Limitations of radiological models

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Note
In this document the references are coded by Q-numbers (e.g. Q6). Each reference has a unique number in this coding system, which is consistently used throughout all publications by the author. In the list at the back of the document the references are sorted by Q-number. The resulting sequence is not necessarily the same order in which the references appear in the text.

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1 Radiological models

Report *Health effects of radioactivity* discussed several publications on the health effects of radioactivty. Widely different viewpoints exist, not only regarding health hazards under normal operating conditions of nuclear installations, and limited nuclear accidents, but also on the greater risk and effects of large-scale exposure to radioactivity caused by nuclear disasters such as Chernobyl and Fukushima.
The reasons for the controversies turn out to be based on fundamentally different approaches to looking at this complex matter: mainly the use of physical models versus empirical evidence. In addition, the economic and financial interests of the nuclear industry play an important role. Reliance on physical models will be briefly discussed in report m05 *Downplaying and denial of health effects*.

Uncertainties in dose estimates

The estimation of radiation doses contracted by individuals as a consequence of nuclear activities and accidents is not widely understood by scientists, and not at all by members of the public [Fairlie 2009] Q413. The methodology is very complicated as it is based on at least four kinds of computer models in sequence:

- Models for the generation of fission and activation products in reactor cores. The emission data published by utilities are derived from these models.
- Environmental transport models for radionuclides, including weather models.
- Human metabolism models to estimate radionuclide uptake, retention and excretion.
- Dose models which estimate radiation doses from internally retained radionuclides.

Each model has inherent limitations (see next chapter) so the result of each model has an uncertainty range. The uncertainties of the models have to be treated together to gain an idea of the overall uncertainty in the final dose estimate. Further uncertainties are introduced by 'unconservative' radiation weighting factors, dose rate reduction factors, and tissue weighting factors in the official models [Fairlie 2009] Q413. The cumulative uncertainty in dose estimates could be very large as recognized by the report of the UK Government's CERRIE Committee [CERRIE 2004] Q414.
In view of these uncertainties one should not dismiss radiation exposure as a possible cause of the observed results of the studies [KiKK 2007] Q392 and [Geocap 2012] Q494 based on low official dose estimates. These studies are not discussed in the publications of the International Atomic Energy Agency (IAEA) and World Nuclear Association (WNA).

Uncertainties in risk estimates

Risk models are used to estimate the likely level of cancers. The risk models have their inherent imperfections and uncertainties as well as the dose estimate models. The current official risk models are mainly based on studies of the Japanese survivors of the nuclear bombs in 1945. How reliable are the official risk models? Uncertainties are introduced by a number of factors, such as:
- The Japanese bomb survivor study was started five years after the bomb blasts, so the deaths in the first five years were not counted.
- The risks estimated from a sudden pulse of gamma rays and high-energy neutrons are not applicable to environmental releases which result in chronic, slow, internal exposures to often low-range beta radiation (many kinds of radionuclides released by nuclear processes and accidents are beta-emitters).
- Application to adults only.
- Application of age and gender-averaged risks.

- Arbitrarily halving the risks to take account of cell studies suggesting lower risks from low doses and low dose rates.

For discussion of these uncertainties see [CERRIE 2004] Q414.

Troublesome detection of radionuclides

An impediment for sound health risk assessments is the fact that a number of dangerous radionuclides, e.g. tritium, carbon-14, iodine-129 and a number of alpha emitters, are hard to detect with commonly used radiation counters. As a result of the difficult detectability, severe radioactive contamination with these radionuclides may escape notice during prolonged periods. Not every spill or release contains 'marker' nuclides which are easily detectable, such as ^{137}Cs.

An examples of 'unnoticed' releases are the routine releases of nuclear power plants under nominal operating conditions. For that reason it would be advisable to check on regular occasions food and drinking water for the presence of those troublesome radionuclides, even if no direct threat seems apparent. Risk estimates based on models are not likely to be completely accurate.

2 Limitations of radiological models

Inherent limitations

Any model in physics, chemistry, economics or any other field, inevitably has two kinds of limitations: inherent limitations and the specific limitations resulting from the choice of input data: constants, variables and other data.
By definition a model is a simplified description of the reality, the practice, and is based on a number of axioms and assumptions. Models are widely used in science to describe specified phenomena in nature and to build a theory which enables scientists to predict the occurrence of such phenomena under conditions different from the investigated ones. As a result of the simplification of reality a model is only valid within specific system boundaries and has a limited application range. The wider the system boundaries of a model, the more complicated its structure. [Bouchaud 2008] Q425 put it as follows:

> 'If empirical observation is incompatible with a model, the model must be trashed or amended, even if it is conceptual beautiful or mathemathecally convenient.'

Two examples of scientific models used in chemistry may illustrate this statement. The simple model of atoms and molecules formulated by Dalton in the 19th century is able to describe some basic chemical phenomena. To explain why water has the formula H_2O and not H_3O and to predict chemical compounds yet unfound, one needs the greatly more complicated atom model of Bohr. However, not all chemical phenomena can be explained by the Bohr model, for that too has its limitations.

Input limitations

The results of an investigation by means of a model are determined by the input data, such as physical constants, variables and properties of the entities of the model.
How reliable are the axioms the model is based on and the input data? Are they experimentally verified and are they widely accepted by the scientific community? How large are the uncertainty ranges of the numerical input data and how do these uncertainties filter their way into the results? How sure can we be that the investigator's choices of the input data of his model were not biased, wittingly or unwittingly?

Radiological models

The radiological models being used by the nuclear industry to assess health risks by radiation were conceived during the 1940s, 1950s and Cold War, Personal safety was in that time not always the first priority. The atomic bombing exposures were predominantly high-dose-rate gamma radiation with a small contribution of neutrons. These studies started in 1950, five years after the bombing.

The Committee [UNSCEAR 2010] Q531 stated:

> "the single most informative set of data on whole-body radiation exposure comes from studies of the survivors of the atomic bombings in Japan in 1945. The atomic bombing exposures were predominantly high-dose-rate gamma radiation with a small contribution of neutrons."

For more information on the relationship between UNSCEAR, two other international nuclear organizations (IAEA, ICRP) and WHO see report m34 *Conflict of interests, flexibility of regulations*.

In his analysis of the World Health Organization report [WHO 2013a] Q553 on the Fukushima disaster [Rosen

2013] Q561 discusses eight objections to that report, one of them reads:

> "The authors explain this procedure, by basing their assumptions on the Lifetime Span Studies (LSS), performed on the survivors of the nuclear bombings of Hiroshima and Nagasaki – studies that were only started in 1950, five years after the events occurred. How studies on the survivors of the mostly external radioactive exposure of the nuclear bombs, without any scientific knowledge from the first five years, including no records of miscarriages, neonatal mortality or congenital defects, could be transferred to a scenario where children and fetuses were exposed to mostly internal radioactivity after a nuclear catastrophe is not adequately addressed by the report's authors."

Which assumptions form the basis of the currently used radiological models? Which phenomena are included in the models and which are not?

What was the original purpose of these 60 years old models, developed in a time the basic premises? These studies started about five years after the bombings, so the deaths during these first five years are not counted [CERRIE 2004] Q414. More on questionable aspects of the way of constructing the radiological model are discussed by [Hoffmann 2016] Q681.
Was the purpose to estimate the acute radiological risks for military personel in wartime, during the 1940s and 1950s, the Cold War, or to estimate the health risks for millions of people in the 21st century posed by chronic exposure to a number of radionuclides from failing civilian nuclear power stations?

During the 1950s and 1960s the first nuclear power plants came into operation, and since that time the world civil nuclear generating capacity grew from tens of megawatts in the 1950s to hundreds of gigawatts today, a factor 10 000, and correspondingly increased the quantities of radioactive materials circulating within the biosphere.

The time has come to base health risk estimates on published and verifiable empirical facts, not on computer models originating from the closed nuclear industrial complex and based on secret data from the 1940s and 1950s. The epidemiological studies [KiKK 2007] Q392 and [Geocap 2012] Q494 proved that the existing exposure and health risk models are unable to explain the empirical observations of these studies, so the models should be revised.
The dominant role of radiological models in the nuclear world with regard to health effects of contamination with radioactivity takes shape in the way of reporting the consequences of the Chernobyl disaster by the World Health Organization WHO and the International Atomic Energy Agency IAEA in, for example, [WHO 2005] Q498 and [Chernobyl Forum 2008] Q497. This matter is addressed in report m05 *Downplaying and denial of health effects*.

Economic flexibility of radiological models

From a scientific/mathematic viewpoint the radiological models should be unvaryingly verifiably accurate under specified physical conditions.
The radiological models turn out to be conspicuously flexible under economic pressure, as is proved by the relaxation of authorized radioactivity standards for drinking water in the USA, necessary to keep the aging nuclear power plants economically operable, and the relaxation of exposure standards in Japan after the Fukushima disaster.

Limited scope of the radiological models

The models are based on the effects of gamma- and X-ray radiation from sources *outside* the human body. Probably for that reason the nuclear industry is speaking invariably about effects due to exposure to *radiation* and not about effects due to contamination by *radioactive materials*.

During the past six decades the models were not or hardly adjusted. Health effects with long incubation periods, years to decades, were hardly or not known at the time of the conception of the radiological models. Newly discovered effects, such as non-targeted and delayed effects, are not incorporated, nor empirical evidence that could not be explained by the old models.
Biomedical properties of radionuclides are not included in the radiological models, let alone the synergistic behaviour of a number of radionuclides of different chemical elements simultaneously. In the case of large nuclear accidents dozens of different types of radionuclides are released into the human environment and consequently residents become contaminated not just by one type of radionuclide but with a number of different radionuclides. Effects of chronic contamination by radionuclides via inhalation (gases, dust) and ingestion via food and drinking water are not incorporated into the radiological models either.

Epidemiological studies in Germany and France proved that authorised routine releases of radioactive materials cause an increased incidence of childhood cancer in the vicinity of normally operating nuclear power plants.
What quantities are involved in the routine discharges of nuclear power plants into the environment?
Which radionuclides are involved? Data on these issues are scarce in the open literature.
According to the radiological models applied by the nuclear industry the routine discharges are by far too low to cause observable health effects.
Apparently not included in the radiological models are:

- biochemical reactions of radioactive atoms inside the body
- effects of internal contamination by a multiple of different radionuclides simultaneously
- synergetic effects of radiotoxic and chemotoxic properties of radionuclides inside the body
- chronic exposure to various radionuclides in contaminated areas via air, drinking water en food
- accumulation of radionuclides in specific organs
- phenomena found in recent decades, particularly non-targeted and delayed radiation effects, including gnomic instability, bystander effects, clastogenic effects and heritable effects.

The methodology and scope of these studies do not comply with present scientific views and insights, based on the vast amounts of emprirical data available. The epidemiological studies [KiKK 2007] and [Geocap 2012] proved that the existing exposure and health risk models are unable to explain the empirical observations of these studies, so the models should be revised.

Exposure to radioactivity implies more than radiation alone

The radiological models used by the nuclear industry are based on the effects of gamma- and X-ray radiation from sources *outside* the human body. Probably for that reason the nuclear industry is speaking invariably about effects due to exposure to *radiation* and not about effects due to contamination by *radioactive materials*.
Biomedical behaviour is not included in the radiological models, let alone the synergistic behaviour of a number of radionuclides of different chemical elements simultaneously. In the case of large nuclear accidents dozens of different types of radionuclides are released into the human environment and consequently residents become contaminated not just by one type of radionuclide but with a number of different radionuclides. Uncertainties are exacerbated by the fact that many dangerous radionuclides are not detectable by means of hand-held radiation counters. Only a few are easily detectable, for example the strong gamma emitters iodine-131 and cesium-137. As illustrated by dispersion maps published after the Chernobyl disaster and Fukushima disaster, the dispersion of the various radionuclides during a calamity may have different patterns. The extent of contamination by cesium-137 is far from a reliable measure for

the extent of contamination by other radionuclides, due to their different physical and chemical properties. Consequently the extent of radioactive contamination is insufficiently known.

What are the effects if the exposure is chronic as a result of continuous intake (food, water), inhalation of gases, dust and fine particulate matter (PM) due to the burning of material contaminated by radionuclides for heat or cooking, or due to wildfires in contaminated areas over the course of many years? Or proximity to radioactive waste incinerators, which release, by definition, very fine particulate matter?
How reliable are estimations based on models?

- Measurement of the gamma radiation from one or two radionuclides tells only a part of the potential exposure to radiation from a number of radionuclides.
- Exposure to radiation tells only a part of the potential contamination by radioactive materials, internal as well as external, as pointed out above.
- Health consequences of radioactive contamination by one kind of radionuclide over a long term period are poorly understood, let alone contamination by a number of different radionuclides.
- Health consequences observed during the first few years after radioactive contamination tell only a minute part of the health consequences in the long run.

3 Radiation dose measurement

The chance of developing a cancer as a result of exposure to nuclear radition is assumed to increase linearly with the contracted dose of radiation, according to the Linear No Threshold (LNT) model. The dose is defined as the amount of energy from the nuclear radiation absorbed per kilogram of body mass. Because different types of radiation inflict different degrees of biological damage the biologically effective equivalent dose has been defined as absorbed dose multiplied by the *radiation weighting factor* (also called the *quality factor*). This factor gives the Relative Biological Effectiveness (RBE) of the various kinds of ionizing radiation. The unit of the biological effective radiation dose is the *sievert*, symbol Sv.

The World Nuclear Association [WNA-rad&life 2012] stated:

> *"Grays and Sieverts*
>
> The human senses cannot detect radiation or discern whether a material is radioactive. However, a variety of instruments can detect and measure radiation reliably and accurately.
>
> The amount of ionising radiation, or 'dose', received by a person is measured in terms of the energy absorbed in the body tissue, and is expressed in gray. One gray (Gy) is one joule deposited per kilogram of mass.
>
> Equal exposure to different types of radiation expressed as gray do not however necessarily produce equal biological effects. One gray of alpha radiation, for example, will have a greater effect than one gray of beta radiation. When we talk about radiation effects, we therefore express the radiation as effective dose, in a unit called the sievert (Sv). Regardless of the type of radiation, one sievert (Sv) of radiation produces the same biological effect.
>
> Smaller quantities are expressed in 'millisievert' (one thousandth) or 'microsievert' (one millionth) of a sievert. We will use the most common unit, millisievert (mSv), here."

Because of the simple relationship between measured gamma-activity and dose or dose rate, the sievert continues to be the model generally used by regulatory agencies as the base for human radiation exposure.

The sievert is not a measurable unit in itself but is composed of the radioactivity of a given amount of matter measured in becquerels per second (Bq/s) multiplied by the weighting factor, which depends on the kind of radiation, as pointed out above. In principle the activity (in Bq/kg) is a measurable quantity, although a number of important radionuclides are not detectable by common radiation counters. The value of the weighting factor is based on models and arbitrary assumptions and therefore is not unambiguous. Consequently the sievert is an ambiguous unit, and its use may lead to wrong conclusions with regard to health hazards.

4 Unanswered questions

- To what extent are doses cumulative, for example does a once-only dose of 1 Sv during 1 hour equal 1000 hours of exposure to a dose rate of 1 mSv/h?
- What is known about chronic exposure to ‘low’ doses?
- How is a ‘low’ dose defined? Is it an invariable quantity?
- Are the different biochemical properties of the dozens of types of radionuclides released into the environment by the nuclear power system accounted for in the models?
- How do the models handle exposure to a number of different radionuclides simultaneously, for example after a nuclear disaster like Chernobyl and Fukushima?
- Which radiation-induced diseases are included in the models used to define the weighting factors and the safety standards? Are only solid cancers accounted for, or also other, non-cancerous diseases?
- What is known about bioaccumulation of radionuclides in the food chain? How is this phenomenon incorporated into th models?
- How can aerial surveys of easily detectable radionuclides as Cs-137 over contaminated areas, presented in average dose rates (mSv/h), be translated into health hazards for individuals living in that area?
- The models seem to be based only on the physical interaction of radiation with matter. Are biochemical mechanisms, involving biologically active and hardly detectable radionuclides like tritium and carbon-14, included in the models?
- On what assumptions are the models based? Are these assumptions continually verifed and adjusted on the basis of empirical evidence coming available year by year?
- What was the original purpose of the models? To estimate the acute radiological risks for military personel in (nuclear) wartime, or to estimate the health risks for the public posed by chronic exposure to radionuclides produced and released by civilian nuclear power?
- For what reason does the nuclear industry exclude extensive epidemiological studies of the health effects of exposure to radiation and to radionuclides inside the body?
- Why not start from empirical evidence?

5 Radiation hormesis

Radiation hormesis, also called radiation homeostasis, is the hypothesis that low doses of radiation – within the region and just above natural background levels – would be beneficial, stimulating the activation of repair mechanisms that protect against disease, that are not activated in absence of radiation. The reserve repair mechanisms are hypothesized to be sufficiently effective when stimulated as to not only cancel the detrimental effects of ionizing radiation but also inhibit disease not related to radiation exposure [wikipedia 2012a] Q509.

The radiation hormesis hypothesis seems to be based on limited model studies, not on empirical evidence, and on analogy with chemical hormesis. Chemical hormesis is the phenomenon that some chemical species are assumed to be not toxic in very low doses, or even beneficial (e.g. selenium), but toxic in higher doses. In fact this view seems to be based on the ideas of Paracelsus (1493-1541), summarized in his statement: *dosis facit venenum* ('the dose makes the venom'). The analogy with the supposed chemical hormesis is highly questionable, because of the very different biological mechanisms involved in the effects of chemical species and of radioactivity in the human body.
More important is the evidence that a number of substances exhibit the reverse effect: at very low doses they have significant and often unpredicted detrimental effects, much higher than expectation based on a linear dose-effect relationship [Fagin 2012] Q516.

The studies of radiation hormesis seem to focus on the incidence of solid cancers, other radiation-induced diseases are not included. Apparently only external exposure to radiation is included in the models. Biomedical properties of radionuclides inside the body and contamination with more than one radionuclide, as is usual in case of discharges and accidents, are ignored. Epidemiological evidence of the hormetic effect of low radiation doses is absent [Wikipedia 2012a] Q509. On the contrary, the studies [KiKK 2007] Q392 and [Geocap 2012] Q494 proved that very low doses of radioactivity have significant detrimental health effects and that these effects cannot be explained by the usual radiological models.

Comparison of 'low' doses with background radiation, as is done in numerous publications, involves a caveat. How is the 'background radiation' defined? Only gamma radiation from easily detectable radionuclides? What about the doses from background radiation in areas where radionuclides are constantly being released into the environment, for instance in the vicinity of nuclear power plants, or in areas being contaminated by large releases of radionuclides elsewhere in the world after a large-scale accident?

Consensus reports by the United States National Research Council and the National Council on Radiation Protection and Measurements and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) argue that there is no evidence for hormesis in humans and in the case of the National Research Council, hormesis is outright rejected as a possibility [Wikipedia 2012a].

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