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NUCLEAR TECHNOLOGIES: PUBLIC PERCEPTIONS, REALITIES AND EDUCATION

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by
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ABSTRACT

Utilizing published information, the lecture addresses selected issues related to the societal benefit of nuclear technologies, how these are perceived by the public, some of the reasons why public perception is often negative and how proper information and education can contribute to a more ethical and rational approach to radiation risk.
The weaknesses and strengths of a better approach to decision making based on the comparative risk assessment of nuclear and radiation technologies versus other technologies providing similar benefit to mankind or activities normally considered safe by the public, are presented. The lecture is structured in four sections. In Section I examples of problems society is presently facing and how nuclear technologies can help in finding solutions to them, are shortly described. Section II illustrates some issues related to the public perception of nuclear technologies. In Section III some elements of comparative risk assessments are presented. In Section IV the phenomenon called “Radiophobia” and some of its causes and societal consequences are briefly highlighted. In Section V the contribution that education at the secondary and tertiary level (university level) can give to a more rational and ethical approach to decision processes related to nuclear and other technologies, is briefly presented.

INTRODUCTION

Nuclear technologies are still suffering by many misconceptions and their broad range of potential and positive contributions to many sectors of society are still insufficiently known. Experience has shown that whether one is dealing with policy makers, representative of the media, green activists, students, laymen or even non-nuclear scientists and engineers, simply describing in isolation the benefits and risks of nuclear technologies and what radiation does and does not to living organisms, is in general insufficient to remove fears and scepticism. This is depriving society at large of technologies that can substantially contribute to reduce under-development and in many cases to alleviate human suffering.

Therefore it is considered of particular importance that the new generation of nuclear scientist and engineers also develop skills to understand and communicate factual and documented information not only on the various societal benefits of the several nuclear technologies available today but also on the comparative risks of nuclear technologies versus other technologies producing similar societal benefits. Comparative risk assessments, in spite of some intrinsic limitations, are especially useful as, by putting all technological and other risks in a general context, the actual risks associated with nuclear technologies can be more properly appreciated and more rational and ethical decisions, in the interest of all sectors of society, can be taken.

Utilizing peer-reviewed scientific publications, information published by the International Atomic Energy Agency and original considerations, the lecture addresses selected issues related to the societal benefit of nuclear technologies, how these are perceived by the public, some of the reasons why public perception is often negative and how proper information and education can contribute to a more ethical and rational approach to radiation risk.

The lecture is structured in four sections. In Section I examples of problems society is presently facing and how nuclear technologies can help in finding solutions to them, are shortly described. Section II illustrates some issues related to the public perception of nuclear technologies. In Section III some elements of comparative risk assessments are presented. In Section IV the phenomenon called “Radiophobia” and some of its causes and societal consequences are briefly highlighted. In Section V the contribution that education at the secondary and tertiary level (university level) can give to a more rational and ethical approach to decision processes related to nuclear and other technologies, is briefly presented.

I. SOCIETAL BENEFITS OF NUCLEAR TECHNOLOGIES

I.1.Energy

Energy scenarios agree that if sustainable development has ever to be achieved a 60% to 180% growth in energy use must be reached by the year 2050 [1]. Increase in energy use is not only important for the already industrialised countries but particularly for the developing ones. The world’s poor two billion people, representing one third of the world’s population, mostly living in developing countries, still lack access to affordable modern energy. If these two billion people are to be provided with access to basic services in a way that does not destroy the carrying capacity of the natural environment, unprecedented changes in technology, lifestyles, and social organization will be needed, with energy being central to achieving this goal.

Regretfully much of the world’s energy is currently being produced and consumed in ways that cannot be sustained if technology is to remain constant and simultaneously overall quantities were to increase substantially. Although in the past century increases in energy use have often meant increases in pollution, thanks to technology, the expansion of energy supply and use in the future can be much cleaner and more efficient than it has ever been. In this context nuclear power can play an important role as it minimizes the use of the very valuable but finite fossil energy sources, has a minor impact on potentially irreversible climatic changes and reduces permanent environmental damage [2]. In addition it broadens the resource base by putting uranium to productive use; reduces harmful emissions of particulate matter; expands electricity supplies and increases the world's stock of technological and human capital. It is also ahead of other energy technologies in internalising all externalities as the costs of safety, waste disposal and decommissioning, in most countries are already included in the price of nuclear electricity. Furthermore the complete nuclear power chain, from resource extraction to waste disposal, including reactor and facility construction, emits only two to six grams of carbon per kilowatt-hour, about the same as wind and solar power. This is less than natural gas and two order of magnitude below coal. In addition, nuclear power avoids the emission of many other air pollutants, such as sulphur and nitrogen oxides. Last but not least, its future average cost is expected to be in the range of 4 to 6 cents of US $ per kWh , which is equal or less than that of low-carbon emitting (gas-fired combined cycle plant, integrated gasification combined cycle) and non-fossil (wind, photovoltaic, thermal solar) technologies [3].

I.2 Human development

Good health, sufficient food and water, and a safe environment are fundamental elements for our quality of life. Yet they are still not available to too many people in many parts of the world. In addition sustainable industrial development is necessary to provide the economic resources needed to raise the standard of living in many countries. Nuclear technologies have a larger role to play in human development than just energy and many non-power nuclear technologies can contribute, and indeed are in many cases already contributing, to human development. However, their broader use is necessary if the world wants to make also use of technology to solve many of the problems mankind is still facing.

Nuclear technologies offer unique tools in the quest for sustainable development. They are often the best approach to gather technological and scientific information and provide solutions that would not otherwise be possible or practical. They are used to diagnose and treat disease, breed better crops and fight insect pests; assess new sources of fresh water and monitor pollution. Isotopes can be used to "label" materials under study and as they can be identified and measured at very low and harmless concentrations, labelling is often used in diagnostic medical tests, in studies of underground sources of water, and to trace pollutants, such as heavy metals and pesticides. Isotopes are also used in nutritional studies to follow the metabolism of vitamins and trace minerals in food supplements. Other nuclear techniques utilise radiation, to kill cancer cells, sterilize tissue grafts for burn victims, protect food against disease-causing pathogens, induce favourable and harmless genetic changes in plants, or scan body organs for abnormalities [4-14].

A more extensive description of many non-power nuclear technologies and the problems they can help solving is reported in Appendix 1.

II. PUBLIC PERCEPTION

II.1 Technology, fears and the media

We live in a complex, technological world and everything we do or is done to us carries some risk to our health and welfare. Therefore there is no such thing as zero risk or absolute safety. Moreover, in today's technological world very often we feel that other people are deciding things that affect the quality and length of our lives and frequently we know little about how decisions are reached. Yet they affect matters, which touch us every day, such as transport, electrical power, health services or the food we eat.

In a world where technology rules such a large part of our lives, where so many decisions are taken out of our hands, we may feel threatened by our inability to do much about anything. Many people feel that technology is imposing a whole set of new risks on us, such as the burgeoning use of synthetic chemicals, artificial additives in food, air and water pollution and nuclear radiation. The extraordinary rate of technological change also increases the potential for the introduction of risks that we cannot assess until perhaps is too late. For example, about 1000 new chemicals are produced each year and there is a decreasing time between the identification of new technological development and its widespread use in the community (e.g. cellular phones). Most people fear disaster, lack of personal control, potential irreversible effects and risk to their children. Some categories of risk are especially feared such as nuclear power generation, radiation, pesticide use, food additives or genetically modified organisms. In the public eye such risks too often overwhelm in importance those more familiar ones we have faced for generations, neglecting the undeniable benefits that scientific progress has brought on the whole to mankind's welfare.

It must be added that in every society, primitive or sophisticated, it is impossible to completely eliminate stimuli that arouse public fears of hypothetical dangers, vague and uncertain, as they may be. Fear arises when a hazard is imaginatively conceived, but its reality is not detectable or difficult to measure. Hypothetical fears may arise form idle rumours, or scaremonger hyperboles intended to create public support for a cause. The corresponding risk then becomes a political reality, and may dominate public policies and world issues. We can again quote as examples nuclear power, food irradiation and genetically modified organisms.

Often the fears and the associated risks are the result of illegitimate extrapolations either of the frequency of recorded rare events or of known exposure to high levels of a given external agent projected to low levels, in absence of any experimental or convincing theoretical evidence. Frequently the policy choice for non-detectable risks has gone so far as to outlaw the source, a step defined as the "precautionary principle", forgetting that this principle is not necessarily correct as it is demonstrated by the many external agents that at low concentrations or doses can have a beneficial effects (e.g. chemical elements, UV and visible radiation, vitamins). We know that in these cases it is actually the dose, which determines if an agent is either a "remedy" or a "poison". Last but not least, the precautionary principle is a retreat and not an answer and when carried to the extreme, it maintains the *status quo* by stopping economic and public health progress. Regretfully some hypothetical fears can be used by the media to exploit society's credibility and the resulting political pressure may lead to disastrous long-term national policies. It is today's reality that some very contentious hypothetical fear (such as nuclear power, radiation or genetically modified organisms) have become so politically significant, both at national and international level, that the danger they could develop into long-term doctrines, which can become politically enduring, difficult to modify and eventually extremely destructive for the whole society, must be seriously considered. Therefore, in order to make sensible decisions about the risks we run in our present way of life, we need information and, whenever available data permit, we have to put risks in perspective, assigning numbers that allow to the extent possible their rating.

It must be added that the media too often also neglect to correctly emphasize that public health issues have to be considered by society together with a mixture of several other complex objectives such as economy, energy, employment, ecology and national security. Therefore, in practice, decisions have to be compatible with the overall national resources available. It follows that resource allocations among different social needs must be determined by a judgmental comparison of the public welfare values of proposed alternatives. If any alternative is too heavily weighted by hypothetical public fears, the decision process may be unintentionally flawed with serious negative consequences for all members of the human society.

Nuclear technologies and radiation fear at low doses delivered at low rates are examples of minor public health hazards being raised to major issues by its proponents. It also illustrates that the moral high ground assumed by well-meaning activists may well be socially immoral, when evaluated by the welfare of the entire society. This can be appreciated when one considers that presently there are countries that consider acceptable spending about US $ 180 million to save one human life by implementing the present radiation protection regulations [15], but are reluctant in supporting much cheaper life-saving technological approaches that can save lives by fighting cancer, malnutrition, low birth weight, early childhood diseases, communicable diseases, tuberculosis and malaria, producing more, safer and cheaper food, giving access to safe and affordable drinking water or removing the millions of landmines that continuously kill civilian population.

II.2 Experts versus public perception of radiation and nuclear risks

The different perception of nuclear and radiation risks by experts and the public has been extensively discussed in the specialised literature. A good and comprehensive description of the topic has been recently published by Grimston and Beck in the book "Double or Quits: The Global Future of Nuclear Energy" [16]. In this section some of their major findings and conclusions are summarised.

In general the opinion of the "nuclear experts" is that nuclear technologies can play an important role in serving many basic human needs. Nevertheless these benefits are not always equally appreciated by the general public, the media and the decision makers. Far too often nuclear technologies are perceived as a greater "risk" for mankind than many other conventional non-nuclear ones and "fear" is often interpreted as the same as "risk". This has led to a strong debate between two polarised extremes, the advocates (in general consisting by "experts") and the opponents (in general consisting of green activists claiming to represent the interest of large sectors of the general public). This debate has created problems to the decision makers who have been confronted by an apparently non-resolvable paradox. On one side the highly technical nature of the nuclear field suggests that decisions should be taken by those with suitable experience and qualifications. On the other, the social implications of nuclear technologies imply that a large number of individuals and interest groups should contribute to decisions regarding their deployment. The result is that the debate between the advocates and the opponents has seen an unwillingness, or perhaps even an inability, to engage in meaningful discussions with all stakeholders. Especially with respect to nuclear power there have been many examples of "advocates" claiming, often with apparent frustration, that the public simply does not understand how beneficial nuclear technology is, while making little apparent attempts to fully understand this concern. Certainly lack of public understanding is an important factor. For example a survey conducted in the UK in 1980 [17,18] found that only 31% of the respondents believed that uranium was present in the fuel of nuclear reactors. 59% believed nuclear power to be responsible for acid rain and only 13% were aware that radiation could come from both natural and man-made sources. In spite of this, as demonstrated by the good public acceptance of other advanced technologies, it is too simplistic to conclude that the opposition is only caused by the low level of technical and scientific knowledge of the public.

Moreover, correctly perceiving public opinion is a complex issue and the very concept of a single public opinion is probably of limited value in pluralistic societies. The population should be better viewed as an interlocking pattern of smaller publics whose opinion can change with time and location. Factors on which a person or group of people's opinion can be pro- or anti-nuclear may change depending on factors such as (i) the perception of the need for the technology (more popular in countries with serious concerns about energy security and large growth in energy demand), (ii) the perception of the risk (less popular after an accident, especially if occurred locally or a nearby country), (iii) the social and political situation (political parties can hold very different views on nuclear technology).

An additional complication is introduced by the fact that the perception by the decision makers of public attitudes may also not be necessarily correct. Decision makers often interpret as public opinion their own perception of public opinion. In other words they may be dealing with a perception of a perception and there is some evidence that this second-order perceptions can be subject to error. For example there has been evidence that in, UK and Sweden decision makers wrongly assumed the public opinion more negative about nuclear power than it actually was [19]. Among the explanations one can find the attitude of certain elements of the popular media and the greater effectiveness of anti-nuclear pressure groups in organizing anti-nuclear demonstrations, public campaigns and letter writings.

Some reasons for the present anti-nuclear public attitudes also find their origin in the past approaches that characterized the information released and the decision-making processes related to nuclear technology. In the past a technocratic mode of decision-making was predominant, to the detriment of the dialogues with, and control by, normal democratic institutions. The secrecy associated with the military use of nuclear materials also exacerbated this tendency.

Although today there is some evidence that communities that have nuclear installations in the vicinity tend to be the more pro-nuclear and often even express resentment at outsiders intruding to campaign against the installation in question, the legacy of the past approach to the selection of the sites for nuclear facilities, often based on the Decide-Announce-Defend (DAD) approach, is still present. To the point that several communities in areas without any activity involving nuclear technology have become increasingly adept at finding an array of measures to prevent major nuclear projects going ahead on the ground of the so called Not In My Backyard (NIMBY) principle. In some instances this kind of negative attitudes has gone even further, replacing NIMBY with BANANA (Build Absolutely Nothing Anywhere Near Anybody).

An example of how differently risks can be perceived by different sectors of the society and how these perceptions compare to the actual risks of death form various causes is shown in Figure 1 [20]. Although the data are more than twenty years old and refer to specific and probably not very representative groups, they clearly indicate how social differences can influence the way risk is perceived and how far they can be from actuarial estimates. Particularly striking are the differences in perception of nuclear power that both the league of women voters and the college students rated as the highest.

Last but not least it should be taken into account that suspicion in some sectors of the public about a cosy relationship between industry and government, even if based on evidence from some years ago, is not easy to overturn and imposes new approaches to public acceptance of nuclear technology. Democratic societies now require that communication be open, accountable, inclusive and equitable. New, flexible consultative techniques that are (i) informative (seeking to provide an informed viewpoint and not instantaneous reactions), (ii) deliberative (producing views reached through interactive group discussions), (iii) independent (taken independently of the bodies concerned with the final decision), and (iv) inclusive (seeking to involve a wide range of interested parties, including those who are sometimes disenfranchised or under-represented), have to be utilised.

Whatever the reason behind the persisting nuclear scepticism, it is a fact that in many countries public opinion now must be taken into careful consideration before decisions regarding nuclear technologies are taken. This has not only led to a decision stalemate but the perception of a negative public opinion has already had very negative economic consequences for the investors in nuclear power. In six OECD countries 21 nuclear power plants, with a total combined capacity pf about 14 GW, and one mixed-oxide fuel production plant, have been closed or halted in advanced stages of construction since 1978 for non-economic reasons [16].

III. RISK AND COMPARATIVE RISK ASSESSMENT

The mathematical definition of risk (R) is in general expressed as the product of the probability (P) that a given undesired event, the risk, will occur, times the consequences of this event (C), i.e. R = P x C. This is also called mathematical expectation of the consequence.

In principle risks could be compared by simply ranking them according to the different values of R. However this simplistic approach is not always possible because the product P x C can become misleading when it is not clearly quantified what both the probability and the consequences are and the respective uncertainties are poorly known. In addition many risk specialists also claim that risks have non-quantifiable sociological and psychological elements that should be taken into account. Risk is a multi factorial quantity and to correctly compare risks all factors, circumstances and assumptions should be mutually equivalent and quantified.

Moreover the mathematical probability of a given consequence can be calculated with minor uncertainty only when large amounts of historical data (for example risk of dying in car accidents caused by drinking) or very reliable epidemiological studies are available. However the latter are in practice very difficult to perform, the main reason being that they should always be corrected for all confounding factors and using very large cohorts. Therefore, probabilities are often calculated by not sufficiently reliable epidemiological studies, extrapolating to human beings data from animal experiments or obtained from calculated fault and tree events (especially for very rare events).

Moreover, when presenting comparative risks to the public it has to be taken into account that the “rationality” of physical science and mathematics and the “rationality” of everyday life can diverge quite radically. A typical perception problem is presented when comparing a risk with a small probability of severe consequences with that of a situation with high probability and mild consequences. Here maximum divergence between the perception of the experts and that of the public can be experienced. As an example the different expected causalities for three risks (A, B, C) having probabilities of 0.1, 0.001 and 0.000001 and consequential death tolls per day of 10, 500 and 100,000 respectively, are shown below.

The rationality of physical science and the rationality of everyday life can diverge quite radically

Activity	Example Casualties in 10 years (P x N x 365 x 10)
A has a probability of 0.1 of killing 10 people per day	3650
B has a probability of 1/1000 of killing 500 people per day	1825
C has a probability of $1/10^6$ of killing 100,000 per day	36.5

Public generally fears C > B > A

While a nuclear expert would typically perceive risk C as "the preferable risk to run" the general public would generally rank the fear as C> B> A.

To overcome the difficulty associated to communicate the actual meaning of very low risks in terms more easily understandable by the public, many laudable efforts have been made. In this context it is worth quoting the work conducted by Cohen et al. [21, 22] where different risks have been expressed in terms of days of life expectancy lost (or "Loss of Life Expectancy" (LLE)). Increase in life expectancy (LE) is generally appreciated by the public as a sign of progress and a typical example of the increase of LE over time in the advanced nations of Europe is presented in Figure 2 [23]. The LLE due to a risk can be easily understood as the average reduction of lifetime for individuals involved in a given activity. Another advantage of using LLEs in comparing risks is that these can be calculated for various age ranges, thereby permitting to quantify the fact that the premature death of an elderly person is less regrettable than the death of a much younger person.

On the basis of the consideration that loss of life expectancy is a concept that could be more easily understood by the public when presented with small risks such as 10^{-3}, 10^{-6} or 10^{-9} , LLEs have been calculated utilizing mortalities rates (m_i) obtained form Census statistics for a number of different causes (accidents in general, occupational risks, unemployment, being overweight, lack/presence of social connections, using small versus large cars, passive and active smoking, drinking alcoholic beverages, breathing polluted air, exposure to environmental pollutants, presence of carcinogens in natural food, practicing sports, living in different geographical locations, epidemics, socio-economic factors, living near a nuclear power station, exposure to radiation, exposure to various environmental pollutants etc.). Utilizing simple equations and changes in mortality rates (expressed as deaths per year per 10^5 people) from m_i to m_i^*,where m is the mortality rate in presence of a given risk and m* is the mortality rate when that risk was removed) the LLE (LLE = LE* - LE) was calculated.

A simple and hypothetical example of LLE for players of "Russian Roulette" is presented in Figure 3.

The original data obtained by Cohen are shown in Figure 4. Here the LLEs due to nuclear power according to the different estimates made by the anti-nukes and government experts are highlighted as black rectangles.

The LLE data allow one to compare the amount of exposure giving the same risk. As Figure 5 shows, using this information one could for example conclude that living one year near a nuclear power plant has the same risk incurred by a smoker smoking one extra cigarette every six years or by a 20% overweight person due to a weight increase of 0.6 grams [22].

Mortality rates can also be used to compile lists of events or activities implying the same risk. As most people consider activities and/or events implying a few microrisk as acceptable (1 microrisk = 1μR = $1/10^6 = 10^{-6}$), comparing different activities involving the same risk of 1 μR, can be a useful approach to put different risks into perspective. Examples are shown Figure 6 [24]. However, when confronted with these risk comparisons the limitations due to the uncertainties present in the primary data should never be ignored.

IV. RADIOPHOBIA: SOME CAUSES AND SOME CONSEQUENCES

Radiophobia can be defined as the irrational fear that any level of ionising radiation is dangerous. The causes of radiophobia appear to be several and among them the following have been mentioned by Jaworowski [25]: (i) psychological reaction to the devastation and loss of life caused by the atomic bombs of Hiroshima and Nagasaki, (ii) the psychological warfare conducted during the cold war (fear that a nuclear war could partially or entirely wipe out mankind form the Earth), (iii) lobbying by fossil fuel industry, (iv) interest of some radiation protection lobbies striving for recognition and budget, (v) interest of the media that profit by inducing fear (bad news sell much better than reassuring news), and (vi) the assumption that a linear, no-threshold relationship between radiation dose and detrimental biological effects is a fully demonstrated scientific theory holding also at low doses delivered at low dose-rates. Although it would probably be too simplistic to claim that (vi) is the main cause of radiophobia, in this Section we will only concentrate on this point as there is increasing scientific evidence that the linear assumption (or its derivative, the linear quadratic with allowance for low dose and dose rate effects), initially used only as a convenient hypothesis to facilitate radioprotection and only later transformed by many into a scientific dogma, may indeed not be valid.

The linear relationship between biological radiation effects and radiation doses is indeed supported by many experimental data at high doses (> ~0.5 Sv). At low doses (<~200 mSv) no conclusive experimental data exist. This is schematically shown in Figure 7.
One argument against the validity of a linear no-threshold relationship at low radiation doses and dose rates comes form the observation that the percentage of cancer cases and other adverse health effects in regions with high natural background radiation, appears to be equal or even lower than in regions experiencing average background radiation levels (2.4 mSv/year).The situation is schematically summarised below [26,27].

Examples of maximum doses in areas with high background radiation in countries around the world

Country	**Dose (mSv/year)**
Germany	**3.8**
China	**5.4**
Norway	**10.5**
Brazil	**35**
India	**35**
Iran	**260**

- **No adverse health effects have been ever detected in these areas.**
- **The % of cancer cases are equal or lower than in areas with natural background (2.4 mSv/y)**

Further evidence comes form scientific epidemiological studies such as those performed by Cardis et al.[28] on the effects of low doses and low dose rates of external ionising radiation on cancer mortality among nuclear industry workers in selected countries and by Cohen [29] who critically re-examined the mortality among the survivors of the atomic bombs of Hiroshima and Nagasaki. This latter study led to the conclusion that the atomic bombs survivors who received instantaneous radiation doses of less then 200 mSv did not suffer any significant induction of cancers. Apparently no adverse genetic effects have been also observed after 50 years in the progeny of the atomic bomb survivors who were exposed to very high, near lethal radiation doses [30].

Radiobiological consideration also seem to provide evidence leading to similar conclusions. One argument is that the linear extrapolation to doses as low as $1/10^4$ of those for which there is direct evidence of cancer induction by radiation, should imply that a single particle of radiation interacting with a single DNA molecule can initiate cancer. However it should be taken into account that DNA damage occurs all the time in our bodies with each human cell averaging more than 200,000 damage events every day and that reparative biochemical mechanisms continually mend this damage. Double-strand DNA breaks (DBS), the one believed to be cancer initiators, however occur much less frequently. Experiments have shown that only about 200 DSB per year are taking place in a cell (i.e. less than 1 per day) and that an exposure of ~ 100 mSv causes about 4 DSB. Therefore the hypothetical lifetime exposure of 100 mSv should increase the cancer initiating events by only 2%. On the contrary the linear no-threshold hypothesis at low radiation doses and dose rates predicts an increased cancer risk of more than 150% [29,31].

A further criticism to the validity of the linear no-threshold hypothesis at low radiation doses and dose rates comes from the supporters of the phenomenon called hormesis, namely the beneficial effects, if not the essentiality, of low doses of radiation for the well being of all living organisms. Hormesis has been claimed since many years but until recently little solid scientific information existed in its support. Over the past five years a group of scientists systematically reviewed the scientific literature for evidence of hormesis. More than 1000 articles were subjected to very critical scrutiny and many showed clear evidence of hormesis to some degree [32]. The findings of this search were that stimulatory responses to low-doses are not restricted to any particular taxonomic group but are broadly observed across the microbial, plant and animal kingdom. The types of agents shown to cause hormesis were without apparent restrictions and included agents of all chemical classes and different type of physical stressors, including various types of radiation. The range of biological effects observed included growth, longevity, better reproduction ability and decrease in disease incidence. The implication of hormesis for cancer risk assessment is that it provides a biologically based foundation supporting the concept of threshold for many stressing agents, including radiation. The regulatory goal of exposure to radiation and other carcinogenic agents should then be not zero, but aimed at achieving an optimised health-based response. Although much remains to be explored in the field of hormetic effects, the considerable progress made by molecular biology now provides tools that can enhance our understanding of the mechanistic foundations of many dose response relationships at very low doses.

The potential significance of hormesis on the validity of some of the present radiation protection recommendations can be very substantial. If an agent (such as radiation) produces a significant beneficial effect at low doses, and such low-level of exposure is not permitted, conservative standards may be more harmful than less stringent ones. In other words if a standard, by preventing low-level exposure to a regulated agent, eliminates the attainment of a potential beneficial effect, this has to be recognised and justified to the public in future standard setting activities. Presently most regulatory agencies assume that there is no safe level of exposure to carcinogens. However the hormesis concept suggests not only that this could not be correct, but that low level of exposure may have some net benefit to the organism.

It must be added that many epidemiological studies do not contradict, and some even appear to corroborate, the phenomenon of radiation hormesis. For example in Yangjiang (Guandong province of China) 150,000 peasants with the same genetic background were examined [27, 31, 33]. 50% lived in a region where they received a two to threefold higher radiation dose (5.4 mSv/y) than the control group (2 mSv/y). No difference was found for the total mortality for cancer and leukaemia between the studied group and the control population and hereditary diseases and congenital deformities in children were the same as in the control area. Moreover cancer mortality for the age group 40 to 70 years was statistically lower than in the control group. Similarly in Kerala (India) a population of more than 100,000, receiving a dose averaging 15.7 mSv/y (with peaks to 33 mSv/y) was extensively studied [33, 34]. The results indicated that there were no statistical significant biological effects in the population in comparison with the control group.

In this context another phenomenon called "adaptive response", sometimes erroneously confused with hormesis, must be mentioned. Experimental scientific evidence collected through *in-vitro* and *in-vivo* studies on various types of cells [35] indicates that exposure to low level of radiation may reduce the number of chromosome aberrations from subsequent exposure to larger radiation doses. This effect is ascribed to the stimulated production of repair enzymes by low level radiation, supporting the claim that low level of radiation stimulates the biological defence mechanisms.

What reported above leads to the conclusion that the linear no-threshold hypothesis is not fully justified and a more appropriate representation of the relationship between radiation doses and the detrimental biological effects could be of the type shown in Figure 8.

In conclusion the linear no-threshold hypothesis at low radiation doses and dose rates may not represent the real effects of exposure to low level of radiation and lead to a grossly over-estimate of the radiation risk to human health. It follows that its continuing use by many regulators and radiation protection specialists, as if it was a scientifically proven theory, is not only responsible for the unjustified and irrational fear by the general public that any level of ionizing radiation is dangerous, but can also be the cause of considerable financial damage to society at large.

A few examples of unjustified, huge financial and social price paid by society have been reported in the literature. It has been calculated that after the Chernobyl accident the cost of destruction of slightly contaminated produce and milk (containing only about 20% additional activity to that naturally present due to ^{40}K) in Germany amounted to about 300 million US $ and the radiological component in the remediation of former uranium mining areas in former East Germany would amount to about 2,000 million US $ [36]. Similarly huge expenditures could be faced in the USA [37] for the cleanup of radioactive contaminated sites (about 6 billion US $ were budgeted for the fiscal year 1997) and the cost efficiency in saving one life by implementing the radiation emission standards was estimated to amount to US $ 180,000,000 [15]. Assuming the correctness of these figures it is therefore difficult to disagree with the statement made by Cohen [38] that *" such costs are absurd and immoral, especially when compared to the relatively low cost of saving lives by immunization against measles, diphtheria and pertussis, which in developing countries entails costs of 50 to 99 US $ per human life saved."*

V. EDUCATION

The democratization of society and the associated increased participatory role of all sectors of the public in many important decision making processes, require that the general public becomes more knowledgeable about the overall short and long term impact of these decisions. This is not an easy task in view of the complexities of many issues, especially when scientific and technological expertise is also needed in a mix with economic, sociological, psychological and political considerations. This is often the case when decisions about the introduction of nuclear and radiation technologies have to be taken.

One approach that can help moving towards more rational and ethical, but still democratic, decision making processes is increasing education in the relevant subjects at all levels. This is an ambitious goal and may require very long times. To begin tackling the problem a new generation of scientists and engineers dealing with nuclear and radiation technologies that are more aware of the social, economic and risk implications of the science and technologies they will contribute to develop and apply once they have entered the work force, should be created. To this aim these new scientists and engineers must have access to educational modules that will extend their knowledge and awareness beyond the mere technological and scientific aspects and curricula containing elements related to economic, sociological and psychological implications, ethical principles, impact on the national resources and implications for the national security, the role the media play in informing the public on the actual hazard of alternative technological approaches, short and long term strategic considerations, must become available.

In particular the new generation of scientists and engineers should become more familiar with the methodological approaches required to conduct meaningful and unbiased (to the extent possible) comparative risk analyses of the different technological solutions that can be chosen to various problems, including the ones based on nuclear and radiation principles. They should also acquire skills on how comparative risk analyses can be independently performed, publicized and offered to the scrutiny of policy, decision and opinion makers and as many sectors as possible of the general public. This would imply introducing educational modules where elements of disciplines that traditionally have been thought separately such as mathematics (probability and statistics, dynamic of non-linear systems), chemistry, physics, biology, engineering, risk analysis in various industrial sectors, as well as economy, sociology, psychology, philosophy and ethics, are mixed together in a coherent and logic frame-work. Such a type of approach, although restricted to medicine, is already being experimented with success in some medical schools.

APPENDIX 1

Examples of non-power nuclear technologies and the problems they can help to solve

1. Human Health.

The use of radiation to treat cancer is so widespread and well known that the benefits of its use do not require any further argument. It can only be mentioned that nowadays hardly a single major hospital exists in the industrialised world, which does not have a department of radiology and where radio-pharmaceuticals are not used. Unfortunately the same it not true for many developing countries. Here not only cancer treatment by radiation is lacking but malnutrition and hunger have devastating consequences, contributing to low birth weight, developmental problems, mental retardation and a weakened immune system. Nuclear technologies can significantly contribute to alleviate these problems. They can be used to monitor a wide variety of malnutrition problems and improve the management of food supplementation programmes. Tuberculosis and malaria are also serious threats to human health in many developing countries. TB kills about 1.5 million people each year. Malaria accounts for one in five of all childhood deaths in sub-Saharan Africa. Molecular method based on isotopes are able to detect drug-resistant strains of both TB and malaria in a matter of hours, rather than the several weeks required by traditional methods, permitting appropriate treatment to be started early, thereby saving many human lives. In addition nuclear technique are also used in preventing hypothyroidism and treating thyroid cancer and iodine deficiency.

2. Food and Agriculture

Although the climate in many poor regions of the world is generally favourable to growing food, soil conditions, insect pests and lack of water can severely affect crop yields. Nuclear technologies can be used to increase food production in developing countries by combating insect pests, improving the crop varieties used, and improving irrigation practices. Insect pests can be controlled using the sterile insect technique, where male insects are first raised in the lab and then gamma irradiated to make them sterile, so they cannot reproduce when released into the environment. The techniques has been successfully used to combat the tsetse fly, the source of human sleeping sickness and the livestock disease called "Nagana", in African countries. It has been also used in many countries to control the medfly, a threat to some 250 species of fruit and vegetables. Radiation can be also used to create favourable and harmless subtle genetic changes in plants. This technology has been very successful in making commercial crops more resistant to disease or drought according to local conditions. Several improved crop varieties, such as rice, wheat, banana, potato, yam and soya have been developed in this way and are in current use. Agriculture accounts for the largest amounts of fresh water used in the world. In the face of the growing demand for water worldwide, the efficient use of water in agriculture is a high priority. A method called fertigation can reduce wastage of water by supplying both water and nutrients (fertilizer) directly to the root zone of crops, maximizing efficiency. Nuclear techniques are in this case used to evaluate the effectiveness of fertigation for a variety of annual crops.

3. Industry

Many industrial applications of nuclear technologies are well established. They are used in process development, measurement and automation and quality control. Radioisotopes are used in thickness gauges for the complete automation of high speed production lines for steel-plates or paper. Tracers experiments are used to obtain exact information on the condition of expensive processing equipment and increase its usable life. A wide range of different industries use tracer technologies including: coal, oil, gas and petrochemicals, cement, glass, building materials, ore processing, pulp and paper, iron and steel, non-ferrous metals and automotive. They are used for process investigation (residence time, flow rate, velocity, modeling, parameter estimation), in controlling mixing (mixing time, mixer optimization, mixer performance), to address maintenance issues (leak detection, investigation of malfunctions, material transport), and to study wear and corrosion (engine wear, corrosion of process equipment, lubrication).

Other industrial applications of nuclear technologies can be quoted just as illustrative examples. Gamma radiography is applied for checking welds, casting, assembling machinery (such as jet engines) and in ceramics. The small size of radioisotope sources allows inspections of parts or machinery that cannot be examined by X-ray tubes. Radiation is also used for checking the welds in pipelines, where the radioisotope source is located inside the pipe and a detecting system is outside the weld. For checking long pipelines, sophisticated, self propelled crawlers that travel in the pipe are used. Autoradiography is widely used in metallurgical studies to investigate solidification zones during the casting of steel, the observation of segregation of certain alloying elements and to study the distribution of lubricating films in bearings. Neutron radiography, a technique based on the attenuation of a neutron beam when interacting with matter, is used for testing nuclear reactor fuel, to detect flaws in gas turbine blades and corrosion of aircraft components, to control the quality of ceramics and the presence of lubricating films inside gear boxes or bearings.

Nuclear technology is also widely used in the manufacturing industry. It is used in the making of plastics or to graft plastics on other material. Some polymers can be tailored to shrink when heated, a property exploited in packaging applications. Wires and cables can be insulated with radiation induced cross-linkage of polyvinyl chloride. Such insulation has better resistance to heat and chemical attack, increased cut-through resistance and is more compact. These products are used in the automobile, telecommunications and the aerospace industry and in home electrical appliances. The wood and printing industries also make extensive use of radiation technology to cure surface coatings and the vulcanization of rubber sheets by radiation in the manufacturing of tires, instead of using sulfur, is being used commercially by several tires industries.

On the economic side, a few example of the high saving that radiation technology has permitted in industry can be quoted. In the development of a new engine the cost of testing a new cylinder amounts to about US $ 400,00 for each liner, when using traditional wear measuring devices. By using the nuclear technology the cost is reduced to about US $ 50,000, bringing the overall cost saving for the 10 liner modifications needed on average for the development, to about US $ 3.5 million. In the case of testing bearing cups, saving amounting to about US $ 3.2 million have been calculated. In metal coatings, such as galvanizing or tin-coating of steel plates, the use of a nuclear technique called “radioisotope gauging” to control the coating process, saving of about US $ 200,000 per year have been reported for an individual plant.

4 Water

Today one in five people on Earth lack access to safe and affordable drinking water and, by 2025, it is expected that more than half the world’s population could be short of freshwater. An array of nuclear techniques based on the use of isotopes can be used to assess sources of fresh water to help improving water management. This nuclear-based technology, called isotope hydrology, can determine the age, movement, and conditions of water to help improving water usage. Another important process for making freshwater from salty seawater is desalination. Nuclear power can be used as a source of energy for desalination, responding to the increasing demand for water, using a new generation of small and medium sized nuclear reactors, This also avoids the emission of greenhouse gas occurring when the traditional fossil fuel is burned.

Nuclear techniques are also used to provide critical information on the possibility of using salty water to irrigate salt tolerant crops. Thirty salt tolerant plants, from pistachio trees to barely, to Acacia, are already successfully grown using salty water. Nuclear techniques have helped in demonstrating that the source of water will not run out and by determining how to use it without building up more salt deposits.

5 Protection of the environment

Nuclear technologies also give a significant contribution to the protection of man and his environment and to the improvement of the quality of life. Marine pollution has a significant impact on the Earths environment. Oceans provide high quality proteins for a good portion of the planet’s population and play a major role in regulating climate. Nuclear techniques are used to monitor for potentially toxic marine contaminants, such as heavy metals and pesticides. Moreover as natural and man-made isotopic tracers are present in the oceans, they are used to understand ocean dynamics and hence the role they play on climate.

Nuclear technique have also been recently used to rapidly detect toxicity in marine food contaminated by toxins produced by harmful algal blooms. In the terrestrial environment nuclear technologies cover a wide range of applications and disciplines, addressing the prevention of pollutant releases, measuring and monitoring pollutants, assessing their dispersion and transport in ecological systems, and providing means for remediation and cleaning of contaminated sites.

Acidic pollutants like sulfur and nitrogen oxides are emitted in millions of tons during fossil fuel combustion, causing hazard to the environment and human beings through acid rain and smog formation. Electron beam technology has been proven to be efficient in removing those pollutants by treatment of the off-gases from coal-burning installations. The toxic compounds are eliminated and at the same time transformed into useful and harmless fertilizer and not merely transferred from one medium to another, as is the case for traditional scrubbers or absorbing media.

Electron beam technology is also effective for the destruction of toxic volatile organic compounds in off-gases, in particular at low concentrations. In this way another problem connected with fossil fuel combustion and waste incinerators, namely the emission of poly-aromatic hydrocarbons (PAH), including dioxins, can be eliminated. Nuclear technologies, involving electron beams, electromagnetic radiation or isotopic sources have been also applied for decontaminating and disinfecting aqueous effluents, sewage waters, industrial wastewaters and sludge by destroying harmful and toxic organic substances and micro-organisms. A combined technology, using an electron beam and ozone, has been developed for the removal of chlorinated hydrocarbons from water. Another application permits the radiation sanitation of biological sludge from biological wastewater treatment, allowing the sludge eventually to be used as fertilizer.

Portable X-ray fluorescence equipment with radioisotope sources, scanning electron microscopes, mass spectrometers, nuclear reactors (for neutron activation analysis) and particle accelerators and synchrotrons, have also put at our disposal an impressive arsenal of tools and techniques to search for harmful substances in the environment. A recent development worth mentioning, is the use of electron accelerators for the irradiation of mail to destroy toxic substances such as anthrax spores.

Abandoned landmines continue to haunt civilian populations, including a large proportion of women and children, in more than 60 countries of the developing world. They constitute immense constraints to socio-economic development, cause many mutilations and loss of lives, limit the use of land, displace people and perpetuate underdevelopment. A typical anti personnel landmine contains very little metal and is therefore difficult to detect by the metal detection techniques commonly used. Nuclear technology, based on interrogation by neutrons, is one of the few methods enabling non-intrusive elemental analysis of buried objects. Equipment currently available uses *in-situ* neutron activation combined with gamma ray spectrometry to measure concentration ratios of light elements for the detection of explosives in shallow-buried objects.

Nuclear techniques are also widely used for environmental monitoring and research as natural and artificial radionuclides in the geo-sphere are outstanding indicators for atmospheric, terrestrial and marine transport processes. The advent of radionuclide methods in geochronology has revolutionized our understanding of modern sedimentary processes in aquatic systems and are used as quantitative tools in marine and lake sediment geochronology and stratigraphic studies. Using nuclear techniques the assumptions and consequences of geological models have been validated, the influence of complicating factors, such as sediment flux variations and post-depositional diffusion of nuclides have been assessed, local or dispersed chemical, nuclear, or other waste material of concern in a variety of areas around the world, have been traced back to the contaminant sources and their environmental impact assessed and predicted. Nuclear techniques also provide excellent tracers for the behaviour and transport of non-radioactive pollutants, and for ecological and biological studies. Natural and anthropogenic radionuclides strongly absorbed at the soil surface, present at very low but still measurable concentrations, have been used to study soil erosion and soil deposition phenomena.

FIGURE CAPTIONS

Figure 1
Risk sources expressed as contributions to annual number of deaths in the USA ranked as perceived by selected non-expert groups and as determined by actuarial estimates (adapted form ref. [20])

Figure 2
Life Expectancy (LE) variation with time in the advanced nations of Europe (data from ref.[23])

Figure 3
Example of loss of life expectancy (LLE) calculation

Figure 4
Loss of life expectancy from different causes (from ref. [22])

Figure 5
Comparison between the loss of life expectancy (LLE) by living one year near a NPP, smoking one cigarette/day and being 20% overweight (data form ref. [22])

Figure 6
Examples of activities involving the same death risk of $1/10^6$ (data from ref. [24])

Figure 7
Total radiation effect vs. radiation dose showing the regions where reliable data exist (solid line) and few or no statistically significant data exist (dotted line)

Figure 8
Total radiation effect vs. radiation dose qualitatively showing the existence of a region of hormetic response at low doses.

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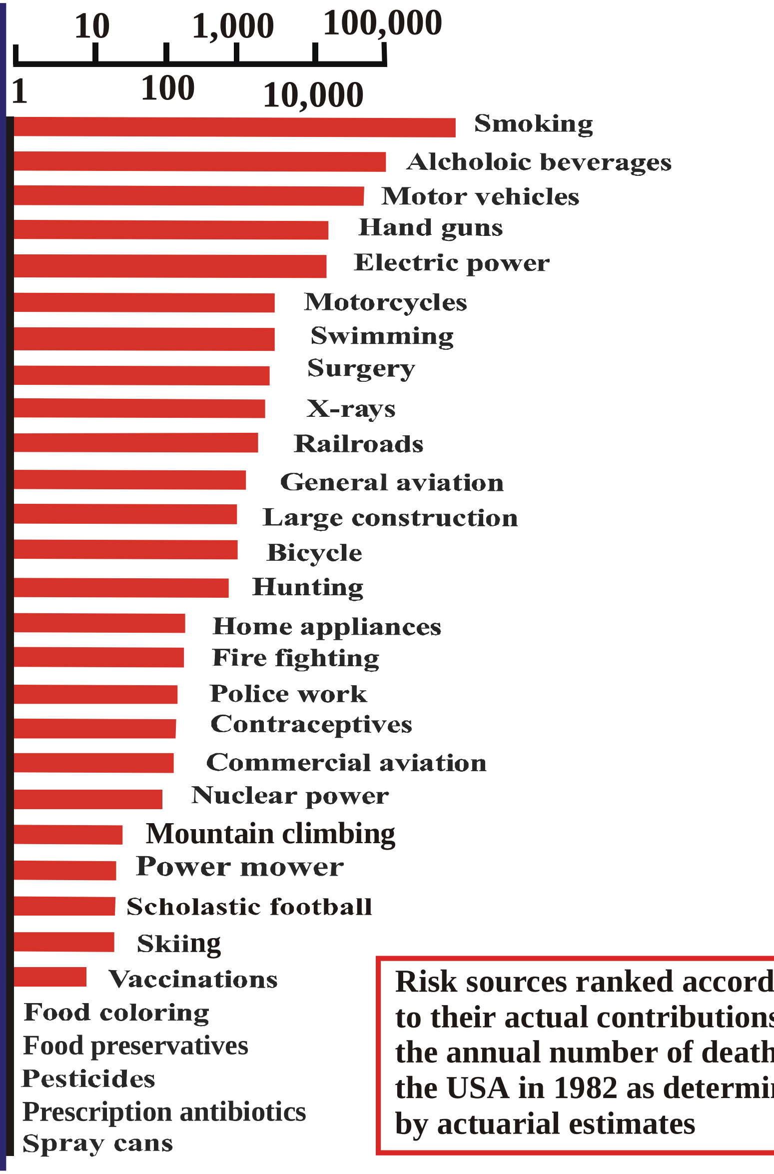
Figure 1

A COMPARISON BETWEEN PERCEIVED AND ACTUAL RISKS

PERCEPTION OF RISK BY SELECTED NON-EXPERT GROUPS

LEAGUE OF WOMEN VOTERS	COLLEGE STUDENTS	BUSINESS AND PROFESSIONAL CLUB MEMBERS
Nuclear power	Nuclear power	Hand guns
Motor vehicles	Hand guns	Motorcycles
Hand guns	Smoking	Motor vehicles
Smoking	Pesticides	Smoking
Motorcycles	Motor vehicles	Alcoholic beverages
Alcoholic beverages	Motorcycles	Fire fighting
General aviation	Alcoholic beverages	Police work
Police work	Police work	Nuclear power
Pesticides	Contraceptives	Surgery
Surgery	Fire fighting	Hunting
Fire fighting	Surgery	General aviation
Large construction	Food preservatives	Mountain climbing
Hunting	Spray cans	Large construction
Spray cans	Large construction	Biclycles
Mountain climbing	General aviation	Pesticides
Bicycle	Commercial aviation	Skiing
Commercial aviation	X-rays	Swimming
Electric power	Hunting	Commercial aviation
Swimming	Electric power	Electric power
Contraceptives	Food coloring	Railroads
Skiing	Prescription antibiotics	Scholastic football
X-rays	Mountain climbing	Contraceptives
Scholastic football	Railroads	Spray cans
Railroads	Skiing	X-rays
Food preservatives	Bicycle	Power mowers
Food coloring	Scholastic football	Prescription antibiotics
Power mowers	Home appliances	Home appliances
Prescription antibiotics	Power mowers	Food preservatives
Home appliances	Vaccinations	Vaccinations
Vaccinations	Swimming	Food coloring

ACTUAL RANKING OF RISKS (number of deaths)



Risk sources ranked according to their actual contributions to the annual number of deaths in the USA in 1982 as determined by actuarial estimates

Figure 2

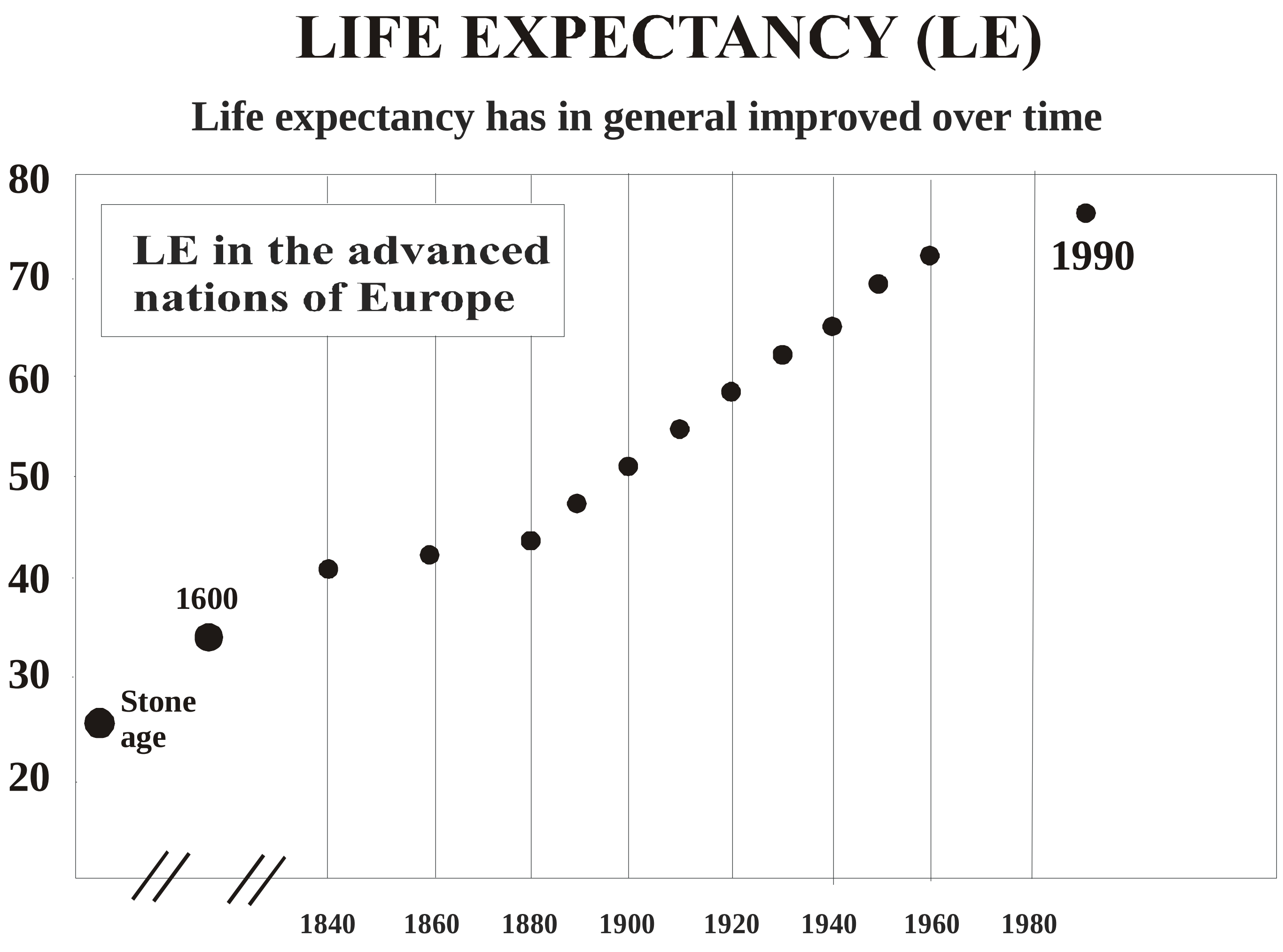

LIFE EXPECTANCY (LE)
Life expectancy has in general improved over time
LE in the advanced nations of Europe
80
70
60
50
40
30
20
1600
Stone age
1990
1840
1860
1880
1900
1920
1940
1960
1980

Figure 3

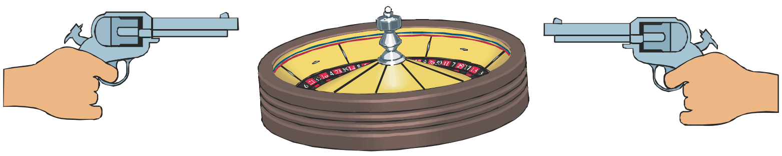
LOSS OF LIFE EXPECTANCY (LLE)

The LLE due to a risk can be understood as the average reduction of lifetime for those involved

EXAMPLE

600 people in a certain age group (40-50) have 30 years of (remaining) life expectancy

They decide to play Russian Roulette (one in six dies instantly)



100 will die losing 30 years of LE and 500 stay alive (do not lose any LE)

The average LLE in that age group will be (100 x 30)/600 = 5 years

Figure 4

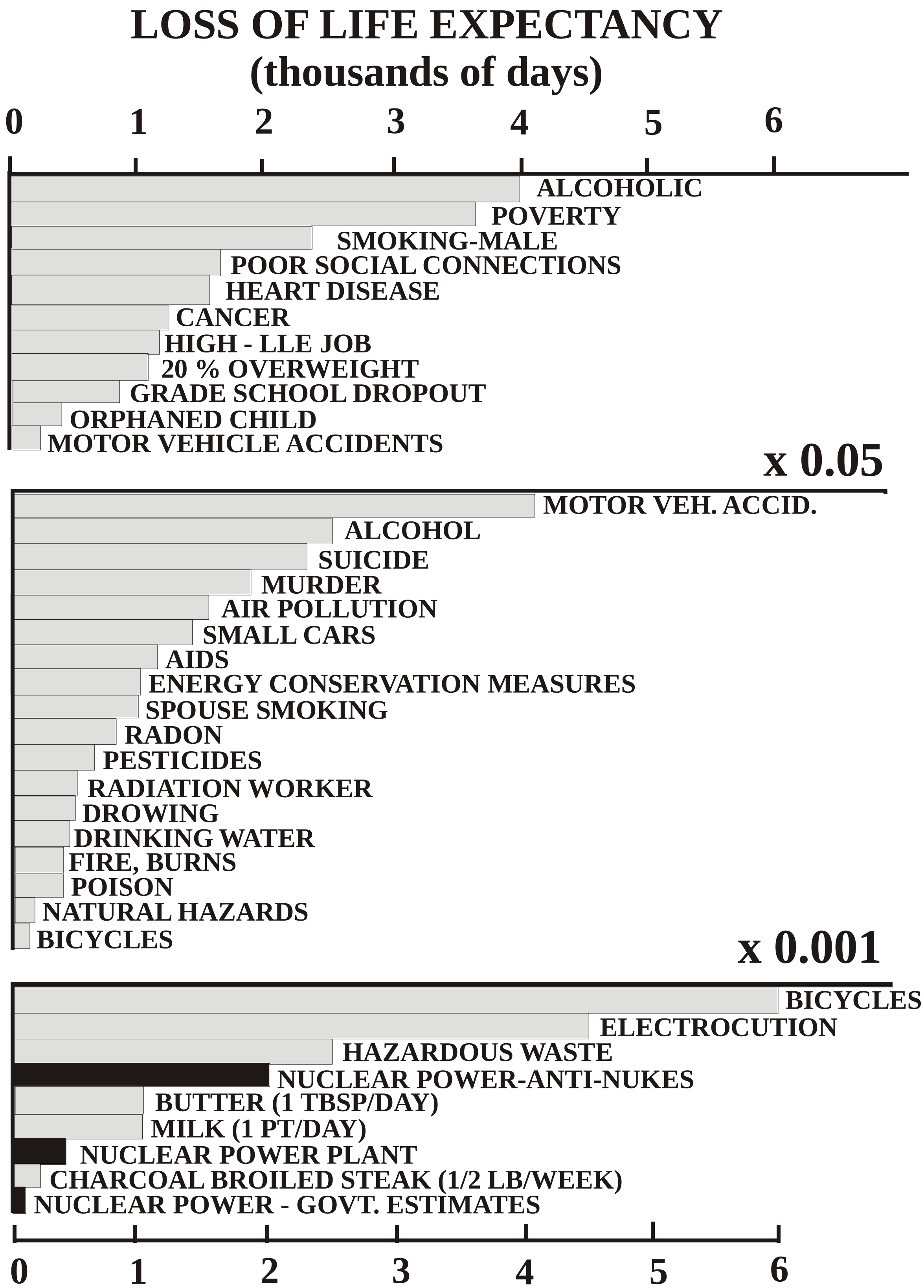
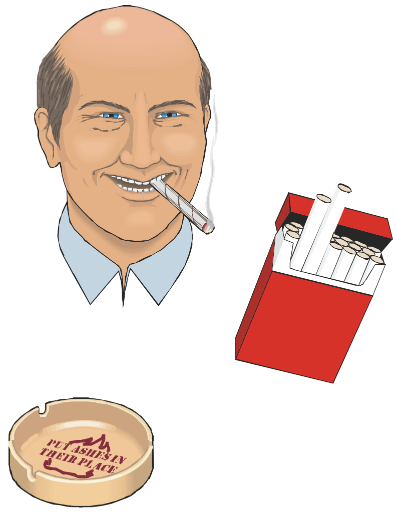

LOSS OF LIFE EXPECTANCY
(thousands of days)
0
1
2
3
4
5
6
ALCOHOLIC
POVERTY
SMOKING-MALE
POOR SOCIAL CONNECTIONS
HEART DISEASE
CANCER
HIGH - LLE JOB
20 % OVERWEIGHT
GRADE SCHOOL DROPOUT
ORPHANED CHILD
MOTOR VEHICLE ACCIDENTS
x 0.05
MOTOR VEH. ACCID.
ALCOHOL
SUICIDE
MURDER
AIR POLLUTION
SMALL CARS
AIDS
ENERGY CONSERVATION MEASURES
SPOUSE SMOKING
RADON
PESTICIDES
RADIATION WORKER
DROWING
DRINKING WATER
FIRE, BURNS
POISON
NATURAL HAZARDS
BICYCLES
x 0.001
BICYCLES
ELECTROCUTION
HAZARDOUS WASTE
NUCLEAR POWER-ANTI-NUKES
BUTTER (1 TBSP/DAY)
MILK (1 PT/DAY)
NUCLEAR POWER PLANT
CHARCOAL BROILED STEAK (1/2 LB/WEEK)
NUCLEAR POWER - GOVT. ESTIMATES
0
1
2
3
4
5
6

Figure 5

Some risk comparisons

From the catalogue of risks it is possible to compare the amount of exposures giving the same risk

Living one year near a NPP gives a LLE= 0.05 days.
Smoking one pack (20) of cigarettes/day gives a LLE= 2,250 days.
Smoking 1 cigarette/day gives a LLE= 112.5 days = 0.308 years
LLE of 0.05 days (NPP) corresponds then to 0.162 cigarettes/year or 1 extra cigarette every 6 years



Being 20% overweight for one year (14 kg over 70 kg) gives a LLE of 1200 days.
LLE of 0.05 days (NPP) corresponds to a weight increse of 0.05 x 14/1200= 0.6 g

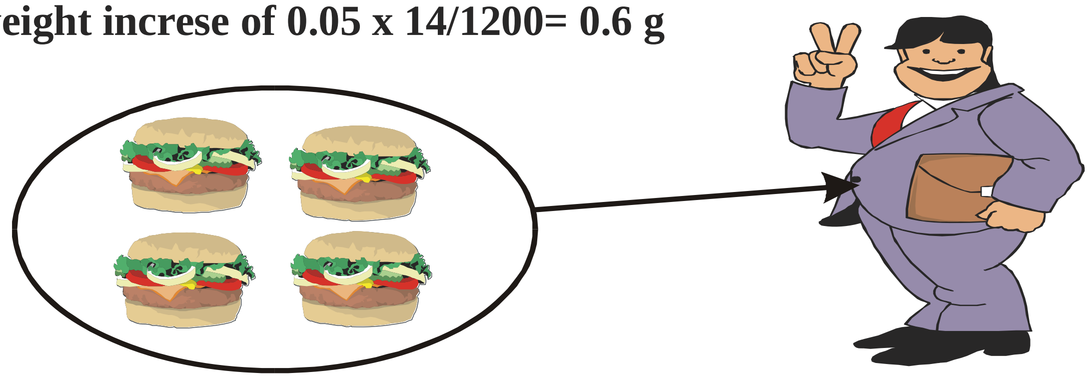
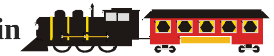
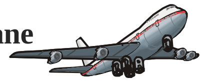


Figure 6

Examples of activities involving the same death risk of 1 microrisk R = $1/10^6$

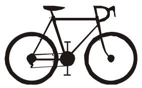
$R = C \times P$ (C = 1, i.e. death)

Travelling 2500 km by train
(accident)


Flying 10,000 km by plane
(cancer from cosmic radiation)


Travelling 80 km by bus
(accident)


Driving a car for 65 km
(accident)


Bicycling for 12 km
(accident)


Riding a motorcycle for 3 km
(accident)


Smoking a cigarette
(cancer and heart desease)


Living 2 weeks with a smoker
(cancer and heart desease)


Drinking half a liter of wine
(cirrhosis of the liver)


Normal consumption of tap water for 1 year
(cancer from chloroform)


Drinking 30 cans of diet soda
(cancer from saccharin)


Eating 40 tablespoons of peanut butter
(liver cancer from aflatoxin B)


Eating 100 charcoal broiled steaks
(cancer from benzopyrene)


Living in a brick house for 10 days
(cancer from radon)


Living 2 months in high mountains
(cancer from cosmic radiation)


Living 5 years next to a nuclear power plant
(cancer from ionising radiation)


Living 50 years within 5 miles of a nuclear power plant
(accident)

Breathing in a polluted city for 3 days
(air pollution)


Spending 1 hour in a coal mine
(black lung desease)


Spending 3 hours in a coal mine
(accident)

Figure 7

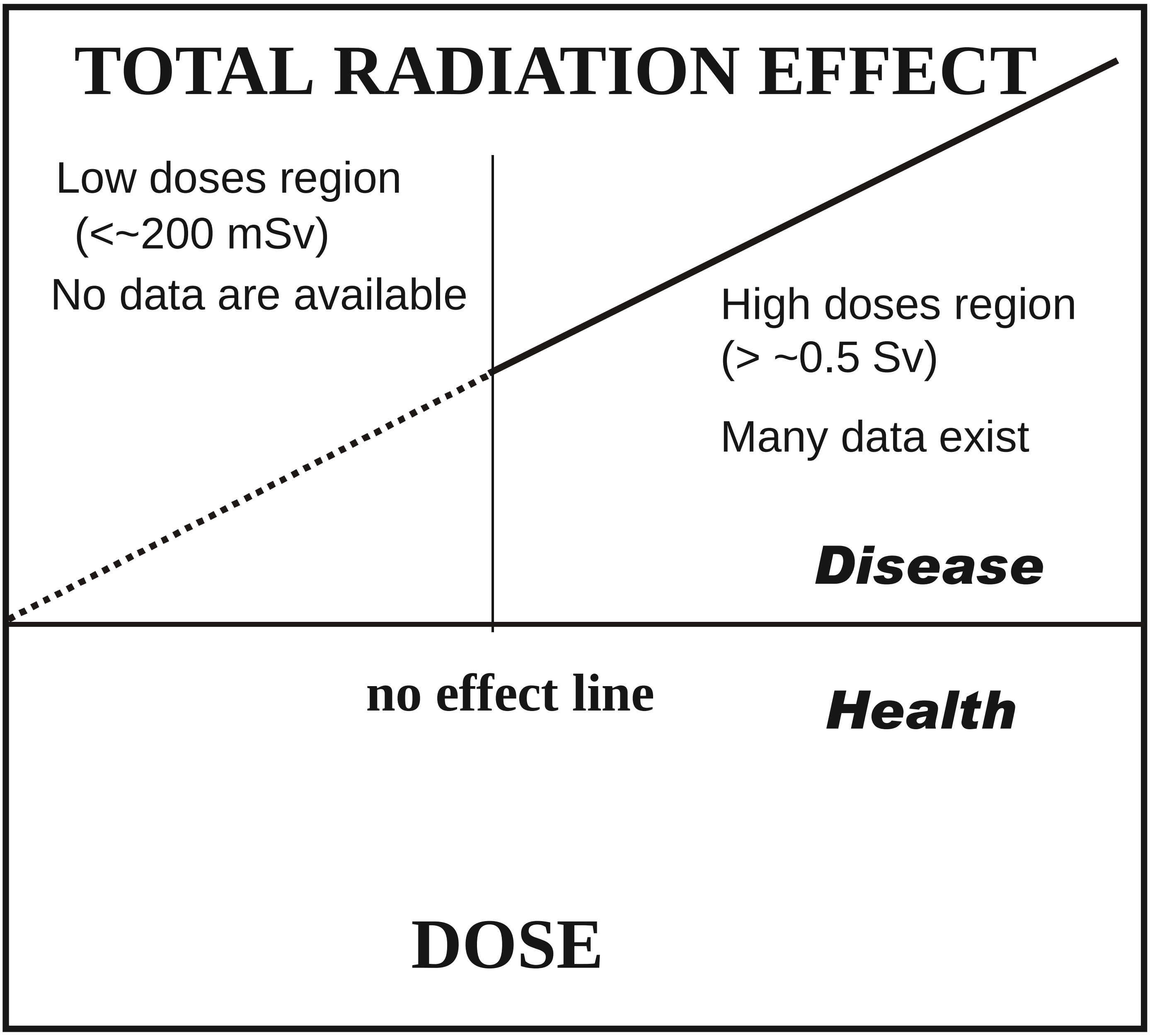
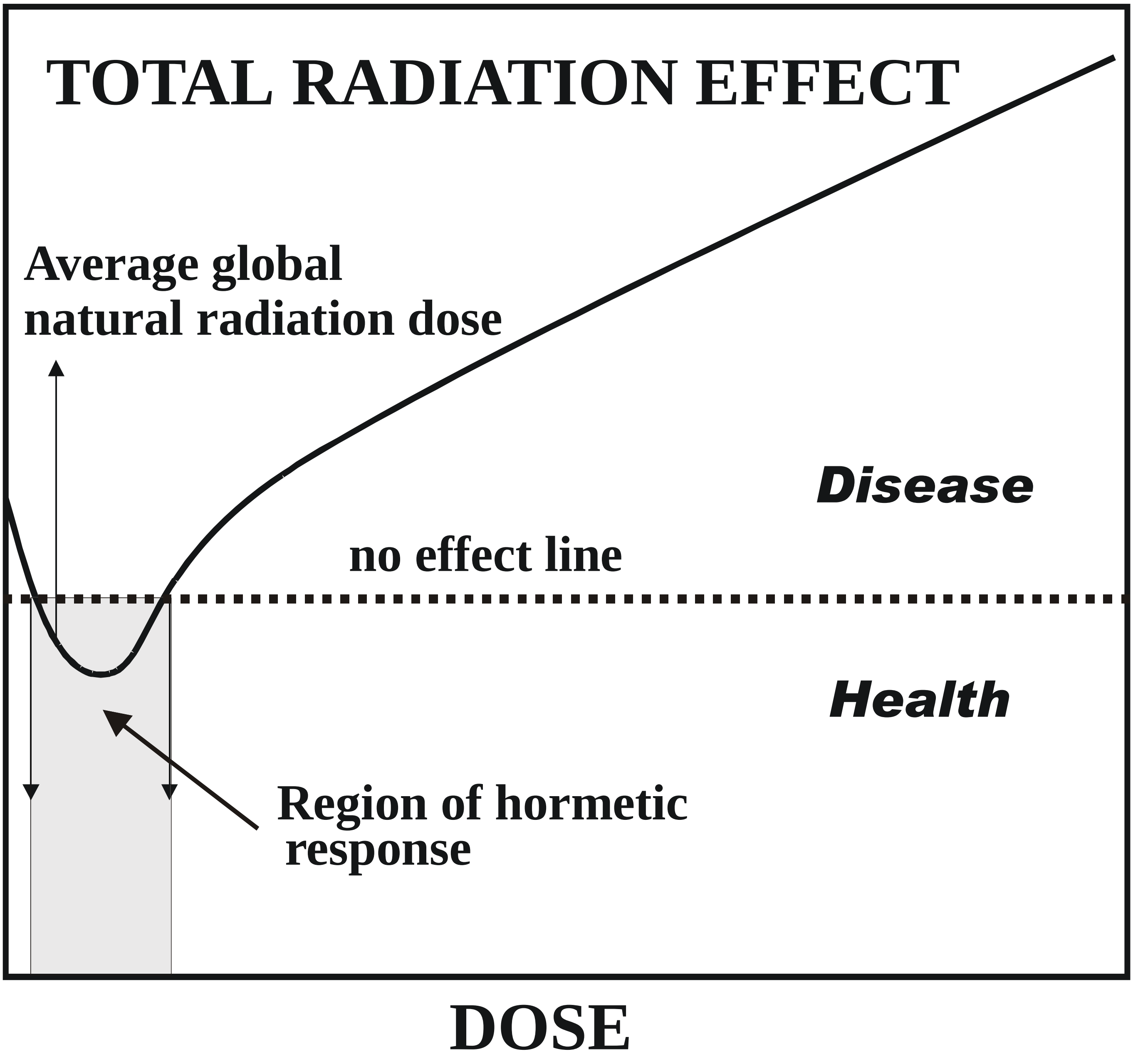

TOTAL RADIATION EFFECT
Low doses region
(<~200 mSv)
No data are available
High doses region
(> ~0.5 Sv)
Many data exist
Disease
no effect line
Health
DOSE

Figure 8


TOTAL RADIATION EFFECT
Average global
natural radiation dose
Disease
no effect line
Health
Region of hormetic
response
DOSE