OPERATING A VERY OLD FLEET OF NUCLEAR POWER PLANTS

Climate crisis: Why Nuclear is not Helping
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Climate Change and Nuclear Power Plants

- The current anthropogenic climate change affects nuclear energy production in several ways, including
  1. *Efficiency of nuclear power plants decreases with increasing temperature, and increasing number and duration of outages due to lack of cooling water;*
  2. *Some sites may lose safety, with sea-level rise being of particular importance;*
  3. *Frequency and intensity of extreme events change with possible consequences for safety requirements.*

- **Can ageing plants contribute to energy security and which additional risks will arise due to climate change phenomena?**

Outline

- Limited contribution of new nuclear power plants to energy supply security
- General risk connected to the operation of NPPs
  - ***Risk of severe accidents***
  - *Proliferation risk and risks connected to mining and radioactive waste*
- Specific risks of weather-related events for ageing NPPs
- General consideration of ageing problems
- Increasing risks due climate changes
- Examples for weather related events as threats for the safety of NPPs
- Less profits versus expensive back-fittings

1 ENERGY SUPPLY SECURITY IN TIMES OF CLIMATE CHANGE

1 Energy Supply Security in times of climate change – Introduction

- Limited contribution of new nuclear power plants to energy supply security
  - *Significant delays between planning and operation of NPPs*
  - *Comparatively high costs and investment risks of NPPs*

- Limited contribution of ageing nuclear power plants to energy supply security
  - *Ageing related outages*
  - *Climate change related outages*

Average load factors in 2018

- **United Kingdom** operated 15 reactors, average age of reactors: **35.5 years**
  - *U.K.'s reactor fleet achieved an average load factor of **68.4 percent**,*
  - *Age related cracking at the reactors at Hunterston*
- **France**: average age of 58 reactors: 34.4 years, annual load factor: 69.6 percent
  - *According to operator EDF, generation performance was affected by exceptional damages and large generation incidents (costing around 12.5 TWh), longer-than-expected outages (5 TWh) and environmental constraints (2 TWh). Outage extensions experienced were caused by maintenance and operational quality issues, technical failures and project management deficiencies.*

Average annual load factors 2018

- Belgium, average age of reactors: 39.3 years
  - *On average, the seven Belgian units were down half of the year (average annual load factors: 49 percent) and in October 2018 power prices reached record levels (€205/MWh).*
  - *In summer 2012, the operator identified thousands of hydrogen-induced crack indications in the reactor pressure vessels of Doel-3 and Tihange-2.*
  - *In April 2018, the International Nuclear Risk Assessment Group (INRAG) stated on Tihange-2 that "the risk of failure of the reactor pressure vessel is not practically excluded" and requested that "the reactor must therefore be temporarily shut down".*

Nuclear Power’s Poor Performance under Climate Change

- Nuclear reactors must be permanently cooled to ensure their safety. For this purpose, water is taken from a river or sea.
- Summer of 2003: France, Spain, Germany and other European nations are hit with extraordinary heat wave and drought – ultimately killing over 30,000. Spain shuts NPPs down; France and Germany allow some NPPs to exceed standards and thermal discharge regulations, while shutting others.
- July, 2009: 20GW of France’s total nuclear generating capacity of 63GW was out of service due to reaching thermal discharge limits for French rivers.
- 2018, France saw an 0.7% loss of output.
- In Switzerland , Axpo 's 760-MW Beznau nuclear plant in Switzerland reduced its output by 50% July 24 and 25 as the temperature of the Aare River, which supplies its cooling water, reached 24 C (75) Betreiber Axpo protestiert, Die Axpo argumentiert, sie habe im Vertrauen auf die unbefristet gültige Einleitbewilligung namhafte Investitionen in die Anlage getätigt.

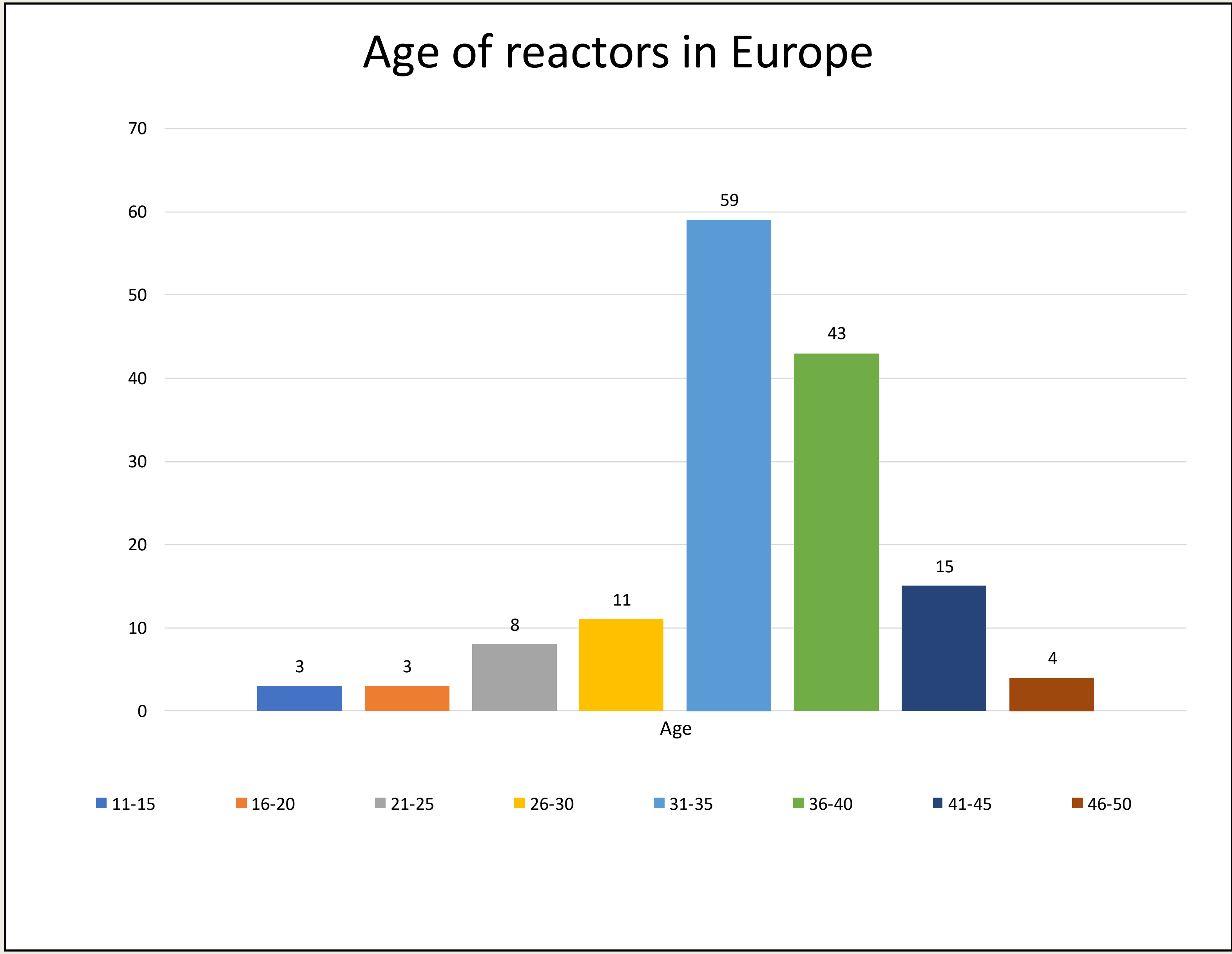
AGEING REACTORS

INRAG Study 2019

- Members are academics, former members and heads of nuclear authorities, members of technical support organizations, independent scientists and experts
- Members from Austria, Bulgaria, France, Germany, Sweden, the UK and the USA…
- INRAG - International Nuclear Risk Assessment Group
  - *provides international independent expertise in the nuclear field*
  - *performs analyses, based on scientific and technically sound knowledge and expertise*
  - *makes international expert knowledge available to the public and decision-makers*
- Study: Assess problems and risks connected to life time extension (LTE) and long term operation (LTO) of nuclear power plants
- Study performed for 'Alliance of Regions for Phasing out Nuclear Power across Europe'

Situation in Europe

- Europe is looking at a fleet of aging reactors, currently planning to continue their operation for a long time



Physical aging (1)

- Physical aging: degradation of structures, systems and components (SSC) due to variation in temperature, stress, ionizing radiation, chemical processes
- Examples: Aging of reactor pressure vessel, primary system components, valves, pumps, concrete structures, electrical systems
- Aging effects like corrosion, wear, embrittlement, reduce the effectiveness or quality of safety systems / safety relevant components.
- Aging management program consists in identifying, monitoring and timely replacement of aging structures
- Aging components increase the risk for abnormal operational occurrences and accidents.

Physical aging (2)

- Aging management works well with known aging mechanisms and accessible and replaceable SSCs
- However,
  - *some components cannot be replaced (example: RPV), aging effects here reduce the safety margin*
  - *Some components are difficult to access (example: piping in concrete)*
  - *Not all aging effects are known*

Physical degradation due to ageing mechanism is one of the most important contributors to common cause failures.

  - *Common cause failures: the simultaneous failures of redundant components, could result in the lost of one or more levels of protection of the defense in depth concept.*
  - *Since April 1998, the NEA has formally operated the International Common-Cause Failure Data Exchange (ICDE) Project.*

Obsolescence (1)
(Conceptual/Technological Ageing)

- Meaning that SSCs are out of date compared to current knowledge, standards and technology
- Huge steps forward in technology/standards occurred after major accidents (TMI, Cernobyl, Fukushima)
- Changes are often be such that full retrofitting is impossible (concepts like redundancy, diversity, physical separation)
- The safety design of NPPs is very important to prevent as well as to deal with accidents.
- The concerns are growing due to the Fukushima accident, as it revealed that there could be basic safety problems with the old units, whose design was prepared back in the sixties or seventies.
- The safety design of all operating plants is outdated and showing deficiencies (e.g. in equipment qualification, separation, diversity, protection against external events)
- Development of science and technology continuously produces new knowledge, e.g. about possible failure modes, properties of materials. This leads to technological ageing of the existing safety concept in NPPs.
- Very often, new regulatory requirements are applicable only to new nuclear power plants, while for existing plants different criteria are applied. This concerns, among others, the protection against fire.

Obsolescence (1) (Conceptual/Technological Ageing) Examples – limits of backfitting

- Higher requirements
  - *in redundancy (e.g. n+2 concept instead of n+1) and*
  - *in diversity*
  - *of physical separation of safety systems*
- Requirement of safety related systems able to manage a core melt (core catcher, in-vessel retention)
- Protection against external hazards

Double Standards

- The design of current reactors is out of age and would not be accepted today
- In many cases, existing reactor designs would not receive a construction license, would the operator apply today. To nowadays standards, their risk is not acceptable.
- Most European countries accept different standards for existing and “new” reactors (Council Directive 2014/87/Euratom has different provisions for reactors with construction license before and after 4 August 2014)
- On the basis of the EU stress tests (2011/12), the lessons learned from the Fukushima accident and the safety requirements of WENRA and IAEA, the EU amended its Nuclear Safety Directive in 2014.

CLIMATE CHANGE

Climate Change Introduction

- As Earth’s climate has warmed, a new pattern of more frequent and more intense weather events has unfolded around the world.
- Global warming can contribute to the intensity of heat waves by increasing the number of very hot days and nights.
- Warming air also boosts evaporation, which can worsen drought. More drought creates dry fields and forests that are prone to catching fire,
- Global warming also increases water vapor in the atmosphere, which can lead to more frequent heavy rain and snowstorms.
- In addition, global warming causes sea level to rise, which increases the amount of seawater, along with more rainfall, that is pushed on to shore during coastal storms. That can result in destructive flooding.

Rainstorms over Europe

- From late May until mid-June 2016, a persistent large-scale weather pattern with thunderstorms produced intense precipitation which caused both local flash floods and widespread flooding in central Europe.
- The floods struck many places with no warning.
- South of Paris, the River Loing rose to a record level. In Paris, the Louvre had to be closed and works of art moved to higher stores.
- From 31 May to 1 June, further flash floods followed in Saxony, Bavaria, and in Austria.
- In Simbach in Lower Bavaria, the stream of the same name rose from 0.5 metres to around 5 metres within just a few hours, flooding around 5,000 households. Seven people lost their lives.
- The floods in central Europe stemmed from an unusual general weather pattern that persisted for an exceptionally long time, from 27 May to 9 June. A characteristic feature of the pattern was that the fast-flowing, high-altitude air current known as the jet stream formed a wave over Europe
- The block had devastating consequences in some regions. In Germany, storms formed on a daily basis from 28 May to 5 June, each bringing over 50 mm of rainfall. As the storms hardly moved, all of the rain fell on an area of just a few square kilometres.
- Besides the inundation depth, the key factor for damage caused by the flash floods was the flow velocity and the trees, boulders, debris and sludge the waters swept along with them. However, it is extremely difficult to account for such variables in catastrophe models.
- That is, we are now observing persistent weather patterns more and more frequently during the summer half-year in the northern hemisphere. Their long duration can result in extreme outcomes.
- Following the events of 2016 in Europe, it should be clear that extreme amounts of precipitation within a very short time are possible almost anywhere.

Climate Change and NPPs Introduction

- Of relevance for the safety of nuclear power plants can be particularly high or low temperatures, prolonged heat or cold episodes as well as dry phases, and particularly high or low humidity values.
- Heavy precipitation (rain or snow), high or particularly gusty winds, snowstorms, freezing rain, thunderstorms, lightning, hail with particularly large grains and tornadoes are also among the potential hazards.
- In areas with more winter precipitation, snowstorms and ice build-up can block cooling water inlets and outlets, especially when wind is blowing at the same time.
- A special safety problem is the so-called biofouling, i.e. the disturbance by plants or animals that can settle at the inlets and outlets of the cooling water under appropriate conditions.

Global Change Climate

- Global average temperature rise is currently already 1.1°C
  - *According to recent estimates, with every increase of 1°C in global mean temperature, nuclear plant generation output declines by 0.4–0.7% at low temperatures and by 2.3% at high temperatures*
  - *If current nuclear generation is projected for 20 years for all current nuclear plants, the global cost of rising temperature is on the order of €1–6 billion*
- Even if the Paris Climate Convention is adhered to, temperature increases of well over +1.5 and +2°C must be expected on land.
- Threats to NPPs due to climate change are relevant for coastal locations, as sea levels are expected to rise by 50 to 90 cm by the end of this century. (IPCC)
- Other experts derive a possible non-linear rise in sea level of 1 m within the next 50 years from ice surface losses in Greenland, and a rise of another 1.4 m within the following decade, i.e. 2.4 m to about 2070.

Gradual Climate Change

Most of the adaption options for old reactors impossible or expensive

Impact	Potential vulnerabilities	Examples of adaptation options
Higher mean temperatures	Decreasing thermal efficiency Decreasing cooling efficiency	Select sites in cooler local climates when possible Design different cooling systems
Lower mean precipitation	Less and warmer cooling water, leading to potential reductions in output or even short term shutdown	Reuse wastewater, recover evaporated water in recirculating systems Improve wet cooling; install dry cooling
Increased windiness near coasts and dry areas	Salt sprays from sea leading to long term corrosion and short circuit of exposed electrical equipment; dust and sand carried by wind, leading to equipment malfunction	Weather seal critical equipment
Sea level rise	Flooding of low lying coastal sites	Raise dykes and other protective embankments

Extreme Weather Events (1)

- Various types of EWE can affect critical safety systems and increase the risk to human health and the environment, making adaptation more than an economic calculus for plant owners.
- Ensuring that external events do not lead to safety system failures is the highest priority for adaptation to EWEs.
- Generally, many acute safety threats from EWEs can be minimized by shutting down nuclear reactors until an event has passed, but this strategy leads to increasing outages as climate change.
- Moreover, a shutdown state during an EWE may not be the safe state.
- Adapting plants so that reactor shutdowns become less frequent would minimize outages as well as avoid costly plant related damages that would have occurred without plant adaptation.
- Extreme weather events and climate-related hazards may directly affect nuclear power plants, but may also be relevant to safety through indirect effects in the surrounding area, because they
  - *limit accessibility (e.g. forest fires or floods), are*
  - *associated with problems (e.g. a dam burst upstream) or*
  - *they affect the power grid (e.g. disturbance by falling trees) with consequences for the availability of off-site energy.*

Extreme Weather Events (2)

- The possibility of two extreme events occurring at about the same time has to be taken into account.
  - *Two extreme events can have the same cause (as in the case of a tropical cyclone which is accompanied by strong rain, giving raise to floods).*
  - *Furthermore, because of the increasing frequency of extreme events, it cannot be excluded that an NPP site will be hit by two independent events within a short time – the second event occurring while the damage from the first has not yet been repaired.*
- Extreme weather conditions can lead to failure of the electricity grid. In this situation, emergency power systems are required which are not necessarily sufficiently reliable and the failure of which can lead to a severe accident.

Extreme Weather Events (3)

- Nuclear power plants are designed to withstand very rare events.
- Probabilities of occurrence are usually derived from past data series using statistical methods.
- In a phase of climate change, however, these data series are no longer valid.
- Estimation of probabilities for extreme events resulting from climate change, is extremely difficult due to fact that there is no sufficient database.
- However, as climate changes, past events are becoming an increasingly inappropriate basis for the prediction of the severity of future events.
- Furthermore, because the situation is constantly evolving, any data that can be acquired may be outdated by the time their evaluation is concluded.

Extreme Weather Events

Impact	Potential vulnerabilities	Examples of adaptation options
Extreme heat	Heat can limit water discharge if temperatures are too high for water quality regulations, which can in turn reduce generation or force a shutdown	Reduce generation to avoid raising stream temperatures from discharged water above regulation
	Heat can further reduce the effectiveness of cooling	Switch from once through cooling to recirculating to reduce temperature of discharged water Switch from wet cooling to dry cooling
	Heat can foster the rapid growth of biological material that can clog cooling water intake, leading to reduced generation or shutdown	Increase maintenance of screens to ensure that biological matter does not clog water intake system
Extreme cold	Ice can clog water cooling systems, leading to reduced generation or automatic shutdown Ice can inhibit plant access Freezing pipes can lead to internal flooding Ice can damage the grid system	Route heated water from cooling system to inlet area Insulate critical piping
Precipitation	Excessive rain or snow can collapse unreinforced structures Excessive rain or snow can inhibit plant access to critical personnel and supply deliveries	Ensure that all buildings housing critical systems are reinforced Develop emergency weather plans Establish special procedures for removal of snow and ice

Extreme Weather Events

Impact	Potential vulnerabilities	Examples of adaptation options
Drought	Low water levels can force plants to reduce generation output or shut down	Implement alternative cooling options: reuse wastewater Recover evaporated water in recirculating systems Switch to dry cooling systems
High winds	Wind generated missiles can damage buildings and backup generators High winds can knock out grid system interconnection	Install tornado missile shields
Floods or sea level rise	Some coastal plants are increasingly vulnerable to storm surges as sea level rises and storms become more intense, whereas other plants may be vulnerable to river floods, both of which can force an automatic shutdown but can also damage critical safety systems and grid system interconnections and threaten spent fuel storage	Consider flood risks in site selection for new plants Build earthworks to minimize risk of flooding Upgrade flood resistant doors Raise elevation of backup diesel generators
Lightning	Lightning can short circuit or create false signals in instrumentation Lightning can short circuit on-site power connection and backup diesel connections and controls	Ensure that circuits are insulated and grounded Bury key circuits underground Shield diesel generator controls
Forest fire and wildfire	Forest fires and wildfires can disrupt plant access to critical personnel, supply deliveries and	Develop emergency access and response plans in case of nearby forest fires and wildfires

Flooding

- The expected main effects of flooding on NPP are as follows:
  - *The presence of water in many areas of the plant may be a common cause of failure for safety related systems, such as the emergency power supply systems or the electric switchyard,*
  - *Considerable damage can also be caused to safety related structures, systems and components by the infiltration of water into internal areas of the plant.*
  - *The dynamic effect of the water can be damaging to the structure and the foundations of the plant as well as the many systems and components located outside the plant.*
  - *Flooding may also affect the communication and transport networks around the plant site.*
  - *Flooding can also contribute to the dispersion of radioactive material to the environment in an accident.*

Flooding Example

- France, 1999: The French electricity grid was hit hard by storms on December 27: The NPP at Blayais suffered the loss of auxiliary 225 kV power supplies for the four units at the site, as well as a loss of the 400 kV power grid at units 2 and 4. The elf-supply with electrical power failed. This led to an automatic shut-down of these two units. The diesel generators were started and functioned until the connection to the 400 kV power grid was restored, after about three hours.
- Furthermore, a flood caused by the confluence of the rising tide with exceptionally strong winds resulted in the partial submergence of the Blayais site.
- The flood started two hours before the tidal peak.
- The winds pushed the water over the protective dyke. Invading the site through underground service tunnels, the water flooded the pumps of unit's 1 essential service water system (ESWS), and one of the two trains (with two essential service water system pumps each) was lost because the motors were flooded. Furthermore, other facilities were flooded;
- The French standard safety rule contains two criteria for flood protection: (1) placing the platform that supports safety-relevant equipment at a level at least as high as the maximum water level; and (2) blocking any possible routes through which external waters could reach reactor safety equipment located below the level of the site platform.
- At Blayais, both criteria were not met: the concrete platform was 1.5 meter too low; and the resistance of the fire doors in the tunnels to the underground safety equipment was miscalculated:
- the waters surged into the tunnels and simply broke through the doors. Before the incident, EDF declared that the underground tunnels were perfectly safe.
- Before the floods, EdF had been planning to raise the dike around Blayais by 50 cm, to 5.70 m, as required by the 1998 safety analysis report.
- This work had been delayed. Furthermore, the waves on December 27 rose to more than a meter above the dike level of 5.20 m

Flooding

- Tsunami (seismic, volcanic, submarine land sliding, meteorite impact) including drawdown
- Flash flood: flooding due to local extreme rainfall (note links to other meteorological phenomena)
- Floods resulting from snow melt
- Flooding due to off-site precipitation with waters routed to the site (including river floods)
- High ground water
- Flood due to obstruction of a river channel (downstream or upstream) by landslides, ice, jams caused by logs or debris, or volcanic activity)
- Flood resulting from changes in a river channel due to erosion or sedimentation, river diversion
- Flood resulting from large waves in inland waters induced by volcanoes, landslides, avalanches or aircraft crash in water basins
- Flood and waves caused by failure of water control structures and watercourse containment failure (dam failure, dike failure) due to hydrological or seismic effects
- Seiche
- Bore (tide-induced and induced by water management)
- Seawater level: high tide, spring tide
- Seawater level, lake level or river: wind generated waves
- Seawater level: storm surge

Biological / Infestation

- Marine/river/lake growth (seaweed, algae), biological fouling
- Fish, jellyfish
- Crustacean or mollusk growth (shrimps, clams, mussels, shells
- Airborne swarms (insects, birds) or leaves
- Infestation by rodents and other animals
- Biological flotsam (wood, foliage, grass etc.)
- Microbiological corrosion
- During the night of 1 December 2009, a massive amount of vegetable matter (around 50 m^3 compared with a monthly average of 5 m^3) blocked the water intake of the common pumping station of Cruas NPP units 3 and 4, by clogging the pre-filtration trash racks. The total loss of heat sink of unit 4 lasted 10 hours.

Other Events

- Long-lasting and repeated heat waves can also lead to unexpected acceleration of ageing processes, increasing the probability of safety system failure in case of an accident.
- Other risk factors are the possibility of increased frequency and intensity of hailstorms and sleets.
- Heat and dry weather have led to an increased occurrence of forest fires. Threat, particularly during strong winds,
- Air temperature extremely low, also for longer periods of time: Threat in particular during outages.
- Formation of slush ice/floating ice: Threat primary heat sink and also the alternate heat sink affected at the same time

Natural hazards fukushima

- Fukushima accident highlighted the importance of the continued need to ensure the design basis adequately addresses external hazards.
- In September 2014, the WENRA published its Safety Reference Levels (SRLs), including a new SRL T for Natural Hazards introduced as lesson learned from Fukushima Dai-Ichi accident.
- The SRLs within the new issue natural hazards (issue T) address:
  - *A target of 10-4/y for event selection, are set;*
  - *the need to develop a protection concept to minimize threats to the plant, relying preferably on **passive features**;*
  - *the consideration of events that may exceed the design basis, to ensure that sufficient margins exist before **cliff edge effects** may occur.*
- T6.1 Events that are more severe than the design basis events shall be identified as part of DEC analysis. Their selection shall be justified. Further detailed analysis of an event will not be necessary, if it is shown that its occurrence can be considered with a high degree of confidence to be extremely unlikely.

Information on risks

- Operation of NPPs means accepting a residual risk of catastrophic accidents
- To decide whether or not the risk is acceptable, it should be known and transparently communicated to the public
- However, the risk cannot be fully known, since not all processes, state of materials, state of safety systems and weather-related events are fully known
- Even if the risk is known, it is not transparently communicated. Instead, the assessment of the risk is up to the regulatory authority, which then communicates that the plant is “safe”, which means, it adheres to safety regulations.
- Furthermore, often not the current safety level but the future safety level is assessed

Public participation

- Operation of nuclear power plants and the decision on long term operation is within national authority
- However, the risk of operation of nuclear power plants is affecting also citizens across national borders
- International standards like IAEA Safety Standards, WENRA reference levels are not binding.
- European countries provide the possibility for public participation for new builds of nuclear power plants (e.g. during environmental impact assessment)
- Life time extensions, even if of greater impact considering the risk, do not necessarily require public consultation process

Conclusions

- Long term operation of the aging fleet of nuclear reactors increases the risk for significant radiological releases in Europe.
- Severe accidents can happen in all currently operating European reactors.
- Aging of the reactors increases the risk of severe accidents
- Partial back fitting cannot change the situation.
- Nuclear power plants are very complex facilities, and aging is a multifaceted process, complex on its own, requiring multiple disciplines for understanding
- While physical aging seems to be manageable in principle with monitoring and replacement, this is not always possible.
- Obsolesce, in many cases, simply cannot be avoided. Back-fittings are not always possible
- The combination of physical aging and obsolesces pone a significant increased risk, which, looking at current plans, will be present in Europe for a long time.
- Extreme weather events, rising sea levels, fires and warming water temperatures all increase the risk of nuclear accidents, while the lack of safe, long-term storage for radioactive waste remains a persistent danger.

- Position of Foratom :
- LTO is unarguably economically advantageous compared to other power sources. It requires a much lower capital investment cost, leading to low investment risks for investors and capital markets, and lower consumer costs.
- From a technical point of view, the LTO of nuclear reactors provides a great advantage thanks to the *"…timely implementation of reasonably practicable safety improvements to existing nuclear installations*" which brings older generation reactors to a level of nuclear safety standards in compliance with the amended Nuclear Safety Directive.