Radiation versus radiation: Nuclear energy in perspective

A comparative analysis of radiation in the living environment

by Abel J. González and Jeanne Anderer

Many people are anxious about releases of radioactive materials into the environment and their possible consequences for humanity. And yet throughout history people have lived in a changing radiation environment. One part is natural, the other man-made. Gradually, even this artificial radiation has been integrated in the steady radiation environment. Human interaction with this environment and the resulting modifications underscore the dynamic of change: today's radiation environment differs from that of yesterday, and will be continuously transformed in the future.

The paradox extends further: nuclear energy, a negligible contributor to the average dose of radiation people receive, is the target of most public concern, whereas radiological medicine, the largest sources of exposure from man-made sources, is prudently welcomed for its benefits. There is even less apprehension about the most prodigious and least controlled sources of exposures: natural radiation sources.

In fact, it is virtually impossible for people to avoid exposures to radiation from their living environment, although some are more exposed than others because of their type of dwelling, where they live, their lifestyle, and the level of medical care they receive.

There is good reason to believe that a proper perspective on the impact of nuclear energy in the living environment emerges from looking with fact and foresight at radiation exposures from all radiation sources. Insights gained from this comparative approach can help to illuminate how humanity lives in and modifies the radiation environment and, more importantly, how reasonable judgements can be made about all human practices involving radiation. This article aims to contribute to this understanding. Its main source is the 1988 report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).* The report and its scientific annexes provide an authoritative and dispassionate factual basis for examining radiation from all sources.

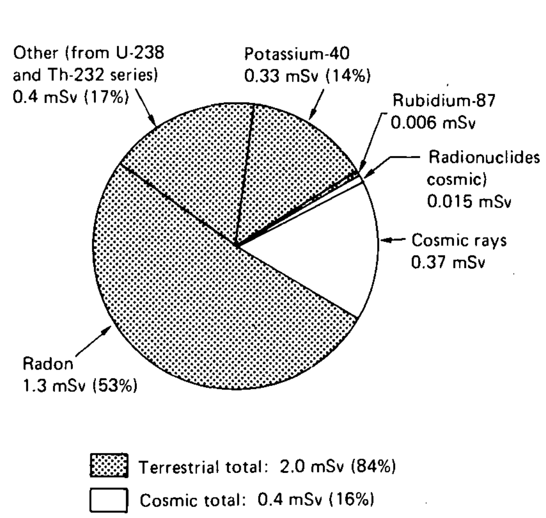
The comparison of radiation exposures in the living environment is made in terms of radiation doses, and the results are expressed on an individual basis, with average *(per caput)* values and with extremes; and on a collective basis, with values representative of the total collective radiation impact from a source or practice.

The natural radiation environment

Natural sources deliver the highest radiation dose that people normally receive. *(See accompanying graph.)*

* *Sources, Effects and Risks of Ionizing Radiation,* United Nations Scientific Committee on the Effects of Atomic Radiation, report to the UN General Assembly, with Annexes, New York (1988).

Estimated annual doses per head from natural sources



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The average annual dose from natural sources is some 2.4 millisievert (mSv). This value is used here as the reference level of natural background radiation. Hidden within this statistical average are individual doses that range from 1 to 5 mSv a year and, in extreme cases, to 1 Sv or more.

The two major natural radiation sources are the cosmos, which irradiates people continuously with cosmic rays; and the earth's biosphere, comprising radionuclides that have existed mainly in the earth's crust for billions of years. Irradiation occurs externally, through exposures to extraterrestrial radiation and to radiation from radioactive natural materials remaining outside the human body; and internally, through exposures to natural radionuclides biologically present in the human body or incorporated in inhaled air and ingested food and drink. These distinctions are important, as terrestrial radiation is by far the largest source of natural irradiation, contributing as much as 85% to the average annual dose. Moreover, more than two-thirds of natural irradiation occurs internally, and a substantial fraction of such exposures can be technically controlled.

The cosmic source. Effectively all the cosmic irradiation comes from one source: cosmic rays. Cosmic-ray levels are relatively stable at the earth's surface, but they are affected by the earth's magnetic field, the polar area receiving more than the equatorial zones. More importantly, the level increases greatly with altitude, nearly doubling every 1500 metres. Most people live at or close to sea level, so there is little variation around the average dose from cosmic radiation of 0.37 mSv. However, in high altitude cities (such as Denver, USA; Bogota, Colombia; and La Paz, Bolivia) the annual cosmic doses to residents may be as much as four times the normal level, reaching 1 mSv or more.

Similarly, air travel subjects passengers and crews to abnormally high cosmic irradiation, although for limited periods.

Terrestrial sources. Terrestrial radiation can be found throughout the environment at various levels, depending on the activity concentration in such natural materials as rocks, soils, water, air, food and even the human body. The most important terrestrial sources are potassium-40, rubidium-87 and the two series of radioactive elements arising from the decay of uranium-238 and thorium-232. Other radionuclides, such as those in the uranium-235 decay series, have little effect on total radiation exposures.

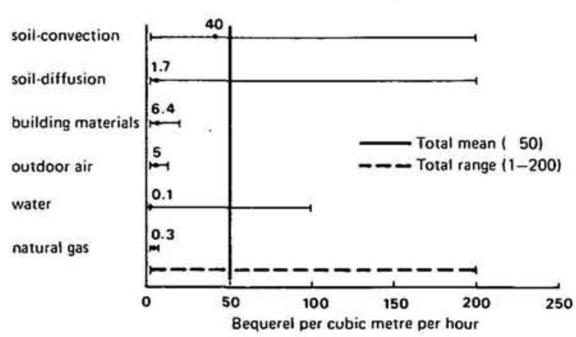
The radioactivity in certain rocks and soils is the main source of terrestrial irradiation to people while outdoors. Generally, igneous rocks such as granite are more radioactive than sedimentary ones, but with highly radioactive shales and phosphate rocks as notable exceptions. Recent surveys of outdoor external radiation levels in 23 countries, representing more than half of the world's population, revealed only minor variations. These studies suggest that about 95% of the world's population lives in areas where the average annual dose of 0.4 mSv is distributed normally. Even so, there are well-documented areas where people are exposed to exceptionally high levels of terrestrial irradiation. In the coastal areas of Kerala and Tamil Nadu in India, thorium-rich monazite sands result in dose rates that can be up to 1000 times higher than the normal radiation background. Elsewhere, in the Brazilian areas of Guarapari, Meaipe, and Pocos de Caldas, dose rates can be as much as 100 times the normal level.

Since people spend most of their time indoors, radiation levels in dwellings are crucial to their exposures. Practically speaking, most internal terrestrial irradiation can be traced to one all-pervasive source: the odourless gas radon. (Radon refers here to the nuclides radium-222 and radium-220 and the chain of their decay products — so-called radon daughters.)

On average, radon constitutes slightly more than half of the *per caput* dose from natural background radiation (or 1.3 mSv per annum). For buildings there are several channels for radon entry, the most important being the underlying or surrounding soils, and to a lesser extent, building materials, outdoor air, tap water, and natural gas. *(See accompanying figure.)* Indoor survey results are only recently available and it is likely that exceptionally high radon levels will be recorded for dwellings in many areas of the world which are either built on or with highly radioactive materials.

Internal irradiation by terrestrial sources other than radon is caused mainly by the intake of potassium-40, lead-210, and polonium-210. Compared with radon exposures, their contribution to the average annual dose level is small. As the intake of potassium-40 is homeostatically controlled in the body, the variability range is low. Conversely, dietary patterns can influence internal exposures to lead-210 and polonium-210. For example, these nuclides concentrate in seafood, and in Japan, where this is a preferred food, concentrations

Radon entry rates in a reference house



Radon entry rates in a reference house. Parameters: 250 m^3; 100 m^2 surface floor area; 300 m^2 wall-ceiling surface area; 450 m^2 total surface area; 1 h-1 air exchange rate; 0.2 m thickness of concrete floor-ceiling; 0.2 m thickness of external brick walls.

were found to be 5 times higher than those in the Federal Republic of Germany and India and 10 times higher than those in the United States. An exceptionally large intake of these radionuclides is also known to occur in the extreme northern hemisphere where tens of thousands of people subsist on mainly reindeer or caribou meat. These animals, grazing on lichens that concentrate lead and especially polonium, result in doses to this exposed group that are about 10 times higher than the normal level. Lead-210 and polonium-210 have also been detected in tobacco and in cigarette smoke.

Altering the radiation environment

Three major human practices unrelated to the generation of nuclear electricity alter the radiation environment: the expanding use of medical radiation, atmospheric testing of nuclear weapons, and industrial processes involving natural radionuclides. Related occupational exposures seemingly play a lesser modifying role.

Medical uses of radiation. Medical irradiation is a major modifier of the radiation environment. The annual average dose is between 0.4 and 1 mSv, depending on the methodology used to estimate doses.

Medical radiation is used largely for diagnostic X-ray examinations, including medical and dental radiography, diagnosis in nuclear medicine involving internally administered radionuclides, and radiation therapy in treating cancer and other diseases. Radiation therapy in the context of this article is unique. Unlike dental and other radiological examinations that people experience frequently and indifferently, they regard radiation therapy as highly improbable, remote from their lives, and unrelated to their radiation environment. As such, people are not directly concerned with radiation from therapeutic practices. In effect, the risks of this high-level radiation practice have remained outside the agenda of the public debate about radiation hazards. Statistically, the reality is likely to be otherwise: some one-quarter of the population will probably require radiation therapy during their lifetime. However, radiation exposures from therapeutic medical practices are excluded from the comparative analysis.

Unfortunately, reliable and well-defined information on radiation in medical practices are available mainly for the populations of the well-developed countries, which represent less than one-quarter of the 5 billion global inhabitants. Sparser data exist for yet another quarter of the population. For more than two and a half billion people, virtually nothing is known about what medical irradiation they receive, if any. The information gap suggests a truly disproportionate situation, leading some experts to conclude that nearly three-quarters of the people in the world have not benefited from substantial diagnostic radiological assistance.

Diagnostic radiography. Diagnostic X-ray examinations account for nearly 95% of the total doses people received yearly from medical irradiation. These totals conceal widespread variations in both the radiodiagnosis intensity and the impact of this practice. For example, on average one X-ray machine is shared by 4000 people in countries with the highest level of health care (as grouped by UNSCEAR) and by 170 000 people in countries with the lowest level. In the first group of countries, on average there are 800 examinations annually per 1000 people; in the other group, there are less than 30 examinations per 1000 people.

Independently of the practice intensity, individual doses also differ, depending on such factors as the type of examination, the procedure adopted, and the performance efficiency of the equipment. For one thing, the standard practice of mass chest X-rays is no longer considered relevant in most developed countries, whereas in many developing countries the situation appears to be the opposite. In some Asian countries, for example, more than three-quarters of all diagnostic medical examinations are of the chest. More importantly, while radiographic techniques are used exclusively or extensively for chest examinations in most developed countries, data for the developing countries suggest large-scale use of fluoroscopic techniques which can result in 15 times higher doses to patients than radiography.

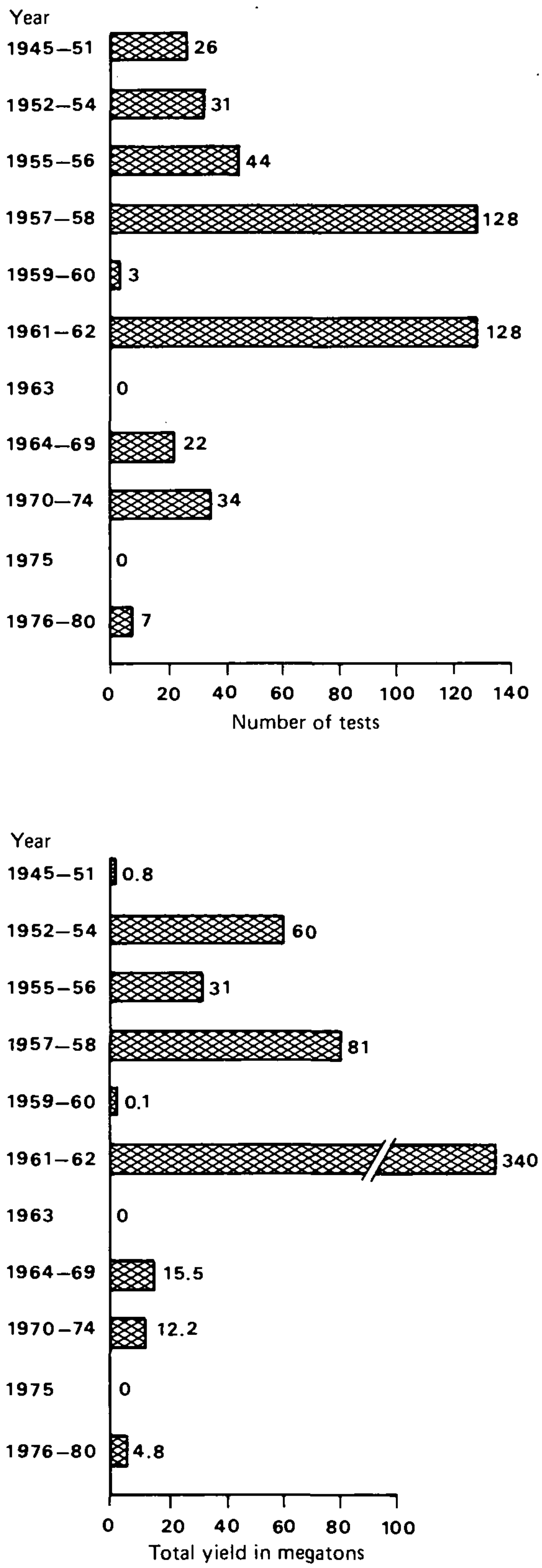
The lack of data on the use of fluoroscopy in countries with less developed health care systems is a major uncertainty constraining robust conclusions about doses from diagnostic X-rays. Another open question affecting dose levels is the performance efficiency of the diagnostic equipment, particularly in many developing countries. Significantly, 30-70% of the equipment is estimated to be malfunctioning.

Dental radiography. Dental radiography represents only 1% of medical exposures, with the dose for individuals averaging 0.04 mSv per examination. This is the most frequently used type of diagnostic X-ray examination; some 340 million procedures are performed yearly, mainly in countries with well-developed health care systems.

Diagnostic nuclear medicine. Worldwide the frequency of nuclear medical practices has progressed since these practices were introduced some 30 years ago. In a few countries, the frequency has declined periodically, because of the alternative use of computer tomography for radionuclide brain scans and other, non-ionizing radiation techniques such as ultrasound. Exposures represent only 4% of all medical irradiation. All medical irradiation practices differ among and within countries; diagnostic nuclear medicine is no exception. The type of radionuclide used, (e.g., iodine-131 versus technetium-99m) accounts for the wide range in the average annual doses.

Nuclear weapons testing. Since 1945 more than 400 nuclear explosions have been carried out in the atmosphere to test nuclear weapons, most recently in 1980. *(See graphs, page 24.)* Atmospheric testing reached two peak periods: 1957–1958 and 1961–1962, each with 128 tests but with the yield for the latter period

Number and yield of atmospheric nuclear weapons tests

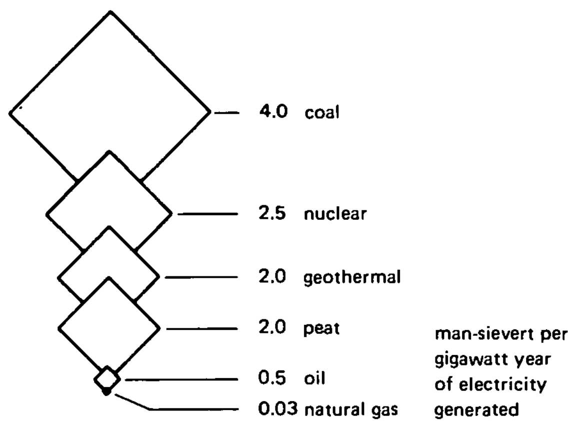


about four times higher than the earlier peak. Irrespective of judgements about the ethics of this practice, the fact is these tests occurred, injecting substantial amounts of radioactive materials into the environment.

The fallout from atmospheric testing contains several hundred radionuclides, but only four are of concern to present and future populations: carbon-14 (with a half-life of 5730 years), caesium-137 (half-life 30 years), strontium-90 (half-life 30 years) and tritium (half-life 12 years). Currently, carbon-14 accounts for some two-thirds of these exposures; given the half-life of the other radionuclides, by the end of this century only carbon-14 will be important. A very small contribution from plutonium-239, plutonium-240, and americium-241 (0.1%) to the dose rate will occur over thousands of years. Individually, the average annual dose is only 0.01 mSv but the collective dose commitment for future generations is the highest from man-made sources.

Industrial processes and natural radionuclides. Industrial processes, such as geothermal energy production and phosphate mining, bring to the earth's surface materials with above average concentrations of natural radionuclides. Other processes, such as coal combustion and phosphate fertilizer production, treat materials with average or above average amounts of natural radionuclides, concentrating them in one or more products or by-products. The impact of these exposures on the radiation environment has not been noticeable. However, these exposures are not systematically monitored, and the accelerated growth patterns associated with many processes, particularly energy production, strongly suggest a sizeable impact in the decades ahead. In fact, electricity generation from energy sources other than nuclear results in radiation exposures to the public, and the radiological impact from some conventional power plants is comparable to that from nuclear power plants. *(See accompanying diagram.)*

Estimated collective dose commitments due to systems of electricity production (normalized)



In many countries coal is a viable energy option for meeting the increasing demand for electricity. In fact, nearly 70% of the 2.7×10^9 tonnes of coal equivalent produced worldwide in 1981 was used for generating electricity, 20% for carbonization, and 10% for domestic heating and cooking. Coal, like most natural materials, contains natural radionuclides that are released during combustion. How much is released depends on the activity concentration in the coal, the ash content, combustion temperature, the partitioning between the heavy slag-ash at the bottom of a furnace and the lighter fly-ash, and the efficiency of the emission control devices. Basically, two types of coal-fired power plants exist worldwide: "old" plants that release about 10% of the fly-ash, and "modern" plants equipped with sophisticated pollution control devices that release only 0.5% of the fly-ash. Assuming that two-thirds of the plants worldwide are characteristically old, the generation of a gigawatt year of electrical energy would result in a normalized collective dose commitment of 4 man Sv per gigawatt year of electricity generated.

Coal usage also gives rise to other radiation hazards. Much of the fly-ash collected by emission control devices ends up being used to manufacture cement and concrete, so that the use of this radioactive material in construction can enhance radiation exposures. What is not commercially applied is frequently dumped in the vicinity of the power plant, posing potential radiation hazards from resuspension and contamination of surface and underground waters. Unfortunately, radiation dose assessments for these practices are lacking.

Geothermal energy is another source of radiation exposure. Although its share in electrical energy consumption is small, its relative importance is expected to grow. Most of the activity concentrated in the geothermal fluids comes from the uranium decay chain, specifically from radon. Based on measurements of radon in geothermal fluids for several countries, the normalized collective dose commitment is estimated at 2 man Sv per gigawatt year of electricity generated.

Peat is burned for energy production in several areas of the world, notably in Nordic countries. Flowing surface and ground waters carry the natural radionuclides into the peat bogs, where they are eventually absorbed in the peat matter. Little information is available on the environmental discharges of natural radionuclides from peat power plants. Assuming that the combustion of 5 billion kilograms of peat is needed to generate 1 gigawatt of electrical energy a year, the normalized collective dose commitment is estimated at 2 man Sv per gigawatt year of electricity generated. Over the long term, the storage and disposal of uranium-rich peat ash may have the greatest radiological impact.

Both oil and natural gas play a lesser role in radiation exposures from electricity generation worldwide. The normalized collective dose commitments are comparatively low: 0.5 and 0.03 man Sv per gigawatt year of electricity generation, respectively.

Occupational exposures. Natural radiation is also responsible for related occupational exposures. Obviously, airline flight crews encounter exceptionally high levels of cosmic irradiation. From information available for 1979–83, the annual individual dose approached a possible maxima of 15 mSv. Workers in office buildings, stores, and workshops with high radon levels and even domestic workers in homes with high radon concentrations also incur natural dose levels which could be surprisingly high — much higher than the occupational dose limits used for the nuclear industry.

Data on occupational exposures from industrial activities involving natural radionuclides are available only for a few countries and even in these cases they are not well-defined. Estimates can therefore only be roughly made. For workers at coal-fired plants, exposures are caused mainly by the inhalation of airborne fly-ash. Roughly, the collective dose worldwide is 60 man Sv. Doses from processing and transport of rock phosphates are estimated collectively at 20 man Sv. For those engaged in handling phosphate fertilizers, worldwide the collective dose may be as high as 50 man Sv. Data on occupational exposures for the fuel cycles associated with weapons testing are not readily available. However, given the radiotoxicity of some of the radionuclides involved and the fact that these practices are not always covered by the same stringent radiation protection measures associated with the peaceful uses of nuclear energy, the radiological impacts seemingly are not insignificant.

For those occupationally engaged in all uses of medical irradiation, the annual collective dose equivalent is 1 man Sv per million population. Although medical radiation practices are increasing worldwide, the limited trend data suggest decreases in the annual doses, by 10–20% each decade.

Radiation and nuclear energy

The following explores radiation levels for the normal generation of nuclear electricity. Since the first commercial nuclear power plant began operation in 1956, the nuclear power industry worldwide has accumulated more than 5000 reactor-years of relatively safe operation. However, nuclear generation of electricity, like all human endeavours, has the potential for accidents, although a highly improbable one. The accident at Chernobyl-4 nuclear power unit in the Soviet Union underscored this possibility, essentially taking the analyses of severe accidental exposures out of the hypothetical realm. Given the uneven distribution of exposures it is questionable whether exposures from the Chernobyl accident can be compared with those from other steady sources, including natural radiation. Even so, such comparisons are useful for understanding the impact of this extreme case.

Since the issue of disposal of radioactive nuclear wastes commands attention in the public debate about the development of nuclear energy, it is useful to consider briefly the potential radiological impact from these wastes. Frequently, public concern stems from the misconception that radioactive wastes cannot be controlled or managed safely over long periods. These concerns contrast sharply with the views of specialists, who are confident of technical solutions. In short, the radiological impact from the proper disposal of the wastes resulting from an adequate treatment of the spent nuclear fuel is so negligible that even under the most pessimistic assumptions the resulting doses to the (hypothetical) population living thousands of years from now would be effectively nil. For this reason, the subject of waste disposal is not considered in the comparative analysis of radiation levels.

Routine generation of nuclear electricity. Normally, nuclear electricity generation releases only negligible amounts of radioactive materials into the environment. On average, the annual dose from all practices in the nuclear fuel cycle is only a tiny fraction (less than 0.1%) of that from natural radiation.

Exposures from nuclear energy production occur at all stages of the fuel cycle, and radiation doses to the public and workers are assessed over space and time. *(See accompanying graphs.)*

Uranium mining and milling. Operations at mines give rise to radioactive effluents mainly in the vented air from underground mines or from the pit releases for surface mines. The stockpiles of ore and other materials from uranium extraction are responsible for atmospheric releases over the short term and to a greater extent for the longer period. The current practice is to store tailings in open uncontained stockpiles or behind engineered dams or dikes with a solid or liquid cover. Radon released over 5 years from mining and milling results in dose commitments of 0.1 man Sv per gigawatt year of electricity generated. Collective dose commitments to local and regional populations from mining and milling are 0.3 and 0.04 man Sv per gigawatt year of electricity generated, respectively.

Fuel fabrication. Comparatively speaking, fuel fabrication gives rise to very few atmospheric and aquatic discharges. Most uranium compounds are solid, and can be easily removed from airborne effluent streams. The collective dose commitment to the public is 0.003 man Sv per gigawatt year of electricity generated.

Reactor operation. Doses to the public from reactor operations have steadily declined over the past few years, even as electricity generating capacity increases. This is attributed partly to the extensive radiation protection systems at nuclear power plants and partly to increased plant operational efficiency. For example, atmospheric releases of carbon-14 from reactor operations are now nearly half of those UNSCEAR reported in 1982. This is significant, as carbon-14 accounts for much of the public's collective dose commitment of 2.5 man Sv per gigawatt year of electricity generated.

Reprocessing. A small number of reprocessing plants are operating commercially, including Sellafield (formerly Windscale) in the United Kingdom and La Hague and Marcoule, both in France. Together these facilities reprocess only a small percentage of the world's irradiated fuel. The rest has been stored, pending policy decisions in countries on reprocessing. Long-lived nuclides (e.g. carbon-14, tritium, krypton-85, iodine-129) are of major concern in reprocessing effluents. Liquid discharges from reprocessing plants are responsible for most of the collective dose commitment of 1.27 man Sv per gigawatt year of electricity generated.

Transport. Exposures to the local and regional population from transport along the fuel cycle chain are comparatively low, with a collective dose commitment of about 0.1 man Sv per gigawatt year of electricity generated.

Occupational exposures. Exposures to those engaged at the various facilities of the nuclear power industry differ markedly. Maintenance workers and especially repair personnel at nuclear power plants receive the highest doses. Uranium miners, particularly those working underground, face radiation hazards posed by radon and its daughters.

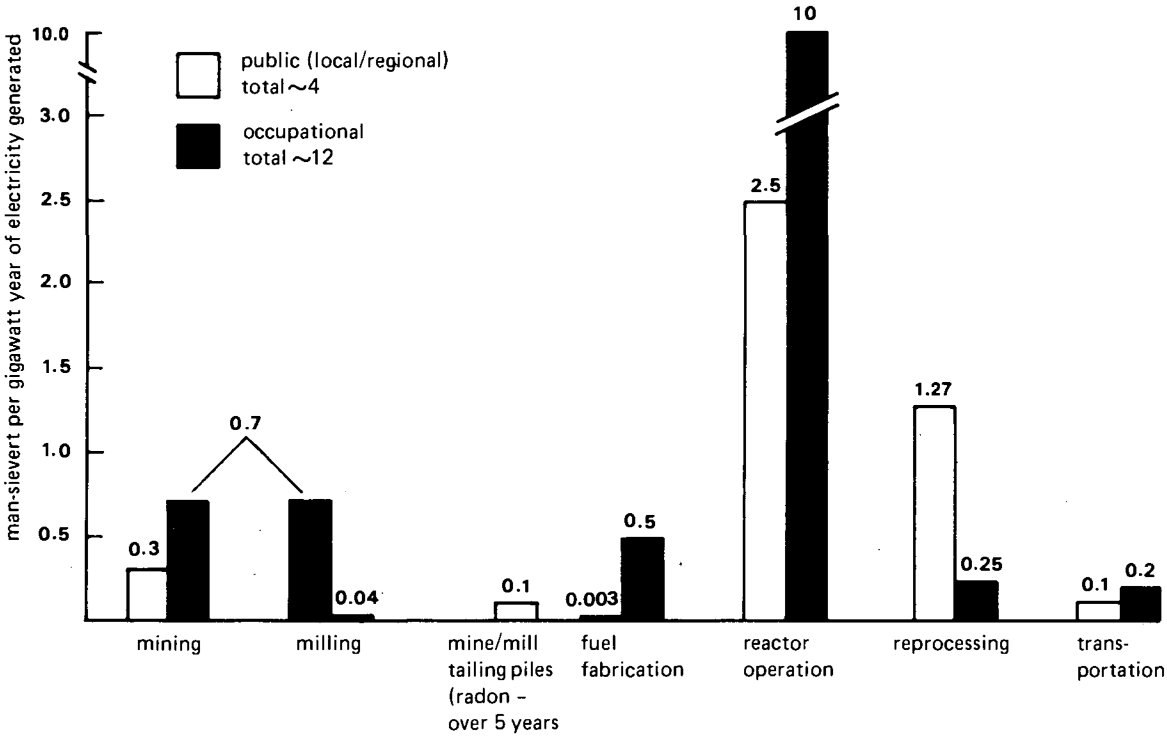
Long-term prospects. The fuel-cycle operations also give off much longer lived radionuclides which remain in the biosphere for thousands of years. Assuming that these radionuclides deliver doses over a hypothetical infinite time, the collective dose commitment is 69 man Sv per gigawatt year of electricity generated. However, only 10% of this total will be delivered over the next 100 years. Over the next 10 000 years, radon exposures from mill tailings would commit as much as 150 man Sv per gigawatt year of electricity generated.

The Chernobyl accident: Beyond the hypothetical realm. Although the radiological impact from the routine generation of nuclear electricity is very small, concerns remain about the consequences of potential accidents. But now, radiation exposures from the Chernobyl accident can be viewed through a realistic lens: the extensive information available from international and national groups collecting and analysing data on radiological fallout since the Chernobyl accident. In particular, UNSCEAR, together with the World Health Organization and the IAEA, assessed the global radiological impact of the accident, based on data from nearly 40 countries.

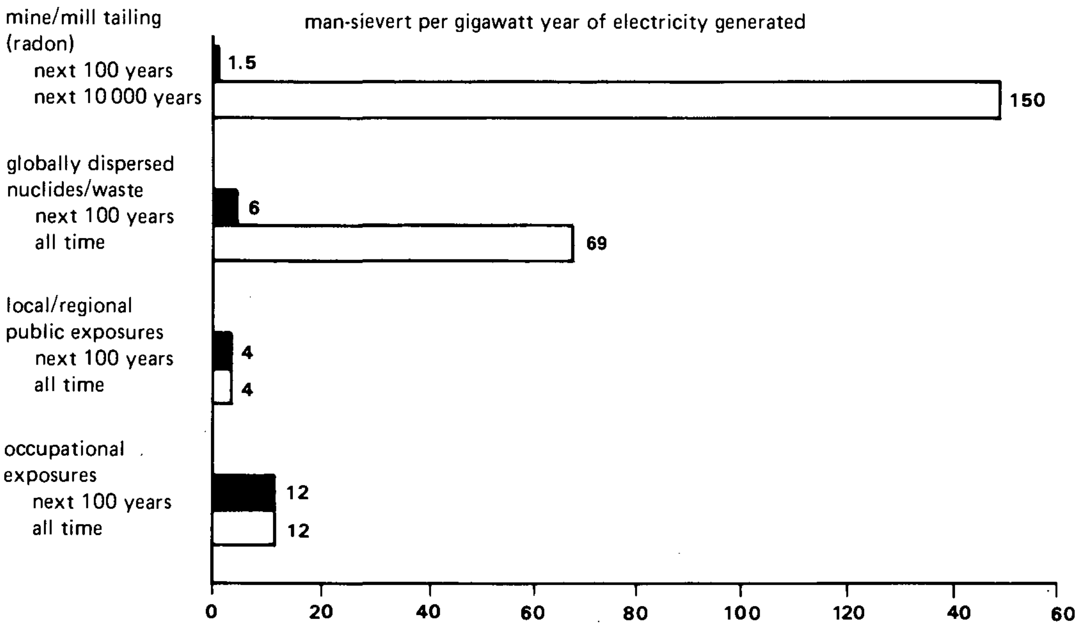
The accident. The accident on 26 April 1986 at Unit 4 of the Chernobyl nuclear power station occurred during a low power engineering test, when safety systems were switched off. The ensuing uncontrolled instabilities caused explosions and fires that severely damaged the reactor core and containment structures. Radioactive gases and dust particles were environmentally released: 25% the first day, and the rest over the next nine days. The fire was extinguished and the reactor core was sealed off by the tenth day after the accident. The reactor is now permanently entombed in a sarcophagus which confines the residual radioactivity.

The initial releases of radioactive materials spread with winds in a northerly direction; subsequent releases dispersed towards the west and the southwest, and in

Estimated collective dose commitments over short term to local and regional population and occupational exposures due to nuclear fuel cycle (normalized)

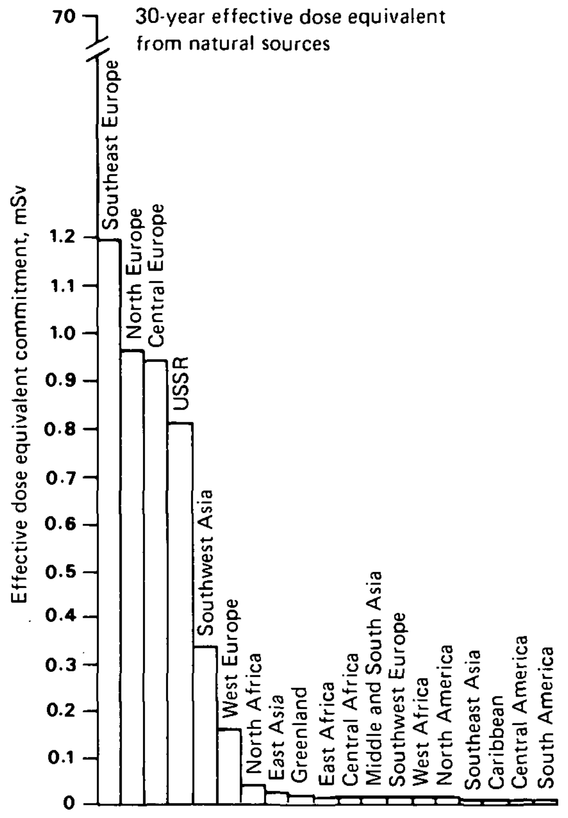


Estimated collective dose commitments over long term due to nuclear fuel cycle (normalized)



Note: All values are rounded.

Regional average effective dose commitment from Chernobyl



other directions as well. Long-range atmospheric transport spread the released radioactivity throughout the northern hemisphere. But no airborne activity was deposited in the Southern Hemisphere. Fallhout of airborne radioactivity was governed mainly by sporadic rainfall. Iodine-131, caesium-134, and caesium 137 were the more relevant radionuclides deposited, giving rise to radiation exposures externally from ground contamination and internally from the ingestion of contaminated food.

The response. The forceful public health measures initiated by Soviet authorities immediately after the accident and the ongoing public health programmes have substantially reduced the risk of public exposures to radiation. Decontamination measures, topsoil removal, food and livestock monitoring and destruction, and agricultural restrictions have reduced radiation dose levels in the area to well below worst-case assessments made shortly after the accident and before radiation emergency handling had any impact on the contaminated areas and their populations. By summer 1987, 60 000 houses and other structures in some 600 population centres had been decontaminated.

Outside the Soviet Union, countermeasures taken in many countries immediately after the accident effectively lowered both individual and collective doses.

Radiation doses: How much, where, and why. The findings on the major radionuclides released indicate widespread variations in the estimated doses to the public. The doses committed from the accident will be delivered mainly over the next 30 years or so and mostly due to the continuing exposures from caesium-137. Even the highest average regional commitment (nearly 1.2 mSv) recorded for populations in southeastern Europe represents only a tiny fraction of the 30-year dose (some 70 mSv) people will inevitably receive on average over this period from the natural background radiation. *(See accompanying figure.)*

The doses received during the first year after the accident are also not alarming. For the exposed population of the Byelorussia region, the first year average dose was on the order of one year exposure to natural background radiation. Elsewhere in Europe, first-year doses varied, representing 25–75% of the annual doses from the natural background. Countries in the most western part of Europe, and also those in Asia, North Africa, and North and Central America, were less affected. These findings are in accord with the deposition pattern.

No grounds for concern. Admittedly, Chernobyl was the most serious radiological emergency humanity has experienced. In addition to the assurances emerging from the UNSCEAR report, in January 1988 the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development published the findings of its evaluation of the radioactive fallout recorded in the OECD countries from the accident. It concludes that "... individuals in the OECD countries are not likely to have been subjected to a radiation dose significantly greater than that received from one year of exposure in the natural radiation background. As a consequence, the lifetime average risk of radiation-related harm for the individual members of the public has not been changed to any noticeable extent by the accident; the number of potential health effects (cancers and genetic effects) that can be derived by calculating collective doses will not constitute a detectable addition to natural incidence of similar effects within the population".

Adding it all up

A comparative analysis of radiation in the living environment can now be made on an individual basis and collectively for the dose commitments to the world's population. A clear factual basis emerges.

- The contribution of nuclear energy to the radiation environment can be considered negligible: it is orders of magnitude lower than the exposure an individual receives from all other sources. From the perspective of the collective dose commitment, under normal conditions and excluding the commitment from the very long-lived radionuclides, public global exposure from a year of production of nuclear electricity is equivalent to slightly less than one additional hour of exposure to natural background in that year. When these radionuclides (mainly carbon-14) are included, the committed dose is equivalent to roughly 37 additional hours of natural irradiation. *(See graphs.)*

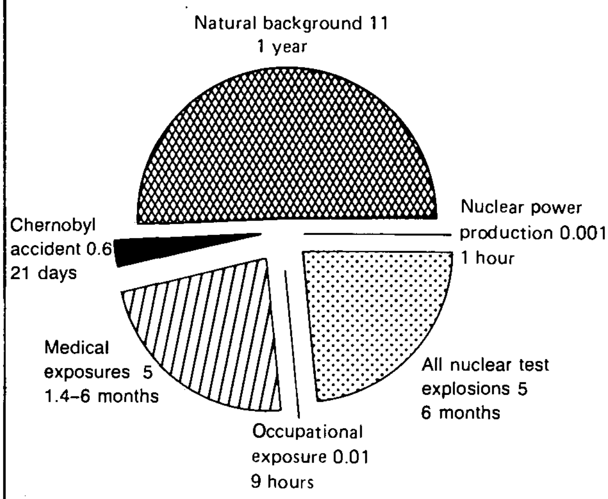
Even in the extreme case of Chernobyl, the collective dose commitment (mainly from caesium-137, delivered over the next 30 years) is equivalent to only 21 days of additional exposure to the natural background.

- Medical irradiation is a major modifier of the radiation environment. The average annual dose from the uses of medical radiation, particularly diagnostic X-ray examinations, is 20–45% of that an average person receives yearly from the natural radiation background. The frequency and intensity of these practices vary dramatically among the population, with typical individuals receiving twice as much irradiation from medical uses than from natural exposures. Collectively, the exposures from medical irradiation are equivalent to 1.4–6 months of additional exposures from the natural background. Moreover, medical irradiation is likely to increase over the next several decades, as people live longer and medical services reach more of the population in the development world. By 2000, the collective dose will probably have increased by 50% and by 2025 by 100%.
- Obviously, irradiation from carbon-14 affects the dose commitment from the atmospheric nuclear tests that have occurred over the past few decades. When the human exposure from this very long-lived radionuclide is included in the estimate, the collective dose commitment is equivalent to 28 months of additional natural irradiation.

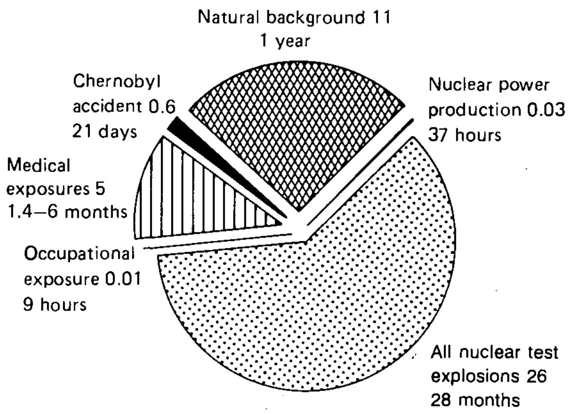
To complete the picture, human exposures that are incurred occupationally are equivalent to slightly less than 9 hours of additional natural irradiation yearly.

Collective dose commitments (millions of man sieverts) and equivalent time of natural background exposure

Excluding commitment from very long-lived radionuclides

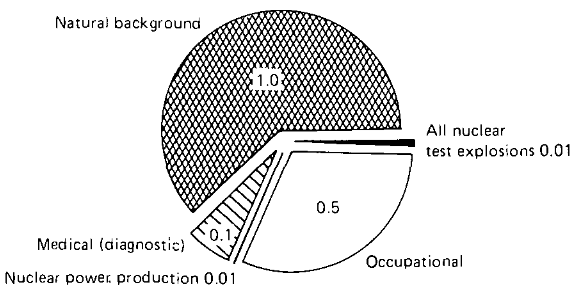


Including commitment from very long-lived radionuclides

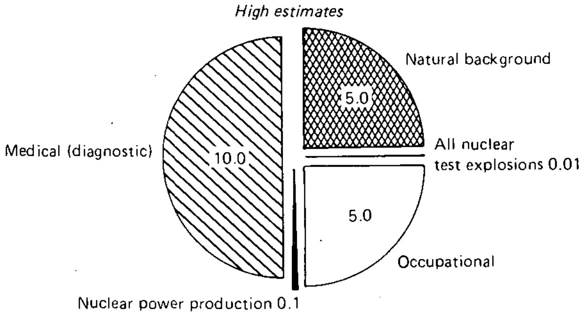


Present annual doses for typically exposed individuals (mSv)

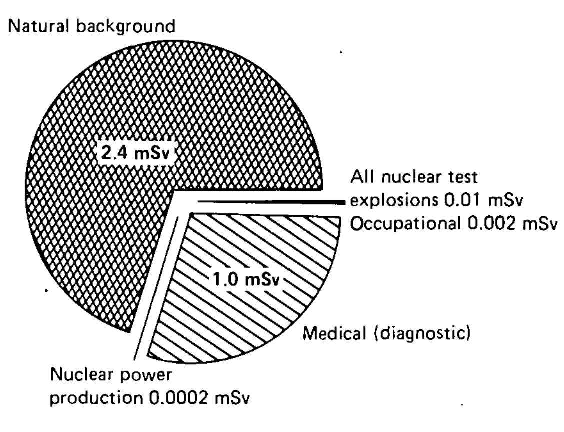
Low estimates



High estimates



Present annual *(per caput)* individual radiation doses from natural and man-made sources



The implications

The communication problem. Logically, it can be concluded that the normal generation of nuclear electricity does not significantly change the radiation environment. Properly viewed, the consequences of the Chernobyl accident are not as catastrophic as often mistakenly depicted. Why, then, has the impact of nuclear energy been so deeply misunderstood? One possible explanation is that people view radiation somewhat myopically: it is considered to be primarily a nuclear-related agent, offering no tangible benefits. Indeed, exposures from other human practices are welcomed or tolerated. For a patient, the benefits of medical irradiation are apparent. For an unquestioning person accustomed to the convenience of electricity, the advantages of nuclear energy and the disadvantages of a nuclear phase-out are less obvious.

The communication problem is serious, caused by the lack of common levels of understanding between the specialists knowledgeable about the low-level exposures from nuclear energy and a concerned public whose uneasiness is not easily soothed by bland expert reassurances. There is a need to frankly address public concerns about radiation, communicating factually in a language that fosters understanding, trust, and credibility. The UNSCEAR evaluation provides an opportunity for bridging this gap.

Dose reductions: vast possibilities. Additionally, many possibilities exist for reducing radiation doses without jeopardizing the benefits of radiological practices. Efforts to control natural irradiation show promising results. For example, the application of aluminium foil to walls built with radioactive alum shale-based concrete has reduced the radon entry rate nearly 50%, and wall surface coatings have lowered radon rates by 20–80%. There are also possibilities for eliminating unnecessary medical irradiation. New diagnostic techniques, such as ultrasound and magnetic resonance imaging, are replacing X-rays, particularly for the spine, kidney, and gall bladder. Technological progress over the past two decades has paved the way for much lower doses to patients. By far, the largest reduction is feasible through the replacement of chest fluoroscopy and photofluorscopy with radiography, by factors of 20 and 5, respectively. Some simple and low cost methods known to offer modest dose reductions involve collimation, added beam filtration, and gonadal and thyroid shielding during radiographic examinations. Training in the use, calibration, and quality assurance of medical equipment could reduce doses, possibly by as much as 50%. In many countries more than half of those performing radiological examinations have little or no formal training.

In spite of its small contribution to the radiological impact, this progress can be and is being matched by the nuclear power industry. According to the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development, radon exposures from uranium tailings could be significantly reduced; reduction factors of more than 6 million are considered feasible. Similar trends can be found throughout the fuel cycle. Doses from nuclear reactor operations are declining despite increasing capacity, mainly because of advanced protection systems and the expanded use of robots. The backend of the fuel cycle is no exception: an important role for fuel reprocessing is to diminish the radiological impact from the direct disposal of spent fuel elements. The dominant trend in reprocessing is towards greater efficiency, particularly at Sellafield.

Radiation exposures and radiation safety. Surprisingly, the marked variations in contributions from radiation sources and the potential for controlling these exposures have had a relatively minor influence on setting priorities in radiation safety. Ironically, radiation safety efforts have concentrated mainly on nuclear energy, effectively ignoring or underplaying the much larger hazards posed by other radiation sources.

Given the enormous variation in radiation levels and the potential for reducing exposures to all radiation sources, it is regrettable that these considerations have had such a minor influence on the prioritization of radiation safety.

In principle, radiation protection standards exist for occupational exposures from all practices involving radioactive materials. These are strictly enforced in the nuclear industry, whose staff includes many highly-trained radiation protection professionals. Generally, such high levels of protection do not prevail elsewhere, with notable exceptions such as technically advanced hospitals. Even so, the occupational exposures to workers at nuclear installations are on the order of one magnitude higher than those recorded for other radiation practices, such as medical irradiation. These numbers should be interpreted cautiously. For one thing, record-keeping at nuclear installations is comprehensive and stringent. Moreover, sophisticated occupational monitoring systems are enforced throughout the nuclear fuel cycle; this sophistication is unmatched elsewhere.

Dose reductions versus increases: the tradeoff. People are often confronted with a tradeoff involving radiation exposures: to opt, say, for a relatively high dose from a computer tomography scan, or to incur the risk of an undetected and untreated illness. Medical specialists face a similar conflict: an underexposed radiograph that cannot be interpreted is of no benefit to a patient, even though the absorbed dose is low.

Collectively, the goal of avoiding radiation exposures or reducing them *per se* is not always the ideal in a dynamic world in which populations are growing, economies are expanding, people are living longer, and the aspirations for a quality life spread throughout the globe. Over the next 30 years, the world faces the steepest growth in population, from 5 billion to slightly more than 8 billion in 2015. The trend towards urbanization continues worldwide, with the urban population expected to be some 57% by 2015, in contrast with the present share of 30%. Traditionally, city dwellers have received a higher share of medical services than the rural population. The recent phenomenon of population aging, particularly in the developed countries, necessarily increases demands for medical services. Whereas in 1980 some 380 million people worldwide were 60 years old or more, by the year 2000 the number could be 607 million, reaching nearly 1200 million by the year 2025.

Social and economic development requires energy, especially electricity. Nuclear and coal are viable options for meeting large-scale electricity demands, but both result in radiation exposures. Consumers in the industrial and domestic sectors are shifting from oil to electricity, not only for the greater energy independence but also for the economic advantages associated with the high end-use efficiency of electricity. While the other fossil fuels and the renewables can contribute to supply, for most countries nuclear and coal are the most viable options for meeting these large-scale demands.

The projected increases in nuclear generating capacity will increase the levels of radiation exposures. Viewed from a proper perspective, these exposures can be seen as representing then, as now, only a small percentage of the living radiation environment. However, an expanded role for coal generated electricity is attended by not only larger radiation exposures but also the myriad environmental hazards of fossil fuel combustion.

Radiation doses

Absorbed dose: The amount of radiation energy that is absorbed per gram of tissue. It is expressed in a unit called the gray (Gy).
Dose equivalent: The absorbed dose weighted to take into account different types of ionizing radiation and their energies. It is expressed in a unit called the sievert (Sv), and the submultiples millisievert (mSv, microsievert (μSv), etc. For most practical applications, the weighting is unity; that is, one sievert is equal to one gray.
Effective dose equivalent: The dose equivalent weighted to express the sensitivity of different human organs to radiation exposure. Since it is a (modified) dose equivalent, it is also expressed in sievert.
Collective effective dose equivalent: The effective dose equivalent to a group of people from a source of radiation. It is expressed in a unit called man sievert (man Sv).

Note: In practice, these quantities are expressed as rates (for example, mSv per hour, or man sievert per year). If the rates are summed up over time, the resulting quantity is generally called commitment. Unless specified, the integration time for a dose commitment is theoretically infinite; for example, the collective dose commitment is the sum of all doses received by all individuals (present and future individuals over all time) as a result of a practice or action involving radiations.