HEALTH ASPECTS OF HIGH-LEVEL RADIOACTIVE WASTES

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FOREWORD

NWMO Background Papers: Helping to define possible approaches for the long-term management of used nuclear fuel

NWMO has commissioned this background paper as part of a series which presents factual information about the state of our knowledge on important topics related to radioactive waste. The purpose of the background papers is to provide input to defining possible approaches for the long-term management of used nuclear fuel. As well, the background papers are intended to contribute to an informed dialogue with the public and other stakeholders. All of the papers will be posted on the NWMO web site.

The topics of the background papers can be classified under the following broad headings:

> **Legal and Administrative Framework -** These papers outline the current relevant legal and administrative requirements that may be applicable to the long-term management of spent nuclear fuel in Canada, including legislation, regulations, guidelines, protocols, directives, policies and procedures of various jurisdictions.
>
> **Technical Updates and Research Reviews –** These papers provide information on the current status of relevant research, technologies and procedures applicable to radioactive waste management. They include descriptions of current efforts to reduce radiation and security risk, as well as the status of research into our understanding of the biosphere and geosphere.
>
> **Management Systems -** These papers provide general descriptions of the three approaches for the long-term management of used nuclear fuel as defined in the NFWA, as well as other possible approaches and related system requirements.

In addition to the preparation of background papers, NWMO is continuing to pursue multiple opportunities for receiving and reviewing information and comments from the public and other stakeholders through meetings, submissions and presentations.

HUMAN HEALTH ASPECTS OF HIGH-LEVEL RADIOACTIVE WASTES By John K. Sutherland.

Author Biography:

The author has worked with radiation for the last forty years at university, in industry and most recently as a supervising Health Physicist for a CANDU nuclear power facility. His recent responsibilities were to conduct the environmental radiation monitoring program, and external dosimetry measurements for about 700 permanent employees and more than a hundred outage workers. Both the environmental monitoring and dosimetry programs are a requirement for an operating license for all nuclear power facilities in Canada. The environmental radiation measurements and monitoring sites included many in, and associated with, the Radioactive Waste Management and Dry Spent Fuel Storage facilities. He also participated in providing radiation protection training and support during nuclear outage maintenance work and in station-related activities including transfers of spent fuel into dry fuel storage canisters. He was a member of a long-running ad-hoc committee on external radiation dosimetry for the AECB (now the CNSC). He is an adjunct professor at UNB where he teaches a course on Nuclear Safety and Reliability to graduate and undergraduate engineers. He has made numerous presentations on the subject of radiation to professional groups, university classes, high school physics teachers, and while training radiation workers, firefighters, and other emergency responders. He is widely published and has written many scientific papers dealing with radiation, radiation risks, energy, nuclear cycles and nuclear wastes.

Abstract

This paper covers general aspects of all radiation in our living environment including that from nature; from radioactive wastes; and from the many uses and sources of radiation in society, including nuclear power. It examines the radiation exposures and possible related health effects of some of the most highly exposed groups in both the general public and worker populations. There is a critical analysis of the Linear No Threshold (LNT) hypothesis; used to derive risk estimates of radiation exposures whether they are received chronically or acutely. The risk data for LNT were derived from very large acute radiation exposures on one very large population (the Japanese bomb survivors) and have been used to assess the hypothetical risks from chronic low dose and low dose rate radiation exposures to all others ever since. It provides empirical details of the many epidemiological studies of the actual health of those large populations of the general public, medical patients, medical professionals, and the numerous radiation worker groups that have been exposed over several decades to the large range of mostly chronic low dose and low dose rate radiation exposures. Many studies concern the health outcomes of large groups of people - mostly medically exposed patients - who receive very large acute radiation doses under treatment; doses which are hundreds to thousands of times the legal and regulated dose limits. The analysis includes a perspective evaluation of the relative positioning of the assumed and calculated human risks from radiation exposures, in the context of a ranking of the common and significant social risks in our advanced society.

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Executive Summary

Everyone in society is unavoidably exposed to radiation from many sources and at an average annual chronic dose of about 3 millisieverts (mSv). Except for those individuals who undergo medical radiation treatments to counteract cancer or other health problems and who might receive up to several sieverts of acute dose, most individuals receive nearly all of their total lifetime radiation dose from natural sources of radiation.

On average, about 75% of anyone's annual dose comes from nature, about 25% comes from medical sources of radiation, and about 1% is derived from industrial uses, other exposures, and sources within the home. Less than about 0.01% of the average radiation dose in society comes from all aspects of nuclear power including radioactive wastes [1] and yet it is this latter contribution that attracts the greatest media and political attention and thus causes the most public concern.

Studies on the health effects of radiation from extremely high and significant exposures, usually from bomb survivors, medical uses, or from radiation accidents, show that very high radiation exposures are associated with both short-term injurious somatic effects and - potentially - with long-term adverse health effects which extend out to several decades.

Radiation at acute doses of about 7 to 10 sieverts (Sv) is likely to be fatal in the short-term (weeks), to most of those who receive it. Those who survive, then face a longer-term radiation risk - suggested to be about 10%/Sv - of contracting a fatal cancer from 10 to 30 years following the exposure. Most individuals survive an acute dose of 1 sievert.

From about 1 sievert down to about 200 mSv of acute dose, short-term fatalities do not occur, and delayed effects are possible but are not expected. Long-term adverse effects can be calculated and may be epidemiologically defined, but are usually not obvious.

Below about 200 mSv of acute dose, no adverse health effects - short-term or long-term - can be statistically defined with any significance. For both low dose and low dose rate exposures, whether acute or chronic, the longer-term risk, assuming a straight-line relationship to dose, is believed to possibly overstate the risks by a factor of up to about 10. In this region, a low dose and low dose rate reduction factor of 2 is applied to the risk relationship, and the risk of development of a future fatal cancer is assumed to be 5%/Sv.

Health studies of occupationally exposed groups whose work exposures are comparable to average natural background levels - about 3 millisieverts per year - are not statistically associated with definable ill health that might be attributed to their exposures.

The average individual public dose from emissions from nuclear power production is suggested to be less than about 0.2 microsievert per year on average to each of the world's population [1], or about 15,000 times less than natural background exposures. There are no health studies which are statistically capable of defining any adverse health effect from any chronic radiation dose as low as 1 microsievert, or even of 10 millisieverts (ten thousand times larger) in a year.

As currently managed, high level radioactive wastes, contributing less than about 1 microsievert of dose each year to the public, and less than a few millisieverts each year to those who work with such wastes, do not appear to present a significant health risk.

Purpose and Scope of the Background Paper

In the last forty years there has been a growing concern about society's ability to manage its ever-expanding needs while protecting the general public, the environment, and future generations from those present activities that are presumed to be unusually hazardous or environmentally damaging. One of the many such activities is that associated with the production of energy and of radioactive wastes, and their management and potential health effects.

The purpose of this paper is to define what we know about the human health aspects of radioactivity associated with short-term and long-term management of high-level radioactive wastes. It is generally recognized that if we protect humans - those most significantly exposed to such wastes and their associated radiation - then other generally less radiation-sensitive species [2] that are much less exposed or much less sensitive, will also be adequately protected [3]. However, this assumption has led to detailed evaluations of the effects of radiation on non-human biota to ensure that it is indeed reasonable and valid in all circumstances. Whereas human protection is concerned mostly with individual protection, the concern about non-human biota is more to do with species protection in individual habitats.

The paper is divided into several broad parts. The first describes some basic aspects of radiation. The second briefly describes and defines radioactive wastes, especially high-level radioactive wastes. The third provides a simple overview of what we know about radiation-related health effects learned over the last 100 years of radiation use, especially from its widespread use in medical procedures, where the highest acute radiation doses are received. The final section briefly looks at a ranking of the most significant social risks in our society and attempts to place the well-defined chronic radiation risks from nuclear power and high-level radioactive wastes into the broader social context of risks and harm.

Introduction

Natural radiation occurs universally and provides most of us with our entire chronic radiation dose in a year. Lesser - on average – acute radiation doses come from medical and industrial uses, though many medical uses of radiation to those tens of thousands individuals who undergo specific radiation therapy treatments each year, are among the highest radiation doses anyone might receive in their entire lives; sometimes exceeding several sieverts. However, it is the small doses, typically less than a few tens of microsieverts per year (a microsievert is a millionth of a sievert), that we might get from managed, relatively highly-radioactive wastes (mostly spent fuel) from the nuclear cycle now and into the future, that appear to be of some focused social concern.

Nuclear wastes, of one kind or another, are found in many areas of society. Most are low level wastes from mining and processing of many minerals including those of uranium and thorium. Many phosphate deposits, some shales, some copper, lead, zinc, silver and gold ores, some granites, and even some coal formations can also contain significant and sometimes commercial quantities of uranium and other naturally radioactive elements. Production and processing of these ores, including burning coal and disposing of the ash, adds to the quantities of usually uncontrolled low-level radioactive wastes dispersed throughout the environment.

High level radioactive wastes include the fission wastes from reprocessed spent fuel; spent nuclear fuel itself (mostly uranium-238 with minor uranium-235, and transuranic nuclides) where it is not reprocessed to remove the fission wastes; and some retired medical and industrial sources. The required management interval, no matter how the waste may be secured or disposed of, is a function mostly of the contained radioactivity (Bq/g), which is decreasing all the time because of radioactive half-lives. In general the public does not encounter such materials and does not have access to them.

The quantities of spent fuel produced in the world amount to about 15,000 tonnes per year at this time. This is produced almost entirely from about 440 large commercial nuclear reactors, and is managed at most of the reactor sites where it is produced. An individual Pressurized Water (PWR) or Boiling Water Reactor (BWR) of which there are about 350 in the world, and which uses enriched fuel, may produce about 20 tonnes of spent fuel each year (about 3 cubic metres). The CANDU reactor of which there are about 31 in the world, using natural uranium, usually produces from 80 to 150 tonnes of spent fuel per year (about 10 to 20 cubic metres). The very small volumes of spent fuel, amounting to about 5 cubic metres (without cladding or air spaces) per year on average at each reactor, are securely managed according to regulation and law, usually at the locations at which they are produced. These quantities of high-level waste from all of the world's reactors, if they were brought together into one place, would occupy a total volume of about 1,500 cubic metres - neglecting air spaces and cladding. This is the volume of a single, moderate-sized house of 10 by 15 by 10 metres. The total world production of spent fuel to the end of 2002 amounts to a cumulative total of about 240,000 tonnes or about 24,000 cubic metres. This is the approximate volume enclosed by a large arena of 100 metres by 40 metres by 6 metres high. If this spent fuel is reprocessed, then the volume of the true wastes - fission nuclides - is about 5% of the original spent fuel volume, or about 1200 cubic metres – a very small total volume, and readily managed if it were in one location.

Spent enriched fuel is commercially reprocessed in several countries of the world because of the energy value remaining in the unfissioned residual uranium-235 and in the transuranic nuclides, formed mostly from uranium-238, in the spent fuel. With reprocessing, the approximately 20 tonnes of spent fuel is separated into about 1 tonne of highly radioactive fission nuclides, while the remaining 19 tonnes of relatively low radioactivity uranium and transuranic nuclides (nuclides above uranium in atomic number; plutonium etc.), are returned to the reactor cycle to produce additional energy. The small mass of fission wastes, which are the most highly radioactive part of spent fuel and amounting to about 1 tonne from each year of reactor operation, then requires longer-term management.

1. RADIATION AND RADIOACTIVITY IN SOCIETY

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Sources of Radiation
Natural Radiation
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Units.

Commonly used units of radioactivity and dose are the becquerel (Bq), curie (Ci), sievert (Sv), millisievert (mSv) and microsievert (:Sv). Some explanation of these units, and of half-life, is presented in Table 1.

Table 1. Commonly Used Radiation and Radiation Dose Units.

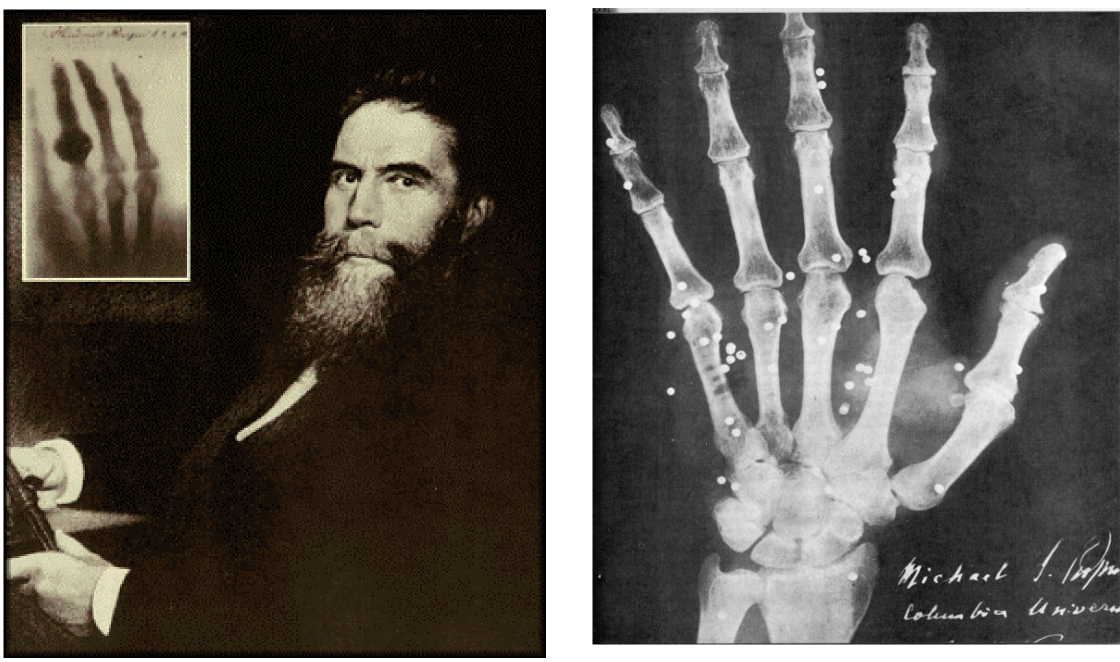
Unit	
Becquerel	A becquerel (Bq) is one radioactive disintegration each second.
Curie	A curie (Ci), is 37 billion (3.7E10) radioactive disintegrations each second.
Half-life	This is the time that it takes for a radionuclide to lose half of its activity by radioactive decay. Each radionuclide has a characteristic half-life. Some half-lives are as short as milliseconds, while others (Table 3) are of the order of billions of years. After 10 half lives, only about 0.1% of the starting activity remains in any mass of radioactive material.
Sievert (Sv)	This very large dose - usually delivered acutely (in a short time, at a very high dose rate) - is common in some medical treatments. It is also at the upper end of the chronic annual dose (delivered at a low dose rate) from natural background radiation in some regions of the world. It is also well above the chronic lifetime dose to anyone exposed to an average annual background of radiation found throughout the world.
Millisievert (mSv)	A millisievert is one thousandth of a sievert. An average natural background chronic dose is about 3 mSv per year. Typical occupational (chronic) doses lie in the range from about 1 to 5 mSv per year.
Microsievert (:Sv)	A microsievert is one thousand of a millisievert or 1millionth of a sievert. The average public dose in the world from nuclear power facilities - including High Level Radioactive Wastes - is much less than about 1 microsievert in a year [1].

History.

Natural radiation has existed on earth since before life began, and at much higher levels than we see today. Prior to the last 100 years, we lived with it, worked with it and otherwise were affected by it without either knowing of its existence, or recognizing any effects from it.

Man-made radiation on the other hand came into existence with the first experiments with electricity and vacuum tubes but was not recognized for many decades. In 1842, the first photographic effects of ionizing radiation were seen, but were not interpreted. In 1859, Plucker noted fluorescence coming from vacuum tubes operated at a high voltage, but did not identify the cause. In 1869, Crookes noted fogging of photographic plates in his laboratory but believed that it was due to defective packaging of the film, rather than recognizing that he had been generating X-rays from experiments. In 1875, Hertz noted that rays emitted from the cathode of his tubes were able to penetrate solids, but did not investigate them further. Nicolai Tesla, one of the researchers into electricity and especially of AC electricity, appears to have generated X-rays in some of his experiments, but did not follow up on this discovery. In 1890, Goodspeed exposed film and coins accidentally to X-rays, but ignored the results. Finally, in 1895, Roentgen discovered, investigated and named these penetrating rays, X-Rays, and took the first deliberate X-ray photograph; that of his wife's hand as shown in the inset in Figure 1.

Figure 1. The First X-ray Photograph taken in 1895, (inset left) of Frau Roentgen's Hand, with a photograph of Wilhelm Roentgen (Health Physics Society calendar). A much higher quality Medical X-Ray Photograph taken just shortly afterwards (right) in the U.S., shows shotgun pellets from an accident. The operating surgeon was able to remove all pellets. This was said to be the first operation guided by an X-ray photograph. Without the operation, the patient would have been in great pain for the rest of his life.



X-rays were widely adopted in medical use within weeks of their discovery, wherever there was an electrical supply to generate them.

Within weeks there were reports of their beneficial effects in countering disease, and of reducing pain and inflammation. Numerous published reports described how they were used to ease the pain of inflamed and painful joints (rheumatism); ease the discomfort of 'Consumptive Patients' (those suffering from tuberculosis); and in many other treatments in the relief of joint, and other pain. A general overview of many of the observations and milestones during this history of medical uses can be found in 'A Chronology of Nuclear Medicine' by Marshall Brucer [4].

Such reports of positive and beneficial effects soon began to be overshadowed by reports of serious injury from very large acute doses (e.g. severe blistering). Over a period of several years, over 300 early medical radiation workers were reported to have died from the unmonitored, very large, radiation exposures they received [5].

Other properties and sources of different radiations, requiring no electrical power source to generate them, were outlined by Becquerel and the Curies in 1896. Following Marie Curie's separation of polonium-210 and radium-226 in the following years from uranium-rich wastes discarded from the Joachimstal silver mine, the demand for radium in medical use far exceeded the supply. This scarcity was not surprising as there are only about 3 milligrams of radium-226 in each tonne of 1 percent uranium ore. Previously discarded mine tailings containing uranium, and uranium deposits from which the minute quantities of radium could be extracted, soon began to be widely exploited throughout the world as the price of radium climbed to more than US$180 milligram^{-1} by 1914 ($5,000,000 an ounce), before gradually declining in value. Total world production of radium up to the 1930s seems to have been no more than about 750 grams (about 27 ounces). As a result of this exploitation, Low Level Radioactive Wastes (LLW) began to accumulate in rapidly increasing quantities.

The development of particle accelerators in the 1930s produced a new stream of high-purity man-made radionuclides which were also in great demand in medical procedures. Unlike the process for production of radium (which could reject tonnes of long-lived radioactive materials for each milligram of radium produced as there was no major demand for uranium), particle accelerators produced only small quantities of highly radioactive materials and wastes which were usually of relatively short half-life.

With the development of nuclear fission in 1942 the demand for uranium increased dramatically, along with the production of uranium mine tailings wastes containing small quantities of residual uranium and the then rapidly devaluating radium. The increasing use of commercial nuclear power is the source of most high level radioactive wastes in the world today, amounting to about 15,000 tonnes of spent fuel - world-wide - per year containing about 450 tonnes of high specific-activity fission nuclides associated with the 95 to 99% of remaining uranium.

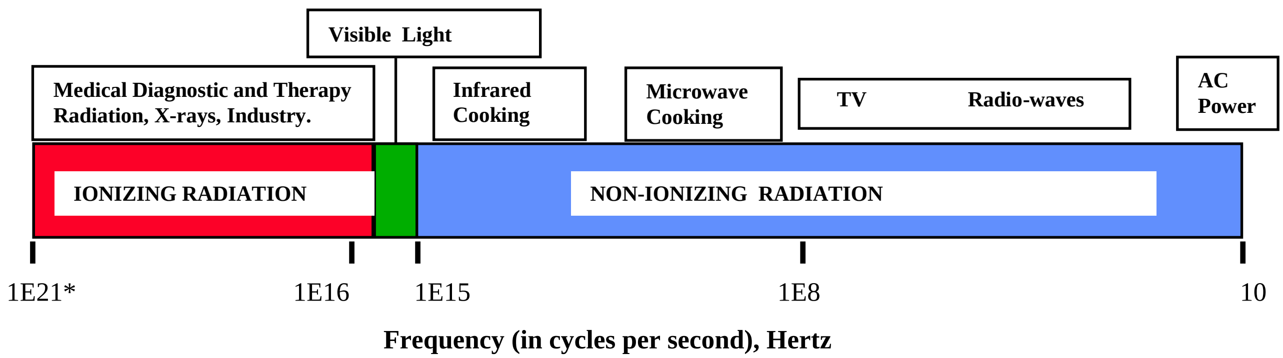
Nuclear reactors also produce most of the numerous medical and research isotopes in use throughout the world today, from neutron activation and fissioning, resulting in about 18,000,000 shipments of small quantities of very high specific-activity radionuclides (high activity per gram, for example, iodine-131 (4.6E15 Bq/g), or molybdenum-99 (1.75E16 Bq/g)), mostly to hospitals, each year.

Most medical radionuclides are produced in quantity by neutron activation, fission, or transmutation of pure materials introduced temporarily into the core of certain reactors. A few large commercial electrical production reactors (CANDU - the Canadian-designed reactor) are also used to produce most of the world's supply of industrial-grade cobalt-60 used in millions of radiation therapy treatments to kill cancers, and in industrial irradiators of which there are about 170 in the world. The irradiators are used for hospital supply sterilization, food irradiation and in many other uses in about 37 countries. About 500 million tonnes of food (spices, some fruits, poultry, meat) are irradiated in the U.S. each year to kill pathogens and to reduce spoilage.

What is Radiation?

Radiation is a group name which describes the electromagnetic spectrum of energy and wavelengths shown in Figure 2. This radiation spectrum is found throughout nature. We make use of many of the characteristics of this spectrum in many applications.

Figure 2. The Electromagnetic Spectrum



* 1E21 is the SI (System International) shorthand scientific notation for 1 times 10 to the 21st power, or 1 followed by 21 zeros. 1E6 means 1 million, and 1E3 means 1 thousand.

These 'radiated energies' range from electrical transmission low-energy wavelengths (60 cycles per second), through visible light to which we are especially sensitive, to the shorter wavelength, high-energy radiations (photons – gamma rays and X-rays) associated with medical X-rays and nuclear radioisotopes used in medical and industrial applications (medical diagnosis and therapy treatments, industrial weld inspections, sterilization of pharmaceuticals and medical supplies, food irradiation etc.).

Non-ionizing or low energy radiation is not definably associated with adverse health effects, though widely publicized allegations concerning microwaves, radar and the electro magnetic fields associated with electrical transmission lines and leukemia, have resulted in the expenditure of billions of dollars over the last 20 years without discovering any consistent statistically-definable adverse relationship thus far.

Ionizing radiation, is the name applied to all radiation of short enough wavelength (high energy) capable of ionizing atoms (temporarily removes electrons; requiring a minimum of 12 electron volts to knock the outer electrons off a relatively high atomic-number atom) with which they come into contact. The major ionizing radiations, are shown in

Table 2. These include the photons in the electromagnetic spectrum, as well as relatively massive alpha particles (a helium nucleus with two positive charges), and beta particles (negatively, as well as positively-charged electrons). As the charged particles approach an atom, their electrical fields begin to exert coulombic forces on each other (the atom contains negatively charged orbital electrons and positively charged protons in the nucleus) which results in a rapid loss of the radiation energy. On average, about 34 electron volts of energy is given up with each ionizing interaction. Neutrons and photons, are uncharged particles (and energies) which ionize **indirectly**, through random collisions rather than through coulombic interactions.

Alpha particles give up all of their energy over a very short distance - perhaps just a millimeter or so in tissue or a few centimeters in air. There may be as many as about 5,000 ionizing - energy-loss - events for each millimeter of travel in soft tissue of an alpha particle. This high density of ionization in a short distance is described as high Linear Energy Transfer (LET).

Beta particles lose their energy more slowly - with perhaps only 10 ionizing events for each millimeter of travel in soft tissue (low LET) - and thus go further before they lose all of their energy - perhaps a few millimeters in tissue, to as far as a few metres in air.

Table 2. Common Ionizing Radiation, Radioactive Emissions and Energetic Particles	
Common Particle or Radiation	**Common Origins and Uses**
Alpha - This particle consists of a helium nucleus. It is a relatively massive particle with a double positive charge. It leaves a dense, ionizing track through coulombic interactions with atoms. These particles are unable to penetrate beyond the outer layers of dead skin. If they get into the body by inhalation or ingestion then they are more damaging to living tissue.	Emitted from unstable heavy elements. Used as a thermo-electric energy source.
Beta (negatron) - This is a single negative electron. It is a low mass particle which leaves a medium-density ionizing track. They are mostly stopped by clothing and skin.	From decay of a neutron to a proton - the usual radioactive decay process.
Beta (positron) - A single positive electron.	From decay of a proton to a neutron.
Gamma ray (photon). An uncharged particle or wavelength (it displays both properties - known as particle duality). It has a low-density ionizing track and can pass through solid materials very easily.	Energy quantum ejected to achieve stability after beta decay. Used in radiation therapy.
X-ray* (photon). An uncharged particle or wavelength as for gamma rays. It has a low-density ionizing track. High energy X-rays can pass through the body.	Energy emitted from the electron shells around the atom, and rarely from a nucleus. Medical diagnostic X-rays.
Neutron. A relatively massive nuclear particle. It is neutral - without an electrical charge and causes tissue damage through nuclear collisions with the nucleus of hydrogen and other light elements. These strongly interact with water molecules in the air and in our bodies.	Released during fission and from special neutron generators (e.g., Ra-Be). Medically used to destroy tumours.
* X-rays are most commonly produced by the bombardment of a pure metal target by electrons emitted from an electrically resistance-heated filament in a vacuum. Removal of the applied voltage immediately eliminates the production of X-rays. Proton radiation is mostly of cosmic origin.	

Gamma rays (similar to X-rays but originating from the nucleus rather than the electron shells) are indirectly ionizing and highly penetrating, meaning that they can cover relatively large distances at the speed of light while only occasionally interacting with nuclei. They are low LET radiation. Like neutrons, they have no charge, and gradually lose their energy by collisions with atoms. In air, photons may travel tens to thousands of metres or further depending upon their energy. They are stopped most effectively by dense materials like lead and uranium (the usual shielding materials); high density concrete (or moderate density bone (compared with tissue) in the case of medical X-rays); or a few metres of water. This is why large gamma ray sources, as in gamma irradiators, may be stored underwater when they are not in actual use, and is one reason why spent fuel can be safely stored under just a few metres of water. Hospital therapy, radionuclide devices are usually shielded by either lead or depleted uranium, with a movable shield to allow a beam of radiation to be emitted from the shielded container, in a controlled manner

Neutrons are relatively massive **uncharged** particles that lose energy by bouncing off atoms in much the same way as billiard balls bounce off each other. As they have almost the same mass as a hydrogen atom, they can severely disrupt and ionize water molecules, which contain two atoms of hydrogen. As the human body consists mostly of water, neutrons are significantly damaging to living tissue when they collide with the hydrogen nuclei and give up some of their energy in the recoil.

If these energy losses occur in living tissue, whether the radiation originates from outside or within the body, then the deposition of energy results in what is called radiation absorbed dose (the rad or the gray; there being 100 rads to 1 gray). The deposition of 1 joule of such energy in a kilogram of tissue, imparts a dose of 1 gray (the same as 1 sievert) if it comes from low LET radiation (gamma or beta), but may be as large as 20 sieverts if it comes from high LET radiation such as alpha radiation or neutrons of a certain energy. Most radiation doses come from gamma rays.

Some perspective of the relative abundance and sources of radiation is shown by the following estimates (modified from a report of the NRPB [6]) of their unavoidable and natural interactions with each of our bodies. None of these events is sensed by any of us, though some of them may eventually lead on to epidemiologically definable health effects as with sunburn and skin cancer, and possibly lung cancer from radon, though most lung cancers are smoking related:

- From the sky there are about 100,000 cosmic ray protons and neutrons, and about 400,000 secondary cosmic rays which pass into and sometimes through us each hour, as well as billions of neutrinos which pass through us without being slowed or stopped.
- From the air we breathe there are about 30,000 atoms of radon and radon progeny which disintegrate (mostly alpha and beta decay with subsequent gamma emissions) in our lungs every hour (about 8 Bq each and every second) and deposit their energy in lung tissue. In some regions this number of radon atoms continuously decaying in the lungs may reach many millions.

- From our diets there are about 15,000,000 potassium-40 atoms which decay each hour, and about 7,000 uranium atoms which decay in each of our bodies every hour, and emit alpha and beta particles (stopped in the body) and gamma energies (which mostly escape to irradiate everything around us). Bananas are an excellent source of potassium in our diets, and therefore of radiation. Brazil nuts are a well-known source of alpha emitting energies because of the radium that is concentrated by the plant into these nuts. Tobacco use is a major source of radiation dose to smokers (up to about 80 mSv of chronic dose in a year to the mouth and trachea of a pack-a-day smoker) from polonium-210 (a daughter of radium-226) in the tobacco leaf.
- From soil and building materials there are over 200,000,000 gamma rays which pass through each of us every hour. In locations with much higher natural radiation backgrounds, this figure may be in the billions.

Although we cannot see or sense any of these events, it is intriguing to consider that considering the numbers of events and interactions happening inside us and around us all of the time, all of humanity lives immersed in a sea (soup) of radiation energies.

All of these radiations can collide with or otherwise influence atoms in the body. Any energy that they lose by such collisions or in coulombic (electrical) interactions with atoms, is left behind as thermal energy which disrupts molecular bonding, and liberates electrons, and corresponds to radiation dose. The more radiation energy that is left behind in our tissue as the radiation passes through it, the larger the radiation dose.

Radioactivity and Half-life

Most of the short-wavelength ionizing radiation to which we are exposed, comes from the radioactive decay of certain natural radionuclides. As they decay, they emit energetic beta particles as well as gamma energies. Radioactive decay is measured in becquerels. A becquerel (Bq) is the decay of a single atom. Stable elements do not emit radiation.

All radioactive isotopes undergo radioactive decay; usually to other elements, and are characterized by what is called the half-life. The half-life is the time that it takes for half of the atoms in a radioactive isotope to decay either to a stable nuclide, or to a radioactive daughter nuclide. Some half-lives are of the order of billions of years, while others are as short as a few seconds or less, as shown in Table 3. The end point of all radioactive decay is eventually a stable, non-radioactive, element. All uranium and thorium isotopes eventually decay to stable lead isotopes.

A mass of about 81 kilograms of uranium-238 initially has a continuous emission of radioactivity from about 1 billion atom disintegrations (1E9 Bq) each and every second (ignoring the activity of the many daughter radionuclides). It is a slowly decreasing quantity in terms of both mass and radioactivity. After one half-life - 4.5 billion years - there would be only 40.5 kilograms of uranium-238; about 40.5 kilograms of stable lead with minor quantities of intermediate radionuclides; and the activity would have fallen to 0.5 billion disintegrations each second from the uranium-238.

In contrast, there are 1 billion disintegrations (1E9 Bq) each and every second from 0.54 micrograms of iron-59, with a half-life of 44 days. After 10 half-lives (440 days), the amount of iron-55 has decreased to 0.0005 micrograms, and is decaying at a rate of less than 1 million becquerels. Unlike uranium-238, which has many radioactive daughters, the iron-59 decays to stable (non-radioactive) cobalt-59.

A more detailed diagrammatic overview of radioactive decay, and radioactive progeny, using uranium-238 as an example, is given in appendix A.

Sources of Radiation

Externally, we are bombarded by radiation from space, from building materials and rocks; from the ground we walk on and even from each other. External doses are notably high in some underground caves and most mines because of radon gas. Cosmic radiation doses also increase with altitude, doubling for about each mile of altitude. We receive external doses of radiation when we undergo medical diagnostic tests such as a chest or dental X-ray. More extreme and large external doses might be received when we need to undergo targeted radiation therapy to kill a cancer.

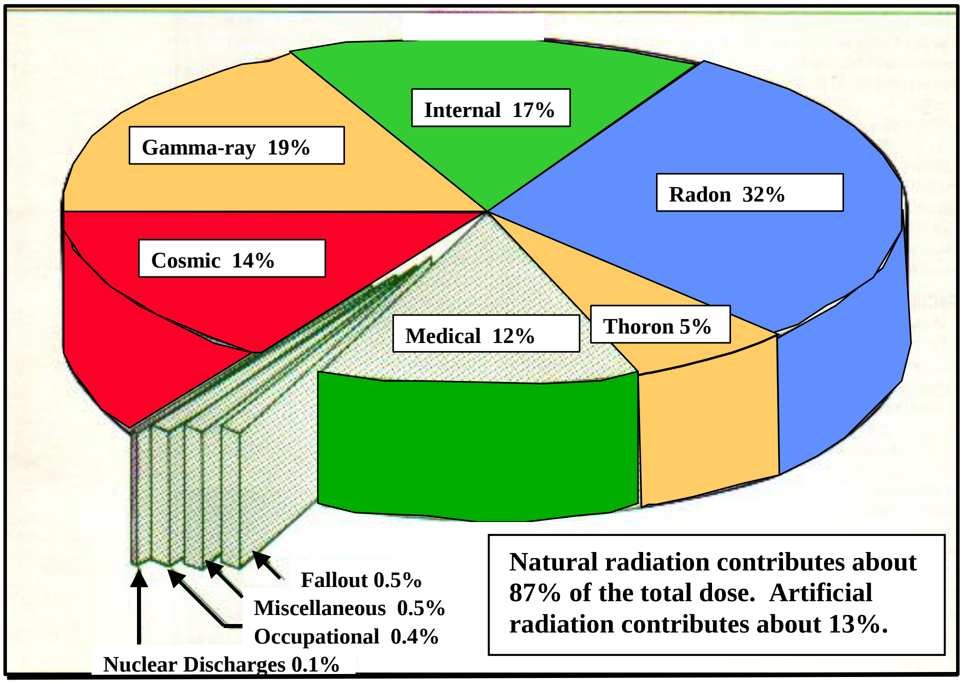
Internally, we receive radiation from the many natural radionuclides (including potassium-40; a small fraction of all of natural potassium) in all of the foods that we eat; from the air we breathe; and from the fluids that we drink, all of which, without exception, are naturally radioactive. Some natural well-waters are highly radioactive, but even milk, beer and whiskey contain radioactivity depending upon the region in which the cows graze, and the radioactivity of the water used in the household water supply or in the brewing or mashing processes. All milk - human and that of other mammals - contains potassium-40. The air we breathe contains radon gas and radioactive particles in the airborne dust. Some medical procedures introduce radionuclides into our bodies to diagnose the functionality of certain organs and processes. Destruction of a diseased thyroid may use a one-time internal administration of iodine-131 as a safer alternative to surgery.

In our society, **on average**, we receive about 75 percent or more of our entire radiation dose of about 3 millisieverts each year from nature; about 25 percent or more from medical treatments; and less than 1 percent from all industrial exposures, with less than 0.1 percent from all nuclear power facilities throughout the world. An example of a pie diagram of this kind is shown in Figure 3. Thoron (Rn-220) is only one of several isotopes of radon gas that comes from the decay of Th-232 in the thorium decay chain.

Each of us has a different and variable pie diagram of radiation doses, which reflects what we as individuals do, where we live, what we eat and drink, how we conduct our lives, and what medical treatments –if any - we receive.

In general, the lowest radiation doses across society are those associated with industrial uses of radiation, and those from the operation of nuclear power facilities, while the largest are associated with medical treatments and natural exposures.

Figure 3. Pie Chart of Approximate Radiation Contributions from Natural and Artificial Sources of Radiation



Natural Radiation

Everything in society is naturally radioactive to some degree. There are approximately 100 naturally occurring radionuclides surrounding us, contained in our food, air, water, soil, rocks and building materials; many of which are shown in Table 3.

Table 3. Some Naturally-Occurring Radionuclides					
Uranium-238 Decay Chain. * Each succeeding radionuclide is the daughter of the one above it.		**Natural Radionuclides formed by Cosmic Particle Bombardment of the upper Atmosphere.**		**Some Natural Radionuclides of Terrestrial Origin (other than from Uranium and Thorium Decay Chains).**	
Isotope	**Half-life**	**Isotope**	**Half-life**	**Isotope**	**Half-life**
Uranium-238	4.47E9 y	H-3	12.3 y	K-40	1.28E10y
Thorium-234	24.1 d	Be-7	53.6 d	V-50	6E15 y
Protactinium-234m	1.2 m	Be-10	2.5E6 y	Rb-87	4.8E10y
Uranium-234	2.46E5 y	C-14	5730 y	In-115	6E14 y
Thorium-230	7.54E4 y	Na-22	2.6 y	Te-123	1.2E13y
Radium-226	1599 y	Na-24	15 h	La-138	1.1E11y
Radon-222	3.8 d	Si-32	650 y	Ce-142	>5E16 y
Polonium-218	3 m	P-32	14.3 d	Nd-144	2.4E15y
Astatine-218	2 s	P-33	24.4 d	Sm-147	1.0E11y
Lead-214	27 m	S-35	88 d	Sm-148	>2E14 y
Bismuth-214	20 m	Cl-36	3.1E5 y	Sm-146	>1E15 y
Polonium-214	1.6E-4 s	S-38	2.87 h	Gd-152	1.1E14y
Thallium-210	1.3 m	Cl-38	37 m	Dy-156	>1E18 y
Lead-210	22.6 y	Cl-39	55 m	Hf-174	2E15 y
Bismuth-210	5 d			Lu-176	2.2E10y
Polonium-210	138 d			Ta-180	>1E12 y
Mercury-206	8.2 m			Re-187	4.3E10y
Thallium-206	4.2 m			Pt-190	6.9E11y
Lead-206	Stable				
*** Similar decay chains exist for naturally occurring uranium-235 and thorium-232. Much of the data are from Eisenbud [7] and others.**					

Human activities occasionally concentrate some of these uranium-sequence radionuclides and create waste materials that have elevated levels of radiation (some mining wastes, fertilizer production from phosphate deposits, coal burning wastes, some copper mining). These are known as Technologically Enhanced Naturally Occurring Radioactive Materials (TE-NORMS) indicated in the upper part of Table 4.

Table 4. Estimated Annual Production (Tonnes) of Technological Enhanced -Naturally Occurring Radioactive Materials (TE-NORMs) and of Nuclear Wastes in the U.S. (Most Data are from the IAEA).		
TE-NORMs (LILW)	**Tonnes**	**Common Radionuclides**
Base-metal mining (copper, lead, zinc) and some gold mining.	1,000,000,000	U and Th daughters
Coal ash, from the contained uranium and thorium.	85,000,000	U and Th daughters
Oil/Gas-well solids, from the radium and its progeny brought up in the groundwater.	640,000	Radium daughters
Water treatment solids. Any radium and its progeny can become trapped in the filters.	300,000	Radium daughters
Phosphate processing, from the uranium and its daughters that are commonly associated with natural phosphate deposits.	40,000,000	U and Th daughters
Geothermal solids, from radium and its progeny in the groundwater.	50,000	Radium daughters
NUCLEAR		
Spent fuel (HLW)	2,000	U fission nuclides
Nuclear utilities wastes (LLW)	10,000	U fission nuclides
Other radioactive wastes (LLW)	5000	Industrial and Medical nuclides.
LLW, LILW, HLW are Low Level, Low and Intermediate Level, and High Level Wastes Respectively.		

The lower part of Table 4 shows the relative masses of radioactive wastes and spent fuel from the nuclear industry in the U.S. – with about 25% of the world's reactors - for comparison.

Most of these were regarded as wastes simply because no value or purpose for them was evident. This changed about the mid 1800s, when uranium - a byproduct of mining for some other metals - began to be used as an additive to crockery glazes, producing various bright colors (Fiesta red); to glass, producing a pale green color; or was used for tinting in early photography.

Today, uranium obtained from uranium ores, some coal ash (formerly), alum shales (formerly), phosphate production, and from some copper and gold mines is used as a source of energy; and in the case of depleted uranium, as a radiation shield that is denser and more effective than lead; as a counterweight in the tails of some aircraft and the keels of some yachts; and as an armour-piercing tip in anti-tank weapons.

Medical Radiation

When the first X-ray photograph was demonstrated to the world, a medical revolution took place almost overnight. For the first time doctors were able to see what went on inside the body; seeing normal and fractured bones, and foreign objects such as shrapnel or bullets; and eventually being able to distinguish organs and cancerous growths.

With the discovery of radium in 1898 by Marie Curie, a new kind of radiation began to interest the medical community. With radium, radiation could be used within the body as well as outside of it, but for the first few decades of the 20th century, there was never enough radium produced to satisfy the demand for it. Not only could medicine now see into the body using X-rays, but it could also insert small radium-containing 'seeds', encased in gold, into a cancer and then retrieve them after the cancer had received a calculated fatal dose of radiation. The X-rays showed where the cancer was located and verified that the radium seeds were properly placed and removed, and then it showed the degree of success of the treatment by following the fate of the cancer.

From 1895 to the present, the use of X-rays has grown in its value and application in medicine and in other uses, though the medical use of radium has long since stopped. Today, radium has been replaced by a more versatile array of radionuclides to look at what goes on inside the body, and by other medical radiation devices (cobalt-60) and linear accelerators, to target and destroy cancers from outside of the body.

The benefit of the uses of radiation in society is most obvious in the hundreds of medical applications using various radiation techniques and many radioisotopes which are capable of targeting certain organs, or of being attached to various chemicals which can themselves target specific organs in order to determine their function or character. Some of the radionuclides used in medicine are shown in Table 5. There are about 15 to 20 million medical procedures carried out globally each year, which use various radioisotopes [8] out of a total of more than 130 million medical diagnoses per year using radiation in general.

Along with the use of radiation in this way, and from medical radiation and other accidents, there are associated radiation doses, and radiation-related health risks.

In many medical uses, individual doses range from a few microsieverts of acute dose (diagnostic chest X-ray), up to 100 sieverts of targeted acute dose when a human thyroid is ablated (destroyed), or a cancerous tumour is destroyed as part of a medical treatment.

Table 5. Some Commonly-used Medical Diagnosis and Therapy Radionuclides Produced in Medical Reactors and Cyclotrons (Most Data are from the IAEA)

Reactor-Produced Isotopes	**Use**	**Half-life**	**Cyclotron Produced Isotopes**	**Use**	**Half-life**
Mo-99 (Tc-99m)	Skeletal and Heart imaging	2.75 d, (6 h)	Tl-201	Myocardial studies	73 h
			I-123	Thyroid studies	13 h
Cr-51	Labels red blood cells	27.7 d	Kr-81m	Lung studies	13 s
			In-111	Brain studies	67 h
Co-60	Radiation therapy	5.27 y	C-11	Brain imaging, PET scans, Cardiology	20 m
I-131	Thyroid diagnosis and ablation (destruction)	8.02 d	N-13	Cardiology	10 m
			O-15	Oxygen utilization studies	2 m
Ga-67	Tumor studies	78 h	F-18	Epilepsy studies	110 m

Doses far in excess of 10 sieverts are usually required to kill cancers, but are delivered to the target cancer in such a way (fractionation, or rotation around the body while maintaining focus upon the target cancer) as to spare the surrounding healthy tissue as much as possible from radiation damage, and to give it time to recover.

When used in internal medical procedures, the radionuclides of most value are those of short half-life (iodine-131, molybdenum-99). They emit their penetrating radiation energy from a very small and easily managed (shielded to protect hospital personnel) quantity of material in a short space of time and soon decay or are rapidly eliminated from the body. Their dual character - useful (to the patient) or hazardous (to everyone else) - depends upon where they are used, how much is used, what they are used for, and their interaction with those who are not receiving the treatment, but who look after or visit the patient, or are nearby.

Industrial and General Uses of Radiation

Radiation is used in thousands of different ways by modern society. Some of these many uses are shown in Table 6.

Table 6. Some Modern Uses of Radiation * - Most of which Contribute to Sources of Radioactive Wastes in Society.

Medical Processes	**Industry**	**Consumer Products**	**Scientific Research**
Medical isotope production. Radiation Therapy devices. Radio-Immuno-Assay. Sterilizing medical equipment and hospital supplies.	Irradiation Facilities for sterilizing packaged products. Sterilizing sewage & water. Weld inspection. Process tracers.	Exit Signs. Smoke detectors. Antistatic devices. Sterilizing cosmetics, tampons & other consumer products.	DNA matching. Biomedical research. Detecting art forgery. Biological and Industrial process tracing & tracking.
Agriculture	**Pest Control**	**Energy**	**Others**
Irradiation of meats & poultry to kill salmonella & other pathogens. Irradiation of fruits to avoid spoilage & prolong shelf life. Tracing Irrigation and other Water Resources	Eradicating insect pests - (Sterile Insect Technique, SIT) (screw-fly, fruit fly, tsetse fly, blow-fly). Protecting stored foods from insects. Irradiating exported forestry products to kill insects and larvae.	Commercial electrical energy. Industrial Co-60 production. Thermo-electric generation (RTGs and SNAP). Satellite energy systems. Remote buoy and navigation and location systems.	X-ray devices at border crossings and airports. Oil well logging. Level gauges. Polymerization. Engine-wear measurements. Wood laminate hardening. Remote locations lighting. Emergency signs.
Many of these various uses are described in detail in the numerous publications of the IAEA.			

All of these uses are associated with the production of some quantities of radioactive wastes, mostly of very small volume and subject to stringent regulatory control.

Some of the more important uses are in medical sterilization of pharmaceuticals and hospital supplies such as gauzes, syringes and other supplies used in the operating rooms. It is also increasingly used to eliminate insect pest and to irradiate certain foods to eliminate salmonella and other pathogens which cause thousands of deaths and losses of billions of dollars each year through avoidable food-poisoning illnesses. Major food loss through spoilage could be avoided by greater use of irradiation. Some hospital patients with reduced immune-system function require irradiated - pathogen-free - food. Some radionuclides are significant sources of energy, used in satellite energy systems or as a small, constant, and reliable source of energy in remote locations.

Radiation Exposure and Dose.

Radioactivity emitted from radioactive substances can interact with other materials (dose) where it gives up some of its energy or is stopped. For example, in a chest X-ray, the X-rays are attenuated (partially blocked) by relatively dense materials such as bone or a tumour, while passing easily through less dense fleshy tissue. The contrasts which show up on an X-ray photograph (readily seen in Figure 1, showing the shotgun lead pellets), or on a modern digital image, reveal the internal features. Radiation can also be visually seen in the interactions with fluorescent materials (e.g. zinc sulphide) in a darkened room, or by condensation trails in a Wilson cloud chamber. Marie Curie and her husband were said to have been enthralled by the faintly glowing vials of radioactive preparations in their laboratory at night after their eyes had become accustomed to the dark.

As radiation passes through air, it ionizes the atoms of air into positively and negatively charged particles (ions) which can be attracted to electrically charged locations in a measuring device - usually an ion chamber - where they can be collected and measured. Such a measurement of the electrical charge (in coulombs) carried by these particles gives an indication of the amount of radiation passing through, and interacting in the air space. A collected charge of 2.58E-04 coulombs (1 ampere second) per kilogram of air is defined as a roentgen (R). This is a unit of radiation exposure which is relatively easily measured and forms the basis for subsequent assessment of radiation dose.

Interaction of such radiation with solid materials with which it comes into contact, causes similar ionization of the constituent elements (in most solids it is too difficult to measure), and leads to the deposition of radiation energy (dose) in that material. This is then known as 'radiation (absorbed) dose' (or rad), expressed in grays at the present time. Some materials can be used to detect such radiation because of the obvious chemical or physical changes that the radiation causes, such as oxidation (e.g. ferrous to ferric), or a change of colour as with potassium iodide, which turns purple upon irradiation to a high dose. Photographic fogging is one obvious change that has been used for more than a century to detect radiation and to show other features in diagnostic X-rays. Such materials can be used as radiation dosimeters, and when worn on the body during work with radiation, can serve as a proxy, to show the magnitude of the dose to which we have been exposed.

When the radiation interaction is with living tissue then the absorbed dose from certain particulate radiations (alpha, neutron and perhaps beta - and they **can** be distinguished) needs to be weighted to reflect the estimated potential of the different radiations to do damage to that tissue. After weighting, using defined radiation weighting factors of from 1 (no weighting) to 20, it is known as 'dose equivalent' and is usually expressed in sieverts. Where the weighting (quality) factor is one, then grays and sieverts are identical.

The various definitions of radiation exposure (usually measured in air); absorbed radiation dose (measured in any material); and dose equivalent (estimated dose in living tissue after correction with a radiation weighting factor) are shown in Table 7. Very approximately, 1 roentgen of exposure in air, is equivalent to 10 milligray of absorbed dose in a target medium, or 10 millisieverts of dose in living tissue, but the actual relationship depends upon the energy of the ionizing radiation - as only fairly high energy gamma radiation can actually penetrate anything fairly solid - and its 'quality factor' (1 for gamma and beta, up to 20 for neutrons, and 20 for alpha particles).

Only if radiation gets inside the body as, for example, when we inhale radon gas, or ingest radium (both are alpha emitters) do we need to consider the damage from alpha particles. In this case the dose is indirectly calculated as it cannot be measured.

In the case of an ingested nuclide such as tritium (a pure beta emitter with a 12.33 year half-life) in tritiated water, the activity measurements in bioassay samples (urine) over an interval of time, indicate the changing concentration in the body; the rapidity of elimination; and the 'effective' half-life in the body, which for tritium is about 10 days in body fluids. Other fat-bound tritium is turned over less quickly, with an effective half-life that is about 100 days. From these measurements, and allowance for known fractions of tritium being distributed in different body 'compartments', a dose from tritium can be calculated and a 'committed dose' assigned into the future for the exposed individual.

Table 7. Activity, Radiation Exposure, Absorbed Dose and Dose Equivalent Definitions

Unit of Activity, Exposure or Dose*	Definition
becquerel (Bq), the basic unit of activity.	One disintegration per second of any radionuclide.
roentgen (R) the basic unit of radiation exposure, adopted in 1931.	The amount of ionization in air that produces 2.58E-04 coulombs per kilogram of air.
gray (Gy) the base unit of absorbed dose	The absorption of 1 joule (J) of energy in 1 kilogram of any material.
sievert (Sv) the base unit of Dose Equivalent	The absorption of 1 joule of energy in 1 kilogram of tissue. Absorbed dose adjusted by a radiation weighting factor, or Quality Factor (QF).

* The roentgen (R) can be directly measured, but the gray and a sievert are not directly measurable. They are exceptionally large radiation doses that are encountered by the public usually only in medical treatments. Millisieverts (mSv) and microsieverts (:Sv) are the sub-units more commonly used in radiation protection. In terms of the older radiation units, the rad and the rem, the gray is equivalent to 100 rads, and the sievert is equivalent to 100 rems. The curie (Ci), an early unit of activity, was defined as the radiation emitted by 1 g of Ra-226. This was later defined (by committee) to be 3.7E10 disintegrations each second as it is far too difficult to measure directly because of the additional activity from the rapidly ingrowing daughters. It can be indirectly obtained by measurement of the equilibrium radon-222 activity which, as a gas, can be removed from the radium-226 and its radioactivity promptly measured.

Radiation interactions within the body, whether originating inside or outside of the body, do not make the target material any more radioactive than it already is, they merely deposit energy in it. (The exception to this is in the case of neutron bombardment from outside of the body. Certain elements within the body can capture a neutron and become activated (radioactive)). No one is any more radioactive after a chest X-ray than before the X-ray, as the radiation is outside of the body and either passes through it entirely or deposits a small amount of thermal energy where the radiation is stopped - usually by bone and other dense materials. However, if a patient ingests or is injected with a specific radionuclide, for example iodine-131 (8 day half-life) during a medical procedure concerning the thyroid, the body then contains this additional radiation, and emits this radioactivity and its deposited energy, until the radionuclide either decays away; is eliminated from the body by exhalation or in body wastes, usually in a matter of hours or days; or is reduced through some combination of the two.

A typical range of radiation doses actually encountered by the public and nuclear workers is shown in table 8, along with the current regulatory dose limits which govern their exposures from industrial and nuclear sources of radiation.

Table 8. Typical Individual Annual (Chronic) Radiation Doses, Recommended Radiation Protection Quantities, and Acute Doses from Various Medical Treatments.	
	Individual annual chronic dose (mSv)
NATURAL RADIATION.	
'Average' natural radiation background dose in the world	About 3
Typical range in natural background dose	2 to 1,000
Extreme values of natural dose in some home basements, caves, and mines	Up to 10,000+
INDUSTRIAL AND OCCUPATIONAL	
Recommended regulatory occupational primary dose limit of 100 mSv maximum, in 5 years, for designated radiation workers, ICRP-60 [9].	**20 average, per year; no more than 50 in one year of the five**
Typical average occupational dose received by nuclear radiation workers [1]	2
Maximum occupational dose received by a very few radiation workers	Up to 50
Recommended regulatory public dose limit from industrial exposures	**1**
Typical additional dose to the public who live near a nuclear power facility	0.002
Typical additional dose to the public who live near a coal burning facility	0.02
Typical frequent flyer and air-crew dose from cosmic radiation	Up to 10
Typical natural radiation dose to full-time health workers in a geothermal hot spring or spa. (Their doses are not usually subject to regulatory controls).	Up to 200
Projected maximum estimated individual dose from all future nuclear waste disposal, following facility closure (AECL research on the integrity of a completed deep geological disposal facility) [10].	0.000,000,01
MEDICAL AND DENTAL	**'One-time' individual acute dose (mSv)**
Range in public diagnostic medical radiation doses (approximate)	**0.01 to 100***
Range in public cancer therapy doses (approximate)	**20,000 to 100,000***
Single medical CT scan	**About 20***
Single dental X-ray 1990 (TLD-measured data of about 100 dental exposures - Canada)	**2***
* These are acute doses (received in a very short time, usually less than 1 second, but up to a few hours or even 1 day), the rest are chronic (longer than 1 day, but typically received over the course of a year). In 1966 an average dental X-ray gave an acute dose to the head of about 20 millisieverts (mSv).	

Hospital nuclear workers (medical staff) are governed by occupational dose limits, but the patients in their care, and being treated with radiation are NOT subject to any legal limits on their dose while they are under treatment. It is assumed, and is easily demonstrated, that whatever hypothetical long-term damage may be done by the radiation exposure, especially at the very large doses used, will be more than compensated by the immediate benefit from the treatment.

Typical Radiation Doses.

The extreme range in magnitude of a few natural and medical radiation exposures, and doses from some industrial uses of radiation is shown in Table 9 on a logarithmic scale, with each step ten times larger than the one before it, going up the scale. They span a range of more than ten decades.

Table 9. Logarithmic-Scale of Some Typical Radiation Doses in Society

Grays/Sieverts	
100,000	
	Commercial sterilization of meat, poultry, special hospital Foods and foods for cosmonauts and some military.
10,000	
	Region of food irradiation. The U.S. FDA now approves meat for irradiation (1997 and 2003). Poultry was approved in 1990.
1,000	
100	Typical acute dose to destroy the thyroid in radiation therapy.
	Area of chronic lifetime doses from high natural background.
	Region of targeted radiation-therapy treatments.
10	Hospital Leukemia treatment (10 Sv, acute) - 85 percent successful.
1	***900 mSv - Annual chronic dose in high natural background areas***
milli-sieverts	***200 mSv: Annual dose to some health spa workers.***
100	***100 mSv: Radiation worker occupational Dose Limit over 5 years.***
	50 mSv: Radiation worker occupational Annual Dose Limit.
	Two weeks dose on a beach in Brazil (about 15 mSv).
10	
	Typical natural background annual dose (3 mSv).
1	***1 mSv a^{-1}: Recommended Public Dose limit from Industrial Radiation.***
	Most medical diagnostic doses fall in the range from
0.1	0.01 to 5 mSv.
0.01	***Local dose from natural radiation from burning coal.***
	Annual dose from luminous signs, TV, smoke detectors.
0.001	***Dose to local residents from radioactive emissions from nuclear power plants.***
0.000,000,01 (1E-08 mSv)	***Maximum estimated annual ingestion dose from a failed geological repository for radioactive nuclear waste [10].***

ACUTE doses are shown in normal font. ***CHRONIC doses are shown in bold italics.***
Occupational or General Public Dose Limits do not apply to medical patients undergoing medical radiation treatments. Note the major scale break at the bottom. *Sutherland*

Summary Points About Radiation

- We are surrounded by natural radiation. It occurs naturally in our food, in the air, in water, in our bodies, and throughout the environment.
- In the early history of the earth, when life was evolving, radiation levels were much higher than at the present time.
- Many areas of the world, especially regions of geothermal activity and many mines, are naturally radioactive at thousands of times higher levels than others, and provide doses far in excess of those that are occupationally controlled.
- Higher topographic elevations (e.g., Denver) receive more cosmic radiation than those close to sea level. Frequent flyers and cosmonauts are exposed to relatively high doses of such radiation during their flights [1].
- There is no difference in their character or effect between natural and man-made radioactivity.
- Radiation and radioactivity were discovered more than 100 years ago, and were widely used around the world in medical treatments within weeks of their discovery.
- Radiation is now widely applied in thousands of uses throughout the developed world.
- Public and occupational exposures from industrial uses of radiation are limited by the application of dose limits. Medical exposures are not limited.
- The major sources of dose to the public are natural and medical sources of radiation.
- The most extreme radiation doses to anyone are usually encountered in medical uses and applications involving patients.
- Some of the lowest radiation doses to the world's population come from operating nuclear power plants, which contribute about 0.1 percent or less of a local individual's average dose each year.
- Most sources of industrial radiation, as with most hospital radiation sources and nuclear materials, can be shielded to protect workers and the public.

2. RADIOACTIVE WASTES AND THEIR CHARACTER

What are Radioactive Wastes?

Radioactive wastes consist of 'any material that contains or is contaminated by radionuclides at concentrations or radioactivity levels greater than the exempted quantities established by the competent authorities, and for which no use is foreseen.' What this means is that it is radioactive at some level above 'normal' background levels of radiation, and may need to be managed.

They may include various wastes from: -

- Uranium and thorium mining and processing activities
- Nuclear fuel cycle operations such as refining, conversion, enrichment, fuel fabrication and spent fuel reprocessing
- Operational and maintenance wastes at nuclear power facilities
- Decontamination and decommissioning wastes from nuclear facilities
- Institutional uses (industry, hospital, research) of radioisotopes.
- Various industrial processes: coal burning solids and fly ash; oil and gas drilling scale, sludges and water; water treatment and filtration solids; geothermal deposits; phosphate processing residues, etc., as shown in Table 10.
- Military weapons-program wastes.

Table 10. Typical Very Approximate Activity or Activity Ranges in Selected Industrial Uses, Wastes and Various Radioactive Materials in Society	
Industrial Radioactive 'Waste'	**Activity (Bq/kg or as indicated)**
Base-metal mining and uranium and thorium mining wastes	Background to 400,000
Coal ash (containing uranium and thorium and their progeny	200 to 25,000
Scale in oil/gas pipes (from radium and its progeny in groundwater)	Background to 15,000,000
Oil/Gas sludges (from radium in the groundwater)	Background to 40,000
Oil/Gas produced water (radium and its progeny)	10,000 to 40,000
Water treatment solids (radium and its progeny)	600 to 1,300,000
Phosphate processing solids (uranium and its progeny)	5,000 to 25,000
Geothermal solids (Radium and its progeny)	Background to 400,000
Nuclear 'Wastes'	
Depleted uranium (DU) and refined natural uranium (no progeny).	12,000,000
Spent Fuel (40,000 MWdays/tonne), after 6 years	**2E13**
Low and Intermediate Level radioactive Wastes (fission nuclides)	100,000 to 1E9
Other Radioactive Materials	
Pure pitchblende or uraninite ore	160E6
Radiography inspection device (iridium-192)	About 1E12 per device
Radiation therapy Co-60 source*	**Up to 8.4E14 per device (20 grams)**
*** The dose rate delivered by this device is about 750 grays/hour at 60 cm. It takes about 100 seconds to deliver a total dose of about 20 gray to a cancer target within the body. Note that the activity of a large radiation therapy cobalt-60 device (with only 20 grams of Co-60), is greater than the activity of 1 kilogram of spent fuel that is 6 years old, yet is safely used. Data are from the IAEA and other sources.**	

All radioactive isotopes are characterized by one major feature: they decay, and become less radioactive with time. Some relatively pure materials e.g. Th-232 from refining, or depleted uranium (uranium-238, DU) produced as a byproduct from the uranium-235 enrichment process, are of relatively low specific activity (Th-232 -- 4E3 Bq/g, and U-238 -- 1.2E4 Bq/g) because of their very long half-lives. They also gradually become more radioactive with time as their daughter nuclides begin to ingrow (Figure A1 in the appendix). They eventually reach the radioactivity of the originally-mined thorium and uranium once all of the daughters reach secular equilibrium with the parent nuclide, as they usually are in nature, unless radon gas is lost from the orebody.

Some materials have very long half-lives and decay slowly. For example natural uranium takes hundreds of millions of years (uranium-235) to billions of years (uranium-238) to decay, eventually becoming stable lead isotopes which are always found with natural uranium deposits.

Some materials have very short half-lives of a fraction of a second, a few seconds, days or years. If they are daughters of longer half-life materials such as uranium-238 (as shown in Table 3), then although they continually decay according to their own half-life, they are also continually being produced. They exist as long as the parent exists and produces them as it decays. If they are not associated with such a parent, then they decay to stable elements without replenishment, and according to their defined half-life. For example, fission nuclides, of which there are about 600, are formed continually – and decay continually - in the reactor. Once spent fuel is discharged, the fission nuclides are no longer being formed, and they decay with half-lives which range from a few seconds (gone within the first hour or so of the spent fuel being removed from the reactor), to days (gone within a few years at most). The two most significant fission nuclides which remain in aging spent fuel (cesium-137 and strontium-90, with half lives of almost 30 years), are detectable for about 300 to 500 years, before they too, have almost entirely decayed away.

By the time a radionuclide has gone through ten half-lives its starting radioactivity has been reduced by a factor of more than 1,000, though it may still be significantly present and detectable if the starting activity was high. After 20 half-lives, its radioactivity has been reduced by a factor of more than 1 million from its initial activity.

Classification of Radioactive Wastes.

A general classification of radioactive wastes that is generally accepted, internationally, is shown in Table 11.

Table 11. Broad Classification of Radioactive Wastes, Management Time Frame and Some Considered Disposal Options (Mostly from IAEA)

Category	**Exempt and very Low Level Wastes**	**Low Level and Intermediate Level Wastes (LILW) - heat output less than about 2kW m^{-3}, and activity - ILW > 4,000 Bq g^{-1}**		**High Level and Transuranic Wastes (HLW) (high radioactivity and >2kW m^{-3} heat output)**	
Half-Life	**Long or short half-lives**	**Short half-lives <30y**	**Long half-lives >30y**	**Short half-lives <30y**	**Long half-lives >30y**
Material	Uranium mine and other mine tailings. Some coal ash. Some wood ash. Phosphate fertilizer wastes.	Most nuclear maintenance wastes contaminated with fission nuclides. Some hospital and medical wastes.	Some nuclear maintenance wastes, and by-product wastes containing transuranic nuclides.	Separated fission products (Cs-137 and Sr-90 are the significant nuclides). Some retired medical, industrial and research devices.	Spent fuel, if not reprocessed. Retired military plutonium warheads, if not used as reactor Mixed Oxide (MOX) fuel. Defense wastes.
Management or Security Time Frame	Usually low radioactivity. Uranium mine wastes are highly regulated.	Typically less than 20 years, and half-life dependent.	Hundreds to thousands of years, based upon nuclides and half-lives.	Several hundred years, more or less, depending upon half-lives.	Thousands of years. Security of plutonium is the long-term issue, rather than radiation.
Disposal Options	Disposal as for other possibly-hazardous mine wastes. There are strict disposal regulations for U mine wastes.	Enclosed surface, or near-surface facility.	Near surface facility or intermediate-depth geological facility.	Near surface, intermediate depth, or Deep geological disposal facility. Medical devices may be processed and recycled	Surface management with eventual reprocessing, or stored in a deep geological disposal facility.
Radionuclides with half-lives longer than 30 years are regarded as long-lived wastes; those with half-lives less than 30 years are considered short-lived. Intermediate Level Wastes, although containing significant radioactivity relative to low-level wastes, do not give rise to notable heating effects, as do High Level Wastes for the first few years. Individual Jurisdictions usually specify their own criteria for definition and control.					

Any radioactive wastes arising from the nuclear fuel cycle are highly regulated in Canada by the Canadian Nuclear Safety Commission (CNSC). Naturally Occurring Radioactive Materials (NORMs) and TE-NORM wastes, if not associated with the nuclear fuel cycle, are regulated to some degree by the provinces in which they are produced.

High Level Radioactive Wastes (HLRW)

High-level radioactive wastes arise mostly from nuclear power operations, with lesser quantities associated with some medical and industrial uses of radiation. No matter how such waste originates, the management requirements are similar, and the same degree of public protection is mandated through international radiation protection regulations, transportation regulations and legal dose limits.

These wastes may contain short-lived (<30 year half-life) and long-lived (>30 year half-life) radionuclides. They consist of those materials that contain sufficient radioactivity and heat, that they require shielding, isolation and management controls to limit radiation exposures and heating effects over some defined interval of time depending upon half-lives, activity per unit mass (Bq/g), total activity under management (Bq), and security requirements.

The main HLW materials are:

1. Spent fuel (made up of about 95 to 99% unfissioned uranium, 1% transuranic nuclides, and about 3% of highly radioactive fission nuclides. About 15,000 tonnes of spent fuel is produced worldwide each year, and about 5,000 tonnes of this is recycled at the present time.
2. Transuranic nuclides - mostly from military nuclear programs (not further considered here).
3. Fission nuclides, where separated from spent fuel. About 150 tonnes of the 450 tonnes of fission nuclides produced in the world each year, are separated from spent fuel and managed worldwide.
4. Medical retired therapy sources (cobalt-60, Cs-137) and industrial irradiation sources. These are usually returned to the manufacturer and, if economically feasible, may be re-processed and recovered for re-use. Others are discarded into licensed waste management facilities.

Medical and Industrial HL Wastes

These include various retired therapy devices and irradiators (including Co-60, Cs-137, and Ir-192), which have significantly decayed and may then be replaced by others. They are usually returned to the manufacturer, who is either responsible for their continued management for several years, or for reprocessing and recovery of the residual nuclide for use in another device. The advantage of using such short-half-life, high specific activity materials, is that the mass of the effective radionuclide is very small - typically just a few grams or less - and it is relatively easily shielded, transported and managed at any licensed facility, and its radiation hazard is significantly reduced or gone after a minimum management interval.

Many such medical therapy and industrial devices are, kilogram for kilogram of radionuclide, much more radioactive than even fairly young spent fuel, as is shown for cobalt-60, in Table 10.

Spent Nuclear Fuel

Spent fuel is initially highly radioactive when first discharged from the reactor, but rapidly decays. The dose rate and radioactivity decrease by about 99.9% in the first 10 years because of the decay of the numerous short-half-life fission nuclides (Figure 4, Table 13).

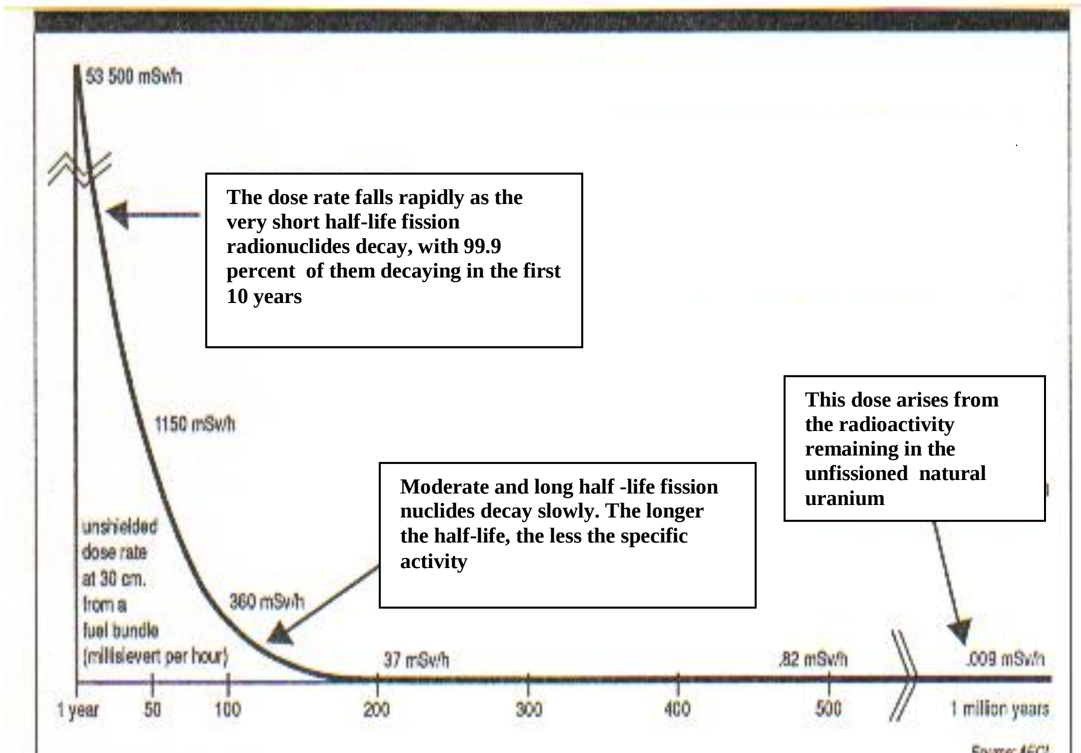


Figure 4. Radioactive Decay and Associated Dose Rate in a CANDU Spent Fuel Bundle after burn-up of about 7,800 MWdays per Tonne of Uranium. Comparable data are shown in Table 16, but at a distance of 1 metre. Modified after Atomic Energy of Canada Ltd.

Spent fuel consists of three significant constituents:

1. Unfissioned uranium-235 and uranium-238, making up 95 to 99% of the fuel matrix. These constituents are of relatively low specific activity (Bq/g).
2. Highly radioactive and mostly short half-life (high specific activity) fission nuclides making up from about 1 to 4% of the fuel matrix, depending upon the total burn-up, per tonne, in the reactor and
3. Transuranic nuclides (mostly isotopes of plutonium and americium - Table 15), making up about 1% of the fuel. They are continuously produced in the reactor core and contribute to energy production, though some remain in the fuel matrix after the spent fuel is discharged. About 40% of the energy produced in a CANDU reactor cycle is derived from fissioning of these TU nuclides.

Because of the energy value contained in the un-fissioned uranium and in the transuranic nuclides it may be cost-effective - where the reprocessing facilities exist - to reprocess spent enriched fuel, rather than to regard it as waste.

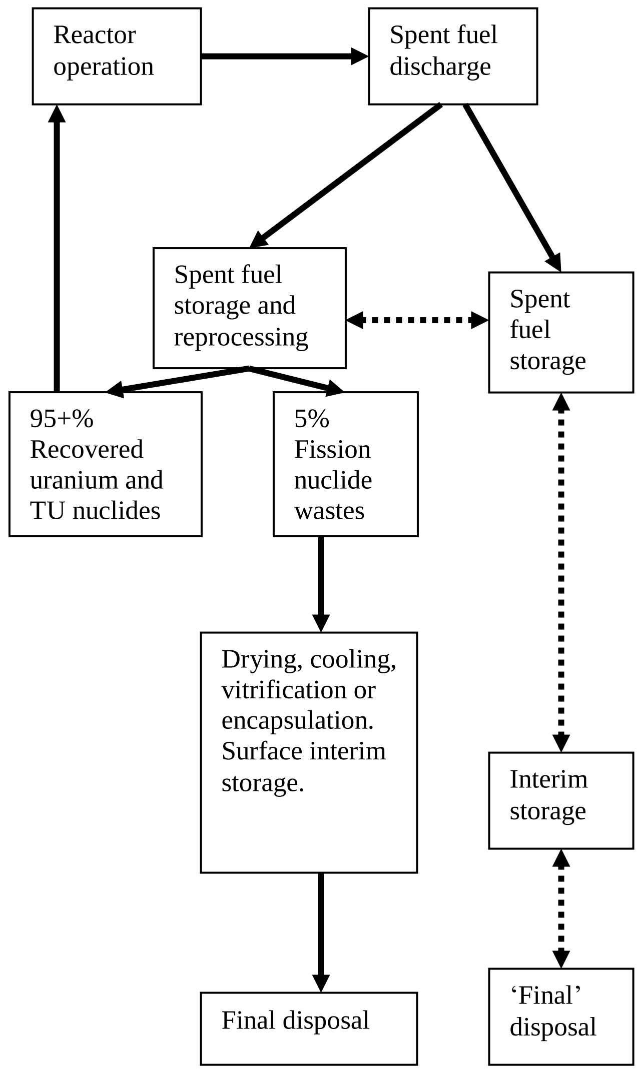
In the case of natural uranium (used in the present generation of CANDU reactors), which is relatively cheap at this time (about U.S.$30/kg*), it is not cost effective to reprocess spent natural fuel. In the future, as the costs of reprocessing diminish as the material decays, and as the cost of uranium increases, there is likely to be increasing commercial value in spent fuel.

- The price in 2007 was about $120/pound or about $300/kg.
- In 2009, the price seems to be about half that, or about $60 per pound.

Management Options

The various options for management of spent fuel and related high level wastes (fission nuclides) are dependant upon whether or not it is reprocessed, or is likely to be reprocessed at some future time. A general schematic outlining how spent fuel may be directed or managed is shown in Table 12.

Table 12. Options for Spent Fuel Management.

Reactor Operation Fuel loading and spent fuel discharge.	
Spent Fuel Bay Storage Reprocessing after about 150 days - the recovered uranium and TU are returned to the reactor cycle. Fission wastes are vitrified and stored as HLW until final disposal. Continued storage of spent fuel for 7 to 10 years if not reprocessed, with movement into dry fuel storage.	
Dry Fuel Storage Management for up to 50 years with reassessment for continued management, reprocessing, or moved to central storage for further management.	
Final Disposal Spent fuel may be retrieved at any time for reprocessing, as dictated by economics and regulatory approval.	

Reprocessing

Reprocessing - to remove fission nuclides and to recover uranium and the TU nuclides - usually takes place no more than about 150 days after discharge from the reactor.

Reprocessing as early as possible, allows the significant potential energy contained in some of the short half-life transuranic nuclides (Table 15), to be captured rather than being allowed to decay away. After the highly radioactive fission nuclides have been removed, then the approximately 95% of unfissioned uranium and transuranic nuclides (about 1%) are returned into the reactor cycle.

The separated fission nuclides (about 5% by volume of the spent fuel) are managed as high-level waste. For ease of handling and to render them insoluble, they are usually either dried and vitrified (made into glass), or are dried and mixed into a solid matrix with heat dispersal properties, and enclosed in steel drums. In this form, they can be safely managed for a period of time proportional to the half-life of the dominant long-lived fission nuclides, which are strontium-90 and cesium-137, with half-lives of less than about 30 years.

Fission Nuclide Wastes

Most of the more than 600 fission nuclides in spent fuel have half-lives of less than 24 hours, with only 12 of them having half-lives longer than 10 years, as detailed in Tables 13 and 14.

Table 13. Summary of Fission Product Nuclides and Their Half-lives

Fission-product Half-lives	**Number of Defined* Fission Nuclides**
Less than 24 hours	438+
1 day to 1 year	42
>1 year to 10 years	4
> 10 years	12
Stable fission isotopes	101
Total fission nuclides	615

*** Many fission nuclides have extremely short, and difficult-to-define half-lives.**
The data are summarized from the Chart of the Nuclides [11].

After about 20 years, these 12 nuclides are the dominant fission nuclides remaining in any spent fuel, whether natural or enriched, and in the separated fission wastes from spent fuel reprocessing. Most of the radioactivity in spent fuel or its fission wastes is thus lost in the first few years of storage, as more than 98% of the fission nuclides have completely decayed. The remaining TU nuclides make up less than 1% of spent fuel, but some have extended half-lives as shown in Table 15. They remain in spent fuel after nearly all of the fission nuclides have decayed. However, once the fission nuclides have decayed, after about 500 years, the spent fuel is only a few times more radioactive than the natural uranium from which it was manufactured (Figure 4).

Table 14. Fission Radionuclides with Half-lives Greater than 10 Years (in order of Increasing half-life)		
Fission Radionuclides *	(Fission yield percent)	Half-life (years)
Krypton-85	1.319	10.7
Strontium-90	**5.8**	**29**
Cesium-137	**6.19**	**30.07**
Tin-121	0.013	55
Samarium-151	0.419	90
Tin-126	0.059	1E5
Technetium-99	6.1	2.13E5
Selenium-79	0.045	6.5E5
Zirconium-93	6.35	1.5E6
Cesium-135	6.54	3E6
Palladium-107	0.146	6.5E6
Iodine-129	0.54	1.57E7
The fission yield percentage refers to the total of all of the fission nuclides with this mass number, of which there may be 10 or more, and not to the individual radionuclide. * Radionuclides beyond Cs-137in this table have low fission yield; have low energy emissions; or are so long-lived as to be of low specific activity. Data are from the Chart of the Nuclides [11].		

Table 15. Significant U and TU Nuclides Listed in Order of Their Increasing Half-lives (Decreasing Specific Activity)	
Nuclide	**Half-Life in Years**
Californium-250	13.1
Plutonium-241	14.4
Curium-244	18.1
Curium-243	29.1
Plutonium-238	87.7
Californium-249	351
Americium-241	432.7
Californium-251	900
Americium-242m	1141
Curium-246	4.76E3
Plutonium-240	6.56E3
Americium-243	7.37E3
Curium-245	8.5E3
Curium-250	9.7E3
Plutonium-239	2.41E4
Neptunium-236	1.55E5
Curium-248	3.48E5
Plutonium-242	3.75E5
Plutonium-244	8.0E7
Uranium-234	**2.46E5**
Uranium-235	**7.04E8**
Uranium-238	**4.47E9**
Many of the TU nuclides are, or become fissionable in the reactor cycle and are an important source of energy. They are also most effectively destroyed in the reactor cycle. Most data are from the Chart of the Nuclides [11].	

Without Reprocessing

If spent fuel is not reprocessed to remove the fission nuclides, then it is managed indefinitely. However, as the main source of radioactivity in spent fuel is from short half-life fission nuclides, then spent fuel - whether reprocessed or not - becomes of relatively low radioactivity after the fission nuclides have decayed, and is then approaching the relatively low specific activity of natural uranium (Figure 5) with its equilibrium daughters.

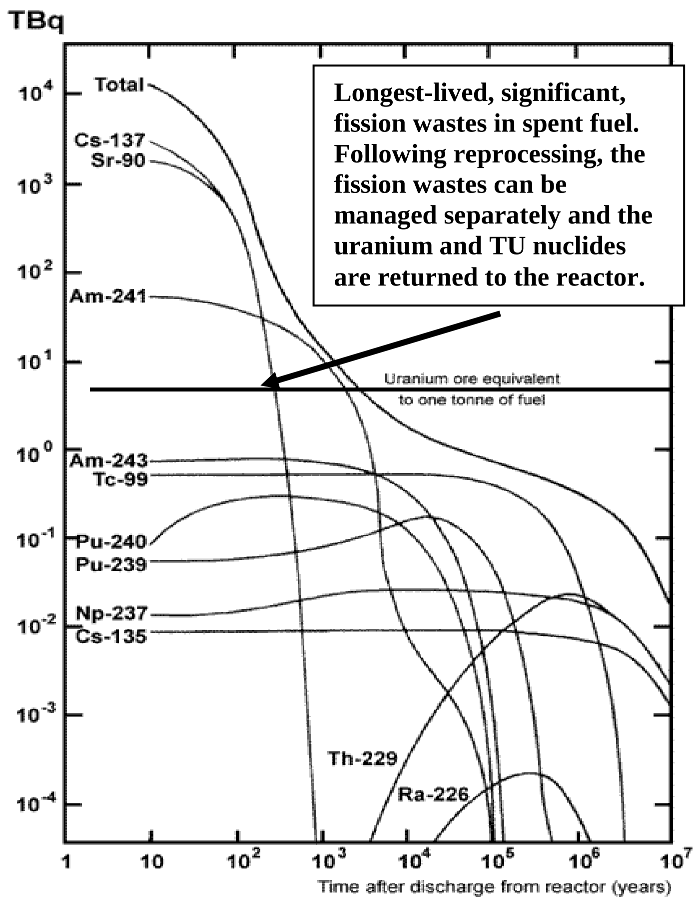


Figure 5. Activity of High-Level Waste from 1 Tonne of Spent PWR Fuel.
TBq means tera-becquerel or 1E12 becquerels.
Source: IAEA, 1992 - Radioactive Waste Management.

The general and widely publicized belief about such spent fuel is that it is dangerously radioactive for millions of years.

As almost 100% of its radioactivity is from the fission nuclides, which are essentially decayed after about 300 to 500 years, leaving a matrix of relatively low specific activity uranium and the fairly long half-life radioactive transuranic nuclides (Table 15), this perception is incorrect. It is certainly highly radioactive for several decades after leaving the reactor, as shown in Table 17, but it becomes significantly less radioactive and less hazardous with time. What is rarely acknowledged is that high-level radioactive wastes eventually become low-level radioactive wastes.

When the fission nuclides have decayed, the focus of management is likely to be more to safeguard the plutonium isotopes which remain in the uranium matrix than because of the, by then, relatively low radiation fields associated with the spent fuel. Management will be because of political and proliferation concerns, even though the mix of plutonium isotopes in fuel that has been in a reactor for 18 months to six years is undesirable for weapons use. In any case, any presumed proliferation or security risk can be diminished by reprocessing the spent fuel. This reduces the tonnage of spent fuel at a multiplicity of storage sites; reduces the quantity of plutonium and other transuranic wastes in managed storage; and generally brings the recycling process and management of most radioactive wastes into one central, secure reprocessing facility. Tonnages of plutonium will be significantly reduced and kept at a relatively low level by recycling this fuel through the reactor cycle. Others believe that as the technology to reprocess fuel is the same technology used to extract plutonium from which nuclear weapons can be made (despite differences in isotopic ratios which make commercial spent fuel undesirable for this purpose), that encouraging global recycling and extraction and isotope separation technologies could lead to proliferation.

Current Management of Spent Fuel

Spent fuel, the most radioactive material produced in the reactor cycle, is typically contained at its point of origin for several decades, unless it is to be reprocessed in order to recover and recycle the uranium, plutonium and other Transuranic nuclides.

The initial stage of spent fuel management following fuel discharge from the reactor must take into account the need for both radiation shielding and heat removal. Both of these requirements are met by initial storage in water-filled spent-fuel bays, and both are continuously decreasing with time (Table 16, and Figure 5). These storage locations not only provide both cooling water and adequate radiation shielding for the first few years, but also allow visual inspection of the fuel and allow it to be remotely manipulated and moved into storage racks.

Table 16. Decay Heat Character in a CANDU Natural Uranium Fuel Bundle vs. Time Since Discharge from a CANDU-600 Reactor (Most Data are from Atomic Energy of Canada Ltd.)			
Cooling time following discharge	**Heat from actinides (watts/bundle -containing 21.0 kg UO_2 at the start)**	**Heat from fission nuclides (Watts $bundle^{-1}$)**	**Total heat (watts/bundle) (burn-up 7800 MWd Mg^{-1} U)**
1 second	**1810**	**23,700**	**25 500**
1 hour			**9000**
1day			**3000**
1 year			**60**
6 y	**0.44**	**5.64**	**6 (300 watts/Mg)**
8 y	**0.47 +**	**4.44**	**4.9**
10 y	**0.50 + (23.8 watts/Mg)**	**3.95 (188 watts/Mg)**	**4.4* (209 watts/Mg)**
15 y	**0.56 +**	**3.34**	**3.9**
20 y	**0.60 +**	**2.94**	**3.5**
30 y	**0.66 +**	**2.30**	**3.0**
50 y	**0.71 +**	**1.43**	**2.1**
100 y	**0.70**	**0.44**	**1.1 (52 watts/Mg)**
Natural Uranium			**0.1 watt/Mg**
+ Increasing heat in the medium term is from in-growing daughter radionuclides. * About 90 percent of this much-diminished heat output after 10 years, comes from Sr-90 (+Y-90) and Cs-137. For PWR spent enriched fuel with higher burnup, the heat output is about 1 kW $tonne^{-1}$ after ten years.			

If fuel reprocessing is to take place, the fuel is transferred after about 150 days into shielded, crash-resistant transportation flasks that meet or exceed transportation safety requirements, and is conveyed to a reprocessing facility.

If reprocessing is not required then the spent fuel remains in the cooling bay for at least seven to ten years, where it cools and loses sufficient of its radioactivity that it can be transferred, in shielded flasks, to a controlled - usually adjacent - dry fuel storage facility consisting of concrete bunkers or silos with about 1 metre thick walls.

A Dry Fuel Storage facility on the controlled site of a CANDU nuclear plant is shown in Figure 6. The cylindrical canisters in the background are designed to accommodate spent fuel. The rectangular structures in the foreground are designed to hold all other lower level radioactive wastes.

Figure 6. A Typical Spent Fuel and Radioactive Waste, Surface-Storage Facility in Canada. The Cylindrical Concrete Canisters in the Background (100 of them) are sufficient to safely hold the approximately 1000 Tonnes of Spent Fuel from about 10 Years of Full Power Operation of a CANDU Reactor. The Site will accommodate 200 more such Canisters to securely contain all Spent Fuel from at least Thirty Years of Reactor Operation. The Concrete Structures in the Foreground hold relatively low to moderate dose rate Maintenance and Process Wastes. (Photo, Courtesy of NB Power).

The structures are designed and constructed to withstand even extreme conditions, including earthquakes, tidal waves, floods and major washouts, hurricanes and forest fires. The 1 metre-thick steel re-enforced and steel lined concrete shielding is designed to reduce the dose rate from freshly-placed spent fuel (perhaps 7 to 10 years old), immediately outside of the filled container, to no more than about 25 microsieverts per hour in order to protect those workers who may spend much of their working year at that location.

Measurements taken in contact with the filled cylindrical containers indicate that the dose rate is typically less than about 0.5 microsieverts per hour, rarely up to 1 microsievert/hour [12], and is continuously falling because of radioactive decay within the containers. Just a few tens of metres away, the ambient dose rate of about 0.1 microsievert/hour is from natural background radiation, and the radiation within the containers is not detectable. Many natural environmental locations, e.g. geothermal hot springs, health spas, and many populated regions have higher natural background radiation than this.

The measurement of the cumulative annual radiation dose at the fence line around these facilities, just a few metres from the canisters, is typically and almost entirely from the natural background radiation in the area that existed before the storage site was constructed. Any additional contribution from the radiation fields associated with the canisters is barely detectable within the range of natural background radiation variation from one year to the next [13], though there is a slight increase in the fields detected by the fence-line dosimeters immediately adjacent to the concrete canister that is being filled. This is attributable to the momentary 'shine' (a few seconds) from the spent fuel during transfer between the shielding flask and the canister, which is also detected by health physics staff monitoring the transfer process. The dose rate at the facility fence line is about 40 microsieverts per hour for these few seconds.

After about 50 years or so in this facility, the spent fuel is of much lower activity per gram, and of heat output, and could continue to be stored in this way indefinitely. It could also be safely removed to a central storage location or to a more permanent disposal facility; or reprocessed and recycled.

Options for Longer-Term Management of Spent Fuel

The main options of several that have been considered if the spent fuel is not promptly reprocessed are:

1. Leave the spent fuel where it is, in managed and secure dry fuel storage which is capable of safely storing the low volumes indefinitely without detectable harm to the public.
2. Dispose of it eventually in a central repository, recognizing that it may be retrieved in the future. Transportation and repository-work risks should be considered if this disposal option is chosen. Some of the risks from this option were researched by AECL [10] and are shown in Table 18.
3. Reprocess it when the economics of doing so are more favourable, though this option is not economic at this time for spent CANDU (un-enriched) fuel.

Dose Rates from Unshielded Spent Fuel

Table 17 indicates the calculated ***unshielded*** dose rates at about 1 metre from a spent fuel bundle.

With radioactive decay, the dose rate associated with any radioactive material decreases with time. By the time 1,000 years have passed, there are no significant fission nuclides present, and the dose rate reflects the natural uranium content and the remaining transuranic nuclides. Figure 4 data are for the unshielded dose rate at 30 cm, so are about 10 times higher than in table 17 for a 1 metre distance, in accordance with the inverse square law of dose with distance.

Table 17. Approximate Dose Rate from the Side of an Unshielded CANDU Spent Fuel Bundle (21 kilograms of uranium oxide), following Burn-Up of about 7,800 MW Days/Tonne of Uranium.

Time Since Discharge from the Reactor	**Approximate gamma Dose Rate in grays per hour at 1metre from an unshielded spent fuel bundle.**	**Time to receive a radiation dose of 10 sieverts) from an unshielded fuel bundle of this age at 1 metre distance. (Such exposures, other than from the extremely low dose from handling of new fuel, do not occur).**
Dose rate from a new fuel bundle not yet used in the reactor.	<<0.05 mGy/h	Very low activity (Bq/g). No injuries of any kind can be seen, or can be statistically associated with this exposure.
In the reactor - immediately before discharge, after about 1 year of burn-up	(about 1,000 gray/hour)	Very highly radioactive (Bq/g), but there is no possibility of exposure.
1 hour	1,000	36 seconds (acute dose)
1 day	300	2 minutes (acute dose)
1 month	80	7.5 minutes (acute dose)
1 year	2	5 hours (acute dose)
10 years	0.2 (200 mGy)	50 hours (acute/chronic dose)
100 years	0.04 (40 mGy)	10.5 days (chronic dose)
200 years	0.004 (4 mGy)	100 days (chronic dose). Fatalities are unlikely but are statistically suggested
1,000 years	0.000,05 (0.05 mGy)	23 years (chronic dose). Fatalities are not expected but may be statistically suggested

The oldest man-made* spent fuel in the world is about 60 years old. No-one has been exposed over the regulatory limit by managed spent fuel over this interval of time, and no-one is known to have been injured by it.

The accident at Chernobyl in 1986, exposed several firefighters to fuel which had been ejected from the reactor onto the roof of the adjacent turbine building, and which they attempted to remove. Twenty-eight of the 31 fatalities stemmed from this ill-advised work.

*The oldest spent fuel is present in nature. It is that associated with the Oklo uranium deposit in Gabon, Africa. Oklo was a natural reactor which operated about 1.8 billion years ago. All of its wastes remained in place and are indicated by the unusual abundance of certain stable elements in the ore deposit.

Because of the regulations which govern the handling and management of radioactive materials, and which stipulate radiation protection practices, including dose limits and dosimetry, no radiation worker nor any member of the public is allowed to have access to unshielded spent fuel at any time.

Dose from Spent Fuel Management.

Some measurements and estimates of potential radiation doses and risks associated with normal management, handling and disposal of these **shielded** wastes, and other sources of radiation in society are shown in Table 18.

Table 18. Perspective on Documented Public and Worker Annual Radiation Doses from Nuclear Power Plant Operation, and Management, Present Handling of Radioactive High Level Wastes and Future Potential Doses from Disposal of HLW (most of the latter data are from AECL).

Source of Radiation Dose	**Annual Chronic Dose - mSv.**	**Probable Risk or Health Effect**
High Natural Background chronic radiation dose	**1,000**	**No adverse health effects have been epidemiologically defined, and may not occur.**
Acute Dose below which health effects are unlikely	**200 (acute)**	**Adverse health effects are not epidemiologically definable, and may not occur.**
Worker annual occupational dose limit (maximum).	50	The radiation risk to workers is assumed to be calculable, though it may not be epidemiologically definable.
Average natural background radiation	3	Adverse health risks from any of these low dose and low dose rate exposures are not epidemiologically definable on any population. Any attempt to suggest potential adverse health effects in a large population by summing any of these very small doses over billions of potentially exposed individuals, and over an interval of hundreds to thousands of years, and then assuming that some detriment can be determined from this, is not scientifically justified. No deep disposal facility is in operation at this time.
Worker average dose from all occupational exposures	2	
Public annual dose limit from all industry	1	
Nuclear Power Operation		
Measured public dose from an adjacent NP facility	**0.001 to 0.02**	
Average public dose (estimated) in the world from all NP operations (UNSCEAR 2000) [1]	**0.0002**	
Estimated maximum local public external dose from HLW management at this time *	**<0.001**	
Estimated upper level of public dose in the world from HLW management *	**<<0.0001**	
Estimated probable public external dose from significantly expanded HLW operations - with surface management *	**<0.0001**	
Disposal Facility Operation AECL[10]		
Maximum estimate of local public annual dose from transportation of High Level Radioactive Waste under normal conditions [10]	**0.09 (by road) 0.0004 (rail) 0.05 (canal)**	
Disposal facility operation effects on the adjacent public in a farming operation and to aboriginals who may eat large quantities of fish [10]	**0.0005 (farm) 0.003 (aboriginals)**	
Maximum dose to a disposal facility worker [10]	**17**	
Accidents with movement of spent fuel at the facility - maximum possible dose to the public [10]	**0.25**	
Estimated maximum public ingestion dose from spent fuel in the vicinity of a deep disposal facility immediately after emplacement, and at any time following emplacement, assuming total loss of institutional controls [10]	**<0.000,000,01**	**This is equivalent to about 1 second's worth of an annual natural radiation dose.**
*** Guidance for these estimates is obtained from UNSCEAR 2000 [1], and references [12] and [13]**		

Because of the potentially high-dose consequences (to workers) of upset and accidents with high-level radioactive wastes, significant planning goes into their safeguards and management. To the present time, there has been no significant accident or upset associated with the management of any of these materials that has significantly affected either workers or the public.

Some indication of the relative radiation contributions to the public at the present time, from various sources of radiation including natural and medical radiation and high-level radioactive wastes including spent fuel, are shown in Figure 7, with estimated average doses and collective doses [1] for comparison shown in Table 19.

Figure 7. Approximate Percentage of Public Annual Radiation Doses from all Potentially Significant Sources of Radiation throughout Developed Society, and Showing the Relative Contributions from all Radioactive and Nuclear Wastes, and Spent Fuel Management.

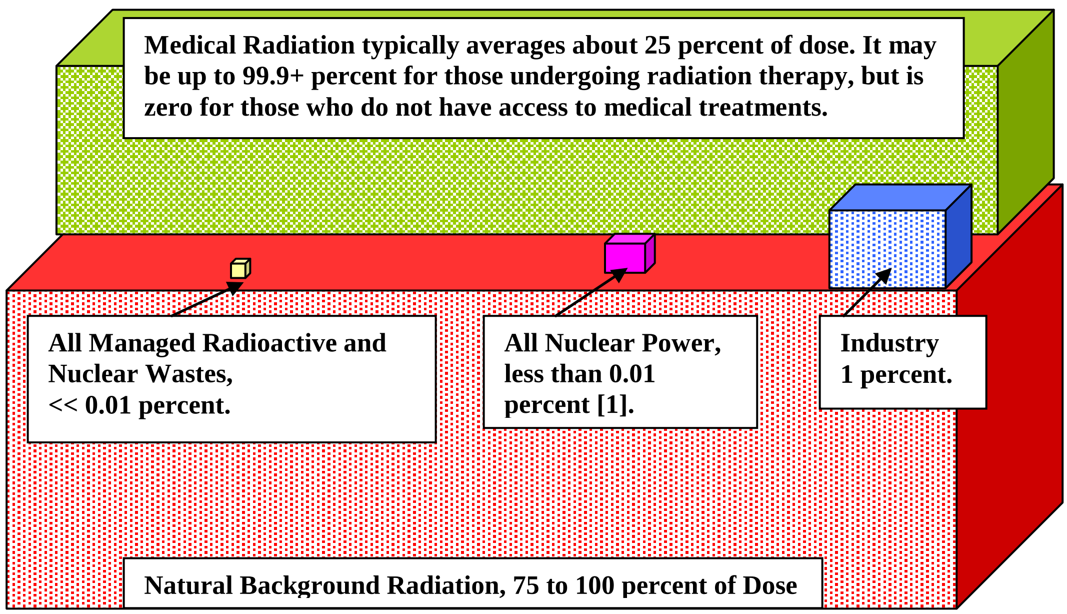


Table 19. Average Radiation Doses and Collective Dose at Year 2000 from some Natural and Man-Made Sources of Radiation (Most Data are from UNSCEAR 2000 [1]) Expressed in Millisieverts (mSv) and Person Sieverts		
Radiation source	**Worldwide* average annual effective dose (mSv)**	**Collective annual dose (person sieverts) over a world population of 6 billion**
Natural background	2.4*	14,400,000
Diagnostic medical examinations	0.4**	2,400,000
Atmospheric nuclear testing (ended)	0.005 (decreasing)	30,000
Chernobyl accident (one time)	0.002 (decreasing)	12,000
Coal burning	0.02 - 0.2	120,000 to 1,200,000
Nuclear power production	0.0002	1,200

* 2.4 mSv multiplied by 6 billion persons is a collective dose of 14.4E6 person sieverts.
** Worldwide averaging of data causes a significant understatement of individual medical exposure contributions in any population where only a few percent of the populace are exposed each year.

Summary Points for High Level Radioactive Wastes (HLRW) and Spent Fuel

- All uses of radiation and some industrial processes produce radioactive wastes.
- Anyone who is exposed to industrial or nuclear radiation, (other than during medical treatments), and their wastes, is protected by legal dose limits which may not be exceeded. Such limits, which are rarely approached, ensure that the possible risks of injury are minimized.
- All radioactive wastes from Nuclear Power facilities and hospitals are managed and controlled, usually at their location of origin. The public does not have access to the former, and rarely encounters the latter.
- Any source of industrial radiation, as with most hospital radiation sources, is shielded to protect workers and the public.
- High-level radioactive wastes throughout the world are small volume and are effectively shielded and managed.
- Although spent fuel is initially highly radioactive and emits radiation energy of limited range, it does not emit radionuclides.
- Radioactivity is a continuously decreasing quantity which is a function of the half-life (lives) of the responsible radionuclides. Spent fuel becomes less radioactive with time.
- Of all public radiation doses, the least significant arise from industry and nuclear operations and all of their wastes.
- The potential energy value in spent fuel suggests that it should be surface-stored, as at present, and ultimately reprocessed when economically feasible, to make use of its unused energy.
- Spent fuel consigned to any repository, must be ensured to be retrievable for possible future energy use.

3. HEALTH EFFECTS OF RADIATION

Some Definitions
What we know about Radiation Effects
Assessing Risks from Low Doses: The Linear No-Threshold Hypothesis
Radiation Protection and Dose Limits
Human Health Studies
Summary Points Concerning the Health Effects of Radiation

Some Definitions:

- **An acute dose** (a potentially high dose delivered at a high dose rate) is one which is delivered in less than a day and typically in a fraction of a second. Most medical exposures are acute.
- **A chronic dose** (any dose – low or high - delivered at a low dose rate) is one which is delivered over a longer period of time from days up to a lifetime. Natural background radiation is a chronic radiation dose.
- **Short-term (early) effects** are those which occur within minutes to hours of a very large acute exposure. They range from nausea and other intestinal upsets, to recognized acute radiation syndrome(s) (ARS) and perhaps to death, depending upon the total dose that is acutely received and individual sensitivity. Some people are more or less sensitive to radiation than others.
- **Long-term (late) effects** are those which are statistically predicted to arise in the future decades following any survivable acute or chronic radiation exposure.
- **Somatic Effects** are those suffered by the exposed person (for example skin reddening or acute radiation syndromes).
- **Genetic effects or hereditary effects** are those effects which appear in subsequent generations. If an exposed individual produces no offspring after exposure, then there can be no genetic or inheritable effects from any mutational effect. The probability of the appearance of a genetic effect is taken to be about 1%/Sv. However, radiation-related hereditary effects in humans have not been seen in the Japanese bomb survivors [1], nor in any other exposed human population.
- **A low dose** in medical usage, is considered to be less than 200 mSv, regardless of dose rate [14].
- **A low dose rate** in medicine, is considered to be less than 0.05 mSv per minute, regardless of total dose [14]. This implies an annual dose of up to 26 sieverts. This low dose rate was later changed (doubled) to be less than 0.1 mSv per minute, whatever the total dose [15].
- **A stochastic effect** is one for which the probability of its occurrence is a function of dose, without threshold. The larger the dose, the larger the risk, for example in the possible development of a future radiation-related cancer; a late effect.
- **A deterministic effect** is one for which the severity of the effect is a function of dose, and one for which a threshold may therefore occur. For example, following a radiation exposure, skin reddening, cataract development, depilation, sterility

and Acute Radiation Syndrome (ARS) fatalities occur only above certain dose thresholds.

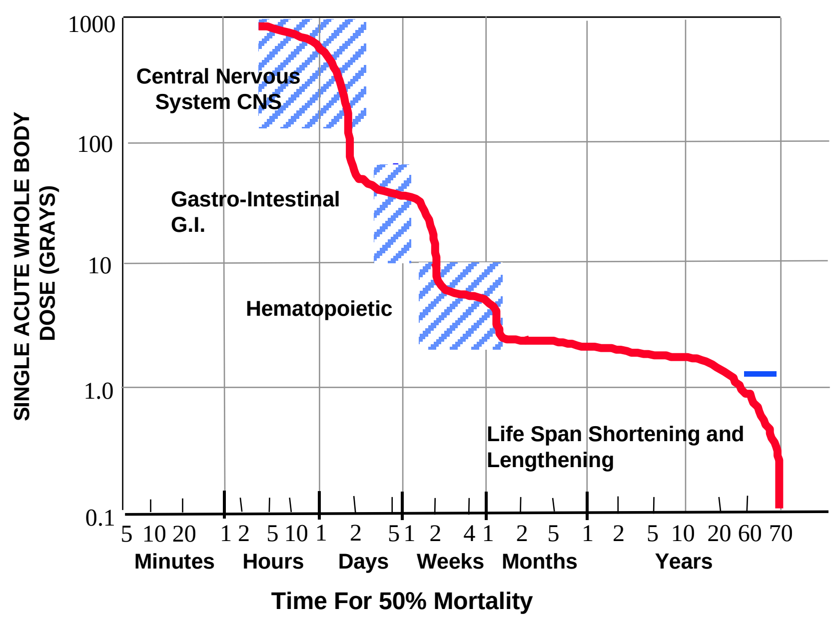
What we know about the Effects of Radiation

High Dose Effects. We know that very high acute radiation doses above about 7 sieverts are sufficiently damaging to DNA and the cells throughout the body, that they cause the death of the exposed individual in the first few days to weeks following exposure (Figure 8, Table 20). There were two such deaths from criticality accidents in the Manhattan Project in the 1940s, and some 28 deaths of firefighters following the Chernobyl accident in 1986. Other fatalities have been documented from medical therapy device over-exposures (Zaragoza, Spain, 1990, Costa Rica 1996, and others); radiographer carelessness (Peru, former USSR); from operator carelessness in irradiator accidents (U.S. and others); and from scrapyard exposures from dismantling (usually stolen) medical therapy devices (Goiania, in Brazil, and in Thailand).

At very high acute doses, acute radiation syndromes (radiation sickness) become evident with increasing dose, as shown in Figure 8.

Survival times and the onset of nausea following very large exposures, decrease with increasing dose. Hematopoietic - bone marrow - effects may be completely survivable. Gastro-intestinal and Central Nervous System syndromes are typically not.

Figure 8. Dose/Response Syndromes for Acute Radiation Doses in Humans



At very low doses, but still well above an average background dose, there are features associated with well-documented life lengthening in many experimentally-exposed animal groups [16] (and described in BELLE publications of Calabrese and colleagues, available on the internet site belleonline.com) and the same feature may be true of humans, but cannot be epidemiologically defined. Although all radiation, even down to low doses, is assumed to do harm, there are also features of immunological benefit associated with such low dose exposures. Unfortunately, such benefit is difficult to define for humans, as the effects are not readily definable at low doses, and the statistical uncertainty is affected by those individuals and families who are cancer- and injury-prone because of genetics. At some increasing exposure level - which is different for each of us and is not yet definable with our current knowledge of the human genome - but appears to lie well above existing background levels of radiation for most of us, the potential benefit is outweighed by the harm.

Table 20. Defined Human Response to an Acute Whole-Body Radiation Dose *

Total Dose (grays) **	**Delivered ACUTELY (seconds to hours). Cellular repair may be only partially effective.**
50 to 100	Nausea, vomiting, diarrhea. Rapid onset of unconsciousness. Death in hours or days from damage to the Central Nervous System (the CNS syndrome).
10 to 50	Rapid onset of nausea, vomiting, diarrhea. Death in days to weeks, mostly from Gastro-intestinal complications (GI syndrome).
3 to 10	Nausea, vomiting, diarrhea in most individuals. About 50 percent survival rate without hospital treatment. (Hematopoietic Syndrome).
1 to 3	Delayed nausea and fatigue in some individuals. Eventual total recovery of most individuals, though with statistically definable, long-term adverse health effects on an exposed population.
0.25 to 1	Somatic injury unlikely. Delayed effects possible but improbable, with statistically definable long-term adverse effects on some of those exposed.
0 to 0.25	No statistically definable short-term adverse health effects, though minor blood and cell changes can be temporarily detected. Delayed effects are unlikely

* Cellular responses and changes can be detected at all doses, as with any toxicity insult.
** At very high doses, above occupational dose limits, the gray is usually quoted rather than the sievert.

We also know that high acute radiation doses that do not overwhelm the ability of the DNA to repair itself, do not usually kill anyone, but may make the individual ill for a few weeks (the early effect). After recovery, those who were exposed may face an increased risk of longer-term injury - cancer - from the initial damage to DNA and the cell. This late radiation effect, which is assumed to apply to all radiation exposures, may appear from 10 to 30 or more years into the future, or not at all. We assume that these late effects also apply to any survivable radiation dose, and in proportion to dose; the higher the dose the greater the likelihood of a future adverse effect, and vice versa. However, few cancers in any society are demonstrably radiation-related. Most are related to genetic characteristics, lifestyle, diet and other factors.

Survivable doses at this level also may be associated with cellular changes which may be passed on to future generations (hereditary effects). The major study population which might be expected to show such effects, that of the Japanese who were exposed during the bombings of Hiroshima and Nagasaki, shows that none of the thousands of children born in the decades following the bombings have shown any increase in the natural mutation rate. [1].

With decreasing acute doses, fewer of those exposed are likely to die in the short term. At about 3.5 sieverts of acute dose, close to 50% of those exposed are expected to survive without medical treatment.

About 1 sievert of acute dose is an approximate boundary below which short-term fatalities are unlikely to be seen, except in those few individuals in society who show unusual genetic sensitivity to many agents including radiation; for example those with Down's syndrome, Ataxia telangiectasia, or with Xeroderma pigmentosum, among others. Undoubtedly, some of the assessed average risk of radiation exposures on populations includes such genetically vulnerable individuals and thus probably overstates the risks for the more numerous and less susceptible individuals, while understating the risks for those very few who are genetically sensitive. Recent research indicates a similar risk effect in smokers, where there is a range in sensitivity for the development of lung cancer from smoking. Some individuals have a genetic susceptibility to develop lung cancer (in the deficiency of a specific repair enzyme) that is about 10 times that of others.

Low Dose Effects. Lower acute doses up to about 100 to 200 mSv, and chronic doses no matter how large, spread out over a year, are not usually associated with any definable short-term injury to any individual. Evaluation of potential injuries from such exposures requires the statistical analysis of very large groups of exposed and unexposed (control) individuals. The lower the individual dose in such an exposed population, the larger the uncertainty in the risk estimate. Such population statistics are also poor indicators of individual risk, yet they are used to estimate individual risk.

What we do not know is what adverse effect low doses, whether acute or chronic, of radiation - those below 200 mGy - may have, and those in which the dose rate is less than 100 mGy per hour [9] - as we cannot statistically define any adverse health effect. However, we assume that there is still a risk associated with the exposure. Chronic annual natural doses at this level of 200 mGy, are to be found in many areas of the world; in Iran and Brazil, as well as in many regions of most countries, but adverse health effects due to elevated natural background radiation are not definable in these populations with the required statistical confidence, even though many millions of individuals have been exposed for their lifetimes and over many generations.

Many health studies have been undertaken where radiation doses are little different from typical natural background levels (about 3 mSv on average in a year) or at typical occupational levels of dose (an additional 2 mSv on average in a year). Relatively robust epidemiological studies [17], [18], [19], [20], which are usually provoked by initial and premature allegations of adverse health effects on workers, and which are often based upon usually unscientific allegations, show that they are not definable and may not occur.

At doses below even this, such as around many nuclear facilities where the largest individual chronic dose from the facility may be a few microsieverts in a year, health effects from this additional exposure from a dose that is thousands of times less than the natural background, are not reasonably to be expected and cannot be seen.

The problem with attempting to derive protective guidelines and limits for moderate radiation doses and from low dose and low dose rate exposures where health effects cannot readily be defined, was unsatisfactorily resolved by extrapolating from known high dose effects and by assuming that the relationship was linear (or linear quadratic) even down to zero dose. This tacitly assumes that all doses of radiation carry some degree of risk.

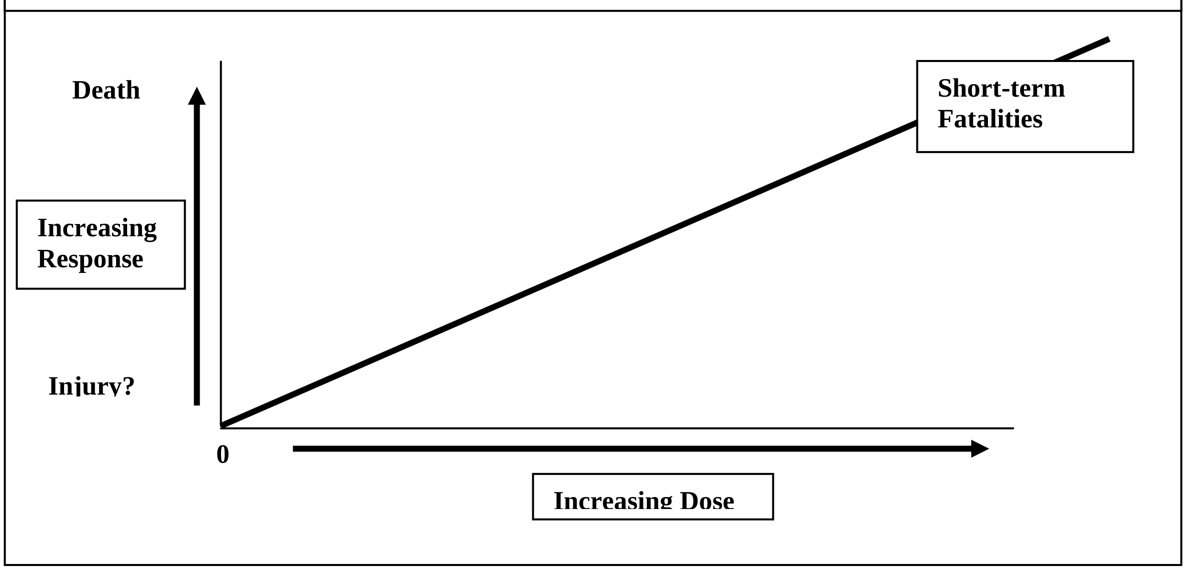
The Linear No-Threshold Hypothesis and Assumption of risk

A definition of the general-population risks associated with high radiation exposures was derived from actual studies of the tens of thousands of Hiroshima, Nagasaki bomb survivors. This group of individuals, across all age ranges, has been followed since about 1950, and is one of the best and largest populations from which to define radiation risks from high acute exposures [1].

The difficulty has always been to adequately define the risks from much lower doses and lower dose rates of radiation - those typically received in occupational exposures and others - in order to place some scientifically-derived protective limits upon lower radiation exposures that would be likely to minimize the development of long-term health effects.

A simplifying assumption concerning how we might assess the risks of radiation to other populations and groups at any lower dose or dose rates, where health effects and responses are not immediately obvious, was to assume that there is a linear relationship between those high acute doses that are known to be injurious or fatal, and extrapolating the risk relationship derived from the Japanese data, down even to zero dose. This is known as the Linear, No Threshold hypothesis (LNT) as shown in Figure 9.

Figure 9. Simple Representation of the Assumed Linear Relationship Between Dose and Response.



Some change in the slope is assumed at lower doses and dose rates to allow for the possibility of cellular repair from lower doses. This is expressed in a reduced risk figure for low doses and low dose rates of 5%/Sv, rather than the 10%/Sv at much higher acute doses and high dose rates.

It is recognized that assumptions of harm from low dose and low dose rate radiation doses (in the range of natural background doses, and near the bottom left of the graph), which arise from application of this hypothesis, may lead to an over-estimate of harm, by at least a factor of two [9], with other radiation professional groups suggesting that it may overestimate the risk from low doses by as much as ten [14]. This factor is known as the Dose and Dose Rate Effectiveness Factor (DDREF) and it is recognized as being 'somewhat arbitrary and may be conservative' [9]. The risk from low dose and low dose rate exposures may even be zero. However, as pointed out in ACRP-18 [21], 'there does not seem to be a good reason to abandon its use (the LNT assumption of risk)… as the assumption of linearity may be quite appropriate for practical purposes in radiological protection…'.

In complete contrast, there are more than one thousand referenced publications [16], which suggest that there is a radiation damage threshold, and that low doses and low dose rates may not only have zero effect, but may have beneficial, bio-positive effects on many animals, with some supportive data from some human studies. This bio-positive effect is known as Hormesis, and is an effect that is well documented, showing the stimulatory and beneficial effects of low dose exposure from many otherwise toxic chemicals (toxic only at high doses), as well as radiation.

These interesting issues concerning the diverging and conflicting views of the effects of low dose and low dose rate radiation by radiation professionals (The American Nuclear Society [22], The Health Physics Society, BELLE newsletter (Biological Effects of Low Level Exposures), Luckey [16], and many others), are ignored for the moment in all applications of radiation protection and in decisions concerning the setting of dose limits. To take them into account would require a major revision of risk estimates at low doses and low dose rates; the possible establishment of a threshold value ('Below Regulatory Concern') for assuming harm from radiation exposures; and a complete revision of existing radiation protection regulations and practices, which universally – and with great social expense - regard all radiation exposures, no matter how low, as potentially harmful. Many radiation protection professionals, decry this waste of resources to address what is in effect a minor problem from radiation exposures less than about 100 mSv/a. Attempts to establish a dose which would be regarded as 'below regulatory concern' have met with no success, possibly because of political sensitivity.

Radiation Protection and Dose Limits

There were attempts to define radiation protection practices and even some limits to dose, even before the formation of the various national radiation protection societies and groups which were established in the 1920s.

These groups had few definitive data on which to base their deliberations, and only in the last few decades has there been sufficient definition of high doses and related injuries to be able to establish reasonably supported dose limits for occupational exposures. Following this, there were recommendations made concerning much lower general public dose limits from industrial radiation exposures. The risks are no different, but as the public is not monitored, as are radiation workers, and receives no monetary reward for tolerating any exposure - as workers generally are assumed to - its limits were set lower.

The intent was that by implementing a dose limit at some level well below that associated with somatic radiation injuries, that not only would early radiation injuries be entirely avoided by controlling doses, but that the risks of long-term effects would be minimized to some acceptable degree of risk. Unfortunately, by assuming that there is no threshold for injury, despite the absence of adverse health data at low doses and thus absence of scientific justification for increasing protection, the temptation has been to push dose limits ever lower.

These whole body dose limits, as recommended by ICRP-60 [9] at this time, are 100 mSv in 5 years for occupational exposures (or an average of 20 mSv in each year), and 1 mSv a year for public exposures from industry.

The occupational dose limit was further limited by stipulating that no worker should exceed 50 mSv of dose in one year of the five. Previously, ICRP 26 [3] had recommended a whole body dose limit of 50 mSv each year for workers and 5 mSv each year for the general public.

In practice, a typical radiation dose to those who work with radiation, averages about 2 mSv per year, with a few individuals that may approach their dose limit. Such limits are rarely exceeded other than under exceptional and usually approved circumstances, as the regulatory penalties for accidental over-exposure are severe. Also, typical radiation doses to the public from nuclear power facilities (including uranium mines and processing facilities) - the only industry that measures and assesses its radiation effects upon the local population and the environment - are generally no more than about 2 microsieverts per year to local residents, with a world average individual dose from this source estimated to be less than 0.2 microsieverts per year [1].

Despite the establishment of dose limits and adherence to them, there is a general paradigm which governs all radiation work, and that is the assumption that all radiation is potentially harmful and should be avoided if possible, and minimized if not. This precautionary assumption known as ALARA (keeping doses As Low As Reasonably Achievable) is inherent in the LNT hypothesis.

Although there are advantages in using the LNT assumption (it is assumed to apply to all exposures, acute or chronic, and across all dose rates, and is thus simple to use in all exposure circumstances), there are also some limitations and disadvantages which are the subject of increasing criticism. These are targeted at the statistical weakness, or complete absence of definable adverse health effects below about 200 mSv of dose; the likelihood of the existence of a threshold for injury; and with how the linear risk data may be misapplied in certain circumstances (for example, in the calculation of assumed risks from any collective dose, no matter how small the dose or dose rate). All of these raise questions about the validity of using the LNT hypothesis for small and chronic doses.

Weaknesses of the LNT Hypothesis.

There are several implicit assumptions in the LNT hypothesis which give rise to severe criticisms from some radiation professionals (Muckerheide [23], Pollycove [24], Taylor [25], Jaworowski [26]):

- Assuming (wrongly) a linear dose response across all doses and dose rates.
- Assuming (wrongly) that there is no threshold for injury.
- Assuming (wrongly) that one can calculate detriment from low doses at and below background levels of radiation, and where detriment cannot be defined.
- Assuming (wrongly) that there is some validity to being able to assess radiation risks from population collective doses and across many generations.
- Assuming (wrongly) that effects of chronic and acute doses are the same (with minor possible DDREF differences, but with a risk assumption that still goes to zero).
- Assuming (wrongly) that there are no DNA repair mechanisms.
- Ignoring cellular DNA repair from dose fractionation relative to a single dose.
- Ignoring protective 'adaptive response' effects.
- Ignoring the possibility of Hormesis - a bio-positive effect from radiation doses significantly above normal background dose.

Brief examination of these points, follows:

Linear dose response across all doses and dose rates.

The risk figure calculated for the bomb survivors was derived from instantaneous high acute exposures. After reducing the risk with a DDREF of 2 to 5%/Sv, it is assumed to be valid to assess the risk from chronic doses of any magnitude received over a year and even over a lifetime. It does not allow for cellular repair mechanisms, nor for the possibility that there is a threshold for damage.

No threshold

It is assumed that there is no threshold for stochastic effects, though there is for deterministic effects. The assumption is that all doses of radiation, no matter how small or how they are delivered, are likely to induce some degree of harm, including the extremely remote possibility that even a single DNA-damaging event could lead on to a fatal cancer.

Calculation of detriment from low doses at and below background levels

The use of the 5%/Sv risk figure is assumed to allow a probable radiation response to be calculated from doses delivered at low dose rates. This ignores cellular repair mechanisms, and the possibility of a threshold at lower doses.

It is generally used to calculate the risks to the general population from chronic radon exposures by various regulatory bodies (e.g. EPA), which predict that elevated radon exposures in U.S. society may be responsible for as many as 20,000 cancer deaths per year (EPA). BEIR IV [27], predicts 14,000.

Validity of being able to assess risks from population collective doses.

The assumption of linearity of risk, and the risk figure of 5%/Sv, are misused in some cases to try to assess potential population detriment from cumulative very small exposures to individuals in that population (some collective doses are shown in Table 19).

For example, application of the LNT suggests that the risk from a chronic dose of 1 mSv to each of 1 million people (1,000 person sieverts of population dose), would carry the same risk as 1 Sv of chronic dose to each of a group of 1,000 people (1,000 person-sieverts of population dose), and we might expect to see 50 cancer deaths related to the radiation exposure in each case. UNSCEAR 2000 [1] has generally cautioned against drawing such unjustified conclusions from collective doses and its members stress caution in making assumptions about the LNT hypothesis.

This assumption of the validity of the LNT, is similar to the invalid and obviously flawed argument, that if 1 person dies after taking 200 aspirin (a fatal dose), that we would expect one death in a population of 200 individuals where each of them takes one aspirin (200 person aspirin). Similar foolish analogies can be made concerning alcohol use or sleeping pills. It is no more true for them, than it is for radiation.

Attempts have also been made to extrapolate collective doses and assumed population risks out to hundreds to thousands of years. An example of this comes from nuclear waste disposal, where the U.S. EPA calculated that there might be 10 premature deaths from cancer in the U.S. population, over the first 10,000 years after closure of a repository for each 1,000 tonnes of waste [25]. Such a socially and scientifically **unjustified** calculation presumes that such risks can be validly calculated from minuscule doses, and that society and medical knowledge and capability will remain static from this moment forward. In 2009, it was reported that a new drug had been developed which could protect from radiation exposure effects.

The assumption that harm can be calculated in this way for chronic doses that are an extremely small fraction of natural background radiation is unjustified on any epidemiological basis, and is an extreme outcome of the misapplication of the LNT hypothesis.

Differences between chronic and acute doses.

We know that an acute dose of 10 sieverts is usually fatal. In many areas of the world, natural background chronic radiation doses of up to about 1 Sv per year are known (parts of Iran, Brazil, southern France etc.). These may also include elevated radon exposures in many home basements (Reading Prong area, Pennsylvania) and in some mine environments (a tin mine in Cornwall formerly used for training prospectors, where the dose from radon for full time occupancy was suggested to be 100 sieverts per year).

Although the annual doses are generally not so high as above, the cancer death rates in many elevated radiation (radon) areas are not significantly higher than those of lower chronic radiation areas, but may actually be lower, [28], [29], [30], [31].

DNA damage and repair mechanisms. [32], [33], [34], [35].

Estimates of natural DNA breaks, suggest that the DNA in each of the 100 trillion cells of the body undergoes about 240,000 such breaks each day (10,000 per hour) because of natural processes other than radiation.

Most of these breaks are successfully repaired within seconds or minutes, by the action of more than 130 DNA repair genes [35]. Incorrect repair, which is common with such a large number of breaks, either has no effect on the cell; results in the cell undergoing programmed cell death (apoptosis, a protective response), or may lead on to some other biological effect, including the remote possibility of cancer.

The probability of a single break in DNA leading on to a fatal cancer in the average human appears to be about 1 chance in 1E24 or one chance in a trillion trillion (derived from: 240,000 breaks per cell per day, 1E14 cells per human, 70 years of human life) assuming that all cancers are caused by a single damaging event, and that every human being eventually dies of cancer, when only about 20% of us do in a healthy ageing society. Strangely, a high cancer death rate in any advanced society is indicative of a healthy society! (contact the author for an explanation).

In comparison, a moderate radiation dose of 10 millisieverts to the whole body, produces about 20 such similar (single-strand) breaks in each cell, (double-strand breaks begin to occur over 100 mGy of acute dose). If this dose is spread out over a year (chronic) and is received every year, then the lifetime risk of this 10 mSv dose of radiation causing a cancer (making the same assumptions as above) is less than 0.000014% of the chance of normal cell processes causing a cancer. However the calculated lifetime risk from this dose each year, using the 5%/Sv LNT figure, which does not allow for cellular repair no matter how low the dose, is 1.2 to 1.8% [9], (about 120,000 times higher) depending upon the risk projection model.

Although a chronic dose of 10 mSv in a year, has a relatively low impact upon DNA, an acute dose of **10 sieverts** in an hour to the whole body (generally fatal) would produce 20,000 such breaks in the DNA of each cell, and is usually fatal in the very short-term because it begins to overwhelm the ability of the DNA to make repairs in any cell.

Dose fractionation effects relative to a single dose

A large acute dose is known to be fatal, if large enough. If the same dose or even a much larger dose is delivered in fractions of the dose at regular intervals over several days or weeks, the dose is generally not fatal, because of cellular repair. This is usually the technique used in some localized medical therapy exposures, allowing the healthy tissue surrounding a cancer to recover (tissue sparing) before the next high dose. Unfortunately, the surgeon must also allow for the fact that the cancer may also benefit from dose fractionation in the same way and may even show signs of adaptive response as described below.

Adaptive response (AECL research)

UNSCEAR 94, [36] noted the substantial evidence of adaptive response in selected cellular systems, following acute exposure to conditioning doses of low-LET radiation. Numerous experiments on various animals have shown that a moderately high dose of radiation delivered prior to a much larger dose, causes the cell defensive mechanisms to be stimulated, and to respond more effectively to counteract the second dose. The cells have been stimulated by the first dose, rather than damaged by it. This effect appears to fade after about 24 hours though may still be evident up to about 30 days.

Hormesis [16].

Hormesis is the feature of a low dose of a 'toxic' agent producing a beneficial, stimulatory, effect. Doses that are too high, or too low of anything, produce injury. This effect is seen in the body's response to essential minerals and nutrients such as vitamins and trace metals, when too little of either are available in the diet. Too much and too little are both harmful. Radiation shows similar effects. Animals that are deprived of radiation die prematurely, just as do those that receive too much. At an optimal radiation dose, usually well above natural background doses, the test animals generally outlive those receiving lower or very much higher doses. Hormesis does not support the view that all radiation is

> invariably harmful, but suggests that radiation may be a desirable part of our existence up to some level that is above the present average natural background level of radiation.
>
> This feature is well documented in over 1,000 references assembled by Luckey [16], and is broadly described on the BELLE web-site (belleonline.com).

Some partial clarification of these difficult issues with the LNT - both supportive in the case of many high acute exposures, and not supportive for low dose and chronic exposures - comes from empirical health studies of hundreds of exposed populations followed over several decades.

Until there is a scientifically acceptable alternative to the LNT hypothesis then, in the judgment of some radiation protection professionals, we will continue to probably over-estimate the risks and effects of low dose and low dose rate exposures, and set dose limits that are likely to be too low and therefore highly costly to society as a whole.

Health Studies.

Over the last few years, many radiation health studies have reached some degree of scientific maturity with the accumulation of decades of health and mortality data.

By far the most important ongoing study is that of the survivors of the 1945 bombings of Japan, followed by those which involve very high acute doses, whether in medical treatments or accidents.

Occupational doses, which are mostly chronic and relatively low doses, and which were initially linked to concerns of adverse health effects (e.g. the naval shipyard worker allegations in the U.S. by Najarian and Colton [37]) have now proved (in rejection of the initial allegations) to be of value in demonstrating that workers do not appear to be at unusual risk from radiation at work but may be benefited by them. The general impression for many years was that such occupational doses were a significant health risk. An examination of many of these earlier claims of adverse health effects was compiled for the Argonne National Laboratory by several researchers [38]

Some of the worker data (a few studies are shown in Table 21) now available, tend to show that such workers are in much better health than their unexposed co-workers. Other worker studies (appendix B), are inconclusive.

At elevated natural background doses in the environment, there has also been a general expectation that adverse health effects might be visible - they can be calculated from the LNT relationship - but this has also proved not to be the case.

A few of the more important, and statistically robust studies are listed below, though there have been many hundreds of such studies conducted. Many are described in various compilations [39] and registries such as the U.K. Register on the Biological Effects of

Ionising Radiation, which documents more than about 170 such research programs in the UK alone.

Brief summaries of a few of the various studies are in Appendix B.

High Dose Studies:

1. Hiroshima - Nagasaki (bomb survivors)
2. Tuberculosis studies (including the Canadian Fluoroscopy study) (medical)
3. Ankylosing spondylitis (medical)
4. Radium dial painters (occupational)
5. Thorotrast injections (medical)
6. Cervical cancer treatments (medical)
7. Tinea capitis treatments (medical)
8. Medical Occupational Radiation - radiologists (1897 to 1997) (occupational)
9. Reactor accidents.

Low Dose Studies:

10. U.S. Nuclear Shipyard Worker Study (occupational)
11. Uranium and Iron ore miners (occupational)
12. Natural Background studies (environmental)
13. Effects of Weapons test fallout (environmental)
14. Plutonium workers (occupational)
15. Animal studies at elevated and reduced doses (research).
16. Sellafield childhood leukemia and other cancer clusters (occupational).
17. AECB (CNSC) study of the incidence of public leukaemia around Canadian nuclear facilities (environmental)
18. Mortality study of workers conducted at AECL (Canada) (occupational).
19. Hanford public exposures (environmental).
20. Nuclear Workers Studies - U.S., Canada, U.K. (occupational)

Selected Environmental and Occupational Radiation Studies

A selection of a representative few of the many studies is briefly presented below.

Environmental Radiation (low dose) Studies.

These studies are of populations that live in slightly elevated radiation background regions of the world. When these groups are compared with those matched populations in the same region who are exposed to lower radiation doses, the expectation (from the application of the LNT hypothesis) is that the group living in the higher radiation area should show indications of adverse radiation health effects relative to the comparison group. The reverse is usually shown, with the more highly exposed populations showing better health than expected, and often better than that of the lower exposed populations. Most of these studies are under constant review and criticism, but nonetheless point either to an opposing conclusion regarding the health effects of low-level radiation, or are inconclusive.

The Cohen radon study [29] which covered about 90% of the U.S. population, empirically showed that States with higher radon levels also show the lowest lung cancer mortality. This study is still undergoing critical review after 10 years.

In China, a comparison of the health of two populations of about 70,000 people was undertaken [30]. The population that lived in the area with the higher dose from background radiation showed half of the cancer rate of the lower background region. Further studies were less conclusive.

In Japan, cancer mortality in a spa area (Misasa), with a relatively high radon background, showed [31] that relative risks were lower overall for the inhabitants of the Misasa area, than the control, lower background, area.

What is perhaps significant is that there are no scientifically based studies of this kind, which show, with any statistical robustness, that moderately exposed populations show significant **adverse** health effects because of their slightly higher radiation exposure compared with a lower exposure group. If there was truly no effect, then one would expect that about 50% of the studies would show adverse effects and about 50% would show bio-positive effects around an overall average for all exposed groups. Adverse effects are generally not evident.

Occupational Radiation (Low Dose) Studies.

Data on four of the most recent occupational studies, which have followed large groups of moderately exposed workers for several decades, are shown in Table 21.

Table 21. Total Cancer Mortality in Nuclear Workers

Facility	**Shipyard Workers (U.S.)***	**Weapons Program (U.S.) Hanford, Oak Ridge, Rocky Flats.**	**Weapons Program (U.K.)**	**Energy (Ontario Hydro, Canada)**
Report Author	**Matanoski [17]**	**Gilbert [18]**	**Kendall [19]**	**Abbatt [20]**
Exposed Workers	40 774	15 318	36 272	4000
Control Workers	111 757	20 619	58 945	21,000
Years Observed	16	33	30	20
Average annual occupational dose (mSv)	3.4	4.3	5.7	7.0
Cancer Mortality in Workers	968	318	96	8
Cancer Mortality in Matched Controls	3086	718	584	463
Mortality ratio**	0.84	0.60	0.27	0.09
p value	<0.001	<0.001	<0.001	<0.001

* U.S. Department of Energy, unpublished study.
** Ratio of the mortality rate in workers, over the mortality rate in the matched controls.

In each case, the more highly exposed workers are all in significantly better health, as shown in the mortality ratio, than the closely matched controls from the same worker population with whom they were compared. Comparing workers with workers, as in these examples, avoids the difficulty of the 'Healthy Worker Effect' in which studies of almost any group of employed individuals shows that they are typically in much better health than the population at large.

These data are typical of those from many comparable worker studies. Of all of the many groups studied that are exposed to relatively low chronic doses of radiation, none (with the possible exception of the studies upon certain miners) show significant adverse health effects with any statistical power. This contrasts completely with the earlier health allegations on some of these same workers before defined epidemiological studies commenced [37].

One of the more obvious limitations with occupational studies lies in the data used. For example, national dose registry archives usually document only occupational exposures. They do not record natural radiation contributions to dose, nor those from routine or unusual medical exposures to those who are also exposed occupationally. Adverse health effects which are deduced from epidemiological examination of the occupational registry data, are assumed to arise only from occupational radiation exposures as these are the only data recorded. All other sources and doses of radiation which, cumulatively, may be many times larger, are ignored. This inevitably correlates any presumed radiation injury with lower radiation doses than any individual actually received during his or her lifetime, and thus exaggerates the associated risk. This inevitably suggests that radiation is more dangerous than it really is, and further contributes to the setting of possibly unrealistically low dose limits, and certainly contributes to the probably erroneous assumptions concerning low dose and low dose rate radiation risks and effects.

Summary Points Concerning the Health Effects of Radiation

- High acute doses of radiation, above about 200 mSv are known to be increasingly injurious in proportion to the size of the dose. The risk figure for the general public, derived from the high exposures of the Hiroshima-Nagasaki survivors is 5%/Sv, and is assumed to apply linearly down to zero dose for all chronic radiation exposures.
- Lower acute doses of radiation below about 200 mSv are not readily defined to be injurious, though there is an assumption that the risk can be calculated.
- Use of the LNT hypothesis for chronic low dose and low dose rate exposures may overestimate the risk of injury by a factor from 2 to 10 [14].
- The actual Risk from such chronic low doses may be zero [9].
- Organisms which are maintained in artificially-reduced radiation background environments in the laboratory, usually die prematurely compared with matched controls which are not shielded from such radiation.
- The first forty years of medical uses of radiation from 1897, scientifically demonstrated the numerous beneficial effects to human health of moderate doses of radiation in countering joint pain, inflammation, and many other health problems, by stimulating the immune system. Acknowledgement and publicity concerning these well-documented hormetic and beneficial effects, have been largely suppressed in the last 40 years, in the current regulatory climate and because of widely publicized and influential, but flawed research (as described in BELLE).
- Mounting scientific evidence [16] shows that low doses of radiation (still well above natural background) are more beneficial than harmful to the general population (Hormesis), though this is not taken into account in any radiation protection protocol.
- There are many reliable occupational, medical, and population health studies which show that populations exposed to chronic low doses of radiation - still above a 'normal' background - are generally in better health, and certainly not worse, than those lesser exposed members of the same populations [17], [29], [30], [31].
- Early, widely publicized allegations of adverse health effects from occupational [37], [38], and other low radiation dose circumstances close to natural background levels and within the range of occupational dose limits, have been generally shown to be statistically in-valid.

4. PUTTING DEFINED RADIATION RISKS IN THE CONTEXT OF A RANKING OF SOCIAL RISKS

Individual public doses actually received from all nuclear power operations including High Level Radioactive Wastes and from their current management are very small. They are too small to be measurable, but are estimated to be much less than 0.2 microsievert each year, on average, to each individual in the population of the world [1] in a natural background that is more than 10,000 times larger.

Radiation doses to the public from the operation of nuclear power facilities, from emissions, are defined and controlled. Typically they are less than 1 microsievert per year [13] but may reach 20 microsieverts to some local inhabitants around some reactors. They may reach about 100 microsieverts around certain phosphate processing operations [1]. As radiation shielding of high level radioactive waste facilities ensures that dose rates even adjacent to a storage facility are at or close to background radiation levels [12], public doses from managed waste facilities are consistently much less than 1 microsievert per year.

In the event that HLRW are to be moved to a permanent disposal facility, an upper estimate of dose to those who might be close to any of the transportation routes is expected to be no more than about 100 microsieverts per year [10]. In the case of an accident in transferring spent fuel to the facility, a local dose of 250 microsieverts might be expected to a member of the local general public, and a dose of about 20 millisieverts to workers [10].

Maximum public ingestion doses (in water and food) from a deep geological disposal facility after closure, and at the time that significant failure and leakage might occur [10], have been estimated to be no more than about 1E-08 mSv (one 10 billionth part of a millisievert) per year. This extremely small dose is equivalent to about 1 second of anyone's exposure to natural background radiation.

By placing these defined and estimated radiation doses and their potential risks into the perspective of every-day and significant social risks which face most of us each day (ranking risks), society can ensure that social resources are not disproportionately directed towards addressing small risks, while larger and more socially significant risks are ignored.

Ranking Risks.

Society needs to consider how it addresses risks and be able to objectively and scientifically rank them. Societal spending should generally be targeted towards the top of the ranking; be justified in terms of cost-benefit determinations; and be in proportion to the defined risk. Too frequently, society misallocates resources based upon publicity rather than defined risk (as with the calculated risk assumptions concerning radon), and usually overspends on minor risks, while neglecting or under-funding those risks that would return much greater social benefit [40], [41].

Some of the more important of the fairly well defined risks in our society are ranked in Table 22, from the work of Bernard Cohen [42]. It shows the ranking of some risks in the U.S. in terms of Loss of Life Expectancy across the population. Canada is comparable.

Table 22. Ranking of Some Lifetime Risks In the U.S. to Show Relative Loss of Life Expectancy (LLE)+
These are population statistics and are thus not directly applicable to identifiable individuals.

Individual Activity or risk	Population Average LLE (days)	Individual Activity or risk	Population Average LLE (days)
Living in poverty	3500	Married to smoker	50
Being male (vs. female)	2800	Speed limit 65mph vs. 55 mph.	40*
Cigarettes (male)	2300	Falls	39*
Heart disease	2100*	Fire, burns	27*
Being unmarried	2000	Coffee (2.5 cups/d)	26
Socio-economic status	1500	Air pollution from coal burning	12*
Working as a coal miner	1100	Birth control pills	5
Cancer	980*	**All electricity - nuclear (UCS)**	**1.5**
30 lb. overweight	900	Peanut butter (1 Tbsp/d)	1.1
Grade school dropout	800	Hurricanes, tornadoes	1*
Sub-optimal medical care	550*	Airline crashes	1*
Stroke	520*	Dam failures	1*
15 lb. overweight	450	**All electricity - nuclear (NRC)**	**0.04***
All accidents	400*		
Mining construction	320	**1 mSv of dose each year**	**21**
Alcohol	230*	**10 microsieverts each year**	**0.2**
Motor vehicle accidents	180		
Pneumonia, influenza	130*	**1 microsievert each year**	**0.02**
Drug abuse	100*	**(current NP emissions)**	
Accidents at home	95*	**Nuclear waste disposal**	**0.0000002***
Homicide	90*	**(chronic dose - AECL study)**	
Air pollution	80*		

* Averaged over total US population. The remaining risk assessments are for those who are uniquely exposed to the particular risk, either through choice, or being caught up in that particular lifestyle or circumstance. Many individuals are captured by several risk circumstances. For example, being poor, ill-educated, smoking, dangerous occupation, overweight, and others, can all apply to single individuals, though one should not try to assess individual risks from such population statistics. We are all individually different in our responses.

\+ Data are mostly from the many published works of Bernard Cohen, professor of physics at Pittsburgh U.

Most data have been derived from actual, observed mortality data, while others are defined by epidemiological comparisons of groups and populations. Some affect an entire population (air pollution), others affect only those who fall into the group (miner, being overweight).

They are population averages derived from large populations, and cannot be applied to individuals. They suggest that those who live in poverty (for example), are likely to die about 3500 days sooner, on average, than those who do not live in poverty, though some who live in poverty die much more than 9 years prematurely, and some live as long as the rest of us.

Two of the bolded figures in the table 'All electricity nuclear' are calculated estimates of the Union of Concerned Scientists (UCS) (at present this is a group with an anti-nuclear agenda), and of the Nuclear Regulatory Commission (NRC) (a nuclear regulator), which assume the population LLE, if all electricity in the US were to be generated by nuclear power. They show the relative risks that these two organizations calculate for such use of nuclear power, as no **observed or defined** epidemiological data exist to cover the low doses so far below natural background exposures.

Other bolded figures which have been added to the table at the bottom right, show the very approximate loss of life expectancy calculated - using the LNT assumptions and chronic risk figure of 5%/Sv, for various radiation exposures received annually, over an assumed lifetime of 70 years. They assume that a premature loss of adult life is equivalent to 6,000 days (almost 16 years) according to industrial convention. 'The average loss of life expectancy attributable to a radiation-induced fatal cancer in workers is calculated to be about 13 years (LLE of the individual affected) on the basis of the new relative risk projection model, as compared to about 20 years for an additive risk projection model.' (ACRP-13) [43].

This calculation suggests that a dose of 1 mSv received each year over a lifetime might cause a loss of life expectancy (LLE) of 21 days, with a correspondingly lower LLE at lower doses. The method and assumptions of the calculation, as well as using the LNT risk assumptions derived from high acute doses, as though they applied equally to chronic low doses, are likely to dramatically overestimate the effect.

Nonetheless, the similarly calculated and probably over-estimated risks from nuclear power operation (from measured **chronic** radiation doses) and from high level nuclear waste disposal [10] at even lower **chronic** doses, show that even the pessimistically assumed risks from these two activities are still towards the bottom of a social ranking of many risks. Their actual health risks are possibly much lower even than indicated, and are unlikely ever to be measurable, if they occur at all, yet we publicize, address, regulate, and fund these potential and minuscule risks as though they were near the top of the ranking of significant social risks, rather than close to the bottom of such a ranking.

5. CONCLUSIONS

Radiation surrounds us and we are unavoidably exposed to it at an average level of about 3 mSv of chronic dose each year, with some natural chronic exposures up to almost 1 sievert and even higher in some natural circumstances. Radiation and radioactive materials, and their associated radiation doses are common throughout society, often at very high levels in nature (chronic doses) and when used in medical procedures (acute doses). In almost every social use they are associated with significant social benefit and are not associated with any obvious or definable injury.

Radiation at high acute doses (accidents and some medical uses) is known to carry some risk of harm, as individual injuries may be obvious. Radiation at low and chronic doses is not demonstrably harmful, with the possible exception of its effects on uranium miners from radon exposures, though the confounding factors in this occupational case are not fully defined. For such low dose and low dose rate exposures, population statistics are used to attempt to mathematically define individual risk, as individual injuries are not readily distinguishable in the background of expected health outcomes.

The LNT assumptions are probably valid for acute doses above about 200 mSv, but do not appear to be valid for lower acute doses or chronic doses. Radiation at moderate to high doses up to about 200 mSv, is not statistically associated with ill health, though there is a general protective assumption that it is, and that it should generally be avoided or minimized where possible.

Radiation at low doses - acute or chronic - even well above the average natural radiation background, is not associated with ill health, but is more associated with either no demonstrable unusual health effect at all, or is noted in some structured epidemiological studies of large exposed populations, to be possibly associated with health improvement relative to other populations exposed to lower radiation levels.

Average radiation doses to the world's population from emissions from normal nuclear power operations are estimated [1] to be no more than about 0.2 microsievert per year, and much less than this from nuclear waste. Doses of this magnitude are not credibly associated with any adverse health effects to anyone.

Experience over the last few decades has shown that accidents involving nuclear materials, including nuclear waste, are rare, and usually do not result in any dispersal of radiation. They are mostly of immediate and short-term local effect only. Any exposure would be monitored and controlled, and would be mostly confined to those who would work to recover the material. The public would not be expected to encounter any significant dose from this [10].

Health risks from exposure to low doses of radiation from any source of exposure, including radioactive wastes, are among the least of all risks in any society. We consistently over-estimate the risks of low dose and low dose rate radiation, at great social cost.

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7. GLOSSARY

Acute dose	Any (usually high) dose of radiation received in less than one day
Apoptosis	Programmed cell death (triggered by the cell itself) in response to damage that the cell cannot repair
AECB	Atomic Energy Control Board (now the CNSC)
AECL	Atomic Energy of Canada Limited
ARS	Acute Radiation Syndrome(s). Effects resulting from large acute, and often fatal, radiation exposures.
BEIR	Advisory Committee on the Biological Effects of Ionizing Radiation
BELLE	Biological Effects of Low Level Exposures. A web site (belleonline.com) devoted to Hormetic effects from low level radiation and chemical exposures.
Bq	Becquerel. A unit indicating one atomic decay disintegration each second.
CANDU	CANadian Deuterium (natural) Uranium
Chronic dose	Any (usually low) dose received over an extended time of (usually) weeks to years.
CNS	Central Nervous System syndrome following a massive acute radiation exposure
CNSC	Canadian Nuclear Safety Commission (formerly the AECB)
Curie	Named after Pierre Curie to describe the assumed radioactivity of a quantity of radium, or radon gas in equilibrium with it, and subsequently fixed as 3.7E10 becquerels (Bq).
DDREF	Dose and Dose Rate Effectiveness Factor. A factor used to derive risk estimates of low doses of low-LET radiation at low dose rates, from risk estimates calculated from data associated with large doses at high dose rates (ACRP-13)[43]
DNA	Deoxy-riboNucleic Acid
DREF	A factor used to derive risk estimates of exposure to low-LET radiation at low dose rates, from risk estimates calculated from data associates with exposures at high dose rates (ACRP-13)[43]
EPA	U.S. Environmental Protection Agency
FDA	U.S. Food and Drug Administration
GI	Gastro-Intestinal syndrome following a massive acute radiation exposure
Gy	gray, SI unit of absorbed dose, influenced by incident radiation energy, radiation type, and density of the absorbing medium.
HLW	High Level (Radioactive) Waste
Hormesis	Low dose stimulation of bio-positive effects
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ILW	Intermediate Level Waste
LET	Linear Energy Transfer
LILW	Low/Intermediate Level Waste

LLW	Low Level Waste
LNT	Linear, No Threshold hypothesis concerning radiation and other 'toxic' agents
µSv	microsievert, one millionth of a sievert
mGy	milligray, one thousandth of a gray
MMR	measles, mumps, rubella vaccine
mSv	millisievert, one thousandth of a sievert
NORMS	Naturally Occurring Radioactive Materials
NRC	U.S. Nuclear Regulatory Commission
NRPB U.K.	National Radiological Protection Bureau - U.K.
Outage	A period of planned maintenance work during reactor shutdown
PWR	Pressurized Water Reactor (U.S. design)
Q	Quality Factor (radiation weighting factor), from 1 to 20, to derive 'dose equivalent' radiation effect to tissue from different LET radiations
RERF	Radiation Effects Research Foundation. The organization studying the ongoing health effects of the Japanese bombing survivors and their offspring.
roentgen (R)	Quantity of radiation-induced ionization in air of 2.58E-04 coulombs per kilogram
RIA	Radio-Immuno-Assay, in vitro use of radionuclides in Nuclear Medicine
RTG	Radio-isotope Thermo-electric Generator (for example plutonium-238 formerly used in heart pacemakers)
SIT	Sterile Insect Technique method of eliminating certain insect populations
SMR	Standardized Mortality Ratio. A statistical tool for better comparing slightly different populations and groups
SNAP	Systems for Nuclear Auxiliary Power (Nuclear Space Reactors)
Specific Activity	(Intrinsic Specific Activity) The activity contained in a gram of a pure radionuclide. This is a function of half-life.
Sv	sievert, unit of dose equivalent derived from radiation absorbed dose
TE-NORMS	Technologically Enhanced NORMS
TLD	Thermo-Luminescent Dosimeter, used to derive a measure of radiation dose
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

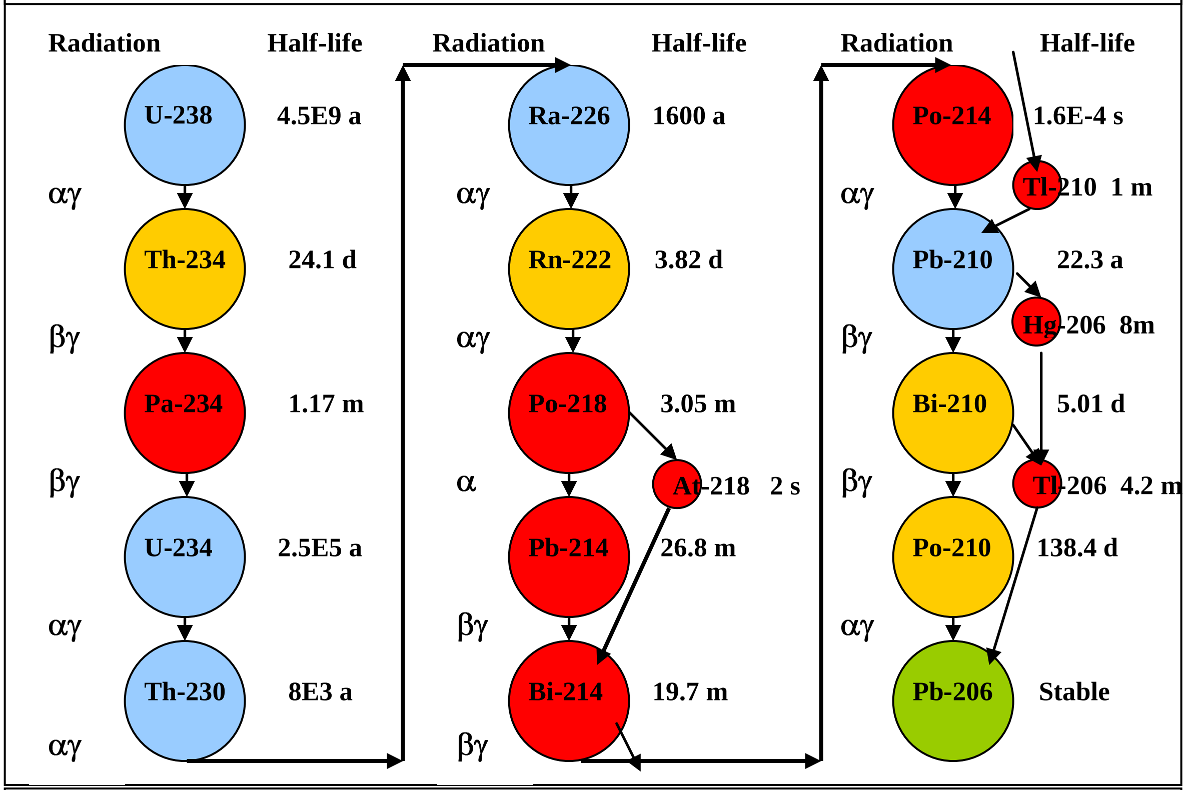
Units which are named after an individual should appear in lower case, for example, gray, roentgen, sievert, whereas their abbreviations should appear with the first letter capitalized (Gy, R, Sv).

8. APPENDICES

Appendix A

Uranium-238 with a half-life of 4.5 billion years is a very long half-life natural radionuclide with many sequential radioactive daughters as shown in Figure A 1. Most radioactive isotopes show just one or two such intermediary daughters before they become stable.

Figure A 1. Schematic of the Uranium-238 Decay Chain Showing the Decay Relationships, Half-lives and Radiations Emitted.



Emitted radiation: α - alpha particle, β - beta particle, γ - gamma radiation.
Decay half-lives: a = years, d = days, m = minutes, s = seconds.

Natural uranium-238, gradually decays through each daughter nuclide - emitting radiation at each step - until it is all transformed to stable lead-206 after many billions of years. As it occurs in most of nature, it has all of its daughters present and in secular equilibrium with it, provided radon-222, which is a gas, cannot escape to break the sequence. Refined uranium-238, which is separated and purified, initially has very low radioactivity and no progeny, but within a few seconds begins to develop its chain of radioactive daughters once more, though it takes more than 1 million years to once again approach secular equilibrium (the major hurdle is the 250,000 year half-life of uranium-234, the third daughter). This is why refined uranium, free of all of its progeny, and as used in reactor fuel, is of relatively low radioactivity. When all daughters are at secular equilibrium with the parent, as they typically are in nature, then the total radioactivity has increased by about fourteen times, as each daughter eventually decays at the same rate as the parent uranium, no matter how short its half-life.

As shown in Table A1, if the starting activity of a pure uranium-238 sample were, for example 10,000 becquerels (10,000 disintegrations each second), then at equilibrium, each of the many daughters (with a mass proportional to the half-life) has the same activity: 10,000 becquerels, and the total activity coming from the sample would be about 140,000 Bq. The final lead-206 is stable. After one half-life of uranium-238 (4.5E9 years, i.e., 4.5 billion years), half of its mass will have decayed through the decay chain to stable lead, and the total activity of the sample would then be about 70,000 Bq, with 5,000 Bq coming from uranium-238 and each of the daughters. At this time, the mass of each of the equilibrium daughters would also be halved.

Table A 1. Relative Masses of the First Six Daughters, at Equilibrium with the Parent Uranium-238

Nuclide	**Equilibrium Activity (becquerels)**	**Half-life**	**Mass of this radionuclide in equilibrium with the U-238**
Uranium-238 (mass 1,000 grams)	1.24E7	4.5E9 years	
Thorium-234	1.24E7	24.1 days	1.45E-08 gram
Protactinium-234	1.24E7	1.17 minutes	4.88E-13 gram
Uranium-234	1.24E7	2.5E5 years	5.48E-02 gram
Thorium-230	1.24E7	8E3 years	1.72E-03 gram
Radium-226	1.24E7	1600 years	3.39E-04 gram
Radon-222	1.24E7	3.82 days	2.18E-09 gram

Appendix B

Data on many of the various health studies are summarized in UNSCEAR 2000 [1] and BEIR V [44]. A detailed summary of many earlier allegations of health effects related to radiation exposures was provided in [38].

High Dose Studies:

1. Hiroshima - Nagasaki
2. Tuberculosis studies (including the Canadian Fluoroscopy studies)
3. Ankylosing spondylitics
4. Radium dial painters
5. Thorotrast injections
6. Cervical cancer treatments
7. Tinea capitis treatments
8. Medical Radiation - radiologists (1897 to 1997)
9. Reactor accidents.

Hiroshima - Nagasaki Survivors: Life Span Study.

As reported in UNSCEAR 2000 [1], mortality data were updated on 86,572 survivors, of whom about 56% were still alive at the end of 1990. It was **estimated** that 421 excess cancer deaths had occurred, with 334 of them from solid cancers and 87 from leukaemia. The data above 0.2 Sv (200 mSv) suggest a linearity of risk in proportion to dose. With so many of the study group still alive, this study will continue to be refined for several decades. This was the only group exposed to a significant dose from neutrons. The actual dosimetry on this large group is still uncertain and subject to change. Dosimetric re-evaluations from the bombs, and the study protocol (multiplicative or additive), cause the assessed risk figures to vary on the same population.

Some life-lengthening effects and aspects of possible hormesis are evident in this population in comparison with the control population in Kobe. As elevated radiation exposures caused the early deaths of those who were genetically at high risk from such exposures, it might be expected that the survivors would show risk factors that are less than those of any comparable unexposed control population. The unusually good health of many of the offspring of the survivors, compared with that of the children of the control population (RERF data) was presented as evidence at the Sellafield enquiry.

In addition, for many of these survivors, medical radiation exposures now constitute a significant fraction of their individual lifetime radiation exposures. This is ignored in deriving risk estimates, and will further contribute to over-estimation of risk.

Tuberculosis Treatment Studies (low LET) and Breast Cancer.

As reported by Gentner (1995) [45]. …A recent study indicated that the data on the Canadian fluoroscopy (for TB) studies (31,710 women - (BEIR V)[44] exposed to a maximum dose of 20 gray) provided more statistical power than the Hiroshima, Nagasaki data. It provides the first strong support, based on empirical data from humans, that a large effect of dose fractionation exists for low-LET radiation and lowering lung cancer risk relative to predictions using the Hiroshima, Nagasaki risk assumptions. The paper is "***Lung Cancer Mortality between 1950 and 1987 after Exposure to Fractionated Moderate-Dose-Rate Radiation in the Canadian Fluoroscopy Cohort Study and a Comparison with Lung Cancer Mortality in the Atomic Bomb Survivors Study***". It is authored by **Professor Geoffrey Howe**, Head of the National Cancer Institute of Canada Epidemiology Unit, University of Toronto. The manuscript was published in *Radiation Research*, vol. **142**, pages 295-304, **1995**. [46].

BEIR V [44] noted that the cohort was monitored for mortality between 1950 and 1980. By 1980, 482 breast cancer deaths had been noted. No cancer incidence data have yet been obtained for this cohort.

Ankylosing spondylitis (Low LET) (BEIR V [44])

The treatment used high doses of X-rays (chronic) to alleviate extreme arthritic back pain due to inflammatory joint disorder of the spine and limbs. Follow-up of 13,000 patients irradiated in the period 1935 - 1954, was undertaken when the problem of an increased incidence of cancer was recognised. By 1960 the study had been expanded to cover 12,000 men and 2,300 women and also covered people with the disease who had not been treated by X-rays. For every case of mortality except cancers, the treated group had the lower mortality rate, but in general the mortality of this untreated group was still much different from that of the general population.

The initial exposure for 1 treatment was estimated to be 3.5 to 5.4 Sv. Subsequent treatments gave about 3.2 to 3.5 Sv. Eighteen of the treated group who received only 1 treatment developed leukaemia, whereas fifty-two of the treated group who received up to 4 courses, did.

By 1970, the 397 cancer deaths among the group was nearly 60% more than the 257 expected. For leukemia the excess was more marked, 28 versus the 6 expected. Deaths in those not treated in this way was also about 60% above expected. Thus it seems that radiation was responsible for only a small proportion of the excess. Up to 1970, 124 patients had died of lung cancer versus 87.3 expected.

Data to the present time, after 50 years of study, are still largely inconclusive.

Radium dial painters (High LET)

Rowland, R. E. 1994. Radium in Humans: A Review of U.S. Studies. Argonne National Laboratory. ANL/ER-3. [47].

Data were compiled on a group of 1,530 women studied from the 1920s and 30s. There were 46 cases of bone sarcoma, 19 cases of head sinus carcinomas, and 3 cases had both.

The 46 bone sarcomas had appearance times from 7 to 63 years after the start of exposure. There is no linearity of fit with the data and there is indication of a threshold of between 3.9 to 6.2 Gy of chronic average bone dose. Ten grays (200 sieverts) of chronic average bone dose, was suggested as a practical threshold.

Thorotrast Injections (TB Studies)

Thorium suspension, injected to improve the contrast of X-ray photographs, was used in Nova Scotia Sanatoria in the early 1950s. This contributed to the treatment dose on these patients, and appears to have contributed to the deaths of some of them. This group in Nova Scotia is a sub-cohort of the Tuberculosis Studies described above.

Cervical Cancer Treatments (BEIR V [44]).

The study cohort consisted of about 150,000 women treated for cancer of the uterine cervix. About 70% were treated with radium implants or external radiotherapy. A second primary cancer was identified in records of 4,188 of the women. Doses to the bladder were in the range of 30 to 60 gray and were associated with the development of bladder cancer in some patients.

Tinea capitis Treatments (low LET) (Israel)

A study of about 10,800 children in Israel given X-ray treatment for Tinea capitis indicated a correlation with thyroid cancer. Doses to the scalp were of the order of several gray (about 4.5 average), whereas the average thyroid dose was calculated to be about 100 mGy. The risk of thyroid cancer (not generally fatal), was consistent with a linear, dose response relationship including doses that were less than 150 mGy.

Similar thyroid cancers were noted in a cohort of 2,657 children in New York State given X-ray treatment of the thymus gland, and in other groups of infants treated for enlarged tonsils.

In 7 combined studies of thyroid cancers, a linear dose response was suggested down to about 100 mGy.

Medical Radiation - radiologists (1897 to 1997) [48], [49].

The following summary is taken from Cameron [49]. The 100-year study of British Radiologists (1897-1997) [48], showed that the earliest British radiologists (up to 1920) with chronic occupational doses estimated at about 1 Sv per year had a much greater cancer death rate than other male MDs in England and Wales. However, even these early British radiologists outlived, on average, their medical colleagues. (It might not be unreasonable to suggest that their older survival rates contributed to their higher cancer death rate, rather than their occupational radiation exposure having done so!)

In 1920 the British X-ray safety committee recommended techniques to reduce the occupational dose to radiologists. No group of British radiologists after 1920 had a

cancer death rate greater than their medical colleagues (possibly because they then, no longer outlived them). After 1920 their cancer death rate was significantly lower than that of all men in England and Wales (suggesting a healthy worker effect, or a beneficial effect of their radiation exposures – hormesis).
The British radiologists' health continued to improve over the decades. British MDs who joined a radiological society between 1955-1979 had a cancer death rate 29% lower; a death rate from non-cancer causes 36% lower and a premature death rate from all causes 32% lower than their male medical colleagues. The chance of this health improvement being accidental was less than one in 1,000. [49]. This amounts to an increase in longevity of over three years.

Reactor accidents.

There have been three notable reactor accidents:

1. Windscale (1957): A fire in the graphite moderator of the shutdown reactor, during a release of Wigner energy. No containment building.
2. Three Mile Island (1979). Release of radionuclides into a WET environment within containment, in which they were mostly trapped. Some noble gases escaped.
3. Chernobyl (1986). Transient over power of an operating reactor, followed by a graphite fire. No containment present.

Short-term (early) health effects were noted only in the Chernobyl accident in which 31 people (28 firefighters) died. One hundred and thirty four of those exposed, received mostly acute doses between 0.7 to 13.4 gray. [1].

Long-term (late) effects were noted only in the Chernobyl accident in the possible relationship between childhood thyroid cancers (usually treatable) - about 1800, [1] - and iodine-131 exposure from the accident. Apart from the thyroid cancers no increases in overall cancer incidence or mortality have been observed that could be attributed to the accident. [1].

The most notable long-term adverse health effect appears to be psychosomatic disorders which are a result of radiation phobia. [31], [50], [51]. Various medical observers of this and other exposed populations have noted that fear of radiation is usually more damaging to health than radiation itself.

Low Dose Studies:

10. U.S. Nuclear Shipyard Worker Study
11. Uranium and Iron ore miners
12. Natural Background studies (Argonne, China, U.K., Japan, Cohen)
13. Effects of Weapons test fallout
14. Plutonium injections (from 1945), and plutonium workers.
15. Animal studies at elevated and reduced doses.
16. Sellafield childhood leukemia and other cancer clusters.

17. AECB (CNSC) study of incidence of leukaemia around Canadian nuclear facilities.
18. Mortality study of workers conducted at AECL (Canada).
19. Hanford public exposures.
20. Nuclear Workers Studies - U.S., Canada, BNFL (U.K.)

U.S. Nuclear Shipyard Worker Study

The absence of significant adverse health effects related to low occupational chronic radiation exposures is shown in the issued but unpublished report of results of the U.S. nuclear shipyard worker study (NSWS). [17].

The study compared 28,000 nuclear workers with the highest cumulative doses (>5mSv) to 32,500 matched shipyard workers. The only significant difference between the two groups was that one received chronic occupational radiation exposures. The cancer death rate of the shipyard nuclear workers was about 15% lower than that in the unexposed shipyard workers. The data tables also show that the nuclear shipyard workers death rate from all causes was about 24% lower than that of the unexposed shipyard workers.

Uranium and Iron ore miners (radon -high LET)

The exposure response relationship in the combination of selected data from eleven studies of radon-exposed miners and lung cancer, is consistent with linearity [1]. However, there were major confounding factors with respect to smoking and arsenic exposure which were not fully detailed, and both are strongly correlated with the development of cancer, including lung cancer. For example, information on tobacco use was available on only 6 of the 11 cohorts, and of these 6, only three of them had information on duration and intensity of tobacco use.

The major difficulty in deriving risk estimates from radon exposures is that lung cancer is a common disease which is mostly correlated with smoking.

Natural Background Studies (BEIR V, UNSCEAR 2000, and others)

Elevated natural background radiation is noted in regions of Brazil, India, China, Italy, France, Iran, Madagascar, Nigeria [52] and many others. BEIR V [44] noted that 'no increase in the frequency of cancer has been documented in populations residing in areas of high natural background radiation.'

An Argonne National Laboratory report [28] showed that the six U.S. states with the highest background radiation had a cancer death rate 15% lower than the average for the 48 states.

Comparison of leukemia mortality in two large population groups in China [30], show that though the differences were not statistically significant, they suggested a lower risk in the more highly exposed population. A second, larger study covering about 100,000 individuals suggested a slightly larger risk, but the combined data were still not significant. Yet a third study found no significant differences but that, if anything, the death rates in the high-background-radiation area were lower.

In the U.K., a recent report (June 2002) in the British Journal of Cancer [53], in a scientific peer-reviewed study of several thousand subjects concerning the effects of radon on childhood cancers, noted that there was no evidence that radon, at the elevated levels found in many enclosed British homes, was in any way linked to childhood cancer.

The 1952 - 1988 cancer mortality records for inhabitants of the Misasa spa area, Japan, which has a high radon background and a neighbouring control area were analyzed. SMRs for cancers of all sites were significantly lower among the inhabitants of both Misasa and the control area than in the whole Japanese population. Relative risks were lower overall for the inhabitants of the Misasa area, than the control area [31], [54].

In a study of the potential relationship between natural radon exposures and lung cancer, Cohen [29] (University of Pittsburg) examined radon data covering about 90% of the U.S. population. The conclusion reached was that with or without corrections for variations in smoking prevalence, there was a strong tendency for lung cancer rates to decrease with increasing radon exposure. This empirical observation contrasts completely with the calculated predictions of the EPA and with those of BEIR IV.

There are many other areas in the world with high levels of natural background radiation: locations in Brazil, India, Iran and others. Epidemiological studies of the populations in many of these areas do not show radiation related adverse health effects.

Effects of Weapons Test Fallout

A report issued by the U.K. NRPB (NRPB-R266) [55], concludes that participation of 21,358 men, in the nuclear weapon testing programme in Australia and the Pacific ocean between 1952 and 1967, has not had a detectable effect on the participants' expectation of life nor on their risk of developing cancer or other diseases.

As reported in Nuclear News (Dec. 1999) [56], a study conducted by the U.S. Institute of Medicine (IOM) of the National Academies concluded that cancer rates among the U.S. veterans of bomb tests from the 1950s, are not statistically significantly different from cancer rates on a similar group of veterans who did not participate in the bomb tests. There were 70,000 military participants who observed the bombings that were included in the study, compared with 65,000 who did not. The report is known as 'The Five Series Study: Mortality of Military Participants in U.S. Nuclear Weapons Tests.'

Plutonium Injections (from 1945), and Plutonium Workers.

To evaluate the relationship between urinary excretion and plutonium body content in the thousands of workers in the nuclear weapons programs, 17 (BEIR III) [57] or 18 persons (Cohen, Nuclear News, March 1994) [58], selected because they had been diagnosed as ‘terminally ill’ (life expectancy less than 10 years), received intravenous injections of plutonium between 1945 and 1947. The chronic doses were up to 220 mSv per year, each year for the rest of the test subjects' lives. All subjects had incurable diseases and were not expected to live beyond the next ten years, which would have been the time required for them to be affected by the long-term effects of this radiation. However, seven of the 18 survived beyond ten years. Five survived beyond 14 years, and the last survivor died in 1992 after 45 years. None of the survivors died of liver or bone cancer - the expected diseases predicted after plutonium injection - and thus none appeared to have been adversely affected by the plutonium.

A study of a population of 260 deceased plutonium workers (Gold and Kathren) [59], suggested that their occupational exposure to plutonium or other radiation did not contribute to their deaths.

Bastin noted the data below in the following report: The report "Toxicological Profile for Plutonium and Compounds" (December 1990), prepared by the Atlanta-based Agency for Toxic Substances and Disease Registry of the Centers for Disease Control in collaboration with the U.S. Environmental Protection Agency, provides results of studies by medical doctors of workers exposed to plutonium. These studies indicate a possible beneficial health effect and certainly no adverse health effect.

‘The first study was begun in 1952 on a group of 26 workers with plutonium at Los Alamos during World War II for the Manhattan Project. They have now been studied for 37 years (as of 1990, the year of this report). Follow-up has included extensive medical examinations and urine analyses to estimate plutonium body burdens, which showed plutonium deposition ranging from 2,000 to 95,000 pico-curies plutonium with a mean of 26,000 pico-curies. Mortality in this group as compared to that of United States white males in the general population was significantly less than expected (2.0 vs. 6.6 in a comparable number of the general population). In addition, no cancers occurred during this extensive follow-up.

A study of an additional group of 224 male workers at Los Alamos was begun in 1974. Average whole-body deposition was estimated at 19,000 pico-curies of plutonium. Mortality, adjusted for age and year of death, was compared to that of United States males in the general population. Among this group, 43 deaths were observed as compared to 77 in a comparable number of the general population. The number of deaths due to cancer was considerably lower than expected, 8 vs. 15 in the general population, including only one lung cancer vs. five in the general population.

A study of 7,112 workers at the Rocky Flats plutonium facility during 1952-1979 showed comparable results. Observed deaths of workers were significantly fewer than those in comparable numbers of general populations (452 vs. 831). Cancers were also less (107 vs. 167).’

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Animal studies at Elevated and Reduced Doses [16], [60].

Experiments on Cancer induction, and observations on life lengthening and life shortening, as well as overall improvements in health were noted in numerous animal (mammals and fish) and other organism experiments. The studies confirmed that very large doses of acute radiation contributed to cancer formation and the early death of many animals, but also showed that at lower doses – still well above background - significant improvements in health and longevity were statistically defined compared with control groups that were not exposed to elevated radiation.

Sellafield Childhood Leukemia and other Cancer Clusters.

Widespread publicity was accorded the Gardner (1990) study [61] in England concerning the potential relationship between occupational radiation exposure to males, and the development of leukaemia in some of their subsequent offspring. The radiation doses were chronic and low, and well within accepted dose limits; the number of cases of leukemia was small (13), and the correlation was weak with a relative risk of less than 2.

It was subsequently rejected as the probable cause of the leukaemias when Kinlen suggested that population relocation into many areas was more consistently associated with the development of such small numbers of isolated cases of leukaemia, and at many sites where there were no paternal occupational radiation exposures.

Following this (2002), a report by COMARE (UK) [62] repeated that there is no valid statistical base for assuming that there is a cause-effect relationship between offspring leukemia and low radiation occupational exposure of the fathers. They noted that an infection mechanism may probably be a factor effecting the risk of leukemia and Non-Hodgkins Lymphoma.

AECB (CNSC) Study of Incidence of Leukaemia around Canadian Nuclear Facilities.

As a consequence of the initial Sellafield allegations, the AECB funded a study by independent researchers to examine leukaemia incidence around several Canadian nuclear facilities (AECB INFO report 1992) [63]. The initial report indicated that the development of leukaemia around the facilities was not significantly different from its development in the population at large. A second, more expanded study came to the same conclusion. The study sites included the Chalk River Laboratories, the uranium refinery at Port Hope, the uranium mines and mills at Elliot Lake, and the Nuclear Power plants at Pickering and Bruce Counties. The report concluded that there was no association between childhood leukaemia and the occupational exposure of fathers to ionizing radiation prior to the time of conception.

The following summary of a CNSC pronouncement was reported in the CNA newsletter for June 2002. 'The Canadian Nuclear Safety Commission released a medical study on June 17 that found that overall cancer rates in Port Hope, Ontario were comparable to cancer rates throughout the province of Ontario. The study was subjected to scientific and independent peer review before publication. The study, carried out by Health Canada, reviewed the incidence of cancer, particularly those types of cancer most prone to radiation propagation, for the years 1956-1997. Its finding of no excess of cancer in Port Hope was consistent with earlier studies of the town. Cancer studies have been of interest in the Port Hope and surrounding communities because of concerns regarding the long-term presence of low level waste from the radium and uranium refineries dating back to the 1930s'. CNSC, 06/17/02.

A similar study was conducted by the U.S. National Cancer Institute 'Cancer in Populations Living Near Nuclear Facilities'. [64] The study, released in 1990, looked at the health of populations in areas near 62 major nuclear facilities. It showed that the overall results showed no evidence of any increase in Cancer. The NCI noted particularly that, compared to the 'control counties', the mortality risk from leukemia and childhood leukemia was lower overall in the 'study counties' in the years after the facilities started up. (Health Physics Society Newsletter, November 1990).

Mortality Study of Workers Conducted at AECL (Canada).

Howe et al, [65] conducted a follow-up study of about 9,000 Radiation Workers employed by AECL Ltd, Canada, from 1950 to 1981. In common with other occupational groups exposed to chronic low LET radiation, the average total accumulated doses were fairly low (about 47 mSv for males and about 3.9 mSv for females); the numbers of studied workers were relatively small, the deaths were relatively few, and the observed health effects to the time of the report were not indicative of a statistically definable relationship between exposure and adverse health effects. A smaller group of more highly exposed workers (412) with average cumulative doses of 430 mSv over 21 years, similarly showed no significant increase in standardized mortality ratios.

Hanford Public Exposures.

The risks of thyroid disease in Hanford Thyroid Disease Study (HTDS) participants were about the same regardless of the radiation dose they received from I-131 from the Hanford Nuclear Weapons Production Facility in Washington State between 1944 and 1957. This was according to the report on this study which was released by the Centers for Disease Control in June 2002. The study was reported in the Health Physics Newsletter [66].

Nuclear Workers Studies - U.S., Canada, U.K [21].

In the U.S. in addition to the shipyard study (above), several studies have been conducted on nuclear industry workers. The grouping of about 36,000 workers at Hanford, Oak Ridge, and Rocky Flats facilities (Gilbert et al) [18] showed no increasing trend of risk of any cancer or leukemia with dose.

In the U.K., an initial examination of the data in the National Registry for Radiation Workers (NRRW) looked at 95,000 workers. The risk relationship with dose was positive but not statistically significant. A second study covering 124,743 workers, showed a marginally significant increase in risk with dose, though the data are also said to be consistent with there being no risk at all.

In Canada, a cohort of 206,620 workers, monitored between 1951 and 1983 with follow-up to 1987, and showing 5,425 deaths, was studied. A trend of increasing mortality with increasing cumulative radiation exposure was found for all causes of death. However, the very low SMR of 0.59 for all-cause mortality, is indicative of a healthy worker effect, and suggests interpretation problems with the data.

End.

John K. Sutherland. 2004.