Dose-Response: An International Journal

Volume 7 | Issue 1 Article 3

3-2009

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Dose-Response, 7:52–89, 2009
Formerly Nonlinearity in Biology, Toxicology, and Medicine

ISSN: 1559-3258
DOI: 10.2203/dose-response.08-024.Cuttler

NUCLEAR ENERGY AND HEALTH

And the Benefits of Low-Dose Radiation Hormesis

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□ Energy needs worldwide are expected to increase for the foreseeable future, but fuel supplies are limited. Nuclear reactors could supply much of the energy demand in a safe, sustainable manner were it not for fear of potential releases of radioactivity. Such releases would likely deliver a low dose or dose rate of radiation, within the range of naturally occurring radiation, to which life is already accustomed. The key areas of concern are discussed. Studies of actual health effects, especially thyroid cancers, following exposures are assessed. Radiation hormesis is explained, pointing out that beneficial effects are expected following a low dose or dose rate because protective responses against stresses are stimulated. The notions that no amount of radiation is small enough to be harmless and that a nuclear accident could kill hundreds of thousands are challenged in light of experience: more than a century with radiation and six decades with reactors. If nuclear energy is to play a significant role in meeting future needs, regulatory authorities must examine the scientific evidence and communicate the real health effects of nuclear radiation. Negative images and implications of health risks derived by unscientific extrapolations of harmful effects of high doses must be dispelled.

Keywords: sustainable nuclear energy, radiation health effects, radiation hormesis, social acceptance, regulatory implications

INTRODUCTION

As populations grow and developing countries strive for a higher standard of living, the rate of energy consumption rises, as shown in Figure 1. By 2030, global energy demand is projected to increase by 50%, with electricity generation nearly doubling worldwide—an annual increase of 2.4% (IEA 2003, IEA 2008, DOE/EIA 2008a, 2008b). Nuclear energy is receiving much attention today because of concerns about our energy sources. Environmental groups are urging large reductions in our combustion of coal and hydrocarbons (the source of 88.6% of our primary energy) to reduce the increasing concentration of carbon dioxide in the atmosphere. While the impact of carbon dioxide emissions on global warming is controversial, the pollution from large-scale burning of coal and other fuels is generally recognized as having an adverse impact on air quality and health. Sharply rising oil and gas prices both generate and

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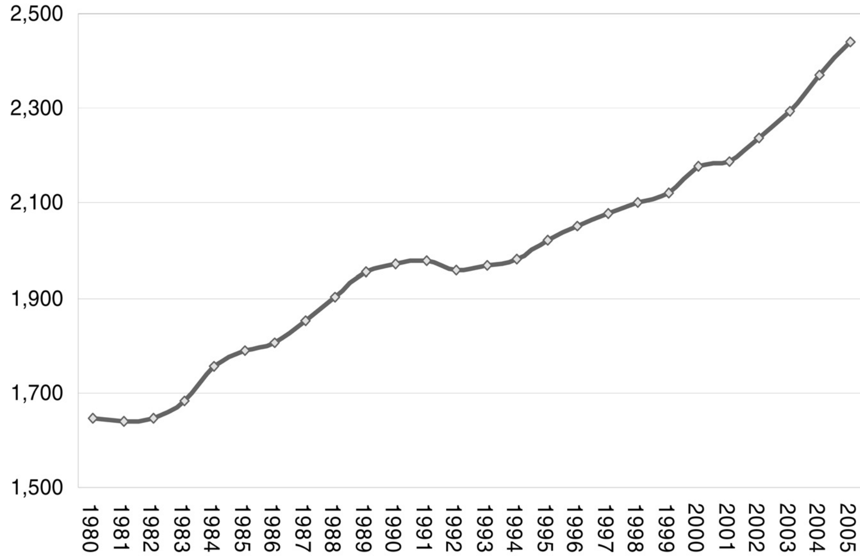

FIGURE 1. Per Capita World Electricity Consumption 1980-2005 (ordinate: kWh per person per year; abscissa: year). Source: US EIA, *International Energy Outlook (Table 6.2)*

reflect concerns about future supplies of these fuels, yet many environmental groups advocate options that avoid the use of nuclear power for electrical generation. They feel that such use would expose living organisms to radiation and increase the risk of nuclear weapons proliferation.

This article discusses nuclear energy and how this energy source affects health. Many people are very apprehensive about nuclear power. For more than sixty years, they have received much information that associates nuclear technologies with health risks and almost no information about the health benefits. They are worried about potential exposure to nuclear radiation and consequent cell damage. The incidence of adverse health effects has been assumed to increase proportionally with the amount of cell damage.

DISCOVERY OF NUCLEAR RADIATION AND FISSION

Radiation can be divided into ionizing and non-ionizing radiation based on its ability to remove an electron from an atom or a molecule to form an ion. Non-ionizing radiation includes low-energy photons of light and electromagnetic radio waves. Ionizing radiation is produced by a beam of electrons striking a target (x-rays) or by cosmic radiation, radioactivity and nuclear reactions, which release energetic photons (gamma rays, x-rays) and/or particles. Ionizing radiation penetrates living organisms and alters cells, which then send signals to initiate various defensive responses.

X-rays were discovered by Wilhelm Roentgen in 1895 when a covered photographic plate was accidentally exposed to radiation from a high voltage discharge tube. Radioactivity[1], the disintegration of unstable nuclei of atoms, was discovered a few months later in 1896 by Henri Becquerel while trying to induce x-ray fluorescence in a uranium phosphor with sunlight. Many scientists began extensive studies to understand x-rays and radioactivity. They strove to find applications in many fields of science, such as physics, chemistry and biology, and in areas of technology, especially in medicine. Efforts by Pierre Curie and Maria Sklodowska-Curie to separate the chemical element responsible for radioactivity led to their discovery in 1898 of polonium and then radium. Three types of radiation (alpha, beta and gamma) were identified. Ernest Rutherford scattered radium alpha radiation from gold atoms in a very thin foil and discovered, in 1911, the "nuclear" atom—a very small, massive, positively charged nucleus surrounded by distant, negatively charged electrons. Alpha particle radiation on beryllium resulted in a nuclear reaction that emitted nucleons with zero charge and the discovery of the neutron in 1932 by James Chadwick. In 1939, medium weight atoms were produced in experiments designed to create new chemical elements by irradiating uranium with neutrons. This led to the discovery, by Lise Meitner, Otto Hahn and Fritz Strassmann, of the splitting or fission of the uranium nucleus. This very important reaction releases an enormous amount of energy, neutrons, other types of radiation and on-going "decay heat" from the radioactive fission products.

NUCLEAR FISSION AND WEAPONS

The total amount of energy released in each fission reaction is about 200 million electron volts, which is about 100 million times the amount of energy released in a typical chemical combustion reaction (and more than ten times the energy released in hydrogen fusion reactions). Scientists immediately realized the potential military application of the fission reaction as a means to end World War II, providing that a self-sustaining chain reaction could be developed. The American Manhattan Project accomplished this objective by separating the fissile uranium-235 isotope (abundance of 0.7 percent) from natural uranium. This project also discovered that the capture of a neutron in the uranium-238 isotope "breeds" transuranic plutonium-239, which also fissions readily. Nuclear

1 The SI unit for the activity of a radioactive material is the becquerel (Bq). A becquerel is equivalent to one disintegration per second. The older and much larger unit is the curie (Ci). A curie is the amount of radioactive matter that decays at the rate of 37 billion disintegrations per second, approximately the decay rate of one gram of radium. One curie equals 3.7×10^{10} Bq (or 37,000 MBq or 37 GBq). Microcuries and picocuries are often used.

reactors were designed specifically to breed plutonium. Subsequently, the cities of Hiroshima and Nagasaki were destroyed by two bombs; one used uranium-235 and the other used plutonium-239. The USSR and several other countries also developed and tested nuclear weapons. An arms race ensued, and the energy release of bombs escalated from about 20 kilotons to more than 50 megatons of TNT. Stockpiles of warheads grew to tens of thousands in the USA and the USSR. Many tests were carried out, mostly in the atmosphere, to develop special purpose bombs and optimize their performance.

PEACEFUL APPLICATIONS OF NUCLEAR ENERGY

Soon after World War II ended, Captain Hyman Rickover of the US Navy conceived the idea of using the energy released in a nuclear reactor to propel submarines (Rockwell 1992). Construction of the USS Nautilus prototype began in August 1950, and it was "underway on nuclear power" in January 1955. Hundreds of nuclear-powered naval vessels and ice breakers have been built since then. The design and construction of nuclear power plants came next. Commercial plants began operating in 1956 in the UK (Calder Hall) and in 1957 in the USA (Shippingport). Following the first Atoms for Peace Conference in 1955, the International Atomic Energy Authority was created and many peaceful applications of nuclear technologies were promoted, especially nuclear power plants. Since then, more than 500 nuclear power reactors have been constructed in 32 countries, and more than 440 are in operation. In many of these countries, nuclear energy generates a significant fraction of the electricity for domestic, service and industrial applications, as shown in Figure 2.

Nuclear power is a controversial energy option because of the exaggerated concerns that have been raised about economic affordability, sustainability, reactor safety, accidents, used fuel management, radioactive waste and weapons proliferation.

The capital cost of a nuclear power plant in the United States was about $1500 per kilowatt in the 1960s (DOE/EIA 2004). If many plants are constructed, the cost today is expected to be about $2500 per kilowatt (DOE/EIA 2008c).[2] This is greater than the cost of a coal-burning plant[3] but operating costs are lower, mainly because of low nuclear fuel costs.

2 An average home in North America draws electrical energy at the rate of about one kilowatt. If the capital cost of a nuclear power plant were to be paid by the consumers according to their usage, the average homeowner's "portion" of the capital cost would be $2500—an affordable amount.

3 A "clean" coal-burning plant that sequesters carbon-dioxide and captures the other undesirable stack emissions for effective disposal will likely cost more than a nuclear plant. In view of present-day environmental concerns, it is very unlikely that many "dirty coal" power plants will be constructed in the western world.

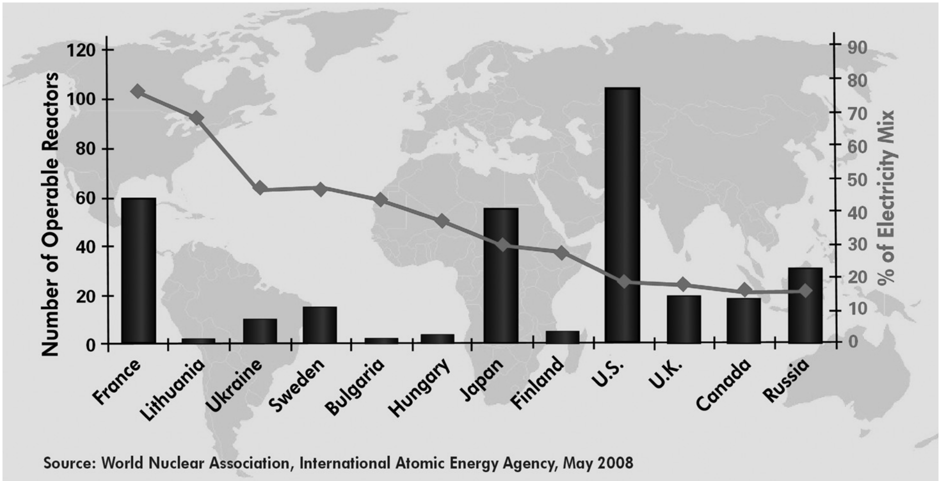

FIGURE 2. Number of Reactors and Percent of Electricity Mix

The electricity production cost of nuclear power is very competitive with coal-fired power (DOE/EIA 2008b). The value of the energy generated over the expected lifetime of a nuclear plant (60 to 100 years) far exceeds the capital cost invested.

NUCLEAR ENERGY'S POTENTIAL TO SUSTAIN HUMANITY

It is self-evident that an adequate supply of affordable power is one of the key ingredients needed to sustain a healthy social economy. Power drives the industries and commerce that generate the revenues needed to support a comprehensive public health infrastructure and a high level of employment. Unemployment leads to poverty, one of the greatest health risks faced today.

A supply of sanitary water is very important for public health. Fresh water is essential for agriculture and the raising of livestock. Nuclear power plants can be employed to desalinate seawater on a large scale and to pump the water to where it is needed.

An enormous supply of hydrogen is needed for the "hydrogen energy economy." Environmental organizations have been advocating that humanity progressively change its current energy economy, which is based on burning coal, oil and methane, to one based on the combustion of hydrogen and the use of "renewable" sources, such as hydro, wind, solar and geothermal. This would avoid the production of carbon dioxide, a greenhouse gas, and the polluting emissions that are associated with the combustion of carbon fuels. Unfortunately, hydrogen is *not* a source of energy; it is an "energy currency." Hydrogen does not exist naturally in a separated form; a source of energy is needed to manufacture

it. Nuclear reactors can be used to release the energy necessary to manufacture the required amounts of hydrogen.

Nuclear reactors also produce radioisotopes, such as cobalt-60, which are used in many vital applications in medicine and industry.

Can nuclear power sustain humanity in the long term? Current power reactors fission a fraction of the uranium-235 and some of the plutonium-239 (produced from the uranium-238), releasing less than 1% of the energy available from uranium. The rate of uranium consumption in present-day reactors suggests that the estimated conventional reserves are only adequate for several hundred years. However, breeder reactors could be built that would enable more than 90% of the potential energy in uranium to be released by converting uranium-238 into plutonium-239. This would extend the fuel supply to tens of thousands of years. The availability of breeder reactors would allow an additional source of fission energy to be exploited, namely the conversion of thorium-232 into uranium-233, which fissions readily. Because thorium is three times more abundant than uranium, its use would extend the fuel supply to many tens of thousands of years. To address the concern about the diversion of plutonium to make nuclear bombs, breeder reactor fuels must be fabricated in a form that cannot be used for weapons. Processes have already been developed that accomplish this, as described later on.

With breeder reactors, it would be feasible to extract uranium from the oceans and still keep the fuel cost below one percent of the cost of electricity (Cohen 1983). Rivers are carrying uranium into the seas at a rate that would allow at least 6,500 tons of it to be withdrawn each year. This amount would be adequate to generate approximately ten times the world's present electricity usage, year after year. Fission of uranium in breeder reactors is consistent with the definition of a "renewable" energy source in the sense in which that term is generally used.

The notion of sustainable development, applied to electricity generation, requires that the power projects of the human species not unduly threaten the development of other living species. Many people view nuclear power as uniquely threatening; whereas, it is one of the few fields that takes this issue seriously. It is one of the least environmentally offensive enterprises because so little material is excavated, transported and disposed of, to generate so much energy. Sustainable development is not a nuclear problem, but a nuclear advantage because of proper reactor design, siting, construction, operation and decommissioning, as well as the proper management of uranium mining, fuel manufacture, recycling of nuclear fuel, and disposal of waste. All of these steps receive careful application of good science and reason, in efforts to reach the environmental ideal.

Unfortunately, progress on fuel recycling and breeder reactor technology is hampered by the criticism of anti-nuclear activists who continue

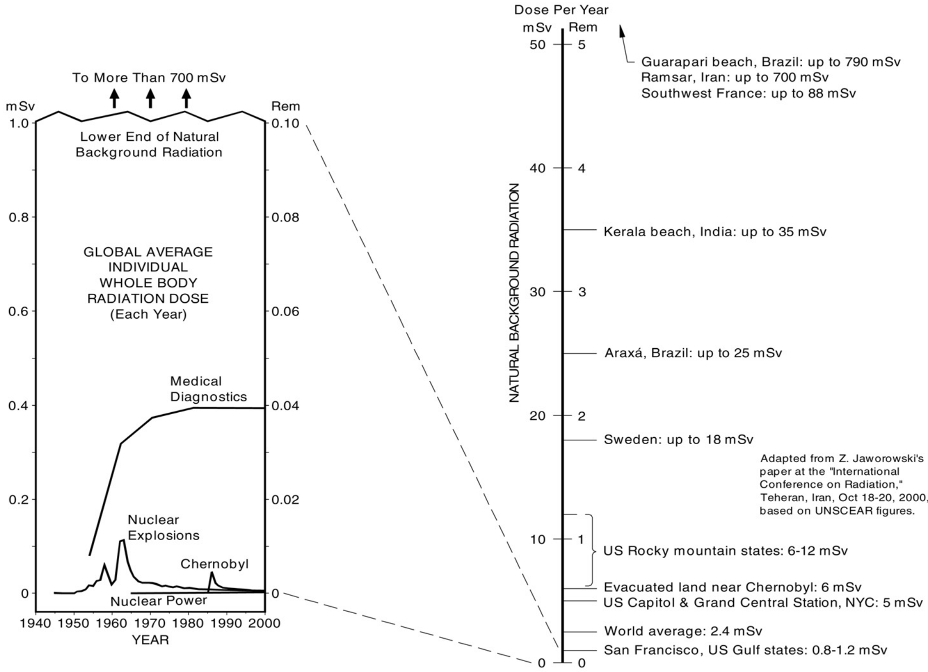

FIGURE 3. Human-Made and Natural Radiation (Rockwell 2003)

to promote health scares, all of which are related to the fear of any exposure to radiation. Figure 3 indicates the dose rate of natural radiation.[4]

RECYCLING NUCLEAR FUEL, MANAGING WASTES AND SAFEGUARDING PLUTONIUM

The excellent safety performance of nuclear reactors has caused the anti-nuclear activists to focus their criticisms on "the unsolvable problems" of radioactive waste and nuclear proliferation (von Hippel 2008).

Because of the enormous amount of energy released in fission, the amount of (solid) used fuel is relatively very small in volume. For many decades, nuclear plant owners have been storing their used fuel without harm to the environment. Initially, used fuel is placed in an underground water tank where the heat output from fission product radioactive decay is removed by the pumped cooling water flow. After several years of storage in water, the fuel is transferred to very heavy, robust, sealed containers made of steel and reinforced concrete. These containers are cooled

4 Sievert (Sv) and roentgen equivalent man (rem) are dose equivalent units (HPS 2008). For short-term exposure to x-rays, gamma radiation or beta (electron) radiation, the dose equivalent (rem or sievert) is the same as the absorbed dose (rad or gray), which are defined later in this article.

by natural air flow and can store used fuel for centuries. Radiation levels are constantly measured around nuclear facilities and compared with levels in the surrounding environment. If there is no added dose, there can be no harm. No one is being injured by used fuel, and there is no reason to believe that anyone will be injured by it in the foreseeable future. Programs have been started in several countries to plan and construct deep (~500 m) underground geological repositories to receive radioactive materials, including used nuclear fuel, after decades of dry storage.

Anti-nuclear activists have been raising unfounded concerns about long-lived radioactivity migrating to the surface after 100,000 years, but simple analyses have shown that the dose rate above a repository, even at a poorly chosen site, would not significantly exceed the average natural radiation background level (Cohen 1990, 2005). This level is at least three orders of magnitude below the threshold dose rate for adverse health effects (discussed later). The dose range of natural background radiation extends more than two orders of magnitude above the average value (Figure 3), yet the dose limit that has been set by the U.S. authorities for the increase from the Yucca Mountain repository after 10,000 years is 15 millirem per year (EPA 2008), or about 5% of the average U.S. background radiation level.

Environmentalists are naïve in believing that future generations will regard the management of used nuclear fuel as a heavy burden of responsibility. On the contrary, they will probably regard this slightly used fuel as an important asset to be recycled for their growing energy needs. Recycling used fuel removes fission products, which "poison" the chain reaction. Only one percent of the fuel is fissioned in today's nuclear reactors. Advanced fast-neutron breeder reactors will be employed to utilize the remaining 99%. Plutonium will be a key ingredient.

PUREX is the process that was developed to separate weapons-usable plutonium. Used fuel is dissolved in nitric acid and then pure plutonium is chemically extracted. Most recycling today employs this process, and great care has been taken to prevent the diversion of plutonium for weapons purposes.[5] A better process would recover all of the usable energy content in the used fuel and leave a waste stream that can be dealt with comfortably. There are several techniques that can accomplish this.

One process is UREX, an adaptation of the PUREX process that chemically extracts fission products and then uranium. The residue is reduced to metallic form, which is used to make fast-reactor fuel, after blending back an appropriate amount of uranium.

5 An alternate route to weapons, which does not employ nuclear reactors, is the use of gas centrifuges or other technologies to separate U-235 from uranium.

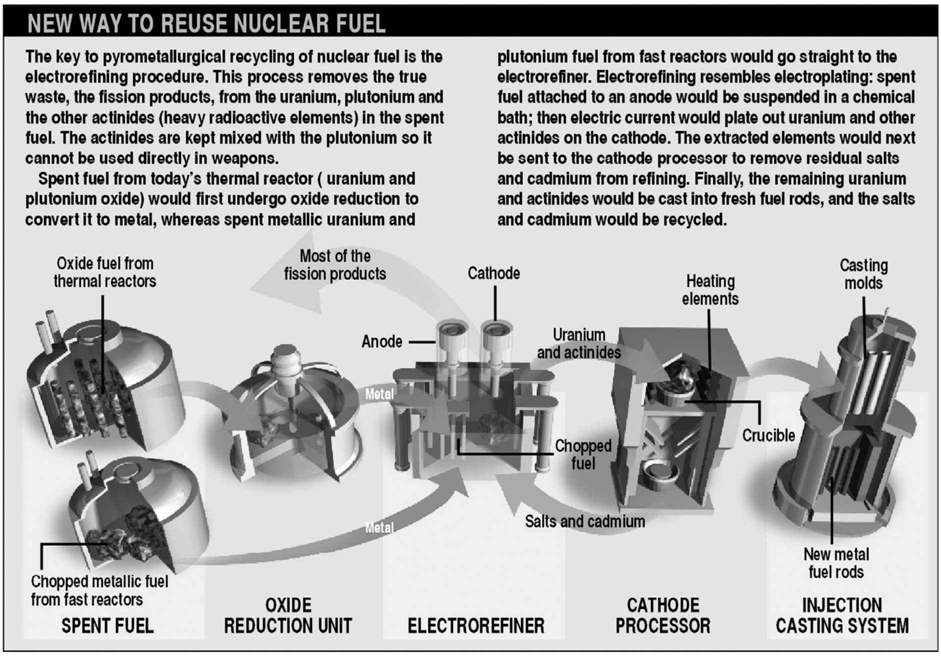

FIGURE 4. Pyro-processing to recycle nuclear fuel[6] (Hannum 2005)

Another technology, shown in Figure 4, is *pyro-processing* in which used fuel is chopped and placed in a bath of chloride salts (Hannum 2005). The process can be run so that essentially no plutonium or other transuranics remain in the salt. A significant fraction of the fission products carry over or are encapsulated as the plutonium collects; the remainder is left in the salt.

The plutonium and other transuranics are extracted; the salt is cleaned and recycled. The products are: a) fission products with no uranium or transuranics, b) clean uranium and c) a melange, containing all the plutonium and other transuranics, some uranium, and a fraction of the fission products. This third mixture is very difficult to divert for weapons, but it is an ideal fuel for recycling back into a fast reactor.

Use of these processes would send the long-lived radioactivity back into the reactor as fuel, leaving only fission products that are dominated by cesium-137 and strontium-90, which have 30-year half lives. The so-called "unsolvable problems" of radioactive waste and nuclear proliferation would become more manageable.

6 Illustration by Don Foley

Critics still point to the "dangers" and the large monetary investments that would be required to develop, design, construct and operate the fuel recycling facilities and breeder reactors (von Hippel 2008), but they do not calculate the value of the enormous amount of energy that would be generated. This value far exceeds the estimated investments, which are affordable. If new nuclear regulatory standards were prepared based on radiobiological science and realistic risk assessments, the costs would be much lower and more predictable.

REACTOR LIFE EXTENSION AND REPLACEMENT

All chemical processing plants eventually become old and worn.[7] Equipment becomes progressively obsolete. Because the design, siting and construction of a nuclear power plant require a considerable financial investment, plant owners pay very close attention to plant life management and extension. The operating life of a reactor can be extended, possibly to 100 years, by assessing the condition of the plant structures, systems and components, and by carrying out appropriate equipment refurbishments and design upgrades. The world nuclear community constantly studies operating experience and continually analyzes potential upset scenarios. Nuclear standards are revised to address this information. Suppliers of new reactors offer design improvements that comply with the latest standards and provide better performance. Before requesting a licence from the nuclear regulator to extend the life of a plant, the owner carries out an assessment of the plant's condition against its design and performance requirements, and reviews the latest nuclear regulatory standards to determine which upgrades would be cost-effective.

Eventually, a time would be reached when it would not be economical to extend the operating life of a plant; it would be shut down and decommissioned. This would involve removing the existing structures and equipment. Over the past 60 years, technology has been developed and deployed to decommission many nuclear facilities, with no undue impact on the environment. In many cases, an existing nuclear site will be reused for a new nuclear power plant.

Nuclear power was economical, affordable and considered to be reasonably safe in the 1960s and the early 1970s. However, mounting social fears of radiation and increasing regulatory concerns about nuclear safety have delayed later projects and increased their costs. This increase is ultimately borne by the consumers of the electricity produced. Public knowledge about the real health effects of radiation could significantly reduce the social costs of nuclear energy.

7 Operation of a water-cooled nuclear plant is generally less stressful on its structures, systems and components than is the case for operation of a coal-fired plant.

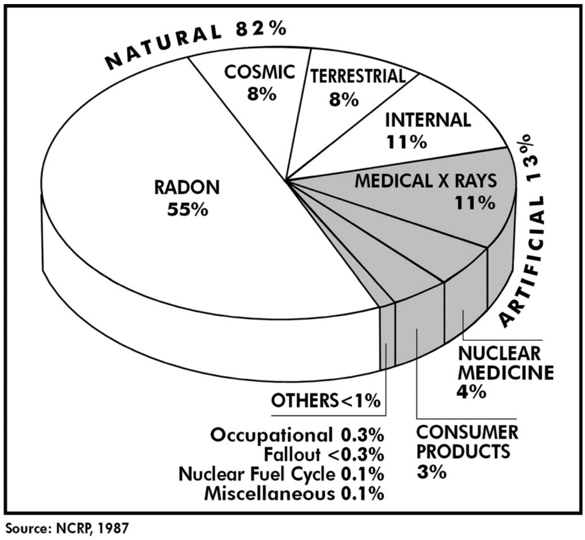

FIGURE 5. Dose contributions to individuals in the United States (NEA 1994)

IS NUCLEAR POWER REALLY A SIGNIFICANT HEALTH RISK?

Is nuclear radiation from power plants really the serious threat it has been portrayed to be? Is it appropriate that social attitudes toward nuclear energy be based on the many negative images that have been communicated? This article presents surprising scientific evidence about health effects of radiation, both low dose (acute exposure received in a time period ranging from an instant to about a day) and low dose rate (dose per unit time, e.g., per hour or year, for a chronic exposure received over many days, weeks, years or a lifetime). For example, the average global natural radiation dose rate is 2.4 mSv per year. Figure 5 shows the contribution from various sources in the U.S.

Modern nuclear power plants are carefully designed, constructed and operated to provide energy in a controlled manner while retaining the radioactive materials. A large staff of carefully trained and highly motivated people is employed to operate and maintain the structures, systems and components. These people are imbued with a strong safety culture and carry out their work according to comprehensive procedures. All plants are subjected to extensive regulatory inspections and reviews on a nearly continual basis. Releases of radioactivity are generally less than 1% of permissible levels, and do not add detectably to the natural background radiation near nuclear power plants.

What if an accident occurs? In spite of the extraordinary care taken to avoid such events, an accident could happen and a release of radioactivity is possible. As with any industrial accident, people living near the

plant would be informed promptly and emergency measures would be taken to prevent anyone from receiving a significant dose of radiation. No immediate deaths in the surrounding population would be expected. The question is whether there might be adverse health effects that might shorten life expectancy. Research has shown that a low dose or a low dose rate of ionizing radiation in living organisms is generally stimulatory rather than inhibitory (UNSCEAR 1994, Kondo 1993, Académie des Sciences 1997, Pollycove and Feinendegen 2001, Mitchel 2007a). This means that the radiation exposure would not be harmful and might even be beneficial. The 1986 Chernobyl disaster, the most severe nuclear power accident to date, melted a large fraction of the reactor's fuel and also opened the barriers designed to prevent the release of radioactivity into the environment. The health effects of this accident are discussed later in this article.

Scientists and physicians have been using nuclear radiation in medicine for more than 100 years. Some of the early medical uses of radium in the U.S. are identified in *Radium in Humans* (Rowland 1994). Results were published in the journal *Radium* until 1921. Studies on medically prescribed exposures to radon in air and water have been described by Becker (2003). Many studies using x-rays have been published in the journal *Radiology* and in other journals and textbooks. Generally, beneficial effects have been observed following exposures to low doses or low dose rates, while adverse effects have been noted following high doses or high dose rates. Recent research has revealed a great deal about biological mechanisms, such as antioxidant production, cell repair and removal of altered and mutated cells, and how these processes are affected by radiation. This has led to an understanding of both the positive and negative health effects. A brief discussion and references to some of the detailed studies are given later in this article.

Radiation penetrates matter and deposits energy. Its effects are generally measured as a function of the amount of energy deposited in a unit of mass, known as the radiation absorbed dose. Two units are commonly used for measuring radiation absorbed dose:

unit of radiation absorbed dose (rad)	1 rad = 100 erg per gram
System International (SI) unit, "gray" (Gy)	1 Gy = 1 joule per kilogram

These units are related; 1 Gy = 100 rad and 1 joule = 10 million ergs. The world average dose rate from naturally occurring sources of "background" radiation is 0.24 rad per year = 0.0024 Gy/year, or 2.4 mGy/y (UNSCEAR 2000).

Radiation protection organizations have developed methodologies for quantifying health effects. Various assumptions and concepts are in use. These include multiplying the absorbed dose by weighting factors

(for different types of radiation) and other modifying factors to account for the potential of a biological effect, in order to obtain the dose equivalent. The traditional unit is roentgen equivalent man (rem); the SI unit is sievert (Sv) (HPS 2008). For short-term exposure to x-rays, gamma radiation or beta (electron) radiation, the dose equivalent (rem or sievert) is the same as the absorbed dose (rad or gray).

Communicating the real health effects of radiation would remove many of the objections to the construction of nuclear power plants. Although the design, construction and operation of such plants are superior to those of the past, some people are worried about potential exposure to radiation. A few serious accidents have occurred during more than sixty years experience of operating hundreds of reactors and managing their used nuclear fuel. These incidents have demonstrated that the public would receive a low dose or low dose rate exposure in the very unlikely event of a mishap. The expected exposure would be in the range of naturally occurring radiation (Figure 3), to which living organisms have become accustomed.

The doses or dose rates that residents receive from a nearby operating nuclear reactor does not add detectably to their exposures from natural radiation. Nuclear plant accidents, even major ones, would not be expected to expose nearby populations to radiation doses above the threshold for adverse health effects, especially if reasonable actions were taken to avoid potentially large doses. This would also apply also to individuals who are genetically more cancer prone or more sensitive to radiation (Mitchel 2007a). Therefore, raising undue public concerns about radiation risks when discussing nuclear power is inappropriate. The safety risks inherent in the possible interruption of the electricity supply should be a more important consideration. Paying strict attention to modern radiobiological evidence would necessitate a reconsideration of long established recommendations and regulations of worldwide radiation safety organizations and so remove the basis of the very expensive constraints on nuclear power developments, including management of used fuel.

The growing demand for energy, and concerns about security of supply, pollution and carbon-dioxide's impact on the global climate, are forcing humanity to reconsider the use of nuclear energy. As of early 2008, more than 200 nuclear power reactors were being planned, in addition to the 440 reactors[8] operating in 32 countries (ANS 2008). By 2030, about 55 countries are expected to be operating nuclear reactors. The number

8 The number of naval nuclear power plants in the U.S. and Russia exceeds the total number of civilian plants.

that will actually be constructed will depend on the perceived health effects of radiation.

PRECAUTIONARY RADIATION REGULATIONS NEED TO BE REVISED

Government authorities have been regulating all nuclear-related activities very strictly, taking extreme precautionary measures to minimize the risk of exposure to any human-made radiation. These actions are based on the advice of the International Commission on Radiological Protection (ICRP 2008), which is based on the simplistic assumption that the risk of fatal cancer is proportional to the number of biological cells damaged by radiation; that is, the linear no-threshold (LNT) hypothesis of radiation carcinogenesis. Physicians are carefully taught that any exposure to radiation increases the risks of cancer and congenital malformations (Hall 2005). However, the Health Physics Society and the American Nuclear Society have both issued position papers acknowledging that below 5-10 rem (which includes occupational and environmental exposure) risks of detrimental health effects are either too small to be observed or are nonexistent. They recommend against quantitative estimation of health risks below an individual dose of 5 rem per year, or a lifetime dose of 10 rem, in addition to background radiation (HPS 2004, ANS 2001). The evidence that a small amount of ionizing radiation-induced cell damage stimulates protective activity that reduces endogenous cell damage is not accepted by the ICRP, NCRP, or government authorities. The extensive scientific evidence of the beneficial effects following low dose or low dose rate exposures (e.g., 192 studies in UNSCEAR 1994), and the scientific explanations for these effects (Pollycove and Feinendegen 2001), appear to have been ignored.

Lauriston Taylor, former president of the National Council on Radiation Protection and Measurement (Taylor 2008), denounced the use of a procedure to calculate the number of deaths per year resulting from x-ray diagnoses, as follows (Taylor 1980): “These are deeply immoral uses of our scientific heritage.” Unfortunately, this advice was ignored when scientists assessing the Chernobyl accident predicted 4000 excess cancer deaths using a linear mathematical model that is based on questionable high-dose Hiroshima-Nagasaki data. “No one has been identifiably injured by radiation while working within the first numerical standards set by the ICRP in 1934 (safe dose limit: 0.2 rad per day)” (Taylor 1980). Yet members of the public are limited to less than 0.1 rad (0.5 rem in the U.S.) per *year.*

Taylor is not alone in his convictions. Theodore Rockwell, former Technical Director, US Naval Reactors (Rockwell 2008), asked the question, “What’s wrong with being cautious?” and went on to explain the enormous harm caused by protecting people against low doses of radiation (Rockwell 1997). Professor Zbigniew Jaworowski, a former president

of the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR), pointed to the many psychosomatic disorders that appeared in the 15 million people in Belarus, Ukraine and Russia who were affected by the Chernobyl accident. The local residents were convinced that they would suffer serious health problems, such as cancer and congenital malformations. He questioned the ethics of assuming that any amount of man-made radiation can cause harm without scientific evidence to support this assumption. He also estimated that the practice of radiation protection costs society hundreds of billions of dollars each year (Jaworowski 1999). The French Académie des Sciences has also been questioning the unscientific methodology of the ICRP for more than a decade (Académie des Sciences 1997) without receiving a satisfactory response. Many others continue to challenge the LNT paradigm (Jaworowski 2008a). The recent data for cancer and low dose responses *in vivo* have very significant implications for radiation protection (Mitchel 2007b).

LIFE SPAN STUDY OF THE HIROSHIMA-NAGASAKI SURVIVORS AND THE LNT MODEL

Concern about reactor safety is one of the greatest barriers to social acceptance of nuclear energy. Many radiation scares were invented by well-meaning prominent scientists who agonized over their roles in the development and use of the atomic bomb. Figure 6 (Pauling 1962) is an example of the many extreme public actions taken by scientists to stop atmospheric bomb tests. Such groundless statements fuelled the fear of radiation. Ostensibly authoritative statements are still being made, such as, “no amount of radiation is small enough to be harmless” and “a nuclear casualty could kill as many as hundreds of thousands of people” (Rockwell 2004).

The 1950-2020 Life Span Study on the cancer mortality of the Hiroshima-Nagasaki survivors supports the conclusion that the effects of radiation exposure are grossly overstated and do not reflect the real risks to members of the public. The enormous release of heat from two bombs killed between 150,000 and 200,000 of the total population of 429,000. The study cohort of 86,572 people is roughly half of the survivors who were within 2.5 km of the bombs. Based on the many concerns being voiced about radiation risks, how many of the survivors, in excess of the normal incidence, would we expect to have died from cancer after 40 years? Typical uninformed expectations range between 10 and 30 percent of the survivors. The actual data, indicating only 344 excess solid cancer deaths and 87 excess leukemia deaths (Pierce et al. 1996), is less than one percent, clearly much different and lower than the expected numbers! Since 36,000 of the cohort were far enough away not to have received severe radiation exposure, the fraction is only 0.7 percent (344 ÷ 50,000) of the irradiated

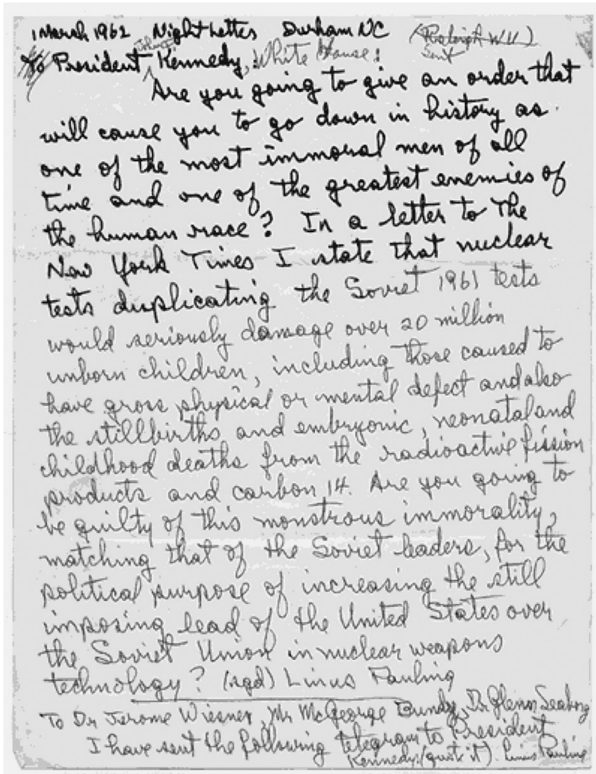
1 March 1962 Night Letter Durham NC (Raleigh WU) Sent
To President John F. Kennedy, White House:
Are you going to give an order that will cause you to go down in history as one of the most immoral men of all time and one of the greatest enemies of the human race? In a letter to the New York Times I state that nuclear tests duplicating the Soviet 1961 tests would seriously damage over 20 million unborn children, including those caused to have gross physical or mental defect and also the stillbirths and embryonic, neonatal and childhood deaths from the radioactive fission products and carbon 14. Are you going to be guilty of this monstrous immorality, matching that of the Soviet leaders, for the political purpose of increasing the still imposing lead of the United States over the Soviet Union in nuclear weapons technology? (sgd) Linus Pauling
To Dr Jerome Wiesner, Mr McGeorge Bundy, Dr Glenn Seaborg
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FIGURE 6. Telegram sent by renowned scientist Linus Pauling to President Kennedy

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survivors. Of the cohort, 56 percent were alive in 1991 and 38,092 had died, indicating that about one percent of them died from radiation-induced cancer. It is estimated that about 800 will have died from radiation by 2020, the end of the study (Lapp 1995); again is about one percent.

The survivors of the bombing experienced many confounding health risks, such as thermal burns, wounds from blast debris, infection, thirst, starvation, pollution and lack of sanitation, shelter, medical care and family support. Their social infrastructure had been destroyed. The excess

number of cancer deaths in this population is the basis for estimating the number of excess fatal cancers due to any radiation exposure in our environment. Of the 4489 survivors who received more than 50 rem, a total of 634 died of cancer—196 more than expected. The authors fitted a straight line to the excess cancer data and extrapolated this line, the LNT model, several orders of magnitude into the low dose range.

Expected doses in a nuclear reactor accident would be in the low dose range, where there is no statistically significant evidence of adverse health effects. Because cancer originates from a mutated cell and radiation alters cells, radiation protection analysts use this LNT model to predict the excess risk of cancer mortality. Evidence of beneficial effects among these survivors (Kondo 1993) and evidence of radiation hormesis have been ignored. Cohen has pointed out that the linear model suggests that cancer risk in an organism should be proportional to its mass (Cohen 1990). Heavier animals have more cells and, therefore, should have a greater incidence of cancer for the same absorbed dose (joules/kg) than lighter animals. Proportionality of cancer risk with size has not been observed.

STUDY OF EXPOSURE TO RADON DISPROVES THE LNT HYPOTHESIS

By far, the greatest exposure to low level radiation is the inhalation of the radon gas present in the air (Figure 5). Radon is produced by uranium radioactivity in the natural environment. A scientific test of the LNT model, as normally used, clearly disproved the LNT hypothesis (Figure 7). Lung cancer mortality is *lower* in US counties where the radon concentration in homes is *higher* (Cohen 1995). In the few counties with exceptionally low radon radiation, lung cancer mortality is higher, as shown schematically in Figure 9. Instead of discarding or modifying the LNT assumption, the defenders of this linear calculation procedure raised generic objections (an ecological study) that were not really applicable to the test. There were no defensible objections to the test or its conclusions; yet the authorities continue to accept the unscientific ICRP recommendations.

RADIATION HORMESIS

From the time of their first appearance, living organisms have been receiving natural radiation over a very broad range of dose rates (in addition to other physical, chemical and biological disturbances). Approximately 30 percent of the chemical elements in nature have radioactive isotopes, which are found in the air, water and soil. Their half-lives range from a fraction of a second to billions of years. As shown in Figure 3, radiation levels in some locations are as much as several hundred times greater than the world average dose rate. Life in those locations has been flourishing. Studies on organisms and human populations living in high dose rate regions have suggested that they are better able

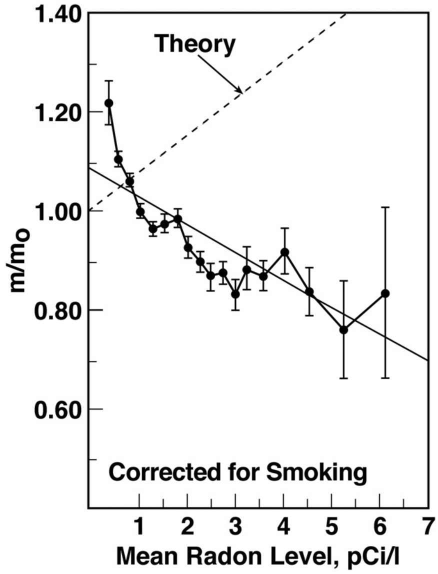

FIGURE 7. Lung cancer mortality rates compared with mean home radon levels by U.S. county and comparison with linear model by BEIR IV (Cohen 1995)
m/m_0 is the ratio of lung cancer mortality rate for residential radon levels to that at 0 level (theoretical), or to that of average residential level of 1.7 picocurie per liter.
Note statistically highly significant increase of lung cancer mortality in counties with very low ambient concentrations of radon, i.e., in radiation deficient portion of Figure 9.

to recover from exposure to a much higher dose of radiation than those living in low dose rate regions (Ghiasi-Nejad et al. 2002).

Toxicologists and medical scientists agree with Paracelcus, the 16th century Swiss physician, who wrote: "… nothing is without poison only the dose makes something not poison" (Mattson and Calabrese 2008). This universal principle applies not only to the intake of chemicals and micro-organisms, but also exposure to physical stress agents including ionizing radiation.

Living organisms function in a dynamic equilibrium state called homeostasis. Exposure to a small dose or dose rate causes stress (and damage), perturbing homeostasis. Organisms respond adaptively to such disturbances. They are stimulated to increase their defensive actions: namely, to prevent/repair/replace/remove damaged cells, neutralize the intrusions and adjust internal processes. Such improvements in protective capabilities make them stronger—a beneficial effect. This hormetic effect depends on the dose or dose-rate and the developmental level of the stress recipient. As shown in Figures 8 and 9, the stress becomes more stimulatory as the (radiation) dose or dose rate is increased from inadequate (or normal ambient) to an optimum level at which stimulation or excitation is maximal. Raising the stress level beyond this optimal point

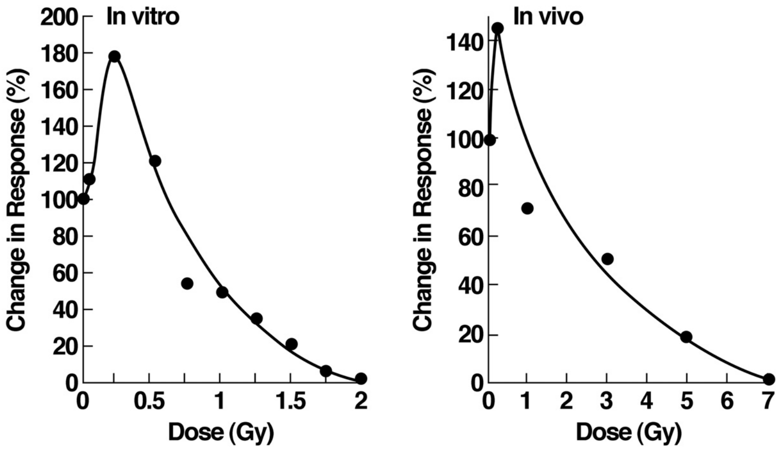

FIGURE 8. Immune system response to an acute radiation dose. Mouse splenic cells primed with antigenic sheep red blood cells (Mackinodan and James 1990)

decreases the beneficial effect until the response crosses the *zero equivalent level* and becomes increasingly inhibitory. The dose or dose rate at this crossover point is the threshold for adverse health effects. Exposing an organism to a dose or dose rate above this threshold would impair biological defences and raise susceptibility to disease above the level that existed at homeostasis. The low dose stimulatory effect is called *hormesis*, from the Greek verb "to excite".

"Hormesis is an evolutionary conserved process characterized by nonlinear biphasic dose-response in which low doses of stressful activity stimulate adaptive responses that increase function and resistance of the cellular organism to moderate to severe levels of stress, in contrast to inhibitory responses to high doses that decrease resistance and function" (Calabrese et al. 2007, Calabrese 2008a). Professor Edward Calabrese has been carrying out extensive research on hormesis for more than twenty years (Calabrese 2003, 2004, 2005). In 1990, he led the formation of Biological Effects of Low Level Exposures (BELLE 2008). Recently Calabrese organized the International Dose-Response Society (IDRS 2008) and the Dose-Response Journal, to provide forums for scientists to discuss and publish research studies on all types of hormesis, which have many important implications for public health (Cook and Calabrese 2006).

Physiologic *conditioning* hormesis is essential for normal development and aging. Physical exercise not only stimulates physical development, it also increases blood supply and function of the brain, heart and immune system. Physical exercise, mental exercise, psychosocial stress and immunologic exposure to antigens are all necessary and beneficial, if not carried to excess. Recent human functional tests coupled with CT and autopsy findings have shown that middle aged or elderly adult human

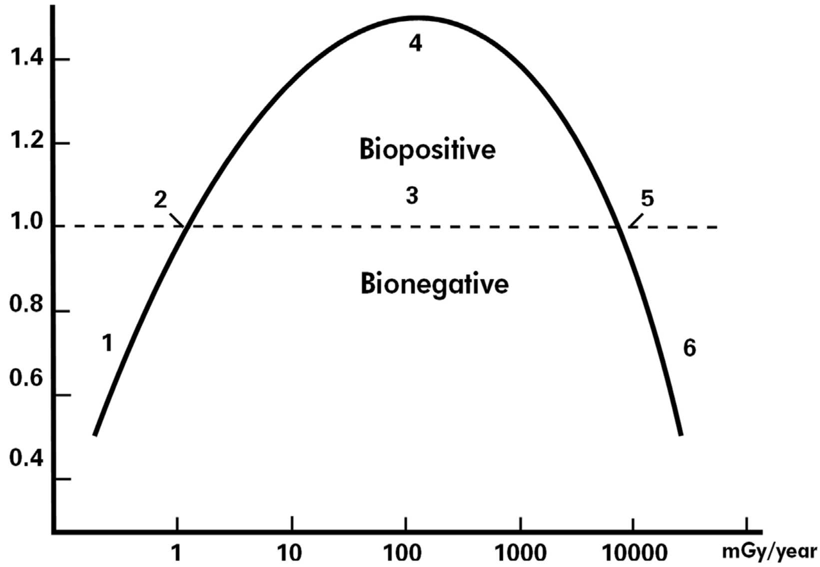

FIGURE 9. Idealized biphasic dose-response curve (Luckey 1991). The ordinate indicates relative response compared with the controls. The abscissa is mammalian whole-body chronic dose rate in mGy per year. The numbered areas are: (1) deficient, (2) ambient, (3) hormetic, (4) optimum, (5) zero equivalent point, and (6) harmful.

brains remain plastic and respond positively to mental exercise (Doidge 2007). Antigenic exposures to non-lethal doses are needed for development of essential immunity. Overcoming non-lethal challenges develops and strengthens the organism.

Chemical hormesis is also beneficial. Rulers have protected themselves from arsenic poisoning by conditioning themselves, i.e., ingesting small but increasing doses of arsenic. Though imbibing more than four alcoholic drinks daily often results in impaired liver function (cirrhosis) and may increase the risk of osteoporosis in post-menopausal women, no more than two drinks daily is healthful (Lin et al. 2005). Liver function and morphology remain normal, coronary artery disease is reduced; and the risk of osteoporosis in post-menopausal women is decreased. Pharmacologic studies of drug effects are concerned with determining the low dose therapeutic range observed between lower ineffective doses and higher toxic doses (Calabrese 2008b).

Radiation hormesis involves non-linear, biphasic dose responses of prevention and repair to another stressful challenge: alteration of DNA and other molecules by ionizing radiation and by endogenous metabolic leakage of free oxygen radicals as reactive oxygen species (ROS). Progressive accumulation of permanent DNA alterations, i.e., stem cell mutations, is generally accepted to be associated with mortality and cancer mortality rates. Epidemiologic studies of human populations in high

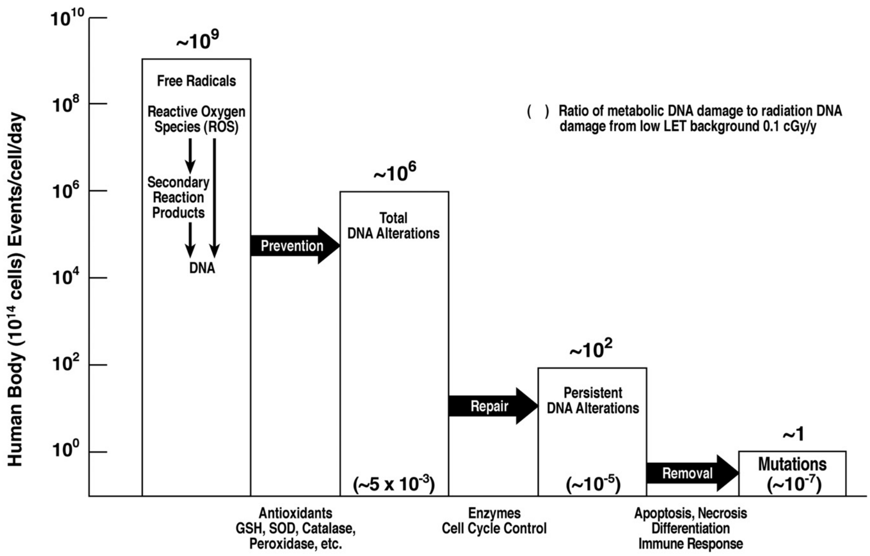

FIGURE 10. The anti-mutagenic DNA damage-control biosystem (Pollycove and Feinendegen 2001)

background residential radiation or chronic intermittent occupational or medical radiation exposure demonstrate a positive hormetic response of decreased mortality and cancer mortality rates (Luckey 1980, 1991, Pollycove and Feinendegen 2001). “Four decades of genomic, cellular, animal, and human data have shown that low-dose ionizing radiation stimulates positive genomic and cellular responses associated with effective cancer prevention and therapy and increased life span of mammals and humans. Nevertheless, this data is questioned because it seems to contradict the well demonstrated linear relation between ionizing radiation dose and damage to DNA without providing a clear mechanistic explanation of how low-dose radiation could produce such beneficial effects. This apparent contradiction is dispelled by current radiobiology that now includes DNA damage both from ionizing radiation and from endogenous metabolic free radicals, and coupled with the biological response to low-dose radiation” (Pollycove and Feinendegen 2008).

The above mentioned positive human response to chronic, increased DNA damage by low-dose radiation is achieved by increased stimulation of: *cellular antioxidant prevention* of DNA damage by free radicals, *enzymatic repair* of DNA damage, *immunologic destruction* of DNA damaged cells by “killer” T lymphocytes (Liu 2007), and *self destruction (apoptosis)* of DNA damaged cells (Figures 10, 11). These studies and similar ones in mice, rats and dogs have led to successful clinical trials in patients (Pollycove and Feinendegen 2008). Acceptance of current radiobiology would facilitate additional, urgently needed clinical trials of low-dose radiation (LDR) cancer therapy.

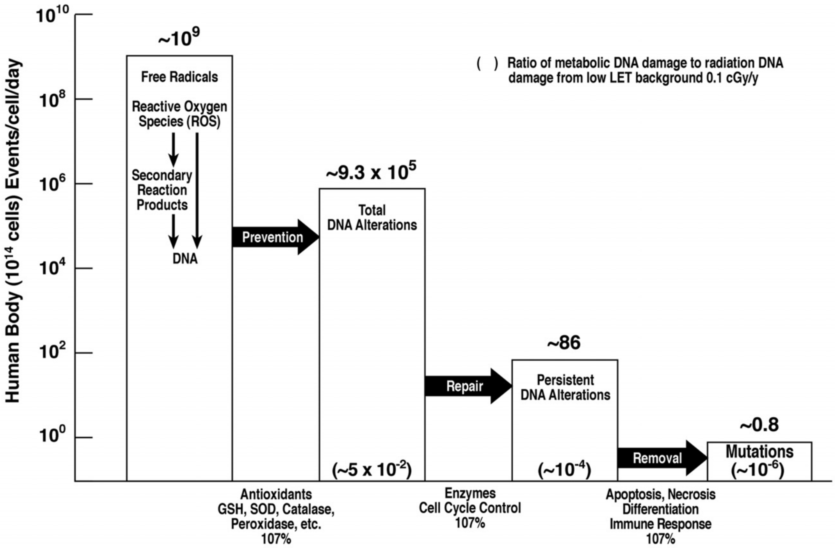

FIGURE 11. Effect of increased background radiation on the DNA damage-control biosystem

Stimulatory effects of low radiation doses were observed soon after x-rays and radioactivity were discovered. Internal and external applications of radium, i.e. drinking a radium salt solution or beaming radiation on specific areas, were used by physicians to treat many diseases, such as arthritis, high blood pressure, hypertension and pain (Rowland 1994). A study of more than 2000 radium dial painters determined the maximum body burden of radium to be 0.1 micrograms (including a 10–100 safety factor). A lifetime dose threshold at about 10 Gy was observed, below which *no* long-term excess bone cancers or other adverse effects appeared (Evans 1974).

Doses of x-rays, each in the range from about 0.5 to 1 Gy, have been used to stimulate defences sufficiently to cure a variety of infections, including very serious ones such as gas gangrene (Kelley and Dowell 1942). From the 1970s until the present, patients have been treated with low doses of radiation, in a number of studies, to prevent and cure cancer (Chaffey et al. 1976, Choi et al. 1979, Sakamoto et al. 1997, Richaud et al. 1998, Sakamoto 2004, Pollycove 2007). UNSCEAR 1994 contains a review of 192 studies of radiation hormesis (or the adaptive response). The results of many radon treatments appear in Becker 2003.

Ramsar, Iran is the site of a well controlled study of two large populations living together in one city, either in a high background area of 300 to 700 mSv/year, or in a low background area of 2 to 3 mSv/year (Figure 3). High background area residents demonstrate a marked increase in DNA repair and a marked reduction of standardized mortality rate and of age adjusted cancer mortality, similar to that seen in the US Nuclear

Shipyard Worker Study (Pollycove and Feinendegen 2001). The clinical trials of Choi et al. (1979) at Harvard University, and Sakamoto et al. (1997) at Tohoku University, evaluated the response of stage-matched relapsed patients with non-Hodgkin's lymphoma, previously receiving CHOP chemotherapy, to further treatment either by resumption of chemotherapy, or by whole body low-dose radiotherapy; namely 150 mSv twice each week for 5 weeks, a total of 1.5 Sv. No subjective negative side effects occurred in patients receiving whole body low-dose radiotherapy. Nine-year patient survival was 84% for those who received 1.5 Sv during 5 weeks of low-dose radiotherapy vs. 50% survival for those continuing with chemotherapy. Based upon *human* data, a single whole body dose of 150 mSv (15 rem) is safe. The high background of 700 mSv/year (70 rem/year) in the city of Ramsar, Iran is also a safe dose limit for continuous chronic exposure. Both dose limits are also beneficial.

The following explanation of the mechanism of radiation hormesis is based on many recent studies. As shown in Figure 10, the endogenous metabolic leakage of free oxygen radicals as reactive oxygen species (ROS) would alter DNA and other molecules in humans at a very high rate. The body produces antioxidants to prevent most of this potential damage. Repair processes markedly reduce the rate of DNA alterations, by a factor of about 10,000; removal processes reduce the rate of remaining mutations to about one per cell per day. The rate of metabolic DNA ROS damage is about 10 million times the rate of radiation DNA damage from 0.1 cGy/year of background radiation. Figures 11 illustrates how an increase by a factor of ten in background radiation, from 0.1 to 1 cGy/y, would stimulate antioxidant production, enzymatic DNA repair activity, and immunologic destruction of damaged cells by "killer" T lymphocytes, and self destruction (apoptosis) of damaged cells in order to significantly reduce the rate of accumulation of permanent DNA alterations, i.e., stem cell mutations, which are generally accepted to be associated with mortality and cancer mortality rates (Pollycove and Feinendegen 2001).

PROBABILISTIC RISK ASSESSMENT (PRA) FOR NUCLEAR REACTORS

To control and limit radiation exposures from a nuclear plant, the reactor, its fuel and all other radioactive materials are designed to be isolated from the environment inside sealed containers (i.e., within multiple barriers). Sources of radiation are surrounded by radiation absorbing materials (shielding).[9] The design includes redundant means of transferring energy, including decay heat, to "heat sinks" to avoid overheating the

9 Additional measures taken to reduce dose include shortening exposure times and increasing the distance between people and sources of radiation.

barriers. Accidents happen when failures of structures, systems and/or components occur due to various causes, including human error.

To assess nuclear reactor safety, engineers use a fault tree analysis to calculate both the likelihood of all conceivable accidents, and the resulting probability that people nearby might be harmed. The analysis starts with the initiating event (e.g., failure of a valve) and is followed by an event tree. The first probability is the probability of that event happening. Then the first branch in the event tree is examined and the probability that each option will occur is entered. Subsequently, the next branch in each option is examined and the probabilities that each of those possibilities will occur are entered, and so forth. Finally, the probabilities of the paths that lead to the accident are summed to obtain the probability of the accident.

The following two public safety goals are considered for US reactors (NRC 1986):

- The probability that a person living near the plant will die soon due to the radiation released must be less than 0.1 percent of the probability of being killed in any accident
- The increased probability of death from cancer for anyone following the accident must be less than 0.1 percent of the total probability of death from cancer from all causes.

The average probability per year that a person will die from all types of accidents is about one chance in 2000. The first safety goal means the probability that this person will die due to the radiation release must be 1000 times less; that is less than one chance in two million per year.

The NUREG-1150 study (NRC 1990) divided the reactor safety analysis into four fundamental parts: frequency of core damage, radioactive source term inside containment, probability of containment failure, and calculated off-site consequences. Using pessimistic assumptions, the average probability of core damage for one plant from all accident scenarios was one chance in 25,000 per year. Next, the amount of radioactivity that can be released into containment was considered, with particular focus on iodine-131, cesium-137 and strontium-90. The next steps addressed the ways that radioactivity can escape from containment and the off-site consequences, which depend on weather conditions, surrounding population density, evacuation plans and damage to health. The final step linked cancer risk to the calculated radiation doses using the "conservative" LNT assumption of radiation carcinogenesis. This study yielded a calculated probability for early death of one to four orders of magnitude *below* the goal. The calculated probability increase for latent cancer death was three to four orders of magnitude *below* the goal. So why are people so concerned about the safety of nuclear power? It seems that analysts continue to express concerns about nuclear safety and urge continuous improve-

ment in analysis and remediation. People will not feel safe until they are informed that a catastrophe is made impossible by the laws of nature and the properties of the materials and processes involved. In light of radiation hormesis, probabilistic risk assessments (PRAs) should only be used to identify potential improvements in design and operation. Cost-benefit analysis would establish whether remedial action would be practicable to avoid power plant failures. PRAs should not be used for calculating low-dose health risks because it is unethical to scare people with frightening myths (Cuttler 2007).

Many of the postulated accident scenarios are not realistic because they do not adequately credit the capabilities of the structures, systems and components, which are designed, manufactured, inspected (periodically tested) and maintained in service to an extremely high quality level. The experiences of nuclear events and accidents are being carefully recorded and analyzed by the Institute of Nuclear Power Operators (INPO 2008) and the World Association of Nuclear Operators (WANO 2008). The lessons learned are communicated to their members. Each licensed operator has been carefully selected, trained and tested periodically using computerized plant-specific simulators. Existing reactors were designed with automatic control and special safety systems to control reactivity, cool the fuel, contain the radioactivity and monitor plant variables. They incorporate features of "defence-in-depth" and active and passive safety measures that take into account the possibility of operator error. New reactors are being designed with improved safety features that exploit the advances in technology.

NUCLEAR REACTOR ACCIDENTS

Of the fourteen accidents that involved reactor core damage, only three occurred in large power-generating reactors (Eisenbud 1997 pg 254). The accident in 1957 at the plutonium-producing U.K. reactor Windscale No. 1 is important because the UK government subsequently set a safety exposure limit. The graphite-moderated core was partly consumed by fire, resulting in a large release of fission products, especially iodine-131, to the surrounding countryside. The contamination on the site did not reach dangerous levels and the dilution from wind variations reduced the hazard in the district. Measures taken to restrict milk consumption kept actual radiation exposures very low. Iodine-131 is the radionuclide of greatest concern because of its high yield in fission, high volatility, high activity (eight-day half-life), its great affinity for, and retention in the thyroid, and the moderately high energies of its beta and gamma radiations. Cancer of the thyroid in children has been known to occur following x-ray doses greater than 200 rad (2 Gy), so it was decided to limit the dose to children (and the entire population) to a maximum of 20 rad or 200 mGy (Eisenbud 1997 pg 390).

In the 1979 accident at the Three Mile Island No. 2 power reactor, failure of a valve and the lack of knowledge and understanding of what was happening led to inappropriate operator action. Removal of decay heat was stopped for a time. About 50 percent of the nuclear fuel melted before cooling was restored. The reactor containment retained almost the entire amount of radioactivity, including the iodine activity. The surrounding population received almost no radiation in excess of the natural background type; however, there was great fear of health consequences because the authorities did not understand what was happening and did not communicate accurate information on the real health risks (i.e., none) to the public in a timely manner. Subsequently, public fear of nuclear power led to the cancellation of some projects that had been underway to construct new nuclear plants in the United States.[10]

The 1986 Chernobyl disaster in the Ukraine is the most significant accident event in nuclear safety. The design of the Chernobyl reactors lacked adequate safety features and procedures that would have made them more tolerant of human mistakes. The operators lacked a strong safety culture, which could have deterred them from operating the reactor improperly and disabling safety systems when difficulties arose during their attempt to carry out a planned test of the Unit 4 turbine-generator rundown capability. The abnormal power manoeuvres put the reactor in a very unstable state. When the absorber rods were dropped to shut the reactor down, the power output unexpectedly increased within seconds to more than 100 times full power and destroyed the reactor. Six tons of highly irradiated fuel and most of the reactor's radioactivity (50 to 60% of the radioiodine inventory) were released to the surroundings (OECD 1996).

Three of the workers who tried to extinguish the fire and remove scattered debris were killed, one by the explosion, one from heart attack and one from thermal burns. Of the 134 who were treated for acute radiation exposure, 28 died within four months. Of the 106 who recovered from the acute exposure, 19 died during the following 18 years (IAEA 2005). This statistic conforms to the *normal* human mortality of about 1% per year. The Chernobyl staff continued to operate the other three reactors on this site until 2000, when the last one was shut down. The evacuated people and the workers who cleaned the site after the emergency received radiation doses that were within the range of the normal annual background level, well below the threshold for adverse health effects (Jaworowski 2004a, 2004b). No increase in mortality due to radiation has been observed, despite the prediction of 4000 excess cancer deaths (using the invalid LNT hypothesis—against the advice of scientific soci-

10 Many were finished if construction was underway. A few were mothballed, but this was because of the 15-18% interest rates on construction costs.

eties). This is an example of the "deeply immoral use of our scientific heritage" at a time when many scientists have a good understanding of the response of living organisms to low doses of radiation.

Screening for thyroid cancer, mainly in children, was begun immediately after the accident, and approximately 4000 cases were identified. Following the thyroid treatments received by affected individuals, nine deaths were recorded.

Communication with the public on the effects of the accident was poor at the start and remains inadequate. Psychological stress was the major adverse health effect in the surrounding populations due to concerns about the potential health consequences that were predicted by the authorities. The permanent relocations also caused great emotional suffering. Throughout the world, there was widespread fear of the radioactive contamination, resulting in very strong social and political reactions. The economic consequences were especially severe in the Ukraine and somewhat less so in neighbouring countries (UNSCEAR 2000).

Based on the relatively few fatalities (31), the Chernobyl accident will be remembered as a validation that nuclear power is probably the safest means of large-scale energy production, as was also demonstrated by the Three Mile Island accident (Jaworowski 2007).

LOCAL ENVIRONMENTAL EFFECTS OF THE CHERNOBYL ACCIDENT

The Chernobyl accident, April 26, 1986, is very important because it quantified the actual consequences of an unsafe reactor that was improperly operated. Although actions have been taken to prevent a recurrence, much can be learned by examining the actual environmental effects. This event released very large amounts of radioactivity on the site of the four-reactor station and into the surrounding environment. Cleanup workers removed the scattered radioactive debris, allowing the plant employees to continue operating the other three reactors for many years. The effects on the surroundings appear to be less severe than those of a forest fire.

In two highly contaminated areas to the south east, covering about 0.5 km^2, the radiation dose rates reached about 1 gray per hour, a few hours after the accident (UNSCEAR 2000). Even though the activity of the short-lived radionuclides was rapidly decreasing, standing there for 24 hours would have been lethal. Pine trees covering 500-600 hectares were severely damaged by doses in excess of 100 Gy, mostly from beta radiation. The deciduous trees in this zone suffered only partial damage. A larger area of about 3000 hectares received doses above 10 Gy. In a zone of 12,000 hectares, there were moderate effects, including growth suppression and needle loss. During the summer of 1986, as dose rates declined, there was continuing inhibition of growth. New growth was also evident, dependent on the accumulated dose. By the spring 1987, stems

and leaves were actively growing, although some morphological changes were noted in trees that received doses greater than 2 Gy. With the decline of dose rates to less than 10% of initial values, growth of trees continued and by 1988-1989 was apparent even in the highly contaminated 3000 hectare area. In 1986-1987, there was a marked reduction in the number of small insect species in the 30 km Exclusion Zone around the plant. Within this zone, the radiation doses to small rodents (up to mid-May 1986) exceeded lethal levels. There has been no report of a local population of a single species having been eliminated as a consequence of the radiation exposure. Radiation-related effects have been observed, along with some homeostatic adjustment or adaptation to altered conditions. There is evidence of recovery, in many instances, from the initial acute-phase responses, and in all areas, the populations continue to survive under long-term chronic irradiation (UNSCEAR 1996).

No acute effects have been reported in plants and animals outside the Exclusion Zone (OECD 1996). "Biota recovery in the Exclusion Zone has been facilitated by the removal of humans and the cessation of agricultural and industrial activities. As a result, populations of many plants and animals have expanded. Indeed, environmental conditions have had such a positive impact on biota that the Exclusion Zone has paradoxically become a unique sanctuary for biodiversity" (ANS 2005, IAEA 2005). Baker and Chesser (2000) describe the very remarkable creation of a wildlife preserve at the Chernobyl site.

THYROID CANCER IN CHILDREN

A comprehensive set of guidelines for patients with thyroid nodules and differentiated thyroid cancer (Cooper et al. 2006) states that nodules are a common clinical problem. The prevalence of palpable nodules is about 5% in women and 1% in men who are living in iodine-sufficient parts of the world. High-resolution ultrasound can detect thyroid nodules in 19%–67% of individuals. The clinical importance of nodules is the need to exclude thyroid cancer, which occurs in 5%–10%. Nodules are less frequent in children than in adults. Some studies have shown the frequency of malignancy to be higher in children than in adults, whereas other data indicate a similar frequency. Biopsy is sensitive and specific in the diagnosis of nodules. The relatively high incidence of naturally-occurring nodules casts doubt on their attribution to recent radiation exposure.

Radioiodine is used increasingly as the first-line therapy for hyperthyroidism, having been employed for this purpose for more than 60 years. The on-going concerns about the risk of cancer led to a 7417-patient study (Franklyn et al. 1999) that demonstrated significant decreases in overall cancer incidence (0.83, 95% CI = 0.77-0.90) and mortality (0.90,

CI = 0.82-0.98). "The decrease in overall cancer incidence and mortality in those treated for hyperthyroidism with radioiodine in reassuring." What makes this study so remarkable is the very large iodine-131 dose given to the patients: Mean (SD) = 308 (232) MBq. A hyperthyroid person treated with I-131 (sodium iodide) receives about 0.180 mGy/MBq total body and 1 Gy/MBq to the thyroid (Roedler et al. 1978). These patients receive a mean total body dose of 54 mGy and a mean thyroid dose of 308 Gy. Other studies of such patients also have not confirmed an increase in cancer incidences, as noted below.

Because of the very common belief that children are particularly susceptible to radiation-induced thyroid cancer, studies have been carried out to validate this notion. Early experiments with radiation led to applications for treating many medical conditions. A CDC study estimated that between 509,000 and 2,600,000 children received nasal radium irradiation treatments as a "standard medical practice" from 1945 through 1961 to shrink adenoids. Calculated doses were 20 Gy contact and 2 Gy at 1 cm from each applicator. A group of 902 school children, of whom 667 were followed up about 20 years after treatment, indicated three brain cancer deaths, one death from cancer of the soft palate and an 8.6 fold excess of a non-malignant thyroid disorder, which may be related to irradiation of the pituitary gland (Farber 1996).

A study of thyroid cancer in 14,351 infants after radiotherapy for skin hemangioma (abnormal concentration of blood vessels in the skin) (Lundell et al. 1994) revealed a total of 17 thyroid cancer deaths. An evaluation of seven major studies (Ron et al. 1995) included 58,000 exposed and 61,000 non-exposed subjects. The authors state that many issues remain unresolved because of insufficient data in individual studies. One was a study of 2,856 persons given x-ray treatment as infants for an enlarged thymus; it identified 42 thyroid cancers. Another was a study of 10,834 children who received x-ray therapy for Tinea Capitis (ringworm infection of the scalp). The number of thyroid cancers totalled 60; however, pituitary gland irradiation, affecting the hormone system, was likely a factor. Similarly, other studies of many children given large doses of radiation for enlarged tonsils and adenoids identified relatively few thyroid cancers. Because of the high rate of natural occurrence of thyroid cancer, it is not appropriate to attribute such thyroid cancer cases to radiation exposure (Lenihan 1993).

A review of studies of thyroid cancer after radiotherapy for childhood cancer (Inskip 2001) found that radiation-induced tumours appear five to ten years after irradiation and the excess risk persists for decades. These cancers are mostly of the papillary type, for which the cure rate is high if the tumours are detected early. Using LNT methodology, the author estimates that the average excess absolute risk is probably close to 0.4 cases per 10,000 person-years-Gy, implying about 200 thyroid cancers

among 10,000 children who received thyroid doses of 20 Gy and were followed for 25 years. "The apparent incidence of thyroid cancer is influenced by the aggressiveness of case-finding (screening). Papillary thyroid cancer often is asymptomatic, and the probability and timing of occult tumours depend on the level of medical surveillance. This may contribute to the very large relative risks for thyroid cancer reported when cancer patients or other irradiated populations under close medical surveillance are contrasted with the experience of a general population not subjected to equally close diagnostic effort" (Inskip 2001). There is little evidence that radiation-induced papillary thyroid cancers behave differently clinically than spontaneous tumours.

The effects of better reporting, heightened awareness, and screening after the Chernobyl accident may be a cause of the observed increase of thyroid cancer in Belarus; it might not be an effect of radiation at all (Jaworowski 2008b). A screening program in the USA revealed an incidence of thyroid cancers and of nodules that was seven and seventeen times higher (respectively) than before screening (Ron et al. 1992). This is the same as the increase seen in Belarus. Screening is mentioned eight times in a paper (Ron 2007) on this subject, but it is tied to thyroid cancer only three times:

1. "Extremely brief time period between radiation exposure and thyroid cancer diagnosis is striking and has not been documented previously." Actually, UNSCEAR 2000, Vol. II, p544, Table 57, points out the first high increase in thyroid cancer incidence of 9.1 cases in 100,000 children, that was observed in Russia in 1987, was one year after the exposure, which was contrary to all previous knowledge that suggested about 30 year latency period. Yet the paper states, "Whether the short latency ... is related to ... early detection screening ... is unclear."
2. "Because increased medical surveillance and early detection screening were introduced after the accident, comparison of thyroid cancer incidence before and after the accident can be misleading."
3. In quoting of the work of Ivanov et al, "These results suggest that the increased cancer rates in Bryansk compared with the general population rates are due to thyroid cancer screening and better reporting rather than radiation exposure." This view is supported by the fact that the thyroid cancer incidence was lower in the highly contaminated Bryansk region than in the general population of Russia.

Any serious work on Chernobyl thyroid cancers should discuss the problem of occult thyroid cancers, which is directly related to the effect of the enormous screening programs being carried out in the contaminated areas. Up to 90% of children are screened every year! Yet most papers on Chernobyl do not cite a single paper from the rich literature

on occult thyroid cancers, the incidence of which is much higher than that of the "Chernobyl cancers." There are Scandinavian studies showing that iodine-131, used in high doses for diagnostics and therapy, did not result in an increase, but rather a decrease of thyroid cancer incidence (Hall et al. 1996, Holm et al. 1988, Holm et al. 1991). These studies seem to be ignored by many investigators and the regulatory authorities. The abstract of the Ron 2007 paper states, "Twenty years after the accident, excess thyroid cancers are still occurring ... we can expect an excess of radiation-associated thyroid cancers for several more decades." The summary concludes with: "Further research also is needed" and a request for "Long-term follow-up of Chernobyl-exposed populations."

CONCLUSIONS

About 89% of the enormous global demand for energy is provided by burning coal and hydrocarbon fuels, and demand is growing rapidly. Society has valid concerns about the impact of the emissions on the environment and human health. Furthermore, current sources of petroleum products are not sustainable in the long term. Coal mining, oil and gas drilling, and transporting these fuels to consumers all have significant adverse effects on the environment and worker health and safety. There are also strategic considerations about the long-term sustainability of energy dependence upon and funding of hostile countries that supply these fuels. Energy from nuclear fission of uranium (and thorium) could sustain humanity indefinitely; however the application of this technology is constrained by health myths and anti-nuclear political activity.

Present-day nuclear power plants and the methods of designing, constructing, operating and maintaining them are very well understood. These facilities provide a very high level of nuclear and industrial safety so long as the people who design, build, operate and maintain them are properly trained and imbued with a strong safety culture. The designs of modern plants have many layers of defence-in-depth, which afford considerable tolerance of human error. The result of all these efforts is that most failures do not result in any release of radioactivity, and the worst realistic case, including fuel melting and containment compromise, is expected to cause few, if any, fatalities to the public. The industry is well aware of the immense public fear of radiation and the media's strong desire to publicize and exaggerate the significance of any nuclear incident.

Scientists and engineers have developed technologies for many different types of nuclear power plants, including breeder reactors that can convert uranium-238 and thorium-232 into readily fissionable fuels. With breeder reactors, it would be feasible to extract uranium from the oceans and still keep the fuel cost below one percent of the cost of electricity. Rivers are carrying uranium into the seas at a rate that would allow at least

6,500 tons of it to be withdrawn each year. This amount would be adequate to generate approximately ten times the world's present electricity usage, year after year. Fission of uranium in breeder reactors is consistent with the definition of a "renewable" energy source in the sense in which that term is generally used.

Techniques have been developed and tested to recycle used nuclear fuel in a manner that does not yield materials and pathways for diversion to the manufacture of nuclear weapons; however, these innovations are not widely known. The volume of used fuel and the amount of radioactive waste from recycling is relatively small. Compared to fission, roughly 100 million times more coal, oil or gas material is burned to produce the same amount of energy, and the ratio of the waste is therefore similar. The half lives of the major radionuclides from *completely* recycled nuclear fuel (cesium-137 and strontium-90) are relatively short, about 30 years. Surface storage of used fuel and waste in robust containers presents no hazard to the environment because there are no exposures. Geological disposal of waste has been shown to be technically feasible. Demonstrating social acceptance of this solution has been challenging because of the fears that have been created regarding adverse health effects of low doses of (human-made) radiation.

The number of severe nuclear power plant accidents and the number of fatalities are quite low. Because reactors have a very high power output and hold very large amounts of radioactivity, considerable care has been taken to control the reaction, cool the fuel and contain the radioactivity. Nuclear safety is the number one priority. Accidents are very expensive because of the loss of electricity supply to many consumers who depend on reliable power, the very high cost to repair the damage, and the loss in revenue. Injuries would result if plant employees receive high radiation doses. Even though low radiation doses are beneficial, nuclear plant owners will continue to maintain a very high degree of nuclear safety. Any accidents that release radioactivity would result in loss of social acceptance.

It has been claimed that thyroid cancer is the most common long-term effect of low dose radiation exposure in children. Nuclear safety regulations are based on tight radioiodine dose limits. A review of many recent scientific publications does *not* support this concern. Thyroid cancer is not an uncommon occurrence in most populations; it does not appear to be related to radiation exposure. Radioiodine treatment of hyperthyroidism does not appear to cause a detectable increase in cancer. On the contrary, decreases in overall cancer incidence and mortality are reported.

The short-term health effects of nuclear radiation on humans and other living things have been extensively studied for more than a century. Over the past 50 years, a vast multitude of studies have been carried out to determine the long-term health effects of nuclear radiation.

Adverse health effects are observed following high doses (or high dose rates), and much of the data has been fitted by a straight line function of dose (or dose rate) in the high range. It has been generally impossible to detect significant adverse effects in the low dose range, so predictions of adverse effects in this range were made by extrapolating the straight line fit to zero (LNT hypothesis). Professional societies have issued position statements advising analysts not to use the LNT hypothesis to predict adverse health effects in the low dose range. Studies that looked for beneficial health effects generally revealed increasing stimulation with increasing radiation dose (or dose rate) above the ambient level, until a maximum was reached. Decreasing stimulation was noted as exposures were increased beyond the optimum value, followed by a crossover into the inhibitory domain (radiation hormesis model, Figures 8 and 9). The results of these important studies have not been factored into the radiation protection regulations.

Based upon human data, a single whole body dose of 150 mSv (15 rem) is safe. The high background of 700 mSv/year (70 rem/year) in the city of Ramsar, Iran is also a safe dose limit for continuous chronic exposure. Both dose limits are also beneficial.

People are generally not familiar with nuclear radiation. While they understand light and accept exposure to radio waves, they have been taught to fear ionizing radiation (x-rays and nuclear radiation). Most people are frightened of human-made radiation, but some are aware of, and seem to accept, naturally occurring radiation (average of 15,000 events in the body per second).

Ionizing radiation was discovered more than a century ago and low doses of radiation were used extensively in medical treatments for about 50 years, even though the biology underlying the beneficial health effects was not known. Fear of any exposure to radiation was created mainly by the nuclear community, and the anti-nuclear activists endorsed it. The advent of antibiotics and other biochemical agents in the 1950s led to the abandonment of radiation as a stimulatory agent for most of its medical applications. Today, tumours are irradiated with high doses of gamma rays (from radium or cobalt-60) and with x-rays from electron accelerators to kill cancer cells. X-rays and radioisotopes are widely used in medical imaging, but concerns continue to be raised about potential genetic effects and long-term risk of cancer from these low doses.

From the early 1900s until about 1960, many successful medical treatments with low-dose radiation were given to patients with serious infections and other illnesses. Between the early 1970s and the present, low-dose radiation treatments were provided to many patients to prevent and cure various types of cancer. Good results were achieved. These treatments, which stimulate protective biological processes, are still unaccepted.

RECOMMENDATIONS

Professional and scientific societies, both nuclear and medical, should organize meetings and other events to discuss the benefits of low-dose radiation and the changes needed to technical standards and procedures, and to regulatory standards. Compliance with these standards, which are based upon the transparently erroneous LNT hypothesis, requires the expenditure of hundreds of billion dollars annually.

National and international nuclear regulatory authorities and health organizations should examine the extensive scientific evidence and their own attitudes about the health effects of ionizing radiation. New standards for radiation protection should be prepared that are realistic, i.e., based on evidence from radiobiological science and the ubiquitous occurrence of natural radioactivity. These standards should reference carefully reviewed scientific publications, particularly those ignored or summarily dismissed by policy-setting studies. The literature indicates a lack of definitive evidence of harmful health effects and strong evidence of beneficial health effects after exposures to low doses or low dose rates. Harmless and beneficial doses of radiation should not be regulated.

After bringing the nuclear community and its policies and practices into line with the science, a public communication program should be carefully developed, including a strategy on how to explain the reality of low-dose radiation hormesis effects. The beneficial health effects of low doses and low dose rates should be emphasized. This program would lead to widespread social acceptance of nuclear technologies, which then could supply the major portion of the world's growing need for energy. A further benefit would be a rational public reaction to terrorist "dirty bomb" explosions that would release radioactivity.

Emergency response personnel should be taught the reality of radiation effects, and they should factor this information into their plans and procedures.

The standard for releases of radioactivity from geological nuclear waste repositories should reflect radiobiology and the response of humans and other living species to natural and medical radioactivity.

Used fuel management should reorient from deep geological disposal to recycling in breeder reactors.

Even though low doses are beneficial, nuclear plant owners and operators should continue to exercise great care in containing radioactivity releases and controlling worker exposures in the potentially harmful range.

Because they identify weaknesses in design and operation, probabilistic risk assessments (PRAs) are carried out to suggest improvements that can reduce the likelihood of accidents. However, in light of radiation hormesis at low dose levels, PRAs should not be used for calculating low-dose health risks because the result, a prediction of an increased cancer

risk rather than a decreased cancer risk, would be both erroneous and misleading.

ACKNOWLEDGMENTS

The authors are pleased to acknowledge the support provided by The American Council on Science and Health.

The authors wish to thank the following for their comments on the manuscript: Bernard L. Cohen, Michael R. Fox, Zbigniew Jaworowski, P. Andrew Karam, Rita Keating, Carl J. Paperiello, Theodore Rockwell, Gilbert L. Ross, Andrzej Strupczewski and Hugh L. Thompson.

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