Nuclear safety

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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 Ageing of materials and structures

Second Law of thermodynamics

All materials and structures inevitably deteriorate by time due to a combination of spontaneous chemical and physical processes, a phenomenon usually called ageing. The rate of ageing of materials and components depends partly on the operating conditions.
As a consequence of the Second Law of thermodynamics spontaneous processes are always degrading the quality of materials and structures. Common examples of such degrading processes are corrosion of metals, wear of moving components, weathering of concrete and quality loss of plastics. The degradation processes may be retarded by dedicated effort and investments of useful energy and materials, but never can be eliminated.

Ageing processes are generally difficult to detect because they usually occur on the microscopic level of the inner structure of materials. They frequently become apparent only after a component failure has occurred. Not always leakages or other signals can be detected before a component, for example a pipe, catastrophically fails.

Important factors influencing the ageing processes of nuclear power plants and its components are:
- nuclear radiation (alpha, beta, gamma, neutrons)
- thermal loads
- mechanical loads
- corrosive and abrasive processes
- combinations and interactions of above mentioned processes.

Thermal and mechanical loads can cause creep and cracking and so may clear the way for chemical processes. Corrosion comprises a gamut of physical and chemical processes. Nuclear radiation, especially neutron radiation, causes embrittlement of metals and accelerates other degrading mechaniosms. Many materials and components in a nuclear power plant are exposed to elevated temperatures and nuclear radiation and most of them also to water and air.

Often changes of mechanical properties cannot be recognised by non-destructive examinations. Therefore it is difficult to get a reliable, conservative assessment of the actual state of materials. In case of limited accessibility due to the layout of components and/or high radiation levels not all components can be examined one hundred percent. Therefore, it is necessary to rely on model calculations in order to determine the loads and their effects on materials. Not even the most complex calculations can cover all conceivable synergistic effects. With increasing age of plants, damage mechanisms might occur which have not been foreseen, or which had even been excluded from the models, exacerbating the ageing problems [Hirsch et al. 2005] Q169. Models always have their inherent limitations.

Croncete is also subject to ageing. Damage mechanisms to concrete stuctures in the presence of nuclear radiation are largely unknown.
Safety analyses are based on design material parameters. Weakening of structures with time are cannot be included in the models and probabilistic risk assessment (PRA) studies in a reliable way, because most ageing mechanisms are not well understood and besides non-quantifiable factors may be also important. This could have serious consequences in case of, among other, seismic events.

Electronic devices

In an NPP, many electronic devices are being used. Temperature and radiation are the main factors leading to ageing. Additional degradation can occur due to humidity and chemical attacks. Because of the great variety of different devices and the complex ageing phenomena, which have not been systematically investigated so far, reliable lifetime estimates are very difficult. With increasing age of a plant, the reliability of electronic devices can thus be reduced – while at the same time, safety margins in the whole system are decreasing [Hirsch et al. 2005] Q169.

Life extension of nuclear power plants

Extension of the operational lifetime of a nuclear power plant may be the single most important determinant of nuclear electricity production in the coming decades, according to the IAEA. As the world's nuclear power plant population gets older, there are efforts to play down the role of ageing, including conveniently narrowing the definition of ageing.

There are ageing effects leading to gradual weakening of materials which may have no consequences during reactor operation, but which could also lead to catastrophic failures of components with subsequent severe radioactive releases. Most notable among those is the embrittlement of the reactor pressure vessel, increasing the hazard of vessel bursting. Failure of the pressure vessel of a PWR or a BWR constitutes an accident beyond the design basis.

A quote from [Hirsch et al 2005] Q169 reads:

> Thus, it is clear that the risk of a nuclear accident grows significantly with each year, once a nuclear power plant has been in operation for about two decades. But it is not possible to quantitatively describe this continuous increase of risk. Increased vigilance during operation and increased efforts for maintenance and repairs have the potential to counteract this tendency, at least to some extent. However, in the age of liberalization and growing economic pressure on plant operators, the trend rather goes in the opposite direction, even as the reactor fleet is ageing.

2 Ageing of spent fuel

Degradation

As a consequence of the Second Law of thermodynamics spontaneous processes always degrade the quality of materials and structures. The previous chapter addressed the issue of ageing of materials and structures of nuclear installations.

Degradation of the condition of spent fuel elements with time, during interim storage after removal from the reactor, is no exeption of above observations. On the contrary, one might expect the ageing of spent fuel occurring faster than of the materials and components of the nuclear power plant and of non-nuclear materials and structures, due to the elevated temperature of spent fuel, the presence of dozens of different chemical species and the presence of energetic nuclear radiation.

Above observations are of great importance for the interim storage of spent fuel in cooling ponds and dry casks. An analysis [NWTRB 2010] Q514 addressed the problems facing the interim storage in dry casks, but its conclusions apply to cooling pools as well.

The dry storage components (fuel cladding, containers, casks, internals, concrete shield) all degrade during dry storage, a consequence of the Second Law of thermodynamics. The materials are exposed to elevated temperatures and nuclear radiation and most of them also to water and air. Some degradation mechanisms may be active during the early years of dry storage, while different mechanisms may be active during extended storage, at low temperatures.

The most significant potential degradation mechanisms affecting the fuel cladding during extended storage are those related to hydriding, creep, and stress corrosion cracking, according to [NWTRB 2010] Q514.

Hydrogen from the spent fuel, and so tritium, slowly migrates through the zirconium cladding, a part of the hydrogen and tritium forms hydrides with the metal, the remaining part (80-90%) escapes into the air. The presence of zirconium hydride renders the spent fuel cladding extremely flammable at elevated temperatures and less ductile, enhancing the risk of failure.

Conceivable degradation mechanisms, affecting fuel cladding as well the containers, may be caused by dislocations of atoms in the metal crystals as a result of radiation from the radioactive content disturbing the stucture and weakening the metal. Reactions with high activation energies, normally not of concern at low temperatures, are possible by the highly energetic radiation within the container. In case of leaking fuel pins the released radionuclides within the container may initiate unknown reactions.

The degradation mechanisms and their interactions are not well understood. High-burnup fuels tend to swell which increases the cladding stresses and can lead to creep and stress corrosion cracking of cladding in extended storage; cladding can become brittle at low temperatures. These problems are not typical for dry storage, but are also of importance for wet storage in cooling pools.

One of the main deterrents to corrosion of the fuel cladding and the canister or metal cask internals during extended dry storage is the presence of helium. If the helium leaks and air is allowed to enter the canister or cask, this, together with the moisture in the air, can result in corrosion of the fuel cladding, the canister, and the cask. The Review Board [NWTRB 2010] Q514 observed a lack of essential information on the degradation mechanisms of the dry storage system and the absence of the inspection of and the means to confirm the presence of helium inside the containers of the spent fuel.

Regardless of the length of storage,spent nuclear fuel eventually will have to be moved from the reactor sites to off-site interim storage facilities, or to spent-fuel reprocessing facilities, for recycling of uranium and plutonium, or to a geologic repository for definitive storage. Subjects of concern are the integrity of the transportation casks and the condition of the spent fuel inside. The casks should not fail in the event of a transportation accident and the fuel should remain subcritical in any case. During extended storage the condition of the spent fuel degrades unavoidably, so the fuel elements will be more susceptible to damage as a result of transportation operations, the longer they have been stored. This might pose a problem, because some fuel elements are leaking already at the moment of removal from the reactor. The consequences may include release of fission products into the canister or the cask interior, which must be contained during a transportation accident, with the potential for release of radioactive materials into the human environment.

Summarized [NWTRB 2010] Q514 concludes:

- No information is available on the behavior during dry storage of the more advanced materials now being used for fuel cladding and fabrication of fuel-assembly structural components.
- The physical state of the cladding when fuel is placed into dry storage is currently not well characterized. In some cases the cladding may be close to failure.
- Cladding-degradation mechanisms, their interactions with each other, and the expected behavior of cladding after aging in extended dry storage are not well understood.
- Corrosion mechanisms will cause degradation of the metal components of dry-storage systems during extended dry-storage periods: for example, the outer surfaces of fuel canisters.
- Several concrete deterioration and rebar-corrosion mechanisms are known to cause degradation of reinforced concrete in dry-storage systems, including the storage pad.
- Some plausible off-normal and accident scenarios for the handling and transport of used-fuel casks have not been fully evaluated.
- There are security risks associated with the dry storage of used fuel, and the risks will likely change with time.

Dispersion of radioactivity from spent fuel

During interim storage of spent fuel 80-90% of the tritium in the fuel will diffuse through the zirconium cladding and is released into the environment. The tritium releases are authorized, because it is technically nearly impossible to retain this radionuclide. In addition other radionuclides will escape into the environment as a result of leaking fuel pins. As pointed out in the previous section, the condition of spent fuel elements unavoidably deteriorates over time, so leaks will become more frequent with time.

If the spent fuel is stored in cooling pools, the escaped radioanuclides end up the cooling water. Gaseous fission products escape from the water and are released into the air, especially the noble gases krypton-85, xenon-131 and xenon-133, which cannot be retained. Other radionuclides can be separated from the water by a filtering and purification system. Some very soluble radionuclides, such as iodine-129 and cesium-137, may partly escape from the water purification step and are released into the environment.

If stored in dry casks the radionuclides from leaking fuel pins end up in the inner vessel (‘container’). When this container also fails due to corrosion and other degrading processes, the outer vessel (‘cask’) is the only barrier to the environment. It is a matter of time before the outer vessel starts leaking. Probably the outer vessel will fail first, because it is exposed to air, water vapor, contaminants in the air and nuclear radiation. From the outside of the concrete radiation shield it is hardly possible to check the condition of the two metal vessels inside, other than the detection of radionuclides when the containment of the spent fuel has failed.

Conceivable mechanisms of dispersion of very large amounts of radioactivity are addressed in report m17 *Pathways of radioactive contamination*.

3 Bathtub hazard function

Failure rates

The risks for catastrophic breakdown of technical devices, including nuclear reactors, change as the devices age, much like the risks for death by accident and illness change as people get older. There are three distinct stages in the lifetime of a technical system or living organism:

- the break-in phase, also called the burn-in phase or the infant mortality phase,
- the middle life phase, also called the useful life,
- the wear-out phase.

The risk profile, the failure rate as a function of time, for these three phases curves like a bathtub (see Figure 1). The bathtub curve is drawn from statistical data about lifetimes of both living and nonliving things, such as cars, cats or nuclear reactors [Sheldon 2009] Q165, [Stancliff et al. 2006] Q433, various classical textbooks on this subject).

Applied to technical devices only, the bathtub curve may be considered to be the sum of three types of failure rates:

- Early life ('infant mortality') failures, caused by bad design, defective manufacturing, material imperfections, faulty installation, unanticipated interactions, poor workmanship imperfect maintenance and ineffective operation. The failure rate of this type decreases with time. The steepness of this curve depends on factors such as the amount of 'pre-flight' testing and the effectiveness of the quality control during manufacturing.
- A constant rate of random failures during working life, caused by accidents and random events. The height of this rate depends on, among other things, the quality of the materials, of the design and the professionalism of the operators. In principle the random failure rate does not change with time.
- Wear-out failures, caused by ageing, deterioration of materials, etcetera. This rate increases with time. Wear-out failures are typically the consequences of Second Law phenomena.

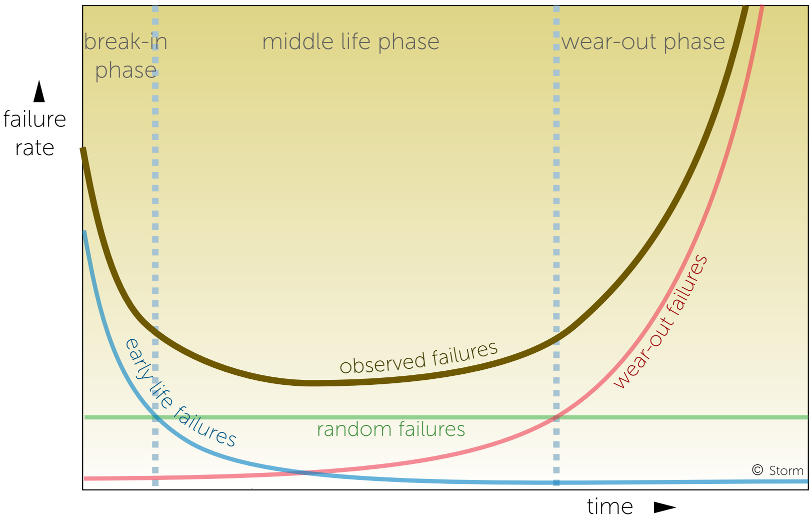

Figure 1

The bathtub hazard curve is the sum of three types of failures rates: the early life failures, decreasing with time, the random failures, constant over time, and the wear out failures, increasing over time, these are typical Second Law phenomena. The bathtub curve is valid for technical devices, including nuclear installations, as well as for living organisms.

Preflight testing

The concepts behind the bathtub curve are playing an important part in space technology. The reliability and predictability of the behavior of each component of a spacecraft or launch vehicle has to be extremely high to achieve a specified reliability of the complex assembly as a whole: the spacecraft or launch vehicle. Extensive testing and screening procedures are applied to pass all components and assemblies through the break-in phase and to eliminate design flaws, manufacturing defects, etcetera. Functional flexibility by redundancy in the design of the spacecraft systems and very high quality standards minimalize the occurrence of random failures and postpone the wear-out failures. Exhaustive screening and pre-flight testing and stringent quality control enables a spacecraft to function unattended for a decade or longer. The effort needed to achieve such a level of reliability is exceedingly large, a direct consequence of the Second law. Large efforts mean high input of energy, materials and human resources, and consequently high financial cost.

Bathtub function and nuclear technology

In commercial nuclear technology no ‘pre-flight’ testing occurs. A nuclear power plant is assembled at the location chosen by the utility that will operate the plant. Design flaws and manufacturing defects are uncovered during construction and the first several years of operation of the nuclear power plant: the burn-in phase. Historical evidence indicates the burn-in phase of nuclear power plants to be several years. Major failures of nuclear reactors, including Three Mile Island 2 and Chernobyl, occurred during the burn-in phase.

As [Lochbaum 2004] Q76 put it, describing the situation in the USA:

> The nuclear power industry’s chronic quality control problems during design and construction are legendary, as is the NRC’s (Nuclear Regulatory Commission) consistent inability to do anything about it.

How is the situation in other countries?

Ageing processes of technical systems are consequences of the Second Law. Ageing processes are difficult to detect because they usually occur on the microscopic level of the inner structure of materials. The consequences are two-fold. Firstly, the number of incidents and reportable events will increase. Secondly, the aging process is leading to the gradual weakening of materials that could lead to catastrophic failures. Most notable among these processes is the embrittlement of the reactor pressure vessel. Failure of the pressure vessel of a PWR or BWR inevitably will lead to a catastrophic release of radioactive material into the environment.

These factors are contributing to the burn-in phase failures that are one of the causes of massive cost overruns of nuclear power plants and other large technological energy projects, as analyzed by the RAND Corporation, [RAND 1981] Q126 and [RAND 1979] Q127. Recent examples of a common course of events within the nuclear industry, building before testing, are the troubled construction of the European Pressurized Reactors (EPR) at Olkiluoto in Finland and at Flamanville in France, causing dramatic cost overruns and time delays.

No human-made structure can be made absolutely fail-safe for an operating lifetime of decades. Accidents and random events are unpredictable by definition. The functionality of materials and structures predictably declines with time by cracking, wear, corrosion and other Second Law phenomena. The rate of wear-out failures predictably increases with time. These observations lead to one conclusion:

> *Inherently safe nuclear power is inherently impossible.*

4 Nuclear safety

Nuclear safety, or better: safety of nuclear power, is a complex issue, involving all aspects of nuclear power which could inflict directly or indirectly harm to the health and wellness of people and/or damage to material belongings.

Military and civil nuclear technology are inseparable

Military and civil nuclear technology are inseparable. Military applications (weapons, nuclear propulsion) are not discussed here. However, civil nuclear technology can be used for military purposes: if this happens in unfriendly countries the notion proliferation is often used. Another (semi) military threat which may originate from civil nuclear technology are terroristic actions with primitive nuclear weapons made from civil MOX fuel.

Proliferation

It is possible to apply civil nuclear technology to create nuclear weapons. By means of commercial enrichment bomb-grade uranium-235 can be produced (the fissile isotope of uranium). In research reactors bomb-grade plutonium can be generated from non-fissionable uranium-238. In a reprocessing plant the plutonium can be separated from the uranium and fission products. If the process is aimed at the production of weapon-grade plutonium the irradiation time of the nuclear fuel is kept short and the reprocessing of the spent fuel is not extremely demanding. Technology needed to make nuclear bombs from fissile material is available outside of the established nuclear-armed countries and in the open literature, as the Nth Country Experiment proved [Frank 1967] Q591, [Schneider 2007] Q590.

Nuclear terrorism and MOX fuel

Plutonium recycling in light-water reactors (LWRs) using MOX fuel (Mixed OXide) unavoidably generates uncontrollable risks of nuclear terrorism and proliferation. Using elementary chemistry MOX fuel can be separated into uranium and plutonium. The plutonium could be used to produce a crude nuclear weapon. Evidently such a weapon wouldn't have the reliability and yield of a military weapon, but even a nuclear explosion of a few kilotons in a town may be devastating. Even without a nuclear explosion the dispersion of several kilograms of plutonium over a town by a small plane may render the town inhabitable.

Reactor safety studies are discussed in next chapter, Theory versus practice

Main safety concern: dispersion of radioactivity

A unique feature of nuclear power is the generation of huge amounts of man-made radioactivity. All radioactivity is harmful and dangerous to humans. Apart from military and terroristic nuclear explosions, the safety issue of nuclear power concerns the possibilities of dispersion of the radioactivity into the human environment and the exposure of millions of people to radioactivity, leading to insidious and not seldom fatal diseases, usually after a long time delay.

This threat exists every day and involves vast and densely inhabited regions of the world: all regions with nuclear power stations and/or activities related to nuclear power. In addition the chance of releases of massive amounts of radioactivity increases year by year, due to:

- rapidly increasing amounts of human-made radioactivity: 370000 nuclear bomb equivalents per year are added to the world inventory,
- increasing number of temporary and vulnerable storage facilities,
- unavoidably progressive deterioration of the confinement of the stored radioactive materials.
- increasing economic pressure, the more so in times of crisis, leading to less than optimal handling of the radioactive wastes.

5 Theory versus practice

Limited scope of safety studies

Security and safety are terms with different connotations in different contexts. 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 reactor-years.
The present world reactor fleet encompasses about 400 reactors. A chance of one major accident per million reactor-years would mean that a major accident could be expected once every 2500 calendar years (1 million divided by 400). Negligible compared to other risks, posed by other events in the society, as stated by the nuclear industry.
Empirical evidence proves the results of the reactor safety studies to be of little practical meaning. During the past decades three major reactor core meltdowns occurred: Three Miles Island (1979), Chernobyl (1986) and Fukushima (2011), an occurrence of once every 10-20 years, not counting other disasters in the former Soviet Union. This empirical fact is still invisible in the official publications of the nuclear industry concerning nuclear safety.

The claims of safe reactors by the nuclear industry are based on a small number of theoretical model studies, not on empirical data or on ‘preflight testing’. In addition it is a fallacy to state that nuclear power is safe when the reactors are ‘safe’ (however defined). Firstly, there are many other potential sources of large-scale accidents. Secondly, inherently safe nuclear reactors and other nuclear installations are inherently impossible, as is explained in chapter 3.

Another aspect of the theoretical basis of the security culture in the nuclear industry is its reliance on computer models. Each computer model has two kinds of limitations: inherent limitations and choice limitations. Inherent limitations follow from the fact that each model is by definition a simplified presentation of the reality. Choice limitations originate from the choices of parameters and variables and their values incorporated in the model.
Well-established regulations on paper are seen as the best way to prevent large nuclear accidents, proliferation, terrorism, etcetera. Adequate inspections and surveillance and means to enforce the regulations get less attention from the nuclear industry. Fulfilment of the regulations is usually left to the operators of the nuclear facilities, for they are too costly to implement effectively on an international scale. Besides that, political complications often play a part. Unfortunately, the consequences of a nuclear disaster do not stop at the border of a country.

Reactor safety studies of the Western nuclear industry

The first major study on reactor safety was the famous ‘Rasmussen Report’ [WASH-1400 1975] Q416. This report has been updated in 1990 [NUREG-1150 1990] Q417 and is at present being updated in the State-of-the-Art Reactor Consequence Analyses (SOARCA) by the US Nuclear Regulatory Commission NRC. Up until today only LWRs (light-water reactors) in the USA have been analyzed. Internationally the results of the US nuclear safety studies seem to be adopted as standards for other safety studies.

The official safety studies are Probabilistic Risk Analyses (PRAs), which have a limited scope:
- the PRA methodology does not cover all kinds of events which can cause a severe reactor accident,
- ageing and other Second Law effects are hardly quantifiable and are not included,
- unpredictable human behavior cannot be quantified.

The limited significance of PRA studies is also discussed by [Dorfman et al. 2013] Q288 and [Hirsch 2006]

Q426.
Only a fraction of the processes comprising the worldwide nuclear energy system turns out to be examined in detail, for the safety analyses focus on nuclear reactors, in particular light-water reactors from Western vendors. What do we know about other reactor types (gas-cooled reactors, heavy water reactors, liquid metal-cooled reactors) and, equally important, about reactors from vendors in Russia, China, India, Japan, and Korea?

In the US the Nuclear Regulatory Commission (NRC) is found to be highly reliant on information from licensee risk assessments. There are no PRA standards, no requirements for licensee's PRAs to be updated or accurate, and consequently the quality of the assessments varies considerably among licensees (NRC 2002). Another limitation of the official safety studies is the fact that the other processes comprising the nuclear chain are only marginally, or not at all, addressed.

Those other industrial processes of the nuclear chain are practically invisible to the public, but not less important with respect to security. The amounts of radioactivity present at a given location of one of the back-end processes may be greater than the inventory of an operating nuclear reactor.

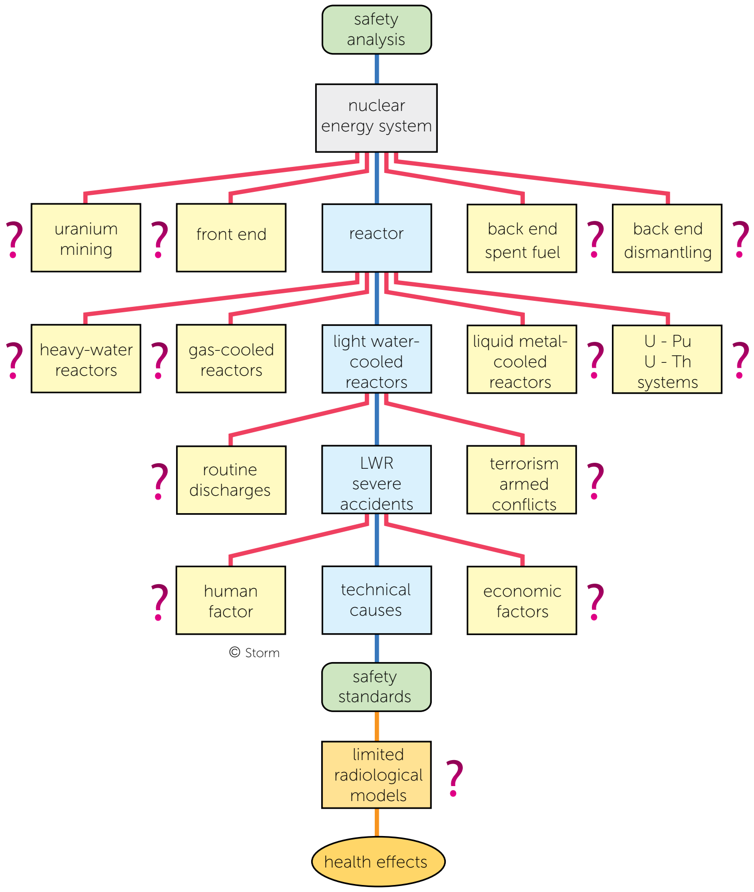

Figure 2

Decision tree of the analysis of the safety of nuclear power. Only a fraction of the processes comprising the worldwide nuclear energy system turns out to be examined in detail, for the safety analyses focus on nuclear reactors, in particular light-water reactors from Western vendors. The majority of the nuclear safety issues (see the queries in above diagram) may never have been investigated, at least not as thouroughly as the technical LWR safety issue.

In the USA the Nuclear Regulatory Commission (NRC) is found to be highly reliant on information from licensee risk assessments. There are no PRA standards, no requirements for licensee's PRAs to be updated or accurate, and that the quality of the assessments varies considerably among licensees [NRC 2002] Q175.

Another limitation of the official safety studies is the fact that the other processes comprising the nuclear chain are marginally or not mentioned, see the queries in Figure 2. After unloading from the nuclear power plant the generated billion-x amounts of radioactivity are passed on to the downstream processes. How safe are these downstream processes?

The emphasis on the reactor safety may also be prompted by the high public visibility to the of nuclear power plants and by the accidents at Mayak in 1957, Three Mile Island-2 in 1979, Chernobyl in 1986 and Fukushima in 2011. The other industrial processes of the nuclear chain are practically invisible to the public, but not less important with respect to health risks. The amounts of radioactivity present at a given location of one of the downstream processes may be a hundredfold of the inventory of an operating nuclear reactor. The safety of nuclear power is a very complex issue comprising a lot more contributing factors than the chance of a technical failure in a nuclear reactor leading to a severe nuclear accident. Besides, that chance is not determined only by the technical safety standards of the reactor as described on paper, for non-technical factors could initiate such accidents as well.

6 Engineered safety

Narrow safety margins

No technical system is perfect. In every production plant at any moment something may go wrong: a leaking coupling, a stuck valve, a bad electric contact, or whatever. Generally such failures can be ironed out without interruption of the production process or without endangering the personel. In a nuclear plant the health risks are much larger than in conventional plants. A small spill, only a nuisance in a conventional plant, may have serious consequences in a nuclear plant. For that reason the quality specifications for materials, control systems and personel in a nuclear plant and other nuclear facilities, such as reprocessing plants, are considerably higher than in non-nuclear plants.

Narrow safety margins are not typical for nuclear technology, but are typical for all high-tech applications, for example manned space flight. The crashes of the American space shuttles Challenger (1986) and Columbia (2003) are caused by ostensible minor technical imperfections. The launch vehicle of the Challenger exploded as a result of an O-ring that was too cold at launch. The Discovery broke up during reentry because some pieces of plastic insolation came off the fuel tank during launch and damaged a critical part of the heat shield of the spacecraft.
The difference lays in the extent of the consequences of an accident involving a high-tech object. The crashes of the two space shuttles took the lives of their crews, 14 people. A similar technical failure in a nuclear power plant may take the lives of tens of thousands of people and the health of millions of people, as has been proved by the Chernobyl and Fukushima disasters.

High quality requirements

High quality specifications mean a high degree of predictability of the properties and behavior of materials and structures. The higher the specifications the lower the tolerance for random occurrences, for impurities in the materials and for deviation from the dimensional specifications of the structures. High quality standards can be met by stringent control during the production process and by a large input of useful energy, most of it embedded in materials, specialized equipment and education of highly skilled personel. From the Second Law follows that the energy inputs exponentially increase with increasing quality specifications of a given amount of material or piece of equipment.

Unrealistic faith in high-tech systems seems to be based on some implicit assumptions:
- availability of perfect materials,
- 100% predictability of the properties and behaviour of a technical system
- 100% perfect controllability of a system.

The latter assumption implies, among other, a 100% predictable human behavior.
The first two assumptions are in conflict with the Second Law of thermodynamics. One of the consequences of the Second Law is that separation and purification processes never go to completion, so 100% pure materials and 100% reliability of constructions are impossible.

High quality specifications mean a high degree of predictability of the properties and behavior of materials and structures. The higher the specifications the lower the tolerance for random occurrences, for impurities in the materials and for deviation from the dimensional specifications of the structures. High quality standards can be met by stringent control during the production process and by a large input of energy, most of it embedded in materials and specialized equipment. From the Second Law follows that the energy inputs exponentially increase with increasing quality specifications of a given amount of material or piece

of equipment.
One of the conclusions of [Paulitz 2012] Q559, in his analysis of the Fukushima accident is:

> "Not to be underestimated is also the fact that every nuclear reactor has its own—albeit unlikely— "trigger event" or accident scenario for which there is simply no solution and, to all intents and purposes, the workforce is obliged to look on helplessly while the meltdown takes place."

Human factor

Even if the engineered safety measures of nuclear power work according the design criteria, which of course is not always the case, risks are introduced by the human factor. Routine tasks such as operation and maintenance are susceptible to errors, sloppiness, poorly educated personel and incompetention. Any company and organisation may have to deal with this kind of factors, but in the nuclear industry the safety margins are small and the consequences may be disproportionally large and irreversible.

Problem identification and resolution programs – how plant owners find and fix safety problems – are often flawed or even dysfunctional. Violation of the Technical Specifications, part of the operating license issued by the NRC to the owner of each power reactor in the USA, is another problem [Lochbaum 2004] Q76 observes. How is the situation in other countries?

Bad management, shortage of funds and qualified personel, shifting priorities, matters of prestige and cognitive dissonance will lead to less than optimal control and consequently to enhancement of risks. Financial interests may entice people to make choices based on a belief in unproved technology and the economy of the marketplace or an unshakeable faith in security measures which seem perfect on paper but turn out to exist only in cyberspace, while arguing away the contra-indications.

7 Economic preferences versus security

The economic connection

Non-Proliferation Treaty

Investments in nuclear power plants, reprocessing plants and other nuclear facilities are exceedingly high. Not surprisingly the nuclear industry seeks new markets, to sell their products or technology to other countries, however questionable from a political point of view. In 1970 the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) entered into force. Since that date numerous violations of letter and spirit of the NPT, involving many countries, such as, USA, Canada, Russia, France and China [Schneider 2007] Q590. Do economic motives prevail over security risks?

MOX fuel

Use of plutonium in MOX fuel generates high risks of diversion, hijacking and theft of bomb-usable fissile material. From an energy point of view there are no physical arguments in favour of recycling plutonium in light-water reactors, for the energy balance of the use of MOX is negative. The recovery of plutonium by reprocessing spent fuel and the fabrication of the MOX fuel elements consume more energy than can be generated from the MOX fuel, if all processes from cradle to grave are included in the energy balance. Especially the decommissioning and dismantling of the reprocessing plant will require a massive investment of energy, materials and human effort.

So for what reason MOX is still used, despite the very serious security issues it raises? Just for short-term profit making, to generate some return on the extremely high investments of the reprocessing plants?

Independence

Nuclear security may easily become at odds with economic preferences if the required investments do not generate a return on investment in the short term. Safety measures are vulnerable to economic priorities and short-sighted choices: the standards, the quality control and the independence of inspections. The strained connections between economics and nuclear security is clearly expressed in the French Roussely report [Roussely 2010] Q427:

> 'La question du risque nucléaire acceptable, ou plus généralement du risque technologique acceptable, est un débat de société à part entière pour lequel la ou les réponses à donner sont naturellement du rôle du Politique. Force est néanmoins de constater que la notion même de compétitivité du nucléaire et l'hétérogénéite des règles de sûreté selon les Etats renforcent l'actualité de ce débat et la nécessité de préciser certaines exigences de sûreté. La seule logique raisonnable ne peut pas être une croissance continue des exigences de sûreté.'

In English translation:

> 'The question of what is an acceptable nuclear risk, or more generally an acceptable technological risk, is a debate that concerns the entire society and for which the answer(s) obviously belongs in the political domain. However, one must note that the concept itself of competitiveness of nuclear power and the heterogeneity of the security rules according to each country reinforce the relevance of this debate and the need to specify certain security requirements. The continued increase of security requirements cannot be the only reasonable rationale.'

Radiological protection recommendations

The International System of Radiological Protection that is used across Europe and worldwide is based on the recommendations of the International Commission on Radiological Protection ICRP and the International Commission on Radiation Units and Measurements (ICRU), according to [SCENIHR 2012] Q533. These recommendations are based on three fundamental, essentially economic, principles:

- justification

- optimization
- dose limitation.

The principles of justification and optimization apply universally to all three exposure categories defined by the ICRP, whereas dose limits apply only to planned exposure situations, except some medical exposure situations.

The main task of the ICRP seems to be the formulation of a legal framework for authorities and politicians on how to cope with liabilities which may arise by exposure of people to radiation and/or radioactive materials, see for example [ICRP 103 2007] Q544 and [ICRP 111 2009] %35.

Life extension of nuclear power plants

De-regulation (liberalisation) of electricity markets has pushed nuclear utitlities to decrease safety-related investments and limit staff [Hirsch et al. 2005] Q169.

Extension of the operational lifetime of a nuclear power plant may be the single most important determinant of nuclear electricity production in the coming decades according to the IAEA, as quoted by Hirsch et al 2005. This trend is clearly grounded in economics: the cost of the currently operating reactors escalated during construction by a factor 2-5, so there is a strong incentive to extend the operational lifetime of the reactors beyond their intended design lifetime. New reactors are even more expensive; costs overruns are the rule in the nuclear industry.

Licensing procedures for lifetime extension are based on the as-designed quality of materials and structures. However, the reactors in question are now in the wear-out phase of the bathtub function, implying that the failure rate of components is increasing exponentially.

As the world's nuclear power plant population gets older, there are efforts to downplay the role of ageing, including conveniently narrowing the definition of ageing. There are ageing effects leading to gradual weakening of materials which may have no observable consequences during reactor operation, but which could lead to catastrophic failures of components and thus subsequent severe radioactive releases. Most notable among those is the embrittlement of the reactor pressure vessel, increasing the hazard of vessel bursting. Failure of the pressure vessel of a PWR or a BWR constitutes an accident beyond the design basis.

Relaxation of clearance standards

The high and continually escalating costs of waste management and disposal may provoke undesirable developments and hazardous situations. Standards and regulations may be relaxed to admit higher concentrations of radionuclides in materials for clearance, because of economic reasons. Clearance is the controlled release of materials into the public domain; once released the materials are no longer subject to regulation.

The International Atomic Energy Agency (IAEA) proposed to dilute radioactive materials with non-radioactive and to use concrete rubble as landfill or road paving [IAEA-293 1988] Q36. 'Weakly' radioactive steel scrap – however defined and measured – could be remelted with fresh steel and used for 'special purposes'. Reuse of 'low-activity' contaminated and/or activated steel and concrete by diluting it with fresh steel or concrete, as proposed by the IAEA, might be very risky for several reasons:

- the unknown but potentially hazardous isotopic composition of the scrap and rubble
- the unknown biological behavior of the radionuclides
- problematic detection of a number of radionuclides .
- uncertainties with regard to standards, inspection and control
- the high risk of uncontrolled trade in radioactive materials.

Findings of the National Council of Radiation Protection and Measurements [NRCP-141 2002] Q272, concerning potentially radioactive scrap metals, are indicative of an urgent and problematic situation in the USA:

> 'There is an urgency to establish consistent national/international policies and standards.'

In Europe, with its many different countries, the situation is far more complex and probably more problematic. In case of the waste released by dismantling nuclear power plants and other nuclear facilities, it would be wise to avoid unconditioned waste shipments and trade of radioactive scrap metal and debris as much as possible by packing the materials at the source: the reactor or reprocessing plant being dismantled.

Regulations and quality control

What is the radioisotopic composition of any given radioactive component in the debris or scrap? Will that composition have been measured or will it be estimated based on models from the early 1970s? What is known about the biomedical activity of the radionuclides in the debris and scrap? Another problem is the difficulty in detection of a number of hazardous radionuclides.

In view of the large problems already existing with regard to illicit trafficking, great risks are looming here, even without relaxing the standards. Large volumes of debris and scrap that can be measured in thousands of tonnes, sometimes of high value on the free market, are released by decommissioning and dismantling of nuclear facilities.

If the handling and management of radioactive debris is left to private companies, profit seeking might easily prevail over safety and public health. Financial motives for short-term 'solutions' may be backed by financial constructions that place the liability for failures and mishaps on the customer, which in turn would place it on the taxpayer. Such financial constructions seem to be involved in the contracts for decommissioning and dismantling of the Sellafield reprocessing plant under the authority of the British Nuclear Decommissioning Authority [NDA 2006] Q365.

Relaxation of discharge standards

Economic arguments may also lead to relaxation of the standards for routine emissions of radioactive materials by nuclear installations. An example is the proposal of the US Environmental Protection Agency (EPA) to dramatically raise permissible release levels. The new standards permit public exposure to radiation levels vastly higher than EPA had previously deemed unacceptably dangerous [PEER 2009] Q422. EPA increased permissible public exposure to radiation in drinking water with factors of 1000 to 100 000 involving several fission products with short and long half-lives. In the most extreme case the new standard would permit radionuclide concentrations 7 million times more lax than permitted under the Safe Drinking Water Act. Other aspects of the new EPA proposal are lax cleanups and higher exposures to other sources, such as relaxed dirty bomb standards.

In view of the reliance on models within the nuclear industry and the ease with which models can be adapted to changing financial needs of the nuclear industry, any relaxation of standards should be based on verifiable empirical evidence.

How independent are the inspections?

Several incidents at nuclear power stations in the US during the past years point to reduced quality controls by official inspectors. In a number of countries the nuclear industry urges simplified and shortened licensing procedures to speed up the construction of new nuclear build, with minimalization or even elimination of the participation by the local authorities and the public.

The independence of the controlling institutions may suffer under economic pressure. The above described relaxation of the exposure standards by the US EPA points in that direction. The Roussely report (Roussely 2010) calls for a reduction of the independence of the French Safety Authority ASN (Autorité de Sûreté Nucléaire), see quotes above. The decision process on nuclear power in France is controlled by the president and the Corps des Mines (a technocratic elite), effectively without the participation of the parliament [Schneider 2008] Q428.

How is the situation in other countries?

8 Preventable accidents are unavoidable

The official Japanese investigators called the Fukushima disaster a ‘man-made accident’ and a ‘preventable accident’ [NAIIC 2012a] Q496. Obviously all accidents involving man-made objects and technical installations are man-made. At issue is the question: are ‘man-made’ accidents always preventable? A particular accident may seem preventable, for in principle nearly all failure modes are preventable. However, the occurrence of ‘man-made’ accidents in general is not preventable. Accidents will happen, that is one of the consequences of the Second Law. We just cannot predict where and when and which failure mode will occur. What’s more, nuclear power is inherently unsafe, as pointed out above.

The sinking of the Titanic in 1912, the chemical disaster at Bhopal in 1984 and the crashes of the US space shuttles Challenger (1986) and Columbia (2003) are some well-known examples of non-nuclear preventable accidents. Preventable and man-made accidents, they happened, although nobody wished them to happen. If technical installations with narrow safety margins are involved, such as nuclear reactors and spacecraft, the consequences of a minor mishap could be disastrous.

Chairman Kiyoshi Kurokawa of the official commission that investigated the Fukushima disaster seems to endorse this viewpoint in his Preface to the final report [NAIIC 2012b] Q564:

> The parties involved in this accident had forgotten some fundamental principles: “accidents will occur,” “machinery will break down,” and “humans will err.” They minimized the possibility of accidents to the point of denying it, and in doing so they lost their humility in the face of reality.

To the nuclear industry the qualifications ‘preventable’ and ‘man-made’ seem to suggest that nuclear power in itself is safe and that accidents like the Fukushima disaster could be prevented, for example by writing better regulations; ergo: continuation of the ‘business-as-usual’ mode. Apparently the Chernobyl and Fukushima disasters were not deemed reason to reconsider the indispensability and benefits of nuclear power versus its costs in the sense of economic damage and the harm to the health of millions of people.

As pointed out above the chances of large-scale nuclear accidents are rising with time for a number of reasons, despite efforts to make nuclear power safer. Economic factors might prove a high risk factor.

Nearly all accidents involving technical installations are ‘preventable’. In principle nearly all failure modes are predictable, except the impact of a large meteorite or the landing of a spacecraft with aliens. Each individual accident with a technical installation may seem preventable, but accidents inevitably will happen. We just cannot predict where, when and which failure mode will occur.

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