Severe nuclear accidents

Jan Willem Storm van Leeuwen
independent consultant

member of the Nuclear Consulting Group

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storm@ceedata.nl

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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Summary

Severe accidents, which disperse large quantities of radioactive materials over vast areas within a relatively short period, are possible (and actually happened) at facilities containing spent nuclear fuel, particularly reactors, spent fuel cooling pools and reprocessing plants. Because spent fuel generates heat during decades after removal from the reactor, it has to be cooled actively. If the cooling fails during a critical period, the fuel elements will heat up, or even melt, and start reacting with water and oxygen, which results in powerful explosions. The explosions, accompanied by fires, eject large parts of the reactor core into air. The gaseous and volatile contents of the spent fuel

The risk of fuel meltdown is highest in an operating nuclear reactor, because the fuel has the highest residual heat generating capacity at the moment of fission shutdown. Fuel meltdown in a spent fuel cooling pool will take more time (loss of cooling) than in a reactor, but the radioactivity inventory of the pool may be much larger than that of a reactor core, so much more radioactive materials may be dispersed in case of explosions and fires.

Loss of cooling and radiolysis of water may initiate explosions and large-scale dispersion of radioactive materials from storage tanks of highly radioactive liquid wastes.

Definition

An operating nuclear reactor generates immense quantities of radioactivity: spent fuel contains roughly a billion times the amount of radioactivity present in fresh nuclear fuel. One reactor of 1 GWe generates each year some 1000 nuclear bomb equivalents of human-made radioactivity.

Here a large-scale accident is defined as an event with which an appreciable part of a reactor core or an equivalent spent fuel mass, corresponding with a large number of nuclear bomb equivalents of radioactivity, is dispersed into the biosphere. Obviously no sharp definition of a large-scale nuclear accident is possible. What does mean ‘large’: 1%, 10%, more than 50% of the radioactive inventory of a reactor? Apart from the total amount released, also the rate at which the dispersion occurs is an important factor and the extent to which people are exposed to radioactivity.

The severity of a nuclear accident is determined by the number of people who are contaminated with radioactivity and the extent of the contamination, not only at the moment of the accident and shortly thereafter, but also in the decades following the accident. In many cases a nuclear accident will cause a prolonged or even chronic exposure of the inhabitants of the affected area to a mix of radioactive materials.

The severity of the consequences, as preceived by different groups in society, depends on a number of variables and viewpoints, such as:

- economic consequences,
- societal consequences, or
- health consequences for individuals.

Which timeframe is taken into account, the first month, the first year or the next three decades? Does one count only the casualties caused by ARS and non-nuclear-related accidents, or does one take also the radiation-induced deaths and non-cancer diseases ocurring during the decades following the accident into account?

Stochastic health effects caused by radioactivity - always detrimental - have long latency periods, so it is not possible to assess the severity of the health effects due to a nuclear accident within a short period after occurrence of the accident. For that reason the severity has to be estimated on ground of measurements of the amounts of escaped radioactive materials, of their dispersion pattern and of the number of affected people. Unfortunately there is empirical evidence to base on such an assessment, after the disasters at Chernobyl and Fukushima.

Due to the long incubation periods the relationship between radioactive contamination and deleterious health effects can only be proved by means of epidemiological investigations, see report m11 *Health effects of radioactivity*. This observation gives ample room to downplay the health effects by the IAEA and the nuclear world; this issue will be discussed in report m05 *Downplaying and denial of health effects*.

Potential sources of large-scale accidents

In principle each site holding a substantial amount of spent nuclear fuel, or equivalent amounts of radionuclides is a potential source of large-scale dispersion of radioactive materials, such as:

- nuclear reactors
- spent fuel cooling pools
- reprocessing plants
- spent fuel storage in dry casks
- geological repository
- dismantling site

Contamination of people by radioactive materials is addressed in report m17 *Pathways of radioactive contamination*.

1 Nuclear accidents rating according to INES

International Nuclear and Radiological Event Scale

The International Nuclear and Radiological Event Scale (INES) was developed in 1990 by international experts convened by the IAEA and the OECD Nuclear Energy Agency (OECD/NEA) with the aim of communicating the safety significance of events at nuclear installations. Since then, INES has been expanded to meet the growing need for communication on the significance of any event giving rise to radiation risks [IAEA/NEA 2013] Q517.

Figure 1
International Nuclear and Radiological Event Scale (INES). Source: [IAEA/NEA 2013] Q517

Events are classified on the scale at seven levels: Levels 4–7 are termed “accidents” and Levels 1–3 “incidents”. Events without safety significance in the view of the IAEA and nuclear industry with respect to radiation or nuclear safety are classified as “Below Scale/Level 0”. Epidemiological studies such as [KiKK 2007] Q392 and [Geocap 2012] Q494 proved that this view is wrong.
For communication of events to the public, a distinct phrase has been attributed to each level of INES. In order of increasing severity, these are:
1 ‘anomaly’
2 ‘incident’
3 ‘serious incident’
4 ‘accident with local consequences’
5 ‘accident with wider consequences’
6 ‘serious accident’
7 ‘major accident’.
The aim in designing the scale was that the severity of an event would increase by about an order of magnitude for each increase in level on the scale. Events are considered in terms of their impact on three different areas according to [IAEA/NEA 2013] Q517:

- impact on people and the environment
- impact on radiological barriers and controls at facilities
- impact on defence in depth.

How are the scales quantified?

Above statements suggest that the INES scale is logarithmic and consequently would be quantifiable, but this aspect is not explained.
Is INES an absolute scale, or a relative scale?
How is INES quantified?
Is the scale based on conserved quantities or (partially) on notions which depend on variable assumptions?
Within what timeframe must the rating of a nuclear accident be assigned? Hours, days, weeks, years? How about adverse effects observable only in the long run?

Compared to earthquakes, where the event intensity can be quantitatively evaluated, the level of severity of a man-made disaster, such as a nuclear accident, is more subject to interpretation. Because of the difficulty of interpretation, the INES level of an incident is assigned well after the incident/accident occurs. Therefore, the scale offers limited potential to assist in disaster-aid deployment.
According to [Wikipedia 2015] Q518:

> "As INES ratings are not assigned by a central body, high-profile nuclear incidents are sometimes assigned INES ratings by the operator, by the formal body of the country, but also by scientific institutes, international authorities or other experts which may lead to confusion as to the actual severity."

Critical remarks

The general criteria for rating events in INES as published by the [IAEA 2013] Q517 show some noticeable features, such as:

- Absence of quantifiable criteria for the two highest levels (level 7 'Major Accident' and level 6 'Serious accident') in the category 'People and the environment'.
- Very few quantifiable criteria for the other levels.
- No criteria at all in the category 'Radiological barriers and controls at facilities' for levels 7 and 6.
- No criteria in the category 'Defence in depth' for levels 7, 6, 5 and 4. Only for levels 3, 2 and 1 are criteria defined in this category.
- Apparently only deterministic (non-stochastic) health effects (see report m11 *Health effects of radioactivity*) are considered: several deaths from radiation in level 5, at least one death from radiation in level 4 and non-lethal deterministic health effect from radiation (e.g. burns) in level 3. No mention of deterministic health effects in levels 7 and 6.
- Stochastic health effects, or health effects with long incubation periods are not mentioned at all.
- Societal and economic effects are not mentioned.

Conspicuous also is the presentatation of the INES rating: the distinction between 'accidents' and 'incidents', suggesting that 'incidents' are just a nuisance and not harmful to humans. For what reason does the IAEA make the distinction between 'incidents' and 'accidents'? And on what grounds?
An example of the used euphemisms is the term 'major accident' for a highly visible disaster that took hundreds of thousands of lives and destroyed the futures of many millions of people during the past 25 years (Chernobyl, 1986, happened before formulation of INES) and will do so during the next decades. Most consequences of the Fukushima disaster have yet to become observable.

Graphical representation of INES

Apart from the cheerful colors of Figure 1, the graphical presentation of the INES scale is misleading in another way: the width of the coloured bars is likely meant to represent the frequency of the various classes

of accidents, but why are the heights of the bars drawn lower as the seriousness increases?
This way of representing suggest that the seriousness of a given class of accidents on the population is proportional to its chance of occurrence. The reverse is true: the severity of nuclear accidents is inversely proportional to their frequency. The official presentation of INES is misleading and seems to suggest a downplay of the severity of the consequences of nuclear accidents of the highest categories.

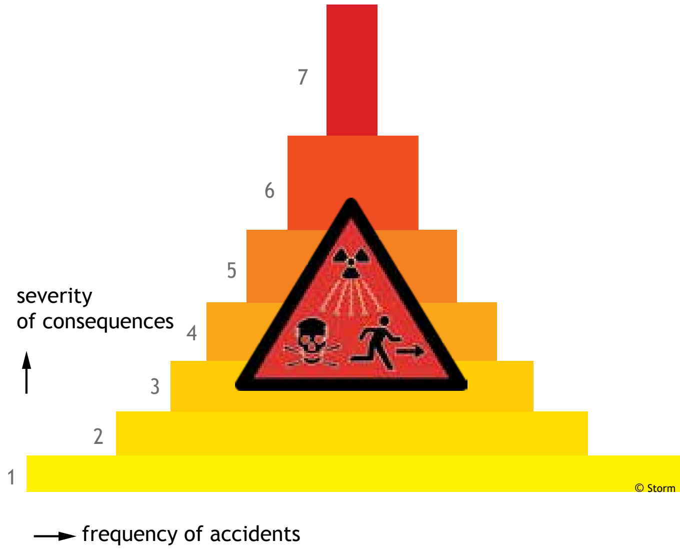

Figure 2

Another way of presenting the International Nuclear and Radiological Event Scale (INES). This scale concerns releases of radioactive materials into the human environment as a result of nuclear accidents, there is nothing cheerful about that. The severity of the consequences increases logarithmically from scale 1 to scale 7. This diagram may represent the seriousness of nuclear accidents better than Figure 1.

2 Large-scale accidents

Definition

An operating nuclear reactor generates immense quantities of radioactivity: spent fuel contains roughly a billion times the amount of radioactivity present in fresh nuclear fuel. One reactor of 1 GWe generates each year more than 1000 nuclear bomb equivalents of human-made radioactivity.
Here a large-scale accident is defined as an event with which an appreciable part of a reactor core or an equivalent spent fuel mass, corresponding with a large number of nuclear bomb equivalents of radioactivity, is dispersed into the biosphere. Obviously no sharp definition of a large-scale nuclear accident is possible. What does mean 'large': 1%, 10%, more than 50% of the radioactive inventory of a reactor? Apart from the total amount released, also the rate at which the dispersion occurs is an important factor and the extent to which people are exposed to radioactivity.
The severity of a nuclear accident may be better determined by the number of people who are contaminated with radioactivity and the extent of the contamination, not only at the moment of the accident and shortly thereafter, but also in the decades following the accident. In many cases a nuclear accident will cause a prolonged or even chronic exposure of the inhabitants of the affected area to a mix of radioactive materials.

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Potential sources of large-scale accidents

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- nuclear reactors
- spent fuel cooling pools
- reprocessing plants
- spent fuel storage in dry casks
- geological repositories
- dismantling sites of reprocessing plants

Violent accidents

With the Chernobyl and Fukushime accidents very large amounts of all kinds of radionuclides from spent fuel were dispersed over vast areas within a short period of time. These releases were caused by meltdowns of reactor cores and spent fuel cooling pools, accompanied by steam and hydrogen explosions. In case of Chernobyl the meltdown and explosions were followed by a fire of the graphite reactor moderator.
As a result of such violent events large fractions of the nuclear fuel present in the reactor core or cooling pool will be emitted, not only the gaseous and volatile fission products, but also the non-volatile radionuclides in the form of aerosols.

Insidious accidents

There are also severe accidents conceivable by which large amounts of radioactivity are dispersed over relatively limited areas insidiously, during a long period at a relatively low rate, sometimes unnoticed. The

insidious character gives the responsable authorities the opportunity to play down or even conceal the severity of an accident. Examples of insidious accidents are large leaks into the groundwater, rivers, lakes and/or coastal sea.
Depending on the charater of a particular insididious accident large fractions of an amount of spent fuel can be released into the environment, including all radionuclides present in the nuclear fuel.

Criticality incidents

An additional risk is the possibility of criticality incidents with the spent fuel. If a large mass of spent fuel elements is compacted sufficiently, for instance by a meltdown and/or explosion, the molten fuel may become critical and an uncontrolled fission process starts. Likely this occurred several times at the cripled reactors of the Fukushima Daiichi power plant and when the hydrogen explosion occurred at reactor 3. At several occasions after the meltdown the release of short-lived fission products has been observed.
Criticality events also happed after the explosions and meltdown of the Chernobyl reactor.

Regions at risk

The area within a radius of 30 km from each nuclear power plant is a potential evacuation area in case of a severe accident at the power plant. Figure 2 shows the areas directly affected by large-scale accidents with reactors and reprocessing plants in Europe. The map shows that nearly the entire inhabitated area of Europe lies within the 300 km zones around nuclear power plants, which could be heavily contaminated in case of an accident. These zones are based on models. The maps of the contaminated areas after the Chernobyl and Fukushima disasters, addressed in reports m02 *Chernobyl disaster* and m08 *Fukushima* disaster, show how far the contamination from one reactor can reach beyond the 300 km zone; see for example Figure 4 below.

Causes and triggers

Various mechanisms are conceivable for dispersion of large quantities of radioactivity from spent nuclear fuel into the environment. Violent releases result from meltdown of nuclear fuel, fires and explosions. Such events in turn result from a loss-of-coolant accident (LOCA).
A loss-of-coolant event, to be discussed in the next section, can be triggered by various events and causes, such as degradation of materials and corrosion, human failures (e.g. bad maintenance), natural disasters (floods, earth quakes), accidents, terrorisms, war acts [Hirsch et al 2005] Q169. Another threat is the infection of the electronic control system by a computer virus or a computer worm, such as Stuxnet.

Radiolysis of water

Radiolysis of water may entail a long-term hazard. If water enters the radiation shield of dry casks, hydrogen and oxygen will be formed from the interaction of nuclear radiation with water (vapor or liquid) and hydrogen explosions become possible. In combination with other degrading mechanisms of spent fuel and its containers such explosions could initiate major eccidents.
During storage of spent fuel in cooling pools radiolysis of water constantly occurs. Under nominal conditions the hydrogen is removed from the air by the ventilation system. If that fails a hydrogen explosion is unavoidable, as happened at Fukushima Daiichi.
Radiolysis of water rises continuously concerns regarding the storage tanks of highly radioactive reprocessing waste liquors. If not cooled and ventilated adequately, such storage tanks could explode

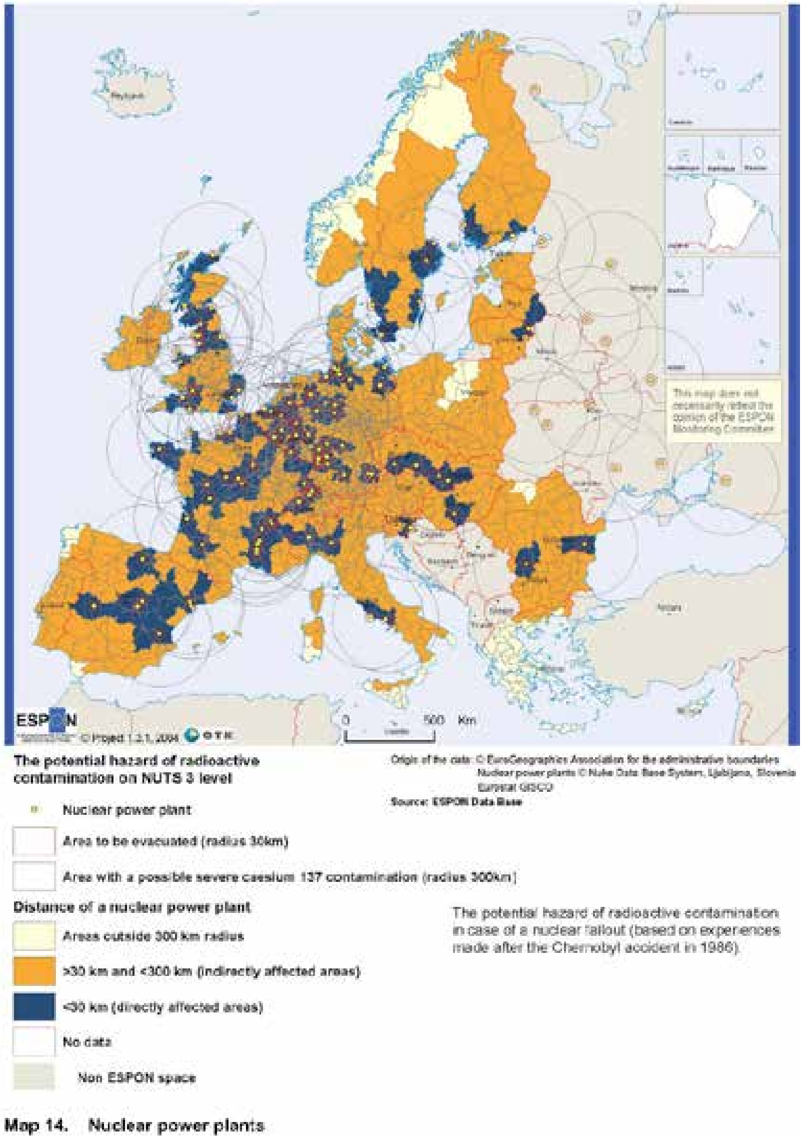

Figure 3

Chart with the nuclear power plants of Europe. The darkest colored areas are within 30 km of an NPP and are the areas to be evacuated in case of an accident releasing nuclear fuel. The risks posed by accidents involving the interim storage of spent fuel might be greater than reactor accidents. Most interim storage facilities are located at the reactor site. Source: [ESPON 2006] Q546.

.Increasing risks

The world civil nuclear power fleet experienced two very large-scale accidents during the past three decades: Chernobyl in 1986 and Fukushima in 2011. A geologic repository for safe storage of spent fuel and other hazardous radioactive materials still does not exist, so all human-made radioactivity ever produced is still stored in more or less vulnerable conditions, if not escaped already into the environment. Severe accidents causing the release into the environment of substantial fractions of the nuclear bomb equivalents generated in nuclear power plants are becoming increasingly probable, for several reasons:

- The amount of human-made radioactivity increases day by day.
- The materials and structures of temperary storage facilities of the highly radioactive materials deteriorate over time and are becoming inreasingly vulnerable to accidents. Ageing is a crucial aspect of nuclear safety; it will be discussed in reports m21 *Nuclear safety* and m38 *Nuclear power and the Second Law*.
- Nuclear power plants and other facilities containing spent fuel and other radioactive materials are

potential targets for terroristic attacks. This aspect will be discussed in report m23 *Nuclear terrorism*.

Unfortunately we might expect that Fukushima will not be the last disaster of its class, if no far-reaching preventive actions are taken now.

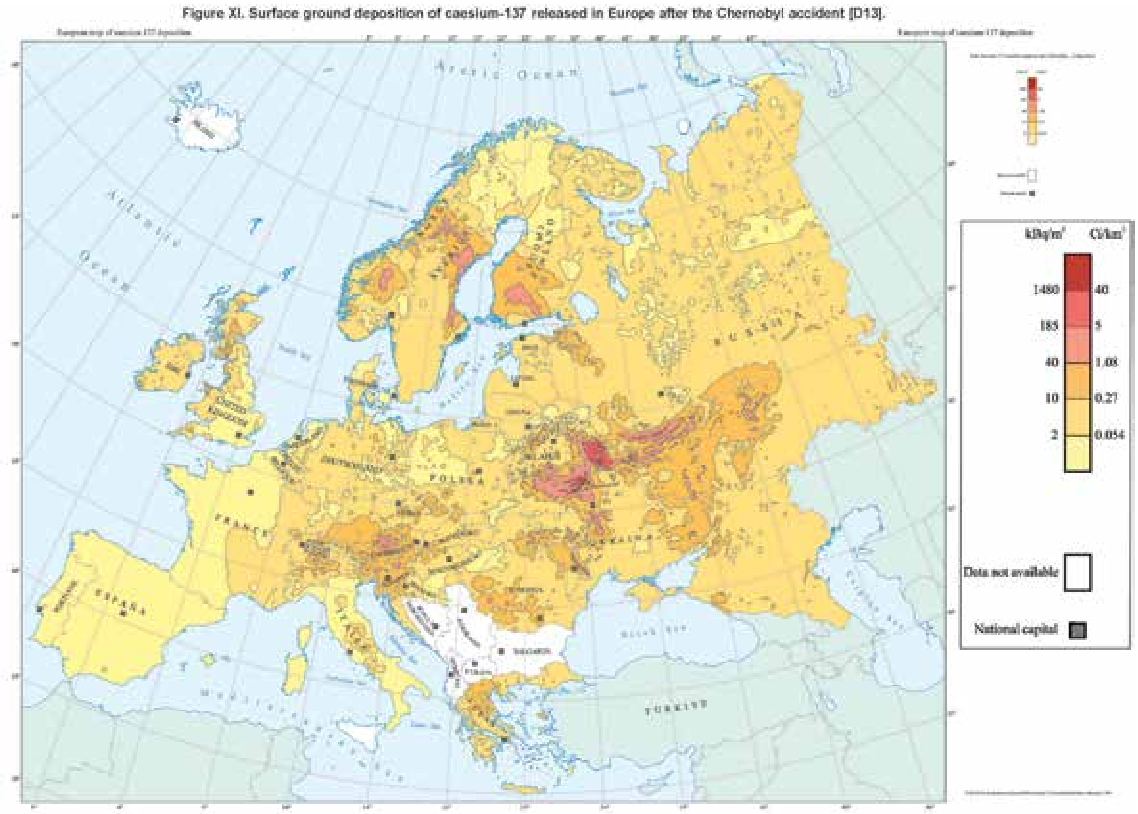

Figure 4

Surface ground deposition of cesium-137 released in Europe after the Chernobyl disaster in 1986. Sources: [UNSCEAR 2012] Q547, [UNSCEAR 2000] Q548. An enlargement of the colour scale has been added by the author of this report. The lightest yellow colour corresponds with a contamination level of 2 kBq/m² of Cs-137 or less, which is attributable to residual levels from artmospheric nuclear weapon testing fallout.

3 Nuclear fuel meltdown

Reactor core meltdown

If the cooling of a nuclear reactor fails, the fuel elements in its core will melt within a short time, due to the radioactive decay of radionuclides. If the reactor is operating at full power at the moment of cooling failure, the meltdown is a matter of minutes; if the reactor is not operating at the moment of a cooling failure, the meltdown may take more time. The molten mass will cause violent steam explosions The Zircalloy (98,5% zirconium) cladding of the fuel elements contains zirconium hydride (ZrH_x, with *x* variable from 1 to 4), which is highly flammable at elevated temperatures. In case of LOCA the spent fuel rapidly heats up and the cladding catch fire, accelerating the meltdown of the fuel. At high temperatures zirconium metal reacts also with residual water, generating hydrogen, and hydrogen explosions are unavoidable. As a result of these violent events the radionuclides from the spent fuel will be dispersed into the air and water, including the non-volatile radionuclides as aerosols. This scenario happened at Chernobyl and Fukushima.

Serious accidents with nuclear reactors are very well possible, despite of reassuring statements of the nuclear industry. The probabilistic safety studies of the nuclear industry do not cover all events which could cause a severe reactor accident, as will be discussed in report m21 *Nuclear safety*. Such an accident could involve a meltdown of the core and a violent explosion, which would sever the reactor vessel and the containment building. Consequently the barriers between the radioactive content of the reactor and the environment would be disrupted, resulting in a Chernobyl-like disaster.

In the commercial nuclear technology no 'pre-flight' testing occurs. A nuclear power plant is assembled and tested at the location chosen by the utility. Design flaws and manufacturing defects are uncovered during construction and the first several years of operation of the nuclear power plant, a period called the burn-in phase. Major failures in the past, including TMI-2 and Chernobyl, occurred with reactors still in their burn-in phase.
New reactor designs incorporate features to make the plants safer and more economical. As [Lochbaum 2004] Q76 put it:

> 'These features, however, are largely untested in the field or have very limited operating experience. Other new reactor designs have operated only in cyberspace and have never experienced the trials and tribulations of real-world operation. The gremlins hiding in their designs have not yet been exposed, let alone exorcised.'

Leaked papers from the Electricité de France (EdF) report serious safety problems, which could cause a Chernobyl-like accident, with the French reactors, including the flagship EPR [Sortirnucleaire 2010] Q537.

A comprehensive study [Hirsch et al. 2005] Q169 concluded:

- All operational reactors have serious inherent safety flaws which cannot be eliminated by safety upgrading.
- Many countries are planning to extend the lifetime of their reactors beyond the original design lifetime. This leads to degradation of critical components and the increase of severe accidents. The age-related degradation mechanisms are not well understood and difficult to predict.
- Utilities are upgrading their reactors by increasing reactor pressure and operational temperature and the burn-up of the fuel. This accelerates ageing and decreases safety margins. Nuclear regulators are not always able to fully cope with this new regime.
- Reactors cannot be sufficiently protected against terrorist threat. There are several scenario's – aside from a crash of an airliner on the reactor building – which could lead to a major accident.
- Climate change impacts, such as flooding, sea level rises and extreme droughts, seriously increase nuclear risks.

The US Nuclear Regulatory Commission (NRC) recently revised its licensing process to virtually eliminate public participation [NRC 2004] Q525. In the UK and in France similar regulations seem to exist. How is the situation in other countries? The lack of public input could drastically curtail discovery of important areas of safety improvements.

Spent fuel cooling pools

Meltdown of spent fuel in a cooling pool followed by explosions may result in the dispersion of huge amounts of radioactive fission products and actinides over vast areas. As the radioactive inventory of a cooling pond may be 10 times as high as the inventory of a reactor core, the consequences of a cooling pond explosion may turn out worse than a reactor core meltdown.

On March 14, 2011, a large hydrogen explosion occurred in the cooling pool of reactor 3 at the Fukushima Daiichi plant, caused by (partial) meltdown of the spent fuel elements in the pool. Apparently the explosion was accompanied by a criticality incident: the fuel became briefly critical initiating an uncontrolled fission process. Probably criticality incidents happened also during the core meltdowns of reactor 1 and/or reactor 2.

The cooling pools of spent fuel are generally located outside of the safety containment of the reactor. PWRs (Pressurized Water reactors) have their pools at ground level (see Figure 5), BWRs (Boiling Water Reactors), including the newest generation, have their cooling pools situated high in the reactor building, at the level of the top of the reactor containment (see Figure 6).

An authoritive American study [MIT 2010] Q429 sees no problems in the USA with the temporary storage of spent fuel during the next decades or even a century:

> 'Scientifically sound methods exist to manage spent nuclear fuel.'

On paper a scientific method may look sound, but the practice is different. One of the basic issues in this report is the disparity between a theoretical concept and the emprirical evidence of its behaviour in practice; this issue is addressed in detail in report m21 *Nuclear safety* and m38 *Nuclear power and the Second Law*..

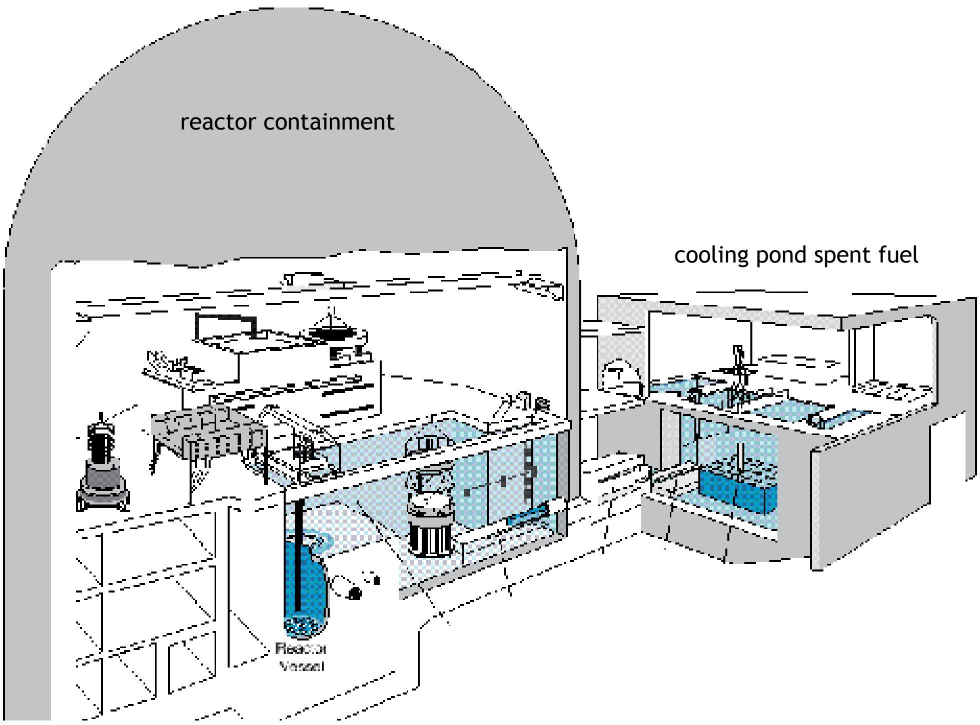

Figure 5

Cross-section of a modern PWR nuclear power plant (Sizewell B in Great Brittain). For reloading the reactor with fresh fuel, the head of the reactor vessel is removed, shielded by many meters of water. The spent fuel elements are hoisted out of the reactor core and transported by robotic equipment to the spent fuel storage basin outside of the reactor containment building. Then the fresh fuel elements are placed into the reactor core, the head of the vessel is replaced and the reactor is restarted.

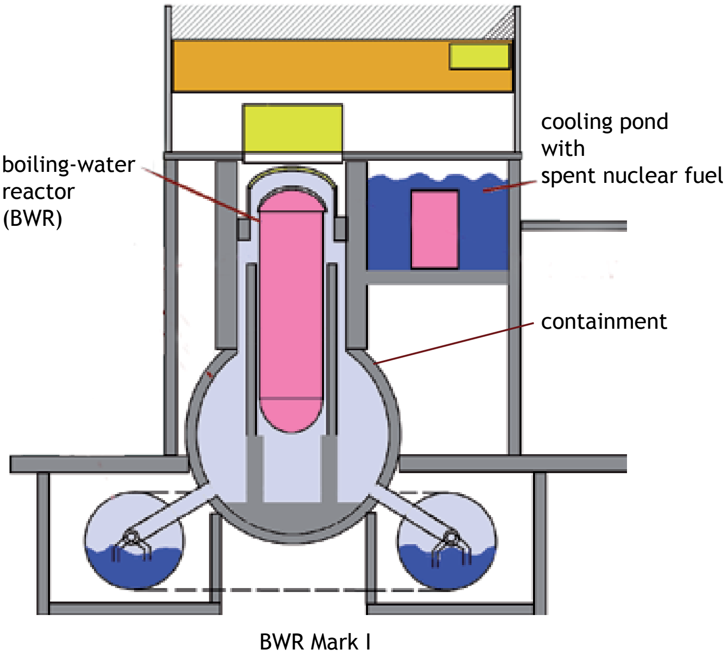

Figure 6

Boiling-water reactor. The spent fuel cooling basin of this type of reactors are outside of the containment structure around the reactor, as is with all other types of nuclear power plants. The reactors of Fukushima Daiichi are of this type BWR. The newest type of BWR, the ABWR (Advanced Boiling-Water Reactor), has a similar outline.

Figure 7

Explosion at the spent fuel cooling basin of reactor 3 at the Fukushima Daiichi plant on March 14, 2011. As a result of the breakdown of the cooling of the basin, the spent fuel partially melted and reacted with the remaining water. The hydrogen generated by this reaction exploded, initiating a criticality incident in the (partially) molten nuclear fuel.

4 Hazards of reprocessing plants

Dispersion of radioactivity

In report m20 *Reprocessing of spent fuel* reprocessing is outlined. In a reprocessing plant the spent fuel of many reactor-years is present, so the radioactive inventory amounts to multiple of 1000s of nuclear bomb equivalents, likely even many 10000s. This radioactive inventory, comprising fission products, uranium, plutonium, minor actinides and activation products, is distributed among a number of solid and liquid waste streams during the separation and purification processes. A substantial part of the radioactivity is discharged into the environment by gaseous and liquid effluents. The historical discharges of total alpha emitters, tritium and total beta emitters in the liquid efflents of the two operating reprocessing plants and of other nuclear installations in Europe (discharging into the Atlantic, North Sea and Irish Sea) are graphically presented in report m17 *Pathways of radioactive contamination*.

Cumulation of discharges

The rate of release incidents may seem not excessive, but the total amounts of released radioactivity become very large. Intended releases are ongoing year after year and unintended releases may easily continue for long periods, before they are noticed and corrected, if at all.
Before reprocessing most spent fuel elements have cooled in cooling pools for a number of years, so the short-lived fission and activation products have decayed to low levels, consequently the discharges contain chiefly long-lived radionuclides.

Alpha emitters
The cumulative alpha discharges in the liquid effluents of the reprocessing plants in Europe during the period 1989-2011 amount to 16.8 TBq, as follows from data of [OSPAR 2001] Q579 and [OSPAR2013] Q581.
In practice the category of alpha emitters comprises all long-lived uranium isotopes, plutonium isotopes except Pu-241 (beta-emitter), neptunium-237 (Np-239 is a beta-emitter), americium-243 and curium-244. The specific activities of Am-243 and Cm-244 are much higher than those of Np-237 and the plutonium isotopes due to their relatively short half-lifes, but these minor actinides constitute only about 0.1% of the alpha emitters. Assumed that roughly 10% of the activity of the discharged alpha waste is determined by Pu-239 + Pu-240, than their activity in the discharges would be about 1.7 TBq. Obviously this figures is a rough estimate, but it indicates the order of magnitude.
According to [Zheng et al. 2012] Q577 the amount of Pu-239 + Pu-240 released during the Fukushima accident was 6.4 GBq. This means that the cumulative discharges of these two plutonium isotopes by the European reprocessing plants might be some 260 times the amount released by the Fukushima disaster. Likely the releases of the other alpha emitters are consequently also larger by a factor 200-300.
It should be noted that the discharges of alpha emitters (as aerosols) in the gaseous effluents of the European reprocessing plants are not known. The releases by Fukushima likely concern only the dispersion of plutonium as aerosol. The amounts of plutonium and other actinides washed into the sea at Fukushima certainly are much larger than the aerosol emissions.

Tritium
The cumulative tritium discharges by reprocessing plants in Europe during the period 1989-2011 amount to 248 PBq, averaged about 11.3 PBq/yr, as follows from data of [OSPAR 2001] Q579 and [OSPAR2013] Q581.
Tritium has a half-life of 12.3 years, so only a minor part of above quantity has decayed at this moment. Compared with the annual cosmogenic production of about 150 PBq/yr the discharges of the reprocessing plants may seem not dramatic. The cosmogenic production occurs in the upper atmosphere of the whole Earth, however, the anthropogenic production ends up in a tiny part of the world seas (English Channel

and Irish Sea) so the concentration of tritium in these waters may become relatively high. Tritium easily enters the food chain, so sea food from the coastal seas near the reprocessing plants may become heavily contaminated with tritium.

Beta emitters

These category includes virtually all fission products and Pu-241. None of these radionuclides occur in nature. The cumulative discharges of beta emitters by the European reprocessing plants during the period 1989-2011 amount to 3.208 PBq, as follows from data of [OSPAR 2001] Q57] and [OSPAR 2013] Q581.

As pointed out in report m17 *Pathways of radioactive contamination*, the beta discharges involve radionuclides with long half-lifes, so only a tiny part has decayed to stable nuclides since their release. Of special concern are radionuclides with high biological activity, such as Sr-90, Tc-99 and I-129. It is difficult to get a clear picture of the presence of these hazardous radionuclides in foodstuffs and drinking water, because they are beta emitters with no or very weak gamma emission and therefore are not detectable with the common radiation counters, which can detect only gamma rays. These radionuclides can only be measured using special equipment. Another hazardous beta emitter, Cs-137, is easily detectable, because it is also a strong gamma emitter.

Insidious disasters

The actual releases by La Hague and Sellafield may be larger than the reported releases, due to unnoticed leaks and other causes. Unintended leaks are practically unavoidable, the size of the leaks may vary widely. The releases into the sea and into the air are not monitored by an independent institute, as far as known.

Even without accidents and without major leaks the operational discharges of reprocessing plants may develop insidiously to the proportions of a disaster, in view of the cumulation of large amounts of long-lived hazardous radionuclides. Buildup of radionuclides in certain ecosystem compartments, e.g. sediment, and bioaccumulation may cause high concentrations in food and drinking water.

The environmental consequences and health effects of the operational discharges, year after year, of the reprocessing plants are not known. These effects might have long time delays before becoming observable and that only gradually. In addition, a causal relationship between these releases and observable health effects is not easy to prove on a individual scale, due to the long latency periods between exposure and health effect. This issue is addressed in reports m11 *Health effects of radioactivity* and m05 *Downplaying and denial of health effects*.

At one hand dilution of the radioactive discharges in seawater may mitigate their harmful effects, at the other hand bioaccumulation may cause hazardous concentrations in fish anf other seafood. The discharges are not a once-only event, but are continuing for decades, so the exposure may be considered chronic. Effects of chronic internal exposure to a variety of long-lived hazardous alpha and beta emitting radionuclides are not well understood.

Above observations obviously hold true for gaseous discharges as well as liquid discharges. Unfortunately little data are available on the actual airborne emissions of reprocessing plants.

On top of the authorised operational discharges large unintended discharges could occur as a result of accidents, failures of crucial equipment or other causes. Such an event could badly aggravate the consequences of the authorised discharges. In view of the exceedingly large amounts of radioactivity present at the reprocessing complex [Hirsch et al. 2005] Q169, [ANDRA 2012] Q576, it may develop to an insidious disaster.

Chances of unintended discharges are increasing with time, due to the unavoidable degrading processes in materials and equipment. This issue is addressed in detail in report m21 *Nuclear safety*.

A highly risky phase comes when a reprocessing plant, or a part of it, is shut down and the cleanup and decommissioning + dismantling phase starts. Unintended releases into the evironment of substantial amounts of radioactive materials by air (gases, dust, aerosols) and via liquid discharges may turn out inevitable. Chances of large-scale accidents seem realistic. These chances may be enhanced by economic arguments: decommissioning and dismantling are extremely costly; see report m04 *Decommissioning and dismantling of nuclear power plants*.

Violent disasters

At a reprocessing plant large quantities of spent fuel are stored in the cooling pools, corresponding with a large number of reactor cores, to let decay the radiation to a level at which chemical treatment is possible. If the cooling pools remain uncooled for a critical period, or are drained by some cause (e.g terroristic attack), a meltdown and hydrogen explosions might be unavoidable, the scenario described in the previous section. A disaster of unprecedented size could evolve, due to to the massive amounts of radioactive materials involved.
Explosions at one cooling pool in a reprocessing plant might cause meltdowns and explosions or major discharges in other compartments of the plant, greatly exaggerating the disaster.

In addition vast amounts of radioactivity are present in the large volumes (many thousands of m^3) of unconditioned liquid and solid wastes originating from the separation processes, as pointed out in report L22p41 *Reprocessing of spent fuel*; see also [Hirsch et al. 2005] Q169 and [ANDRA 2012] Q576. Some of the storage tanks of these wastes have to be cooled and have the potential to boil dry and cause hydrogen explosions resulting in Chernobyl-like disasters. This scenario happened at Mayak (Kyshtym) in 1957. Another threat is the inevitable radiolysis of water, by which a highly explosive mixture of hydrogen and oxygen is formed.

Hundreds of tons of cladding hulls, still containing insoluble components of spent nuclear fuel and highly radioactive, are stored at the site of the reprocessing plant. This material is highly flammable at elevated temperatures and may pose a risk.

Economic disaster

An economic disaster is almost inescapable when a reprocessing plant has to be decommissioned and dismantled. This will be necessary at the end of its operational life, or when the complex becomes inoperable by a severe accident. In the present practice a new compartment of the plant is built when an older one becomes inoperable due to radioactive contamination, equipment failures or other causes. The abandoned compartment is sealed off and awaits its dismantling. For this reason an operating reprocessing complex expands with time.

Report m04 *Decommissioning and dismantling of nuclear installations* addresses the energy debt and the high investments and the massive economic efforts needed to keep vast areas in France and the UK habitable when the reprocessing plants have to be removed.
Dismantling cost of the reprocessing plants at Sellafield is estimated at some €100bn, the final cost will likely be much higher, The dismantling cost of the complex at La Hague could only be guessed, but almost certainly it will be higher, probably several €100bn, because it is a larger plant than Sellafield.

The safety of the decommissioning and dismantling activities may come easily under high economic pressure as a result of the excessive costs. This possibility enhances the chance of a large-scale insidious accident.

Lack of manpower

However, another kind of disaster might happen, even when no large-scale dispersion of radioactive materials would occur. Cleanup and dismantling requires such high investments of materials, energy and human power, that it will be a heavy burden on the economy of France and the UK, the more so in times of economic depression. The efforts require a large reservoir of highly skilled manpower, during at least 100 years. Lack of skilled manpower and loss of expertise concerning hazardous installations decades after closedown pose a high risk for millions of people. Message to the future.
In addition the investments have to be considered pure losses in an economic sense: all effort is aimed at the disappearance of hundreds of thousands of tonnes high-quality materials from the environment forever. The best attainable result is that the regions around the reprocessing plants remain habitable.

5 Next disaster in Europe or in the USA?

Taking into account the 7-10-fold higher population density a disaster similar to Chernobyl in Germany would result in 1.7-12 million cancer deaths, the number depending on the assumptions the estimates are based on [IPPNW 2011] Q452.

Obviously the consequences of a Chernobyl-like or Fukushima-like explosion in the densely inhabited parts of Western Europe would be disastrous. Imagine a situation in which the fallout from Chernobyl would be deposited a 2000 kilometers more to the West. A major accident in a light-water reactor can lead to radioactive releases equivalent to the release at Chernobyl and about 1000 times the amount released by an exploding fission weapon. Relocation of the population can become necessary for large areas (some 100 000 km^2).

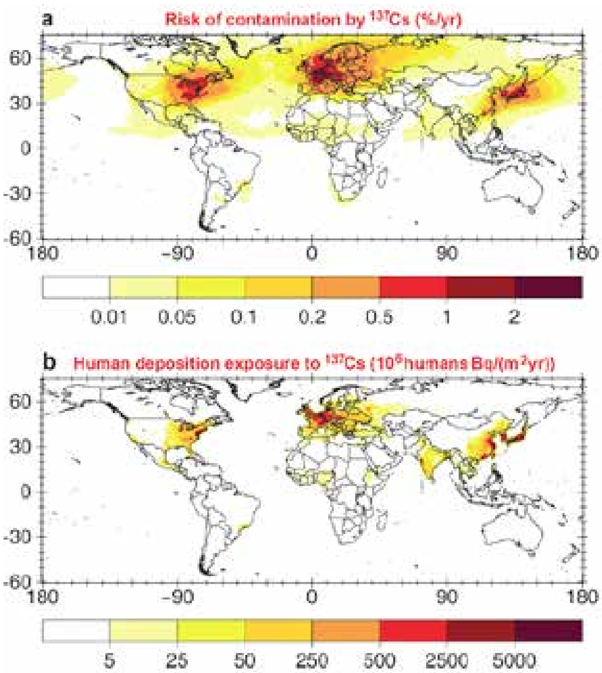

Figure 8
Maps of global risk of radioactive contamination by Cs-137 resulting from large nuclear accidents. (a) Based on the modelled deposition of 40 kBq m^{-2} yr^{-1} Cs-137. The risk is the expected value normalized by 40 kBq m^{-2}. (b) Modelled risk of human exposure to Cs-137 deposition. An area with a deposition of ≥40 kBq m^{-2} Cs-137 is defned as 'contaminated'. Source: [Lelieveld et al. 2012] Q515. An area with a deposition of more than40 kBq m^{-2} Cs-137 is defned as 'contaminated'.

The probability of very large-scale nuclear accidents is much higher than usually estimated. The global risks of contamination with radioactive materials in densily populated regions with a high density of nuclear power plants are mapped by [Lelieveld *et al.* 2012] Q515. Based on armospheric circulation models the dispersion of and contamination with Cs-137 and I-131 after a severe accident, similar to Chernobyl, are simulated.
Acoording to the simulations the surface area contaminated by Cs-137 above the dangerous level after a single core meltdown incident varies from 102000 -165000 km^2 , depending on the region, and the number of affected people may vary from 3-34 million, again depending on the region.

A Swiss study [Piguet *et al.* 2019] Q844 discusses the probability of a major accident in a European nuclear power plant (Beznau, Gösgen, Leibstadt, Mühleberg and Bugey) and evaluated he harm to people. The findings of this study confirm earlier studies.

The nuclear industry claims that nuclear power is safe with safe nuclear reactors. In their view the chance of a major reactor accident, involving a core meltdown (the worst case scenario), is one in the several millions of years. Negligible compared to other risks, posed by other events in the society, is said. The claim of safe reactors by the nuclear industry is based on a small number of theoretical studies.
Empirical evidence proves the results of the reactor safety studies to be of little meaning. During the past decades three major reactor core meltdowns occurred: Three Miles Island (1979), Chernobyl (1986) and Fukushima (2011), a chance of once every 10-20 years. In addition a disaster about as serious as Chernobyl happened at the reprocessing plant at Mayak in the East Urals in 1957 (see report m13 *Nuclear disaster at Mayak in 1957*).

6 Other places at risk

Dry storage of spent fuel

During dry storage the spent fuel elements have to be cooled by natural air circulation. If, by whatever cause, the cooling is interupted during a prolonged period, meltdown of the fuel cannot be excluded. There are various mechanisms conceivable by which such events could happen, for example: flooding, other natural disasters, unintentional and intentional plugging of the air inlets and/or outlets of the outer casks. If the air inlets and/or outlets are blocked in some way, the fuel will heat up and may melt.
What will happen when a major fire occurs at the site of the dry casks, or when an airplane crashes on the site? Criticality accidents cannot be excluded.
Above postulated events may seem a remote possibility, but the chance of occurrence increases with time and with the number of dry storage sites.
Dry cask storage sites are generlly better accessible than other facilites containing spent fuel and therfore ar more vulnerable to terrorist attacks.

Of serious concern are the unavoidable degrading processes, discussed in report m38 *Nuclear power and the Second Law.*. Almost certainly the dry casks will go leaking someday, it’s only unknow when. If the casks are inspected thouroughly and frequently, the leaks may be spotted in an early phase. Overpacking in new casks will be a very costly activity. Transport of leaking casks is practically not feasible for reason of high risks of dispersion of radioactivity and the possibility of criticality accidents.

U.S. nuclear utilities are operating dry-storage facilities for used fuel that are licensed for operating periods of up to 60 years. The fuel in these facilities and the used fuel that will be discharged in the foreseeable future may need to remain in storage for much longer periods. Some have suggested that this period could extend to as long as 300 years [NWTRB 2010] Q514.

If the leaks remain unnoticed for prolonged periods, or when adequate actions fail to occur, large amounts of radioactivity will get dispersed into the human environment. The groundwater in the area will be irreversibly contaminated with dozens of kinds of dangerous radionuclides, an area growing by time.
As the storage facilities are usually located in densely populated regions, such a dry cask disaster might require the evacuation of large numbers of inhabitants. Apart from the damage to the health of numerous people, the evacuation might mean a serious economic regression.
This is typically a scenario of an insidious disaster, The amounts of released radionuclides likely will be smaller than released in a violent accident, but the consequences may be very serious. Moreover, the short-lived radionuclides in the spent nuclear fuel have decayed, so the radionuclides in case of releases from dry casks always are long-lived radionuclides.

Geologic repository

Water ingression and the formation of fast transport channels (fissures, porosity of barriers) are the principal ennemies of a stable isolation of radioactive waste in a repository, as pointed out in reports m32 *Radioactive waste repositories* and m40 *Radioactive waste management*. During the period of construction and operation of a geologic repository, which probably will take tens of years, the repository is open to the surface.
Other risks are posed by mishaps with the robotic equipment needed to place the containers with the highly radioactive materials into the galleries or caverns of the repository.

A geologic repository in which 20000 Mg spent fuel is stored, has a radioactive inventory equivalent to about one million atomic bomb equivalents. The canisters with the spent fuel are heat generating and will corrode at a high rate, due to the elevated temperatures and radiolytic reactions. The canisters with spent fuel are expected to start leaking in a foreseeable future.
If by some cause, such as flooding, only 0.1% of the radioactive content of the repository reaches the surface and the groundwater table, that would still mean an amount of 1000 atomic bomb equivalents of long-lived radionuclides. Another risk is posed by human intrusion of the reporsitory. Knowledge on the repository and its contents may get lost in the years following the final closure.

Neptunium-237, present in sizeable quantities in spent fuel and also the decay product of americium-241 which in turn is the decay product of plutonium-241, is the most mobile actinide in the deep geologic repository environment and may reach the human environment within a relatively short period in case of accidents.

As far as known no assessments of potential disasters with geologic repositories have been published, if done at all.

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