Health and Environmental Issues Linked to the Nuclear Fuel Chain

Section A : R A D I O A C T I V I T Y

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Table of Contents

A: RADIOACTIVITY

I. Introduction

I.1. Rationale of the Study

The most challenging environmental issues of today are those associated with the production and use of energy. Acid rain has damaged our lakes and forests, the greenhouse effect jeopardizes our climate and coastal cities, oil spills have fouled our oceans and shorelines, and radioactive contamination, on a large enough scale, has the potential to threaten the molecular basis of life.

This report is intended to provide a general overview of the health and environmental issues posed by

nuclear power. It is hoped that it will serve as a useful resource document for all parties in the ongoing energy debate by laying out the main concerns related to nuclear power in a balanced, technically sound and informative way.

. . . back to Table of Contents Section A - Section B - Section C

I.2. Structure of the Document

As Peter Dyne of Atomic Energy of Canada Limited stated in 1977,

> The long-term commitment to nuclear power involves handling very large inventories of radioactive materials. Unless society is prepared to accept that proposition you will not -- you can not -- have a large-scale implementation of nuclear power.
>
> **Testimony to the Cluff Lake Board of Inquiry, Saskatchewan, 1977.**

The health and environmental issues characteristic of nuclear power require an understanding of the basic properties of radioactive materials. Therefore, a short summary of the pertinent background information is provided in the first three sections of the paper:

Section A. Physical Properties of Radioactivity
Section B. Biological Effects of Ionizing Radiation
Section C. Fundamentals of Nuclear Fission

This is followed by a concise discussion of the major environmental issues associated with various stages of the nuclear fuel chain:

Section D. Uranium Mining and Milling
Section E. Accidental Releases from Nuclear Reactors
Section F. High Level Radioactive Wastes
Section G. Reprocessing and Advanced Fuel Cycles

The concluding section deals with routine health and environmental problems associated with the nuclear industry.

Section H. Chronic Health and Environmental Problems

Throughout the paper, the object is not to provide a detailed analysis of the issues leading to recommendations, but simply to delineate the nature and scope of the problems.

. . . back to Table of Contents Section A - Section B - Section C

A. Physical Properties of Radioactivity

A.1. Radioactive Emissions

Radioactivity was discovered in 1896 in Paris, when Henri Becquerel noticed a radiating pattern of light imprinted on a well-wrapped photographic plate which had lain for weeks in a closed drawer, close to a piece of uranium-bearing ore. He was astounded by this accidental discovery. Here was a seemingly inert rock, spontaneously emitting a strange form of penetrating energy, without being stimulated by light or any other external agency.

In 1897, in England, Ernest Rutherford observed that ores of uranium and thorium are continually giving off two types of electrically charged particles which he called alpha and beta. Alpha particles have more

energy than beta particles, but less penetrating power, due to their greater mass (an alpha particle is 7000 times heavier than a beta particle). Any material emitting alpha or beta particles is called "radioactive".

Paul Villard (France, 1900) found that radioactive ores also emit a third, more highly penetrating form of energy. Following Rutherford's nomenclature, he called these emissions "gamma rays". Unlike the alpha and beta varieties, gamma rays are not material particles at all, but energetic photons of invisible light. They closely resemble the mysterious x-rays which Roentgen had discovered emanating from a high-voltage electrical apparatus in 1895.

Alpha particles, beta particles, gamma rays and x-rays, all have one characteristic in common. They will ionize any medium through which they pass, and are therefore collectively categorized as "ionizing radiation". At the simplest level, the ionizing property means that the passage of these energetic particles or photons through any medium noticeably increases the ability of that medium to conduct an electrical current. This unique effect has been used from the earliest times to detect and/or measure ionizing radiation. [1]

. . . back to Table of Contents Section A - Section B - Section C

A.2. Radium and Polonium

In 1898, in France, Marie Curie isolated two new radioactive elements, naming them "polonium" (after her native Poland) and "radium" (after the radiating lines in Becquerel's photographic image). Both are alpha-emitting substances, found in tiny amounts in all radioactive ores. They are, gram for gram, millions of times more radioactive than either uranium or thorium.

Two remarkable properties of these new elements soon became apparent. In chemically pure form, even minute quantities will glow in the dark, and prolonged contact with skin will produce burns which are difficult to heal. Accordingly, the two principal uses of radium in the first half of the twentieth century were as a luminous paint, especially on watch dials, and as a therapeutic agent to shrink tumours. Polonium had no specific application until the WW II atomic bomb project, when it was used in the triggering mechanism to initiate an atomic explosion.

. . . back to Table of Contents Section A - Section B - Section C

A.3. Radioactive Decay Products

Atomic research in Canada began in 1899. In that year Rutherford arrived at McGill University to head up a new Physics Lab, generously endowed by MacDonald, the tobacco merchant. In a series of brilliant experiments, the young New Zealand physicist established the basic properties of radioactivity and laid the groundwork for our understanding of the structure of the atom, earning him an undisputed reputation as "the Newton of atomic physics".

Rutherford was puzzled to find a chemically inert radioactive gas (now known as radon) emanating from a sample of radioactive ore. He enlisted the help of Frederick Soddy, a British chemist then at McGill, who confirmed what Rutherford already suspected: no conceivable chemical reaction could produce such a gas. The two scientists concluded (in 1903) that they were witnessing the spontaneous transmutation of one element into another. They conjectured that each alpha or beta emission signals the instant when an individual atom changes its identity. This atom-by-atom process of transmutation is called "radioactive decay" and the new elements formed are called "decay products". Radon, radium and polonium are three of the decay products of uranium.

. . . back to Table of Contents Section A - Section B - Section C

A.4. Rate of Decay and Units of Activity

Rutherford showed that each radioactive element has its own characteristic rate of decay, measured by the half-life (the period of time needed for half of its atoms to decay spontaneously into something else). This law applies to both alpha-emitters and beta-emitters. After ten half-lives, one part in a thousand still remains (e.g. a kilogram is reduced to a gram). There is no known way to influence the rate of decay or to stop the decay process.

In 1910, the CURIE (Ci) was introduced as the basic unit of activity. Originally defined as the activity of one gram of pure radium, the curie was later redefined as 37 billion disintegrations per second. The curie has now been superceded by the BECQUEREL (Bq), which is one disintegration per second. [2]

. . . back to Table of Contents Section A - Section B - Section C

A.5. The Atomic Nucleus

Back in England, Rutherford (beginning in 1911) used alpha particles as probes to prove that each atom has a tiny, massive, positively charged nucleus, orbited by very light, negatively charged electrons. [3] Most nuclei are stable and unchanging, but some are not. The unstable nuclei are the radioactive ones.

Rutherford demonstrated that alpha particles, when they come to rest, are actually helium nuclei, while Becquerel showed that beta particles are really high-speed electrons -- both originating from within an unstable nucleus. Gamma ray photons also come from inside the nucleus, unlike x-ray photons which originate from the actions [4] of electrons outside the nucleus.

. . . back to Table of Contents Section A - Section B - Section C

A.6. The Neutron

In 1920, without a shred of real evidence, Rutherford speculated on the possible existence of a neutral particle or "neutron", having about the same mass as a hydrogen nucleus or "proton", but with no charge at all. He thought of it as a proton with an embedded electron, rather like a hydrogen atom whose solitary orbiting electron had somehow collapsed into the nucleus. This prophetic insight was experimentally verified ten years later.

When W. Bothe (Germany, 1930) bombarded a beryllium target with alpha particles, he was astonished to observe an extremely energetic, highly penetrating form of ionizing radiation never before encountered. F. Joliot (France, 1931) was equally baffled by these results. Only James Chadwick, a colleague of Rutherford's, guessed the truth. With meticulous care, he proved beyond doubt (England, 1932) that the mysterious new "rays" were neutrons, knocked out of the beryllium nuclei under the impact of alpha particles.

. . . back to Table of Contents Section A - Section B - Section C

A.7. Nucleons

Science now holds that every nucleus is made up of protons and neutrons, which are therefore called "nucleons". Inside an unstable nucleus, a neutron may suddenly change into a proton by ejecting its "embedded electron" as a beta particle. This "explains" how a negatively charged beta particle can originate from a positively charged nucleus. [5] Alternatively, an unstable nucleus can emit an alpha particle, which is made up of two protons and two neutrons tightly bound together.

In the vast majority of cases an alpha or beta emission is either accompanied or followed by a gamma

emission. None of the nucleons is altered during a gamma emission; the nucleus simply sheds its excess energy. A radioactive nucleus which is not a gamma emitter is called a "pure" alpha or beta emitter.

. . . back to Table of Contents Section A - Section B - Section C

A.8. The Atomic Number

The number of protons in a nucleus is the atomic number. It is designated by the letter "Z". This number determines the chemical nature of an element, ranging from $Z = 1$ for hydrogen, the lightest element, to $Z = 92$ for uranium, the heaviest element in nature. In the table of elements devised by chemists, called the Periodic Table [6], the elements are listed in numerical order according to the number of protons in the nucleus. That is, they are listed by increasing values of Z.

In a normal, or "non-ionized" atom, the number of electrons in orbit equals the number of protons in the nucleus. Thus an atom of hydrogen has a single orbital electron, while an atom of uranium has 92 electrons in orbit. Since electrons and protons have equal but opposite charges, the net charge on the atom is zero.

. . . back to Table of Contents Section A - Section B - Section C

A.9. Molecules

When several atoms combine to form a molecule, the nuclei are unaffected but the orbital electrons are redistributed. Since the total number of electrons balances the total number of protons, the net charge on a molecule is zero. However, if one of the chemical bonds holding the molecule together is suddenly broken, an electrical imbalance will occur (due to the rearrangement of the electrons). This leaves one molecular fragment with too many electrons and the other with too few, so that each of them has a net charge.

If one of the constituent atoms in a molecule is radioactive, so too is the molecule, as the radioactive nucleus continues to emit ionizing radiation.

. . . back to Table of Contents Section A - Section B - Section C

A.10. Ions and Ionization

There are two kinds of ions, namely the "atomic" and "molecular" ions:

1. if an atomic nucleus is orbitted by too many or too few electrons, in comparison with the number of protons in the nucleus, the resulting charged atom is called an "ion" (it is an "atomic ion");

2. if one of the chemical bonds connecting atoms in a molecule is broken, the electrically charged molecular fragments are also called ions, or "free radicals" (these are "molecular ions").

Ions are far more reactive, chemically, than uncharged atoms or molecules. Whenever a particle (or photon) of ionizing radiation penetrates matter, thousands of highly reactive ions are created all along its trajectory. Indeed, the electromagnetic energy of such a subatomic projectile is so great that orbital electrons from nearby atoms are ripped from their orbits and sent showering among the surrounding molecules, causing a series of random electronic interactions, breaking thousands of chemical bonds, and leaving behind a trail of newly formed ions.

In any kind of material, the presence of these electrically charged ions greatly facilitates the passage of an electric current. But in living tissue, "ionization" can also do profound biological harm, as organic

molecules are subjected to random damage. Of course the DNA molecules, which store genetic information inside a living cell, are of particular importance.

A water molecule has two atoms of hydrogen combined with one atom of oxygen. Its chemical formula is H_2O. If one of these chemical bonds is broken, two ions are formed: a positive hydrogen ion H+, and a negative molecular fragment called a "hydroxyl ion", OH-. When ionizing radiation interacts with living tissue, many hydroxyl ions are formed. It is believed that these play an important role in damaging DNA molecules.

. . . back to Table of Contents Section A - Section B - Section C

A.11. Units of Ionizing Energy

The ionizing ability of any ionizing projectile depends on its energy. The basic unit of energy at the atomic level is the ELECTRON-VOLT (eV). This is the energy acquired by one electron when it is accelerated by an electrical potential of one volt. As usual, the prefixes "kilo" and "mega" are used for "thousand" and "million" respectively. Thus

- 1,000 eV = 1 keV (kilo-electron-volt), and
- 1,000 keV = 1,000,000 eV = 1 MeV (mega-electron-volt)

By way of illustration, consider Roentgen's original x-ray apparatus. It was a glass tube containing two electrodes, with most of the air evacuated. The electric potential between the electrodes was about 50,000 volts. So, when the current flowed, each electron acquired an energy of 50,000 eV = 50 keV. When these speeding electrons hit the target electrode, they decelerated very quickly, and secondary x-rays were given off in the form of "bremsstrahlung" or braking radiation (see note 6). These are the x-rays that Roentgen was the first to observe. Since energy can neither be created nor destroyed, the energy carried by each x-ray photon was 50 keV or less (usually less).

Now, a beta particle, emitted from within an unstable nucleus, typically has an energy of several tens or even hundreds of keV. Some beta particles carry more than a thousand keV (i.e. more than a MeV). A typical gamma ray photon carries an amount of energy in the same general range, that is, between 10 keV and 2,000 keV (= 2 MeV). Note that most beta particles and gamma rays are far more energetic than x-rays (which seldom exceed 150 keV). And in most cases, alpha particles are even more energetic than gamma rays or beta particles, having energies between 1 MeV and 10 MeV.

Such energy is enormous in comparison with the energy that binds molecules together. Indeed, no molecular bond can withstand such a jolt.

The energy binding the atoms together in a molecule is generally between 5 and 7 electron-volts. Thus a single beta particle with an energy of 100 keV could theoretically break between 14,000 and 20,000 of these bonds. Likewise, a single alpha particle with an energy of 4 MeV could break between 50,000 and 800,000 such bonds. However, since much of the energy is actually spent in "exciting" the molecules rather than ionizing them, the number of bonds broken (and the number of ions formed) is only about one-sixth of the number theoretically possible. It is still a large number.

. . . back to Table of Contents Section A - Section B - Section C

A.12. Penetrating Power of X-rays and Gamma Rays

The remarkable penetrating power of x-rays and gamma rays was evident from the outset. Such rays darken photographic plates just as visible light does; however, many substances opaque to visible light are transparent to them. In particular, soft tissues (like flesh) are rendered much more transparent than harder tissues (such as bone), allowing researchers to photograph the inner organs of living creatures without

recourse to surgery.

As already noted, x-rays and gamma rays consist of high-energy photons. Photons travel at the speed of light, and each photon has its own "wavelength". [7] When these photons lose energy by ionizing the medium, they change wavelength, but not velocity. Consequently, there is no absolute stopping distance for photons. Some of them are absorbed [8] or scattered [9] as they interact with matter, but a photon may also pass right through matter without being affected at all, and without causing any effects either. More energetic photons will penetrate more readily than less energetic ones. The thickness of a given material which will allow half of the incident photons to get through can be measured. If this thickness is doubled, one quarter of the photons will get through. If it is increased tenfold, one in a thousand will penetrate. Shielding against x-rays or gamma rays is therefore never perfect. To protect workers or other individuals from undesirable exposures, some decision must be made as to what an "acceptable" exposure ought to be.

. . . back to Table of Contents Section A - Section B - Section C

A.13. Penetrating Power of Alpha and Beta Particles

A beta particle is much less penetrating than a gamma ray. A typical beta particle may travel tens of centimeters in air, but only a few millimeters in soft tissue. A more energetic beta particle will penetrate further, on the average. As it interacts with matter, liberating orbital electrons and ionizing the medium, a beta particle loses energy, slows down, and eventually comes to rest. [10] The stopping distance depends on the initial velocity of the beta particle as well as on the nature and density of the medium. Many radiation monitors, used to measure incoming ionizing radiation, have a mica "window" which, when closed, can stop beta rays without significantly affecting gamma rays. If a radioactive source is emitting both beta and gamma rays, then by taking two readings (one with the window closed, one with it open) the relative contributions of beta and gamma can be calculated. Similarly, most protective clothing can stop beta rays, but not gamma rays.

Alpha particles have the least penetrating power. They come to a complete halt within forty microns (or micrometers, μm) in soft tissue. This stopping distance is equivalent to a few cell diameters; thus, most alpha particles can't penetrate an ordinary sheet of paper. Nevertheless, when alpha emitters are in direct contact with living cells, they are among the most damaging of all radionuclides, apparently because they deliver more energy over a shorter distance. The exact reason for their greater effectiveness remains unknown.

. . . back to Table of Contents Section A - Section B - Section C

A.14. Penetrating Power of Neutrons

Neutrons have no electrical charge. They can lose energy only through direct collisions with nuclei or other particles. Since atoms are mostly empty space (the nucleus being so small), the chance of a collision between a neutron and a nucleus is quite remote. Accordingly, neutrons have great penetrating power. They can go through several feet of solid steel or lead.

When a fast neutron collides with a massive nucleus, it generally rebounds with almost undiminished speed, like a billiard ball banking off the side of a pool table. On the other hand, if a neutron encounters an electron [11] , it will keep on going with about the same velocity, like a billiard ball hitting a raindrop. But if a neutron hits something its own size, such as a hydrogen nucleus (i.e. a proton), it will transfer much of its momentum to that other object, like one billiard ball hitting another. Accordingly, neutrons are best slowed down or stopped by materials containing a lot of hydrogen, such as water or living tissue. [12]

Because they have no electrical charge, neutrons do not directly cause ionization. However, they do collide with protons and other light nuclei, setting them in rapid motion, and these relatively large [13] ,

fast-moving charged particles will, in turn, cause dense ionization in the medium. That is why neutron irradiation is considered a form of ionizing radiation.

. . . back to Table of Contents Section A - Section B - Section C

A.15. Isotopes (or Nuclides) and the Mass Number

In any nucleus the total number of nucleons (protons and neutrons together) is called the "mass number" -- it is designated by the letter "A". You may recall that the number of protons alone is called the "atomic number" and is designated by the letter "Z". Evidently, the atomic number Z is never larger than the mass number A. By subtracting the smaller from the larger (A minus Z) we can calculate the number of neurons in the nucleus.

As previously discussed, each element has only one possible value for Z. However, each element has more than one possible value of A. This is because a given number of protons can be combined with various numbers of neutrons. Different nuclei of the same element, having distinct mass numbers A, are called "isotopes" or "nuclides". Because they share the same number of protons (i.e. same atomic number Z), any two isotopes of a given element will have almost identical chemical properties. This makes it difficult to separate the isotopes from each other.

For example, the lightest element, hydrogen (Z=1) has three isotopes. They are

- **protium** (one proton, no neutrons: A=1 , Z=1),
- **deuterium** (one proton, one neutron: A=2 , Z=1) and
- **tritium** (one proton, two neutrons: A=3 , Z=1).

Similarly, natural uranium (Z=92) is comprised of three isotopes: the most abundant one has 146 neutrons, whereas the scarcer ones have 143 and 142 neutrons respectively.

For the heaviest uranium isotope, A = 92 + 146 = 238 (protons+neutrons).
For the other uranium isotopes, A = 92 + 143 = 235 and A = 92 + 142 = 234.

To signify a particular isotope of any given element, the mass number A is attached to the name or chemical symbol of the element, using a hyphen or superscript prefix.

Thus the three isotopes of uranium mentioned above are

- uranium-238 (also designated U-238 or ^{238}U),
- uranium-235 (also designated U-235 or ^{235}U), and
- uranium-234 (also designated U-234 or ^{234}U).

Similarly. the three isotopes of hydrogen mentioned earlier are

- hydrogen-1, called "protium" (also designated H-1 or ^{1}H),
- hydrogen-2, called "deuterium" (also designated H-2 or ^{2}H), and
- hydrogen-3, called "tritium" (also designated H-3 or ^{3}H).

If desired, the atomic number may also be symbolically indicated by using a subscript (e.g. $^{238}U_{92}$ or $^{3}H_{1}$).

. . . back to Table of Contents Section A - Section B - Section C

A.16. Heavy Water

By tradition, the two heavier hydrogen isotopes are commonly given their own symbols: D for deuterium (^{2}H) and T for tritium (^{3}H).

Water having deuterium in its molecules in place of ordinary hydrogen -- that is, D_2O instead of H_2O -- is called "heavy water".

Heavy water molecules exist in nature, mixed in very small concentrations with ordinary water molecules. Heavy water is similar to ordinary water except for the extra neutron in each hydrogen atom, making it a bit heavier (by about 11 percent).

The Canadian CANDU reactor uses almost pure heavy water to moderate and cool its natural uranium fuel. In fact, CANDU is an acronym for CANadian Deuterium Uranium.

In the context of nuclear power, H_2O is often called "light water" to distinguish it from D_2O. Most operating nuclear plants are "light water reactors", unlike the "heavy water reactors" such as CANDU.

. . . back to Table of Contents Section A - Section B - Section C

A.17. Radioisotopes (or Radionuclides) and Transmutations

Any unstable (i.e. radioactive) nucleus is termed a "radioisotope" or "radionuclide".

For example, protium and deuterium are stable (non-radioactive) isotopes of hydrogen. Tritium, on the other hand, is an unstable isotope of hydrogen; it is a radioactive nuclide. It is, in fact, a pure beta-emitter, giving off no gamma radiation. Tritium, then, is an example of a radionuclide (or radioisotope).

As discussed earlier, any radioactive nucleus must emit either an alpha particle or a beta particle when it disintegrates. But what becomes of the radionuclide when this happens? How, exactly, does it transmute itself into a different element?

Imagine all the elements, listed from lowest to highest according to the number of protons in the nucleus (that is, according to the atomic number Z).

- During an alpha emission a radionuclide loses four nucleons, and that includes two protons, so Z goes down by 2.
- During a beta emission, a neutron changes into a proton, so Z increases by 1.

Thus, an alpha emission produces a decay product two steps lower down on the list of elements, whereas a beta emission produces a decay product one step higher up. [14]

It is this possibility of moving higher up on the list of elements by beta emissions that allows for the creation of new, man-made "transuranic" elements -- elements beyond uranium on the list -- such as

- neptunium (Z=93),
- plutonium (Z=94),

- americium (Z=95) and
- curium (Z=96).

These toxic alpha-emitting elements, produced by nuclear reactors, pose serious long-term disposal problems because many of their isotopes have very long half-lives (from a few centuries to several millenia).

. . . back to Table of Contents Section A - Section B - Section C

A.18. Decay Chains

When a radioactive atom disintegrates, its decay product may also be radioactive. If so, it too will disintegrate, producing yet another decay product. If that one is radioactive, it will likewise decay. This chain of disintegrations (or "decay chain") will continue until it terminates in a stable nucleus.

Uranium-238 is one of three primordial radioactive metals [15] which are as old as the earth. It is an alpha-emitter with a half-life of 4.5 billion years (which is, coincidentally, roughly equal to the estimated age of the earth).

Uranium-238 disintegrates to become

- thorium-234 (^{234}Th),
  a beta-emitter with a half-life of 24 days,

  which in turn decays to

- protactinium-234 (^{234}Pa),
  another beta-emitter with a half-life of just over a minute,

  which is then transmuted into

- uranium-234 (^{234}U),
  an alpha-emitter with a half-life of 245,000 years,

and so on and on.

This decay chain ultimately yields thirteen radioactive decay products -- including

- radium-226 (^{226}Ra),
  an alpha-emitter with a half-life of 1600 years;

- radon-222 (^{222}Rn),
  an alpha-emitter with a half-life of 3.8 days;

- three polonium isotopes (^{218}Po, ^{214}Po, and ^{210}Po),
  all alpha-emitters with quite short half-lives;

  and a radioactive isotope of lead

- lead-210 (^{210}Pb),
  a beta-emitter with a half-life of 22 years
  (which upon disintegration becomes the alpha-emitter polonium-210).

before finally reaching a stable isotope, lead-206 (^{206}Pb), which is a non-radioactive, chemically toxic, heavy metal.

Uranium decay products are important environmental pollutants associated with uranium mining. Given the relatively "short" half-lives of the radioactive decay products, they would have all disappeared from the earth long ago (except for non-radioactive lead-206) were it not for the exceedingly long half-life of U-238 -- the ultimate source of all of them.

. . . back to Table of Contents Section A - Section B - Section C

A.19. Radioactive Equilibrium in Ore Bodies

In an undisturbed uranium ore body, each of the 13 radioactive decay products of U-238 has approximately the same degree of radioactivity. In fact, each of them has about the same activity as the U-238 itself.

Since uranium-238 decays so very slowly, the amount of U-238 has remained practically constant for hundreds of millions of years. And since it is continuously producing all of its decay products, none of these decay products is ever allowed to completely disappear. In fact, after so many millenia in the ground, a kind of balance has been struck. The amount of each radioactive decay product has settled down into a nearly constant quantity, and has remained approximately constant for a very long time.

To maintain this condition of near-constancy, the rate at which each decay product is being formed must approximately equal the rate at which it is disappearing (measured in disintegrations per second). [16]

But the rate of formation of each decay product equals the rate of disintegration of U-238. That is because the disintegrating uranium-238 atoms are inevitably turning into decay products.

Meanwhile, the rate of disappearance of each decay product is measured by its own degree of radioactivity -- that is, how many atoms of that particular decay product are disintegrating each second.

We said that these two rates must be equal, so we conclude that the activity of the decay product (its rate of disappearance) is the same as the activity of U-238 (its rate of formation).

The same argument works for each and every one of the decay products.

An analogy may help to clarify the situation. Imagine a fountain consisting of a series of bowls of different sizes, with water spilling out of the first bowl into the second, and then out of the second into a third, and so on. Once the fountain has been running for a while, each bowl is full to the brim. For any particular bowl, the rate at which water is flowing in must equal the rate at which water is spilling out. A little thought shows that the amount of water spilling out of the first bowl is equal to the amount spilling out of the second bowl, which is equal to the amount spilling out of the third bowl, or for that matter any other bowl, because the first bowl is the source for all the others.

So it is with the U-238 decay chain. The rate at which U-238 is transmuting into Th-234 is the same (approximately) as the rate at which Th-234 is changing into Pa-234, which is the same (almost) as the rate at which Pa-234 is turning into U-234, and so on. Why are these rates "almost" the same, but not exactly the same? It is because the amount of U-238 is getting smaller very gradually, so that the whole process is gradually slowing down. Thus the amount of each of the decay products is also decreasing at about the same rate as the U-238.

This condition of near-constancy, whereby the total activity of the ore body is shared equally by all fourteen radionuclides (U-238 and its thirteen radioactive progeny), is called "radioactive equilibrium".

It follows that when uranium (including both U-238 and U-234) is removed from the ore, the wastes still

contain $^{12}/_{14}$ of the original radioactivity in the U-238 decay chain; that is, slightly over 85 percent. [17] These wastes will remain dangerously radioactive for hundreds of thousands of years, because of the long half-life (about 76,000 years) of thorium-230.

Canada currently has more than 200 million tonnes of sand-like uranium milling wastes, containing about six times as much radioactivity as all the uranium that has been removed. These "uranium tailings" constitute a major waste management challenge.

. . . back to Table of Contents Section A - Section B - Section C

A.20. Inbreeding of Short-Lived Decay Products

The concept of "equilibrium" applies to other decay chains too. If pure radon gas (radon-222) is introduced into a jar, the activity will increase rapidly as the four short-lived radon progeny (polonium-218, lead-214, bismuth-214, and polonium-214) build up due to the decay of radon. None of these has a half-life of more than 28 minutes; and, after about seven of these half-lives (three and a half hours) the short-lived progeny will almost reach equilibrium with the radon. The activity in the jar will then be five times greater than it was initially as the five radionuclides will have equal activities.

Notice that the long-lived radon progeny -- lead-210 (with a half-life of 21 years) and polonium-210 (with a half-life of 138 days) -- will never be in equilibrium with radon, or even close to it, because the radon (with a 3.8 day half-life) will be practically all gone by the time lead-210 attains its maximum value.

As another exaple, suppose a chemically pure sample of natural uranium (over 99 percent uranium-238) is stored on a shelf. Its radioactivity will gradually increase due to the in-breeding of the short-lived decay products, thorium-234 and protactinium-234. The U-238 approaches an equilibrium with these short-lived progeny after about six months [18] , at which time the sample is almost three times as radioactive as it was initially.

Note, however, that it will take over a half million years before the U-238 is in equilibrium with all the other uranium decay products further down the decay chain, such as thorium-230 (with its 76,000 year half-life).

. . . back to Table of Contents Section A - Section B - Section C

A.21. Neutron Activation

In 1919 Rutherford observed that some light nuclei (such as nitrogen) can absorb alpha particles, thereby transmuting into new elements. Heavier nuclei, on the other hand, have such a strong positive charge that they repel all incoming alpha particles (also positive), preventing absorption. Rutherford realized that an uncharged projectile would not experience this force of repulsion, which probably prompted his 1920 speculation about the neutron.

Following the discovery of the neutron, Enrico Fermi (Italy, 1934) demonstrated that it is a very effective projectile indeed. He bombarded some 60 different substances with neutrons, creating over 40 artificial radioisotopes. These new radionuclides, called "activation products", resulted when stable nuclei absorbed extra neutrons, becoming unstable. Fermi found that if the neutrons were slowed down or "moderated" by interposing a hydrogen-rich substance like paraffin, they were more readily absorbed. Fewer of the fast neutrons were absorbed because they would, more often than not, ricochet off the target nuclei.

Neutron activation is an important source of radioactive contamination in nuclear reactors. Non-radioactive cobalt-59, present in trace amounts in the metallic components of the reactor, turns into cobalt-60, an energetic gamma emitter. Heavy water, D_2O, becomes radioactive tritiated water, DTO, as one of the stable deuterium atoms absorbs a neutron to become unstable tritium. There are dozens of

other activation products of environmental significance.

While cobalt-60 and tritium pose serious occupational hazards for workers in CANDU reactors, they have also become important commodities. Cobalt-60 has become the preferred source of gamma rays in radiation therapy, taking over that role from radium. Likewise, tritium has become a substitute for radium in the manufacture of luminous paint. Tritium also has an important military use, being an essential ingredient in the larger, and more sophisticated, nuclear warheads. [19]

. . . back to Table of Contents Section A - Section B - Section C

A.22. Nuclear Fission

In December 1938, in Berlin, Otto Hahn and Fritz Strassman bombarded a sample of uranium with moderated neutrons. They were hoping to create a brand new chemical element, heavier than uranium. They expected that a uranium atom would absorb a neutron and then emit a beta particle, thus forming a new element with one additional proton (atomic number Z=93).

But the results of their experiment were baffling. Increased radioactivity in the uranium sample clearly revealed the presence of new radionuclides, yet chemical analysis showed none of the characteristics expected of an element having an atomic number close to 92. Instead, they found properties typical of substances with very much lower atomic numbers. How was this possible?

The riddle was solved by Lise Meitner and Otto Frisch (Germans in exile, 1939) who coined the phrase "nuclear fission" to describe what happens. When an atom of U-235 absorbs a neutron, it becomes so incredibly unstable that it literally splits (or "fissions") into two or more rather large pieces. These fragments of the original uranium atom are new radionuclides, much lower down in the periodic table.

. . . back to Table of Contents Section A - Section B - Section C

A.23. Fission Products and Fission Energy

When a heavy atom fissions, it yields two or more new radionuclides called "fission products". There are dozens of different fission products, because there are many ways in which the original atom can split. Most of them contain between $^1/_3$ and $^2/_3$ of the original atom's nucleons, having mass numbers in the range 70 to 160 (see the table for a partial listing). They are almost all beta-emitters and gamma emitters.

The amount of energy released in the fission process is about 400 MeV. Though small in absolute terms, it is enormous in comparison with any previously known form of energy release. Harnessed in a nuclear chain reaction, it is this energy which led, a few years later, to the world's first atomic bombs, and two decades after that, to the world's first electricity producing nuclear reactors (see Section C). As the fission process was applied on a large scale, first for military and then for peaceful uses, very large quantities of fission products began to be produced.

. . . back to Table of Contents Section A - Section B - Section C

A.24. The Transuranic Elements: Neptunium and Plutonium

Although their experiment did not produce the expected results, the original intent of Hahn and Strassman was entirely reasonable. It is in fact possible to create new, super-heavy elements, called "transuranic elements", by bombarding U-238 (not U-235) with neutrons.

In any sample of natural uranium, of course, the U-235 and U-238 are inextricably blended together. The spectacular fissioning of U-235 and the vigorous activity of the fission products tend to mask what happens to the U-238 nuclei.

When a neutron encounters a U-238 atom, the nucleus may undergo fission, but it is unlikely to do so unless the neutron is extraordinarily energetic. [20] In most cases, the nucleus absorbs the neutron, becoming uranium-239, with a half-life of 23.5 minutes. It then emits a beta particle to become neptunium-239, with a half-life 2.3 days. This in turn becomes plutonium-239 when another beta particle is emitted. Thus the man-made elements neptunium (Np, Z=93) and plutonium (Pu, Z=94) are created. [21]

Plutonium-239 is the primary nuclear explosive in most nuclear warheads in the world today. The Nagasaki bomb was made from metallic Pu-239.

. . . back to Table of Contents Section A - Section B - Section C

A.25. Plutonium Isotopes and Transplutonic Elements

Inside a nuclear reactor, repeated neutron captures results in still heavier isotopes of neptunium and plutonium (e.g. Pu-240, Pu-241, and Pu-242) as well as additional transuranic elements with even higher atomic numbers, such as americium (Am, Z=95), curium (Cm, Z=96) and californium (Cf, Z=97). These heavier isotopes are produced in progressively smaller quantities.

The transuranic elements belong to the "actinide" family of elements. This family includes actinium (Ac, atomic number Z=89) and everything that comes after it in the periodic table (notably thorium, uranium, and the transuranics). The actinides all have broadly similar chemical properties. They are all radioactive. Those of greatest significance from the point of view of human health and environmental protection are the alpha-emitters (especially the plutonium isotopes) which are extremely toxic and, generally speaking, very long-lived. The half-life of plutonium-239, for example, is 24,000 years, which is four or five times longer than recorded human history.

. . . back to Table of Contents Section A - Section B - Section C

A.26. The Environmental Challenge

With the advent of nuclear fission, mankind began creating large inventories of new radionuclides, consisting of hundreds of hitherto unknown radioactive species, some of them with very long half-lives. Once created, they cannot easily be uncreated. Unlike toxic chemical compounds, which can in principle be broken down into their constituent atoms, radionuclides are elements. As such they cannot be destroyed or rendered harmless by any chemical means. Therefore the key to environmental integrity and the preservation of human health, in both the short term and the long term, is adequate shielding and near-perfect containment.

Once dispersed into the environment, these materials behave much like their non-radioactive counterparts: they become incorporated into natural cycles, undergoing countless chemical transformations, entering the food chain and even performing essential biological functions in the body due to their chemical properties. But, being radioactive, these substances are also among the most toxic of man-made materials. Consequently, living organisms are exposed to many new agents of harmful ionizing radiation.

Besides producing large quantities of new radionuclides, the nuclear industry mines radioactive ore bodies for nuclear fuel, discarding many naturally-occurring radionuclides as waste byproducts having little or no commercial value. As a result, many of these substances are made much more accessible to the environment.

. . . back to Table of Contents Section A - Section B - Section C

A.27. Background Radiation

Although radioactivity was first discovered in the nineteenth century, it is not a new phenomenon. Every living thing is subject to a certain unavoidable level of exposure to ionizing radiation, called "background radiation". Trace amounts of uranium and thorium can be found everywhere on earth: in soils, in building materials, even in sea-water. Consequently, uranium and thorium decay products have existed in the natural environment since the dawn of time.

There are a handful of other primordial radionuclides of terrestrial origin. The most important of these, biologically, is potassium-40 (K-40), with a half-life of 1.3 billion years. It can be found, in minute amounts, in all blood samples.

In addition, extremely energetic ions, neutrons and photons are continually impinging on the earth in all directions from outer space [22] , creating (by activation) a number of radioisotopes in the upper atmosphere. This radiation from outer space is called "cosmic radiation", and the radioisotopes that it creates are called "cosmogenic radionuclides". These include tritium (half-life 12.3 years) and carbon-14 (half-life 5,370 years).

. . . back to Table of Contents Section A - Section B - Section C

A.28. Internal and External Exposures

People are exposed to background radiation not only from sources external to the body, but also from internally deposited radionuclides which irradiate the body from within. These two modes are called external and internal exposures, respectively.

The external component of background radiation exposure (gamma rays and neutrons) comes from cosmic radiation and from gamma-emitting minerals in the surroundings. The cosmic component increases significantly with increasing altitude. The mineral component varies widely depending on geographical location and geological conditions. The most significant exposures due to radionuclides taken within the body come from radon-222 in air (especially indoor air [23]) and from potassium-40 in blood.

. . . back to Table of Contents Section A - Section B - Section C

A.29. Ecosystems and Background Radiation

Ecosystems have evolved and flourished despite the presence of this background radiation, which fluctuates from place to place but which has remained more or less "constant" for many millions of years. It is reasonable to suppose that the viability of ecosystems, as such, will not be threatened in a major way, as long as the exposures resulting from man-made radioactivity are kept to within a small fraction of background radiation levels. The task is therefore one of containment.

That is not to say that natural radiation is harmless, however. Based on everything discovered so far, the leading scientific authorities in the field have concluded that some portion of the natural incidence of cancer, leukemia, genetic damage, birth defects and other diseases in human and non-human populations, is attributable to background radiation. How well existing biological organisms, species and ecosystems can cope in the presence of significantly increased levels of radioactivity is the critical question.

[Section B: Health Effects] [Section C: Nuclear Fission]

[Nuclear Industry Sub-Directory] [COMPLETE DIRECTORY]

FOOTNOTES

1. The unqualified use of the word "radiation" to refer to radioactive emissions (alpha, beta and gamma) can and does cause confusion, and should be avoided. In fact, most familiar forms of radiation (visible light, radio waves, infrared, ultraviolet, and micro-waves) are not ionizing. Moreover, alpha and beta "rays" are not rays at all, but energetic submicroscopic particles.

2. Thus 1 Ci = 3.7 x 10^{10} Bq = 37 GBq (gigabecquerels). Approximately 37 billion alpha particles are released by one gram of radium-226 in one second. (Note: 1 billion = 1,000 million = 1,000,000,000 = 10^9)

3. The details of this model of the atom grew out of discussions that Ernest Rutherford had with Neils Bohr in 1912.

4. These actions are of two kinds.

    - When a fast-moving free electron (not in orbit) suddenly decelerates, a photon of electromagnetic energy is given off; if the deceleration is fast enough, the photon is an x-ray. This phenomenon is called "bremsstrahlung", or "braking radiation".

    - If an orbital electron drops from a higher to a lower orbit (due to a vacancy there), a photon is emitted; if the final orbit is one of the innermost possible orbits, the photon is an x-ray.

5. In fact, some beta particles are positively charged "positrons". Except for their charge, they are otherwise identical to electrons. When such a beta particle is emitted by a radioactive atom, a proton in the unstable nucleus has become a neutron.

6. The Periodic Table of elements is used by phyicists and chemists. In addition to revealing the electric charge on the nucleus, the Periodic Table also calls attention to similarities in chemical properties found within various groups of elements, resulting from similarities in the physical patterns of the outermost orbiting electrons.

7. The shorter the wavelength, the more energetic the photon (these quantities are inversely proportional). Only the most energetic photons are ionizing. Photons of visible light, infrared, or ultraviolet, are non-ionizing, as the wavelength is too long.

8. When a photon is absorbed, it is in fact annihilated. This can happen in two ways. In either case, no trace of the original photon remains.

    - **The Photoelectric Effect.** The entire energy of a photon can be expended by jolting an electron completely out of an inner orbit. A "secondary x-ray" (of lesser energy) is then produced when an electron drops from an outer orbit to fill the newly created vacancy in the inner orbit.

    - **Pair Production.** A high-energy photon (more than 1 MeV) can spontaneously "transmute" into an electron and a positron (oppositely charged, otherwise identical).

9. If a gamma photon is too energetic to expend all of its energy in the photoelectric effect, thereby being absorbed immediately, it may

    - jolt an electron out of an inner orbit (leading to a delayed x-ray emission as described in note 8)

    . . . and, at the same time,

- send another gamma photon of lesser energy off in another direction (the "re-direction" of the gamma photon is called "scattering").

This process can be repeated several times. The final, least energetic gamma photon

- either ends up being annihilated by the photoelectric effect,
- or else it escapes from the medium it is in.

In the first case, the incident gamma photon has been (ultimately) absorbed; in the second case, it has been (ultimately) scattered -- i.e. redirected with reduced energy.

10. If a beta particle collides with a heavy nucleus, it can slow down quite suddenly. When this happen, a secondary x-ray is emitted due to "bremsstrahlung" (see note 6). For this reason, beta emitters should not be kept (for example) in thin lead containers.

11. A neutron (having the same mass as a proton) is 1840 times as massive as an electron.

12. That is why a "neutron bomb" can kill people without damaging property; most of the damaging interactions occur in living tissue.

13. Light nuclei are thousands of times larger than an electron, for example.

14. This "Law of Displacement" was first enunciated by Rutherford's colleague at McGill, Frederick Soddy (England, 1913). He also coined the word "isotope".

15. The others are thorium-232 (^{232}Th) and uranium-235 (^{235}U). Only Th-232 is of independent interest, since U-235 atoms accompany U-238 atoms in a fixed ratio (0.007).

16. By anology, a population remains stable in size only if its rate of increase (births plus immigration) equals its rate of decrease (deaths plus emigration).

17. U-235 is also removed during mining, but it is not a part of the decay chain of U-238. It contributes less than one percent to the overall radioactivity of the ore. In fact, if you consider the U-235 decay products (which are also discarded) the percentage of the original radioactivity that is left behind as waste increases slightly to over 86 percent.

18. The half-life of Th-234 is 24 days, and seven times that is five and a half months.

19. H-bombs (or hydrogen bombs) are generally three stage weapons, called "fission-fusion-fission" devices. The first fission uses plutonium-239 or uranium-235 as the "primary explosive". That ignites the "secondary explosive", consisting of deuterium and tritium, whose atoms fuse together at a very high temperature, releasing enormous amounts of energy. The third stage generally involves the fission of U-238 atoms by the extraordinarily energetic neutrons produced by the fusion reaction. The bomb gets its name from the two isotopes of hydrogen that are involved.

20. The third stage of an H-bomb involves the fissioning of U-238.
See note 19.

21. Historically, the first microscopic traces of neptunium (1940) and plutonium (1941) were created by a team of American scientists in California using a cyclotron.

22. These ionizing particles and photons, it is believed, are remnants of the "big bang".

23. Indoor exposure to radon is generally much more damaging than outdoor exposure, as the radon progeny have a greater chance to accumulate in an unventilated area.