Radiation effects, nuclear energy and comparative risks*

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Nuclear energy had a promising start as an unlimited, inexpensive and environmentally benign source of energy for electricity generation. However, over the decades its growth was severely retarded due to concerns about its possible detrimental effects on the well-being of mankind and the environment. Since such concerns are essentially due to the gigantic magnitude of radioactivity and ionizing radiations associated with nuclear energy, this article starts with a comprehensive account of effects of the ionizing radiation on living systems. Quantitative description of types of radiation exposure and their varied effects is given. The origin, type and magnitude of mutagenic effects of radiation are described. The concept of radiation risk factors, basis for their evaluation and their currently accepted values are presented. With this background, origin and magnitude of radioactivity and associated ionizing radiations in nuclear reactors are presented and the elaborate measures to contain them are described. It is recognized that notwithstanding all the measures taken in the nuclear industry, certain amount of radiation exposure, however small, is inevitable and the values, based on the experience world over, are presented. Estimated health risk due to such exposures is evaluated. For a comparative analysis, risks in other options of electricity generation such as hydel and fossil-fuelled plants are described. It is seen that on an overall basis, the nuclear option is no more risky than the other commonly employed options, and is in fact, significantly less. Lastly, since every option of electricity generation entails some risk, the case of 'no addition of electricity' and its impact on the society are considered. Based on the analysis of extensive data provided by UNDP on the human development parameters for different countries in the world, it is shown that at least for developing countries, any option of addition of electricity would be far more desirable than the 'no addition' option, even from health and environmental considerations.

Keywords: Nuclear energy, nuclear industry, nuclear reactors, radiation effects.

NUCLEAR energy as a source of electric power has had a promising start; it promised an unlimited, safe and environmentally benign source of energy. To quote Dag Hammarskjöld, the then Secretary General of the United Nations Organization, at the opening session of the Second United Nations Conference on the Peaceful Uses of Atomic Energy[1] in 1958 'Atomic energy opens up a most promising future for the under-equipped as well as other countries. It gives certainty that they will never be halted in their industrial development by lack of sufficient power and it guarantees the continuance of expansion'. But over the decades, nuclear energy started facing a unique and essentially non-technical problem; a problem of perception. On the one hand, claims continue to prevail that it can provide an unlimited source of energy to meet the ever-growing demands of power with minimum risk to the operating personnel, general public and the environment. On the other, there has also been a view, rather vocal at that, that it is environmentally disastrous and endangers the health of not only the operating personnel and the public of the present generation, but those of our progeny as well. Notwithstanding such reservations and discordance in perceptions, presently there are 438 nuclear power reactors operating with an installed capacity of about 371,000 MWe, distributed over 30 countries and meeting about 16% of the world's electricity requirement. Besides, 31 power reactors are under construction[2].

There has been an ever-growing demand for electricity, particularly in the developing countries. The world's fossil sources of energy, the mainstay for the present electricity generation, are only finite and their geographical distribution is highly skewed leading to the concern about energy

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security for several countries. Besides, there is also the fear that uncontrolled utilization of fossil fuels would disturb CO_2 balance in the atmosphere with disastrous consequences on the environment. In spite of the strong accent on the development of new and renewable sources of energy, they appear to be only a useful supplement but not a substitute for central electricity generation in the foreseeable future. Owing to these reasons there is an increasing realization, at least in the expert circles, that nuclear energy is one of the few sustainable and environmentally benign options and foreclosing this option for electricity generation can lead to energy crisis seriously affecting the industrial growth, particularly for countries like India. But for this option to be acceptable by the society at large, it is necessary to analyse the reasons for whatever reservations the public has regarding nuclear energy. It is necessary to have an objective study of the risks involved, their causative factors and their comparison with risks in other options for electricity generation and place them before the society. This article is an attempt in that direction.

There have been several analyses for the severe discordance in perceptions regarding nuclear energy, notable amongst which is the IIASA study[3] on the risks of different energy systems. It observes that public perception of the risks with nuclear energy can be classified as: (i) Environmental and physical aspects, (ii) Psychological aspects and (iii) Socio-political implications.

The first two categories of public apprehension are directly traceable to the gigantic amount of radioactivity and ionizing radiations associated with the generation of nuclear power. Hence, any effort to bridge the gap in the perceptions about nuclear energy calls for a comprehensive discussion of this radiation factor. Towards this end, we discuss the types of radiation exposure, their effect on living systems and the associated risk factors. This is followed by the origin and extent of radiation exposures and the estimated risk in nuclear power industry during normal as well as accidental conditions. It also addresses the issue of radioactive waste disposal, which has drawn considerable public debate. A comparative analysis of the risks involved in the electricity generation by nuclear and other energy sources is presented. The impact of 'no additional electricity generation' is also dealt with.

Radiation effects

Radiation exposures

Certain high-energy radiations known as alpha (α), beta (β) and gamma (γ) rays, generally emanating from the radioactive nuclei, while passing through matter, can knock out electrons from the neutral atoms or molecules. This process, which results in free electrons and electron-deficient atoms or molecules called 'positive ions', is known as ionization and the radiations themselves are called ionizing radiations. In the process of ionization, they deposit certain amount of energy in the matter and it is this energy which is responsible for all the radiation effects. Quantitatively speaking, exposure to ionizing radiation is reckoned in terms of the amount of energy imparted by the radiation to the material through which it is passing. It is termed as radiation dose and expressed in 'gray' (Gy; or its sub units). One gray corresponds to the deposition of 1 J of energy in 1 kg of the exposed material. It is well established that for the same amount of energy deposited, different types of ionizing radiations can induce varying degrees of biological effects. To account for this feature, while talking about radiation dose to the living systems, Gy is multiplied by the radiation-type dependent 'quality factor' and the resulting quantity is expressed in sievert (Sv). (As the magnitudes of Gy and Sv are large compared to the exposures normally encountered, their sub-units, milli gray (mGy = 10^{-3} Gy), micro gray (μGy = 10^{-6} Gy), milli sievert (mSv = 10^{-3} Sv) and micro sievert (μSv = 10^{-6} Sv) are frequently employed.) For gamma radiation, which is of widest concern, quality factor is unity, and hence Gy and Sv are synonymously used.

For living systems, the radiation exposure can occur in two different ways. In the first case, the source of radiation is external to the body. Radiation emanating from the source impinges on the body and deposits energy therein. This is called external exposure and it ceases to occur with the removal of the source or when the source is well shielded. The other mode of exposure arises when a living being breathes air contaminated with radioactivity or ingests contaminated water or food materials. Part of the activity thus entering the body gets deposited in different organs depending on the chemical nature of the radioactive substance. It persists there over a period of time, of course in diminishing measure, depending on its radioactive half-life and biological removal rate. Throughout this period the body gets exposed to radiation and this is called internal exposure. In computing the radiation dose for internal exposure, one has to take into account the total energy deposition that is likely to occur over the entire period. This is known as the 'committed' dose.

Generally speaking, external dose is considered important only for γ-radiation, neutrons and to some extent high-energy β-radiation. α-radiation and low energy β-radiation (also called as soft β-rays) contribute only to the internal dose because of their very short range in transit.

The concern

The United Nations Scientific Committee on the Effects of Atomic Radiations (UNSCEAR), in its 1993 report to the General Assembly states that[4] 'The Committee's interest in the biological effects of radiation is mainly concentrated on the effects of low doses'. Over a decade, the situation has not changed much. Today probably no other topic in radiation sciences has been drawing so much attention as the likely health effects of exposure to ionizing radiation at low-levels. This is because of two reasons. In occupations dealing with radioactivity and ionizing radiations, while one can bring down the radiation fields and exposures to very low-levels by proper practices and control, they cannot be totally eliminated. This will be over and above the background radiation, which is ubiquitous, with wide spatial variation depending on the geochemical and other features of the location. Further, the health effects associated with these low-level exposures are, if at all, likely to be a small fraction of natural incidence of such maladies, resulting in the classic 'poor signal-to-background ratio' problem. An obvious question would be, why not extrapolate backwards from the high exposure risk data which are more or less well established? This is not always possible since such extrapolations are wrought with severe uncertainties due to dose-rate effect, repair mechanism, adaptive response, etc. Thus the exact determination of the health risk at low exposures continues to be a challenging task.

The global average dose due to natural background radiation is about 2.4 mSv/yr, corresponding to an average lifetime dose of about 170 mSv. However, the natural background radiation level and consequent lifetime dose vary, ranging over an order of magnitude from place to place[5]. When we say low-level exposure, it generally refers to dose rates of fraction of a mSv/min and/or integrated dose in the range 200–400 mSv.

Biological effects

It is well established that biological effects are of two types; deterministic and probabilistic. Deterministic effects are generally the reduction of red blood cells, skin reddening and blistering, induction of sterility, etc. They arise out of massive cell damage or cell killing due to the exposure of the biological system to ionizing radiation. These effects are characterized by their appearance within a few hours to few weeks after the exposure. An important feature of the deterministic effects is that they occur only above a particular level of exposure called 'threshold dose'. Threshold doses are different for high dose rate (acute) and low dose rate (chronic) exposures. For human species, about 500 mSv of acute exposure is needed for any discernible deterministic effect. Such exposures can occur only in serious radiation accidents or from unwanted but inevitable exposure of healthy tissues in radiation therapy. For more commonly encountered low dose rate exposures the threshold is significantly higher, of the order of a few Sv.

Probabilistic effects, also known as 'stochastic effects', result from the 'mutagenic' action of ionizing radiation, an elementary picture of which is as follows:

In a living cell the deoxyribonucleic acid (DNA), a double-stranded helical macromolecule present in the chromosomes inside the nucleus, is the repository of all the information required for governing cell functioning and its replication. A simplified and de-twisted diagram of the DNA is shown in Figure 1.

The backbone of each strand in the molecule is a string of sugar and phosphate residues and the two strands are linked by a pair of 'nucleotide' bases. Four different nucleotide bases, namely adenine, guanine, cytosine and thymine occur in the DNA molecule. The cardinal feature of DNA is that while the occurrence of a particular nucleotide base along the strand of the molecule is not influenced by the neighbouring ones, base pairing is highly specific. That is, adenine on one strand can pair only with thymine on the other strand, with a similar matching between cytosine and guanine. Thus, the sequence of nucleotide bases on one of the strands of DNA completely determines the sequence on the other. (This plays a paramount role in DNA and cell replication, but we need not go into those details here.) The sequence of such base pairs in the DNA molecule is the 'text' of information required for all cell activities. If the DNA molecule is affected either by changes in the individual base pairs or its sequence, its information content gets altered and such a change is called mutation. If the cell happens to be a somatic (non-germinal) cell in the body, the mutagenic disturbance can lead to loss of control over the cell division, which may eventually result in the induction of cancer. Or, if it happens to be a germ cell, the mutated information can be passed on to the progeny leading to genetic effects. Ionizing radiations are known to bring about such mutations either by directly affecting the DNA or indirectly by producing active chemical species in its vicinity, which can affect the DNA. Both direct and indirect modes of damage are probabilistic in nature and the probability increases with radiation dose. Some common types of damage to DNA are: (i) base damage, (ii) single-strand break, (iii) double-strand break, and (iv) cross-linkage of the molecule. Damage to DNA is subject to efficient repair

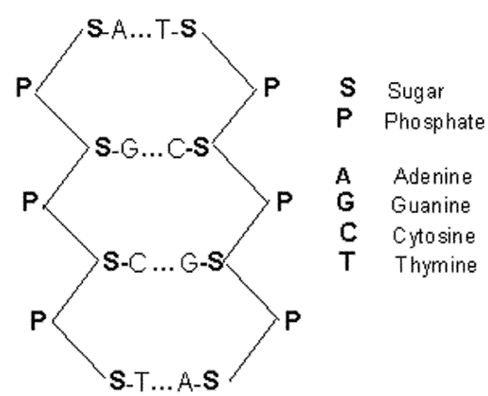

Figure 1. Simplified diagram of the structure of DNA.

Table 1. DNA damage in mammalian cells

Event	Spontaneous events/yr	Events/10 mSv
Single strand break	~ 4.4×10^7	10
Double strand break		0.4
Depurination and/or base legions	~ 1.1×10^7	9.5
Total	~7×10^7	20

mechanisms mediated by enzyme actions. If the damage is confined to a single strand, the repair mechanism uses information provided by the other strand. The repair is then highly efficient and error-free. Mis-repairs are frequent in the case of double-strand breaks. Such instances can result in the loss of biological information that may lead to carcinogenic or genetic effects. It must be mentioned here that the mutations are neither new nor specific to ionizing radiations; they are also introduced by other agents such as excessive heat, certain types of chemicals and viruses, etc. Mutagenic phenomenon has always existed in nature and it is a part of our evolutionary system. Frequency of natural mutations is about a million times more compared to that introduced by the radiation at the levels we are interested in[6], as can be seen from Table 1.

Risk factors

It is the mutagenic effect of radiation that has given rise to maximum concern amongst the public. Unlike deterministic effects, these effects are supposed to have no threshold levels of exposure. According to this model, however small the radiation dose is and whether it is incurred in one shot or over an extended period, the effect, or more appropriately the probability of its occurrence, is proportional to the integrated dose. It is termed cumulative dose. Furthermore, irrespective of the number of persons exposed in the population and the levels of their exposure, the probability of manifestation of these effects in the population is proportional to the sum total of all the individual exposures called collective dose, expressed in person-sievert (PSv). There are several arguments against this 'no threshold' model. However, it is generally accepted as a safe hypothesis in the absence of firm data to disprove it.

It is not that every single mutation automatically leads to the incidence of cancer. The biological information system is built with a large redundancy, which provides it a certain degree of resilience. Besides, cancer is a multifactorial disease which needs more than just an initiator. It is in this context that these effects are called stochastic effects and are dealt with in terms of probabilities. For a quantitative assessment, the biological detriment of these effects is expressed in terms of risk coefficients. Simply put, the risk coefficient is the expected number of undesirable events likely to be introduced into the population due to unit collective dose (there are several variants of this definition, each one having its own advantages).

Understandably, there has been an enormous scientific effort in terms of laboratory studies on animals, *in vitro* experiments on mammalian cells and epidemiological studies towards determining the risk coefficients. While the laboratory experiments have significantly contributed to our understanding of radiobiological basis for risk determination, the risk coefficients themselves have been obtained basically from epidemiological studies. The database currently available from such studies falls under two categories: High Dose Rate (HDR) and Low Dose/Low Dose Rate (LD/LDR) exposures. The HDR database consists of more than 6×10^5 person-years (PY) of Life Span Studies (LSS) of the atomic bomb survivors in Hiroshima and Nagasaki and more than 10^6 PY each from radiation treatment and diagnostic cases. Among them, the LSS are the most thoroughly planned with a cohort of 120,000 (about 93,000 exposed and 27,000 control)[7], starting from 1950. It is essentially based on this study that the UNSCEAR has estimated the risk coefficient for cancer induction to be about 5×10^{-2} per Sv. For the genetic effects, UNSCEAR specifies a risk factor of 1×10^{-2} per Sv. This figure has been derived essentially from animal studies involving higher levels of exposure. None of the epidemiological studies conducted so far, including the LSS, has shown any evidence of genetic effects[8].

Low-level exposure

It is well established that for γ-rays, which are of primary concern in the population exposure, the biological risk has a strong dose and dose-rate dependence. First, the dose-response curve is observed to be nonlinear and backward interpolation of high exposure data tends to overestimate the effects at low doses. The second and more important observation is that for the same total dose, the lower dose rate exposure results in a significantly lower detriment. Based on extensive experimental and epidemiological studies the Dose and Dose-Rate Effective Factor (DDREF) has been observed[9] to be in the range 2–11.

It was mentioned earlier that the basis for the currently used risk coefficients are the LSS of atomic bomb survivors, which is essentially a high dose rate category. To extend its application to low-level exposures, a DDREF of 2 has been used. However, the actual DDREF applicable could be significantly higher, resulting in much lower risk coefficients as actually observed in the LD and LDR epidemiological studies discussed below. In a recent study, Vivek Kumar *et al.*[10] report a value of 3.4 for DDREF.

Presently available LDR data consist of about 2×10^6 PY of occupational workers and more than 10^6 PY of environmental exposure in High Background Radiation

Areas (HBRA). These data do not provide clear support to the presently adopted risk coefficients. It is even consistent with a 'no-risk' model. For LDR, epidemiological investigations in China happen to be the largest. It has about 10^6 PY of observation for people living in HBRA with a mean radiation dose of 5.4 mSv/yr and a similar number in control areas with a mean dose of 2 mSv/yr. The study shows no increase in cancer mortality for the HBRA population[11]. The frequency of observed cancers in the HBRA population is marginally less compared to that of control population (but not significant enough to firmly support any negative correlation of cancer with radiation exposure). A recent report on an Indian epidemiological study in the HBRA of Kerala[12], with radiation levels varying from 1 to 5.5 mSv/yr, concludes that 'The available data does not directly suggest any increase in cancer incidence in relation to radiation levels. People are living in the area since past several generations and increase in cancer occurrence due to radiation, if any, could have been explicitly evident'.

Large-scale LDR epidemiological studies have also been conducted amongst radiation workers in USA, Japan, France, Canada and Sweden. None of them shows any significant association of cancer with low-level exposure. The International Agency for Research on Cancer had conducted a study on the data pooled for radiation workers from three countries[13]. The combined data clearly indicate[14] that the presently used risk factors for cancer are significant over estimates for doses at least up to 300 mSv.

There have also been other reports of health effects due to low-level exposure. In general, they have not been able to stand the rigorous scientific analysis and have been discredited by subsequent large-scale studies. In the mid 70s, Kochu Pillai *et al.*[15] reported higher prevalence of mentally retarded children (12 in the surveyed population of 12,918) in the monazite belt of Kerala compared to zero prevalence (none in 6000) in the control population. The difference was attributed to the higher background radiation, 15–30 mGy/yr, in the monazite belt compared to 1 mGy/yr in the control area. However, later analyses faulted this report on several counts, including the anomalous observation of zero incidence in the control population[16]. Similarly in the UK, Knox *et al.*[17] reported correlation of cancer (leukaemia) with high background radiation. But a subsequent large-scale study on the same did not provide any confirmation for the conclusions of Knox. It was noted that the statistical methods employed by Knox were obscure and the results were difficult to interpret[18].

Gardner *et al.*[19] reported clusters of childhood leukaemia amongst the population living in the vicinity of the UK Sellafield nuclear facilities. A possible linkage of these clusters to radiation exposure of their fathers was suggested. This was in total contradiction of the LSS data; no excess cancer has been observed amongst children of atomic bomb survivors who had significantly higher exposure. However, the report prompted several large-scale and systematic surveys. These studies did not provide any support to the suggestion that radiation exposure of fathers increases the cancer risk for their children[20]. Studies have also been conducted amongst children in the vicinity of nuclear facilities in France, USA, Germany and Canada. None of them gave any evidence for the excess cancer as reported by Gardner.

Over the years, there have been a number of studies, which provide some support for the hypothesis that an initial low-level exposure to ionizing radiation can induce protection against DNA damage and mitigate the severity of deleterious effects of subsequent high exposures[21,22]. There have also been reports that such low exposures can even be beneficial by preparing the cell to face the deleterious agents other than ionizing radiation, a phenomenon called 'hormosis'. However, evidences for such effects are still not unequivocal. If firmly established, they may call for substantial modification of risk coefficients at low-level exposures.

Present status

Detrimental effect of exposure to ionizing radiations is one of the most widely studied subjects. Based on extensive laboratory studies and epidemiological surveys, risk coefficients have been arrived at on a conservative basis. They have been derived from high exposure data. Small as they are, there are reasons to believe that they could be over-estimates for low-level exposures and can be considered only as upper limits. How small they are or whether they exist at all at low exposures are the issues of interest at present.

Radiation exposure limits

Largely based on the analyses of UNSCEAR and the risk coefficients arrived therefrom as mentioned earlier, the International Commission for Radiation Protection (ICRP) has evolved recommendations on the limits of radiation exposure[23]. Bases for these recommendations are:

(i) No practice shall be adopted unless it produces sufficient benefit to the exposed individuals or to the society to offset the possible detriment.
(ii) Magnitude of individual doses and the number of people exposed or likely to be exposed should be 'As Low as Reasonably Achievable, economic and social factors taken into account (ALARA)'.
(iii) Exposure to the individual from all the practices should be subject to the specified limits.

Limits arrived at on the above bases are given in Table 2. It must be mentioned here that ICRP is a non-governmental body and its recommendations are not mandatory. How-

Table 2. ICRP recommendation on dose limits

Application	Occupational	Public
Effective dose	20 mSv/yr averaged over a defined period of 5 years. (Should not exceed 50 mSv in any given year)	1 mSv in a year (in special circumstances, a higher value of effective dose can be allowed in a single year provided that the average dose over 65 years does not exceed 1 mSv/year)

ever, in view of the large expertise behind ICRP, almost all countries in the world accept its recommendations and constitute their own national statutory bodies for their implementation.

Compared to the ICRP limit of 20 mSv/yr, globally averaged exposures for radiation workers in different fields are in the range 2–8 mSv/yr. Further, there is a significant declining trend in this due to improved technology and practices.

Effects on natural environment

By and large, the effects of ionizing radiation on living systems are discussed only in the context of human species. The limits and standards currently in practice are also specifically aimed at protecting mankind against the ill-effects of exposure to ionizing radiation. Even when one studies environmental contamination, it is generally with the end objective of evaluating its impact on human population. An obvious question would be what are the effects of ionizing radiation on the plant and animal species, which anyway constitute the major part of the natural environment? Radiation effects on these species have been widely studied and the results of such studies have been extensively discussed in UNSCEAR and IAEA reports[24,25]. A comprehensive review of the presently available data relevant to the radiation protection of the environment is given by Real *et al.*[26]. However, results of such studies and the conclusions of such discussions have not reached the public to the extent called for. The material presented in this section is mostly taken from the above three references.

Effects of ionizing radiation on plants and animals are considered at two levels: on the individual and on the population. Though the population effects depend on and are derived from the individual effects, it is only the statistical aspect that is important at the population level. While in the case of human species the effects at both levels are given equal importance, for plant and animal species only the effects at the population level are considered. For plant species, population effects are the loss of foliage, reduced growth or yield, loss of reproductive ability and extinction of the species. In the case of animals, they are the reduced density or number, survival fraction, age distribution, sex ratio, etc. These measures are generally considered to be the indicators of health status of the species and a measure of their sustaining ability.

Sources of information: All the available data in the field are obtained from:

(i) Planned experimental exposures of animals and plants.
(ii) Chronic exposures due to radioactivity release from nuclear facilities.
(iii) Exposures from nuclear explosions, and
(iv) Major nuclear accidents.

Planned experimental studies have the advantage of looking at the basic radiobiological effects as a function of the radiation dose and its timing in the life cycle of species. They have provided data on the individual effects such as mortality, infertility, growth reduction, etc., which form the bases for the population attributes of interest. However, since these studies are carried out in the absence of natural environment with its confounding effects, deriving the population attributes from such studies needs confirmation. Studies with nuclear facility discharges, nuclear explosions and accidents have provided such additional data.

Liquid effluents discharged into the aquatic bodies have provided a good matrix for studying the radiation effects on aquatic organisms under chronic exposure. Studies on the effect of such exposures have been conducted around several nuclear installations, particularly in USA, UK, France and Canada. Extensive reviews exist on the ecological effects of radiation exposures from nuclear detonations, particularly the ones at Bikini Atolls, Marshal Islands and Nevada test grounds. Several investigations have been completed on marine organisms around the atolls. However, the observed effects could not be totally attributed to radiation because of large-scale concomitant environmental disturbances. The results are shrouded by the recolonization of the damaged zones by healthy members from unaffected areas.

Nuclear accidents have also provided opportunities to study the radiation effects on plants and animals. A large amount of data are available from the Kyshtym and Chernobyl accidents in USSR[24]. While the accidents do provide scope for studying the plants and animals in their natural environment, their exposure regime depends on several factors related to the accidents, such as the nature and quantity of the activity released, dispersal and deposition pattern, etc. The power reactor accident at Chernobyl involved mostly short-lived activities and high acute exposures (~100 Gy within a few days) as well as chronic exposures. In the Kyshtym accident, the exposures were essentially chronic in nature due to predominance of long-lived ^{144}Ce–^{144}Pr radionuclides (285 days half-life). Further, the periods of occurrence of the accidents from the point of view of the species life cycle were quite different. In the Kyshtym accident, the main part of the radiation exposure occurred in autumn and winter, when the metabolic activities are much subdued. The Chernobyl accident occurred in late April, just as the wild plants and animal populations were entering accelerated and reproductive phase.

Database

Plant species: For higher plants, which are more radiosensitive, the acute lethal dose ranges from less than 10 to 10^3 Gy. Amongst them woody species have lethal dose in the range of 10–100 Gy. On the other extreme, plants such as moss, lichens and unicellular organisms are highly radiation-resistant with lethal doses ranging up to 10^4 Gy. Amongst the cultivated crops, cereals are more radiosensitive compared to pasture crops and forage.

Extensive studies in pine-birch forests have shown that trees of the same species and age have different radiosensitivities depending on external conditions such as light interception, soil fertility, wind erosion, etc. Considering reproductive viability, even though the size and rate of production of pollen is temporarily affected with a low dose of 0.7 Gy, they get restored within 3 years for irradiations up to 12 Gy. Birch trees show a much larger radioresistance. Results from the studies on the pine and birch tree community broadly represent the effects on other plant communities.

In general, chronic exposures call for significantly larger doses for the given effect. Exposures at less than 10 mGy/day do not seem to affect the community at all.

Animal species: Mammals are the most extensively studied species amongst animals, employing laboratory experiments as well as community survey following major nuclear incidents. Similar to the plant species, terrestrial animals show a wide range of radiosensitivity. Amongst them, mammals are the most sensitive with the lethal dose in the range 5–15 Gy. At the other extreme are the bacteria and protozoa with the lethal dose going up to 10^4 Gy. As is to be expected, the lower-order animals are generally more radio-resistant. Studies on different species of birds indicate that their radiosensitivity is similar to that of animals. Reptiles and invertebrates are relatively more radio-resistant. Amongst the aquatic organisms, fish appears to be most sensitive to acute radiation exposure.

Conclusion: There does exist a large amount of data on the effect of ionizing radiation on plant and animal species obtained from laboratory studies, field experiments and studies in the environment following nuclear explosions and major nuclear accidents. Most of the radiobiological data have been derived from planned exposure experiments and field experiments have generally confirmed laboratory findings. Wide variation of radiosensitivity has been observed for different species; generally higher level organisms are more sensitive. Within a particular species, the sensitivity greatly depends on the age of the species at irradiation and environmental conditions. Chronic exposures are associated with reduced sensitivity; there appears to be a threshold below which no detrimental effect manifests at the population level. No species seem to have been lost due to the release from nuclear facilities or from nuclear accidents. However, damages at the individual level and to some extent at the community level have been observed due to severe accidents and their long-term implications are being studied.

The data obtained so far indicate that mankind, being at the top of the evolutionary ladder, is most radiosensitive. In general, the measures adopted to protect mankind against the ill-effects of ionizing radiation are considered quite adequate to protect other species also[25].

Radiation exposures in nuclear industry

Nuclear reactors and radioactivity

Before dealing with radiation exposures from nuclear reactors, it may be in order to provide a brief description of power reactors themselves.

A schematic of the basic principle behind nuclear power generation is given in Figure 2. The energy for generating electricity is obtained from the chain reaction of fissions of uranium-235 (or plutonium-239). The system built to have a continuous chain reaction of fissions, resulting in continuous release of energy, is termed as a 'nuclear reactor'. Energy produced in the fissioning process is enormous; about 200 MeV per fission. In more familiar

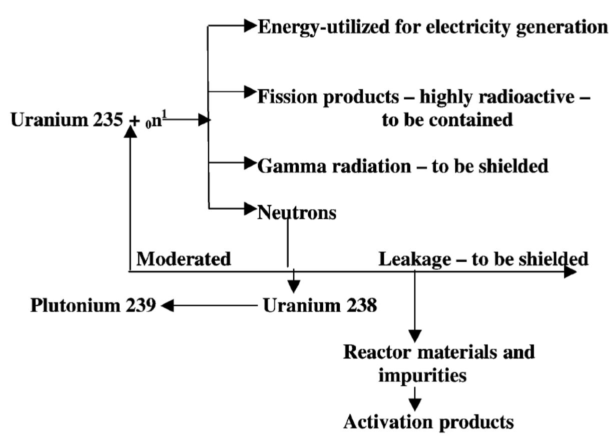

Figure 2. Schematic of nuclear power generation.

Box 1. Nuclear reactors

Of the 2–3 neutrons emitted in the fission, one is used to keep the chain reaction going and of the rest, some are absorbed by the reactor components and some leak out. The absorption can be by uranium-238 that is present in the reactor, leading to the formation of plutonium-239, which is another fissioning nuclide. Or, it could be by other functional materials in the reactor resulting in the generation of new radioactive isotopes termed as activation products. It must be noted here that the neutrons resulting from the fission, being highly energetic, would be travelling at great speeds. Besides, they are also chargeless particles. Hence their interaction probability with matter is quite low and they are more likely to escape from the reactor core than being captured. In order to increase the probability of their interaction with the core materials, specifically with the fissionable material, the neutrons are slowed down using certain low atomic weight materials called moderators. Reactors where fissions are essentially due to the slowed down neutrons are called thermal reactors and almost all the presently operating power reactors belong to this category. An important component of the reactor is the coolant used to remove the heat generated during the fission chain reaction. Widely used coolant in thermal reactors is ordinary water. Some reactors use heavy water, which minimizes the parasitic loss of neutrons, as moderator/coolant. There are also power reactors using carbon (in the form of graphite) as moderator, and CO_2 gas as the coolant. Depending on the type of moderator and coolant used and the operating conditions of the reactors, they are classified as 'Pressurized Water Reactors (PWRs), Boiling Water Reactors (BWRs), Pressurized Heavy Water Reactors (PHWRs) and Gas Cooled Reactors (GCRs)'. Some reactors of Russian design, known as RBMK reactors, use water as coolant and graphite as moderator.

One way of increasing the probability of neutron capture leading to fission without using moderator is to increase the fissile material concentration in the reactor core. This is accomplished by increasing the fraction of uranium-235 (called enrichment) or incorporating large fraction of plutonium-239 in the reactor fuel. Since the fission chain reaction in such reactors is brought about essentially by fast (unmoderated) neutrons, such reactors are called 'fast reactors'. The major advantage of fast reactors is that they can be designed to convert more uranium-238 (which is called fertile material) to the fissile material plutonium-239, than what is consumed to keep the chain reaction going. Hence they are also called 'Fast Breeder Reactors (FBRs)'. Because of this breeding feature, FBRs can, in principle, utilize all the available uranium, including uranium-238. Hence, their potential for electricity generation is high. However, because of the complexity of the system, their deployment is quite low. Total installed capacity of FBRs in the world now is less than a gigawatt as compared to about 371 GW of the thermal power reactors. They can be considered as only at the developmental stage now.

There are other groups of reactors such as research reactors, weapons reactors and mobile reactors. The principle and basic features of all these groups of reactors are the same and categorization has been essentially based on their intended use. Research reactors, which are actually the forerunners of power reactors, are for the purposes of investigations in basic and applied sciences, radioisotope production, radiography, etc. Compared to power reactors, they are much smaller, simpler and generally operate at much lower temperature and pressure. Weapons reactors are built and operated for the production of plutonium for weapons use and mobile reactors are intended for ship propulsion purposes. Their number is small compared to that of power reactors. As such, the impact of all these groups of reactors on the society and the concern about them are minimal. While discussing prospects and public concern about nuclear power, they have little relevance.

terms it is about 10^{11} J/g of fissioning uranium-235. This is equivalent to the energy obtained by burning 1000 tonnes of coal. It is this energy which is utilized to generate steam, which in turn is used to roll the turbine as in the case of conventional electricity-generating systems. The operating level of a nuclear reactor is denoted as its power and expressed in terms of watts (W) or its multiple units; kilowatts (kW), megawatts (MW) or gigawatts (GW). Noting that one fission yields about 200 and 1 MeV equals 1.6×10^{-6} W-s, a reactor operating at 1 W corresponds to about 3.13×10^{3} fissions per second. While dealing with power reactors, two other terms are employed: megawatt thermal (MWt) and megawatt electrical (MWe). While MWt refers to the total rate of energy produced by the fissions in the reactor, MWe specifies its electrical output (often, their multiples, GWt and GWe are also used). A nuclear power plant's efficiency of conversion from thermal to electrical energy is in the range 30–40%, depending on its operating conditions such as system pressure, temperature of the steam generated, etc. Hence, electrical power rating (MWe) would be in the range 30–40% of the thermal power (MWt) of the reactor. Lastly, total electrical energy generated by the power plant is expressed in terms of gigawatt annum (GWa), i.e. the energy generated by the plant operating at 1000 MWe for 1 year.

Each fission is also accompanied by the generation of 2–3 neutrons, γ-rays (high-energy electromagnetic radiation) and two fission fragments (see Box 1). These fission fragments, also known as fission products, are unstable and hence radioactive. They have half-lives varying from a minute fraction of a second to several years, and emit ionizing radiations. Long-lived fission products build up continuously during the operation of a reactor and an operating power reactor can have billions of curie of radioactivity (radioactivity is reckoned in terms of disintegrations per second (dps) and its unit is becquerel (Bq), equal to 1 dps. Curie is an earlier unit ($=3.7 \times 10^{10}$ Bq) and is still often used) in its core. Activation products, mentioned earlier, happen to be another source of radioactivity in nuclear reactors. Magnitude of radioactivity of the activation products is miniscule compared to that of fission products. However, under certain circumstances they tend to be important from the point of view of radiation exposure.

Radiation fields due to γ-rays and neutrons produced during fission as well as radiation emitted by the built-up fission products would be in the range 10^6–10^8 Gy/h inside the reactor 'core'. While utilizing the energy released during fission for our benefit, it is necessary to protect the operating personnel from these intense radiation fields. It is also necessary to ensure that the radioactivity due to fission and activation products is well contained so that no harm occurs due to them either to the operating personnel or to the general public during normal as well as abnormal conditions. This forms the essential theme for nuclear safety.

Reactor safety provisions

Basic safety criteria in the design, construction and operation of power reactors are: (i) Safety of the general public; (ii) Safety of the operating personnel and (iii) minimization of the impact on the environment.

To ensure that these criteria are met with at all times, nuclear power reactors adopt a 'defence in depth' approach. This means that wherever a safety function is involved, dependence on any single equipment or a single system is avoided. There would be adequate backup so that simultaneous failure of several systems, even serially, does not lead to conditions which are unsafe to the operating personnel or the public. Different components of this approach are given in Table 3 and a few key points are elaborated below. Though the description is largely based on Indian power reactors, it represents the approach adopted by power reactors all over.

Redundancy in safety-related systems

Power supply: Since availability of power is crucial for the safety of power reactors during operation as well as in shut-down conditions, it is mandatory that power supply in general should have sufficient back-up and the safety-related systems should have uninterrupted supply. To ensure this, power reactors have the following provisions:

(a) Mains power supply from three independent sources.
(b) Standby diesel generators with at least 150% capacity to take care of all essential loads of the power station.
(c) Uninterrupted power supply from motor generators and inverters fed by rechargeable batteries to meet the reactor protection system loads.
(d) Direct battery supply for the most crucial safety systems.

Shutdown system: In case of any abnormal condition arising in the reactor or associated systems, it is designed to bring the reactor to a safe shut-down condition promptly and reliably. Depending on the type of reactor, shut-down systems vary but the common factor is that there should be high redundancy built in them. There should be multiple shut-down systems and diversity in their shut-down principle, i.e. not all of them should be based on the same working principle.

Coolant system: As mentioned earlier, the primary safety concern in nuclear reactors is the containment of radioactivity. Since any overheating of the fuel can lead to breach of integrity of the fuel, the fuel needs to be provided with adequate cooling at all times. While measures to ensure this in different reactor systems may vary, the following are representative provisions:

(a) Primary Heat Transport (PHT) pumps with adequate capacity, a part of which is operating at all times, including during shut-down conditions.
(b) Auxiliary feed pumps running on emergency diesel power supply.
(c) Steam blowing and shut-down cooling arrangement.
(d) Moderator injection.

Some reactors also provide for cooling by the firewater system as an ultimate measure.

Table 3. 'Defense in depth' approach in nuclear power reactors

Engineered safeguards
Fail safe principles
Redundancy
Diversity in safety systems
Reliability
Multiple barriers
Fuel clad
Coolant boundary
Containment building
Quality assurance
In-service inspection
Operator training and qualification
Safety analyses

Multiple barriers

In spite of all the provisions made in the design, construction and operation of the reactors to prevent any overheating of fuel and consequent damage to the fuel and fission product release, it is recognized that no system can be absolutely fail-safe. To ensure that even in such unlikely events fission products are not released to the public domain, a series of barriers are incorporated to contain radioactivity. The fuel, which is a sintered ceramic of uranium oxide, provides the first barrier. The fuel is clad in a high-strength, high-integrity alloy of zirconium and this acts a second barrier. Further, all the fuel elements reside in the PHT system which forms a closed loop and is isolated from other parts of the reactor system. The PHT system is the third barrier for containing the fission products. As the fourth barrier, the entire reactor system is housed in a 'containment' building. The containment building is designed, constructed and tested for leak rates not to exceed the prescribed limits even under the highest pressures resulting from the worst envisaged reactor accident. In India, where PHWRs happen to be the workhorse of its nuclear power programme, the containment building is enclosed in another 'secondary containment' and the interspace is continuously monitored. In case any radioactivity appears in the interspace, air from this space can be pumped for controlled release through high-efficiency filters.

Besides the above provisions, all the area up to a specified distance from the reactor installation is treated as 'exclusion area'. This would be owned by the power plant, wherein all the public activities are excluded.

Safety analyses

A notable feature of the nuclear power programme is the mandatory requirement of detailed and multi-layered safety analyses and explicit safety clearances for all its activities. Right from the stage of the reactor design through site selection, construction, commissioning and operation, there exist several safety agencies acting serially before the activity is cleared. Another feature, probably unique to the nuclear power programme, is the concept of 'Design Bases Accident (DBA)'. At the very beginning, the designers must make an elaborate accident analysis. They must examine all probable accidents in the system and establish that even in the case of most severe accident with as low a probability as 10^{-6}/yr (that is, one in a million years), the likely radiation exposure to the public is below the permissible limits.

All the safety provisions made in the design, construction and commissioning of nuclear reactors do not complete the task. Any system or equipment is designed to operate safely only up to a particular extent of 'loading'. This is termed as the 'safety limit' and it is essential that this limit is not transgressed at any time. To account for the possible uncertainties in the measurements or estimation of the system loads and to provide sufficient allowance for the transient phenomena, another set of limits called 'limiting conditions for operation', well below the safety limits, is prescribed for all nuclear reactor operations. These limits and conditions, along with the bases to arrive at them, form the 'technical specifications' for operation of the power plant. It is mandatory that no operation shall be planned which may violate the technical specifications. Any unintentional violation is considered as an 'unusual occurrence'. Its implications have to be thoroughly analysed by the plant staff and independent safety bodies.

The term 'unusual occurrence' has lead to some misunderstanding in the public domain. As mentioned earlier, the nuclear reactors are provided with multi-layered protective systems. The principle behind it is that even if one (it could be two or three, depending on the importance) protective system fails, it should not result in an unsafe situation. Thus, the design takes into account failure of one or more protective systems in series. Failure of any one of the protective systems is considered as an unusual occurrence not because it has resulted in an accidental situation, but that one of the several safety barriers has been disturbed. Unusual occurrences are nothing specific to nuclear power plants; they occur in all industrial plants. In nuclear industry, they are highlighted, analysed and used to back-fit the concerned system for improved reliability.

Radioactive waste management

In general, nuclear industry produces little chemically toxic waste, either gaseous, liquid or solid. From the environmental point of view, this is its major advantage. Here the concern regarding waste disposal is related to the enormous quantities of radioactivity associated with the reactor operation. An important part of the nuclear safety programme is the proper management of this radioactive waste generated in different phases of the nuclear industry. The first step in the successful management of radioactive waste is to identify its sources and streams, and characterize them with respect to their radiological hazards. These factors have direct bearing on the selection of proper methods for their handling, treatment and disposal.

Generation of radioactive waste: Different operations starting from mining and milling of materials required for fuelling nuclear reactors to the final disposal of the wastes are together termed as nuclear fuel cycle. Components of this cycle and the radioactive wastes generated in them are given in Table 4. Two important components of the cycle, i.e. reactor operations and fuel reprocessing are briefly discussed below.

Reactor operations: As described earlier, an operating nuclear power plant would have billions of curie of fission products. However, most of these fission products

Table 4. Nuclear fuel cycle and associated radioactive wastes

Component	Wastes
Mining and milling of uranium ore	Mining over burden, milling tailings with radium and its daughters
Fuel fabrication	Low-level uranium waste
Reactor operations	Small quantities of fission and activation products
Fuel reprocessing	Large quantities of fission products.

are well contained in the high-integrity fuel elements and come out as waste only at the fuel reprocessing stage. At the reactor operations stage, a minor fraction appears outside the fuel elements due to small leakages from the fuel elements and fissions due to uranium present as impurity in the system outside the fuel elements. Besides this, there are also activation products due to neutron irradiation of reactor materials. These two constitute the sources of radioactive waste in the reactor installations.

Fuel reprocessing: By far, maximum radioactive waste is generated at this stage where the used up fuel elements are processed for the recovery of uranium and plutonium. Separation of uranium and plutonium gives rise to aqueous and organic liquids containing fission products. They constitute the high level radioactive wastes. Besides this, liquid wastes are also generated in varying quantities from chemical laboratories, off-gas cleaning systems, decontamination and maintenance operations. Separation process also results in the release of gaseous fission products occluded in fuel elements and this constitutes gaseous waste. Principle solid wastes are a metallic discards, including fuel element cladding materials and hulls. They are moderately active.

Management of radioactive waste: Treatment, conditioning and final disposal of wastes are carried out so as to meet the criteria and limits laid down by health and safety authorities. Solid wastes are segregated based on their surface dose levels, and subsequently embedded in suitable matrix material and stored at site in cement trenches, tile holes or high integrity containers. Liquid wastes are treated so that their release to the environment is governed by the ALARA principle. For efficient and cost-effective treatment, liquid wastes are segregated at source as (i) Low Level Wastes (LLW), (ii) Intermediate Level Wastes (ILW) and (iii) High Level Wastes (HLW).

LLWs are characterized by the specific activity below 10^{-3} μc/ml. These wastes are given chemical or reverse osmosis treatment, which may be followed by ion exchange. Subsequently, they are filtered and discharged with adequate dilution to meet the stringent limits for discharge. ILW having specific activity up to 1 μc/ml are subjected to evaporation and the concentrates are embedded in matrices such as bitumen, cement and composite polymers and stored at site.

It is the HLWs, which consist of essentially fission products and some transuranic elements separated from uranium and plutonium at the fuel reprocessing stage, that have drawn maximum public concern. They contain about 99.9% of the total activity associated with the nuclear fuel cycle, with specific activity in the range of 1000 Ci/l. These wastes are immobilized in vitreous matrix. Borosilicate glass matrix with minor additives such as manganese has proved to have good chemical durability[27] with leach rates as low as 10^{-6}–10^{-7} g/sq. cm/day and glass hydrolysis of about 0.1 μm/yr. It also has good heat dissipation characteristics and radiation stability. The vitrified solids are stored in high integrity canisters. These canisters are planned to be stored in engineered storage/surveillance facilities, with a provision for continuous cooling, for a period of about 25 years. They are then sent for final disposal in deep geological formations to provide isolation for thousands of years. The long-term aspects of this disposal scheme are given in Figure 3. Experiments as well as analysis have established it as a technologically feasible solution. However, since this involves storage of waste in isolated repositories for hundreds or thousands of years, perceived concern in the minds of the public is that during this period, isolation may fail and large quantities of radioactive wastes may find their way to the environment. Considering the failure probability of each one of the barriers as shown in Figure 3, the possible leak/leach rates of the sintered waste matrix and finally its diffusion over long stretches, it can be shown that the probability of radioactivity reaching the terrestrial environment is extremely low. Even in such a remote case, its specific activity would be no more than that of natural sources. These estimates are strongly supported by some natural analogues such as the natural reactors that must have existed at the Oklo uranium mine in Gabon, West Africa, about 2 billion years ago and the large thorium ore body in Morro-de-Ferro, Brazil. In both the cases there has been little movement of the radioactivity with migration rates estimated[28] to be in the range 10^{-9}–10^{-8} cm/yr. Thus, based on the laboratory studies and observation of natural analogues, it is evident that the high level radioactive waste disposal poses insignificant threat to the environment. However, apprehensions do exist in the minds of the public and efforts to clear these become important.

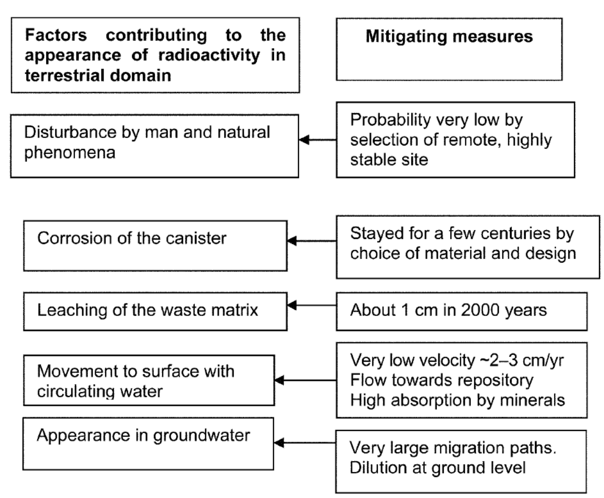

Figure 3. High level waste disposal – long-term aspects scheme: Fixed in vitreous material, sealed in multiple-walled, sealed canisters placed in repositories more than 500 m deep.

Experience

Notwithstanding all the safety provisions in the design, construction, commissioning and operation of nuclear power reactors, radiation exposures cannot be totally ruled out. One also has to consider exposures under accidental conditions. Here again, with all the safety provisions, it may be possible to bring down the accident probabilities and radiation exposures therefrom to low values, but one cannot totally rule out occurrence of accidents. Hence, acceptance criteria for nuclear energy have to be essentially based on experience; experience with respect to radiation exposures during normal and abnormal situations. They are briefly discussed below.

Normal operations – occupational exposure: Radiation exposures during normal operations are to be considered in two parts: (i) exposures to occupational workers and (ii) exposures to general public. The governing principle for the control of exposure to occupational workers is that the collective exposure should be kept as low as possible (ALARA) and in any case the individual dose should not exceed the ICRP limit of 20 mSv/yr (Table 2). Control on the collective exposure would be seen in the normalized collective dose for the station, expressed as person-sieverts per gigawatt year (PSv/GWa). Trends[29] in the average individual dose and the normalized collective dose for reactor operations during the period 1975–94 for all the world reactors are given in Figure 4.

Since obtaining power from a nuclear reactor involves operations in other parts of the fuel cycle such as mining and milling of uranium ore, fuel fabrication and reprocessing, corresponding trends in the exposure for the entire nuclear fuel cycle need to be considered (see Figure 4). As can be seen from Figure 4, for the period 1990–94 the average individual exposures are 1.4 and 1.75 mSv/yr for reactor operations and the entire nuclear fuel cycle respectively. These are well below the ICRP limit of 20 mSv/yr for occupational exposures. Normalized annual collective dose from the entire nuclear fuel cycle has declined over the period from 20 PSv/GWa during 1975–79 to 9.8 PSv/GWa in 1990–94. Furthermore, there is a strong decreasing trend in the individual and collective exposures resulting from the emphasis laid on radiological safety in the nuclear industry. With this collective dose and with the presently accepted risk coefficients for radiation exposure as 5×10^{-2}/Sv for cancer induction and 1×10^{-2}/Sv for genetic effects, the probable cancer incidences and genetic abnormalities amongst the occupational workers are about 0.5 and 0.1 respectively, per GWa of electricity generation.

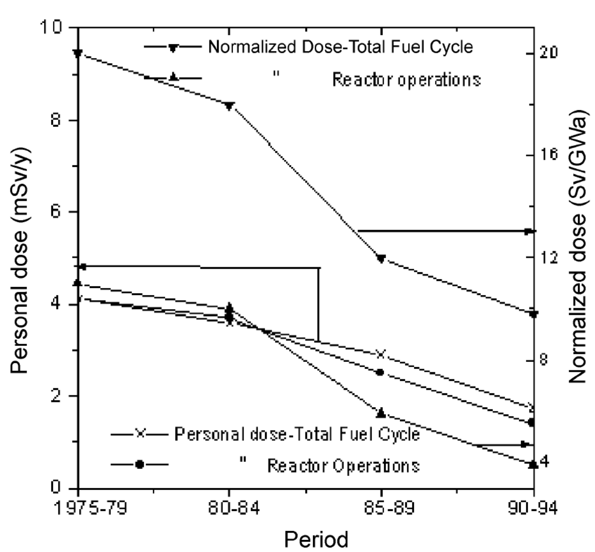

Figure 4. Trends in occupational radiation exposures in nuclear industry.

Normal operations – public exposures: Control of exposure to the public during normal operations is again governed by the ICRP recommendations: It should comply with the ALARA principle and in any case the individual dose should not exceed 1 mSv/yr.

Public exposures arise due to the discharge of radioactive materials from different parts of the nuclear fuel cycle to the environment. Such exposures can be external or internal and can occur through air, water and/or soil routes. Hence its computation is an involved exercise and for the same amount of activity release, dose to the public can vary depending on micro-met parameters, topographic and demographic profiles around the site, dietary habits of the concerned population, etc. Considering typical features of the existing sites, UNSCEAR has made model calculations of the dose to the public due to different parts of the nuclear fuel cycle[30]. Results of such evaluations for the period 1970–97 are given in Table 5.

As can be seen from Table 5, during the period 1970–97 there is a significant reduction in the radiation dose to the public from the nuclear fuel cycle, from 12 PSv/GWa during 1970–79 to 0.91 PSv/GWa during 1995–97. With 0.91 PSv of exposure for 1 GWa electricity generation from nuclear energy, risk to the public domain works out to be incidence of about 0.1 cancer and 0.02 genetic abnormalities respectively per GWa. It must be mentioned here that 0.91 PSv/GWa is for a power reactor with typical features and for individual reactors could significantly vary it. Even if we take the extreme case as ten times the typical case, the risk due to the generation of 1 GWa of electricity would be 1 cancer incidence and 0.2 genetic abnormalities.

The drastic reduction in the normalized radiation exposures to the radiation workers as well as to the public as shown in Figure 4 and Table 5, has come about essentially because of the much improved control on the containment of fission products at the fuel reprocessing stage in the nuclear fuel cycle.

Table 5. Normalized collective effective dose to the public due to effluents from different parts of the nuclear fuel cycle

	Normalized collective dose (PSv/GWa)				
Source	1970–79	1980–84	1985–89	1990–94	1995–97
Reactor operations	3.2	0.9	0.46	0.45	0.45
Fuel reprocessing	8.5	1.9	0.07	0.13	0.13
Mining, milling, fuel fabrication, etc.	0.34	0.34	0.34	0.34	0.34
Total	12.04	3.2	0.97	0.92	0.91

Table 6. Impact of nuclear accidents – experience

Accident	Consequences
Three-Mile Island, USA, 1979 (ref. 31)	Partial core melt. Containment held, insignificant release of radioactivity. 200,000 people voluntarily moved out, but returned shortly. Insignificant radiation exposure to the public. 0.7 cancer deaths (estimated) for a population of 2 million living within 30 miles.
Chernobyl–USSR, 1986 (ref. 32)	Significant core melt and release of radioactivity to the environment. Very large-scale evacuation. Prediction of ~10,000 deaths attributable to the accident induced cancer over the next 50 years. 2005 update of Chernobyl by Chernobyl Forum[34] Only about 4000 thyroid cancer incidences attributable to the accident, for which the survival rate has been 99%. A total of 4000 persons could eventually die of radiation exposure. As of mid-2005, fewer than 50 deaths, including that of highly exposed rescue workers (33), are attributable to the accident.

Accidents: Since severe accidents in the nuclear reactors have been infrequent as they should be, the risk estimate has been essentially by probabilistic methods largely based on extrapolations. There have been only a few notable accidents in power reactors: Browns Ferry, USA, 1975 (2 × 1080 MWe); Three-Mile Island-2, USA, 1979 (880 MWe); Saint Laurent-A2, France, 1980 (450 MWe); Chernobyl-4, Ukraine, 1986 (950 MWe) and Vandellos-1, Spain, 1989 (480 MWe).

The accidents at Browns Ferry, Saint Laurent and Vandellos had little or zero impact on the safety of the workers, public or the environment. It is the accidents at Three-Mile Island and Chernobyl that have drawn maximum public attention (see Table 6). As can be seen from Table 6, the negative impact, health or environmental, of the Three-Mile Island accident has been practically nil. In the initial scare, about 200,000 people voluntarily moved out of the reactor vicinity, but returned shortly thereafter. The estimated[31] increase in cancer deaths due to the accident, in a population of 30 million living in the vicinity, is 0.7. The Three-Mile Island accident is a demonstration of the in-built ability of power reactors against the release of radioactivity, despite malfunctioning of important components.

The accident at Chernobyl, the worst in the history of nuclear power, is the one where uncontrolled release of radioactivity did take place[32]. The accident has been studied in great detail by a large number of national and international groups. Several design deficiencies and operator errors that led to the accident have been identified. What is of relevance to the present discussion is its impact on the population and environment. It severely contaminated vast areas in the States of Belarus, Ukraine and the Russian Federation. Trace contaminations could also be found in all the countries in the northern hemisphere. There was large-scale (116,000) evacuation of people from the reactor vicinity during 1986 and relocation of about 220,000 people subsequently[33]. 33 plant personnel died in the accident. It was estimated initially that in the next 50 years there would be more than 10,000 cancer deaths attributable to the radiation exposures due to the Chernobyl accident. However a recent report (September 2005) of the Chernobyl Forum, consisting of eight UN specialized agencies, has estimated[34] that the total deaths due to the radiation exposure would be about 4000. Alarming as it appears, this figure is to be seen in an overall perspective. During the same period and for the same population, the estimated deaths due to natural incidence of cancer alone is a mind-boggling 1.25 million!

In the 30-km zone around the reactor, called Chernobyl Exclusion Zone (CEZ), increased mortality of coniferous plants, soil invertebrates and mammals, and reproductive losses in plants and animals were seen in high exposure areas up to a distance of 20–30 km. Outside that zone, no acute radiation-induced effects have been reported. With reductions of exposure levels, biological populations have been recovering, though the genetic effects of radiation were seen in both somatic and germ cells of plants and animals. Prohibiting agricultural and industrial activities in the CEZ permitted many plant and animal populations to expand and created, paradoxically, 'a unique sanctuary for biodiversity'[35].

Risks in different electricity-generating systems

It is to be recognized that all the available options for central generation of electricity have certain amount of risk, however small, associated with them. Some options may entail global and long-term impact and in some others acute risks may be dominant. Total risk is the result of negative impact of different component parts or operations in the system. In choosing a particular option, it is necessary to consider the detrimental effects of all component parts of the risk and judge the system based on the overall impact. Hence, to obtain a proper perspective of the risks encountered in the nuclear power reactors, it would be necessary to look into the risks in other options too. Further, in such an analysis, the societal and environmental impact of not having adequate electricity also has to be considered. This is particularly so for developing countries, where poverty and over population are considered to be the two major causes for environmental degradation. In order to project an overall perspective, available data on the risks in the fossil fuelled and hydel options of power generation are discussed below. Part of the data is with respect to India but it is felt that it does provide a representative picture.

Risks in other options

Hydel electricity: Major contribution to the negative impact in the case of hydroelectric power arises from the very installation of power generating system. Till recently, hydroelectric power, which is essentially a form of renewable source of energy, was considered to be environmentally benign. However, opinions are changing fast, at least in India. Large-sized hydel power plants invariably involve construction of huge dams and consequent inundation of large tracts of lands. Table 7 gives the extent of loss of land associated with some major hydel stations in India[36]. This has resulted either in the submergence of environmentally important forests or large-scale rehabilitation of the population with attendant social and cultural impact. Besides, environmentalists associate a number of detrimental effects such as soil erosion, landslip, sedimentation and siesmicity with large dams.

Risk to life, associated with hydroelectricity, is due to dam bursts or dam over-topping. Some known dam bursts and consequent loss of lives since 1960 are given[37,38] in Table 8.

Fossil-fuelled stations: Generation of electricity by fossil fuels, whether by gas, oil or coal, entails a wide spectrum of negative impacts; they could be global or local, long-term or short-term and on the environment or on human health.

Table 9 gives the inputs required and wastes generated for one-year operation of a 1000 MWe power plant based on nuclear energy and coal. It is seen that for the same power generation, fuel required and waste generated are several orders of magnitude more in the case of coal-fired station. In India, most of the coal deposits are under forestland and mining entails significant destruction of forest cover. Further, about two-thirds of Indian coal is from open cast mining. This causes land spoliation as a result of the dug pits and by the overburden dumps outside the mine. Open cast as well as underground mining is known to have affected the water table, resulting in the drying up of wells in the surrounding environment. A more important concern in the coal option is the environmental effect

Table 7. Land submergence due to some hydro power stations in India

Dam	Installed capacity (MWe)	Area at full reservoir level (sq. km)
Jalaput (Andhra Pradesh)	114	91
Srisailam (Andhra Pradesh)	770	617
Donkarayi (Andhra Pradesh)	690	28
Sharavathi Valley (Karnataka)	891	327
Kali Valley (Karnataka)	910	150
Koyna (Maharashtra)	860	117
Yeldari (Maharashtra)	22.5	102
Totaldoh (Maharashtra)	160	77
Gohira (Orissa)	250	353
Jawaharsagar (Rajasthan)	99	22
Rihand (Uttar Pradesh)	300	469
Obra (Uttar Pradesh)	99	18

Table 8. Some reported dam bursts since 1960

Dam/country	Year	Fatalities
Oros, Brazil	1960	30–1000
Kiev, USSR	1961	145
Vajont, Italy	1963	2600–3000
Koyna, India	1967	180
Teton, USA	1977	11
Machhu, India	1979	2500
Hirakud, India	1980	1000
Belci, Romania	1991	116

of the pollutants resulting from coal-burning. As given in Table 9, for one gigawatt year operation, a coal-based station would reject to the environment about 7.0 million tonnes of CO_2, about 100,000 tonnes SO_2, 10,000–20,000 tonnes of nitrogen oxides, besides 1.5–2 million tonnes of ash. While ash has led to severe degradation of the power plant environment, the gaseous effluents pose long-range environmental problems. With increased burning of coal, concentration of CO_2 in the atmosphere is gradually building up and this has caused a serious concern about the 'greenhouse effect', with disastrous consequences on the environment. It is for this reason that several world bodies are strongly arguing for putting limits on coal-burning. Similarly, the released SO_2 and nitrogen oxides get converted into acids in the atmosphere, leading to 'acid rains'. In some regions of Europe and America having large coal-based power stations, there is a significant reduction in the pH of rain water. Such acid rains are known to seriously affect flora and fauna of the region.

For fossil-fuelled stations, the risk due to severe accidents is essentially associated with production of fuel and its transportation. Whether the station is gas or oil or coal-fired, it calls for production and transportation of large quantities of the fuel, and this has resulted in severe accidents. In case of coal, the major contribution to the loss of life has been from the mining sector. Table 10 gives a list of serious mining accidents with each more than 100 fatalities[38] that have occurred during the period 1980–2000. During the same period there were about 20 accidents, each with fatalities ranging from 40 to 100.

Table 9. Land area and material flow for a 1 GWe power station

Power plant type	Land area (ha)	Fuel input (tonnes)	Waste products (tonnes)
Coal-based	70	3,000,000	Ash: 750,000 CO_2: 7,000,000 SO_2: 120,000 NO_x: 20,000
Nuclear	20	50	Unused uranium: 48.5 Plutonium: 0. 5 Wastes: 1. 0

Table 10. Severe accidents (>100 fatalities) related to coal option during 1980–2000

Location	Country/year	Event	Fatalities
	China, 1982	Avalanche	284
	Taiwan, 1984	Fire incidences	314
Dobranja	Yugoslavia, 1990	Mine disaster	178
Cuenca	Equador, 1993	Explosion	200
Spitsbergen	Russia, 1996	Mine disaster	141
Datong	China, 1996	Coal mine explosion	114
Guizhou	China, 2000	Coal mine explosion	150

A list of severe accidents[38] in the production and transportation of oil and gas over the last two decades is given in Tables 11 and 12. In both cases, the accidents have been largely in the transport sector. In the case of gas transportation, all the fatalities have been in the public domain.

Risk comparison

In order to obtain an optimum choice or an optimum mix of choices for the much needed electricity generation, it is necessary to make comparative analysis of the risks involved in the different technological options we have. The risks could be health-related or environment-related. Further, the risk could be accident-related or could be due to normal operations. In any case, a possible indicator for the health-related risk is the additional normalized fatalities resulting from the introduction of the specific technology. Based on the large data available[39], accident-related risk coefficients have been arrived at for different electricity generating options (Table 13). The coal option has maximum risk and the nuclear option has the least. It must be mentioned here that the figures in Table 13 are for immediate fatalities. They do not include the late or delayed fatalities. However, based on the available data, including the late fatalities, it does not seem to alter the picture significantly.

A major problem in evaluating the risk in the nuclear option is that it has tended to be largely subjective. Detrimental effects of radiation, carcinogenic or genetic, are delayed and only incremental over a large natural incidence. This has given rise to a problem of perception; the perception of the experts, and the public, at least a section of them, has a large variance. This problem is further confounded by a large number of statistically inadequate epidemiological surveys whose conclusions vary from radiation hormosis (beneficial effects of exposure) to the detrimental effects being far more serious than the expert evaluation. Consequently, there is a great uncertainty about the effects of radiation and this has heightened the concern in the minds of the public. The real focus in the case of nuclear energy now should be on bringing down this uncertainty by statistically more meaningful studies and an intense and objective public awareness programme.

Table 11. Severe accidents (>100 fatalities) related to gas option during 1980–2000

Location	Country/year	Event	Fatalities
Nile R	Egypt, 1983	LPG explosion	317
San Juanico	Mexico, 1984	Fire and explosion	500
Tbilisi	USSR, 1984	Gas explosion	100
Ash-UFA	USSR, 1989	Explosion	600
Urals	USSR, 1989	Explosion	650–800
Sancarlos	Spain, 1978	Explosion	216

Table 12. Severe accidents related to oil option during 1978–99 (>100 fatalities or extensive environmental damage)

Location	Country/year	Event	Fatalities	Environmental damage
Arnoco Cadiz	France, 1978	Oil spill		367 km coastline
Cubutao	Brazil, 1984	Fire and explosion	500	
Piper Alpha	UK, 1988	Fire and explosion	187	
Exxon	USA, 1989	Oil spill		1600 km coastline
Dduunkha	Egypt, 1994	Fuel depot hit by lightning	580	
Seoul	South Korea, 1994	Oil fire	500	
Taegu	South Korea, 1995	Oil and gas explosion	100	
Warri	Nigeria, 1998	Pipe line leak and fire	500	

Table 13. Worldwide severe accidents, aggregate fatalities and normalized fatalities for all energy options during 1969–2000

Energy chain	No. of accidents	Total fatalities	Normalized fatalities (per GWa)
Coal – global	1221	25107	0.876
Coal with China excluded	177	7090	0.690
Oil	397	20283	0.436
Natural gas	125	1978	0.093
Hydro	11	29938	4.265
Hydro-2*	10	3938	0.561
Nuclear	1	33	0.006**

*Excluding the Banqio/Shimantan dam burst which resulted in 26,000 fatalities.
**This figure is based essentially on fatalities in the Chernobyl accident and the total electricity generated by nuclear energy till 2000. Since 2000, there has been no nuclear accident with fatalities but there is significant addition to nuclear electricity (~ 2000 GWa at 75% capacity factor of the installed power reactors). Hence, the present value of normalized fatality rate in nuclear option would be much smaller.

'No growth' option

While considering various options for electricity generation, since all of them entail some amount of risk, either environmental or health or both, environmentalists raise some basic questions such as: Do we need to go for more energy? Can we not do with the electricity available now with proper management? These issues are briefly discussed below.

There exist a number of parameters associated with an affluent society, but not all of them can be used to characterize the overall well-being of the society. For instance, though the number of cars, refrigerators or cell phones available per capita would indicate the material affluence, it would be debatable to use them as an index of well-being of the society. On the other hand, parameters such as life expectancy, control on fertility and Gross Domestic Product (GDP) are unquestionably measures of the overall quality of life, as they are the indicators of health care and family welfare, control on population growth and mitigation of poverty in the society respectively. Considering these parameters (and also some others such as literacy rate, energy availability, etc.) as indicators of the human development in a country, in 1990, the United Nations Development Programme (UNDP) established a methodology to quantify them and evolve an overall Human Development Index (HDI)[40]. Since then, UNDP regularly publishes data on these indicators for almost all the countries of the world. Considering data from Human Develop Report-2005, which includes about 175 countries[41], correlation of these parameters with the per capita availability of electricity is presented in Figure 5.

An important observation from Figure 5 is the close correlation amongst the human development indicators such as GDP, life expectancy, control on fertility (fertility here is not meant as the biological ability of a woman to produce children, but the number of children she begets during her child-bearing span. This is influenced by societal welfare measures such as family planning, better education, etc.) and electrical energy availability. It is instructive to see that all the countries, irrespective of being developed, developing or less developed, do lie close to the same correlation line. However, there are arguments that such correlations could be fortuitous. It is true that mere statistical correlation between two variables is not adequate to establish their cause–effect relationship; it needs to have a phenomenological basis[42]. In the case of the above parameters, such a basis does exist (Figure 6). It is a well-observed fact that the GDP of any modern society would generally depend on its industrial development, which in turn depends on the raw material and energy availability. Higher GDP, in general leads to improved living conditions such as better healthcare, better nutrition, more educational and other welfare programmes, all of which are the human development indicators. Further, while the improved standard of living creates the demand for increased power generation, higher GDP provides resources for the same. This is the cyclic link between electricity availability and GDP shown in Figure 6. It must be mentioned here that this is the general trend and as in any population phenomenon, there would be exceptions depending on confounding factors such as natural resources, lifestyle, social and religious background, etc. of a particular country. Such exceptions account for the far-off points in the scatterplots shown in Figure 5.

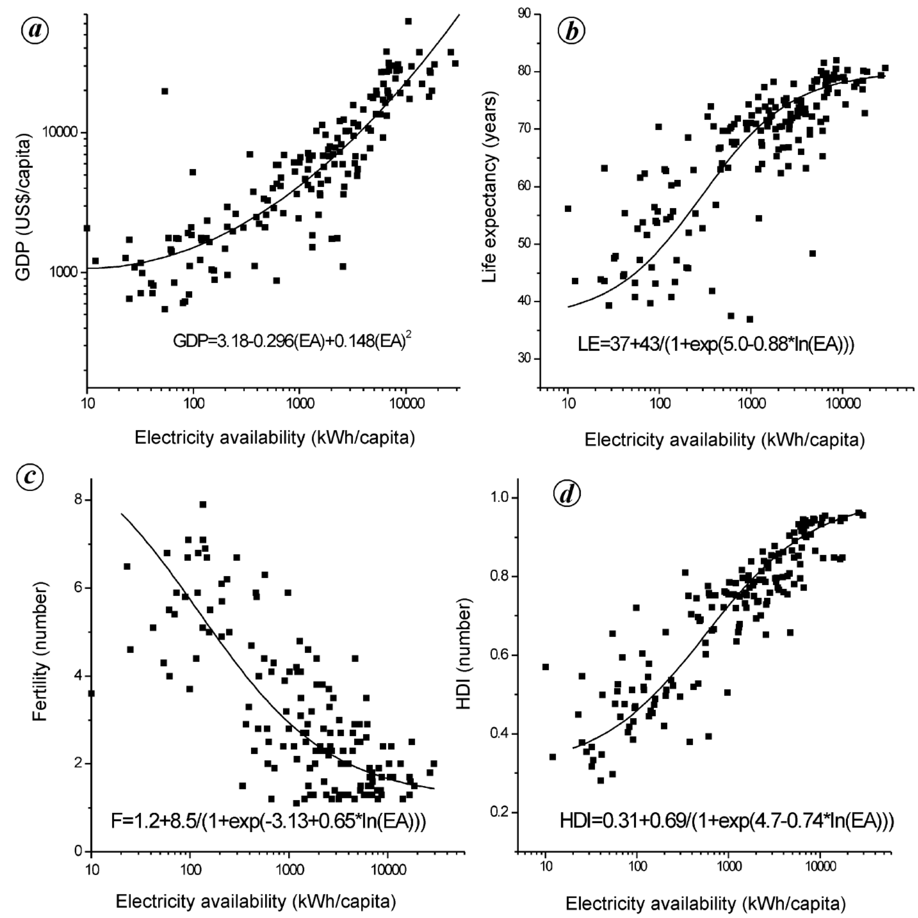

Figure 5. Correlation amongst human development indicators. Continuous lines are the analytical fits for the scatterplots. Fit expressions are given near the *X*-axis.

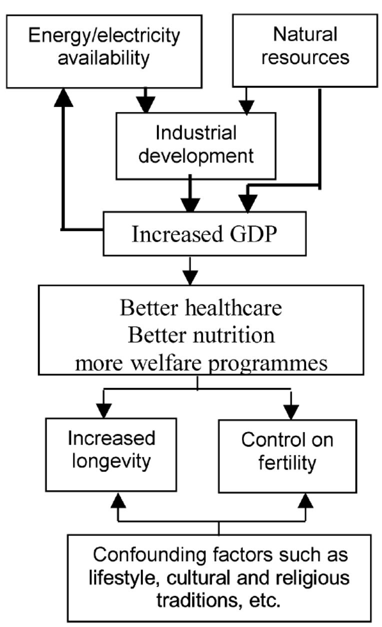

Figure 6. Linkage of electricity availability and HDI parameters.

Another feature to be noted in Figure 5 is the saturation of human development indicator values. The linkage between GDP and electricity availability continues to be strong throughout the range of their observed values following a quadratic relationship. However, impact of either one of them on other human development indicators such as life expectancy, control on fertility, etc. follows logistic distribution and diminishes progressively after about 2000 kWh and approaches saturation around 15,000 kWh. It is in the region below 2000 kWh, where all the developing countries lie, that has the steepest gradient. It is in this region that any addition to the electricity availability leads to considerable improvement of all the human development parameters. To illustrate this point quantitatively, a model calculation of the effect of addition of electricity to the grid in a developing country is given in Appendix 1. As seen there, for a country like India with a population of 10^9, addition of 12 GWa changes the per capita electricity availability from 500 to 600 kWh, with a corresponding increase in the life expectancy from about 63.45 to 65.05 years. Consequent reduction in the death rate is about 3.9×10^5 per year. For the same amount of additional electricity from nuclear power, the expected additional fatalities, due to normal operations as well as accidents, is about seven per year, which is insignificant. It must be mentioned here that cost-benefit ratio for electricity addition by other routes such as hydel and thermal plants would not be much different. This clearly demonstrates that the number of deaths reduced per annum due to this increased life expectancy far exceeds the possible deaths due to the risks associated with any of the options of generating electricity.

There does not appear to be any composite index to quantitatively assess the overall impact of increased electricity generation on the environment. However, it is well known that poverty and overpopulation are the worst offenders against the environment and as can be seen in Figure 5 *a* and *c*, increased electricity availability has distinct positive influence on the mitigation of poverty and control of fertility.

Conclusion

Reservation against nuclear energy in the minds of the public has been by and large due to the conceived risk associated with severe accidents in nuclear power reactors. Experience and analysis do not support this; the risks due to severe accidents form only a small part of the overall risk. Nuclear energy is no more risky than other electric generation systems; if anything, it is significantly less. However, it has a serious problem – that of public perception.

All the electricity-generating systems involve certain amount of risk. In the case of developing countries, with their low base of electricity generation, the negative impact of not having adequate electricity far outweighs the risks from any of the electricity-generating systems considered.

Appendix 1. Cost–benefit (health) analysis of electricity generation in developing countries: A model calculation

Case	
Population (P)	10^9
Electricity availability (EA)	500 kWh/capita
Electricity addition	12 GWa
	~ 10^{11} kWh = 100 kWh/capita
If the addition is by nuclear energy	
Health cost – normal operations	
Collective dose for occupational workers per GWa (see text)	9.8 PSv
For public per Gwa (see text)	0.92 PSv
Total collective dose per GWa	10.72 PSv
Expected cancer mortality per PSv	0.05
∴ Total cancer mortality for 12 GWa addition	10.72 × 12 × 0.05 = 6.4
Health cost – accidents	
Fatalities per GWa (see Table 13)	0.06
For 12 GWa	12 × 0.06 ~ 0.7
Expected increase in total deaths/yr	~7.1

Health-benefit

Addition of 10^{11} kWh for a population of 10^9 changes electricity availability from 500 to 600 kWh/capita

Corresponding change in life expectancy (see Figure 5 *a*): 63.45 to 65.05 years

For a stable or slowly varying population, annual death rate is approximately equal to population number/life expectancy

$$\therefore \text{ Reduction in deaths/year } = 10^9 \left\{ \frac{1}{63.45} - \frac{1}{65.05} \right\} = 3.9 \times 10^5.$$

This is to be compared with likely increase in fatalities of about 7/yr due to the addition of 12 GWa to the system by nuclear energy.

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