Ionizing Radiation And Radioactivity In the 20th Century

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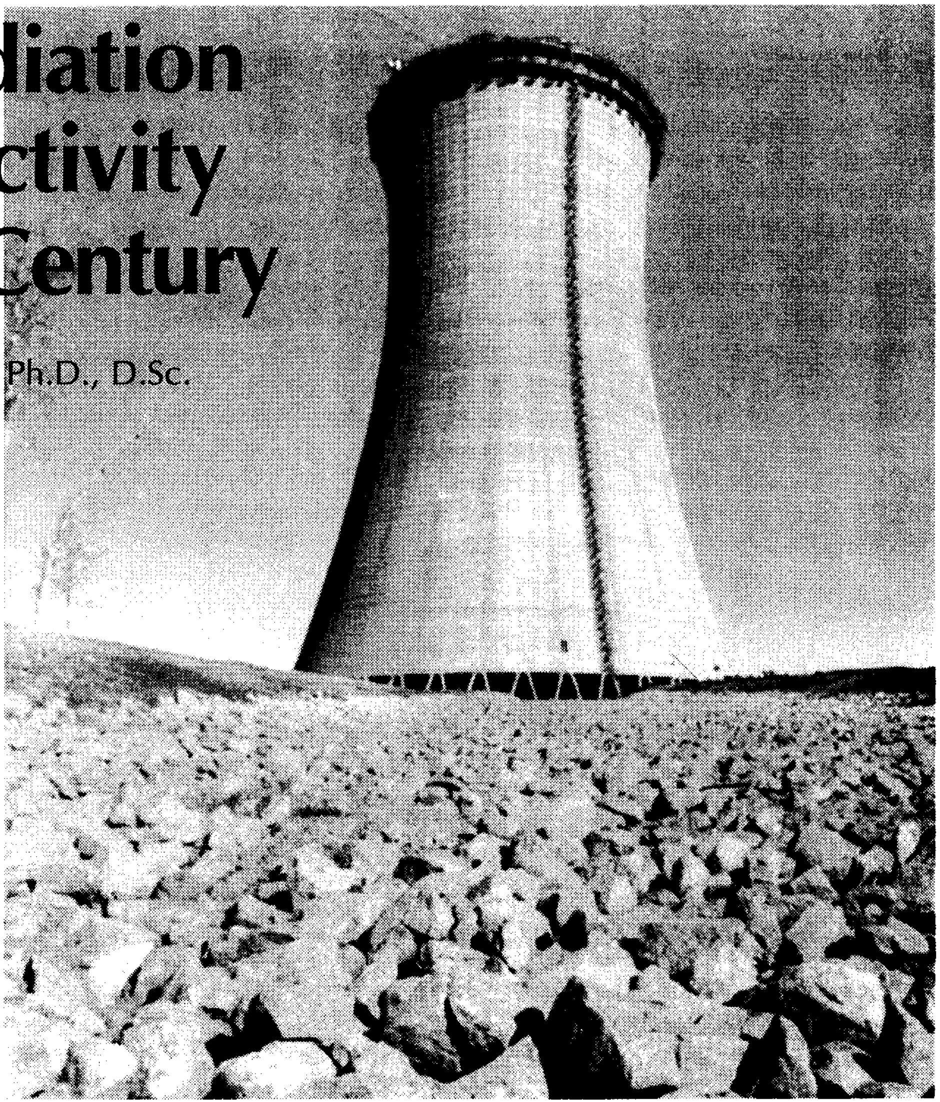

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A nuclear cooling tower—a symbol of Atoms for Peace. Here, Savannah River's K Reactor cooling tower, during construction in 1991.

Since ionizing radiation and radioactivity were discovered at the end of the 19th century, their social status has oscillated between enthusiastic acceptance, and rejection. This oscillation was concurrent with recognition of three basic aspects of radiation: its usefulness for medical applications and for technical and scientific aims, its beneficial effects at low levels, and its harmful effects at high levels.

In the first part of the 20th century, acceptance prevailed; in the second, rejection. The change of public mood, which occurred rather abruptly after World War II, did not result from the discovery of some new danger of radiation, but from political and social processes that were not related to real radiation effects (Jaworowski 1999). The most important factor of this change was the apocalyptic specter of nuclear war, and its illegitimate child, the linear no-threshold theory (LNT), which was applied to the effects of low doses of radiation.

The possibility of the use of ionizing radiation for medical diagnostics was first demonstrated by W.K. Roentgen, who, one month after his discovery, published an X-ray photograph of the hand of his wife, in *Nature* magazine in January 1896. In 1902, Pierre Curie, together with two physicians, C. Balthazard and V. Bonchard, discovered that radium rays are efficient in cancer therapy.

The theoretical basis for this therapy was posed in 1906 by J. Bergonie and L. Tribondeau as the result of their experiments with rats. They coined the following law: "X-rays are more effective on cells which have a greater reproductive activity." From this law, they commented, perhaps too optimistically, that it is "easy to understand that roentgen radiation destroys tumors without destroying healthy tissues."

The beneficial, or hormetic, effects of low doses of ionizing radiation were found two years after Roentgen and, independently, A.H. Becquerel, announced the discovery of ionizing radiation. The first such effects in algae were reported by Atkinson in 1898. He noticed an increased growth rate of blue-green algae exposed to X-rays. This particular observation was followed by thousands of publications on hormetic effects, and it was repeated and confirmed 82 years later (Conter, Dupouy, and Planel 1980).

That ionizing radiation can be hazardous to man was first reported in the German *Medical Weekly* (Marcuse 1896). The early students and users of radiation voluntarily, or unknowingly, exposed themselves to high radiation doses. Among the pioneers of radiation and radioactivity, about 100 persons had died by 1922, and 406 had died by 1992, all from afflictions that could be

"Radiation protection is not only a matter of science. It is a problem of philosophy, morality and the utmost wisdom."

—Lauriston S. Taylor, 1957

Le Radium

Le Radium

Three pioneers of ionizing radiation: (from left) W.K. Roentgen, Pierre Curie, and A.H. Becquerel.

related to radiation. These figures, from 23 countries, include scientists, physicists, medical doctors, nurses, and X-ray technicians.[1]

The first fatal victim of ionizing radiation was a German engineer, F. Clausen, who died in 1900. This experience sounded the alarm, and thus the need for protection against high doses of radiation was realized quite early.

In the 1920s, the concept of "tolerance dose" was introduced, defined as a fraction of a dose that caused reddening of the skin. This fraction corresponded originally to an annual dose (in modern units) of 700 mSv. In 1936, the tolerance dose was reduced to 350 mSv; and in 1941, it was reduced further, to 70 mSv.

This concept of tolerance dose, which was effectively a statement of a threshold dose, served as the basis for radiation protection standards for three decades (Kathren 1996), until, in 1959, the International Commission on Radiological Protection made a new recommendation, based on the linear no-threshold principle (LNT) (ICRP 1959).

The introduction of the LNT principle to radiological protection was stimulated by an undue concern, in the 1950s, for the disastrous genetic effects of man-made ionizing radiation on the human population. At that time, one would often see statements by geneticists in the literature on radiation, similar to this one:

". . . We have reached a stage where human mistakes can have a more disastrous effect than ever before in our history—because such mistakes may drastically change the course of man's biological evolution" (Westergaard 1955).

Subsequent history and, especially, the observations of the progeny of survivors of nuclear attacks on Hiroshima and Nagasaki, demonstrated that this concern was an overreaction, tinged with strong emotions, and evoked by the menace of nuclear war. Such feelings are not the best basis for regulations.

Professor W.V. Mayneord, the late chairman of the ICRP Committee IV, commented on using LNT as the regulatory basis: "I have always felt that the argument that because at higher values of dose an observed effect is proportional to dose, then at very low doses there is necessarily some 'effect' of dose, however small, is nonsense" (Mayneord 1964). Mayneord's worry about the values of ICRP recommendations was, as he put it, "the weakness of the biological and medical foundations coupled with a most impressive numerical facade."

During the past several decades, there has been a tendency to decrease the standards of radiation protection to ever-lower values, which in the 1980s and the 1990s, reached 20 mSv per year for people exposed to radiation because of their occupations, and 1 mSv per year for the general population.

Even lower values have recently been proposed: For example, it is proposed that there be a maximum dose of 0.3 mSv in a year for an individual who receives no direct benefit from a source of radiation (Clarke 1999), and for some instances, that the level be 0.01 mSv per year (Becker 1998). Justification for such low levels is difficult to imagine, as *no one has been identifiably injured by radiation while exposed within standards that are hundreds or thousands of times higher,* set by the ICRP in the 1920s and the 1930s (Taylor 1980; Coursaget and Pellerin 1999).

The life expectancy of the survivors of nuclear attacks on Hiroshima and Nagasaki was found to be *higher* than that of control groups (Kondo 1993), and no adverse genetic effects were found in the progeny of survivors (Schull 1998). There is also ample evidence of beneficial effects of low doses of radiation in people who are occupationally, medically, or naturally exposed to doses much higher than the current radiation protection standards (see, for example, Tubiana 1998).

High Costs, No Benefits

For adherence to regulations based on such low standards, society pays hundreds of billion of dollars, with no detectable benefits. Each human life hypothetically saved by implementing these regulations costs about $2.5 billion (Cohen 1992)! Such spending is morally questionable: first, because the limited resources of the society are spent on preventing an imaginary harm, instead of on real advancement of health, and second, because low radiation doses are beneficial for the body.

In fact, for these two reasons, such expenditures to carry out radiation regulations may actually have an *adverse* effect on the population.

In this presentation, I wish to compare the levels of radioactivity and radiation in various environmental situations, as influenced by natural processes and by human practices. Such a comparison may help put radiation standards in a realistic perspective.

What Is Radioactivity?

When life began some 3.5 billion years ago, the natural level of ionizing radiation at the planet's surface was about three to five times higher than it is now (Karam and Leslie 1996). At that time, the long-lived potassium-40, uranium-238, uranium-235, and thorium-232 had not yet decayed to their current levels.

Table 1
AVERAGE ACTIVITY OF NATURAL RADIONUCLIDES COMPARED WITH ACTIVITY OF NUCLEAR WASTE (in Bq)

Radionuclides	K-40	Th-232	U-238	Total
Concentration of parents in 1 g of soil	0.420	0.045	0.033	0.498
Number of radionuclides in chain	1	9	14	24
Content in crust (17.3×10^{24} g)	7.3×10^{24}	7.8×10^{23}	5.7×10^{23}	8.6×10^{24}
Soil (in 1 ton)	4.2×10^{5}	4.1×10^{5}	4.6×10^{5}	1.3×10^{6}
Soil (in 1 km^3)	8.4×10^{14}	8.1×10^{14}	9.2×10^{14}	2.6×10^{15}
Wastes from nuclear power reactors in 1997				2.2×10^{15}*
Wastes accumulated until 2000 from the whole civilian nuclear fuel cycle, after 500 years cooling				7.4×10^{15}*

Notes

* Estimated by the author

The average activity, measured in bequerels, of whole chains of natural radionuclides in the continental crust and soil, compared with the total activity of wastes from nuclear power. The natural activity from nuclear waste is comparable to that contained in a relatively small block of average soil that is 0.9 km square and 1 km deep. None of the man-made components of nuclear wastes has appreciably higher radiotoxicity (expressed as Sv/Bq) than the natural radioisotope thorium-232.

Source: Jaworowski 1990 and UNSCEAR 2000

Table 2
ANNUAL FLOWS OF RADIONUCLIDE ACTIVITY INTO GLOBAL ATMOSPHERE

Source	Activity (Bq)		Energy (J)[e]	
Natural	Rn-222	3.3×10^{19}	Rn-222	3.0×10^{7}
Nuclear weapons: explosions and production[a]	H-3	7.0×10^{18}	H-3	2.1×10^{4}
Chernobyl[b]	Cs-137	7.0×10^{16}	Cs-137	6.1×10^{3}
Nuclear power[c]	H-3	5.6×10^{16}	Rn-222	1.3×10^{4}
Natural: Volcanic activity (non-eruptive)[f]	Po-210	5.1×10^{15}	Po-210	4.4×10^{3}
Coal burning[d]	Rn-222	8.5×10^{14}	Rn-222	7.6×10^{2}

Notes

(a) Annual average for 1945-1980
(b) Emission during 10 days in 1986
(c) Average for 1981
(d) Average for 1980
(e) Decay energies adapted from Magill 1999
(f) Calculated from data of Berresheim and Jaeschke 1983, and Lambert, Le Cloarec, and Pennisi 1988

Shown here are the most important annual flows of activity of radionuclides and of their radiation energy into the global atmosphere. The activity is measured in bequerels; energy is measured in joules. The flow of radioactivity from natural sources into the global atmosphere is 100 to 100,000 times higher than that from particular man-made sources, and the flow of radiant energy is 1,000 to 100,000 times higher than the flow of radioactivity from man-made sources. On the global scale, man-made emissions of radionuclides, and their impact, are dwarfed by the natural sources.

The content of these radioisotopes in the Earth's crust today is still quite high, and it is responsible for the highest radiation exposure of almost all living beings. One ton of average soil contains about 1.3×10^6 Bq of potassium-40, thorium-232, and uranium-238, and their daughters. This corresponds to 2.6×10^{15} Bq per cubic kilometer (Table 1).

Decay of these natural radionuclides present in a layer of soil 1-kilometer thick, produces 8,000 calories per square meter annually (Draganic, Draganic, and Adloff 1993).

We can compare the natural, extremely long-lived activity of potassium-40 (halflife = 1.28×10^9 years), thorium-232 (halflife = 1.4×10^{10} years) and uranium-238 (halflife = 4.47×10^9 years) in soil, with the activity of much shorter-lived radioactive wastes from the nuclear power cycle.

In 1997, the total annual production of electricity in nuclear reactors was 254.5 gigawatts (GW) (UNSCEAR, 2000a). With an annual production of wastes from nuclear power reactors of 8.8×10^9 Bq per megawatt-electric (MWe) (Saas 1997), the global production of radioactive wastes from this source amounts to 2.2×10^{15} Bq per year, with the longest lived plutonium-244 (halflife = 8.26×10^7 years). This amount of natural activity is contained in a relatively small block of average soil that is 0.9 km square and 1 km deep. None of the man-made components of these wastes has appreciably higher radiotoxicity (expressed as Sv/Bq) than the natural thorium-232 (IAEA 1996).

No special barriers prevent the natural radionuclides from migration from, say, a depth of 1 km to the surface of the ground. They can be transported by mechanical actions, or move in solution.

Thorium is not susceptible to leaching under most geological conditions, and its principal mode of occurrence is in refractory minerals. Uranium is mobile, and may migrate with ground water to distances of several tens of kilometers or more. Radium is highly mobile in sulfate-free neutral or acidic solutions. The average volcanic injections of alpha emitting polonium-210 into the global atmosphere during non-eruptive activity,

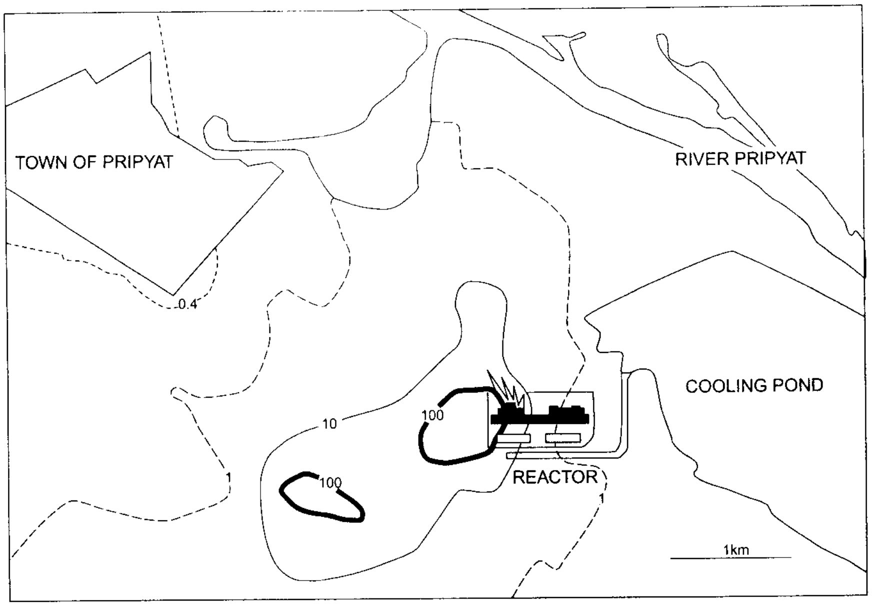


Figure 1

MEASURED RADIATION EXPOSURE RATES IN AIR ON APRIL 26, 1986, IN THE CHERNOBYL AREA

On the first day after the accident, there was a high ground contamination, consisting of two patches in an uninhabited location (heavy lines) with a dose rate of about 1 Gy per hour; this dose rate can be lethal after a few hours. It covered an area of about 0.5 km^2, and reached a distance of 1.8 km from the burning nuclear reactor.

Several hundred meters outside the 1 Gy isolines, the dose rate dropped by two orders of magnitude.

The units of the isolines are in roentgen per hour.

amount to about 5 × 10^{15} Bq per year; that is, almost twice as much as the 1997 production of radioactive wastes from nuclear power reactors (Table 2).

Geochemical differences between uranium, thorium, and radium may lead to drastic changes in their radioactive equilibrium (Jaworowski 1990).

In contrast, for man-made radioactive wastes, many effective, sophisticated barriers are provided in deep underground depositories. At a first glance, one can see in Table 1 that it would take about 3 billion years of such a global production of wastes from nuclear power reactors, at the amount produced in 1997, to double the total activity of natural radionuclides in the Earth's continental crust.

The activity of nuclear wastes that have been accumulated up to the end of 2000, from the entire global civilian nuclear fuel cycle. is much greater. It amounts to 200,000 tons of "heavy metals," which, after 10 years of cooling, corresponds to activity of about 7 × 10^{21} Bq (Semionov and Bell 1993). Disposal of high-level wastes and spent fuel in geologic repositories cannot result in doses to populations until well after 500 years (OECD 2000). After 500 years, the radioactivity of all high level wastes accumulated until now will decrease to about 7.4 × 10^{15} Bq (Chwaszczewsk, 1999), corresponding to the natural radioactivity contained in an average block of soil, about 1.7 km square and 1 km deep, and consisting of about a 1-billionth part of the natural activity present in the Earth's crust.

It is interesting to compare the annual flows into the global atmosphere of radionuclides from natural sources, with flows from nuclear weapon production and explosions, the nuclear power fuel cycle, coal burning, and the Chernobyl catastrophe. The flows of nine radionuclides, with the greatest potential impact on public health (except for the Chernobyl catastrophe) are compared in Table 2 (Jaworowski 1982). Here, I present only the highest flows of activity from particular sources. To account for various energy emissions by different nuclides, the flows of radiation energy are also given.

Table 2 demonstrates that the flow of radioactivity from natural sources into the global atmosphere is 100 to 100,000 times higher than that from particular man-made sources, and the flow of radiant energy is 1,000 to 100,000 times higher than the flow of radioactivity from man-made sources. It appears that on the global scale, the anthropogenic emissions of radionuclides, and their impact, are dwarfed by the natural sources.

In the case of nuclear power, the highest flow of activity is that of hydrogen-3 (5.6 × 10^{16} Bq per year), but the highest flow of radiation energy is that of radon-222, because its decay energy (5.6 MeV) is higher by a factor of 300 than the decay energy of hydrogen-3; radon-222 activity flow is only 1.5 × 10^{16} Bq per year.

This might not necessarily be the case at the local scale, especially in military practices. The widest civilian contamination of ground surface occurred after the Chernobyl accident. On the first day after the accident, which was probably the greatest possible civilian nuclear catastrophe, there was a high ground contamination, consisting of two patches in an uninhabited location with a dose rate of 1 Gy per hour; this dose rate can be lethal after a few hours. It covered an area of about 0.5 km^2, and reached a distance of 1.8 km from the burning nuclear reactor (UNSCEAR 2000).

Several hundred meters outside the 1 Gy isolines, the dose rate dropped by two orders of magnitude (Figure 1). Fortunately, this situation did not pose immediate danger for the general population. This can be compared with an isoline of 1 Gy per hour after a 10-megaton surface nuclear explosion, reaching (at calm weather) to a distance of 440 km (Miller 1968), and covering with lethal fallout tens of thousands square kilometers.

In the localities remote from the Chernobyl power station, the deposition of radionuclides was much lower, and did not reach levels which could lead to acute radiation health effects, or to chronic effects, such as genetic disturbances, leukemia, or solid cancers (UNSCEAR 2000).

The only exception might be the increase of registration of thyroid cancers in children and adults (UNSCEAR 2000c). Until now only one young girl has been suspected as having died from radiation-related thyroid cancer after the Chernobyl accident (Ilyin 2000; Becker 2000). However, the increase of registration of thyroid cancers may be a result of causes other than Chernobyl radiation, the most probable among them being the screening effect.[2]

Radiation Doses

The global distribution of radionuclides in the biosphere, and the use of radiation are reflected in the radiation doses received by the population from various sources. During the past several decades, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has been collecting data on doses from radionuclides in the environment, and from their use in medicine and other applications. Although far from being complete, the UNSCEAR compilation of data is the most comprehensive one available, and it enables estimation of the temporal changes in average annual radiation doses received by the global population from particular sources.

In its reports to the General Assembly of the United Nations, UNSCEAR refrained from presenting the results of such estimations expressed in units of rems or sieverts in graphic form. I present them in Figure 2, based on internal documents of UNSCEAR (for a part of medical and natural exposure), and on the UNSCEAR published data (UNSCEAR 1988; UNSCEAR 2000).

The highest annual radiation dose is received from natural sources. The average natural external and internal exposure of the global population currently estimated by UNSCEAR, is 2.4 mSv per year. The natural dose ranges widely in particular regions of the world. UNSCEAR estimates for parts of East Asia and Europe suggest that 39 percent of the population receives annual doses from terrestrial gamma radiation lower than 1.5 mSv; 30 percent receive doses of 1.5 to 1.99 mSv; 18 percent receive doses of 2.0 to 2.99 mSv; 6.3 percent receive doses of 3.0 to 3.99 mSv; and only 0.4 percent receive doses higher than 10 mSv. However, this estimate does not cover areas of high natural radiation background, such as in Iran, India, or Brazil.

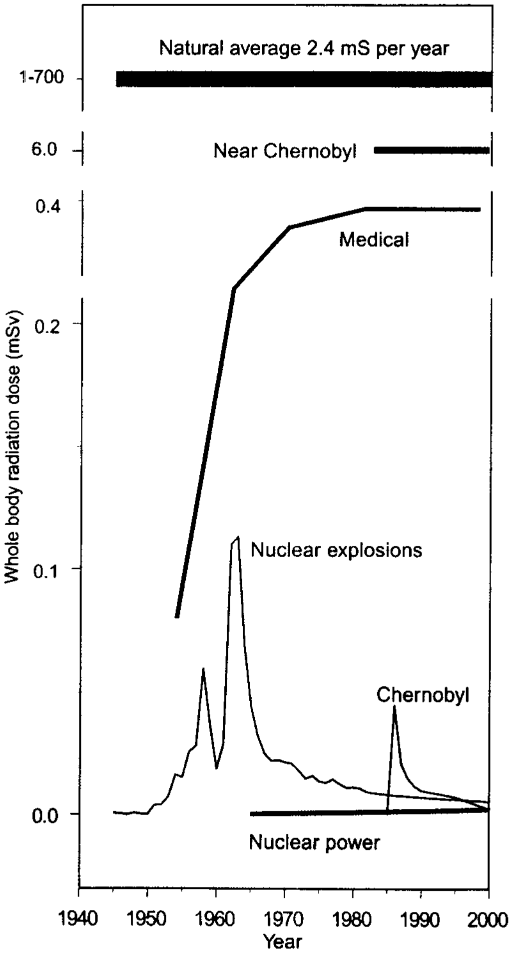


Figure 2
ANNUAL TRENDS IN AVERAGE INDIVIDUAL GLOBAL RADIATION DOSES BY SOURCE (1940-2000)

By far, the highest annual radiation dose is received from natural sources—and has remained constant. The average natural external and internal exposure of the global population currently estimated by UNSCEAR, is 2.4 mSv per year, but doses vary widely across the globe. The natural radiation dose dwarfs that from medical procedures, from nuclear explosions, and from the Chernobyl accident. Radiation from nuclear power plants is near zero.

Source: Based on UNSCEAR 1988, UNSCEAR 2000

For example, in the State of Kerala, India, the annual radiation dose reaches up to 76.4 mGy (a lifetime dose of more than 5 Gy), and it is not associated with an increased cancer incidence or cytogenetic aberrations (Nair et al. 1999). In the area of Araxa, Brazil, which has 74,000 inhabitants, the average annual radiation dose is 24.5 mGy. In the city of Ramsar, Iran the absorbed dose rate in air reaches up to 153 mGy per year (UNSCEAR 2000).

In some parts of Ramsar, people are living in houses where the annual radiation dose is up to about 700 mGy (Mortazavi, 2000). This is comparable to the value of the tolerance dose established in the 1920s, and corresponds to a lifetime dose of about 50 Gy. In the area of Ramsar, people are exposed to such high radiation levels for several generations. Cytogenetic studies have shown differences between these people and control groups, but the Ramsar population shows no increase in the incidence of cancers and leukemia.

Man-made Sources Are Trivial

Compared with the apparently nonharmful annual doses in the high natural radiation areas, the average doses received by the global population from man-made sources seem to be of no importance. This statement is valid also for about 4.8 million people living in areas contaminated by the local fallout from the Chernobyl accident (UNSCEAR 2000), where the average annual radiation dose is about 6 mSv. The highest average dose to the global population from Chernobyl fallout was 0.045 mSv in 1986.

Global exposure from medical diagnostics was rapidly growing from the 1950s, probably the result of steadily increasing access to X-ray technology in the developing countries. However, since the 1980s this exposure seems to have stabilized. Even at its greatest con-

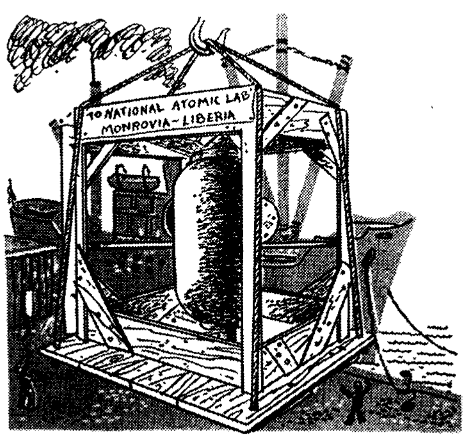
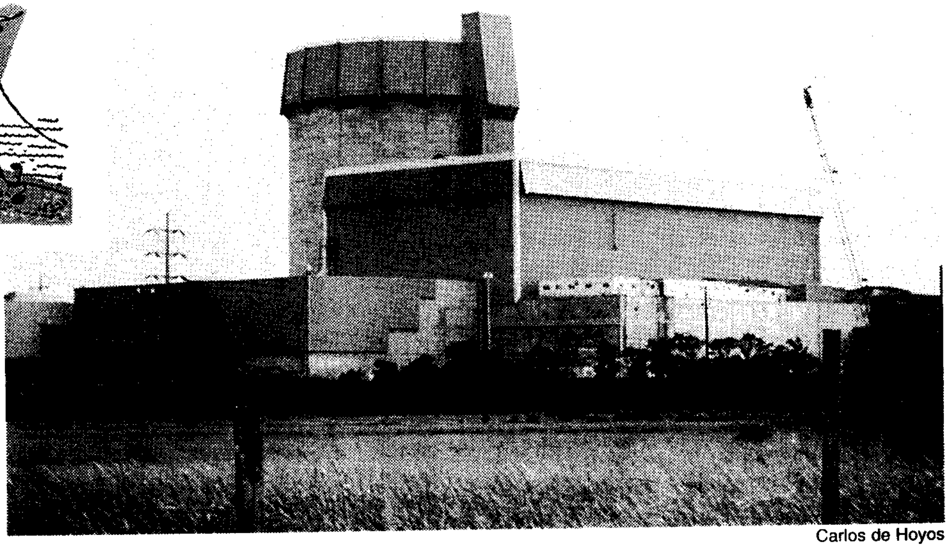


Illustration by George Wilde in Ira M. Freeman, *All About the Atom* (New York: Random House, 1955), p. 123

The promise of nuclear energy for lifting the world's population out of poverty, was cut short by the anti-population, anti-science movement of the 1970s. In the 1950s and 1960s, the "Atoms for Peace" spirit pervaded popular culture, as this illustration from a 1955 children's book shows. Two and a half decades later, Shoreham, a fully ready nuclear plant, was a victim of anti-nuclear pressure on Long Island, New York, and shut down despite the need for electrical power.



Carlos de Hoyos

tribution at the early 1960s, the average global exposure from nuclear weapons tests (0.113 mSv in 1963) was much smaller than medical exposure. The exposure from the civilian nuclear power cycle has been steadily growing since 1955, reaching a trifling value of 0.002 mSv in 2000.

Time for a Realistic Policy

Man's contribution to the contents and flows of radionuclides and of radiation energy in the environment comprises a tiny fraction of the natural contribution. In some areas in the world, the natural radiation doses to man, and to other biota, are many hundreds of times higher than the currently accepted dose limit for the general population. No adverse health effects have been found in humans, animals, and plants in these areas.

In the future reconstruction of the edifice of radiation protection, that now stands on the abstract foundations of the linear no-threshold, a down-to-earth approach will be necessary, taking into account apparently safe chronic doses in the high natural radiation areas, rather than the statistical variations around an average global value. It seems, therefore, that studies of these areas deserve a special attention and support in the coming years.

The 20th century witnessed the dawn of man-made ionizing radiation and radioactivity, the use of this advanced human knowledge to kill people in Hiroshima and Nagasaki, and the greatest nuclear catastrophe in Chernobyl. This 1986 catastrophe has claimed only about 30 deaths of nuclear workers, and probably none, or perhaps one, among the public. This proves that nuclear energy is a comparatively safe means of producing power.

It has also been documented that high, semi-acute radiation doses can cure cancers, and that small chronic doses of radiation are beneficial for health. Man's discovery of "new" radiation, and of radioactivity, which opened the door to unlimited energy sources, is similar to the discovery of fire some 500,000 years ago. Fire made man the most ubiquitous species and enabled expansion of life outside the Earth's biosphere. It took our ancestors many thousands of years to mentally adapt to fire, sometimes even deifying it. It seems that one century has not been enough for such adaptation to ionizing radiation and radioactivity. But there is hope: discoveries today are developing much faster than in the past.

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Acknowledgements

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Notes

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1. The names of all victims are recorded in "Book of Honor of Roentgenologists of All Nations," published in Berlin in 1992 (Molineus, Holthusen, and Meyer, 1992).
2. For a more detailed explanation, see the author's article "A Realistic Assessment of Chernobyl's Health Effects," *21st Century,* Spring 1998.

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