# 4 **Radiation folly**

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> *Radiation protection is not only a matter of science. It is a problem of philosophy, morality and the utmost wisdom.*
>
> *Lauriston S. Taylor, 1957*

To assess the risk of ionizing radiation from a 21st century perspective, we should start by examining the world's greatest nuclear accident which occurred almost 20 years ago: the Chernobyl catastrophe.

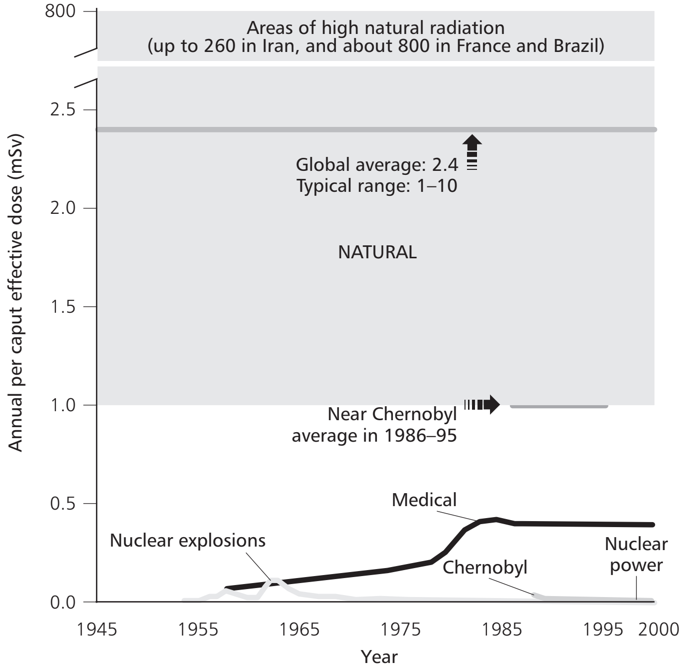
For me, it was a dramatic personal experience, a difficult exam which I am not sure I passed. For many people (but not all) who are engaged in radiological protection, it was a watershed moment. Chernobyl changed the paradigm on which the present safety regulations are based, the holy mantra of the "linear no-threshold" (LNT) assumption, according to which even the lowest, near-zero doses of radiation may cause cancer and genetic harm to human beings.

Chernobyl serves as a yardstick for comparing radiation risks from natural and man-made sources (Figure 4). The incident also sheds light on how easy it is for the global community to abandon rationality in an imaginary emergency.

## The linear no-threshold asssumption

The LNT assumption directly contradicts a vast sea of data on the adaptive and beneficial effects of low doses of radiation – referred to as radiation hormesis. In 1980, as a chairman of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR),

Figure 4 **Worldwide and local (near Chernobyl and areas of high natural radiation) average annual radiation doses from natural and man-made sources**



First year (1986–1987) average dose in most contaminated regions of Belarus, Russia and Ukraine ranged from 0.4 to 2 msv. After UNSCEAR 1988, 1993, 1998, 2000.

I unsuccessfully tried to convince fellow committee members that we should not ignore but rather peruse and assess these data, published in the scientific literature since the end of 19th century. Over the next seven years, I repeated the proposal to no avail.

Finally, the Chernobyl incident was an eye opener. In 1988, two years after the accident, the Committee decided to study radiation hormesis. Six years later after much work and many hot discussions, and fourteen years after my original proposal, an annex appeared in UNSCEAR 1994 Report – "*Adaptive responses to radiation in cells and organisms*". The Annex started a virtual revolution in radiation protection, which is now in full speed.

The LNT/hormesis controversy is not limited to radiation. It poses problems for practically all noxious physical, chemical and biological agents that human beings encounter in life.[1] Ionizing radiation was discovered only at the end of the 19th century but like most other agents, it has been with us since time immemorial.

The Chernobyl accident was a radiation event unique in human history, but not in the long history of the biosphere. Far greater radiation levels have occurred.[2] In terms of human losses, Chernobyl was a minor event as compared with many other man-made catastrophes.[3] But its political, economic, social and psychological impact has been enormous.

## Lessons of Chernobyl

About 9 a.m. on Monday 28 April 1986 at the entrance of CLOR in Warsaw I was greeted by my assistant with a statement: "Look, at 7:00 we received a telex from Mikolajki monitoring station saying that the radioactivity of air is 550,000 times higher than a day before. I found a similar increase in the air filter from the station in our backyard, and the pavement in front of the institute is highly radioactive." To our relief, we found that the isotopic composition of radioactive dust was not from a nuclear explosion, but rather from a nuclear reactor. Successive reports from our 140 monitoring stations suggested that a radioactive cloud over Poland traveled westwards and that it arrived from the Soviet Union. It was only about 6 p.m. the same evening that we learned from BBC radio that its source was Chernobyl.

This was a terrible psychological shock. The air over the whole country was filled with the radioactive material, at levels hundreds of thousands times higher than anything we had experienced in the past, even in 1963 – a year of unprecedented fallout from nuclear test explosions. Curiously, my own attention focused on this enormous increase in air radioactivity, even though I knew that the dose rate of external radiation penetrating our bodies reached 30 $\mu$R per hour, or 2.6 mSv per year, which was only a factor of three higher than just one day before the Chernobyl accident.

Indeed, this dose rate was four times lower than I would experience when visiting certain locations in Norway where the natural external radiation (up to 11.3 mSv/year[4]) from the rocks is far higher than over Central European plane. Other places in the world have even higher levels of natural radiation: the Iranian resort of Ramsar has radiation some 50 times higher, with annual doses reaching 250 mSv per year;[5] Brazilian beaches can have radiation 300 times higher (790 mSv per year),[6] and so does southwest France (up to 870 mSv per year).[7] Amongst people living in areas with high levels of natural background radiation, no adverse health effects were ever reported.

In 1986, the impact of a dramatic increase in atmospheric radioactivity dominated everyone's minds. This led to immediate serious consequences in Poland, in the Soviet Union, throughout the Europe, and later all over the globe.

First were a variety of hectic responses, such as *ad hoc* coining of different principles and emergency countermeasures which lacked a rational basis. One example was limits established for radionuclide concentration in food, implemented a few days after the accident by various countries and international organizations. These limits varied by a factor of up to 50,000[8] and were not based on science, but reflected the emotional state of decision makers, and also political and commercial issues.

For instance, Sweden allowed for 30 times more activity in imported vegetables than in the domestic ones, and Israel imposed lower limits for radioactivity in food imported from Eastern than from Western Europe.[9] The Philippines established a limit of 6 Bq/kg for cesium-137 concentrations in meat, but Norway accepted a limit of 6000 Bq/kg.[10]

The monetary costs of these restrictions were estimated in Norway. At first the cesium-137 limit for meat was established as 600 Bq/kg, which from a health physics point of view is meaningless[11] since consumption of 1 kg of such meat would correspond to a dose of 0.0078 mSv. If a person ate 0.25 kg of this meat every day for an entire year, the internal radiation dose would reach 0.7 mSv. This limit was often exceeded in mutton, so farmers received compensation for destroying the meat and for special fodder they were forced to feed the sheep for months before slaughtering.

The establishment of such a low limit could have destroyed the livelihood of the Lapps, who depend on reindeer, an animal whose diet relies on a special food chain based on lichens. Due to this chain, in 1986 reindeer meat contained high concentrations of cesium-137 which reached up to 40,000 Bq/kg. In November 1986 Norwegian authorities introduced a limit of 6000 Bq/kg for reindeer meat and game. The ordinary Norwegian diet includes only about 0.6 kg of reindeer meat per year,[12] so this limit was intended to protect Norwegians from a low radiation dose of 0.047 mSv/year. In 1994 the costs of this "protection" were evaluated: they reached over $51 million.[13]

Sweden was no better. When the farmers near Stockholm discovered that their cows' milk was contaminated with cesium-137 (above the limit of 300 Bq per liter imposed by Swedish authorities), they wrote to the authorities and asked if their milk could not be diluted with uncontaminated milk from other regions, until the limit was attained – for instance by mixing 1 litre of contaminated milk with 10 litres of clean milk.

To the farmers' surprise, the answer was no, and they were ordered to discard the milk. This was strange, as such practices are common for other pollutants in foodstuffs, and we also dilute the fumes from fireplaces or ovens with the atmospheric air.

Sweden's authorities explained that even though it was possible to reduce individual risk by diluting the milk, this action would simultaneously increase the number of consumers, and thus the risk would remain the same, although now it would be spread over a larger population.[14] This case illustrates a practical application of the LNT assumption and of its offspring, the concept of the "population dose" (i.e. that radiation would create terrifyingly large numbers of "man-sieverts", by multiplying tiny individual radiation doses by a large number of exposed people). An earlier paper demonstrated that this assumption and concept lacked sense and would create negative consequences.[15] This practical application estimated that the costs of the Chernobyl accident in Western Europe probably exceeded $100 billion.[16]

The most nonsensical action however, was the evacuation of 336,000 people from regions of the former Soviet Union. During the years 1986 to 1995, the Chernobyl fallout in these regions increased the average natural radiation dose (of about 2.5 mGy per year) by 0.8 to 1.4 mSv per year, i.e. by about 30% to 50%.[17] The evacuation was based on two factors: radiation limits recommended by International Commission for Radiological Protection (ICRP) for "the event of major radiation accidents"[18] and radiation limits which were tens to hundreds of times lower than natural doses in many countries[19] established to protect the general population.[20]

One such town is the "ghost town" of Pripyat. About 50,000 people were relocated from the town; today no one can enter without special permission. Yet the radiation dose rate measured by a Polish team in May 2001 was 0.9 mSv per year,[21] which is the same as in Warsaw, and five times lower than radiation levels at Grand Central Station in New York. The evacuation led to development of mass psychosomatic disturbances, great economic losses, and traumatic social consequences. Obviously, ICRP will never accept responsibility for the disastrous effects of the application of its pronouncements, which have created a situation where the present system of radiation protection is itself a hazard to health.[22]

To save the population from the effects of exposure to iodine-131, at my instigation the Polish government administered a single dose of iodine to about 18.5 million people over a course of three days (starting on 29th April). This was the greatest prophylactic action in the history of medicine performed in such a short period of time. My medical colleagues and the Ministry of Health were rightly proud of this ingenious and innovative countermeasure.

Recently several countries including the USA planned to follow in our steps.[23] However, I now believe that this action was nonsensical. We endeavored to save Polish children from developing thyroid cancers by protecting them from a radiation dose of 50 mSv to the thyroid gland.[24] At this dose, ICRP recommended implementation of stable iodine prophylaxis.[25]

But in studies of more than 34,000 Swedish patients whose thyroid glands received radiation doses that reached up to 40,000 mSv from iodine-131, there was no statistically significant increase in thyroid cancers in adults or children who were not already thought to have cancer before treatment with iodine-131. In fact, an opposite effect was observed: there was a 38 per cent decrease in thyroid cancer incidence as compared with the non-irradiated population.[26] In a smaller British study of 7417 adult hyperthyroid patients whose thyroids received average radiation doses of 300 000 mSv from iodine-131, a 17 per cent deficit in incidence of all studied cancers was found.[27] Without the stable iodine prophylaxis and milk restrictions, the maximum thyroid dose would reach about 1,000 mSv in about 5 per cent of Polish children.[28] All that I would now expect from this dose is a zero effect.

Fourteen years after the Chernobyl accident in the highly contaminated areas of the former Soviet Union, no increase in incidence in solid cancers and leukemia, apart from thyroid cancers, was observed. In its 2000 Report, UNSCEAR stated that the "population need not live in fear of serious health consequences" and "generally positive prospects for the future health of most individuals should prevail."[29] Although the LNT assumption led to many dire predictions that Northern Hemisphere residents in the tens hundreds of thousands, even millions, would suffer from cancer, no such epidemics have ever occurred.

1,800 new cases of thyroid cancer were registered among the children from Belarus, Russia and Ukraine but this should be viewed in respect to extremely high occurrence of the "occult" thyroid cancers in normal populations.[30] The occult cancers, which do not present adverse clinical effects, are detected at *post mortem* or by USG examinations. Their incidence ranges from 5% in Colombia, to 9% in Poland, 13% in the USA, and up to 35% in Finland.[31] In Finland occult thyroid cancers appear in 2.4% of children 0- to 15-years old.[32] In Minsk, Belarus, the normal incidence of occult thyroid cancers is 9.3%.[33]

The greatest incidence of "Chernobyl" thyroid cancers in children under 15 years old was 0.027%, registered in 1994 in the Bryansk region of Russia. This was less – by a factor of about 90 – than the normal incidence of occult thyroid cancers among Finnish children. The "Chernobyl" thyroid cancers are of the same type and similarly invasive as the occult cancers.[34] The first increase of these cancers was registered in 1987 in the Bryansk region, Russia, one year after the accident.

Since 1995, the number of registered cancers has tended to decline. This observation does not coincide with our knowledge about radiation-induced thyroid cancers, whose risk increases until 15 to 29 years after exposure.[35] In the United States the incidence rate of thyroid tumours detected between 1974 and 1979 during a screening program was 21 times higher than before the screening[36], an increase similar to that observed in three former Soviet countries. I believe that the increased registration of thyroid cancers in contaminated parts of these countries is a classical screening effect.

Besides 28 fatalities caused by very high doses of radiation among rescue workers and the employees of the power station, and 3 fatalities related to other reasons, the only real adverse health consequence of the Chernobyl catastrophe amongst nearly five million people living in the contaminated regions is the epidemics of psychosomatic diseases.[37] These diseases were not due to irradiation from the Chernobyl fallout, but were caused by radiophobia, induced by years of propaganda before and after the accident, and aggravated by improper administrative decisions. These decisions caused several million people in three countries to be "labeled as, and [to] perceive themselves as, actual or potential victims of Chernobyl."[38]

This was the main factor behind the economic losses caused by the Chernobyl catastrophe, estimated to reach $148 billion until 2000 in the Ukraine, and $235 billion until 2016 for Belarus.[39]

In 1986, most of my professional colleagues and myself, the authorities, and the public in Poland and elsewhere, were pre-conditioned to react irrationally. We were victims of the LNT dogma – we wished to protect people even against near-zero doses of ionizing radiation. The dogma influenced everyone's behavior, leading to a mass psychosis. In fact, with the help of mass media, national and international authorities, the Chernobyl accident turned into the greatest psychological catastrophe in history.[40] To these people, it seemed that professionals, international and national institutions, and the system of radiological protection did not meet the challenge of the Chernobyl catastrophe.

The following lessons can be deduced from this accident.

1 Ionizing radiation killed only a few occupationally exposed individuals. The Chernobyl fallout did not expose the general population to harmful radiation doses. The area covered by dangerous radioactive fallout, where the radiation dose rate reached 1 Gy per hour, was limited to about 0.5 $km^2$ in an uninhabited location, reaching a distance of 1.8 km from the burning nuclear reactor. Several hundred meters outside the 1 Gy isoline the dose rate dropped by two orders of magnitude, to a safe level of 0.01 to 0.001 Gy per hour. This is completely different situation than after a surface explosion of a 10 Mt nuclear bomb, when the 1 Gy per hour isoline can reach a distance of 440 km,[41] and the lethal fallout can cover tens of thousands of square kilometres, and endanger the lives of millions of people.

2 Radionuclides were injected high into the stratosphere, at least up to 15 km altitude,[42] which enabled long distance movement in the whole Northern Hemisphere and a penetration over the Equator down to the South Pole.[43] With unique, extremely sophisticated radiation monitoring systems implemented in all developed countries, even the most tiny debris from the Chernobyl reactor was readily detected all over the world. No such system exists for any other potentially harmful environmental agent. Ironically, this sophisticated radiological protection ignited mass anxiety in the public, with disastrous consequences in the former Soviet Union, and strangulation of nuclear energy development elsewhere.

3 Psychosomatic disorders and the screening effects were the only detectable health consequences among the general population. Fighting panic and mass hysteria could be regarded the most important countermeasure to protect the public against the effects of a similar accident, should it occur again.

4 This was the worst possible catastrophe of a badly constructed nuclear reactor, in which production of electric power was unfortunately combined with production of military grade plutonium. The accident caused a complete meltdown of the reactor core, followed by ten days of free emission of radionuclides into the atmosphere. Nothing worse could happen. It resulted in a comparatively minute occupational death toll, which amounted to about half of traffic deaths in an average Polish weekend . The death toll was tens or hundreds times lower than that of many other industrial catastrophes, and no fatalities occurred amongst the public.

## Beneficial radiation and regulations

After ionizing radiation and radioactivity were discovered at the end of the nineteenth century, the social perception of radiation has alternated between enthusiastic acceptance and rejection. This stemmed from recognition of its three basic aspects:

1 The usefulness of radiation for medical applications and for technical and scientific aims;
2 beneficial effects of low levels of radiation; and
3 harmful effects of high levels of radiation.

In the first part of the twentieth century, acceptance prevailed; in the second half, it was replaced with rejection. The public's change of mood which had occurred rather abruptly after the World War II was not due to discovery of some new danger of radiation, but stemmed from political and social reasons which were unrelated to the actual effects of radiation.[44]

The possibilities offered by ionizing radiation for medical diagnostics were first demonstrated by W. K. Roentgen. One month after his discovery, the discovery was published in *Nature* in January 1896 an x-ray photograph of the hand of his wife. In 1902 Pierre Curie, together with two physicians (C. Balthazard and V. Bonchard) discovered that radium rays are useful in cancer therapy.

The beneficial or hormetic effects of low doses of ionizing radiation were found two years after Roentgen and independently by A.H. Becquerel, who also announced the discovery of ionizing radiation. The first observed effect was an increased growth rate of blue green algae exposed to x-rays.[45] During the next decades, this observation was followed by thousands of publications on hormetic effects at all biological levels[46] including human epidemiology (Table 6).

The idea that ionizing radiation can be hazardous for man was first announced in 1896 in the German Medical Weekly.[47] Early students and radiation users voluntarily or unknowingly exposed themselves to high radiation doses. Among the pioneers of radiation and radioactivity from 23 countries, scientists, physicists, medical doctors, nurses, and x-ray technicians, about 100 persons died by 1922, and 406 died until 1992, with afflictions that could be related to radiation. The names of all these victims are recorded in the "Book of Honour of Roentgenologists of All Nations."[48] This early experience alarmed some people, and the need for protection against high doses of radiation was recognized subsequently.

The radiological protection developed since the 1920s reached high standards after World War II. Due to this development between 1945 and 2001 the total number of people exposed worldwide to significant radiation doses was only 2044. Among them 134 persons died; probably 70% of these fatalities occurred in medical applications of radiation.[49] This record includes the Chernobyl victims, and is unusually low when compared to other human activities. This testifies to two facts: (1) excellent radiological protection (but see below for criticism of exaggerated standards); and (2) a low noxiousness of ionizing radiation.

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

The concept of tolerance dose, which was effectively a statement of threshold, served as the basis for radiation protection standards for three decades[50] until 1959. It was then that the International Commission on Radiological Protection based its recommendations on the linear no-threshold assumption (LNT).[51] Introducing LNT to radiological protection was stimulated by undue concern in the 1950s with the allegedly disastrous genetic effects on the human population of ionizing radiation produced by man. In the literature on ionizing radiation at that time, one could observe the following statements of geneticists: "…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."[52]

In the years that followed, even in the progeny of survivors of nuclear attacks on Hiroshima and Nagasaki, no radiation-induced genetic disorders were detected.[53] Also from other genetic studies it became clear that this concern was an overreaction, in tune with strong emotions, evoked by the menace of a potential nuclear war.

However, emotions are not a good basis for regulations. Professor W.V. Mayneord, the late chairman of the ICRP Committee IV, and a highly respected scholar and humanist, made the following comment on using LNT as a 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."[54]

Mayneord's concern about the values applied in ICRP recommendations was in "the weakness of the biological and medical foundations coupled with a most impressive numerical façade". This numerical façade however, is now regarded as epistemologically unacceptable to interpret a biological reality.[55]

The late professor E.T. Jaynes, an outsider to the radiation protection community, presented radiation as a classical example for a common scientific error, where its effects are judged by assuming a linear response without threshold (LNT). He stated that

> to analyse one's data in terms of a model which does not allow even the possibility of a threshold effect is to prejudge the issue in a way that can lead to false conclusions, however good the data….The false premise built into a model which is never questioned cannot be removed by any amount of new data…. False conclusions of just this kind are now not only causing major economic waste, but also creating unnecessary dangers to public health and safety. Society has only finite resources to deal with such problems, so any effort expended on imaginary dangers means that the real dangers are going unattended.[56]

For the past few decades, the main support of the LNT assumption in radiology was interpretation of epidemiological data from a Japanese A-bomb survivor Life Span Study. This population was exposed to extremely high dose rates, as the duration of radiation pulse during nuclear explosion was about $10^{-8}$ second. This dose rate was larger by $2 \times 10^{15}$ than the Chernobyl dose rate in the US (0.0046 mSv over 50 years). It is not only scientifically unacceptable to use the LNT assumption based on such an enormous difference of the dose rates to calculate a precise cancer death toll of 53,400 people.[57] Indeed Lauriston Taylor, the former president of the US National Council on Radiological Protection and Measurements, deemed such extrapolations to be a "deeply immoral use of our scientific heritage." Recently, a meticulous revision of cancer and leukemia incidence data from Hiroshima demonstrated that the data are consistent with the threshold-like dose response model.[58]

During the past several decades there has been a tendency to decrease – to ever-lower values – the exposure dose applied in standards of radiation protection. In the 1980s and the 1990s, this dose became 20 mSv per year for occupationally exposed people, and 1 mSv per year for the general population. For an individual who receives no direct benefit from a source of radiation, a maximum exposure dose of 0.3 mSv in a year has been recently proposed[59] and for some instances, there would be an exemption level of 0.01 mSv per year.[60]

Justification for such low levels is difficult to conceive, as no one has ever been identifiably injured by radiation while standards set by the ICRP in the 1920s and the 1930s were in force, involving dose levels hundreds or thousands of times higher.[61] The life expectancy of survivors of nuclear attacks on Hiroshima and Nagasaki was found to be higher than that in the control groups,[62] and no adverse genetic effects were found in the progeny of survivors. There is also ample evidence of beneficial effects of low doses of radiation in people occupationally, who are medically or naturally exposed to doses much higher than the current radiation protection standards.[63] (See Table 6).

Simply to adhere to regulations based on standards which establish such low dose limits, society is paying out hundreds of billions of dollars with no apparent benefit. Each human life hypothetically saved by implementing the present regulations costs about \$2.5 billion.[64] Such spending is morally questionable since (1) society's limited resources are spent on preventing an imaginary harm, instead of achieving real progress in health care, and (2) because low radiation doses are beneficial for the individual. For these two reasons, such expenditures may actually adversely affect the population.

Table 6 **Deficit of mortality in large human populations exposed to low radiation doses (up to 500 mSv), in comparison with unexposed populations.**

| *Population* | | *References* |
|---|---|---|
| High background area, USA | 15% cancers* | Frigerio and Stowe (1976). |
| High background area, China | 15% cancers | Wei, L., et al. (1990). |
| Nuclear industry workers, Canada | 68% leukemia | Gribbin et al. (1992) |
| Nuclear shipyard workers, USA | 24% all cancers<br>58% leukemia | Matanoski, G.M., Health Effects of Low-Level Radiation in Shipyard Workers, Final Report. 1991, National Technical Information Service: Springfield, Virginia. |
| Nuclear workers, combined Hanford, ORNL, Rocky Flats, USA | 9% cancers<br>78% leukemia | Gilbert et al. (1993). |
| British medical radiologists after 1955–1979 | 32% all causes<br>29% cancers<br>36% non-cancers | Berrington et al. (2001). |
| Plutonium workers, Mayak Eastern Ural, Russia | 29% leukemia | Tokarskaya et al. (1997). |
| High residential radon, USA | 35% lung cancers | Cohen (1995). |
| Accident in Eastern Ural, Russia | 32% all causes | Berrington et al. (2001).<br>Krestinina (1994). |
| Swedish patients diagnosed with iodine-131** | 38% cancers | Hall et al. (1996). |

* incidence
** thyroid doses 0–257,000 mGy

## Natural radioactivity and nuclear wastes

When life on planet Earth 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 the present.[65] At that time, the long-lived potassium-40, uranium-238, and thorium-232 had not yet decayed to their current levels. Their content in the contemporary Earth's crust is still quite high, and it is responsible for the highest radiation exposure of every living organism. One ton of average soil contains about $1.3 \times 10^6$ Bq of potassium-40, thorium-232 and uranium-238 and their daughters. This corresponds to $3.6 \times 10^{15}$ Bq per cubic kilometer (Table 7). The decay of these natural radionuclides (which are present in the soil layer one km thick) produces 8000 calories per square meter annually.[66]

We can compare the natural, extremely long-lived activity of potassium-40 ($T1/2 = 1.28 \times 10^9$ years), thorium-232 ( $T1/2 = 1.4 \times 10^{10}$ years) and uranium-238 ($T1/2 = 4.47 \times 10^9$ years) in soil, with the activity of much shorter-lived radioactive wastes from the nuclear power cycle (Table 7). In 2002 the total annual production of electricity in nuclear reactors was 285.4 GW(e).[67] The global production of radioactive wastes from this source amounts to $3 \times 10^{15}$ Bq per year, with the longest lived plutonium-244 ($T1/2 = 8.26 \times 10^7$ years). This amount of average natural activity is contained in a relatively small block of soil from high activity areas only 0.17 by 0.17 km wide, and 2 km deep. None of the man-made components of these wastes have appreciably higher radiotoxicity (expressed as Sv/Bq) than natural thorium-232.[68]

The activity of wastes accumulated until the end of 2000 from the whole of global civilian nuclear fuel cycle is much greater. It amounts to 200,000 tones of "heavy metals". Disposal of high level wastes and spent fuel in geologic repositories may result in doses to the population that do not begin to accumulate until well after 500 years.[69] After 500 years activity, all high level wastes will decrease to about $5.8 \times 10^{18}$ Bq[70], corresponding to natural activity contained in a block of soil from high activity areas about 7.3 by 7.3 km wide and 2 km deep.

Table 7 **Activity of natural radionuclides in the terrestrial crust and total activity of wastes from nuclear power**

| *Natural radioactivity* | *K-40* | *Rb-87* | *Th-232* | *U-235* | *U-238* | *Total* |
|---|---|---|---|---|---|---|
| Number of radionuclides in chain | 1 | 1 | 11 | 12 | 14 | |
| Concentration of parent in soil, Bq/g | | | | | | |
| Median | 0.4 | 0.08 | 0.03 | 0.0016 | 0.035 | |
| Max | 3.2 | – | 0.36 | 0.016 | 0.9 | |
| Concentration of series in soil, Bq/g | | | | | | |
| Median | 0.4 | 0.08 | 0.33 | 0.019 | 0.49 | 1.32 |
| Max | 3.2 | – | 3.96 | 0.192 | 12.6 | 19.95 |
| Activity of series in 1 km$^3$ of soil (2.7E15 g) , Bq | | | | | | |
| Median | 1.10E+15 | 2.20E+14 | 8.90E+14 | 5.10E+13 | 1.30E+15 | 3.60E+15 |
| Max | 8.60E+15 | | 1.10E+16 | 5.20E+14 | 3.40E+16 | 5.40E+16 |
| Activity of series in terrestrial crust (17.3E24 g[b]), Bq | | | | | | |
| Median | 6.90E+24 | 3.14E+25 | 5.70E+24 | 3.30E+23 | 8.50E+24 | 2.60E+25 |
| *Wastes from nuclear power* | | | | | | |
| ILW and LLW from electricity production in 2002, Bq[c] | | | | | | 3.0E15[e] |
| Wastes accumulated until 2000 from the whole civilian nuclear fuel cycle after 500 years of storage for cooling, Bq[d] | | | | | | 5.8E18[f] |

Jaworowski (2002).

a UNSCEAR (2000); Taylor (1964); Magill (1999). b Magill (1999). c 285.4 GW$_e$.IAEA (2002) and assuming 20% nuclear power station efficiency; and 10,000 GBq/GW(e) y$^{-1}$ for conditioned solid intermediate level wastes (ILW), and 500 GBq/GW$^{y-1}$ low level wastes (LLW); (UNSCEAR (1988). d 200,000 tones of "heavy metal" wastes after ref. 6; decay rate of fission products and actinides from ORIGEN. Bell (1973); Croff (1983). e Corresponds to median natural activity in 0.83 km$^3$ of soil, i.e. in a block of 0.64 × 0.64 × 2 km; or in 0.06 km$^3$ of soil with maximum concentration of natural radionuclides, i.e. in a block of about 0.17 × 0.17 × 2 km. f Corresponds to activity in 1611 km3 of soil with median concentration of natural radionuclides, i.e. in a block of about 28.4 × 28.4 × 2 km; or in 107 km$^3$ of soil with maximum concentration of natural radionuclides, i.e. in a block of about 7.3 × 7.3 × 2 km.

No special barriers prevent the natural radionuclides from migrating from a depth of 2 km to the ground surface. They can be transported by mechanical action, 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 highly mobile, and may migrate with ground water to distances of several tens of kilometres or more. Radium is mobile in sulphate-free neutral or acidic solutions. The average volcano injects alpha emit $^{210}$Po into the global atmosphere during non-eruptive activity, amounting to about $5 \times 10^{15}$ Bq per year[71] (i.e., almost twice as much as the 2002 production of radioactive wastes from nuclear power reactors). Geochemical differences between uranium, thorium and radium may lead to drastic changes in their radioactive equilibrium.[72]

In contrast, for man-made radioactive wastes many effective, sophisticated barriers are provided in deep underground depositories. At first glance, one can see in Table 7 that it would take few billion years of global production of wastes from nuclear power reactors at a level on par with 2002, to double the total activity of natural radionuclides in the Earth's continental crust.

## Conclusions

Humanity does contribute to the content and flow of radionuclides and to radiation energy in certain compartments of the environment, but man's contribution is a tiny fraction of the natural contribution.

In some areas of the world, natural radiation doses to man and to other biota are many hundreds times higher than the currently accepted dose limits for the general population. No adverse health effects were found in humans, animals and plants in these areas. In the future, the abstract LNT approach will need to be revised. Regulators should take into account the apparently safe chronic doses experienced by humans who reside in high natural radiation areas. It seems that attention should be given to such areas in the coming years.

The twentieth century witnessed the dawn of man-made ionizing radiation and radioactivity, the use of this knowledge to kill people in Hiroshima and Nagasaki, and the greatest nuclear catastrophe in Chernobyl. Chernobyl claimed only 31 occupational victims, and probably none among the public, ultimately proving that nuclear energy is a comparatively safe means of power production.

During the twentieth century it was also discovered that high semi-acute doses of radiation can cure cancers, and that small chronic doses of radiation are beneficial for health. Similar to the discovery of fire about 500,000 years ago, it also seems that "new" radiation and radioactivity have opened an unlimited energy resource which is equally significant to humanity.

Fire made human beings the most ubiquitous species and enabled expansion of life outside the Earth's biosphere. Our ancestors had many thousands of years to mentally adapt to fire, sometimes even deifying it. It seems that one century has not been long enough to adapt mentally in the same manner to ionizing radiation and radioactivity. We can hope that attitudes will change in the 21st century, and that humans can accept radiation as a fact of existence.

## Notes

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2 Draganic et al (1993); Karam and Leslie (2002); Karam (2002).
3 Jaworowski (1988).
4 Baarli (2004).
5 Sohrabi (1990).
6 UNSCEAR (2000a).
7 Delpoux (1996).
8 Salo and Daglish (1988).
9 *Ibid*.
10 *Ibid*.
11 Henriksen (1988).
12 *Ibid*.
13 Idas and Myhre (1994).
14 Walinder (1995).
15 Jaworowski, Z. (1999).
16 Becker (1996).
17 UNSCEAR (2000a).
18 ICRP (1984).
19 Jaworowski (1998).
20 Ilyin (1995); Filyushkin (1996).
21 Adamski, J. (2001)
22 Walinder (1995).
23 WHO (1999); Balter (1997); Milligan (2002).
24 Jaworowski (1996).
25 ICRP (1984).
26 Holm et al. (1988); Hall et al. (1996).
27 Franklyn (1999).
28 See note 29.
29 UNSCEAR (2000).
30 Franssila and Harach (1986); Harach et al (1985); Moosa and Mazzaferri (1997); Tan and Gharib (1997).
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39 *Ibid*.
40 Jaworowski (1988); Salo and Daglish (1988).
41 Miller (1968).
42 Jaworowski and Kownacka (1988).
43 Kownacka and Jaworowski (1994).
44 Jaworowski (1999).
45 Atkinson (1898).
46 Luckey (1991); Feinendegen and Pollycove (2001); Pollycove and Feinendegen (2001); Pollycove and Feinendegen (2003).
47 Marcuse (1896).
48 Molineus et al. (1992).
49 Toohey (2002.
50 Kathren (1996).
51 ICRP (1959).
52 ICRP (1959).
53 Schull (1998).
54 Mayneord (1964).
55 Walinder (1987).
56 Jaynes (2003).
57 Jaworowski (1999).
58 Baker and Hoel (2004).
59 Clarke (1999).
60 Becker (1998).
61 Taylor (1980); Coursaget and Pellerin (1999).
62 Kondo (1993).
63 Tubiana (1998).
64 Cohen (1992).
65 Karam and Leslie (1996).
66 Draganic et al. (1993)
67 UNSCEAR (2000a); UNSCEAR (2000b).
68 IAEA (1996).
69 OECD (2000).
70 Chwaszczewski (1999).
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