PROBLEM: What is radon? Where does it come from? How does it get into my home? What are the health risks? What can I do about it?

III. BACKGROUND INFORMATION ON RADON

The United States Environmental Protection Agency (EPA) estimates that between 15,000 and 22,000 Americans die each year from lung cancer caused by indoor exposure to radon. In New Jersey, the State Department of Environmental Protection (DEP) attributes about 500 cancer deaths per year to radon statewide. Exposure to radon in indoor air is second only to cigarette smoking as a cause of lung cancer in this country.

In recent years the State of New Jersey has spent over $3 million on a statewide scientific study of radon, evaluation of potential health effects, testing and remediation programs, and a public information program. Students and their families should know what the EPA and the state agencies have learned about radon, what the risks are, and what can be done to decrease possible health risks. This teacher's guide is intended to provide you with relevant and practical information, activities, and investigations related to radon.

1. Radioactivity

In order to understand how radon is formed, how it disintegrates, and how it can damage lung tissue, we must first review some basic principles of atomic structure and radioactivity. The major components of an atom are protons, neutrons, and electrons. The solid mass of material at the center of the atom is called the nucleus. It is made up of protons and neutrons. Each proton has a single positive charge. Neutrons have no net charge. Orbiting around the nucleus at a very high speed are electrons. Each electron has a negative charge, and the number of negatively charged electrons will always equal the number of positively charged protons in a neutral or stable atom. The mass of each electron is negligible, well under one-thousandth of the mass of a proton or neutron. The bulk of the space taken up by the atom, however, is the empty space through which the electrons pass as they travel around the nucleus. Although the nucleus contains almost all of the atomic mass, it occupies almost none of the space. For example, if a typical atom was the size of Yankee Stadium, the nucleus would lie just behind second base and be about the size of a marble. The electrons would be flying around the rest of the stadium at very high speed.

The number of protons in an atom tells you what kind of element it is. This number is called the element's atomic number; it is designated by the symbol "Z". For example, hydrogen contains only one proton and has an atomic number of one (Z=1). Helium has two protons; carbon has 6, oxygen has 8, uranium has 92, radon has 86, and so on.

Nearly all of the mass of an atom is provided by its protons and neutrons, both located in the nucleus. The number of protons plus the number of neutrons is called the mass number, designated by the symbol "A". The mass number identifies the isotope of an element. Isotopes have the same number of protons (and therefore they are the same element), but they have different numbers of neutrons. For example, all radon isotopes have 86 protons (Z=86), but radon-222 has 136 neutrons (86 + 136 = 222), whereas radon-220 has only 134 neutrons (86 + 134 = 220). The chemical symbol for radon is Rn, and the mass number is usually placed either after the symbol (Rn-222) or to the left and above it (^{222}Rn). In either case, it simply designates the element radon, which always has 86 protons, and that the particular isotope of radon is the one with 136 neutrons. Different isotopes of the same element will behave exactly the same chemically, but they behave differently in terms of the nuclear reactions that they undergo.

Many isotopes of different elements are unstable. In other words, the protons and neutrons in their nuclei are not arranged in a stable configuration, and the nuclei are prone to spontaneous breakdown. During this process, called radioactivity, an unstable atom breaks down or disintegrates in an attempt to reach stability. When a nuclear disintegration or breakdown occurs, one or more particles or energy rays are emitted or given off and the nucleus changes as a result of this emission. Three types of radiation can be emitted: alpha, beta, and gamma.

- **Alpha** particles contain two protons and two neutrons. When a radioactive isotope such as radon-222 emits an alpha particle, it loses two of its protons and two of its neutrons, because they make up the alpha particle that flies out of the nucleus during the disintegration. Thus, when an alpha particle is emitted the atomic number of the isotope decreases by 2, and it becomes a new element. In the case of radon-222, the new element formed is called polonium-218. Also, the mass number decreases by 4. Alpha particles are very large by radiation standards, and they can do a lot of damage to sensitive biological tissue, mainly by knocking electrons off atoms. Although very damaging inside the body, they are easily stopped when they run into things, and cannot penetrate through skin or even pass through a piece of paper.

- **Beta** particles are high speed electrons that are ejected from a radioactive isotope at nearly the speed of light. They have medium penetrating power, and can penetrate a short distance into the body.
- **Gamma** rays constitute a form of high energy electromagnetic radiation, like visible light, but with more energy. Gamma rays are like x-rays, have great penetrating power, and can pass right through your body.

There are a number of radioactive decay chains that occur in nature. A decay chain is a series of radioactive isotopes that are produced in sequence by radioactive disintegrations. The decay chain of greatest interest with respect to the indoor radon problem is the one that proceeds from uranium-238 to eventually form lead-206. During the chain, a net total of ten protons are lost ($Z = 92$ for uranium and $Z = 82$ for lead) and the mass number is reduced by 32. Fourteen different isotopes are produced along the way, including radium-226, radon-222, and polonium-218. Eventually, lead-206 is formed, which is stable or non-radioactive, and the chain of decay is halted. All of the intermediate isotopes, called decay products (sometimes referred to as daughters or progeny), are radioactive or unstable. Some give off alpha radiation and some beta radiation. At some stages, gamma rays are also given off. Since lead-206 is not radioactive it remains lead-206 rather than changing into another element.

There is one additional property of radioactive decay that is important in examining radon issues, and that is known as the half-life. The half-life of an isotope is a reflection of how long it lasts, on average, before decaying into the next isotope in the chain. It is defined as the amount of time it takes for half of the material to undergo radioactive decay, and thereby disappear (be transformed into something else). The half-life of uranium-238 is 4.5 billion years. If you start with one gram (g) of ^{238}U and wait 4.5 billion years, only 1/2 g will be left. The other 1/2 g would have decayed into the next isotope in the chain. If you wait an additional 4.5 billion years, only 1/4 g of ^{238}U will be left (one-half of 1/2 g). Each of the decay product isotopes in the decay chain has its own half-life, and once it is formed it begins its decay to the next isotope in the sequence. The half-life of radon-222 is only 3.8 days. Some isotopes in the ^{238}U decay chain series have half-lives on the order of minutes, and for polonium-214 it is only 164 micro-seconds (millionths of a second). The half-life of ^{222}Rn is just about the right length to cause a problem in homes. Radon is the only member of the chain that is a gas, and therefore the only one apt to make its way from rocks and soil up into your home. If it had a much shorter half-life most of it would change into another solid (polonium-218) before escaping from the soil. If it had a much longer half-life, most of the radon would escape from the house before it underwent its next disintegration to form polonium-218. This is important to note because it is the polonium-218 (with a half-life of 3 minutes) and some of the other decay products that present the greatest risk. They emit relatively high-energy alpha particles that can be especially damaging when the disintegration occurs inside a person's lungs.

2. Radon Characteristics and Occurrences

Radon is a naturally-occurring radioactive gas. You cannot see, smell, or taste it. It is produced from the radioactive breakdown of radium, is found in soils just about everywhere, and continually escapes from soils into the atmosphere. Although some radon can be found in virtually every home, under certain situations it builds up to high concentrations in indoor air, thereby constituting an important health hazard. In order to understand why radon makes its way into homes, how it can build up to dangerous concentrations, and how it can damage your health, we must first introduce some basic information about radon behavior.

There are several different kinds or isotopes of radon, but the one that is of greatest interest and concern regarding possible health effects is called radon-222. Radon-222 is produced during a chain of radioactive disintegration reactions that begins when uranium-238 starts to break down. The uranium-238 is widely distributed in rocks and soils throughout the earth's crust. Most kinds of rocks and soils have some uranium, but usually only a small amount. At each stage in the radioactive decay series, one or more types of radiation is given off, and one radioactive element changes into another. There are eight different elements involved in the series, beginning with uranium-238. Eventually, a stable (non-radioactive) isotope of lead is formed, and the sequence of reactions comes to an end. All of the elements in the chain except radon are solids and tend to stay in place within the rocks and soils where they are produced. Radon, a gas, is the exception. There are five major reasons why radon can be a problem in your home:

1. It is a gas and can therefore move through, and out of, rocks and soils underneath your home.

2. It lasts for several days (that is, has a half-life of 3.8 days) before it breaks down into the next element in the series.

3. It is nonreactive chemically, and therefore does not get tied up in chemical compounds. This allows it to escape from soils into the atmosphere.

4. Radon itself is not the major hazard to biological tissues, but polonium and other radon decay products that are formed when the radon decays can be very damaging inside the lungs.

5. Human senses cannot detect the presence of radon, regardless of how high the concentra tion, because it is odorless, tasteless, and invisible.

3. Geologic Processes and Uranium Distribution

Uranium is a trace element that is widely distributed in geologic materials. Different rock types contain different concentrations of uranium, and pockets of uranium can be formed during and after the processes of rock formation and rock metamorphosis. By identifying rocks that are likely to contain high concentrations of uranium (and to release relatively large quantities of radon gas) and then examining possible routes of radon movement through rocks and soils to the earth's surface, it is possible to evaluate the radon potential of different areas.

The most important uranium ore is pitch blende (UO_2), which is most often found in silicic rocks (those high in silica), like granite. This compound can be dissolved and transported in groundwater, and then later deposited in rock fractures or certain sedimentary rock types. Rich deposits have been found in sedimentary rocks in the Colorado Plateau, Tennessee, Kentucky, and elsewhere. Uranium generally occurs in rocks and minerals as an ion, i.e., in a compound with a positive charge of +4 (U^{4+}). If oxygen-rich waters come into contact with the uranium on a rock surface, it can be oxidized to U^{6+}. U^{4+} is not soluble in water; U^{6+} is soluble, and forms complexes with carbonate. The differences in behavior of the oxidized versus the reduced forms of uranium are important for understanding how uranium is transported through the environment.

Shales often contain high concentrations of uranium because they contain organic materials. Organic deposits are prone to uranium build-up, because dissolved uranium tends to precipitate out of solution in the presence of organics and become deposited in the rock or soil material. Uranium concentrations are extremely high in some black shales, for example the Alum shale in Sweden and the Chattanooga shale in the eastern United States.

As mentioned above, uranium is widely distributed in rocks. During the process of mineral weathering, uranium exposed to the elements will dissolve and be transported in water that moves through the rock materials. In solution, uranium is generally in the form of uranium carbonate. For that reason, carbonate-rich minerals, such as limestone, can contain high uranium concentrations, especially if granite or other high uranium source rocks are weathering nearby.

Marine phosphorite constitutes an example of sedimentary rock material rich in calcium phosphate and uranium. These deposits are mined for their phosphorus, especially in Florida. Uranium is now recovered as a byproduct of the mining process. In years past, however, the mining wastes were used for fill in housing developments. This explains why some homes in Florida have been found to contain high concentrations of radon.

Sandstones are not known for being high in uranium. Pockets of shale and organic matter are sometimes found in sandstone beds, however, and these pockets can be quite high in uranium. The processes that contribute to these uranium-rich deposits in sandstone are relevant to an interdisciplinary treatment that bridges the gaps between geology, mineral weathering, and chemistry (including oxidation/reduction, dissolution, and precipitation reactions). The general scenario is as follows. A layer of sandstone is underlain and overlain by two layers of shale. The sandstone is more permeable than the shale layers and acts as an aquifer (a layer of rock serving as a water supply source), especially when the layers are tilted. As water flows through the sandstone, it carries low concentrations of uranium that it dissolved from the other source rock materials nearby. The uranium exists in solution in an oxidized state, as U^{6+}, which is quite soluble. When the water encounters a pocket of shale and organic matter, the chemical conditions change from an oxidizing (oxygen-rich) en-

Oxidation essentially means combining with oxygen. In the process, electrons are freed, and the ion becomes more positive. (It loses some of its negativity in the form of lost electrons.)

Reduction is the opposite process to oxidation. It can be thought of as the removal of oxygen or as a gain in electrons (negative charge). The charge on the ion is reduced in the process.

vironment to a reducing (oxygen-poor) environment. In response to this change in redox conditions, the uranium in solution is reduced to the U^{4+} form. U^{4+} is much less soluble than U^{6+}, and the uranium precipitates out of solution. Over time, more and more uranium is removed from solution in this manner, leading to rich uranium deposits within the sandstone.

4. Entry into Homes

As discussed in the sections presented above, radon is produced during the radioactive decay series that begins with uranium-238. Uranium is widely distributed in geologic materials and can be transported from place to place via dissoluiton and precipitation reactions. When radon is formed during decay process, it has the potential to escape from the rock or soil material whre it was formed, because, unlike other elements in the series, it is a gas.

Most of the radon found in indoor air comes from the rocks and soils around the home. Some building materials and well water can also be important sources in certain cases, but by far the most important contributor is the ground under the home. Some kinds of rocks, and the soils formed from their breakdown, are more prone to giving off radon than others. These are rocks that have high concentrations of uranium, especially some granites and gneisses, marine shales, and some limestones.

Radon moves through cracks and fissures in rock and through the air spaces in soil to make its way into the home. The type and depth of soil present (especially pore size, density, etc.) and locations of cracks in the underlying rock materials are important factors influencing radon movement upward to the base of a house. It enters via numerous small cracks and openings found in the foundation, concrete slab, and walls. Indoor air concentrations are influenced by the number and size of such openings from the soil and the amount of household ventilation. Concentrations tend to be highest in cold climates during the winter because ventilation is usually reduced during cold seasons (i.e., windows are kept closed), and hot air rising to escape at the top of the house causes a slight vacuum in the lower parts of the house. Radon-contaminated air is pulled into the house from the bottom to fill the vacuum. Because the radon enters at ground level and is removed by ventilation, concentrations tend to be highest on the lower floors of the house, especially the basement. In apartment buildings, radon concentrations are seldom high enough to cause concern above the second floor. dissolution and precipitation reactions. When radon is formed during the decay process, it has the potential to escape from the rock or soil material where it was formed because, unlike other elements in the series, it is a gas.

5. Health Effects

Radon causes human health effects primarily via alpha particle emissions of the radon decay products, especially polonium-218 and polonium-214. These radioactive disintegrations in the air inside the home are of little concern because the emitted alpha particles are easily stopped by a couple of centimeters of air, and they are unable to penetrate your skin. Unfortunately, protection provided by skin is not available inside the lungs, and the alpha particles emitted inside the air passages in the lungs by some of the disintegrating decay products are sufficiently powerful to penetrate the lung lining (epithelium) and damage a layer of sensitive cells called basal epithelial cells. This damage can sometimes lead to lung cancer.

The main air passages leading from the trachea (windpipe) to the lungs are called bronchi. At the ends closest to the mouth, bronchi are lined with tiny hairs, called cilia, that help to trap particles present in the air, including the inhaled radon decay products. The outer layer of the epithelium is comprised of mucus-secreting cells. The mucus also helps to clear away foreign substances. Some of the alpha particles emitted by the radon decay products have sufficient energy to penetrate through the outer layer of epithelium and reach the sensitive basal epithelium. Cell division occurs rapidly here, and this layer is therefore prone to development of cancer. Remember that cancer is essentially out-of-control cell division. Damage is a function of the thickness of the layer of outer epithelial cells and the energy level of the alpha particles that are emitted during radioactive disintegration inside the bronchi.

Scientists and medical professionals don’t have a complete understanding of how radiation damages biological tissues. A current theory is that radiation destroys important chemical bonds in molecules by a process called ionization, which is essentially knocking electrons off neutral atoms to form ions (positively or negatively charged atoms or molecules). This damage appears to be a particular problem in DNA, resulting in the death of individual cells or development of abnormal cellular growth patterns. DNA is a long, thread-like molecule made up of chains of nucleotides that contain encoded genetic information. When the DNA molecule is broken, it can repair itself. If DNA is repeatedly damaged, there is an increased possibility that repairs will be incorrect. Faulty repair can result in an error in the sequence of nucleotides that provide the correct genetic information for cell division. Such coding errors are believed to lead to gene mutation, and sometimes to cancer. Although there are thousands of different substances that are suspected of causing cancer, there are only about two dozen known human carcinogens. Radon is one.

It is difficult to give precise information on the cancer risks from radon contamination in indoor air. We know from studies of underground miners that high concentrations of radon in the air increase the chances of developing lung cancer. Exposure to large amounts of radon appears to increase the cancer risk. Quantification of the risk associated with indoor exposure to concentrations that are lower than those found in the mine studies depends on what assumptions are made about the relationship between the dose of radiation received and the incidence rate of cancer in those who receive the dose. Age and sex differences and other factors, especially smoking, also influence the actual risk. Recent epidemiological studies of household radon exposure suggest that a linear extrapolation from the miner studies to household exposure risks appears reasonable. Although we don't know how many people die each year from lung cancer caused by radon, estimates for the United States range between about 15,000 and 22,000 deaths per year. This is about 10% of the lung cancer deaths attributed to smoking.

6. Measurement

a) *Units of Measure*

There are a number of systems in use for measuring radioactivity. Some are based on the number of radioactive disintegrations that are given off by the radioactive material during a given period of time, and some are based on the amount of radiation that is actually absorbed by a person, or a rat, or whatever. The basic unit of measurement most commonly used in the United States for radioactivity is the curie, expressed as the symbol "Ci". One curie is equal to 37 billion radioactive disintegrations per second; that is a lot of radioactivity! The radioactivity given off by radon and its decay products is usually measured in picocuries (pCi), or trillionths of a curie.

Because the number of pCi tells only how many disintegrations are occurring per unit of time, it is also important to give some information on the space in which those disintegrations are occurring. For example, there are large differences in the amount of radioactivity in the following:

- 1000 disintegrations per second per house
- 1000 disintegrations per second per 10 x 12 x 8 ft living room
- 1000 disintegrations per second per cubic centimeter of household air.

For convenience, household radon levels are expressed as the number of radioactive disintegrations that occur within a liter of air, in picocuries of radioactivity per liter of air (pCi/L).

As discussed above, radon decay products, not the radon itself, are the major culprits in causing lung damage. The decay products of radon are much more difficult to measure because they are solids, whereas radon is a gas. The solids become attached to particles in the air, to furniture, to your cat, and so on. A reasonable measurement of the radon gas concentration in the air will provide a pretty good indication of the concentration of radon decay products. Measurements need not, and cannot, be highly precise. Every time you open the door, build a fire in the fireplace, turn on the kitchen or bathroom fan, or do scores of other routine things, the radon concentration in the air you breathe changes. There is quite a bit of variability in the levels found from room to room in the house, throughout the day, and from season to season.

b) *Levels of Safety and Concern*

Regardless of the variability in measured concentrations, we still need to know what constitutes a "high" concentration. At what level should I become concerned? Should I panic, leave the house, and move to an island in the South Pacific? What is a "safe" level? There is no totally safe level of radon in your household air, any more than it is ever totally safe to hop in your car and drive to the grocery store. You might develop lung cancer from exposure to "low" levels of radon over many decades, or you might get creamed by a Mac truck on your way to the store. The EPA recommends 4 pCi/L as an "action level" for radon in homes. In other words, if the average levels in your home are above 4 pCi/L, EPA scientists think it would be prudent for you to do something about it. This action level is based partially on the study of cancer incidence in underground miners, partially on laboratory animal experiments, and partially on practicality. It is generally possible to reduce indoor concentrations to 4 pCi/L or below. Thus, the 4 pCi/L level is an "achievable" goal for homeowners in trying to minimize their health risk. It is important to realize that standards are subjective. A person with lungs that are highly susceptible to lung damage from radon decay products might be at greater risk in a home with 4 pCi/L of radon than a very healthy individual living in a home with 10 pCi/L of radon.

c) *Methods of Measuring Radon*

Because radon is undetectable by human senses, no matter how high the levels might be, it can only be detected by a test. There are several ways to measure the radon concentrations in your home. Each method has its advantages and disadvantages. The three most common types of radon detectors used for home testing are the charcoal canister, alpha track monitor, and electret ion chamber. Charcoal canisters are used for short term tests (2-7 days) and measure radon gas by adsorption. Alpha track monitors are for long term tests (3-12 months) and measure radon gas by recording the tracks of alpha particles emitted when the radon decays. The electret ion chamber contains a specially charged device that when exposed to the air reacts to the radiation emitted from radon and its decay products. The electret ion chamber can be used for both short and long term tests.

The recommended procedure for all homeowners is to begin with a short term test. Depending on the results of the initial test, a homeowner may need to do additional confirmatory testing. For specific information about testing procedures, interpretation of test results, and mitigation or remediation actions, individuals should contact their state radon programs. See Resources, State Radon Programs.

7. Mitigation

Mitigation is a term that is used to mean “fixing the problem.” If your tests suggest that the radon levels are too high, and you want to do something about it, then the next step is to implement one or more mitigation strategies to decrease the radon concentration and thereby decrease your health risk. There are many different radon mitigation techniques, but they all involve one of two things: 1) keeping radon from leaking into the house, and 2) once radon gets into the house, ventilating it out. The best approach or combination of approaches to use will depend on such things as:

- how high the test results are
- the design and air flow patterns of the house
- the cost of different strategies
- appearance (i.e., exposed ventilation pipes in the basement).

Specific strategies might include sealing the cracks and openings in and around the concrete slab under the house and the foundation, increasing ventilation with fans or heat-exchangers, or drawing soil gas away from the house before it enters. Some corrective measures can be implemented by the homeowners; some require the skills of a professional radon contractor. The cost of effective mitigation may vary from $100 to a few thousand dollars. The work itself can be done by a homeowner or a professional radon contractor. Regardless of who does the work and how much it costs, confirmatory testing should *always* be done to see how successful the mitigation has been.

IV. LESSON PLANS

This section contains ten individual lesson plans and the accompanying teacher's notes. They are structured to be stand-alone units, which can be used in the classroom either individually or as a group. However, lesson plans #2 (What is Radioactivity?) and #3 (What is Radon?) should be considered as necessary prerequisites to those that follow (#4 - #10).

The radon topic is, by its very nature, multidisciplinary. This is a major factor that makes radon both interesting and challenging to students. It allows exploration of a multifaceted and relevant topic, while building process learning skills and higher order thinking skills in the students. Few individuals, however, possess sufficient background in all of the relevant disciplines to fully understand the major factors that can come into play in an integrated discussion of radon. We therefore recommend that you, the teacher, carefully review the background information provided in Section III prior to proceeding with the individual lesson plans.

In completing many of these lesson plans, students will analyze, graph, and interpret different kinds of data. Students are encouraged to manipulate the data in such a way as to draw meaningful conclusions. All of the exercises can be completed without using a calculator or computer.