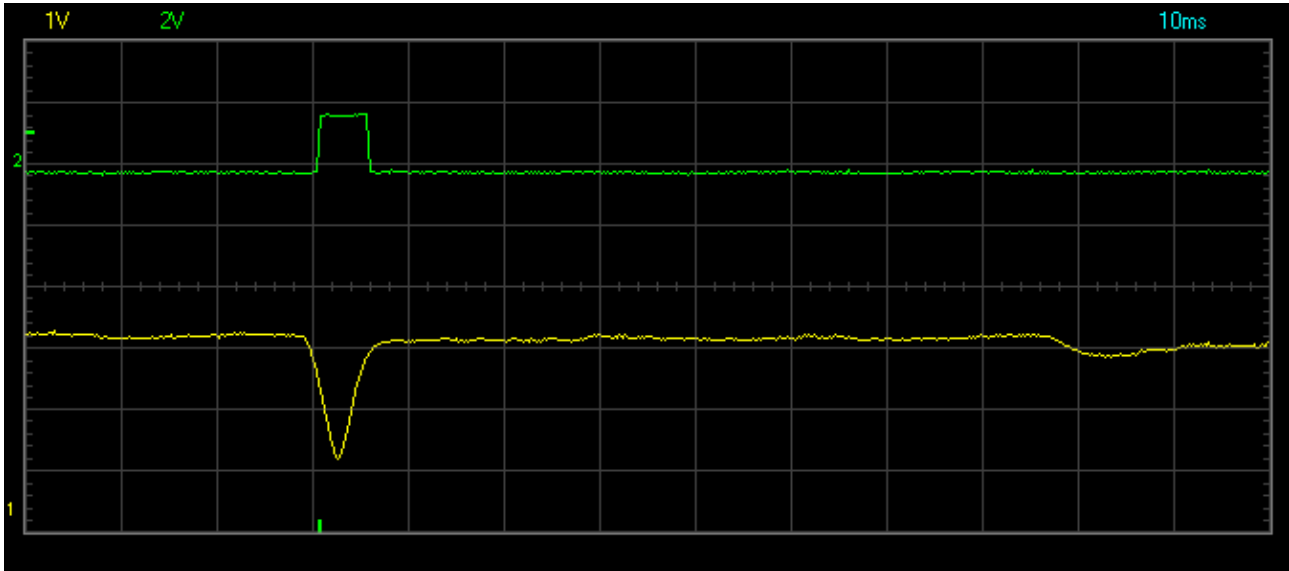
The upper trace is the output produced by the square pulse discriminator trigger.
The lower trace shows the signal before the trigger. On the left a pulse produced by radon, while on the right, one or maybe two closely spaced, whose amplitude, being less than 500 mV, is not counted.

Threshold is set at approximately 500 mV.
Radon and its daughters alpha disintegrations, (5 to 8 MeV) produce pulses with an amplitude of 1 to to 3 Volts.
Beta and gamma disintegrations, produce very small pulses, of amplitude, less than 0.1 volts

Beta and gamma disintegrations, apart from having maximum energies of less than 1 MeV, create a number of electron-ion pairs, 100 times minor than the alpha disintegrations.

Ions present in the air do not cause counts, as they are always individual ions or clusters of a small number of them, resulting in a minimal voltage produced. An alpha decay of radon produces about one hundred thousand electron-ion pairs, generating signals at least thousand times greater.

Even placing a ozone generator, right next to the measuring chamber, the counts don't rise, as ions and free electrons, cannot pass through the dense grid of the brass mesh,which is connected to ground, and enter the chamber.

Discrimination of radon by its daughters

To discriminate the daughters of radon itself, it's necessary to add a layer of thin, transparent polyethylene (plastic bag), in addition to the two dust filters. Polyethylene let pass Radon, but not its daughters. With these filters, since radon diffuses slowly through polyethylene, stabilization time of the chambers, becomes much longer than the normal half an hour.

Could seem counter-intuitive, but if you put the filters that let out the daughters of radon, there's no need to change the calibration coefficient. That's because radon that enters, soon develops a condition of equilibrium, between the production of daughters and their disintegration.

Some research has shown that under certain conditions, concentration of radon and its daughters may be abnormal, due to the different diffusion rate caused by their different atomic weight. This only happens if air is perfectly still. In a real inhabited house, convective transport prevails over the diffusive and errors in measurement, due to lack of equilibrium between radon and daughters are minimal, well below +/- 30%, our target.

We are not interested in accuracy at the expense of speed. Making a measurement that requires a whole day, limits to a single search in a day. This single measure could also be accurate at 10%, but it's enough to open a door or going into another room, to measure completely different values, up to 300% more or less. With this in mind, in our opinion, it is better to remain on a 30% of accuracy, with the possibility of doing many measurements in different conditions, open and closed windows, different rooms etc ...

Disintegrations produced by Radon, have energy very similar to that of his daughters (5.5, 6 and 8 MeV) meaning that daughters, do about the same biological damage, as father's radon decays. This leads us to think that it is right to measure the mixture of air, radon and daughters, as it is present in the environment, without changing the proportions of the components by means of filters. However, the legislation requires that the value, is expressed in terms of activity compared to unit volume, that is the indistinct collection of the decays, directly or indirectly attributable to radon.

Equilibrium between radon and daughters

The relationship between concentration of radon and its daughters is normally expressed as:

F = concentration of radon in equilibrium / effective concentration of radon in the air

F (indoor environment) is normally, from 0.4 to 0.5

Only in very specific cases, (for example, mines) this value takes values significantly different from the standards.

An ion chamber without filters for the daughters of radon, is influenced by the F value, but in the environments of our interest, this influence is minimal.

Test graphics
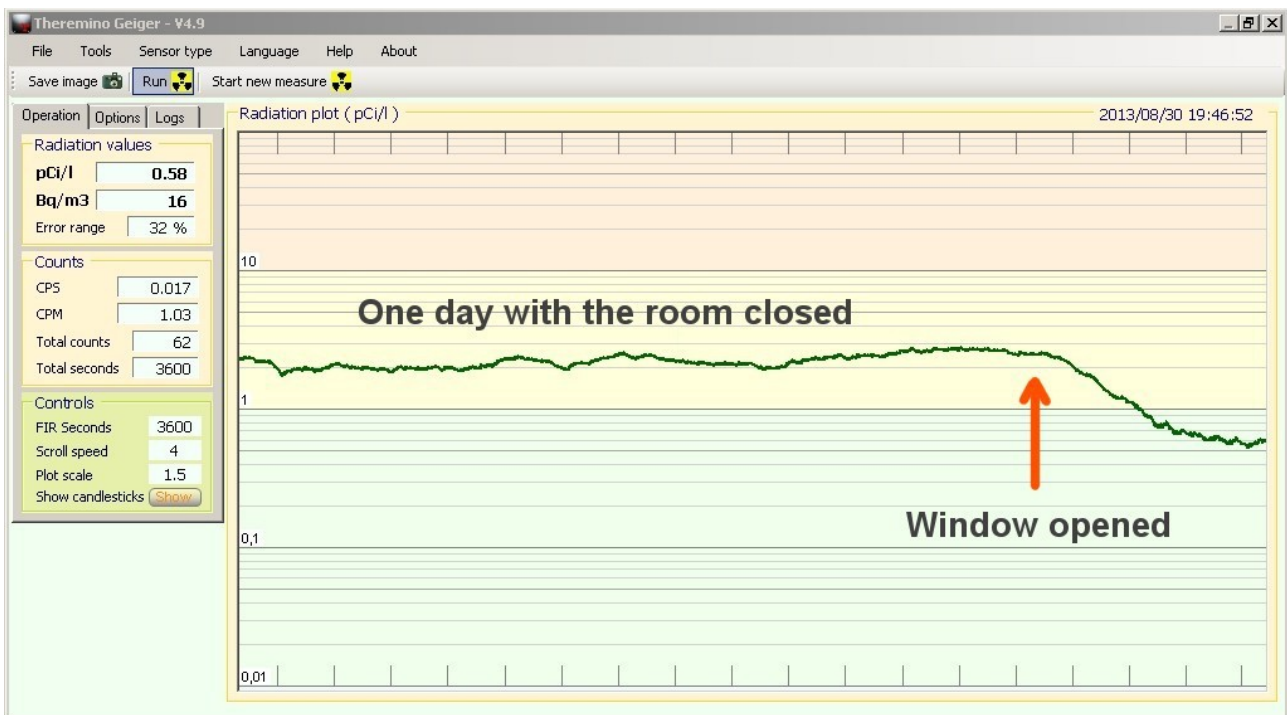
In this graph we can see a fairly normal room, which was closed for a day and that has stabilized at about 3 pCi/l (100 Bq/m3). On the right part, as soon as the window has been opened, the concentration started to decline, and in a few hours, it is brought to about 0.5 pCi/l (about 20 Bq/m3), which is little more than the normal concentration of the outside air.
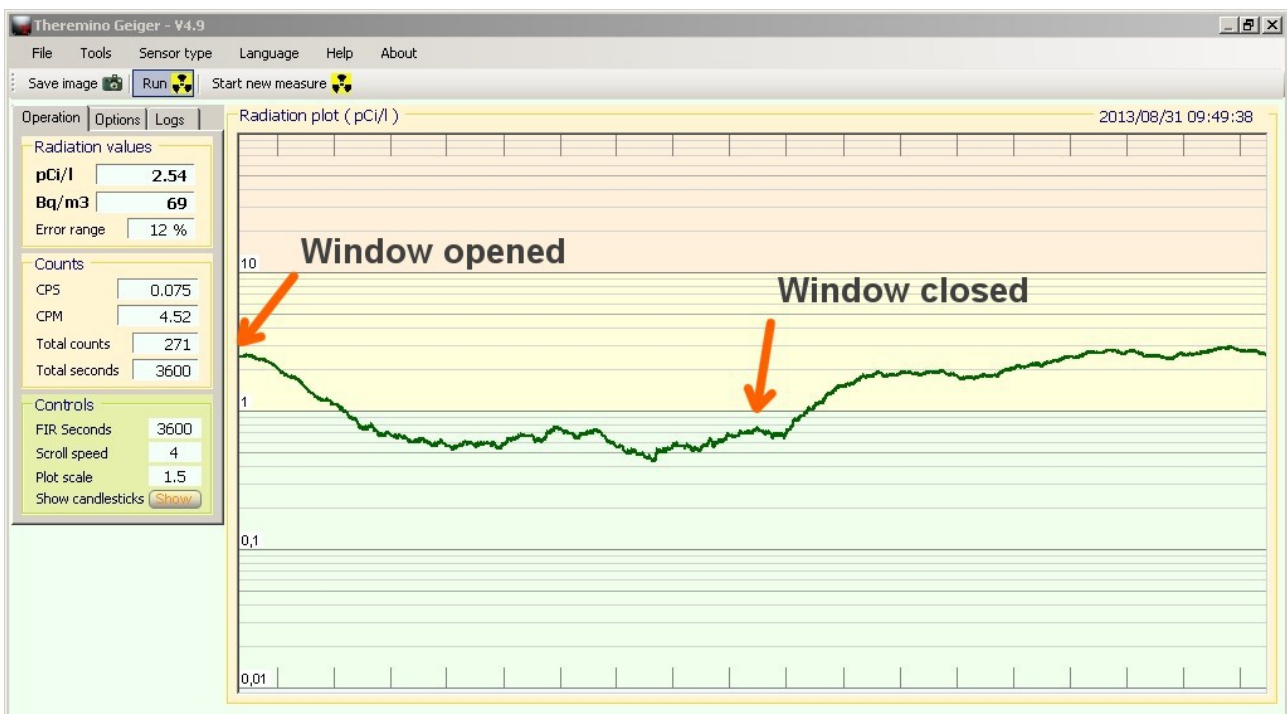
Here we can see that closing the window again, the concentration begins to rise again, but more slowly as the whole room has to gradually be filled with radon.
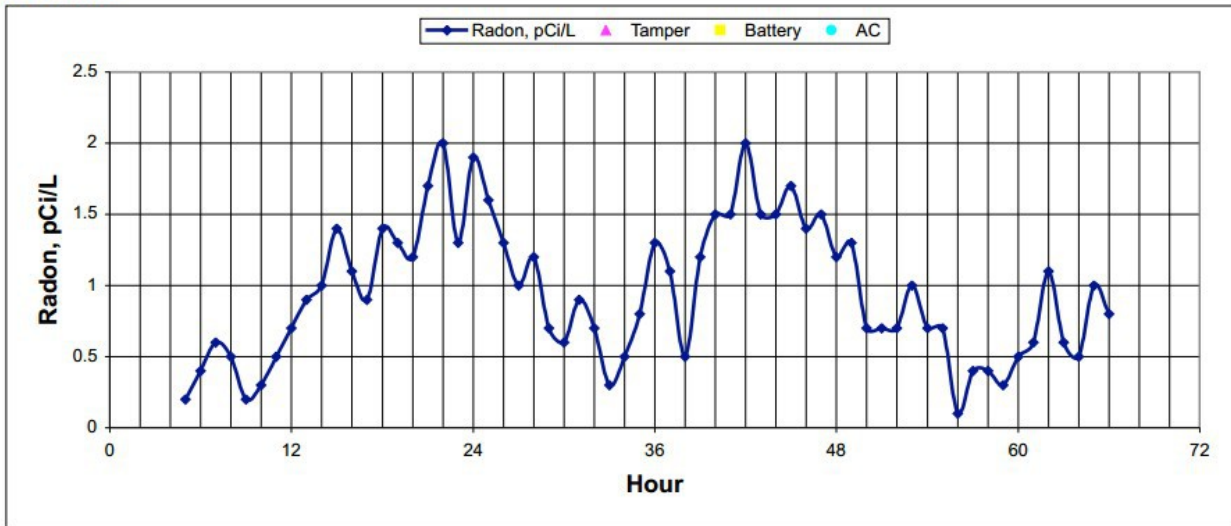
Commercial appliances charts

These graphs give an idea of what values are expected and what are the normal variations over time, in the concentration of radon.

RS300 Radon Test
Serial #01394
Calib. #31022
TestID #30008

Address
Location   Living Room
Technician DeWitt Kimball

**Average Radon Level, pCi/L: 0.9**

As you can see in this chart, is quite normal to see even very large variations during the day. In a few hours, it can change from a maximum of 2 pCi/l (74 Bq/m3), to a minimum of 0.1 pCi/l (3.7 Bq/m3), with a ratio between the minimum and the maximum, of 20 times. The one used, is a pretty expensive (about $ 200) and fast enough, for being a commercial device. Commercial appliances usually transmit data each hour, our graphics are instead one per second.

These variations are due to changes in temperature, which in turn, cause changes in pressure between the various parts of the house. Even wind and people moving around, help radon, which would tend to stagnate at the bottom, to mix with the upper layers of air. Not to be overlooked are the opening and closing of doors and windows. A chart like this, without further indications, let easily imagine that there have been movements of people and other nuisance factors.
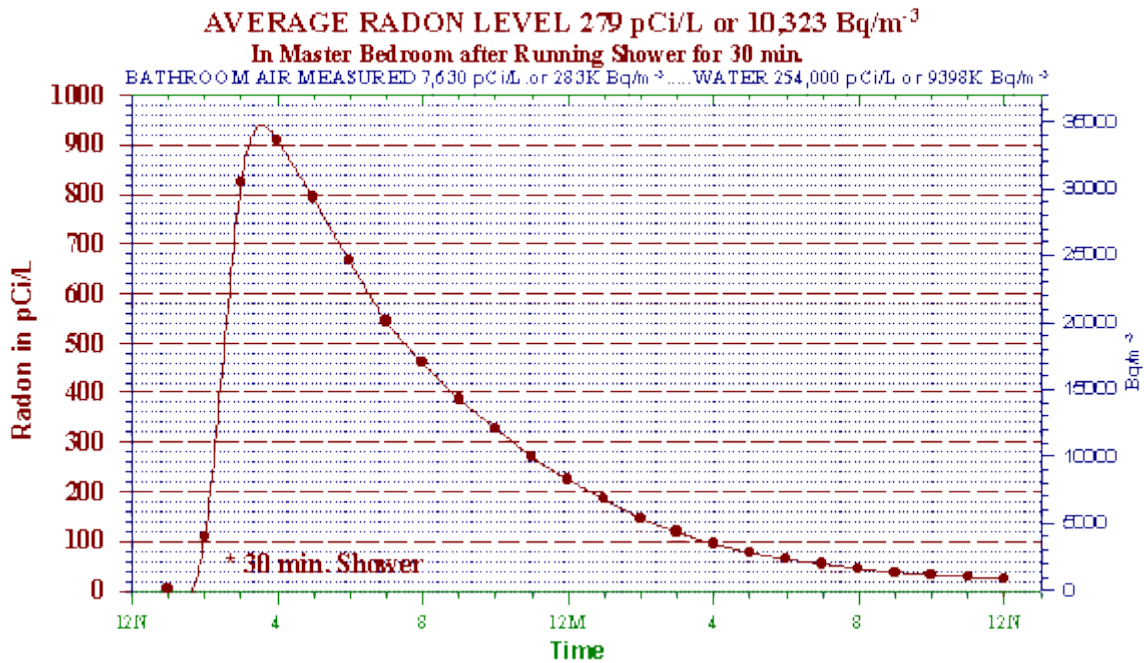
For comparison, here's a graph of a room left closed for almost a day.

Note the stability of the measurement over time. The residual undulations, are due more from the randomness disintegrations, then from the variations of radon concentration.

AVERAGE RADON LEVEL 144 pCi/L or 5328 Bq/m⁻³
AFTER MITIGATION 4.3 pCi/L or 159 Bq/m⁻³
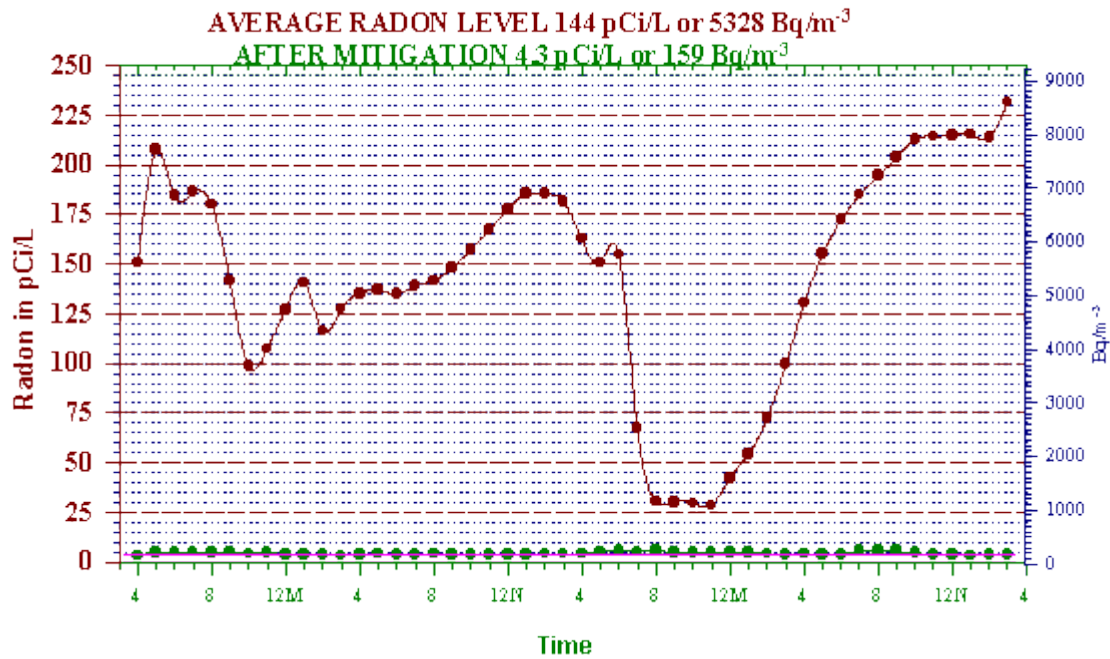
This image is a good example of what can be expected, in case of real danger. The graph was made by an American company, that performs operations on request and refers to a house that required an intervention of "mitigation". Before the intervention the level was twenty times the 400 Bq/m3 that EPA considers as maximum, for older homes. After the process, the radon has dropped to about 200 Bq/m3 (about 5 pCi/l), a level perfectly safe.

AVERAGE RADON LEVEL 279 pCi/L or 10,323 Bq/m⁻³
In Master Bedroom after Running Shower for 30 min.
BATHROOM AIR MEASURED 7,630 pCi/L or 283K Bq/m⁻³ .... WATER 254,000 pCi/L or 9398K Bq/m⁻³

Here we have a really curious graph, that shows how radon behaves often, in an unexpected way. In a bathroom (small and completely closed), just opening the shower for thirty minutes, has raised the concentration up to unbelievable levels. This only happens if you use water from a well, shouldn't happen normally, with water from the water supply.
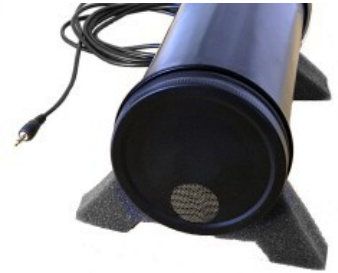
Features

Theremino IonChamber Features
```
----------------------------------------------------------------
Detector              pulsed ionization chamber
Sampling              passive diffusion
Range of measurement  0.5 to 74000 Bq/m3 (0.01 to 2000 pCi/l)
Sensitivity           0.05 cpm/Bq/m3 (2.0 cpm/pCi/l)
Accuracy              +/-50% (calibration not required)
Chamber volume        1000 cc
Memory                unlimited and adjustable intervals
Cost                  about 30 Euro (DIY Project)
```

Features of a professional device - Monitor CRM 510
```
----------------------------------------------------------------
Detector              pulsed ionization chamber
Sampling              passive diffusion
Range of measur.      from 36 to 7400 Bq/m3 (1 to 200 pCi/l)
Sensitivity           0.008 cpm/Bq/m3 (0.3 cpm/pCi/l)
Accuracy              +/-10% (with frequent calibrations)
Chamber volume        about 150 cc
Memory                100 hour intervals (4 days)
Cost                  about 4000 dollars (with accessories)
```

Features of a professional device - Safety Syren Pro3
```
----------------------------------------------------------------
Detector              pulsed ionization chamber
Sampling              passive diffusion
Range of measur.      from 5 to 37000 Bq/m3 (0.1 to 999.9 pCi/l)
Sensitivity           0.0008 cpm/Bq/m3 (0.03 cpm/pCi/l)
Accuracy              +/-20% (factory calibrated)
Chamber volume        about 20 cc
Memory                5 years
Cost                  about 130 dollars
```

The most popular meters (ordered by sensitivity)

Instrument	Principle of Detection	Sensitivity (Cpm/pCi/l)	Cost (Approx)
Safety Syren Pro3	Pulse Ioniz.	0.03	$ 130
Rsens-Rstone	Solid-State	0.06	$ 1500
Passive-Sun Nuclear	Solid-State	0.17	$ 925
Passive RS500	Solid state	0.30	$ 2145
Passive Femto CRM-510	Pulse Ioniz.	0.30	$ 3000
Passive-Radon Scout	Solid-State	0.31	$ 1000
Passive-E-Smart	Current Ioniz.	1.2	$ 2000
Active Radonics	Scintill. Cell	2.0	$ 8000
Theremino IonChamber	Pulse Ioniz.	2.0	$ (*)
Passive Alpha Guard	Pulse ioniz.	2.8	$ 6000
Active Durridge	Solid-State	2.8	$ 4500
Active Pylon AB-5	Scintill. Cell	5.7	$ 3500
Active DOE	Scintill. Cell	8.4	$ 3000
Active Eberline	Scintill. Cell	24.0	$ 6000

The scintillation cell types, do not provide a continuous measurement. Before the use, you mast load a filter with dust, measure it, change the filter every measure and use a pump with a calibrated air flow and constant time.

(*) The price is not comparable because Theremino is a "do it yourself" project, while the others are finished devices with case and accessories.

Appendix 1 - The methods listed by the EPA

EPA (Environmental Protection Agency) considers 15 methods, for the measurement of radon and shortens them with two-letter abbreviations.

The first thirteen are discontinuous methods and consist of two separate phases of collection and measurement. These methods are expensive and unreliable, requiring experienced personnel and procedures difficult to follow. They are still very popular, because in the past, units of measurement were so big and expensive, that was easier to keep them in the laboratory and carry only the samples.

AC - Activated Charcoal Absorption
LS - Charcoal Liquid Scintillation
AT - Alpha Track Detection (filtered)
UT - Unfiltered Track Detection
EL - Electret Ion Chamber (Long-Term)
ES - Electret Ion Chamber (Short-Term)
GC - Grab Radon / Activated Charcoal
GB - Grab Radon / Pump-Collapsible Bag
GS - Grab Radon / Scintillation Cell
SC - Three-Day Integrating vacuumed Scintillation Cell
PB - Pump-Collapsible Bag (1-day)
GW - Grab Working Level
RP - Radon Progeny Integrating Sampling Unit

The last two methods (CW and CR), allow continuous measurement of radon.

CW - Continuous Working Level Monitoring (24-hrs)
This method is based on a pump that accumulates dust in a filter and is classified as "continuous", despite it is on, 24 or 48 hours at most. Before each measurement, (usually 24 hours) filter must be replaced, a calibration of the response with sample source, must be done and measured the flow rate of the pump. To complete the task, you must have the following: Replacement Filters - alpha particle test source - airflow measuring instrument. Devices of this type cost thousands of Euro, the cost of the filters, as well, is not negligible.

CR - Continuous Radon Monitoring
The CR method includes the ion chamber and some more complex variations with an air pump and/or with a scintillation cell. On the following pages, you can read a brief explanation for each method. Note the simplicity of the method CR, compared to all the others.

Discontinuous methods for the radon measurement

AC - Activated Charcoal Absorption
On this method, an airtight container with activated charcoal is opened in the area to be sampled and radon in the air is adsorbed onto the charcoal granules. At the end of the sampling period, the container is sealed and may be sent to a laboratory for analysis. Gamma decay from the radon, adsorbed from charcoal, is counted on a scintillation detector and a calculation, based on calibration information, is used to coun the radon concentration at the sample site. Charcoal adsorption detectors, depending on design, are deployed on site, from 2 to 7 days long. Because charcoal, allows continual adsorption and desorption of radon, the method does not give a true integrated measurement over the exposure time. Use of a diffusion barrier over the charcoal, reduces the effects of air current and high humidity.

LS - Charcoal Liquid Scintillation
This method employs a small vial, containing activated charcoal, to sample radon. After an exposure period of 2 to 7 days (depending on the design), the vial is sealed and returned to a laboratory for analysis. While the adsorption of radon onto the charcoal, is the same as for the AC method, analysis is accomplished by treating the charcoal with a scintillation fluid, then analyzing the fluid using a scintillation counter. Radon concentration on the sample site, is determined by counting pulses per minute, conversion is done checking tables.

AT - Alpha Track Detection (filtered)
The detector is a small piece of special plastic or film, inside a small container. Air being tested, diffuses through a filter covering a hole in the container. When alpha particles from radon and its decay products, strike the detector, they cause damage with the shape of tracks. At the end of the test, the container is sealed and returned to a laboratory for reading. The plastic or film detector is treated to enhance the damage tracks, these are then counted, on a predetermined area, using a microscope or optical reader. The number of tracks per area counted, is used to calculate the radon concentration of the site tested. Exposure of alpha track detectors is usually 3 to 12 months. These detectors are true integrating devices, and may be exposed for shorter lengths of time, to measure higher radon concentrations.

UT - Unfiltered Track Detection
The unfiltered alpha track detector operates on the same principle as the alpha track detector, except that there is no filter present, to remove radon decay products or other alpha particle emitters. Without a filter, concentration of radon decay products, measured from the detector, depends on the equilibrium ratio of radon decay products, in the area being tested, not simply by the concentration of radon. Unfiltered detectors, using cellulose nitrate film, exhibit an energy dependency. This reduces, but not totally compensate, dependency of the calibration factor, from the equilibrium ratio. That's why EPA, recommends not using these devices, when the equilibrium fraction, is less than 0.35 or greater than 0.60, before adjusting the calibration factor. EPA is currently evaluating this device further, to determine more precisely, the effects of equilibrium fraction and other factors, on performance. These tests will lead to the decision, of whether further develop the current protocol, or remove the method from the list.

EL - Electret Ion Chamber (Long-Term)
In this method, an electrostatically charged disk detector (electret), is situated within a small container (Lithium chamber). During the measurement period, radon diffuses through a filter-covered opening in the chamber, where the ionization resulting from the decay of radon and its daughters, reduces the voltage on the electret. A calibration factor, relates the measured drop in voltage to the radon concentration. Variations in electret design, determine whether detectors are appropriate for making long-term or short-term measurements. Detectors of this kind, may be deployed for 1 to 12 months.

ES - Electret Ion Chamber (Short-Term)
The procedure is exactly the same as the previous method, but since the electret ion chambers are true integrating detectors, they may be exposed to shorter intervals, if radon levels are high enough.

GC - Grab Radon / Activated Charcoal

This method requires a skilled technician, to sample radon by using a pump, that draws air through a cartridge filled with activated charcoal. Depending on the cartridge design and airflow, sampling takes from 15 minutes to 1 hour. After sampling, the cartridge is placed in a sealed container and taken to a laboratory, where analysis is approximately the same as AC or LS methods.

GB - Grab Radon / Pump-Collapsible Bag

This method uses a sample bag made of material inaccessible to radon. At the sample site, a skilled technician using a portable pump, fills the bag with air, then transports it to the laboratory for analysis. Usually, air is transferred from a bag to a scintillation cell, performing an analysis as described in the GS method below.

GS - Grab Radon / Scintillation Cell

With this method, a skilled operator draws air through a filter, to remove radon decay products, into a scintillation cell, either by opening a valve on the scintillator, that has previously been previously vacuumed, using a vacuum pump or by drawing air through the cell, until it is in equilibrium, with the air being sampled, then it is sealed. To analyze the air sample, the window end of the cell, is placed on a photomultiplier tube, to count the scintillations, (light pulses) produced when alpha particles from radon decay, strike the zinc sulfide coating on the inside of the cell. A calculation is made to convert the counts, to radon concentrations.

SC - Three-Day Integrating vacuumed Scintillation Cell

In this method, a scintillation cell is fitted with a limiting valve and a negative pressure gauge. Prior to deployment, the scintillation cell is vacuumed. At the sample site, a skilled technician, checks negative pressure and opens the valve. The flow through the valve is pretty slow, so a sampling period of more than 3 days, is needed to fill the cell. At the end of the sample period, the technician closes the valve, checks the negative pressure gauge counter, and returns with the cell to the laboratory. Analysis procedures are approximately the same as the GS method described above. A variation of this method, involves the use of the above valve, but on a rigid container, requiring sampled air, to be transferred to a scintillation cell for analysis.

PB - Pump-Collapsible Bag (1-day)

With this method, a sample bag of a material where radon cannot pass, is filled over a 24-hour period. This is usually accomplished by a pump set to pump small amounts of air at predetermined intervals, during the sampling period. After sampling, analysis procedures are similar to those for the GB method.

GW - Grab Working Level

In this method, a known volume of air is pulled through a filter, collecting the radon decay products onto the filter. Sampling time is usually 5 minutes. The decay products are counted using an alpha detector. Counting must be done with precise timing, after the filter sample is taken. The two counting procedures most commonly used are the Kusnitz and the Tsivoglou methods.

RP - Radon Progeny Integrating Sampling Unit

On this method, a low-flow air pump, pulls air continuously through a filter. Depending on the detector used, radiation emitted by the decay products trapped on the filter, is registered on two thermoluminescent dosimeters (TLDs), an alpha track detector, or an electret. The devices presently available, require access to a household electrical supply, but do not require a skilled operator. Deployment, simply requires turning the device on at the start of the sampling period and off at the end. The sampling period should be at least 72 hours. After sampling, the detector assembly is shipped to a laboratory, where analysis of the alpha track and electret types, is performed using procedures described for these devices (AT, EL, and ES) elsewhere in this appendix. The TLD detectors are analyzed by an instrument, that heats the TLD detector and measures the light emitted. A calculation, converts the light measurement to radon concentrations.

Continuous methods for the measurement of radon

The EPA (Environmental Protection Agency) agency, lists only two methods for continuous measurement of radon, CW and CR

CW - Continuous Working Level Monitoring (24-hrs)

This method includes those devices, that record in real time the measurement of the decay products of radon. Radon decay products are sampled by the continuous pumping of air, through a filter. A junction detector or a surface barrier detector, counts the alpha particles produced by the decay products of radon, while they decay, in this filter. The monitor typically contains a microprocessor, that stores the number of counts for predetermined time intervals, for later recall. The measurement time for the measurement test of the program, is approximately 24 hours.

Defects:
- High cost of metering equipment and accessories.
- The pump must provide a constant flow.
- The measurement also depends on the air humidity.
- The continuous pumping of air dust, accumulates quickly, so it needs to be cleaned regularly.
- The filter should be changed before each measurement (at least every 24 or 48 hours).
- The flow rate gradually decreases, with the accumulation of dust, changing counting over time.
- Measures are not taken in a defined volume, meaning that calibration, has to be done on any measurement, with a test source.
Air filters, source calibration and flow meters, make these devices, even more expensive.
- Despite advertized as "continuous", in reality the measure should be stopped periodically, to change filters.

Finally, translating from the EPA notes again, here we have the CR method, which includes our ion chamber and two similar variations.

CR - Continuous Radon Monitoring

These devices measure continuously the variations of radon concentration. The air is pumped **or spreads** in a counting chamber, which is typically a cell scintillation **or an ionization chamber**. Electronic circuits, **count disintegrations in a known volume,** radon concentration is calculated with a coefficient.
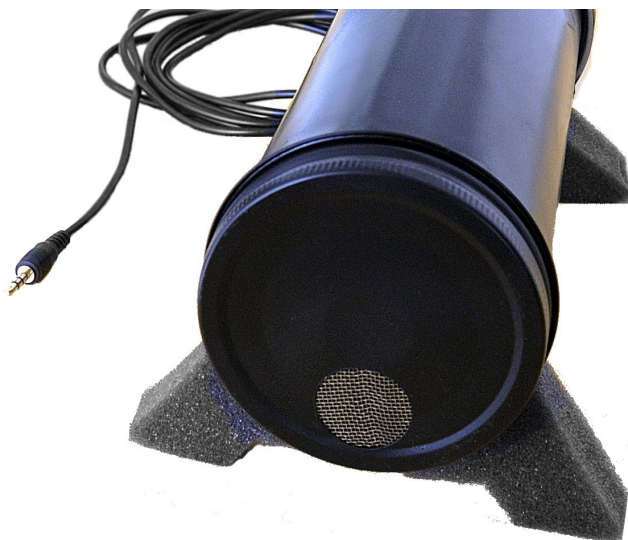
We have highlighted in bold, the parts that relate to our ion chamber, therefore classified as: **"Diffusion type, Ion Chamber for continuous measurement of radon through counting, according to the EPA CR method"**