Nuclear legacy

summary

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Radioactive materials

During the disasters of Chernobyl and Fukushima jointly an amount of radioactivity was dispersed into the biosphere equivalent to the annual production of one nuclear power plant, corresponding with 0.01% of the global human-made radioactive inventory. The nuclear legacy comprises the task to prevent the dispersion of the remaining 99.9% of the human-made radioactive legacy into the the human environment.

At present the global human-made radioactivity is contained in numerous materials:
- about 400 000 Mg of spent nuclear fuel
- hundreds of thousands of Mg of liquid and solid high-level wastes, storaged in reprocessing plants
- operational wastes
- hundreds of millions of Mg of construction materials released by decommissioning and dismantling of:
  more than 600 nuclear power plants,
  more than 30 reprocessing plants
  countless temporary storage facilities.
  All these installations are to be decommissioned and dismantled.
- many millions of Mg of soil contaninated with long-lived dangerous radionuclides, caused by spills, leakages and accidents of radioactive materials.

In addition unknown volumes of materials containing radionuclides are discharged into the enviroment. Epidemiological studies in Germany and France proved that the authorized discharges of radioactive materials by nominally functioning nuclear power plants cause an increased incidence of child cancer in the vicinity of the power plants. According to the commonly applied radiological models these discharges would be harmless. The incidence of child cancer cannot be explained by the models.

Health effects of radioactivity

The effects of exposure to nuclear radiation and to radionuclides fall into two main classes: deterministic and stochastic (probabilistic) effects. Deterministic effects, also called Acute Radiation Syndrome (ARS), become evident within a time period of minutes to weeks, depending on the contracted dose. A clear relationship exists between the effects and the received dose. Deterministic effects may occur in case of exposure to nuclear explosions and to unshielded spent nuclear fuel or other highly radioactive materials, for example in case of large nuclear accidents.
Stochastic effects occur at random and have often long incubation periods: months, years, decades. If a large number of individuals receive the same dose, one can predict the number of individuals who will develop a health effect, but which effect and which individual is not predictable. Stochastic effects involve a number of diseases, lethal and non-lethal. After the disaster of Chernobyl much evidence became available on the health effects of exposure to radiation and contamination by radionuclides, such as:
- chronic diseases (e.g. leukemia),
- many forms of cancers,
- non-cancer diseases (e.g. diabetes),
- premature senescence,
- heriditary disorders,
- congenital malformations,
- premature births,
- low birth-weight and infant mortality.

According to the International Atomic Energy Agency (IAEA) and the nuclear industry non-cancerous diseases cannot be induced by exposure to radioactivity, they must have other causes. Only ARS is recognised as an effect induced by radioactivity. The IAEA states that the death toll of Chernobyl was 51, despite reports from a number of independent institutions with estimates varying from 0.1 to 1 million deaths caused by radioactivity. Fukushima would have caused no deaths. Due to the, often long, incubation periods of diseases induced by doses lower than those causing ARS, the number of deaths as a direct consequence of the Chernobyl disaster rises during the decades after the disaster. Notably the IAEA denies that the many non-lethal diseases observed in the area contaminated by human-made radioactive materials could be induced by radioactivity.

In the reports published by the IAEA concerning the Chernobyl disaster and Fukushime disaster the health effects of these disasters are downplayed and denied, using scientifically flawed methods, such as:

- missing proofs
- models prevailing over empirical evidence
- no falsification of alternative explanations
- ignoring studies with diverging results
- absence of epidemiological studies
- no scientific discourse, ignorance of studies with diverging results
- limited scope of the radiological models, new evidence and new findings are not incorporated.

It should be noted that a conflict of interests plays an important role with regard to health effects by exposure to human-made radioactivity. The IAEA has two mandates: one as watchdog to prevent malicious use of nuclear technology – a role primarily restricted to guarding against illegal nuclear weapons production and proliferation risk –, the other as promotor of nuclear power. Moreover, official publications of the IAEA have to be approved by all member states of the IAEA.
For these reasons the IAEA cannot be regarded as an independent scientific institute. No agency can be a true watchdog for an industry it is tasked with promoting.
Political and economic interests may play a role in the decision processes concerning health issues.

Although the WHO is an independent UN organization, its reports on nuclear matters are subject to IAEA's approval. According to an agreement from 1959 between the International Atomic Energy Agency and the World Health Organization the WHO cannot operate independently of the IAEA on nuclear matters. Concerning health effects of radioactivity the IAEA, ICRP (International Commission on Radiological Protection), UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) and WHO speak with one voice.

Hazards

The nuclear legacy of more than 12 million atomic bomb equivalents of artificial radioactivity is distributed among the above mentioned materials. The largest portion of artificial radioactivity is contained in the spent fuel elements, the remainder in the other materials, with volumes thousands times larger than the spent fuel elements. However, health hazards posed by radioactivity are not proportional to the volume of radioactive materials.
The volume of the spent fuel elements is relatively small compeared to the other waste categories. As long as the spent fuel elements remain intact, and as long as the elements are storaged in secured storage facilities (cooling pools) the chance of exposure to the radioactive contents is small. However, these storage facilities are vulnerable to accidents, terrorism and natural disasters. As a consequence of the accident at Fukushima in 2011 the cooling pool of one of the reactors exploded, dispersing a part of the radioactive content of the fuel elements into the air and sea.

In reprocessing plants highly radioactive wastes, left over from reprocessing of spent nuclear fuel, are stored in large tanks. These tanks too are vulnerable to accidents, terrorism and natural disasters. In 1957 a tank containing highly radioactive liquid waste exploded on the nuclear complex at Mayak (former Sovietunion) contaminating vast areas of inhabited land.

The concentration of radionuclides in the other materials is far lower than in spent fuel and reprocessing wastes. However, the chance to become contaminated by those materials is far greater for several reasons:
- the volumes are thousands of times larger
- these materials are stored at an untold number of places, often in the open air
- the dangerous properties of the materials are unknown or downplayed by the responsible authorities.

The risks to be exposed to radiation and/or radioactive material by ingestion via air, drinking water and food are exacerbated by a number of uncertainties, such as:
- distribution of different kinds of radionuclides among different materials
- properties of present radionuclides
- potential pathways of dispersion and contamination, may be change with years
- flexible standards and regulations, financial and political pressure
- practically it is not possible to check every container
- several hazardous radionuclides are hard to detect with common radiation counters
- ageing of materials and structures
- unpredictable human behaviour
- terrorism
- natural disasters

For reason of the above mentioned factors and uncertainties it may be advisable to classify precautionarily all materials containing human-made radionuclides as waste to be removed from the human environment.

Isolation from the biosphere

One thing is certain: a large part of the nuclear legacy will disperse into the biosphere, if not massive amounts of energy, materials and human effort would be invested to prevent it. The Second Law of thermodynamics is relentless. Dispersion of large parts of the nuclear legacy would dwarf the disasters at Chernobyl and Fukushima.

In order to keep areas of continental scales habitable all radioactive materials must be isolated from the human environment for geologic time periods, to prevent dispersion of dangerous radionuclides into the human environment. The best solution to this challenge seems to be final disposal of all radioactive materials in repositories in geologically stable formations (e.g. granite).

Spent fuel

A large geologic repository, at a depth of 500 meters or more, with a capacity of 40000 Mg of spent fuel would comprise 100 kilometers (km) of galleries, excluding the access tunnels. The design by Sweden and Finland, dating from the 1980s, seems to be the best option and is actually under construction. To dispose of the existing backlog of more than 60 years of civil nuclear power, 10 of such large repositories would be needed. To dispose of the spent nuclear fuel from the currently operating nuclear power stations every 3-4 years a new repository with 100 km of galeries would be needed.
The required volume of the repository per Mg of spent nuclear fuel is 830 m3, so 2290 Mg rock (granite) per Mg spent fuel has to be mined for construction of a spent fuel repository. For construction of 10 deep geologic repositories 920 million Mg of rock has to be excavated. In addition 380 million Mg of bentonite

and a similar amount of sand are needed to backfill the galleries and acces tunnels.

Other radioactive wastes

Liquid and solid reprocessing wastes
No solutions for final safe disposal of this kind of radioactive wastes have been published in the open literature, as far as known.

Operational wastes and radioactive materials from decommissioning and dismantling
During its operational lifetime, each nuclear power plant generates 280 000 m3 of packaged radioactive wastes, operational waste from the upstream and downstream processes, including decommissioning and dismantling waste. These wastes are to disposed of in a geologic repository of a design different from a spent fuel repository. Sweden and Finland are constructing repositories for this class of radioactive waste. The required volume of the repository per m3 packaged waste is 6.3 m3, corresponding with about 18 Mg rock .
To dispose of this class of waste from 600 nuclear power plants a number of repositories are required with a total volume of 1.1 billion m3, corresponding with 2.9 billion Mg rock to be mined. For baclfilling the rooms and tunnels about 450 million m3 bentonite (more than 1 billion Mg) are needed, plus a similar amount of sand.

Contaminated soil and contaminated groundwater
No solutions for final safe disposal of this kind of radioactive wastes have been published in the open literature, as far as known.

Who pays the bill?

The activities needed to defuse the nuclear legacy by safe isolation from the biosphere would occur during the coming period of 100-150 years. These activities have no return on investments, because they are aimed at the definitive removal of millions of Mg from the human environment. Likely not one company or utility - if it still exists by the year 2100 and beyond - could afford the huge costs of the downstream processes. These costs might be larger than the costs of the upstream processes. In all countries of the world, as far as known, the central authorities are responsible for managing the nuclear legacy. Consequently the taxpayer has to pay the bill.
Even in times of a booming economy performing the task would be a demanding one. How are the prospects in a declining economy?

Reports related to the nuclear legacy

The complexity of the issue 'nuclear legacy' takes shape in the numerous aspects to be addressed in the assessment of the scope and proportions of the nuclear legacy. The following reports are related to the subject, each focused on one aspect of the nuclear legacy.

m02 *Chernobyl disaster*
m04 *Decommissioning and dismantling*
m05 *Downplaying and denial of health effects*
m07 *Energy debt, latent CO2 emissions, latent entropy*
m08 *Fukushima disaster*
m11 *Health effects of radioactivity*

m12 *Human-made radioactivity*
m13 *Nuclear disaster at Mayak in 1957*
m14 *Limitations of radiological models*
m17 *Pathways of radioactive contamination*
m21 *Nuclear safety*
m22 *Severe nuclear accidents*
m23 *Nuclear terrorism*
m25 *Mining at Kvanefjeld* (a case study)
m31 *Industrial views on radioactive waste*
m32 *Geologic repositories and waste conditioning*
m34 *Conflict of interests, flexibility of regulations*
m37 *Problems for the future - message to the future*
m38 *Nuclear power and the Second Law*
m40 *Radioactive waste management - future CO2 emissions*
m41 *Uranium mine rehabilitation*
m42 *Tritium, carbon-14 and krypton-85*

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