Human Health Implications of Uranium Mining and Nuclear Power Generation

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EXECUTIVE SUMMARY

Ever since the discovery of radioactivity at the turn of the last century, it has been recognized that ionizing radiation has a deleterious impact on human health. Radiation damage can affect any part of the cell and can interfere with many cellular processes. Most importantly, damage to the genetic material of the cell can lead to cancer, birth defects and hereditary illness. It is generally accepted by the scientific community that there is no safe level of radiation exposure, and that any amount of exposure to ionizing radiation is harmful.

Standards of acceptable exposure in Canada and elsewhere have been reduced many times over past decades, as evidence has mounted of more deleterious health effects. Effects of chronic low-level exposures are poorly understood, especially in children. All stages of the nuclear fuel chain have their associated toxicity. There is also the continuing risk of accidents or meltdowns, which could release massive amounts of radioactivity, such as occurred at Three Mile Island and Chernobyl. Much of the long-lived radioactive contamination we are spreading into our environment now is essentially permanent and irreversible.

This paper will examine the health risks associated with the nuclear power industry at all stages - from uranium mining, to the fission process in reactors, to radioactive waste, and will comment on the risk of nuclear war, which we regard as the ultimate public health issue.

Uranium mining contaminates air, water and soil. Crushing tons of radioactive rock produces dust, and leaves behind fine radioactive particles subject to wind and water erosion. Radon gas, a potent lung carcinogen, is released continuously from the tailings in perpetuity. Drilling and blasting disrupt and contaminate local aquifers. Water used to control dust and create slurries for uranium extraction becomes contaminated. Tailings containments can leak, leach or fail, releasing radioactive material into local waterways. Various organisms can transport radioactive material away from contaminated sites. These sites remain radioactive for many thousands of years, and will be unsafe to use

for most human purposes for that long, as well as being a source of continuing contamination for surrounding populations.

Uranium refining and enriching facilities release radioactive contamination which can impinge on nearby populations. These processes also necessitate transporting many tons of radioactive material by rail or truck. This carries with it the risk of accidents or spills, with further risk of air, water and soil contamination.

All functioning reactors routinely release radioactive material into the air and into the water used to cool them. Tritium, a carcinogen, mutagen and teratogen, is one of these. It is given off in abundance by Canadian reactors because of their dependence on heavy water as a moderator. Several Canadian reactors, particularly those at the Pickering and Darlington facilities in Ontario, are near large populations. Despite this, relatively few studies have been done on the health impacts of these releases.

One of the major health risks of this industry is the highly toxic spent fuel produced by the reactor. There is no safe way to dispose of this spent fuel, which remains radioactive for hundreds of thousands of years. "Geologic storage" which consists of burying the waste deep underground, is being considered, but carries the risk of potential contamination of air and water, and other as yet unknown risks.

A number of health studies done worldwide and in Canada have uncovered some alarming links between chronic low-level radioactive emissions from nuclear reactors and cancer, especially childhood leukemia. Experts continue to claim that the radioactive emissions are too low to explain these cases. In 2008 the German KiKK study provided compelling evidence of an unequivocal positive relationship between a child's risk of leukemia, and residential proximity to a nuclear power plant. This effect was consistent across all sixteen nuclear power plants in Germany meeting the researchers' criteria for size and duration of operation, and was detectable as far as 50 km from the nuclear facility. A number of studies of nuclear facility workers have shown elevated risks of cancer.

Though there are relatively few Ontario studies on this subject, the Atomic Energy Control Board of Canada (AECB) undertook several studies in 1989 and 1991 which found an increased prevalence of leukemia in children living near nuclear facilities. Another AECB study found higher rates of childhood leukemia corresponding to higher radiation exposure of fathers, the largest risk being associated with the fathers who worked in uranium mining. Because few of these findings reached statistical significance, possibly due to very small numbers, the authors claim that these could have been due to chance.

Other studies have found elevated rates of some congenital abnormalities including Down syndrome in proximity to some Ontario nuclear stations. These showed a relationship to tritium releases from the plant during the prenatal period, and to paternal radiation exposure. However, because numbers were again small, most results did not reach the level of statistical significance and were deemed to be due to chance.

The Radiation and Health in Durham Region Study, 2007 was an ecological study looking at a number of health outcomes in the vicinity of the Pickering and Darlington nuclear reactors. Authors found statistically significant increases in combined cancers, breast cancer, thyroid cancer, bladder cancer, multiple myeloma, leukemia and congenital neural tube defects. Rates of several other cancers and congenital diseases such as Down syndrome were also elevated, though the increase was not found to be statistically significant.

There is mounting evidence that even very low levels of radiation exposure may have deleterious health effects over the long term, some of them serious. These are detectable in nuclear workers and in the general population in the vicinity of nuclear installations. Some of these involve genetic material and may affect generations to come. Our understanding of the cellular processes affected by this damage, and the implications for the health of the affected individual and his/her descendents is far from complete.

Given that the dissemination of contaminated material, particularly the long-lived radioisotopes, into the environment is essentially irreversible, and that these will remain toxic for thousands of years, a precautionary approach is advisable. Much genetic damage is irreversible, and may be cumulative, so this becomes doubly important. We as family doctors are concerned about the public health risks of every stage of the nuclear industry.

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HISTORICAL BACKGROUND

Since Henri Becquerel's discovery of radioactivity in 1896, it has been recognized that ionizing radiation has an impact on human health. At that time, it was observed that burns and rashes were resulting from the rather large local exposures experienced by persons handling this material. These burns were similar to those suffered, particularly on the hands, by the early radiologists working with X-rays. Marie Curie, in her work with radium and polonium, which she successfully isolated from pitchblende in 1898 (1), suffered such burns. She later died of aplastic anemia, likely an unrecognized result of her exposures.

In the 1920's, young women painting the dials of instruments with radium paint were found to be developing softening of the bones of the jaw and dental problems, later jaw cancers, and other bone and head cancers (1, 2). Radium emits alpha radiation and has an affinity for bone. The dial painters were ingesting small amounts of radium as they moistened their paintbrushes on their tongues.

During that period, radium was also being used as a tonic, and promoted as a cure for a myriad of diseases from rheumatoid arthritis to cancer to heart disease. "Radium water" was in high demand.

The pitchblende ore used in the isolation of radium, polonium and uranium was from a mine at Joachimsthal, Czechoslovakia, previously the site of a lucrative mine for silver and cobalt (3). Centuries before the discovery of radioactivity, it was recognized that miners in this area were dying of a mysterious lung disease, later identified as cancer. This was likely due to high levels of radon gas in the mines. Mortality reached 40% and up in these miners. Lung cancer has come to be a well-known accompaniment of uranium mining (4, 5, 6).

In 1925, in recognition of the newly appreciated dangers of radioactivity, the first radiation exposure standard was introduced. It was set at 500 mSv/yr (milliSieverts/year; the Sievert is a unit of radiation effect), this being the dose which caused reddening of the hands. In 1934, the newly formed International Commission on Radiological Protection (ICRP) set its first standard at 300 mSv/yr. This was reduced in 1950 to 150 mSv/yr. In 1956, the level was further reduced to 50 mSv/yr for workers in the nuclear industry and other occupations with known exposure, and 1 mSv/yr for the general public. In Canada, the current Canadian Nuclear Safety Commission (CNSC) exposure limit is set at 20 mSv/yr averaged over 5 yrs for workers, and 1.0 mSv/yr for the general public (7, 8). These more recent limits are based on the observed incidence of fatal cancers. They do not take into account birth defects, lowered IQ from in utero exposure or subtle genetic damage and multi-generational effects, hazards which we are only beginning to have the technology to investigate.

In 1957, Dr. Alice Stewart demonstrated that the incidence of cancer was increased in the children of women who had received abdominal X-rays in pregnancy (9). She later established that even a single X-ray could cause a measurable increase in childhood cancer. These findings were greeted with skepticism, but they have been fully confirmed in subsequent studies; it is now standard practice not to X-ray women in pregnancy if it can possibly be avoided.

There is a very long list of products which were considered to be safe when first introduced into the public domain: cigarettes, DDT and many other pesticides, food additives, flame retardants, and drugs such as diethylstilbestrol (DES) and thalidomide. Many have subsequently been removed from the market or had their use restricted. We have no logical basis to assume that radiation exposure will not follow this same pattern, and indeed we have seen allowable exposures to radiation decrease dramatically over the past century as we come to understand its effects. The weight of scientific evidence indicates that there is no safe dose of radiation exposure (10) and there is currently pressure to reduce permissible exposure limits even further.

In the case of medications and tobacco, human exposures stop when these products are no longer used. In contrast, many radioactive byproducts of the nuclear industry, and many radioactive natural substances released into the environment by mining activities, have half-lives in the thousands, millions or even billions of years, and will remain significantly radioactive for several times that long. (The half-life is the time it takes for half the atoms of a given radioactive substance to disintegrate, decaying spontaneously into something else.) Once the process of nuclear power generation begins, we are committed to dealing with the toxic byproducts of the industry for a very long time. This becomes a radioactive legacy that is impossible to reverse.

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TECHNICAL BACKGROUND

In order to fully appreciate the issues related to uranium mining and the nuclear industry, some basic knowledge of the underlying physics is required. Many readers may be familiar with this material; for the others it will be presented briefly.

There are 92 elements occurring in nature on this planet. Several of these have more than one isotope. The isotopes of an element differ from each other only in the number of neutrons in the atomic nucleus and thereby in atomic mass. All isotopes of an element are identical in their chemical properties.

Most isotopes in nature are stable, and remain the same forever. A few are unstable, and prone to ejecting subatomic particles or high energy photons from the nucleus as alpha particles, beta particles and gamma radiation, in the process decaying into a new isotope or element. Such an unstable isotope is said to be radioactive, and the subatomic particles and photons it emits are collectively described as atomic radiation. If the new isotope or element is also unstable, the decay process continues until a stable form is reached. These decay products are known as daughters, or radioactive progeny, of the original element.

Uranium has three isotopes which occur in nature: U 238, U 235 and U 234. All are radioactive. The numbers represent atomic weight or mass.

U 238 makes up slightly over 99% of natural uranium by weight. It has a half-life of 4.46 billion years. It sits at the top of a decay chain involving 14 steps and culminating in lead 206, a stable isotope of lead (see Table 1). U 234, with a half-life of 245,000 years, is part of this decay chain, and although it represents a very small fraction of the weight, it is responsible for up to half of the radioactivity in refined natural uranium.

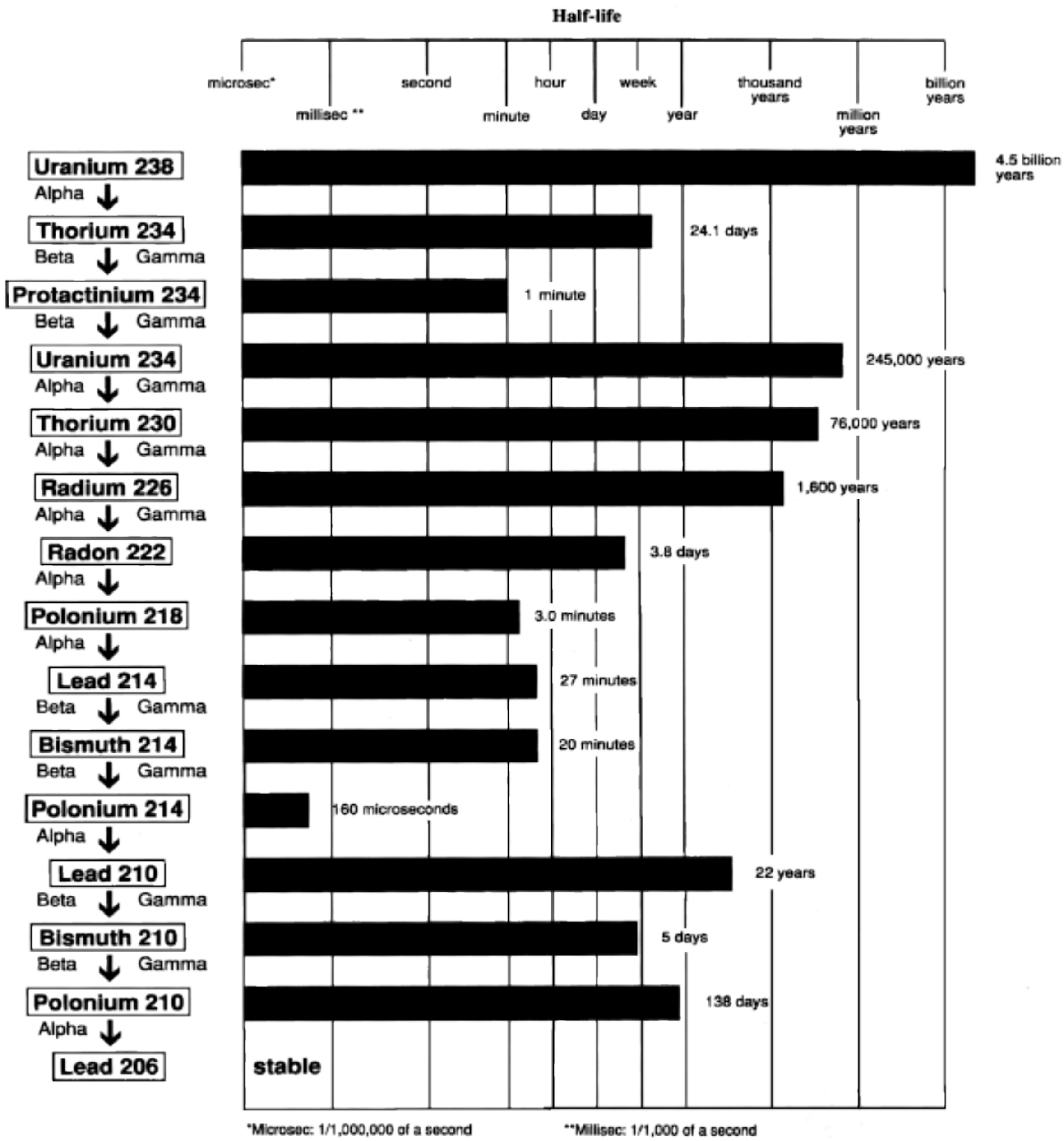

Table 1. The Uranium 238 Decay Series (11)

Uranium 235 makes up somewhat less than 1% (about 0.72%) of natural uranium. It is the isotope that is required for the production of nuclear power and weapons, as it can sustain a fission chain reaction, which the others cannot. Enriched uranium is obtained from natural uranium by removing some of the U 238 so as to increase the percentage of U 235. Some degree of enrichment is a requirement for most designs of nuclear reactors, and a high degree of enrichment is required to make an atomic explosive device. Depleted uranium, mostly U 238, is left behind as a byproduct of the enrichment process. It is not useable as fuel for fission reactors, but has been used as a raw material to produce weapons grade plutonium, used in atomic warheads. Depleted uranium has also recently found a use in bullets, missiles and armour because of its density and penetrating power.

U 235 has its own natural decay series. In human hands however, little of it goes down this stepwise chain. Placed in the core of a nuclear reactor, or the interior of a nuclear bomb, it undergoes a fission reaction in which neutrons, released by splitting atoms, bombard other atoms, causing them to split and release more neutrons. In a bomb, this process of neutron bombardment and nuclear fission accelerates, creating huge amounts of heat and a massive blast. In a power generating reactor, the process is controlled by neutron absorbing and moderating materials. There is still a tremendous amount of heat produced by the fission process. This is used to boil water and produce steam which turns the turbines to generate electricity.

When U 235 atoms are split, many new radioactive isotopes are created. Some of these are simply the broken fragments of the split uranium atoms, called fission products. Over 200 new isotopes and elements, not occurring in nature, have been identified as fission products (12). In addition to the fuel, the metal containment structures, cooling water and other nearby structures are also bombarded by neutrons, often altering their atomic structure. In this way a large variety of new radioactive isotopes are created. Thus the structural materials themselves become radioactive, not only because of contamination with fission products, but because of alterations in their own atomic structure.

U 238 atoms remaining in enriched fuel can absorb neutrons and transmute into heavier human-made elements, among them plutonium. Plutonium is radioactive and highly toxic, but is also fissile and as such can be used in some reactors as fuel. It is also the primary nuclear explosive material used in most nuclear bombs, and as such is highly prized by terrorist groups and governments desiring nuclear weapons capability.

Before entering the reactor, uranium fuel rods manifest a level of external radioactivity low enough that they can be handled with minimal precautions. They give off mainly alpha radiation which does not penetrate skin. Coming out of the reactor, the irradiated fuel rods are so intensely radioactive that a human being standing next to them would receive a lethal dose of radiation in seconds due to the penetrating gamma radiation given off by the hundreds of fission products. The irradiated fuel rods require cooling in circulating water for many years to avoid uncontrolled heat build up, spontaneous combustion and dissemination of radioactive contents. This material remains dangerously radioactive for many thousands of years, as the decay processes initiated in the reactor fuel play themselves out. No safe long term storage solution has yet been found for any of this material. After 40+ years of use, the reactor building itself is largely radioactive waste, and will need to be disposed of accordingly as well.

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RADIATION AND HEALTH

OVERVIEW

There are three types of atomic radiation of principal concern to human health and safety in regard to uranium mining and nuclear power generation. These are alpha, beta and gamma radiation. Alpha and beta radiation involve high-speed electrically charged particles with mass, and gamma radiation involves electromagnetic energy. Neutron radiation is a fourth type of atomic radiation, involving particles with mass but no charge. All of these are capable of displacing electrons from atoms and molecules, and are referred to as ionizing radiation.

Alpha particles, composed of 2 protons and 2 neutrons, and being bulky, are the most biologically destructive of the three. They have been found to be up to 20 times more damaging to intracellular structures than gamma rays. They were once considered to be safe by the nuclear industry because they do not normally penetrate skin. Ingested or inhaled, however, and positioned within living tissue, they can discharge their alpha particles directly into the structures of the cell, damaging the cell's contents, including its DNA. Radon, the second leading cause of lung cancer after smoking, is an alpha emitter, as are plutonium 239, uranium 238 and its daughters, uranium 234, thorium 230, radium and polonium.

Some DNA damage is reparable by the cell, but alpha particles are more likely than other forms of radiation to cause double-strand DNA breaks which are not readily repaired. Attempts at repair can lead to deletions, inversions, acentric fragments and cross-linking, as repair enzymes try to work with missing and scrambled pieces. It is well known that damaged DNA can trigger many diseases in humans such as cancer (13), teratogenic effects including mental retardation and birth defects (14), chromosomal abnormalities (15) and inheritable disease (7,13).

Beta particles are high-speed electrons, with a small amount of mass and considerable energy. Their effects on biological tissue are somewhat intermediate between alpha and gamma radiation, although closer to those of gamma radiation.

Gamma rays are very high-energy photons with good penetrating power and no mass. They are similar to the radiation found in X-rays. They are more likely to cause single point damage in DNA, and single-strand DNA breaks which are more readily repaired. Even here repair is not always perfect. If it is imperfect, a mutation arises and persists. There is evidence now that gamma rays may also be absorbed by certain structures in the cell and give rise to local cascades of high energy electrons which can be more damaging than the gamma ray itself (16). Uranium atoms lodged in tissue can absorb gamma rays in this way, and produce such electrons, as well as being emitters of alpha radiation. This phenomenon is under investigation; to the extent that it occurs in living tissue, it may make uranium more genotoxic than previously suspected. The techniques necessary to properly investigate these genetic effects are in the process of being developed.

BACKGROUND RADIATION

The scientific community generally agrees that there are no "safe" levels of exposure to ionizing radiation, and that any exposure carries the risk of harm (10). "Acceptable" levels are based on "acceptable harm".

Natural background levels in most parts of the world are considered to be in the order of 2.4 mSv/yr, with about 1.0 mSv being gamma radiation, mostly from cosmic rays, and the remainder being alpha radiation, largely from radioactive radon gas. This varies somewhat with elevation and other geographic features. Background levels of radiation are thought to contribute to background rates of cancers and genetic defects, and the aging process. According to nuclear regulatory agencies, an acceptable exposure for the public is currently an additional 1.0 mSv/yr above background. It must be borne in mind that any exposure created by human sources, such as nuclear weapons testing fallout or emissions resulting from nuclear reactor accidents, will be added to background exposures.

Nuclear industry workers are allowed to receive 20 mSv/yr averaged over 5 years. Such an exposure, according to ICRP 60 guidelines (17) would be expected to generate 3.2 excess cases of fatal cancer per 100 workers over a 40 year career. This is in contrast to other industrial toxicological situations in which 1/10,000 to 1/million fatalities are considered acceptable (18).

HUMAN-MADE RADIATION

At the low, chronic levels of exposure relevant to uranium mining and nuclear power installations, the principal radiation effects of concern are cancers, genetic damage, birth defects and mental retardation due to in utero exposure. Other more subtle and less well studied effects of radiation include a general life-shortening effect, and a role in some forms of immune system dysfunction, such as autoimmune disorders and decreased resistance to disease. As well, an increase in disorders worsened by oxidative stress, including atherosclerotic vascular disease has been reported (19). Intracellular free radicals, well known byproducts of ionizing radiation acting upon tissue, play a role in generating oxidative stress. Even diabetes has been linked to radiation exposure in some studies (20). There is mounting evidence for many of these effects, and plausible mechanisms exist for most.

Since 1945, increased amounts of human-made radioactive contamination, some involving long-lived isotopes, have been introduced into the biosphere. The atomic blasts at Hiroshima and Nagasaki, the weapons testing programs in the U.S., Russia and elsewhere, the accidents at Three Mile Island and Chernobyl, emissions and leaching from active and abandoned uranium mines, and discharges from operating nuclear power plants are all sources of radioactive contamination. We have done a very inadequate job of tracking the resulting exposures and monitoring their effects. In fact, relatively few studies have been done to examine radiation effects on humans, and many of these have faced methodological challenges.

In the Life Span Study of Hiroshima Survivors, one group consisted of individuals who were within a certain distance of the hypocenter at the time of the blast. A comparison group consisted of those who were farther away at that time, and were presumed to have negligible exposure. Many of this latter group however came into, and remained in, contaminated areas searching for relatives or helping out; some were exposed to more radiation than survivors closer to the blast who left the area (21, 22). When a comparison, or control group is itself exposed to elevated levels of the toxin or condition under study, increases in illness in the test group will not be as evident. In addition to this source of confusion, data from the first five years after the blast (1945-1950) were not collected, and the study focused on fatal cancers and non-cancer mortality as opposed to all health parameters, an approach which would have been much more informative as to the range of health effects caused by the significant radiation exposure experienced by the survivors of Hiroshima.

Many of the models used by regulatory bodies to determine safe exposure levels for today's populations are derived from these Hiroshima survivor studies (18). Therefore some current regulatory standards may be based on inaccurate information as a result.

Some studies have shown that the above-ground nuclear testing of the 50's and 60's has left us with a significant burden of cancer. According to a 2002 study by Hoffman et al. (23), between 11,000-220,000 (95% confidence interval) excess cases of thyroid cancer in U.S. residents are attributable to iodine 131 released by the testing. It is impossible to determine how many colon, lung, breast and other cancers are similarly attributable as these have other risk factors which confound the assessment. Work continues in this area.

A number of Russian scientists and physicians, many working without funding or official recognition, have done studies in the neighbourhood of Chernobyl showing that incidences of birth defects, neonatal death, and stillbirth are higher than recognized, as are immune system dysfunction, and mental diseases in children. Deformities in fish, insects, trees, and other organisms sharing a radioactively contaminated environment have also been noted (24). Effects of the Chernobyl accident have been felt worldwide and have contributed to radiation exposures far from the accident site. In Northern England and Wales, hundreds of sheep farmers are still required to regularly test their meat for radioactivity levels because of residual contamination from the Chernobyl accident some twenty years earlier (25).

GENETIC EFFECTS

Damage to the DNA of body cells can lead to errors in cell proliferation and eventually cancer. This has become a well-recognized effect of ionizing radiation exposure on living tissue.

Damage to the DNA of germ cells (eggs and sperm) by ionizing radiation can be passed on to future generations, and can be expected, over time, to give rise to increases in levels of malformations and genetic disease. Initially, much of this genetic damage will likely be silent. The human body has two copies of every gene, except those on the X and Y chromosomes in the male. (Note: the X chromosome in the female is duplicated, the XY configuration in the male is not.) Damaged recessive genes, with undamaged partners that can take over function, will go undetected, until they accumulate in a population to the point where two of these recessive genes end up in the same person at the same time, one from each parent. Even then, many of these mutations will be lethal to the developing embryo and will manifest not as defective offspring but as reduced fertility or early miscarriage, events easily missed in epidemiological studies. It must be kept in mind that eggs develop in a female fetus' ovaries during gestation. Therefore a pregnant woman's exposures may affect not only herself and her children, but her grandchildren as well by damaging the eggs in her unborn daughter's ovaries.

The mutagenic effects of radiation in fruit flies were demonstrated as far back as 1928 by Hermann Muller (26). More recently, Cornelia Hesse-Honegger has documented patterns of malformations in insects throughout Europe based on proximity to nuclear facilities (27). These observations raise concern about the effects of radiation from nuclear facilities on human reproductive cells, and on fetuses due to prenatal exposure.

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THE NUCLEAR FUEL CHAIN

URANIUM MINING

Uranium mining is the messiest and most contaminating stage of nuclear power generation. Yet, without it, the whole process cannot go ahead. The cost to the global environment, and to persons, of this stage must be factored into the cost of nuclear power generation.

Uranium mining, in particular open pit mining, which is what is currently proposed in several locations in southern Ontario, involves digging thousands of tons of radioactive rock out of a giant hole. (The Rossing uranium mine in Namibia is 1 km wide, 3 km long and 1/3 km deep (28)). Large quantities of this rock are dumped onto the earth's surface. The ore is then transported to a milling facility, usually nearby, and crushed to a fine sand-like consistency, creating large amounts of radioactive dust and a huge volume of finely ground mill tailings. The uranium is separated out, usually with strong acids or alkalis. The sand-like tailings, containing about 85% of their original radioactivity, and often the chemicals used in the extraction process, are deposited in large tailings ponds or containments nearby.

Dust containing uranium and its progeny is produced in large quantities by rock-crushing operations. This particulate matter, containing long-lived radioactive isotopes, can leave the site on wind. Wind erosion of tailings piles can be significant as long as these remain exposed to weather. Radon gas is continuously produced by the decay of thorium 230, a radioactive decay product of uranium 238, through radium into radon. Thorium 230 has a half-life of 76,000 years, and will produce radon gas unabated for millennia.

In undisturbed uranium deposits, most of the radon gas is trapped within rock formations until it decays into other radioactive byproducts. However, crushed tailings on or near the earth's surface allow considerable radon to escape. In a 10 km/hr breeze, it can travel 960 km within 4 days; much further in higher winds. Radon gas decays sequentially into several other solid radioactive isotopes of polonium, bismuth and lead, before finally becoming the non-radioactive lead 206. These radioactive progeny of radon settle onto crops, bodies of water and soil. Their patterns of accumulation in the biosphere, including our food species, are not well known. The three isotopes of polonium produced by radon, in addition to being radioactive, are among the most toxic naturally occurring substances on earth. The toxicity of lead is well documented.

Radon is a major contributor to the excess of lung cancer seen in uranium miners (4, 5, 6). Radon at levels seen in some residences also carries a risk (29). Radon emanations from bedrock in certain areas may be unavoidable, however these can be greatly increased in the presence or proximity of crushed mine tailings or abandoned mine workings which provide pathways of migration to the surface. Some high residential radon readings are being found by homeowners near old mine sites in the Bancroft/Haliburton area (30).

Groundwater and surface water in the vicinity of uranium mining operations frequently become contaminated (31). At the advanced exploration stage of mine development, holes about 1-2" in diameter and up to 1200 feet deep are drilled into rock, usually into the most concentrated deposits. A hole of this depth is almost certain to penetrate aquifers, giving water access to radioactive rock surfaces. Many uranium compounds and decay products are soluble, toxic and radioactive. In an area of fractured granite bedrock, as found in some uranium bearing areas of Ontario, many of the aquifers interconnect and contamination quickly becomes widespread.

Uranium in drinking water, at levels in excess of the safe drinking water standard of .02 mg/L or 20 ppb, is principally toxic to the kidney, in particular the proximal tubules (32). Uranium can also affect fertility, fetal growth and postnatal viability (33). It may cause malformations in fetuses and might be associated with reproductive cancers. It concentrates in bone and may interfere with the activity of osteoblasts, possibly contributing to bone cancers and osteoporosis (32).

Uranium in well water is often associated with some of its highly dangerous daughter elements such as radium and radon (18). Their combined radioactivity may be a limiting factor in water quality. Radon in well water is a significant contributor to radon levels in houses (34).

During the operation of a mine, the use of copious amounts of water to control dust, or to create a slurry for the extraction of uranium, can contaminate large quantities of water, which then need to be disposed of. Tailings impoundments containing liquid material can leach contaminants into the soil and groundwater. Tailings dams can fail, releasing massive quantities of radioactive material into local waterways (35). Near the decommissioned mines at Elliot Lake, tailings piles were covered with water to prevent the escape of radon gas, a standard procedure. Recent drought has caused serious difficulties with this maintenance protocol. A mere 15 years into the thousand-year period for which it was designed, this environmental safeguard system is underperforming (36). Over 100 million tons of uranium tailings are stored in the Elliot Lake area (37).

Dry piles of uranium mill tailings are subject to erosion by wind and water. Tree roots and plants take up this radioactive material, often concentrating it (38, 39), and are eaten by biological organisms - birds, insects, mice, deer, etc. - which disperse it in their feces or their bodies. Root systems help to bring radon up to the leaves where it can be transpired into the air.

In Ontario, near Bancroft and Haliburton, there are about 5 million tons of uranium mine tailings. Many of these were abandoned by mines which closed before 1977, and as such they are under the jurisdiction of neither the federal nor the provincial governments (40). In 1977, the federal government created the Atomic Energy Control Board (AECB), later replaced by the Canadian Nuclear Safety Commission (CNSC). Uranium mines thus fell under a federal mandate, whereas before this they were a provincial responsibility. Because of this shift, federal and provincial agencies have been locked in a jurisdictional struggle over these older mine tailings. As a result, according to a study by the Canadian Institute for Radiation Safety (CAIRS) (40), many of the tailings "have not undergone any remedial work designed to place them in a safe condition."

Tons of radioactive rock are laying around unprotected, with contaminants leaching out, wind blowing dust, radon gas escaping, fencing and signage falling into disrepair and the area being used more and more for hunting, hiking and recreation. It is possible that fill is being taken for construction purposes from unmarked radioactive sites.

What are the risks from these tailings? According to the CAIRS study, a person walking over a typical tailings pile for 1 hr every day will absorb a gamma radiation dose of, on average, 0.73 mSv/yr (41). This would be in addition to the ~1.0 mSv/yr of background gamma radiation we all receive. Consider that doubling a person's exposure will in general double his/her cancer risk, and that this person will also be exposed to higher than normal levels of radon gas near the tailings.

If a house were built on the tailings, or if substantial amounts of radioactive fill were used near this house, or to mix concrete for the house, and a person or family spent between 8 and 24 hrs/day in this house, their radiation exposure could be substantial. It might well be over the maximum of 1.0 mSv/yr above background recommended for the general public (8). (In this scenario, it could be up to 0.73mSv/yr X 24 =17.52 mSv/yr per person.)

Use of contaminated materials in construction has been a problem not only in the Bancroft area, but in Elliot Lake, in Port Hope, where there is a uranium conversion facility dealing with highly radioactive material, and in the United States in Navaho territory where there was intensive uranium mining in the past (42).

URANIUM REFINING AND ENRICHING

After the uranium is mined and milled, it is refined. Canadian uranium from all sources is sent for further processing to a refinery in Blind River, Ontario or to a conversion facility in Port Hope, Ontario. The Blind River facility produces UO_3; in Port Hope uranium is converted to UO_2 for use in fuel rods for reactors requiring unenriched uranium or is incorporated into uranium hexafluoride (UF_6) in preparation for enrichment. The UF_6 is then sent to an enrichment plant in Kentucky where the isotopes U 238 and U 235 are separated from each other and remixed in more desirable proportions. Uranium with an excess of the fissionable U 235 is "enriched"- this leaves a stockpile of extra U 238 or "depleted" uranium.

Uranium ore, yellowcake (the milled uranium destined for Port Hope or Blind River for refining), and uranium fuel rods for use in reactors are all transported by rail or truck to their destinations. This carries with it the risk of an accident or major spill, with further risk of air, water and soil contamination.

Canadian CANDU reactors use unenriched uranium. Until 1965, all Canadian uranium was used exclusively for American nuclear weapons, including the Hiroshima and Nagasaki atomic bombs. After this, the Canadian government decided that Canadian uranium was only to be used for civilian purposes, such as electricity generation (25). Unfortunately, there is no effective way to track or enforce this once uranium leaves our borders.

Canada does not reclaim the leftover depleted uranium after the enrichment process. The American military now uses some of it in the production of armour for tanks and for armour-piercing bullets. Bullets made from this material combust on impact, producing a fine radioactive smoke which, when inhaled, damages lung tissue. This aerosolized uranium, and the contaminated spent shells remaining on the ground, expose the local population, as well as soldiers, to this radioactive waste for many years (the half life of U 238 is 4.46 billion years). These weapons have been used in Serbia, Afghanistan, Iraq and other theatres of war. This material, and its radioactive daughter products, will remain mobile in the environment for a very long time. Canada is implicated indirectly in this situation, as it supplies the U.S. with uranium.

NUCLEAR POWER GENERATION

CANDU reactors, designed and extensively used in Canada, use heavy water (deuterium oxide) as a moderator and coolant. This material helps prevent the build up of excessive heat and acts to regulate the flow of neutrons involved in the fission process. Because deuterium can easily become tritium by absorbing a neutron, CANDU reactors produce many times more tritium than reactors using light water. Tritium is a radioactive isotope of hydrogen. Like hydrogen, tritium can become incorporated into water molecules, organic carbon-based molecules, and indeed most molecules relevant to living tissue, including DNA. It can therefore become pervasive in the natural environment, and incorporate itself into human tissue. Tritium is a carcinogen, a mutagen and a teratogen. It has been involved in testicular and ovarian tumours, chromosome breaks and aberrations, fetal death and malformations, and in mental retardation after in utero exposure (43, 44, 45). Presently the acceptable level of tritium in drinking water in Canada is 7000 Bq per litre. This contrasts with other jurisdictions such as the U.S., which has an acceptable level of 740 Bq per litre. The E.U. limit is 100 and the public health goal in California is 15 Bq per litre.

Tritium escapes continuously from all operating reactors built to current designs. Most of the escaping tritium is released as steam into the air from the chimneys of the reactors; some is released into the cooling water, and from there into local bodies of water, such as Lake Ontario. Tritiated steam, or water vapour, can be absorbed through the skin or by the lungs. Some tritium can become bound into organic molecules, and incorporated into animals and plants. Elevated tritium levels have been measured in soil and in fruits and vegetables grown in proximity to nuclear reactors (46). This can be an important component of human tritium exposure. Because the half life of tritium is 12.6 years, it will continue to accumulate in the environment until it reaches equilibrium in about 72 years, as long as nuclear reactors continue to produce it at present rates.

During this time it will be free to disseminate itself throughout the biological kingdom. Darlington is the only reactor that has a tritium extraction facility which removes most of the tritium, and sells it for use in luminous dials and in airport runway lights. Much of this tritium will ultimately be released into the environment as well. Tritium is a necessary component in the hydrogen bomb. This raises major security concerns, especially with respect to terrorism and less stable regimes.

In addition to tritium, all functioning reactors routinely release many other radioactive substances to the air and into the cooling water. The noble gases xenon 137 and krypton 90 decay relatively quickly into the deadly cesium 137 and strontium 90. Cesium 137 accumulates in muscle, including the muscle of our food source animals such as cattle, pigs and sheep; strontium 90 accumulates in bone. Other radioactive isotopes of xenon, krypton and argon are also released. Iodine 131 is mostly trapped by filters, but can escape in accidental releases. It is highly toxic to the thyroid, particularly in children. The highly radioactive primary coolant in the reactor core is supposed to be kept separate from the secondary coolant, which circulates in and out from a nearby river, lake or the ocean. In reality, particularly in older reactors, there are many leaks and defects which allow these to mix. Tritium, fission products and isotopes from irradiated structures in the reactor can escape (47).

Recently there have been some reported intentional controlled releases of tritium from the Chalk River nuclear facility into the Ottawa River upstream of the city of Ottawa. The AECL (Atomic Energy of Canada Limited) and the CNSC (Canadian Nuclear Safety Commission) claim that after these releases, levels of tritium in the Ottawa River, the source of drinking water for over a million people, did not exceed safe limits (48). However, as we have seen from past experiences, humans have succeeded in polluting huge volumes of the earth's water, air and soil, by considering each small (or large) release of a contaminant as "safe" or trivial. There is certainly risk that repeated releases of small amounts of a carcinogenic, mutagenic and teratogenic substance such as tritium into the drinking water of a large population will have some health effects.

WASTE DISPOSAL

At the end of its useful life in a fission reactor, the spent fuel contains hundreds of different fission products, many of them not found in nature. Collectively, the fuel rods are so radioactive as to be lethal in seconds to anyone near them, and so thermally hot they must be kept in pools with circulating water for 10 years to prevent them from overheating and releasing their radioactive contents into the environment (49). After 10 years or more, the spent fuel can be placed in large containers for dry storage, where circulating air continues to cool it.

Apart from their own inherent risks, these cooling pools are alarmingly easy targets for sabotage. Interference with water circulation could result in overheating of the fuel rods. The possibility of an intense fire involving the zirconium cladding of the fuel rods could lead to release of massive amounts of radioactivity.

One of the most critical issues facing the nuclear energy industry is its inability to permanently and safely dispose of spent fuel, which remains radioactive and highly toxic for many thousands of years. In Canada, there are plans for so-called "geologic storage", which involves burying the waste in containers a quarter mile down into the bedrock of the Canadian shield, in hopes that it will remain undisturbed for thousands of years until it is no longer a danger. There are many potential risks inherent in this type of storage. The spent fuel will remain thermally hot for many years and in fact does not reach ambient temperature for 50,000 years (25). The effect this enormous heat will have on the surrounding rock is unknown. The integrity of the rock will also have been disturbed by the drilling of an entry hole, and radioactive material could conceivably make its way out again by this route. Quite possibly deep aquifers will have been disturbed and could become contaminated by the radioactive waste. The earth's crust is a dynamic entity. To assume it is possible to predict how it will interact with stored material over thousands of years is unjustified. For this reason deep geologic storage may not ever be a satisfactory solution to the disposal of waste fuel.

Reprocessing is at best a temporary answer to fuel disposal. This procedure allows the removal of many highly radioactive unwanted and deleterious fission products from used fuel so that it can be used again. These must then be disposed of. Reprocessing also involves handling highly radioactive and toxic materials, creating elevated risks for both workers and surrounding communities (50). One such reprocessing plant in Ireland expels some of these highly dangerous radioactive waste products directly into the Irish Sea, making it one of the most radioactive bodies of water in the world (25). Reprocessing also allows the extraction of plutonium, used in some power reactors outside Canada and in nuclear weapons. There are serious concerns about terrorist groups acquiring this spent fuel for its plutonium content and weapons potential. Presently there are no reprocessing plants in Canada although one is being considered for northern Saskatchewan.

STUDIES ON HEALTH EFFECTS

OVERVIEW

For several decades now we have been intensively using radioactive materials and processes for power generation and other purposes. For even longer than this we have known that radioactivity and radiation exposure could have undesirable effects on health. Despite this, there have been surprisingly few definitive human health studies done in this area. Some of these are presented below.

In the 1960's, Dr. Ursula Franklin, a famous Canadian materials engineer and human rights advocate (51), began looking at strontium 90 levels in the teeth of children, and noticed a relationship between strontium levels in children's teeth and increases in leukemia. Strontium 90 is one of the byproducts of the nuclear weapons testing that occurred in the U.S. in the 1950s and is one of the fission products routinely released from nuclear power reactors and in fallout from accidents such as Chernobyl. The studies of Dr. Franklin contributed to the cessation of the above ground nuclear testing program in the U.S. in 1963. The Tooth Fairy Project, based in the U.S., continues to study the relationship between strontium 90 levels in baby teeth and childhood illness (53).

A study by Mangano (52) compared cancer incidence in children living near New York and New Jersey nuclear plants, to strontium 90 levels in children's baby teeth. Cancer incidence in these children paralleled strontium 90 levels in teeth, with a 4-5 year lag period (the suggested latency period for radiation-induced cancer in children). The study also found elevated risks of childhood cancers in areas downwind of Three Mile Island after the partial meltdown in 1979, and in the regions of the U.S. most contaminated by fallout from Chernobyl, as measured in radioactive iodine levels in pasteurized milk.

Other studies have shown disturbing links between low level radiation from nuclear facilities and illness in local populations. One such study examined the infant mortality rate before and after the closing of a number of nuclear facilities across the U.S. and found a decrease in infant mortality rates (up to 53 %) after the closures (53).

STUDY DESIGN

Before examining the health studies in detail, it is important to recognize the limitations involved in studying environmental toxins such as ionizing radiation by epidemiological methods. For ethical reasons, randomized controlled trials, the "gold standard" of study methodologies, in which one group is exposed to a toxin and then compared over time to another group that is not exposed (the control group), cannot be done. Other study designs must be used.

Many epidemiological studies done on environmental toxins are cohort studies. These look at large groups of people that have experienced higher than usual exposures to a toxin or deleterious condition, to see over time whether they develop higher rates of particular illnesses than persons not exposed. Confounders such as smoking, family history and other risk factors cannot be taken into account with these studies. These studies require large numbers of people, and are not always possible if there are not large populations to study. Also, if the disease under study is rare, very large numbers are needed to reliably detect elevated rates of illness.

Another type of study, the case-control study, looks at the characteristics of a group of people who have an illness, and compares these characteristics (such as a history of exposure to certain toxins) to characteristics of a group that did not develop the disease. Other risk factors can be assessed in this type of study, and statistical analyses made of each risk factor separately, allowing assessment regarding whether the environmental exposure could be responsible for the illness. One problem with this study type is that it relies in certain situations on people's memories of exposures, sometimes over a long period of time.

A third type of study, which is less expensive and can be done quickly, is the ecological study. This looks at illness rates in a geographical area. It looks at exposure in a large group of people, not at the individual level. It cannot draw causal links, but can be indicative of a relationship. It can be used to generate hypotheses that can then be tested using one of the other types of epidemiological studies described above. It is therefore the weakest type of study and information derived from ecological studies should be viewed accordingly.

In most epidemiological studies of any design, rates of illness, or characteristics of an ill population, are generally compared to rates of illness or characteristics in a control population, which is assumed to have low or no exposure to the toxin in question. The choice of an appropriate control population is critical to the validity of the study. Failure to recognize or appreciate a source of exposure in the control population can lead to results which obscure a valid effect. The presence of elevated rates of the disease or condition of interest in the control population, for reasons other than the exposure being studied, can do the same. With respect to radioactivity, everyone is exposed to "background" or "natural" amount of radioactivity, which can be variable. To this are added exposures from weapons testing, nuclear facility emissions and accidents (some minor and not publicized, and some catastrophic such as Chernobyl). These are also variable. This means virtually everyone is exposed worldwide, so there really is no true control population. High "background" rates of cancer or other target illness in these control populations may serve to obscure an important effect of radiation exposure in a study as well.

Another confounder, particularly in studies in an occupational setting, is the "healthy worker effect". Workers are generally in the prime of life and healthy enough to hold a steady job. They may have lower rates of many illnesses, or more resilience in the face of physiological insults, than the general population which contains elderly, ill, disabled and very young persons. A direct comparison between the two is not always realistic.

The issue of statistical significance is important in evaluating study results. A result that reaches statistical significance is deemed not to have occurred by chance. Often the reason results do not reach statistical significance is that the number of subjects is too small. This is frequently the case in studies where populations are small, for instance surrounding uranium mines and nuclear installations, or when large numbers are required to demonstrate increases in diseases like leukemia and other cancers that are relatively rare. Many study results do show an increased risk which does not reach statistical significance. Such results should not be dismissed, particularly if they are part of a consistent pattern. Any elevation in illness incidence, even if it is not statistically significant, should be cause for concern and grounds for at least further study.

Another issue of relevance is clinical significance. An increase in an illness that is not serious, even a statistically significant increase, may not be clinically very important. An elevated risk of a potentially fatal illness, such as leukemia, in a child is extremely concerning, even if it does not reach statistical significance in a given study. Many of the diseases linked to ionizing radiation, including fatal cancers and trans-generational genetic effects, have great clinical significance that must be recognized even in the absence of statistical significance in the studies done to date. These findings are worthy of at least sufficient study to establish whether they do or do not occur by chance in a given context.

An important logical flaw encountered in the interpretation of some studies is the assumption that something can't occur because current understanding suggests it shouldn't. For instance, although some studies do indeed show increased rates of childhood leukemia close to nuclear installations, the authors claim that the radioactive discharges from these facilities are not high enough to cause the increase in leukemia. Firstly, it remains possible that surges in emissions could precipitate cancer in a susceptible individual, and that these might not be reflected in measured levels of emissions averaged over a period of time. Many emissions from nuclear facilities are not measured. In addition, we have very incomplete information regarding the dose of radiation that will promote malignant change in the blood cells of a child, or in a fetus, as some childhood cancers may be the result of a prenatal insult. The effects of radiation doses, especially on children, are poorly understood, and many estimates are based on the studies done on adult survivors of the Hiroshima/Nagasaki bombs, studies which as we have seen have their limitations.

The COMARE Studies

In the U.K., a decision was made in the 1980's to do formal studies because of anecdotal suggestions that there were higher rates of childhood leukemia near the nuclear installation at Sellafield. A study was done in 1984 (54), which did indeed find elevated rates of childhood leukemia at Sellafield. The Committee on Medical Aspects of Radiation in the Environment (COMARE) was established in 1985 by the U.K. government to examine these findings. The COMARE has released 11 reports since this time, examining cases of childhood leukemia and other childhood cancers surrounding a number of nuclear facilities, some of them reactors, some reprocessing plants, some enrichment facilities and some weapons production facilities.

The 10th report (50), which was released in 2005, analyzes current data on childhood cancer in the U.K. and examines the proximity of cases to nuclear facilities. The authors looked at children between 0 and 14 years old who developed cancer from 1969 to 1993 and who lived within a 25 kilometre radius of one of 28 nuclear facilities in the U.K. They divided the cancers into 2 groups, with leukemia and non-Hodgkins lymphoma (NHL) as one group, and other solid tumours, which included all other cancers, as the other group. They also divided the children into age groups in 5 year spans.

Their results show excesses of leukemia/NHL in 12 of the 28 locations, most very slightly increased, however with one of them over 2.3 times the expected number, 4 reaching statistical significance, and another almost so. Two of these results remained significant when a different statistical formula was used.

With respect to solid tumours, 13 of the 28 facilities had higher rates, 4 of these reaching statistical significance. However, with the modified statistical formula, none was statistically significant.

In a separate analysis of their data, based on a previous study that had found elevated rates of myeloid leukemia in children age 1 to 4 years old who lived near one particular nuclear facility (55), they examined rates of myeloid leukemia within 10 and 25 kilometre radius of 23 nuclear sites (the other 5 sites did not have any cases, as this is a rare form of leukemia in children). Two of the facilities did indeed have higher number of cases than expected within 10 kilometres of the site, some severalfold, with 2 reaching statistical significance (3.6 and 1.85 times the expected number). These only involved a maximum of 8 cases near any one facility, and some had as little as one case. Statistical significance is difficult to reach with such small numbers. A number of the analyses of cases within a 25 km radius showed increases in myeloid leukemia, but due to small numbers, none reached statistical significance.

It must be kept in mind that this study is an ecological study, the weakest type of analysis. Studying rates of uncommon illnesses such as childhood cancers is difficult for many reasons, some of which have been explained previously in the section above "Studies on Health Effects**".** The COMARE studies looked at rates of childhood leukemia/NHL within a 0-25 or a 0-10 km radius around the nuclear facility and did not analyze data within smaller radii. An elevated rate in children living very close to the installation, such as within 0-5 km, might not be evident in these analyses. They also did not separate leukemia and NHL. Because lymphoma is not as common a cancer in children, an increase in leukemia may not be evident unless the study involved huge numbers of cases which this study did not. Similarly, classing all other tumours together would likely miss an increase in any one type of cancer, unless the numbers of that cancer were extraordinarily large. Generally, the populations surrounding these plants are so small that it is difficult to uncover increased rates of any rare illnesses. In addition, it is difficult to follow the children who move away during the time period of the study and find out whether they developed leukemia. Also there can be many years' lag period between exposure and the onset of illness, making it very hard to evaluate a possible causal relationship.

The COMARE study does suggest excesses of childhood cancers in children living near nuclear facilities, and, despite the limitations of the study, some even reach statistical significance. The authors then conclude that despite the possibility that this excess of childhood cancer might be related to radioactive emissions from the nuclear facilities, the emissions measured at these nuclear facilities were too small to explain this finding. Alternate hypotheses were suggested, in particular the notion of "population mixing". This describes the phenomenon of increased susceptibility of an isolated population to pathogens brought in by persons moving into an area, in this situation presumably viruses that could cause cancer in rare individuals. Often the opening of a nuclear facility prompts an influx of families to the area surrounding the facility for reasons of employment. This is proposed as a plausible explanation for the increases in malignancies found. Despite this, it has been known for many decades that radioactivity, which is consistently emitted from these facilities, is a known carcinogen. Given that the doses of radioactivity that cause cancer in a child are poorly understood, and that a single gamma ray can damage a gene, exposure to low level radiation should be considered as an explanation for the excess of childhood cancer found near these nuclear installations.

The KiKK Study (60,61)

As a result of the first British studies done in 1987 and 1989 (56, 57), which showed a significantly elevated rate of leukemia in children under 15 years old within a 10 mile radius of nuclear plants in England and Wales (and which prompted the COMARE studies described above), the German government also conducted a series of studies. The first of the German studies was similar to the British studies, and looked at rates of childhood leukemia in children under 15 years old, between 1980 and 1990, within a 10-mile (15 km) radius of nuclear plants. This study did not find an increase, but when looking within just a 5 km radius, there was a statistically significant elevation (58). Another study done at the same time showed a statistically significant excess of childhood leukemia near the Krummel nuclear power plant in North Germany (59). These two studies prompted the German government to undertake an extension of the first study. This was done by scientists at the University of Mainz, and included the years 1991 to 1995, along with 1980 to 1990. This study did not show a significantly increased rate in children under 15 years old within 5 km of nuclear power plants, but children under 5 had an elevated risk, though not significant (58). All these studies were ecological studies, which look at rates of illness in general within a geographical area. They indicate possible causal relationships, but cannot confirm these links. Therefore the KiKK study (60, 61) was undertaken, and released in 2008. This was a case-control study looking at individual cases of leukemia between 1980 and 2003 living near one of 16 nuclear power plants, and matching them with children with similar characteristics who did not have leukemia. Residential distance to nuclear power plants was the only measured variable. The research question was "are the places of residence of children with leukemia closer to the nuclear power plant than residences of the matched control children?" In other words, "are children living closer to nuclear plants at higher risk of developing leukemia than children living farther away?" Distance from the power plant was measured in segments of 0 to 5 km, 5 to 10 km, 10 to 30 km, 30 to 50 km, and over 50 km from the chimney of the nuclear plant.

The study showed an unequivocal positive relationship between a child's risk of being diagnosed with leukemia, and residential proximity to the nearest nuclear power plant. This was statistically significant in the 0-5 and 5-10 km zones, and continued as a trend out to 50 km from the nearest nuclear power plant. The authors conclude that these findings are compelling, that the elevated risk does indeed exist and that it is related to the nuclear facilities. In regard to the "population mixing" issue, an examination of migration data in the relevant study areas did not reveal any unusual patterns, nor are any of the plants particularly isolated (60). The authors state that the reason for the elevated risk is unexplained, as the levels of radioactive emissions from these facilities are considered too low to explain the increase in childhood leukemia.

ONTARIO STUDIES

Childhood Leukemia around Canadian Nuclear Facilities, 1 and 2; Clarke et al., 1989, 1991 *(62)*

There have been relatively few studies done in Ontario on health effects in proximity to nuclear reactors. As a result of the U.K. concerns as described by the COMARE studies, three studies were undertaken by the Atomic Energy Control Board (AECB) in Canada. The first two were ecological studies done in 1989 and 1991 (62), and studied childhood leukemia within a 25 km radius of nuclear facilities in Ontario, and a third study looked at rates of childhood leukemia in relation to paternal radiation dose (64).

The first of the two studies, called Phase 1, examined leukemia in ages 0 to 4 years old and the second, Phase 2, expanded this to 14 years of age. They looked at incidence and mortality of childhood leukemia near nuclear facilities at Chalk River (research center), Port Hope (uranium processing plant), Elliot Lake (uranium mining and milling), and Pickering and Bruce (power generation). Incidence is a better measure of occurrence of an illness, especially one such as childhood leukemia, for which the treatment has improved and which is potentially curable, making mortality a less accurate measurement.

In the Phase 2 study, elevated rates (meaning that observed numbers exceeded expected numbers) were found near every facility except Chalk River. Although none of the elevations reached statistical significance, possibly because numbers were small, there were consistently more cases of leukemia than expected in each location other than at Chalk River. When Pickering and Bruce were pooled to increase numbers, an increase of 40% was found (36 observed cases vs. 25 expected), almost reaching statistical significance. Near many facilities, the increased rate of leukemia was more pronounced when place of birth was considered as opposed to place of death. As childhood cancer may be caused by a prenatal insult, place of birth would more likely indicate a link to some causal factor than place of death. In addition, in Pickering rates were elevated after reactors began functioning as compared to before, when place of birth data was examined but not place of death. An ecological study, such as this one, with a wide age range (0 to 14 years old), a large radius surrounding the nuclear facility and such small numbers of cases, does not have the statistical power to find small elevations in risk of rare diseases. The authors indicated that the findings of this study warranted further investigation. Nevertheless, a large case-control study on this subject has never been done in Canada. The fact that increases in leukemia did not reach statistical significance in this study does not necessarily mean that they are purely by chance, and their consistency cannot be dismissed, considering it is a well-established fact that radiation causes cancer.

Occupational Exposure of Fathers to Ionizing Radiation and the Risk of Leukemia in Offspring – A Case-Control Study; McLaughlin et al., 1992 *(64)*

A study done by Gardner et al in 1990 (63) showed excess leukemia in children of fathers exposed to ionizing radiation in the UK. This prompted a similar study in Ontario in 1992 to determine whether there was an association between childhood leukemia and the occupational exposure of fathers to ionizing radiation prior to the time of the child's conception.

This was a case-control study of 112 children with cancer and 890 control children without cancer between 0 and 14 years old. All the children were born in the vicinity of a nuclear facility in Ontario between 1950 and 1988. Radiation exposure history of the fathers, all of whom worked in the nuclear industry, was obtained. The fathers of 11 cases and 84 controls had a history of radiation exposure. Exposure was divided into categories of whole body external dose, and tritium dose. For uranium miners, histories of exposure to radon and radon progeny (the decay products of uranium, also radioactive) were obtained. These were divided into the following time periods: father's lifetime prior to the child's conception, 6 months prior to conception, 3 months prior to conception and the father's lifetime up until the child's diagnosis. The authors admit to some inconsistencies in dose measurement and though the inconsistencies would be similar for controls and cases, this could make interpretation of the data difficult. This study had 80% power to detect a relative risk of at least 2.5.

Several patterns of radiation exposure in fathers were associated with higher rates of leukemia in children, but because of small numbers, these did not reach statistical significance and confidence intervals were very wide. The largest risk was found in the fathers who worked in uranium mining, but because the numbers were small (there were only 5 cases of childhood leukemia in Elliot Lake between 1954 and 1988), the interpretation is again imprecise. The study shows that risk was elevated as much as 5 to 8 times for higher radiation doses received by the father, however again numbers were small, no results reached significance, confidence intervals were very wide and so interpretation is difficult. The authors postulate that this increased risk in children of these men is not due to radon because that primarily affects lung tissue when inhaled and it has never been shown that radon affects sperm and therefore offspring. Though the authors conclude that there is no evidence of a link between radiation exposure of fathers and development of leukemia in children, the limitations of this study would preclude any definitive statements as to this link.

Tritium Releases from the Pickering Nuclear Generating Station and Birth Defects and Infant Mortality in Nearby Communities 1971-1988; Johnson and Rouleau, 1991 *(65)*

This ecological study examined birth defects, stillbirths, and perinatal, neonatal and infant mortality within 25 km of the Pickering nuclear station. It also compared these to airborne and waterborne tritium discharges (stratified into five emission levels) from near the Pickering nuclear station to see if babies born with the above medical conditions correlated to different levels of tritium release during the pregnancies. This study did not directly measure doses of radiation received by the population.

The study found a statistically significant increase in Down syndrome babies born in Pickering (24 observed vs. 12.9 expected, resulting in a 1.85 relative risk). This was correlated to airborne tritium levels during the pregnancies, but not significantly so. There was an elevation of Down syndrome in Ajax also, with relative risk of 1.46 without statistical significance. This correlated with the highest ground level tritium category but was not statistically significant either. In addition, there was an association between central nervous system defects and the highest levels of airborne tritium. Despite the small numbers and relative lack of statistically significant findings in this study, there remains cause for concern, as these results are consistent with studies of Chernobyl survivors which have shown higher risks of babies with Down syndrome associated with radioactive fallout, including tritium (66).

Risk of Congenital Anomalies in Children of Parents Occupationally Exposed to Low Level Ionizing Radiation; Green et al., 1997 *(67)*

Previous studies have indicated that low-level exposure of fathers to ionizing radiation before conception may be related to congenital malformations, specifically neural tube defects, in children (68). Some studies have also shown increases in congenital and chromosomal abnormalities. A cohort study done in India comparing an area of high natural background radiation to a nearby area with low background radiation showed statistically significant increases in Down syndrome, autosomal dominant congenital anomalies and multifactorial diseases, and non-significant increases in autosomal recessive and X-linked recessive congenital anomalies (69). Exposures in the high radiation area in the India study were well below the allowable level for nuclear workers in Canada.

To examine this further, Green et al did a case-control study in Ontario (67), funded by Ontario Hydro, looking at 763 fathers and 165 mothers of children born between 1979 to 1986 with congenital abnormalities. Fathers and mothers of matched children without congenital abnormalities were compared as to radiation exposure to see if parental exposure to radiation was higher in the children with congenital malformations compared to those without.

In this Ontario study, so few mothers received ionizing radiation that they were not evaluated further. Fathers' doses were measured as total whole body dose before conception, whole body dose six months before conception and tritium dose 60 days before conception (60 days corresponds loosely to the period of spermatogenesis). The results showed some increases in different congenital anomalies in all three radiation exposure groups, up to almost double in some cases, but none with statistical significance, perhaps because of very small numbers. (The study had a statistical power of over 80% to detect a 50% increase in risk for all anomalies combined.). It must be kept in mind that some congenital abnormalities are not compatible with life, and these pregnancies end in miscarriage. These fetuses would not be counted in a study such as this, which would then underestimate the real number of congenital malformations.

Analysis of Mortality Among Canadian Nuclear Power Industry Workers After Chronic Low-Dose Exposure to Ionizing Radiation; Zablotska et al., 2004 *(70)*

This study analyzed cancer risks in over 45,000 nuclear power industry workers in Ontario, Quebec and New Brunswick between 1957 and 1994 and included 1600 deaths. Four radiation dose categories were used. Several positive associations were found. Deaths from leukemia (excluding chronic lymphocytic leukemia, a less aggressive type usually found in the elderly) increased in a dose-response fashion (meaning as the radiation dose increased the rate of leukemia increased). The excess relative risk per sievert of exposure was markedly elevated at 52.5, with statistical significance. The excess relative risk per sievert for solid cancers combined was also elevated at 2.8, which almost reached statistical significance. Again, because numbers were small, the data is less reliable and statistically the elevations in leukemia and solid cancers could be due to chance, but are consistent with findings in other studies.

Radiation and Health in Durham Region Study, 2007 *(71)*

This study was an update of a similar study done in 1996 by the Durham Region Health Department (72), which had concluded that there were no adverse health effects due to the nuclear power generating stations in Pickering and Darlington. The more recent report reflected newer research findings and included 11 more years of research data. It replaced Northumberland, an adjacent county, as the comparison population, as Northumberland has a small population and includes Port Hope, which itself has a uranium processing plant and therefore increased radiation levels. Also the categories of health indicators such as cancers, congenital anomalies and stillbirths were modified.

The Radiation and Health in Durham Region Study is an ecological study, which examines rates of illness in a geographical area. It looks at groups of people, not individuals, and cannot make any causal links. It is the weakest form of study, and this particular ecological study has many limitations.

Firstly, as in most studies of environmental toxins, numbers of cases are small, so increases in rare illnesses are difficult to expose. Secondly, the study area boundaries are not measured in distances from the Pickering and Darlington reactors, but are municipality borders. Results from such a study will not necessarily reflect elevated rates of illnesses that occur in residents living close to the reactors. The authors appear not to consider elevations in rates of illnesses in Oshawa-Whitby to be reflective of radiation effects, though it is situated in between the Pickering and Darlington reactors, and increases in illnesses in this population could be the result of low level emissions from each reactor. In addition, these regions have experienced large increases in population in the past number of years. This study does not distinguish between people who are long time residents (with longer low-level exposure to emissions from the reactors) and newcomers, and cannot take into account those residents who have moved away and then become ill, as well as other personal factors such as family history, smoking and occupational exposures. The authors also admit to lack of accuracy in the cancer registry information. The earliest data used for this study began in 1983, though the Pickering reactor began functioning in 1971, so important data in between is missing.

There are other limitations with respect to endpoint outcomes. The authors of the study decided to omit pancreatic cancer because they did not consider it to be related to radiation. The study considered many different congenital chromosomal abnormalities together because the numbers were so small, which would dilute any true increase in any one abnormality. The childhood cancer category included children from 0 to 19 years of age, further limiting the chances of finding increased rates in young children. Some fetal abnormalities are not compatible with life so would be miscarried and not counted in this study.

Considering all these limitations to this study, it is not surprising that it did not find many clear regional patterns in illnesses. However there were some worrisome results.

The rate of neural tube defects was increased significantly in the first time period in Oshawa-Whitby, situated in between the two municipalities which include reactors. (The authors examined the time periods 1981-1992 and 1993-2004, keeping in mind that Pickering nuclear reactor opened in 1971 and Darlington in 1990). Rates of Down syndrome were elevated in the first time period for Ajax-Pickering and the second time period for Clarington (the municipality that includes the Darlington reactor). Though neither reached statistical significance, these results are somewhat similar to those mentioned above in the Johnson-Rouleau and Green studies, and each could be reflective of the opening of the nuclear reactors.

There was an increase in leukemia in males for the period of 1993- 2004 near Darlington after the reactor began operation (1990), and elevations in thyroid cancer in males in Ajax-Pickering were found for the same time period, both statistically significant. The authors admit these could be radiation related.

At Darlington, the combined cancer incidence for men and women rose abruptly after the opening of the nuclear facility, significantly so for men, almost so for women. This trend is worrisome and the authors felt this sudden increase in cancer incidence might warrant further examination.

Bladder cancer mortality was elevated, though not significantly so, in both time periods for females at Darlington. Incidence was significantly elevated for men and women in Oshawa-Whitby. It was also increased significantly for men and women in the whole of Durham region in the second time period.

Breast cancer incidence was significantly higher in Ajax-Pickering in the period 1981-1992. Other databases do not indicate higher mammography rates in the area, so this is not likely due to more screening and detection, and may well reflect a real increase in incidence.

Elevations of multiple myeloma reaching statistical significance were found in men and women in the whole of Durham region, and in Oshawa-Whitby. There were elevations in Ajax-Pickering and in Clarington that were not statistically significant. There were some questions as to misdiagnosis possibly causing an over-representation of numbers. However these worrisome trends cannot be ignored. The authors state that results of findings of multiple myeloma were not consistent with radiological effects.

It must be kept in mind that in a study with multiple comparisons, approximately one in 20 will lie outside the 95% confidence limits, i.e. will either appear significant when it is not, or the reverse. Many others will fall short of significance simply because numbers are inadequate to give that degree of certainty. In such cases further study is called for, with a larger sample size or refinement of study design, to distinguish a valid but not significant effect from a spurious result. In the Durham Region study, increases in incidence and mortality of many cancers, congenital anomalies and Down syndrome were found, but were not felt to be important by the authors because they did not reach statistical significance. The findings are not completely consistent, and numbers are small, but they do indicate a possible relationship with low level radiation exposure. Ontarians should not feel reassured by the authors' conclusion that there were no patterns in this report that would indicate that low level radiation from nearby nuclear facilities was causing any health effects in the local population.

SUMMARY OF STUDIES

In summary, studies done in Europe and Great Britain, particularly the more recent ones with improved methodology and larger sample size, show evidence that there are increases in malignant and inheritable disease in the vicinities of nuclear facilities. Low-level radiation exposures remain a plausible cause of these effects. The Ontario studies, although smaller and often not reaching statistical significance, are consistent with studies done in other parts of the world, showing links between ionizing radiation and a number of health effects, especially childhood leukemia.

Most of the Ontario studies are ecologic in design, and as such not adequate for demonstrating causal relationships. Nevertheless, their results highlight a pressing need for studies of more refined design and sufficient statistical power to answer the questions they raise regarding the health effects of nuclear installations.

It is a matter of great concern that there are so few studies done in Canada, especially with respect to tritium, as Canada releases more tritium than any other country in the world due to the heavy water used in CANDU reactors. Considering that the Pickering and Darlington reactors are very close to large populations, health parameters of the local population should be monitored much more closely than is occurring presently.

THE RISK OF NUCLEAR WAR

Aside from the health risks inherent in the process of producing energy from nuclear fission, perhaps the most daunting and significant health risk is the use of uranium and plutonium for weapons of mass destruction. With the end of the Cold War, the public has become complacent about the threat of a nuclear war, even though the risks are perhaps greater now than ever before.

In 1972, the Non-Proliferation Treaty was created and has been signed by many nations. As yet, very few have eliminated their nuclear arsenals. Now many countries in unstable regions of the world who are not signatories of the treaty possess nuclear weapons. Many thousands of nuclear weapons exist in countries around the world today, though most are in the U.S. and Russia. Longstanding disputes over territory, as between Pakistan and India, or tribal/religious issues as with the Taliban or Al-Qaeda in Pakistan and Afghanistan, or the Arab-Israeli conflict, or any number of local conflicts in many areas of the world could quickly escalate into a full-scale nuclear exchange. Even a limited exchange would have devastating consequences for humanity. With the world's arsenal poised as it is, such a war could even begin by accident because of human or computer error, or in the confusion following a terrorist action.

Nuclear war is the ultimate public health issue (73). Not avian flu, nor influenza, ebola virus, cholera, AIDS nor any natural catastrophe such as an earthquake or tsunami is capable of annihilating as much of the world's human population in such a short time.

Nuclear weapons are inextricably linked to the nuclear power industry. Plutonium, enriched uranium and tritium become readily available as byproducts of this industry, and with the spread of nuclear power reactors these materials could be acquired by unstable governments and terrorists for the purpose of making nuclear weapons.

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CONCLUSION

From the extraction of uranium from rock formations, through the milling, refining, and enriching of uranium, to the operation of reactors, and the unsolved dilemma of what to do with spent fuel, there are major health effects at every stage of the nuclear fuel chain. Although it is widely accepted that there is no safe threshold for radiation exposure, low-level radiation emissions from nuclear facilities have not been considered a threat to human health. A number of studies undertaken in the past two decades have shown worrisome links between low-level exposure to radiation and some serious illnesses, including childhood leukemia. Certainly any one study that has indicated a possible causal relationship could be dismissed as a chance finding, but the consistency of findings, especially with respect to childhood leukemia, across so many studies, is a cause for great concern. The preponderance of evidence in these studies, along with our previous knowledge of the relationship between cancer and radiation, should cause alarm amongst public health specialists and policy-makers.

There are a myriad of new carcinogens in the environment. Many of these were not present when the initial studies on radiation and cancer were done. The interactions between these carcinogens and the effects of radiation exposure are poorly understood. The exposure of the Ontario population to the added radiation emitted by the nuclear industry represents an increased risk of unknown magnitude.

The link between radiation exposure and cancer is becoming increasingly clear, and the cellular mechanisms involved in this process are becoming better understood. However, we are only beginning to understand the genetic and trans-generational effects of radiation damage. Much of the long-lived radioactive contamination we are spreading into our environment now is essentially permanent and irreversible.

There are enormous public health risks posed by the millions of tons of radioactive tailings from uranium mining, and the many thousands of tons of radioactive waste produced in reactors that will remain toxic for thousands of years, not to mention the danger of an accident or meltdown causing a catastrophic release of radioactive particles into the air, water and soil. The use of depleted uranium, which is still significantly radioactive, for munitions in areas of conflict leaves local civilians in these countries exposed to radioactive waste products for many years. This radioactive material will distribute itself around the globe, over time.

The Canadian healthcare system is already straining with an aging population and rising cancer rates. Anything which increases this burden of illness and care must be avoided. In addition we, as Canadians, should also reconsider the huge expenditure of precious tax dollars on new and aging nuclear reactors when there are safer, cleaner energy alternatives. Money spent on nuclear reactors might be better spent on health care, other social programs, education, or on the development, production and distribution of renewable energy capabilities.

As physicians, our job is to maintain, promote and ensure good health to Ontarians. The material in this report should be of great concern, not just because of the significant health risks of all stages of the nuclear energy industry, but also because of the implications with respect to weapons of mass destruction and the risks of catastrophic accidents such as Chernobyl, as well as the devastating and permanent environmental damage this industry causes.

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