A Perspective on the Radiation Protection Problem and Risk Analysis for the Nuclear Era

by K.G. Vohra

To ensure the uninterrupted use of nuclear energy, the radiation protection problem of the "nuclear era" must be placed in proper perspective. Studies in the field of radiation protection span five decades, and we now have a far better understanding of the risks of ionizing radiation than of the risks of toxic chemical substances released from fossil-fuelled power stations, chemical industry and automobiles. In this paper, a comparative study of health risks from the two sources is presented. Cancer mortality and genetic effects are the two main categories of risk associated with ionizing radiation as well as chemical pollutants. Because of their variety and numbers, the chemical carcinogens and mutagens in the human environment seem to have a much larger potential for harmful effects on mankind than radiation. For this comparative study, the risk of cancer mortality in the exposed individuals and populations is considered. A comparative risk analysis for the two sources presented here shows that there is an urgent need to minimize the risk of chemicals, particularly the carcinogens from non-nuclear energy sources.

Table I. Estimates of Absolute Risk of Leukaemia and all other Cancers[a] for Different Age Groups (Risk estimates are for whole life following the latent period)

Age group	Type of cancer	Absolute risk
0–9 years	Leukaemia	2.0
0–9 years	All other cancers	1.0
Above 10	Leukaemia	1.0
Above 10	Breast cancer	1.5
Above 10	Lung cancer	1.3
Above 10	G I including stomach	1.0
Above 10	Bone	0.2
Above 10	All other cancers	1.0
Total for 0–9 age group		3
Total for above 10 age group		6

[a] Deaths per million per year per rem.

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RISK ANALYSIS FOR IONIZING RADIATION

Evidence for the induction of cancer in man by ionizing radiation has been quite unequivocal and all risk analyses are generally centred on this. The absolute risk of a particular type of cancer is generally expressed in terms of deaths per year or number of cases of cancer per year in a population of one million exposed to one rad or rem of radiation dose. The quantitative risk data at lower doses is obtained by extrapolation from the human experience of exposure at high doses and dose rates. The exposed groups falling into this category are the A-Bomb survivors of Hiroshima and Nagasaki, certain groups of patients irradiated therapeutically, and some groups occupationally exposed. Table I gives the estimates of absolute risk for different types of cancer, based on the incidence of death in the above groups, as compiled by the US Advisory Committee on the Biological Effects of Ionizing Radiations (BEIR Committee) Ref. [1]. Typical human data on dose-response used for the risk estimates of Table I (leukaemia and lung cancer) are illustrated in Figure 1.

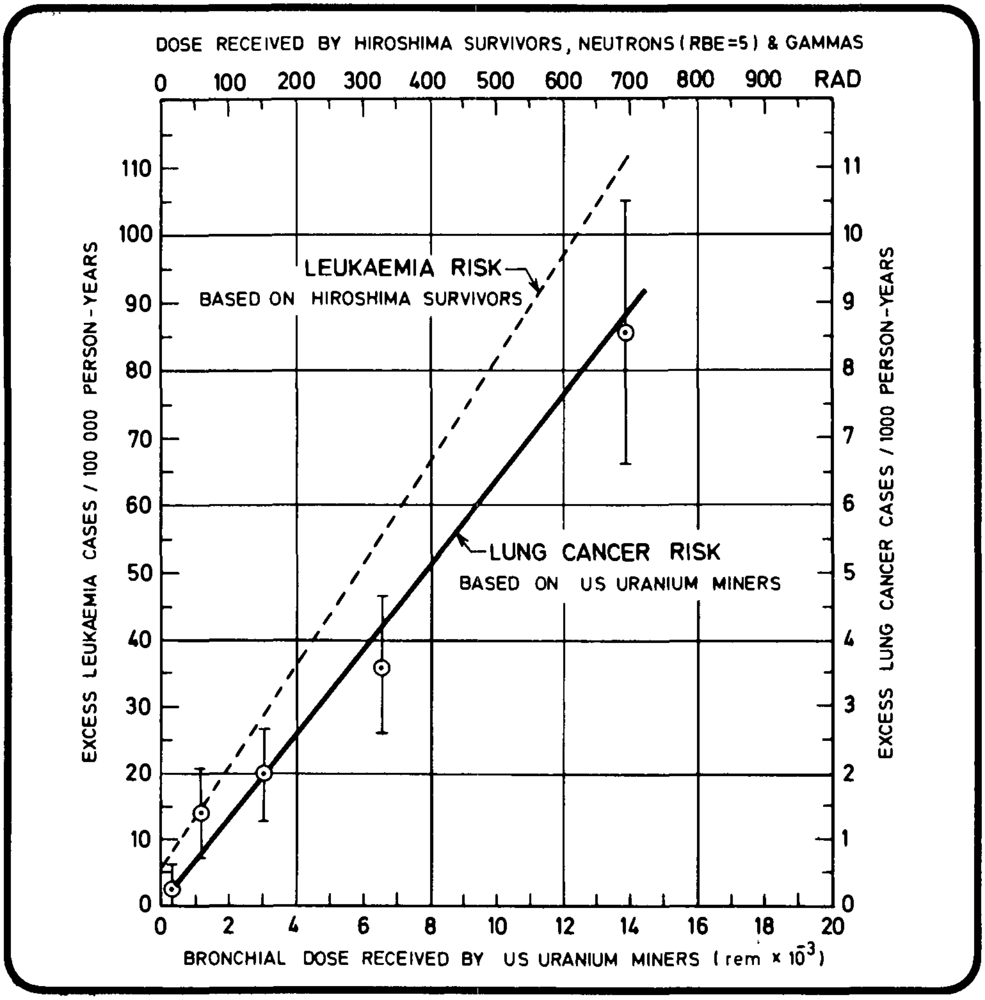

Figure 1. Typical dose-response relationships for Hiroshima survivors (1950—1966) and US uranium miners (1951—1971) (from Ref. [1]).

In these risk estimates, relative biological effectiveness (RBE) of the radiation involved is also taken into consideration. In extrapolating from higher doses to lower doses it is assumed that the incidence of malignancy is linearly proportional to the dose, and there is no threshold dose which does not cause cancer. Although the latter assumption seems scientifically sound, the linearity of the relationship may not be valid for all types of exposures. The risk estimates of Table I for single exposures can be used for calculating the number of deaths per year from continuous exposure at a rate of 1 rem/a for a lifetime This has been calculated from the data presented in the BEIR Committee report Ref. [1] and the estimated value is 150 deaths/million per rem/a, with a most likely upper limit of 200 deaths/million per rem/a. The latter value will be used for calculating the risk of cancer deaths from continuous exposure of groups of individuals receiving doses from gaseous and liquid waste discharges from nuclear power stations, as well as for the assessment of risk in different stages of the nuclear fuel cycle. It is also useful for estimating the risks of occupational exposures in the nuclear industry and of medical exposure.

We shall now examine the doses actually received by the exposed population groups from different sources, particularly the operation of nuclear power stations, and assess the risk. The largest dose received by man still comes from natural sources cosmic rays, terrestrial γ-radiation, ^{40}K, ^{226}Ra and ^{210}Po in the body tissue and human bone, radon daughter products deposited in the respiratory tract during inhalation, and other natural radioactive substances in the human body. Average dose from all these sources adds up to nearly 100 mrem/a, or 3 rem in 30 years. This dose is delivered continuously, at an extremely small dose rate. It consists of exposure from both high LET and low LET radiation, and involves most of the potential sites for human cancer

Whereas natural sources give rise to exposure of the entire world population, dose from the operation of nuclear power stations relevant for risk evaluation is received only by some groups of individuals exposed to gaseous and liquid waste discharges from these stations, in addition to those occupationally exposed. The population dose from these varies with the design and operating conditions of the reactor, and is generally well below the ICRP dose limits. The average dose received by groups of individuals exposed to the discharges from a nuclear power station is estimated to be less than 5 mrem/a for a fully developed nuclear power programme with sound engineering practice This has been amply demonstrated by a number of large stations Refs. [2, 3] This dose is nearly 5% of the natural dose of 100 mrem/a, and includes both internal and external exposures. The risk corresponds to *one* additional case of cancer death per year per million of the exposed group, even if we take the highest estimate of 200 cancer deaths/million per rem/a This one estimated additional case is to be considered in the light of spontaneous cancer deaths in the range of 1000 to 2000 persons per million per year estimated for many parts of the world, and has no statistical significance.

The exposures that do merit serious consideration are those received from medical practice, including X-ray diagnostic exposures and radiation therapy. The annual somatic dose from diagnostic practice is estimated to be in the range of 20 to 100 mrem, depending on the nature and frequency of the examination and the integrity of the diagnostic work practices. If we take 50 mrem as the average annual dose for exposed groups of patients from the medical practice, their cancer risk will be 10/million per year, which is also small. The other miscellaneous sources of radiation exposure are fallout, use of television sets, industrial and domestic appliances, air travel, etc. Their contribution is also very small compared to the natural exposure of man.

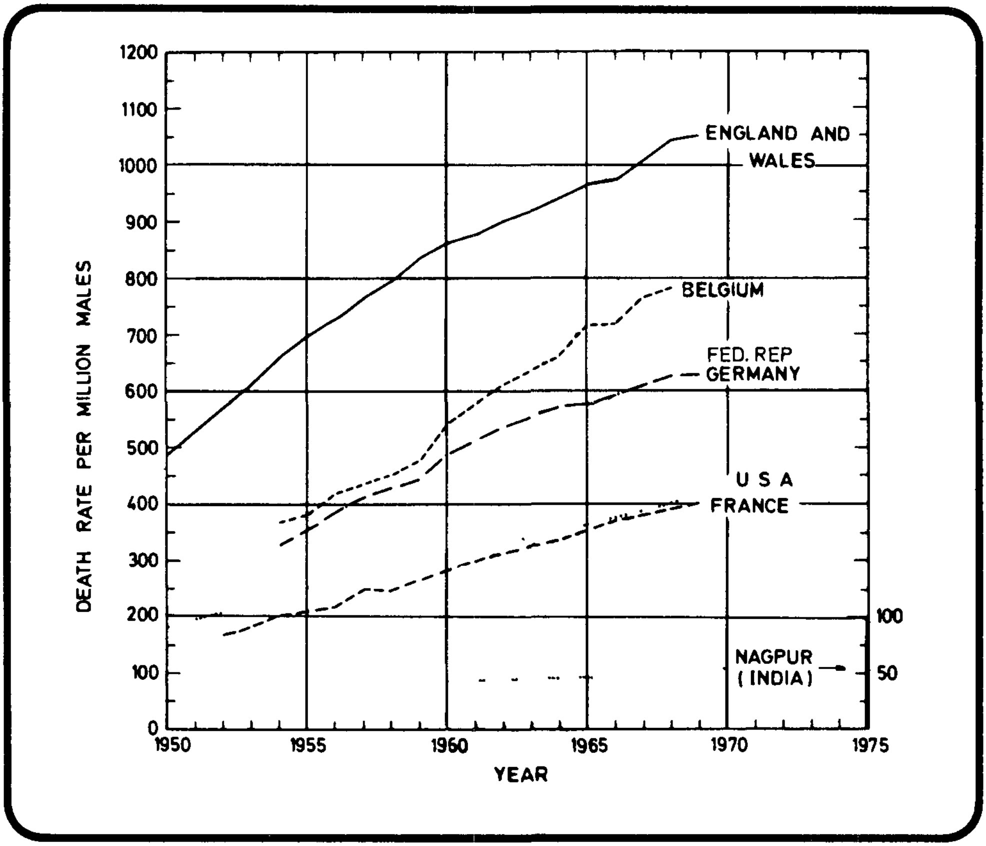

Figure 2. Increasing trend of lung cancer death rate in males for some West European countries, USA and Nagpur (India).

RISK ANALYSIS FOR TOXIC CHEMICAL POLLUTANTS

Although several chemical pollutants have been known to give rise to cancers of different types, there is no systematic human data which can be used for numerical risk analysis as in the case of ionizing radiation. In addition to cancer, chemical pollutants also cause death from heart diseases, emphysema, chronic bronchitis and several other ailments. The overall risk analysis should include death from all such causes. During the last 20 years there has been a rapid rise in the incidence of deaths from cancer and heart diseases, and chemical pollutants probably account for a major part of this increase. It is estimated that nearly 50% of all deaths are caused by cancer and heart diseases Ref. [4].

Several of the pollutants in the environment that can cause cancer have been identified. These include inorganic substances like asbestos, arsenic, chromium, nickel, and organic substances such as benzo(a)pyrene, benzidine, vinyl chloride and coal tar. Benzo(a)pyrene is produced in substantial quantities in the burning of coal, and is also present in automobile exhaust fumes. Risk analysis based on large-scale epidemiological studies can provide very useful information on the risk from such pollutants in large population groups. This has been done on the basis of recently available data showing the increasing trend in lung cancer attributed to air pollution. Figure 2 gives the number of deaths from lung cancer in some West European countries Ref. [5], the United States of America Ref. [6], and India Refs. [7, 8]. The figure shows a continuous increase in the incidence of lung cancer from 1950 to 1970. Such an increase may be associated with continuous increase in the production of power from coal and oil, although several other factors may also be involved.

It is well known that lung cancer is caused by air pollution as well as by cigarette smoking. To establish the contribution of air pollution, methods of regression analysis have been used, with the data on mortality due to lung cancer and available information on smoke pollution and cigarette-smoking Ref. [9], to discover the increase in the incidence of cancer due to pollutants from coal-burning in fossil-fuelled power stations. This analysis showed an increment of nearly 152 cases of lung cancer death per million per year, per tonne of coal consumed per person, in a population with a total age-sex-specific lung cancer death rate of 750 per million from all causes (England and Wales 1958–1959). Although there are limitations in the model used for analysis, the estimates show lung cancer risk due to coal-fired stations orders of magnitude higher than that due to nuclear power stations. The regression analysis also showed a 15% increment in the average lung cancer death rate from cigarette-smoking (for 10^3 cigarettes per year). The overall risk of pollutants from coal-fired stations, including death from causes other than lung cancer, would be even higher. A similar analysis was carried out for lung cancer deaths due to inhalation of the specific carcinogen benzo(a)pyrene from coal-burning, on the basis of extensive data from 48 States in the USA, on the concentration of this carcinogen and total incidence of lung cancer Ref. [9]. The analysis showed an increment of nearly 48 cases of lung cancer death per million, per ng/m^3 of benzo(a)pyrene, in a population with a total lung cancer death rate of nearly 867 per million. Thus, even a single chemical carcinogen shows risk an order of magnitude higher than the risk of discharges from nuclear power stations.

If we now consider the increase in total number of deaths from lung cancer during the last 20 years (Figure 2) and attribute an estimated 85% increase to air pollution (excluding 15% from smoking), we can calculate the total lung cancer risk of air pollution. Figure 2 shows nearly 500 additional cases per million for England and Wales, of which 425 can be attributed to air pollutants, in a population with total lung cancer death rate of 1050 per million in 1970.

All the above data on risk analysis have been set out in Table II, which gives a summary of cancer deaths per million from different exposures to pollutants, including discharges from nuclear power stations and coal-fired power stations, benzo(a)pyrene and general air pollutants. Percentage effect of different exposures in terms of cancer deaths is 0.06% for nuclear power stations, 19% for the effluents from coal-fired stations, and 41.9% for general air pollutants. For benzo(a)pyrene, the specific carcinogen from coal-burning, the effect, i.e. the lung cancer increment, is 5.5% per ng/m^3. Although this comparison is based on data for different countries, it is striking enough to provide a general perspective on the problem.

Table II. Summary of estimated cancer deaths per million from discharges from nuclear power stations and coal-fired stations: Benzo(a)pyrene and general air pollutants

Nature of exposure	Type of risk considered	Total deaths per million from risk considered in Column 2	Contribution from exposure as per Column 1	Percentage of total deaths from exposure
1	2	3	4	5
Dose of 5 mrem from nuclear effluents	Cancer including leukaemia	1500[a]	1	0 06
Benzo(a)pyrene in city air	Lung cancer (increment per ng/m^3)	867[b]	48	5.5
Effluents from coal-fired stations	Lung cancer (increment per tonne of coal per person)	750[b]	142	19.0
General air pollutants	Lung cancer	1050[b]	425	41 9

[a] Estimated average cancer deaths per million per year
[b] Estimated lung cancer deaths per million per year in the population considered (see text)

RISKS OF NUCLEAR POWER AND COAL-BURNING COMPARED

We are now in a position to put the comparative risks of nuclear power and power from coal-burning in a proper perspective, on the basis of radiation exposure and benzo(a)pyrene uptake, respectively. The potential carcinogenicity of both has been fully established, partly from human experience and partly from animal experiments carried out at high levels of exposure. It is not likely that ionizing radiation at low doses causes any new type of harm since man has always been exposed to a fairly large dose of natural radiation. Therefore, if we recognize the limitations in both these risk estimates, a numerical comparison provides a very good basis for assessing the safety of a particular system. Such a comparison, presented in Table II, needs some further explanation. Risk estimates for nuclear power assume a high degree of engineered safety in the design of the station and proper site selection to avoid exposure of any population group to unduly large effluents from multiple stations. All this is reflected in the stringent exposure limit of 5 mrem/a for a substantial nuclear power programme The limit for such exposure as recommended by the ICRP is 500 mrem/a, higher by a factor of 100. We shall now compare these limits with the risk of benzo(a)pyrene uptake.

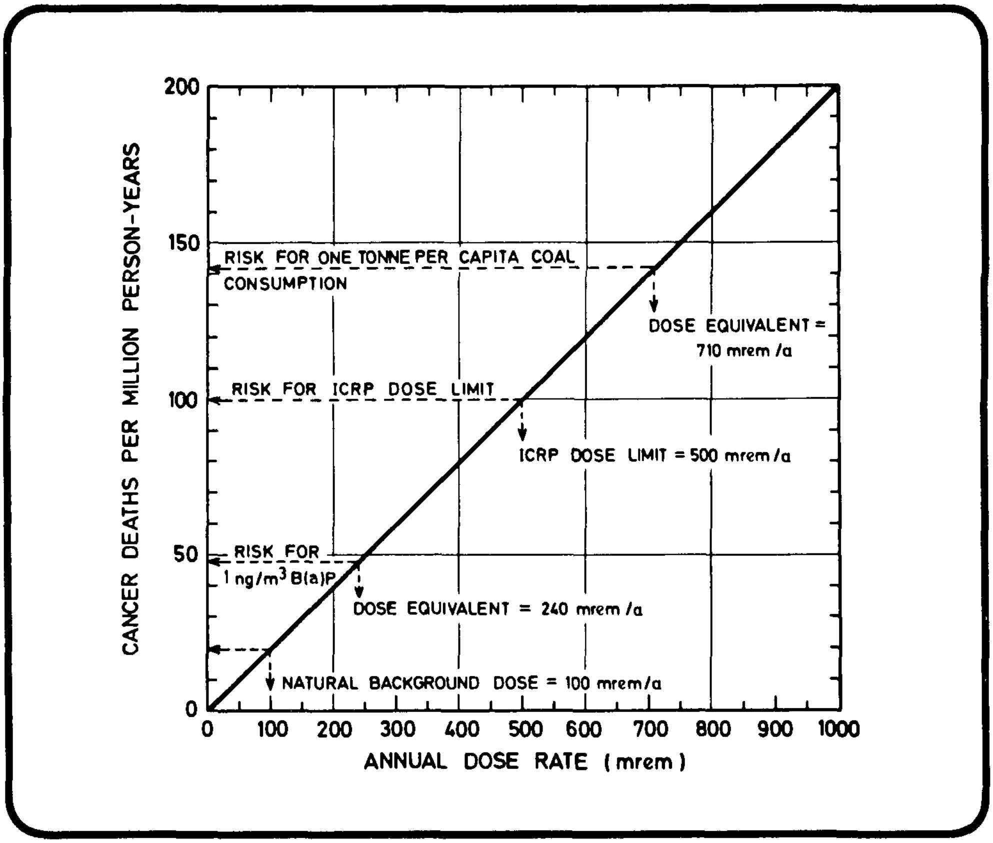

Figure 3. Cancer risk of radiation exposure, based on BEIR Committee Report. Dose equivalents for lung cancer, risk from coal-burning power and risk of benzo(a)pyrene are also shown.

Figure 3 gives a graphic representation of the cancer risk (deaths/million per year) in continuous exposure to different annual dose rates of ionizing radiation. The graph also shows the radiation dose equivalents for one tonne per capita coal consumption and 1 ng/m^3 benzo(a)pyrene in the air. The dose equivalent of 1 ng/m^3 of benzo(a)pyrene for the same risk, i.e. 48 deaths per million (Table II), is 240 mrem/a. This is 48% of the permissible exposure of 500 mrem/a for individuals recommended by the ICRP. The benzo(a)pyrene concentrations in different cities of the world lie in the range of 1 to 4 ng/m^3 (excluding the areas with high industrial concentrations). From this it can be inferred that the current risk of benzo(a)pyrene inhalation alone is nearly 100 times the risk of projected radiation dose of a large nuclear power programme.

Table III. Occupational risk estimates for different stages of the nuclear fuel cycle, for whole-body exposures

Stage of the fuel cycle	Average individual exposure (mrem/a)	Estimated risk (cases/10 000)	Risk of spontaneous (cancers/10 000)
Mining	500	1	15
Milling and processing	100	0.2	15
Reactor operations	200	0.4	15
Fuel transport	50	0.1	15
Reprocessing plants	200	0.4	15

Notes:

1 Estimated risks are for 10 000 persons employed in each operation. For actual numbers employed, risks tend to be negligible compared to spontaneous incidence
2 Risk estimates for miners are only for external whole-body dose.
3. Individual exposures are the best estimates available from different sources See Ref [14] for reactor operations

OCCUPATIONAL RISKS OF THE NUCLEAR FUEL CYCLE

For a complete analysis of the nuclear fuel cycle risk, it is necessary to consider the hazards associated with each stage of operation, including uranium mining, milling and processing, fuel fabrication, reactor operation and fuel reprocessing. Based on the estimated mean dose from each of the operations, it is possible to estimate the risk of cancer for each operation, again using the rate of 200 deaths/million per year/rem estimated by the BEIR Committee for continuous or continual exposure. The data is given in Table III, in which risk is estimated in terms of cases per 10 000 workers. The last column gives the risk of spontaneous induction of cancer. In the case of uranium miners, the current risk is only one per 10 000, against the excess death rate of 15 per 10 000 found from a survey carried out for the period 1950–1967 Ref. [10]. For all the stages of the fuel cycle, the risk is less than one. The risk analysis for the LMFBR fuel cycle may be based on the release of ^{239}Pu and other transuranic elements in fuel reprocessing for these reactors. The population dose from releases from a fuel reprocessing plant for 1000-MWe LMFBR is only 10^{-8} of the natural α-dose, giving an exceedingly small risk estimate on the scale considered Ref. [11].

In comparison, a single coal-fired station of 1000 MWe involves nearly two fatalities per year including mining, processing and transport Ref. [12]. Industrial exposure to some chemicals is known to involve up to 10–30 cancer deaths per 10 000 workers per year Ref. [13]. The industrial use of vinyl chloride, benzidine and several other chemicals has led to widespread incidence of cancer, and steps are now being taken to cut down such occupational risks. In fact, chemical and other industries could learn a lot from the nuclear industry to cut down the occupational as well as population risks.

SUMMARY AND CONCLUSIONS

Quantitative risk analysis based on the human experience of exposure to ionizing radiation has been used for assessing the risks of cancer mortality for different doses. The risk corresponding to the estimated dose of 5 mrem for groups of individuals exposed to discharges from nuclear power stations is *one* per million per year, having no statistical significance compared to the spontaneous cancer death rates of 1000–2000 per million per year. Diagnostic medical exposures lead to doses and risks higher by a factor of 10. Risk analysis has also been carried out for chemical pollutants, mainly the combustion products of coal, including the well-known carcinogen benzo(a)pyrene. It is found that the current risk from inhalation of benzo(a)pyrene in urban air is nearly 100 times the risk of radiation exposure from a large nuclear power programme. The analysis carried out for the occupational risks of the nuclear fuel cycle also shows that the overall risks are extremely small compared to the risks associated with power production from fossil fuel.

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