中国工程院
CHINESE ACADEMY OF ENGINEERING

ACADÉMIE DES TECHNOLOGIES
POUR UN PROGRÈS RAISONNÉ, CHOISI ET PARTAGÉ

INSTITUT DE FRANCE
Académie des sciences

NUCLEAR ENERGY AND THE ENVIRONMENT

CHINESE ACADEMY OF ENGINEERING
NATIONAL ACADEMY OF TECHNOLOGIES OF FRANCE
FRENCH ACADEMY OF SCIENCES
MAY 2019

In Memoriam of Alain Bugat

Alain Bugat, Honorary President of the National Academy of Technologies of France, former General Administrator of the Commissariat à l'Energie Atomique (CEA) and a staunch defender of nuclear energy, initiated the three-Academies collaboration on Nuclear energy. He had invested much time and effort in shaping this report, bringing together experts from the three academies and giving it credibility and excellence. To our great grief, he passed away in January 2019 at a time where the report was already at an advanced stage of completion. The memory of his energetic and charismatic personality rests in our minds.

Nuclear Energy and the Environment

A COLLABORATIVE PROGRAMME
BETWEEN FRENCH and CHINESE ACADEMIES

May 2019

Foreword

This report on nuclear energy and the environment is jointly released by the Chinese Academy of Engineering, the National Academy of Technologies of France and the French Academy of sciences. It is a second collaborative study of the three academies on nuclear energy matters. The first report, issued in August 2017, covered many aspects of nuclear energy and offered joint, mostly technical, recommendations for the direction of nuclear energy in the future. It was an attempt to provide an objective overview of many scientific and technological issues on nuclear energy (its position in the future energy mix, benefits, strengths and weak points, research and development perspectives, technology and safety, engineering etc.), as well as societal issues (education, training, risk perception, public awareness etc.). But it was admittedly far from being exhaustive.

Environmental issues were not considered in sufficient depth in the previous report despite their being crucial for the future of this industry, and the Academies felt it necessary to pursue their cooperation and further address these important issues. They decided to focus the joint effort on the environmental impacts of nuclear energy in normal and accidental situations, including waste and provide a comprehensive analysis of these issues which are essentially similar in France and China. However, the economics of energy production, which also constitutes an important factor for the future, is determined by local and regional conditions, which are fairly different between these two countries, and it was deliberately decided not to address this issue in this joint study.

The first chapter of the present report provides a more detailed presentation of its contents and structure (§ 1.4 Outlook of the report).

Table of Contents

Foreword 1
SYNTHESIS AND RECOMMENDATIONS 5
1. Impacts from NPPs and nuclear fuel cycle facilities under normal operation 5
1.1. Nuclear energy and global impacts on the environment 5
1.2. Nuclear energy and local impacts on the environment 5
2. Impacts from NPPs and nuclear fuel cycle facilities in accidental situations 7
3. Impacts from radwaste management 7
4. Nuclear and radiation safety/security as a tool to prevent impacts on the environment. 8
CHAPTER 1 - Introduction...10
1.1. Trends in Energy Demand 10
1.2. Decarbonization commitment and CO_2 emissions by various energy options 11
1.3. Environmental protection as a requirement to make nuclear energy sustainable 12
1.4. Report contents and organization 13
CHAPTER 2 - Environmental impacts during normal operations of Nuclear Power Plants and fuel cycle facilities 15
Recommendations... 15
Introduction 15
2.1. How to measure impacts of nuclear energy on the environment 15
2.1.1. Main impacts of nuclear energy to the environment 15
2.1.2. Releases 16
2.1.3. Assessments 16
2.1.4. Methodology 17
2.2. Effluents, radiological impacts of nuclear energy and solutions 17
2.2.1. Effluents and radiological impacts of NPPs 17
2.2.2. Effluents and radiological impacts of nuclear fuel cycle 19
2.2.3. Radiation monitoring and surveillance 21
2.2.4. Biological effect of ionizing radiation 22
2.2.5. Transportation of radioactive materials 22
2.2.6. Participation of stakeholders 23
2.3. Environmental impacts of nuclear energy compared to other sources of electricity 24
2.3.1. Land occupation 25
2.3.2. Materials used for construction 26
2.3.3. Water withdrawal and consumption 27
2.3.4. Conventional waste from decommissioning 30
2.3.5. Critical materials 30

2.4. New technology perspectives 30
2.4.1. Reducing Carbon emissions of burnt fuels 30
2.4.2. Transmutation technologies 31
2.4.3. Other advanced technologies 33
2.5. Conclusions 33
Appendix 2.1: More specific considerations about the Chinese situation 35
Appendix 2-2: Large scale epidemiological studies around nuclear sites (examples and results) 37
CHAPTER 3 - Spent fuel and radwaste management 39
Recommendations 39
Introduction 39
3.1. Principles, strategies and framework of radwaste management to prevent environmental impacts 40
3.1.1. Principles of radwaste management 40
3.1.2. Strategies of radwaste management 40
3.1.3. Framework of radwaste management with respect to the environment 42
3.2. Specific characteristics and classification of radwaste 44
3.2.1. Spent fuel or reprocessing radwaste. 45
3.2.2. Specific characteristics of radwaste versus the environment 46
3.2.3. Classification of radwaste versus the environment 47
3.3. Processing and discharge of radwaste 48
3.3.1. Minimization of radwaste 48
3.3.2. Discharge of effluents 49
3.4. Disposal of radwaste 50
3.4.1. Very low-level waste (VLLW) 50
3.4.2. Low and intermediate short-lived waste (LILW-SL) 50
3.4.3. Low-level long-lived waste (LLW-LL) 52
3.4.4. Intermediate level long-lived waste (ILW-LL) and High-level waste 52
3.4.5. Radioactive waste containing only natural radionuclides from the front-end of uranium fuel cycle (uranium mining) 55
3.5. Open/closed nuclear fuel cycle 56
3.6. New technologies 57
3.7. Conclusion 58
Appendix 3 60
CHAPTER 4 - Severe nuclear accidents 62
Recommendations 62

Introduction 62
4.1. Severe accidents 62
4.1.1. Three-mile Island accident (Ref. 36) 63
4.1.2. Chernobyl accident.. 64
4.1.3. Fukushima Daiichi accident (Ref. 42 and 43) 66
4.2. Improvements to make nuclear energy free of environmental impacts in case of accident 68
4.2.1. Improvements in reactor technologies 68
4.2.2. NPP Action after Fukushima Daiichi Accident...................................... 69
4.2.3. Severe Accident Management 70
4.2.4. Insights on similar severe accidents in future...................................... 72
4.3. Conclusions 73
Appendix 4-1: Dedicated Prevention and Mitigation Measures for Severe Accidents of Gen-III NPPs 74
Appendix 4-2: Safety of inland NPP in China 75
Appendix 4-3: Emergency Management after Severe Accidents in China 76
CHAPTER 5- Nuclear safety and the environment 79
Recommendations.. 79
Introduction 79
5.1 The safety of nuclear power plants and their environmental impact 80
5.1.1. Severe accidents and their external consequences............................. 80
5.1.2. Risk-informed defence in depth.. 82
5.1.3. New safety threats 83
5.2. Siting NPPs 84
5.3. Responsibility for Safety and role of the Government 86
5.3.1. The prime responsibility of the operator... 86
5.3.2. The role of the Government and the regulator 87
5.4. Nuclear Safety, and Public understanding.. 87
5.5. Conclusion.. 88
Appendix 5-1: Nuclear safety principles.. 89
Appendix 5-2: Actions taken in China.. 90
CHAPTER 6- Conclusion 92
References 96
Glossary 99
Authors 103

SYNTHESIS AND RECOMMENDATIONS

In August 2017, the three Academies produced a set of joint recommendations for the nuclear energy future. The report was presented as a side event at the September 2017 General Assembly of IAEA in Vienna. This second report deals more specifically with the impacts of the nuclear energy cycle on the environment in response to a strong expectation of society for integrating environmental issues into all human activities. In this respect the public expresses concerns about radioactive impact of NPPs under normal operation or accidental conditions and for the long term about the return of radioactive elements to the biosphere from radwaste disposed of in geological layers.

The Academies have examined all operations from uranium mining to radioactive waste disposal and evaluated global and local as well as short- and long-term impacts in normal or accidental situations. The analysis considers consequences for human beings and ecosystems. It summarizes lessons learnt and actions that have already been or might be taken, to sustainably improve environmental protection. In this respect, it is concluded that the next Gen-III Nuclear Power Plants (NPPs) and their associated facilities and the future Gen IV NPPs will potentially feature a reduced environmental footprint.

Considerations and recommendations are synthesized in what follows. The academies are aware that most of these recommendations correspond to actions which have been undertaken by the nuclear energy stakeholders. They wish to point out that these are valuable actions that should be pursued, and in some cases, that the effort should be intensified.

1. Impacts from NPPs and nuclear fuel cycle facilities under normal operation

1.1. Nuclear energy and global impacts on the environment

According to several Life Cycle Analyses (LCA), nuclear energy generates low amounts of CO_2 per MWh. These emissions are as low as those of hydroelectric energy, notably better than photovoltaic and just a little higher than wind. It is however important to recall that intermittent energy sources need to be compensated when they are not available and that this modifies their environmental performance. In terms of consumption of standard materials for construction and critical metallic materials, nuclear energy requires much lesser amounts than photovoltaic and wind energy for the same energy production. Radiological impacts mainly originate from the releases of radioactive gases (rare gases, tritium, radon, others) and liquid effluents (mainly conveying tritium) to the environment. The radiological impact on the public is a very small fraction –less than about 1% – of the overall impact of natural sources of radiation. There is a debate about long-term effects of low and very low dose/dose rate exposures; however most epidemiological studies around the world provide no evidence of their effects on the life realm; molecular epidemiological studies taking into account identified effects at cell level could prove more efficient and should be encouraged. It is also worth noting that some species, like insects, may withstand high radiation levels.

1.2. Nuclear energy and local impacts on the environment

While fossil fuel plants (and in particular those using coal or lignite) emit large amounts of air pollutants such as particles, nitric oxides, sulfur oxides, heavy metals and various other releases of chemicals, this is not the case for NPPs. In this respect fired coal plants release large quantities of natural radioactivity mainly in the form of gaseous radon and their solid waste contain sizable amounts of uranium and thorium that are managed as radioactive waste (Tenorms – Naturally occurring radioactive materials). Thus, nuclear energy has in fact positive effects regarding local impacts if it leads to the closure of fossil fuel plants. The absence of emissions brings a notable improvement in air quality and reduces damages to the environment such as those of acid rain. The main environmental footprints are those associated with front-end facilities. The front-end of the nuclear fuel cycle starts with ore extraction in the mines and ends with the delivery of the enriched uranium to the nuclear fuel assembly producer (UOX fuel; it includes handling of plutonium for MOX fuel fabrication).

Production of non-radioactive technical waste from the construction of reactors is lower than that associated with the construction of wind turbine or photovoltaic devices, as quantitatively analyzed in Chapter 2.

Land occupation with regard to energy produced is also significantly lower for nuclear energy than that needed for PV or wind farms. Around two thirds of land use are due to mining and the rest to NPPs.

The withdrawal of water from rivers for cooling NPPs is of noteworthy importance, higher per MWh than fossil fuel facilities. The water stress and temperature increase need to be considered when siting inland nuclear plants in view of water availability. In general, most of the water is returned to the river but the present climate change already exhibits warm and dry episodes which occasionally force to operate below the nominal power. The potential impact of global warming should be carefully anticipated.

The Academies consider that a proper evaluation of impacts of nuclear energy on the environment requires that:

- Exposures induced by nuclear activities be compared in all cases with natural exposures.
- Background epidemiological studies be carried out before any operation of a new nuclear facility. They are important and necessary for the comparative analysis of any post-accident epidemiological study, the analysis of radiation risks, and the responses to the public concerns.
- Water stress and future climate change should be considered for siting of inland NPPs.

In addition, the Academies make a general recommendation to reduce the footprint of nuclear energy by:

- Actively developing advanced nuclear technologies that can improve the impacts on the environment from the front-end of the nuclear fuel cycle operations. The impact from nuclear front-end activities is higher than that from the back-end, defined as the management of the spent fuel up to geological disposal. Gen IV NPPs, based on low consumption of uranium, will be beneficial to the environment when they become operational. Indeed, fast neutron reactors or multi-recycling spent fuel have the potential to drastically reduce these impacts. Preparation of their commercial development needs to be pursued.

In general, and except for water, nuclear energy uses low amounts of materials per installed MW, and its radiological and non-radiological impacts to the environment under normal operation and throughout the fuel cycle are limited.

2. Impacts from NPPs and nuclear fuel cycle facilities in accidental situations

The main environmental impacts of nuclear energy resulted from severe accidents (ranked at level 6 or 7 on the International Nuclear Event Scale, INES) that have marked the history of nuclear energy development. The Chernobyl NPP, and Fukushima Daiichi NPPs accidents have had a tremendous impact on the public opinion and on the development of nuclear energy worldwide. Lessons learned from these accidents and from the Three Mile Island accident (ranked 5 on INES) have led to major technology changes in reactor designs and operational procedures, which are implemented in Gen-III power plants and retrofitted in operating reactors as far as reasonable. Environmental risks in the event of a severe accident that might occur in the future have been substantially reduced so that they remain confined to the NPP site premises.

The Academies recommend:

- To continue research on the mechanisms leading to severe accidents (internal events like critical excursion, loss of cooling or external events like earthquakes, plane crash, terrorist attack) and provide support for their prevention and mitigation. Further studies to maintain the integrity of containment, or develop Accident Tolerant Fuels – (ATF) should also be pursued.
- To further accumulate experience in the implementation of severe accident management guidelines and to implement prevention and mitigation measures aimed at coping with large-scale damage in NPPs and multi-unit accidents, and to strengthen emergency response capabilities.

3. Impacts from radwaste management

Nuclear energy yields short- and long-lived radwaste. The management of the former is implemented through industrial channels leading to their disposal in near surface repositories. The management of the latter depends on their radiological activities. The most radioactive waste (spent fuel or high-medium level radwaste from reprocessing) are intended to be disposed-of in deep geologic formations. Radwaste from mining/refining uranium are properly disposed-of (for mining waste, mostly in situ). The immediate impacts on the environment mainly originate from the releases of effluents from processing/packaging crude radwaste. Under the present practices these activities have very low local and global impacts on health and the environment. According to many simulations supported by a large database, long-term deferred impacts, if any, are expected to be less than the impacts of natural radiation. Nevertheless, as perceived by the public, the management of radwaste is one of the major challenges of nuclear energy.

In order to improve the understanding of the real impacts of radwaste management on the environment, the Academies recommend:

– That the methodology to evaluate all environmental impacts (radiological and chemical) and the associated risks be improved taking into considering waste originating both from the front- and back-end of the nuclear fuel cycle, and time scales.

To support this general recommendation, the Academies propose that:

– Quantitative parameters be defined to characterize the hazards linked to radwaste in order to better cope with environmental issues,
– R&D programmes be further developed aimed at a better understanding of the radiological and chemical impacts on ecosystems (reversibility, resilience, bio-availability of elements of interest...) ,
– A comprehensive and responsible system be used to protect the environment (including legislation, competent and independent bodies, funding processes,) and be made clear and visible to the public,
– In general, only the best available technologies (BAT) be used (provided they are robust and with a high technology readiness level) to confine radionuclides at every step of the processes.

4. Nuclear and radiation safety/security as a tool to prevent impacts on the environment

One main goal of nuclear safety is to eliminate the possibility of large radioactive releases from severe accidents into the environment; it is one major problem of nuclear energy. Nuclear and radiation safety, which is the responsibility of designers, operators and safety authorities, has a key role in environmental protection. The goal of security is to prevent malevolent action on nuclear facilities which could also lead to the release of radioactivity. Security is a governmental responsibility.

The Academies recommend that the owners of nuclear facilities:

- Test the resilience of the existing nuclear facilities to external events higher than considered in the design basis,
- Upgrade existing nuclear facilities to meet the same safety objectives as set for new facilities, as reasonably achievable,
- Implement the risk-oriented defence in depth, including beyond design basis conditions, for all facilities,
- Perform external additional reviews of their safety management systems, and not exclusively rely on the reviews carried out by the safety authorities.

As environmental protection is a major sensitive issue for people, it is recommended that nuclear regulatory agencies:

- Organize a transparent supervision of nuclear safety, and enforce transparent communication,
- Establish a permanent dialog with local authorities and the public.

The academies consider that a collective effort should be made to educate and inform the public about nuclear energy matters in particular those related to the environmental impact.

With all these conditions being met, the Academies consider that the requirements to protect the environment are best implemented with energy mixes including nuclear energy in conjunction with renewable energies.

CHAPTER 1 - Introduction

On the one hand, nuclear power has many advantages, in particular providing an on-demand dispatchable source of electrical energy with extremely low levels of greenhouse gases (GHG) air pollutant emissions. In the present context where climate change has become perhaps the most important problem facing humankind, this characteristic is a fundamental asset of nuclear energy. The fact that it produces very limited air pollutants is also of importance when one considers the major degradation of air quality in many parts of the world. On the other hand, like all other sources of energy, the nuclear fuel cycle has an environmental impact. This report provides a comprehensive evaluation of this impact and reviews how it is being limited and controlled; it is thus specifically focused on environmental and safety issues and does not attempt to cover many other topics.

This first chapter comprises three sections. The first briefly considers trends in energy demand. The second section discusses decarbonization commitments and CO_2 emissions from various energy sources. The third section introduces the question of environmental protection as a requirement to make nuclear energy sustainable.

1.1. Trends in Energy Demand

According to many national prospects dealing with the future energy mix, it appears that on a short-term basis, energy demand, worldwide, will not increase. But on a medium- and long-term basis, the increase of the world population, per capita revenues and the improvement of the quality of life will result in an increase of the demand in most countries. Thus, global energy demand will inevitably increase and that will mainly take the form of a growth in electricity demand (IEA – Ref. 1). One way to provide massive electricity delivery while avoiding the combustion of fossil fuels is to use nuclear energy.

At present, sixteen countries make extensive use of nuclear energy which provides more than 20% of the electrical power supply in each of these countries (Figure 1.1). Of the 29 European countries (28 EU member states + Switzerland), fifteen have NPPs with a total of 132 units, delivering 27% of total electricity and 50% of low-carbon energy production. In France, nuclear power contributes to 75% of the country's total electricity generation. The present government strategy is to reduce this share to promote renewables. China plans to raise its installed capacity of nuclear power to 58 gigawatt (GWe) while another 30 GWe are under construction (the largest share in the world) by 2020. The medium- (2035) and long-term (2050) perspective in China is that of a continued increase in electricity demand, a higher proportion of electricity to reduce fossil energy usage, an accelerated decarbonization of the power supply infrastructure and a fast development of clean energy. At present, China's energy production mainly relies on coal, which significantly contributes to air pollution and GHG emissions. China has adopted a clean and low-carbon energy strategy aiming to diminish the growth in coal consumption and to reach a peak level in the use of coal as soon as possible, and then proceeding to reduce this level by coping with the demand using clean energy.

China's key strategic choice in the long-term is to actively develop nuclear power as a pillar of green energy. The French situation is already in line and features a nearly decarbonated production of electricity mainly based on nuclear and hydro power.

Much of the global energy consumption in the recent past was dominated by developed countries. However, this is now changing, and the energy landscape is shared by developing countries. The supply of fossil energy can only slowly grow, the energy mix is now challenged by several constraints including resource availability and environmental impact, the need to reduce GHG emissions in relation with climate change, etc. Energy production and utilization is bound to become more efficient, cleaner and low carbon. The global energy infrastructure will be significantly changed in the decades ahead, giving rise to a diversified energy mix in which oil, gas, coal, renewables and nuclear energy will coexist.

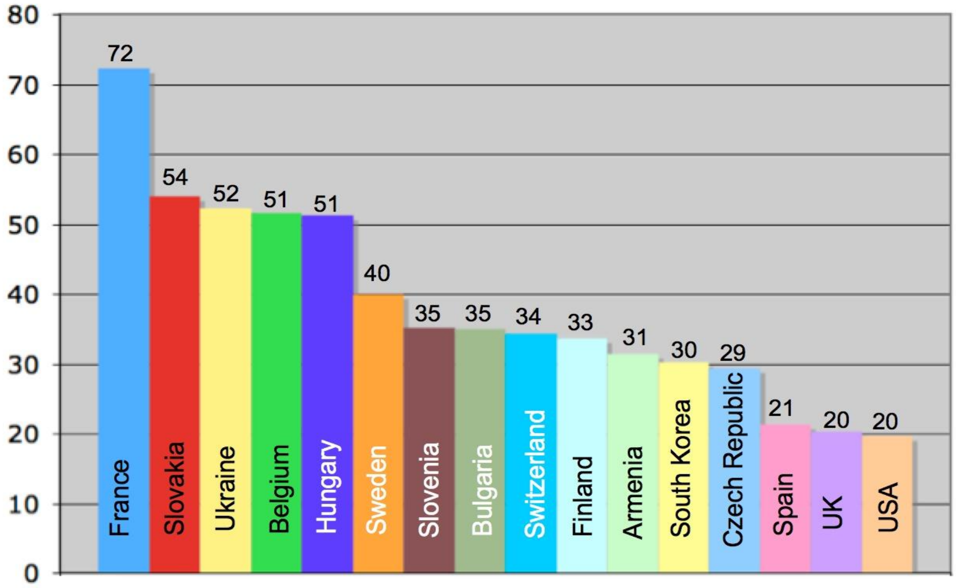

Figure 1-1: Countries where nuclear power accounts for more than one-fifth of domestic electricity supply (December 2016).

In this mix, nuclear power has the advantage of using limited amounts of resources, with a small level of GHG emissions per kWh produced, a relatively low land use and it constitutes an on-demand dispatchable and reliable energy source. The objective of the present report is to develop a comprehensive analysis of its environmental impact, to provide a balanced evaluation of its advantages and weaknesses to consider its sustainability on the long term and its capability to respond to the rising demand in electricity.

1.2. Decarbonization commitment and CO_2 emissions by various energy options

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) put forward a call to stabilize global concentration of greenhouse gases at a level that would prevent a dangerous change in the climate of the planet. Through the Paris Agreement on Climate Change, all contracting parties share the objective to control the average global temperature rise and keep it well below 2°C compared to pre-industrial levels, and pursue efforts to limit temperature rise to 1.5°C. The United Nations have announced that the Paris Agreement came into effect on November 4, 2016, which laid out arrangements for global actions toward climate change after 2020. France has officially ratified the Agreement on June 15, 2016 as the first industrialized nation and China ratified and acceded to the Paris Agreement on September 3, 2016, as the 23rd contracting party. This agreement should have a profound impact on the energy mix that will have to shift to essentially low carbon energy sources. Nuclear energy constitutes an important option for achieving low GHG emission levels and complying with climate goals.

Most of today's nuclear energy is based on fission of uranium atoms. The energy released from the fission of 1 kilogram of fissionable material contained in nuclear fuel is equivalent to the energy released from the combustion of 2 700 tons of standard coal, indicating that nuclear power is much more efficient and intensive as an energy source than a typical fossil fuel. On a more practical level this may be illustrated by comparing the amount of fuel that is being used by a typical nuclear power plant to that of a coal fired plant both operating at a power of 1GWe over a full year. The NPP uses 30t of fuel while the coal plant requires 4 Mt of coal. The analysis of section 2.3 of this report underlines that nuclear energy emits no particulates, and very limited quantities of air pollutants. However, there are emissions resulting from mining, construction and fuel cycle activities, leading to unavoidable CO_2 emissions. In their full life cycles, annual CO_2 emissions by NPPs and reprocessing facilities account for less than 1% of those resulting from coal fired power plants, and they are also lower than those associated with production and integration of solar and wind energy supply chains.

1.3. Environmental protection as a requirement to make nuclear energy sustainable

In addition to being low carbon and to require a relatively limited amount of land, nuclear energy must be safe and economically competitive. It is however important to examine its environmental impact and jointly consider operation of NPPs as well as that of nuclear fuel cycle facilities. It is also necessary to carefully review the management of the spent fuel that is periodically discharged from the reactor, its storage, possible reprocessing and the final disposal of radwaste. These various facilities generate radioactive gaseous, liquid and solid waste. Gaseous and liquid effluents are processed and stored until they have reached regulatory levels which allow their release into the environment. Solid waste are processed and provisionally stored to reduce their volume and activity, to comply with the requirements of the waste minimization principle; they are temporarily stored or directly sent to final disposal.

According to the safety analysis and the environmental impact assessments, the authorized releases from facilities result in doses (radiological and chemotoxic) to people at levels that are lower than what is specified in the regulatory requirements. The national regulations are at least compliant with IAEA requirements but very often more stringent. The target is to remain far below the individual effective dose limit of 1 mSv per year to the representative person, as recommended by the International Commission on Radiological Protection (ICRP).

The authorized limit and practical objectives for the release of effluents are becoming lower and lower and this has led to continuous improvement of the treatment processes.

In 2017 (their first report), the three partnering Academies have analyzed some issues and challenges raised by nuclear energy, with regard to safety, management of radwaste, development and deployment of advanced nuclear energy systems, economics, public acceptance, etc. The environmental impacts of nuclear energy were left aside in comparison with the topic of nuclear energy safety. However, the public is progressively becoming more sensitive to the global and local impacts on the environment from industrial activities and in particular from those required to produce massive amounts of electrical energy. Global impacts take more importance and will drive the future choices of energy mixes. Energy and ecologic transitions become inseparable.

Local immediate or deferred environmental impacts are major components of related social issues that may influence the acceptance or rejection of nuclear energy. It is important to provide a comprehensive evaluation of how nuclear energy impacts the environment, given the considerable attention these issues receive, and thereby offer a complete and balanced account of measures taken to limit such negative impacts. This will hopefully be a useful addition to the first report of our Academies and will allow a better assessment of this topic. The sustainability of nuclear energy depends also on the confidence that the nuclear countries can have towards the newcomers in their capacity to adhere to the principles of environmental impact control.

A key objective of this second report is to assess nuclear energy potential as a means to produce clean energy. To consider this question the Academies decided to look at different indicators used to measure the impacts at global and local scales in constructing, operating and dismantling NPPs and fuel cycle facilities, considering all situations (normal and accidental). All impacts are investigated along the processes implemented at each step of the front-end (from mining to fabrication of fuel assemblies) and back-end (from waste management to dismantling of NPPs and facilities) of the nuclear fuel cycle. As radioactivity is always present in nuclear energy production, attention will be paid first to the risk of exposure to ionizing radiation of living beings over extended periods of time.

1.4. Report contents and organization

This report comprises an executive summary including recommendations and six chapters. The next chapter discusses environmental consequences during normal operations of NPPs and fuel cycle facilities. It includes a comparison of various electricity production systems in terms of greenhouse gas and atmospheric pollutant emissions and then discusses issues related to radioactivity associated with normal operation, water consumption, land use and material requirements.

Chapter three considers spent fuel and radwaste management. It introduces the principles, strategy and framework aimed at preventing environmental impacts. Basically, this management distinguishes various classes of radwaste, the processing and discharge and disposal of radioactive waste, and the different impacts related to the open and closed nuclear fuel cycle. The environmental protection measures that are taken at each step of radwaste management are discussed.

Chapter four reviews severe nuclear accidents (TMI, Chernobyl and Fukushima) to underline lessons learned from these events. It describes upgrades that have been introduced in existing NPPs and improvements that are included in the new Gen III designs in order to limit to the nuclear site boundary, the environmental impacts in cases of accident.

Chapter five describes nuclear safety in relation to the environment. It discusses the objectives of nuclear safety that are to restrict the likelihood of a nuclear accident and the prevention and mitigation of the consequences. It considers the problem of siting NPPs, the role of safety authorities, the responsibility of nuclear plant operators and that of the government.

Chapter six summarizes the main findings of the study. References and a glossary are to be found at the end of the report.

CHAPTER 2 - Environmental impacts during normal operations of Nuclear Power Plants and fuel cycle facilities

Recommendations

The exposures resulting from nuclear activities must always be compared to natural exposures and to exposures resulting from other electricity producing technologies

Although the large majority of epidemiological studies around the world converge to demonstrate that the long-term effects of low and very low dose/dose rate exposures are not harmful, it is still recommended that background epidemiological studies be implemented before the operation of a new nuclear facility, which can provide valuable information for the comparative analysis of post-accident epidemiology studies, analysis of radiation risks, and response to public concerns.

Fast neutron reactors and multi-recycling have the potential to drastically reduce the environmental footprint of nuclear energy, by reducing uranium mining activities, and the quantity and toxicity of nuclear waste. Although this technology is not required in the immediate future, preparation of the commercial development of fast neutron reactors in the coming decades must be pursued.

Introduction

This chapter deals with the environmental footprint of nuclear energy, compares the impacts of this system of production of electricity with other electricity generation systems and discusses some trends regarding the reduction of impacts resulting from the introduction of new nuclear technologies. It begins with some general considerations about the environmental impacts expected from nuclear energy in the framework of human activities.

2.1. How to measure impacts of nuclear energy on the environment

Environmental impacts are temporary or permanent modifications of given parts of our natural environment, including air, water, land, flora, wildlife, etc., with ourselves potentially as an ultimate target. They can, for example, be caused by releases of gas, liquids or solids from human activities.

2.1.1. Main impacts of nuclear energy to the environment

The main environmental impacts are related to climate change (CO_2 and other GHG emissions), air and water pollutions (different releases), water consumption and water withdrawal, creation of made-man land or loss of heritage, degradation of natural land, soil erosion, consumption of raw material, production, processing and disposal of waste, …

Climate change is considered as having the most severe impact on global environment; furthermore, this is accompanied by marine and terrestrial ecosystems degradation, and the loss of biodiversity. These degradations come from acidification and eutrophication linked to emissions of gaseous sulfur and nitrogen oxides together with CO_2. Contributions of nuclear energy to these emissions are very low. Regarding other impacts, such as land occupation, the water cycle, … the contributions are variable according to the fuel cycle options and will be considered further.

Regarding nuclear energy, the releases to the environment are radioactive or suspected to be so. They can generally lead to exposure of human and other living beings to radiation. The potential impacts of these cumulative exposures have to be assessed with respect to human health and biodiversity. To perform these assessments, exposures must always be compared with those of natural sources of radiation, or to those used for medical diagnostic such as:

- Exposures to natural background radiation: the annual average effective dose to the public from natural background radiation for example in France, the USA and China is 2.9 mSv (Ref. 2) 3.1 mSv (Ref. 3) and 3.1 mSv (Ref. 4) respectively; in some high background radiation area, the dose level can be much higher such as in Kerala (India) where it is more than 10 mSv. A New York – Paris round trip flight would expose a person to about 0.05mSv (Ref. 5) .
- Exposures to other natural sources of radiation caused by human activities like those associated with rare earth extraction and processing or those induced by coal-fired power generation. Massive utilization of slag as building material leads to a significant increase of exposure to indoor radon in China (Ref. 4).
- Exposure to medical diagnostic causes on average about 1 mSv per year (rounded value from Ref. 5, page.54).

2.1.2. Releases

The releases to the environment fall into two large categories:

- Immediate releases of radioactive substances from NPPs and facilities leading to their dispersion, dilution, deposition on soils, lixiviation from soils, migration in soils, the driving forces being wind and rain,
- Long term releases of radioactive substances from waste packages (leaching or dissolution of conditioning materials), leading to their migration as true species or colloids, the driving force being natural geosphere gradients (hydraulic, thermal, chemical).

2.1.3. Assessments

There are two ways of assessing the impacts on the environment associated with large energy production systems, depending on the time and scale considered.

When large potential impact target, such as the atmosphere, and impacts over a long period of time from the start of construction to the end of dismantling of nuclear facilities (over about a century), Life Cycle Analysis (from cradle to grave) are considered, it is appropriate to evaluate global impacts. LCA summarizes all the impacts already recorded and the expected ones. Results of LCA support for instance the figures given in section 2.2 and 2.4 of this chapter.

When the impacted target is limited to and around the sites of the facilities and when the time refers to “daily-life” (local impacts), both immediate and long-term deferred impacts are important; but only the former can be measured, while the latter need to be obtained from simulations. This approach is used for instance in the coming section 2.3.

In some cases, natural analogues provide experimental data on long-term impacts, for example: the limited migration of radionuclides during billions of years in the Oklo uranium deposit (Gabon - (Ref. 6)) or alteration of the surface of glasses in the Mediterranean Sea during thousands of years, which have protected these glasses from dissolution.

Assessments consider all the radionuclides and other elements both natural and man-made present in the releases.

Nuclear instrumentation can detect and characterize very low levels of radioactivity, which is less the case for chemotoxicity. Individuals or associations can easily find basic nuclear instrumentation at low cost and do their own *in situ* or remote measurements after an appropriate but short training to assure a correct level of quality. Thus, radioactivity measurements are more and more a domain where independent studies can be done, assuring independence and cross checking of the levels and nature of radioactivity in the environment.

The tools for measuring trace amounts of chemotoxic substances in the environment are more complex than those for measuring radioactivity and the *in-situ* acquisition of chemotoxic data is therefore difficult.

In France and other European and probably also non-European countries where nuclear facilities exist, ***a detailed analysis of all the materials, sources and waste, existing in the nuclear, industrial or medical facilities of the country, is done periodically and a programme for managing them on the short- and long-term is implemented.*** Accordingly, assessments of real or potential radioactive releases can be done.

2.1.4. Methodology

In each domain of interest where impacts are expected, some parameters that measure the various potential or real detrimental effects, can be selected for comparing the environmental impacts of different energy systems.

Then LCA can be implemented according to energy production scenarios and the characteristics of the respective energy systems.

The estimation of local impacts is possible when taking into account the characteristics of the facilities and targets considered and the way of living of local populations.

Radiological and chemical impacts on humans or biotopes may be estimated using simulations. All the codes follow more or less the same steps and rely on large databases. However, they require adequate validations, and some results can be subject to debate. Results from long-term (thousands of years) impact simulations can be even more debatable.

2.2. Effluents, radiological impacts of nuclear energy and solutions

2.2.1. Effluents and radiological impacts of NPPs

The radiological impacts of NPPs in France during normal operation are shown in table 2-1 (Ref. 7).

EDF NPP	DISTANCE TO SITE/km	ESTIMATION OF RECEIVED DOSES, in mSv a^{-1}					
		2011	**2012**	**2013**	**2014**	**2015**	**2016**
EDF / Belleville-sur-Loire	1.8	8.10^{-4}	8.10^{-4}	7.10^{-4}	4 4.10^{-4}	5.10^{-4}	4.10^{-8}
EDF / Blayais	2.5	6.10^{-4}	2.10^{-4}	2.10^{-4}	6.10^{-4}	5.10^{-4}	5.10^{-4}
EDF / Bugey	1.8	8.10^{-4}	5.10^{-4}	6.10^{-4}	2.10^{-4}	2.10^{-4}	9.10^{-5}
EDF / Cattenom	4.8	3.10^{-4}	3.10^{-3}	5.10^{-3}	8.10^{-3}	7.10^{-3}	9.10^{-3}
EDF / Chinon	1.6	5.10^{-4}	5.10^{-4}	3.10^{-4}	2.10^{-4}	2.10^{-4}	2.10^{-4}
EDF / Chooz	1.5	1.10^{-3}	9.10^{-4}	2.10^{-3}	7.10^{-4}	6.10^{-4}	6.10^{-4}
EDF / Civaux	1.9	7.10^{-4}	9.10^{-4}	2.10^{-3}	8.10^{-4}	9.10^{-4}	2.10^{-3}
EDF / Cruas	2.4	5.10^{-4}	4.10^{-4}	4.10^{-4}	2.10^{-4}	2.10^{-4}	2.10^{-4}
EDF / Dampierre-en-Burly	1.6	2.10^{-3}	1.10^{-3}	9.10^{-4}	4.10^{-4}	5.10^{-4}	5.10^{-4}
EDF / Fessenheim	3.5	8.10^{-5}	1.10^{-4}	1.10^{-4}	4.10^{-5}	4.10^{-5}	3.10^{-5}
EDF / Flamanville	0.8	2.10^{-3}	6.10^{-4}	7.10^{-4}	5.10^{-4}	2.10^{-4}	2.10^{-4}
EDF / Golfech	1	8.10^{-4}	7.10^{-4}	6.10^{-4}	2.10^{-4}	3.10^{-4}	3.10^{-4}
EDF / Gravelines	1.8	2.10^{-3}	4.10^{-4}	6.10^{-4}	8.10^{-4}	4.10^{-4}	4.10^{-4}
EDF / Nogent-sur-Seine	2.3	8.10^{-4}	6.10^{-4}	1.10^{-4}	5.10^{-4}	4.10^{-4}	7.10^{-4}
EDF / Paluel	1.4	8.10^{-4}	5.10^{-4}	9.10^{-4}	9.10^{-4}	4.10^{-4}	3.10^{-4}
EDF / Penly	2.8	1.10^{-3}	6.10^{-4}	7.10^{-4}	4.10^{-4}	4.10^{-4}	4.10^{-4}
EDF / Saint-Alban	2.3	4.10^{-4}	4.10^{-4}	4.10^{-4}	2.10^{-4}	2.10^{-4}	3.10^{-4}
EDF / Saint-Laurent-des-Eaux	2.3	3.10^{-4}	2.10^{-4}	2.10^{-4}	2.10^{-4}	1.10^{-4}	1.10^{-4}
EDF / Tricastin	1.3	7.10^{-4}	7.10^{-4}	5.10^{-4}	2.10^{-4}	2.10^{-4}	2.10^{-4}

Table 2-1: Radiological impacts of NPPs since the year of 2011 calculated on the basis of the actual discharges from the installations and for the most exposed reference groups. Note: 8.10^{-4} means 8.0×10^{-4} in table 2-1 and table 2-2.

Monitoring results of gaseous and liquid effluents during the operation of six pressurized water reactors (PWRs) NPPs and one heavy water reactor (HWRs) NPP in China were analyzed, and figure 2-1. shows the average emission of various type of effluents during years 2011 to 2013 of these seven NPPs, of which the maximum emissions are effectively regulated and controlled; in all cases, it is well below the regulatory limits and the natural exposure. Normalized collective dose to the public from effluents of NPPs in China during the years 2011 to 2013 was estimated as 6.4×10^{-2} man-Sv/GWa.

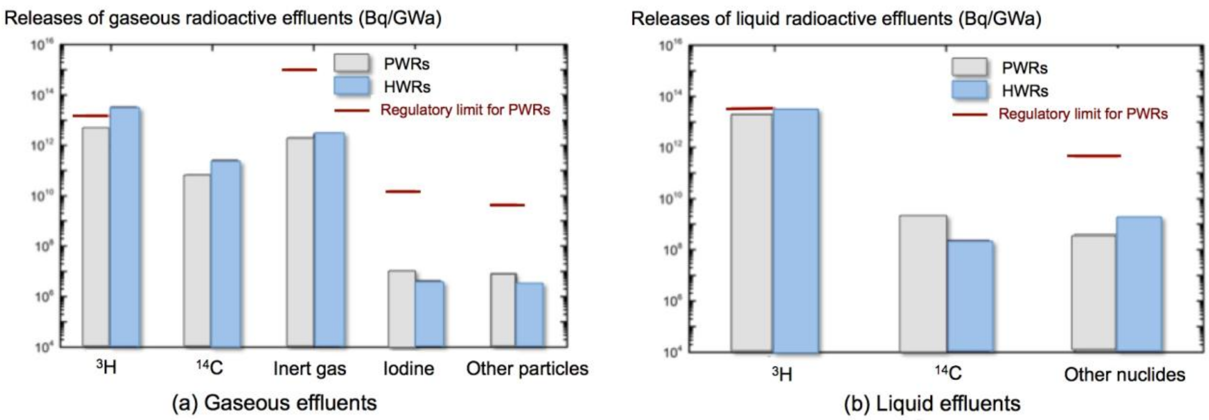

Figure 2-1: the average emission of effluents of NPPs in China (2011 – 2013 - (Ref. 8)).

It is noted that tritium (T) is one of the radionuclides released by NPPs to the environment. As an isotope of hydrogen, its behavior in the environment is mainly linked to the water cycle (HTO or tritiated water) but also to photosynthesis (incorporation of T2 or HT molecules in plants) and to the metabolism of organic tritiated molecules in living organisms (organically bound tritium or OBT). The World Health Organization recommends a guidance level of 10 000 Bq/l for tritium in drinking water for permanent consumption (Ref. 9). Reports from the French Institute of Radiation and Nuclear Safety (IRSN) indicate that there is no evidence of tritium bio-accumulation in vegetal components after decades of study in France (IRSN-Ref. 10). For terrestrial animal products, the conclusion is the same, but based on limited data (Ref. 11) as most studies are focused on the physiological models describing the behavior of tritium in the animals in view of estimating the concentration in the animal products (milk, meats, etc..), however ***transfer factors recently estimated (Ref. 11) are always less than 1, which confirms an absence of accumulation in food originating from animals***.

There is also no evidence of bio-accumulation of Tritium in seawater species (IRSN - Ref. 12).

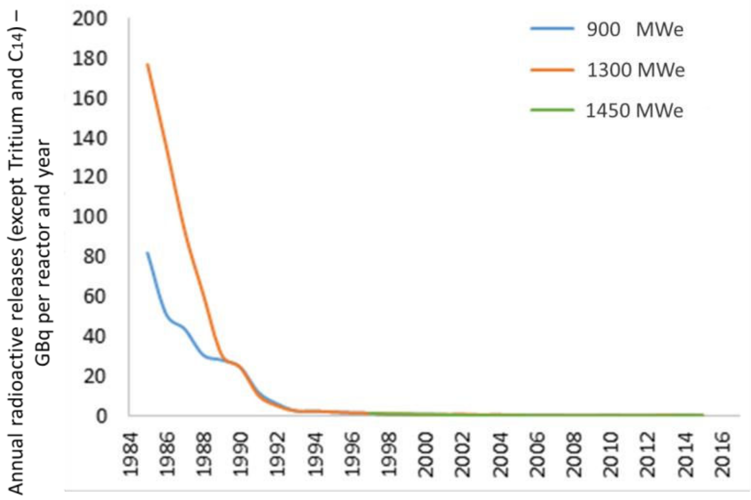

Figure 2-2 Liquid releases of French NPP - 1984 – 2015
Laure Viricel - Revue Générale nucléaire – n°7 - 2017

Over years, and as illustrated in figure 2-2, the liquid and gaseous radioactive releases have been drastically reduced, both in China and France.

2.2.2. Effluents and radiological impacts of nuclear fuel cycle

Nuclear fuel cycle includes the production, fabrication, storage and post-processing activities of nuclear fuel. The estimated radiological impacts of nuclear fuel cycle in France during normal operations are shown in the table 2-2 (Ref. 7).

Nuclear fuel cycle plants	Distance to site (km)	Estimation of received doses in mSv per year					
		2011	2012	2013	2014	2015	2016
Andra/CSA	2.1	3.10^{-4}	1.10^{-5}	1.10^{-6}	2.10^{-6}	2.10^{-6}	2.10^{-6}
Andra's Manche repository	2.5	6.10^{-4}	4.10^{-4}	4.10^{-4}	3.10^{-4}	2.10^{-4}	2.10^{-4}
Areva NP in Romans F	0.2	6.10^{-4}	6.10^{-4}	5.10^{-4}	3.10^{-4}	3.10^{-4}	3.10^{-4}
Areva/La Hague	2.8	9.10^{-3}	9.10^{-3}	2.10^{-2}	2.10^{-2}	2.10^{-2}	2.10^{-2}
Areva/Tricastin	1.2	NA	3.10^{-4}	3.10^{-4}	3.10^{-4}	3.10^{-4}	2.10^{-4}

Table 2-2: Radiological impacts of nuclear fuel cycle plants since the year of 2011 calculated on the basis of actual discharges from the installations and for the most exposed reference groups

The effluents of nuclear fuel cycle in China are well controlled and documented. Figure 2-3 and figure 2-4 show effluent emissions and their radiological impacts to the public of the nuclear fuel cycle in China during the years of 2011 to 2013, respectively.

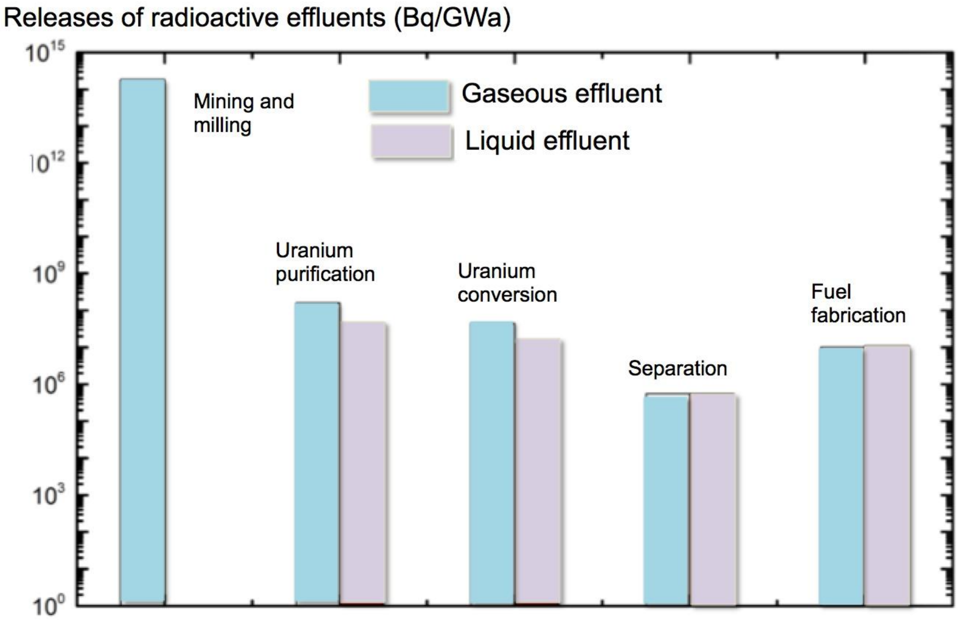

Figure 2-3: Average emission of effluents of nuclear fuel cycle in China (2011-2013). (Ref. 8)

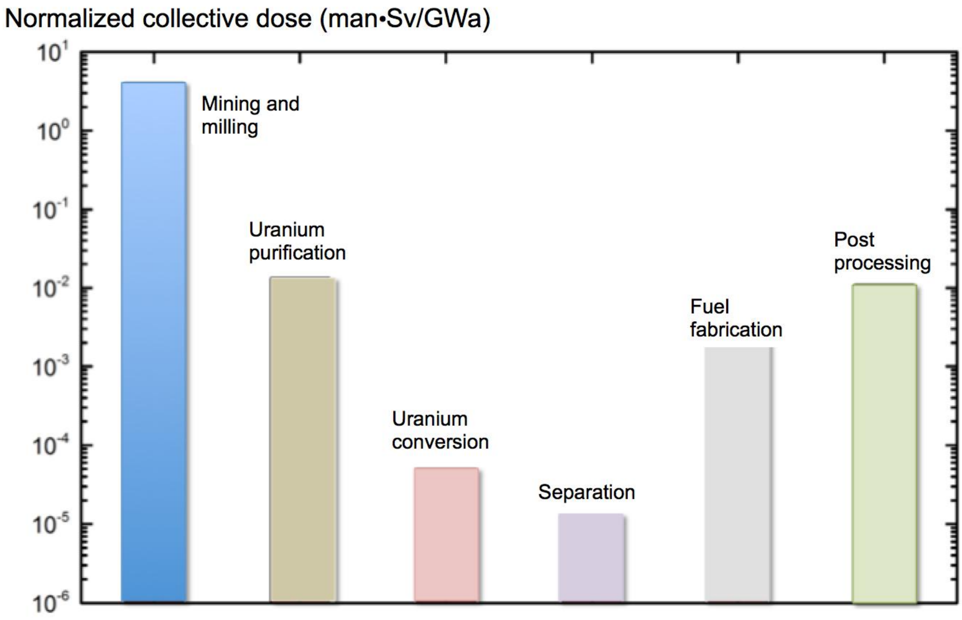

Figure 2-4: Public normalized collective dose from nuclear fuel cycle in China (2011-2013) (Ref. 8).
(Mining and milling data refer to ^{222}Rn emission; others refer to total uranium)

In addition, public normalized collective dose from LCA of nuclear power generation in China during the years of 2011 to 2013 was estimated as 4.6 man-Sv/GWa (80 km diameter around the site, detailed in Appendix 2-1, as well as radiological impacts resulting from other power generation technologies), of which 86% was contributed by uranium mining and milling. As the in-situ leaching uranium mining technologies get expanded in the near future in China, the dose to the public from nuclear power chain will be further reduced.

2.2.3. Radiation monitoring and surveillance

Monitoring of the radioactivity in the environment is the main concern of all operators and safety and environmental authorities in all nuclear countries. We here focus on the French and Chinese systems.

In France monitoring of radioactivity is implemented through three tele-surveillance networks:

- The system of drills (water monitoring) and beacons (air monitoring) installed and operated by the owner/operator of the nuclear site in the vicinity (0-10 km in France) of the site,
- The network for monitoring radioactivity in the air, the purpose of which is to immediately detect any unusual increase of radioactivity in the air: in France, Teleray includes 400 beacons spread over the national territory with special focus on large cities situated less than 30 km of a nuclear site,
- The network for continuously monitoring radioactivity of water in the seven main French rivers upstream of their estuaries or of their point of passage into a neighboring country: limits of detection are very low, in the range of 0.5 to 1 Bq/l for cesium 137, iodine 131 and cobalt-60.

In addition, networks of surveillance by sampling are set up to evaluate the impact on ambient air of all human activities using radionuclides: OPERA-AIR operated by the French IRSN, with forty stations including thirty-two in the vicinity of nuclear sites, sampling of water, mud and sediments, and sampling of milk.

The Chinese surveillance system consists of a multi-level environmental radiation monitoring network, so as to keep detecting environmental radiation levels during the operation of nuclear facilities:

- Immediate site vicinity (generally within a 5 km radius from an NPP site): the fixed automatic monitoring stations (autonomous monitoring), which are set up, run and managed by the operator,
- Long range distance to sites: (generally 20 km radius away from the site): the fixed automatic monitoring stations (supervising monitoring), which are set up by the operator, but run and managed by the provincial environmental protection administration departments. The autonomous monitoring is combined with the supervising monitoring to measure the environmental γ radiation level and sampling the air in the respective areas,
- Intermediate distance to a site (generally 10 km radius away from the site, including the inner area): Environmental media samples, such as surface water, underground water, receiving water, soil, bottom mud, are monitored and analyzed by the operator.

In major cities and regions of the nation, the environmental medium, such as air, water and soil, should be monitored, sampled and analyzed by the national radioactive environmental monitoring stations.

2.2.4. Biological effect of ionizing radiation

Deterministic effects are induced by ionizing radiation higher than an established threshold, while stochastic effects, generally cancer or heritable diseases, might be induced at low doses and low dose rates.

In China, since 1972, the possible health effects on large populations induced by ionizing radiation exposure at low dose and low dose rate, has been investigated in high background radiation area (HBRA) in Yangjiang, Guangdong province, and in normal background radiation in control area (CA), of which the annual average natural radiation dose to inhabitants was estimated as 6.4 mSv and 2.4 mSv respectively (revised to 5.9 mSv and 2.0, respectively, in 2000).

No harmful impacts were found by natural radiation in HBRA, based on the investigation on cancer mortality from 1,008,769 person-years in HBRA and 995,070 person-years in CA, and on heritable diseases, congenital malformations, chromosome aberrations and immune function of peripheral blood lymphocytes from 13,125 persons in HBRA and 13,087 persons in CA.

In European and American countries, since the 1950s, epidemiological investigations have been performed near nuclear facilities. However, the results showed that no significant difference was found of cancer mortality and childhood leukemia incidence near nuclear facilities as compared to control areas. This is mainly due to very low doses to the public induced by the radioactive emissions during normal operation of nuclear facilities. The additional dose received by the critical group is as low as about 10 µSv in one year, about 1% of the natural background radiation level (the order of a few mSv in one year) excluding radon exposure.

There exist large uncertainties to low doses of ionizing radiation in the mechanisms of cancer induction and the biological effect, and the dose assessments to the public near nuclear facilities, thus it is difficult to reach quantitative conclusions on radiation risks by epidemiological investigations, making it useless to implement large-scale conventional studies. New approaches based on biochemical signature of radiation effects are expected but are not yet operational.

However, implementing background epidemiological studies before the operation of a new nuclear facility could provide very valuable information for the comparative analysis – in case of an accident - of post-accident epidemiological study, the assessments of radiation risks, and the responses to the public concerns, considering the possible relatively higher exposure doses to the inhabitants around the nuclear facility due to the possible large quantities of radioactive substances released during and after accidents.

More results on epidemiological investigations are given in appendix 2-2.

2.2.5. Transportation of radioactive materials

Around 900,000 radioactive packages are transported in France every year for the needs of industry, the medical sector or research; the bulk of it handle very low sources and waste. Only 15% are related to fuel and low, intermediate or high-level radioactive waste. For the whole world the number of nuclear packages reaches 10 million, which represents only 2% of the total of all hazardous material packages transported.

With respect to humans and the environment, the main risks are irradiation and contamination. In France one to two transportation accidents occur per year inducing radioactive releases to the environment. They all have had limited impacts; in the most serious cases weak contamination has been detected and treated by local decontamination operations.

Railway transportation is the priority means with a very high level of safety for heavy or bulky packages.

Maritime transportation is used for around 4% of the total transportation of nuclear materials, and mainly for fresh or spent fuel and high-level radioactive waste. Ships are specifically designed according to the requirements of the International Maritime Organization.

Road transportation is the most flexible means to transport radioactive materials. It is submitted to special rules to avoid crowded periods and housing areas.

Air transportation is used only for small and urgent packages, such as radiopharmaceuticals, and over long distances.

Suitable options should be chosen based on the characteristics of radioactive materials and the requirements of transportation.

2.2.6. Participation of stakeholders

In France, local commissions for information of stakeholders (CLI) are set up for the most hazardous facilities classified as important for environmental protection (ICPE).

Fifty-three CLIs exist in France, including thirty-eight around nuclear sites. They bring together around 3 000 members: local politicians, trade unions, representatives of associations, experts and qualified persons. They have the general mission of informing the public about the safety of the facilities classified as above and their impact on persons and the environment. In the nuclear domain, the Transparency and Security Act (June 2006, 13) gave them a legal basis (Art. 125-7 of the Environmental code).

A national association of the CLIs (ANCCLI) gathers the experience and wishes of 37 CLIs and brings their collective insight to the attention of national and international authorities.

China has established a public communication system featuring central-supervising, government-leading, enterprise-acting and society-participating to promote popularization of science, public participation, information publicity, public opinion response and integrative development.

The Nuclear safety Law is the legal basis and guarantee of the public’s right to know about, participate to and supervise major nuclear energy projects. The development of major new nuclear projects is incorporated into the review system of local people's congresses, and public communication on major nuclear related projects is included into the local social management system. Enterprises are required to develop public communication strategies and medium- and long-term plans, into their operational management. In addition, peer review is carried out by professional and authoritative third parties such as social organizations, universities and think tanks, for example the China Nuclear Energy Association, the Chinese Nuclear Society, the China Association for Science and Technology and the China Environmental Protection Association.

2.3. Environmental impacts of nuclear energy compared to other sources of electricity

Power generation has environmental impacts which depend on technologies.

Within the framework of the transition to a decarbonized economy the objective of this section is to look at the non-radiological environmental impacts of various power generation technologies, for example the GHG emissions, land occupation, material consumption for construction, water consumption and decommissioning waste (the radiological impacts of nuclear energy are detailed in section 2-2). Most of these figures originate from Life Cycle Analysis (LCA). Appendix 2-1 summarizes the recent analysis results on the life cycle GHG emissions and radiological impacts of various power generation technologies in China.

Figure 2-5 below (Ref. 14) shows that CO_2 emissions from fossil fuel fired electrical power plants are one to two orders of magnitude higher per MWh produced than those from nuclear, wind, solar and hydro.

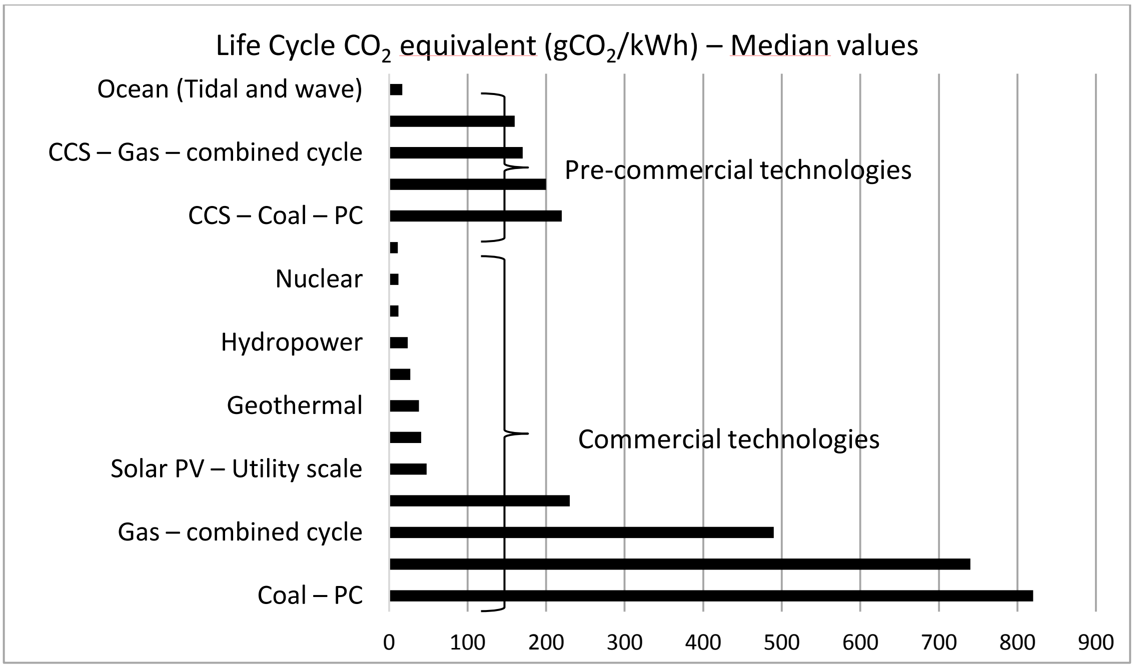

Figure 2-5: Life cycle CO_2 equivalent (from selected electricity supply technologies. Arranged by decreasing median (gCO_2eq/kWh) values.

The contribution of nuclear energy to the emission of SOx and NOx gases (around 20 kg/MWh) is 100 and 10 times less than those from fossil fuels and photovoltaic electricity respectively and consequently has a low impact on acidification of soils and eutrophication of water. SOx and NOx emissions from hydro- and wind-power are less than 10 kg/MWh.

Wind, solar, nuclear, and hydro-power have their own environmental impacts. We shall look at the following impacts:

- Land occupation,
- Material usage for construction,
- Water consumption,
- Deconstruction waste.

Wind and solar, as intermittent sources of electricity, should also be assigned CO_2 emissions from fossil fuel facilities which have to be operated as back-ups when they are not available.

2.3.1. Land occupation

Many studies and research projects have addressed the land-related impacts on energy systems which, increasingly, are focusing on “renewables”. Drawing from this body of knowledge, table 2-4 (Ref. 15 and 16)) provides a brief synthesis of the land footprint relating to these systems on a MW basis (LCA - Life Cycle Analysis).

Energy technology	m^2/MW	System boundary Energy resource extraction area plus power plant site
Hydropower. reservoir	20,000 – 10,000,000	Site of reservoir and generators
Solar PV	10,000 – 60,000	Site of PV system, which includes the area for solar energy collection. PV systems on pre-existing structures have essentially no net increase in land use.
Solar thermal	12,000 – 50,000	Site of concentrating solar thermal system, which includes the area for solar energy collection
Wind	2,600 – 1,000,000	Low-end value is for the site only, which includes the physical footprint of the turbines and access roads. The high-end value includes the land area between turbines, which is typically available for farming or ranching.
Nuclear	6,700 – 13,800	Low estimate is site only. High estimate includes transmission lines, water supply, and rail lines, but does not include land used to mine, process, or dispose of waste.

Table 2-4: Land use intensity per MW of installed capacity.

The figures proposed for hydro seem to be high; however, power generation, in many cases, is but one of the various purposes of the dam (water storage for irrigation, domestic and industrial uses, shipping, flood protection). The land use is due to the extent of the reservoir where one is needed. Regarding energy supply, the purpose of the reservoir is not only the delivery of power but also flexible storage of electricity, thus creating added value.
The direct land use from nuclear power plants is very low, thus nuclear power is a favorable option with regard to land use, and consequently to preserve biodiversity which is undermined by land occupation and artificialization.

It is noted that the global perception of nuclear energy is influenced by the footprints generated in case of an accident, as occurred in Chernobyl and Fukushima (see chapter 4). Public opinion is legitimately concerned with restriction of use of radioactive areas following severe nuclear accidents. One of the consequences has been to devise technologies that would confine the impact of an accident to the premises of the nuclear site and thus to avoid any evacuation (see chapter 4). Nuclear accidents have local negative externalities that need careful follow-up actions. It is worth noting that GHG emissions concern the whole planet and constitute a negative externality that cannot be localized.

2.3.2. Materials used for construction

The civil works for nuclear power plants require more concrete and steel than a coal fired power plant or a CCGT power plant of the same installed power: around 600 tons per MW compared with around 10 tons per MW respectively. This is due to the para-seismic design of safety-classified buildings, the containment system, the protection shell against airplane crash and the complex concrete raft where a containment tank (core catcher) is designed to collect and cool the core in the case of accidental melting. Some of these features are specific for nuclear power plants of the third generation. However, the quantity of concrete and steel becomes less important when relating it to the amount of kWh produced by a single site during the life span of 60 years.

Onshore wind farms require somewhat more concrete per MW and MWh than NPPs since its relatively lower load factor. Offshore wind farms laid on the subsea ground require much more cement, aggregate and rockfill for the construction of the foundation on the subsea floor if a gravity basement is selected. The present experience of floating offshore wind farm is too brief to produce a sound figure for the required anchorage foundations. However, the volume of aggregate and rock fill will be far lower than for masts laid on the subsea ground.

The solar PV farms as well as concentrated solar energy farms require steel and concrete. In both cases, there are slabs of reinforced concrete, and steel supports. The low concentration of power associated with a low load factor give rise to a relatively high demand of material per MWh delivered.

There is a large requirement for copper and aluminum in the connection system within the site and also for connecting the site to the grid. The need for copper is high especially for offshore wind farms which have to be connected between themselves and to the shore.

The estimates for hydro are not very relevant for the reasons mentioned in §2.3.1, and because the need for aggregate and cement depends on the availability of rock and aggregate close to the dam site. Many large dams are embankment dams, because they are the cheapest solution. The volume of concrete of this type of design remains, however, significant and depends on the size of the maximum flood and the installed power.

According to several reports ((Ref. 16 and 17) this factor leads to the following ratio of material used per TWh of electricity produced on an LCA basis (figure 2-6).

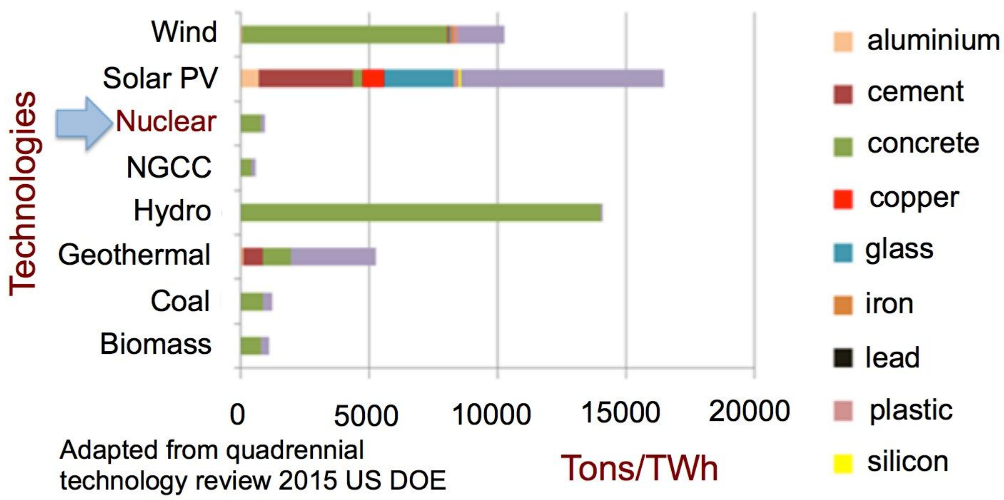

Figure 2-6: Material required (fuel excluded) for various technologies.

2.3.3. Water withdrawal and consumption

Nuclear power plants require large quantities of water to condense the steam driving the main turbine. Because of the Carnot rule which applies to all thermal plants, roughly one third of the thermal energy of the reactor is converted to electricity, and two thirds is dumped to the environment. This paragraph provides a brief review of the environmental consequences of this issue, which depend on selected technologies.

a) Many nuclear power plants are built close to the seashore, and are cooled with sea-water. The temperature of the cooling sea water increases by ~7°C in the condenser before being returned to the sea: surface seawater heating after first dilution does not exceed 1 °C in an area that can vary from 1 to 20 km^2 (Ref. 18). The cooling water flow has to be sufficient to ensure a temperature increase that respects the needs of aquatic life in the vicinity.

b) When nuclear power plants are built inland near large rivers, two technical options may be used (Figure 2-7):
b1) once through cooling system: the cooling water withdrawn from the river is returned after having cooled the condenser. A large water flow is necessary to ensure a limited temperature increase. But actual water consumption is limited to extra evaporation of water returned to the river with an increased temperature. Large amounts of cooling water are needed, but consumption is significantly smaller.
b2) wet tower cooling system: part of the water having cooled the condenser is steamed to the atmosphere, and is diverted from the other water demands.

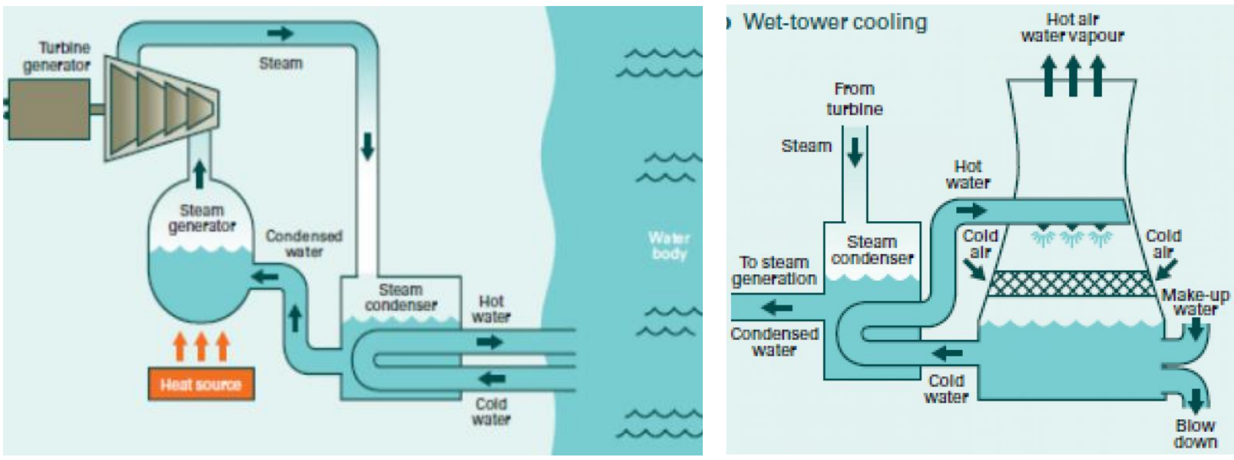

Figure 2.7: Once through cooling systems. - Wet tower, cooling system - Courtesy of SFEN.

As the latent heat of water is much higher than its sensible heat (five times more energy is needed to vaporize one liter of water, than to heat it from 0°C to 100°C), wet tower cooling withdraws less water than once-through cooling, but more water is lost.

The following data issued from a study on "*Life cycle water use for electricity generation: a review and harmonization of literature estimates*" (Ref. 19) in the US show that water withdrawals and water consumption vary widely according to the power technology selected and also according to the water scheme retained for each technology.

The range of water consumption[1] for each technology is summarized in the following sketch (figure 2-8) where CSP means concentrating solar power and PV means photovoltaics.

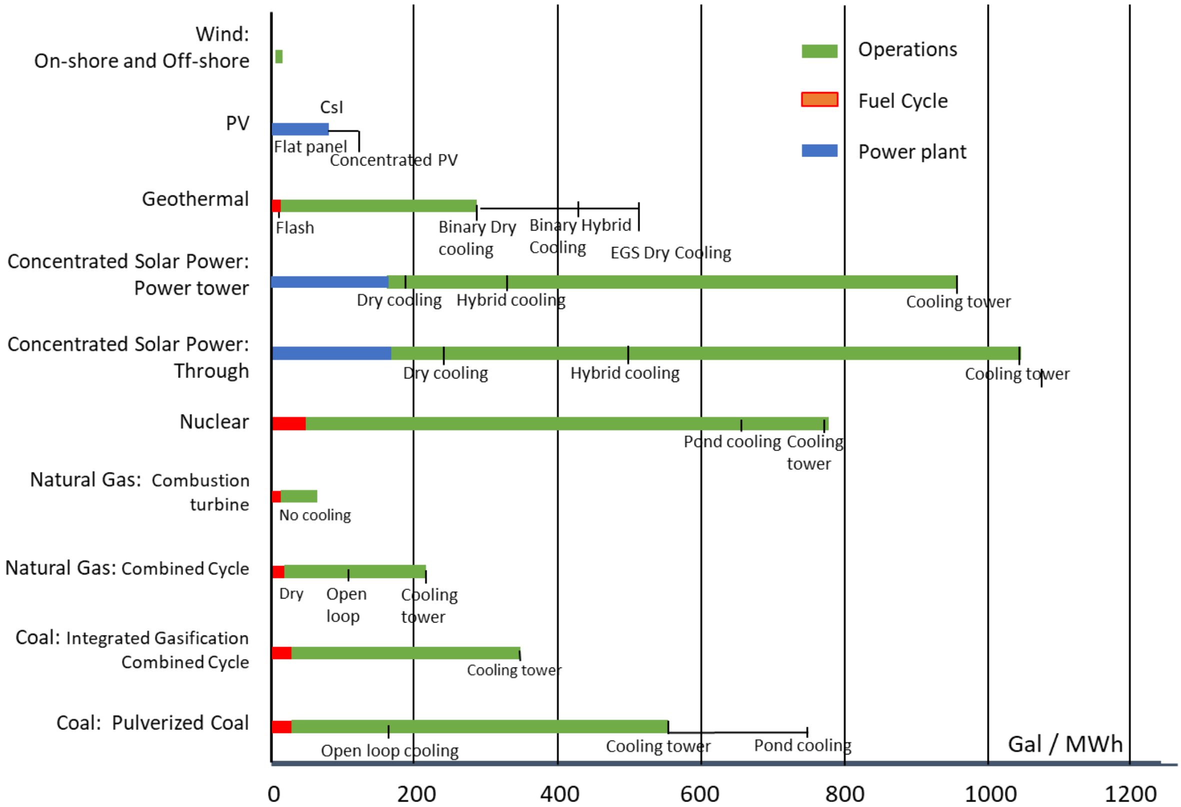

Figure 2.8: Water consumption by technology (Gal / MWh).

This sketch shows that that wind and geothermal plants consume much less water than nuclear plants. Many concentrated solar plants also consume less water, but this depends on their cooling schemes. This figure also shows that nuclear plants consume more water than gas and coal fired plants because of their lower thermodynamic efficiency.

The range of water withdrawals is also shown in figure 2.9 (open cycles use an amount of water per MWh that exceeds the scale adopted in this sketch, and they cannot be fully displayed).

1 As usual for water assessments, this paper classifies water use into water withdrawals, referring to 'water removed from the ground or diverted from a surface-water source for use', and water consumption, referring to the portion of withdrawn water not returned to the 'immediate water environment'

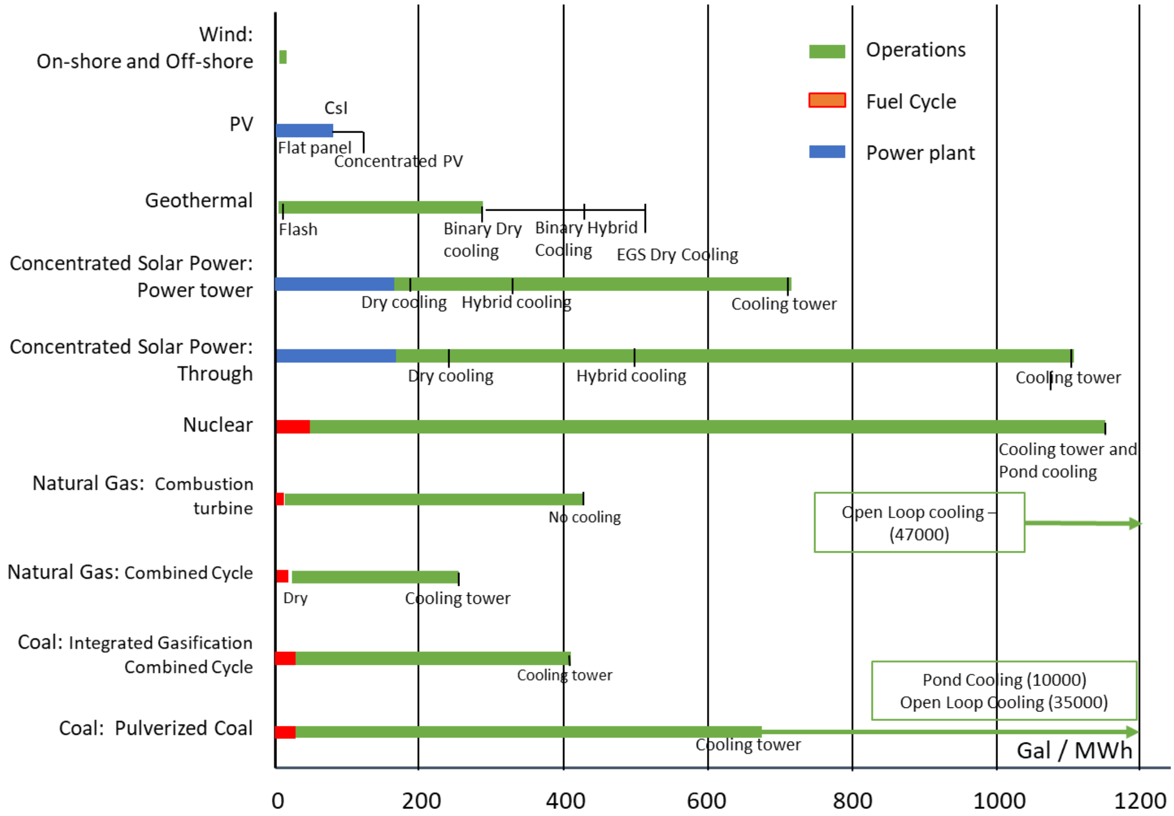

Figure 2.9: Water withdrawal by technology (Gal / MWh).

Typically, in France, water withdrawals for electricity generation account for 61% of water annually withdrawn; but most of it is used by only six units having once through cooling and return to the river; the amount of consumed water calculated with the above figures which are applicable to all PWR units, is about 6% of the total annual withdrawals.

Water withdrawal by sector in France (Mm^3)	2013	
Potable water	5283	19%
Industry and other commercial usage	2745	10%
Agriculture	2776	10%
Thermal power generation	17023	61%
Total	27827	100%

Table 2.5: Source: INSEE/BNPE Water statistics.

It holds true that a significant quantity of energy is dumped to the environment. In France, only its first six river-cooled units are using direct cooling; and the Authority imposed wet tower cooling for all subsequent units; as the cooling water temperature is higher, it results in a loss of efficiency, and therefore of electrical generation, of about 4%. Furthermore, restrictions on the temperature of discharged water are implemented, which impose to reduce the plant output if constraints to the environment are excessive; however, their consequences remain limited: from 2000 to 2017, the average loss of output due to thermal constraints has been 0.18%, with a maximum of 1.2% in 2003 in a situation of an exceptionally hot summer (Ref. 20).

Along the French Rhône river are sited 14 NPPS; their contribution to water temperature increase is 1.2°C (average), or 1.6°C (eighteen hottest days of the year), which remains reasonable (Ref. 21). But the siting of inland power plants must be very carefully planned, as cooling the power stations may be competing with other needs, especially in water stressed regions.

2.3.4. Conventional waste from decommissioning

This paragraph does not deal with the radioactive waste that is treated in chapter 3 of this report. But it is worth to remember that nuclear energy produces 10^4 and 10^3 less technological non-radioactive waste than coal and oil, respectively. The graph "Material required" (Figure 2-4) shows that, except for lead**,** solar and wind power plants are consuming between 10 and a few hundred times more material than nuclear power plants. Amplified by the relative power factor of renewable versus nuclear, one needs twenty to a few hundreds more material, such as for example concrete, copper and aluminium, per kWh in comparison to nuclear power plants.

The relatively short service life of both solar and wind technologies should also be mentioned. Dismantling and reconstruction are relatively frequent and the recycling of at least part of the materials is an open question.

2.3.5. Critical materials

Another important parameter in terms of environment is the scarcity of some materials mainly used in solar PV and wind technologies (e.g. rare earths elements) vs. almost no use in the hydro and nuclear technologies (Ref. 16). There is an exception with Nickel which can be considered as a strategic element: nuclear plants mobilize large quantities of stainless steel, and therefore of Nickel.

2.4. New technology perspectives

Commitments taken as part of the Paris agreement includes the goal to *"achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century"* (article 4 - 2015); this goal is generally referred to as "Carbon Neutrality". The bulk of anthropogenic CO_2 emissions (87%) stems from the burning of fossil fuels like coal, natural gas and oil (Ref. 22). Electricity, heat generation, and mobility account for 70 % of the CO_2 emissions from burning fuels in 2014 (Ref. 23). It is consequently of paramount importance to drastically limit, and if possible, replace carbonated energy used in these sectors. In this section we review the major perspectives to reduce carbon emissions from burning fuels. As one of the main means to achieve this goal is the use of nuclear energy, we also review the perspectives of reducing waste from nuclear power stations.

2.4.1. Reducing Carbon emissions of burnt fuels

Two main routes can be considered to reduce carbon emissions of burnt fuels: carbon capture and storage (CCS), and direct generation of carbon free electricity.

- CCS faces three challenges: reducing costs, improving public acceptance and developing storage capacities. Presently only 40 Mt/a of CO_2 are stored in the world; 4,000 Mt/a should be captured and stored by 2040 (30% in OECD countries and 70% in non-OECD) according to IEA 2°C scenario (Ref. 24). It is also worth underlining that the efficiency of carbon capture is at the maximum of about 90%; therefore, it would not meet the goal of carbon neutrality without developing carbon sinks. All in all, carbon storage can only reduce CO_2 emissions, but won't be enough to achieve Carbon Neutrality.

- Carbon free electricity generation is the key to both a decarbonized mobility and a decarbonized energy system. Carbon free mobility can be provided by biofuels, or electricity stored in batteries, or generated by fuel cells converting H_2 into electricity.
  Biofuels are one of the means to achieve Carbon Neutrality; but their limitations are acknowledged, as the energy per square meter of land which can be harnessed from biofuels is small compared to what solar or wind can provide for an identical land use. And they compete with the production of food which may have to be given priority when world population is steadily increasing. Therefore, leading technologies being considered to generate carbon free electricity are wind and solar. Their costs have plummeted in recent years; but they share the same limits of intermittency.
  The only solution to cope with intermittency is storage. So far, batteries can be used for daily storage. However, much greater capacities than daily storage need to be considered. Batteries cannot be a solution to store the great amount of energy required to balance surplus and deficits over weeks or even decades. Many alternate solutions could be considered: mechanical (compressed air, hydroelectric energy storage); thermal (molten salts, etc.). However, none offers the storage capacities which will be required.

From this review, it can be concluded that only hydro -for which available sites are scarce-, and nuclear have the potential to generate dispatchable, carbon free electricity.

2.4.2. Transmutation technologies

Transmutation is an option for waste minimization of HLW generated in the nuclear fuel cycle. The two main transmutation technologies are acceleratior-driven system (ADS) transmutation and fast neutron reactor (FRs) transmutation.
Scientists including Nobel laureate Carlo Rubbia promoted concepts of Accelerator Driven Systems (ADS). In such systems, criticality would be achieved by the addition of an external source of protons, generated by spallation and accelerated, which would transmute fission products. Technical challenges faced by these technologies are significant, and their economic competitiveness for electricity generation is questionable. While they would have the potential to transmute actinides, fission products transmutation would be highly challenging. As the long-term risk of a geologic repository is usually dominated by fission products which are generally more mobile than actinides, the benefit of ADS – should their cycle efficiently work – would remain limited (Ref. 25).

A fleet of FRs would essentially burn depleted uranium, circumventing the front-end of the fuel cycle, in particular uranium ore mining, thus further reducing the environmental footprint of nuclear energy systems. In addition, they could control the plutonium stockpile, minimizing the risk of its dissemination, and subsequent proliferation. The Generation IV International Forum (GIF), a framework for international co-operation in research and development for the next generation of nuclear energy systems, encouraged the development of six promising reactor technologies, four of them being fast neutron reactors (Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (including Fast spectrum MSRs (MSFRs)), Sodium-cooled Fast Reactor (SFR)).

Spent nuclear fuel back-end cycle has limited impact compared to front-end activities (ore mining and milling, conversion of U_3O_8 into UF_6, enrichment of UF_6, conversion of UF_6 to oxide). The lowest impact is provided by multiple recycling, and Fast Reactors.

Below Table 2-6) is a comparison (Ref. 26) based on a Life Cycle Analysis (LCA) of the French nuclear installed base, between:

- (OTC) once through fuel cycle (spent fuel is considered as an ultimate waste),
- (TTC) twice through fuel cycle (spent fuel is processed once to recycle plutonium in MOX fuel and uranium in URE fuel, as deployed today in France),
- (SFR) Gen IV fast neutrons reactors fuel cycle (theoretical 100% sodium fast reactors design study but easily extendable to other Gen IV fast neutrons reactor designs).

Impact Indicators	Unit	OTC	TTC	SFR
CO_2 emissions	g/kWh	5.45	5.29	2.33
SOx emissions	g/MWh	18.73	16.28	0.59
NOx emissions	g/MWh	29.01	25.3	3.83
Land use	m^2/GWh	222.6	211	50.2
Liquid chemical effluents	kg/GWh	333.92	287.53	12.6
Gaseous radioactive release	MBq/kWh	0.8	1.22	0.53
Liquid radioactive release	kBq/kWh	2.8	27.2	3.56
High Level Waste (HLW)	m^3/TWh	1.17	0.36	0.3

Table 2-6: comparison of three fuel cycle options.

It clearly demonstrates that multi-recycling activities improve environmental indicators.

The benefit of a linear combination of both 3rd (Gen-III) and 4th (Gen-IV) generation reactors can be derived from this analysis.

Implementation of recycling substantially reduces the volume of high-level waste, which determines the size of geological repositories required by its high residual thermal power: with recycling, the repository volume and surface are divided by a factor greater than two.

The increase in radioactive gaseous and liquid releases with TTC compared to OTC results from dissolving the spent fuel in the reprocessing plant and is mainly due to krypton (^{85}Kr) and tritium. These radioactive releases are well below regulatory limits, and have a negligible effect on health and the environment. Their impact is lower than 10 µSv/a or 1% of natural sources of radiation.

A short outlook on technologies being developed

Pool type, sodium cooled reactors remain the preferred route of development of fast reactors despite the many issues raised by this technology. Among ongoing achievements and developments, it can be mentioned:

- BN-800 reactor is a sodium-cooled fast breeder reactor, built at the Beloyarsk Nuclear Power Station, in Zarechny, Sverdlovsk Oblast, Russia, achieving commercial operation in 2016.
- China has plans to develop a 600 MWe demonstration SFR based on the CEFR (China's Experimental Fast Reactor – 65 MWth – 20 MWe) experience.
- The French Atomic Energy Commission (CEA) completed the basic design of ASTRID, (Advanced Sodium Technological Reactor for Industrial Demonstration), a 600 MW sodium-cooled reactor including an advanced sodium gas concept to transfer energy from the reactor to a gas turbine.
- Other technologies are also being considered. Among them, it is worth to mention molten salt fast reactors concepts, such as the MOSART concept in Russia without or with Th–U support, or the Molten Salt Fast Reactor, sketched by the French Research Institute CNRS. These reactors claim to allow a progressive shift from a Uranium based (scarce) to a Thorium based (abundant) cycle if needed. However, this goal may be questioned, as the Fast reactors by themselves would alleviate any concerns related to Uranium scarcity; and use of Thorium would require investing in a completely new fuel cycle infrastructure.

2.4.3. Other advanced technologies

Other advanced technologies are:

- Development of new generation of Accident Tolerant Fuels (ATF); ATF are designed to better withstand a nuclear accident; SiC fuel cladding would be beneficial for fuel cooling under normal operation, and limit fuel temperature by notably reducing hydrogen generation from zirconium water reaction with chromium coating or SiC cladding. Fuel pellet would be designed to increase thermal conductivity and reduce radioactive release. By themselves, ATF have no impact on waste.
- Artificial Intelligence (AI) tools, protected against cyberattacks, will help operation of Nuclear Power Plants (NPP), combining sensors integrated to NPP equipment and NPP numerical twins with algorithms delivering diagnosis and monitoring equipment behavior.

2.5. Conclusions

As a general conclusion one may note that impacts of nuclear energy on the environment are well documented.

Concentrations of radionuclides in the environment are easy to measure and counter-check. It is more difficult to quantify concentrations of chemotoxic elements.

The monitoring of radioactivity in real time is a warning sign to preserve the environment and the data obtained allow checking the results of simulations of real or expected releases. The controversial problem, if any, is the estimation of the associated detriment. For radiological detriment, the dose is an additive parameter. Such parameter does not exist in the protection against chemotoxic substances.

Nuclear energy does not release chemical pollutants resulting from combustion to the atmosphere (Ref. 5). The impacts on the environment come from the potential release of radioactivity at each stage of the nuclear fuel cycle, for instance during transportation.

The radioactivity levels of the releases are regulated by the competent radiation protection authority. Discharge authorizations are provided on the basis of doses to the most exposed individuals or critical group close to the site, according to scenarios. The actual releases reach only a few per cent of the authorized levels. There are also limitations based on the calculated maximum admissible limits in Bq fixed by international organizations for waters, air and some bio-indicators. They derive from scenarios taking into account exposures due to all possible radioactive releases and corresponding to a committed maximum dose (see later) of 1 mSv in one year.

The local radiological impacts on living species, including humans, are usually low to very low, when compared to those due to the radioactivity of natural environments or to that associated with the use of fossil fuels like coal or shale gas; as a matter of fact, they are so low that they cannot be identified. It is the same situation for chemical pollutants released from nuclear facilities compared to other possible transfers from man-made activities. These assessments are based on the results of numerous monitoring devices implemented by operators, authorities and stakeholders, and of epidemiologic studies.

According to LCA of energy systems, which take into account all impacts on the environment generated during the fabrication of materials for the construction of power plants and facilities as well as during their operations, nuclear energy is characterized by a quasi-zero emission of CO_2 (and other greenhouse gases) compared to all fossil fuel-fired energy systems and is the energy that is consuming the least amount of land and material. With respect to other decarbonized sources of energy, nuclear energy occupies in the order of tens to hundreds of times less land for the same amount of energy production, needs less concrete and steel per MWh and does not demand critical materials such as rare earth elements.

The consumption of water to cool inland reactors is significant, and must be seriously considered in water stressed regions. However, there are no significant cooling water issues for plants cooled by sea water or large rivers.

If one focuses on civil works to build a Gen-III nuclear reactor, it appears that the use of concrete and steel is higher than for a fossil fuel-fired power plant. This is due to safety requirements with regard to external and internal events (earthquakes, aircraft crash, etc.).

Fast reactors and multi-recycling have the potential to drastically reduce the environmental footprint of nuclear energy, and their developments should be adequately funded.

Appendix 2.1: More specific considerations about the Chinese situation

The growth of nuclear energy in China is the fastest of all nuclear countries. In recent years, China has carried out much research on greenhouse gas emissions and the environmental impact of radiation from nuclear power, fossil energy (coal-fired power stations), and renewable energy sources (hydropower, wind power and photovoltaic power generation), using Life Cycle Analysis (LCA) to examine the direct greenhouse gas emissions and radioactive releases during construction and operation, as well as the indirect emissions and releases from energy and raw material consumptions of the energy systems and related infrastructures during mining, manufacturing, processing and transportation. The emission from main materials used for construction are added to the total emission of the power source.

Figure A2-1 shows the normalized life cycle emissions of greenhouse gases from different power sources: the greenhouse gas emissions from nuclear power, hydropower and wind power are lower than those from coal power by two orders of magnitude. The emissions from photovoltaic power generation are lower than those from coal power by one order of magnitude, placing them at the medium level. Emissions are due to the energy consumption of nuclear power related activities in the total life cycle (mining, transportation, etc.) accounting for 84% of total emissions, indicating that the greenhouse gas emissions related to nuclear power depends on the Chinese energy mix. If the primary power is provided by nuclear power plants or other renewable energy sources instead of coal power, every generation of 1kWh power could decrease CO_2 emissions by 1kg, featuring considerable potential for the reduction of greenhouse gases. It is predicted that, from the year 2020 up to 2050, the share of non-coal-fired power generation in China will increase from 28% to 47%, and the share of coal power will diminish from 69% to 49%. Furthermore, in that case, when power-generating capacity in China grows by 70%, the emission of greenhouse gases will rise by merely 23% (according to the maximum level of normalized greenhouse gas emissions from different power sources). In conclusion, clean energy sources (nuclear power and renewable energy sources) have great potential capacity for the reduction of greenhouse gas emission, and are essential to build a low-carbon energy system and speed up the transformation of power generation and demand.

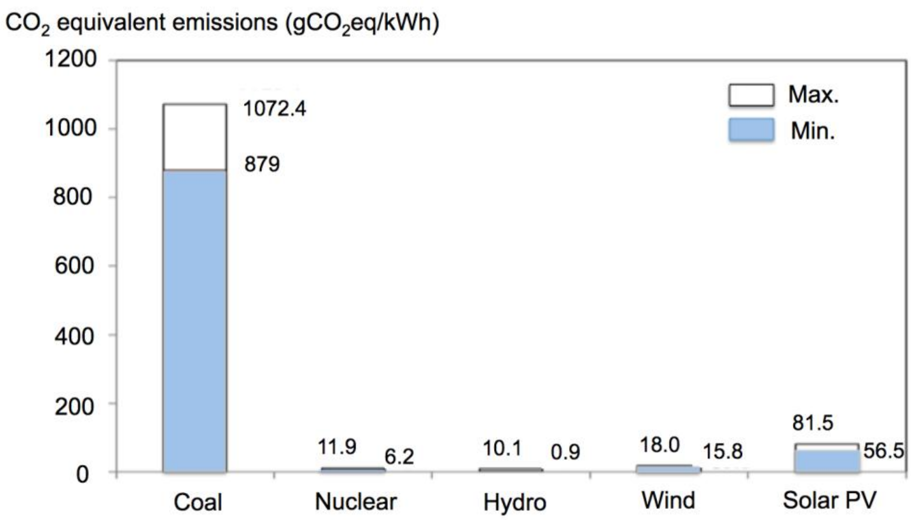

Figure A2-1 Normalized greenhouse gas emission from different power sources in the life cycle (Ref. 27)..

Figure A2-2 shows the normalized collective dose from different power sources in the life cycle (assessment range: 80km surrounding the site). As for hydropower, wind power and photovoltaic power, the public dose is relatively low (until today, there is no such research on the direct radioactive releases from the development and electricity generation of renewable power sources, such as for example radon released from water in hydropower plants). As for nuclear power plants, 86% of the public dose comes from the mining of uranium, but as the in-situ leaching uranium mining technologies get expanded in the near future in China, the public dose from nuclear power will be further reduced. At present, coal power is the first and foremost energy in the Chinese energy structure. With the upgrading of power plant structures, making the 300 MWe and above units gradually becoming mainstream, and the reduction of coal consumption for power supply together with the development of de-dusting technologies, public doses generated from coal power (except for the utilization of coal ash and slag) will drop greatly. But coal has relatively low energy density and generates lots of ash and slag. In China, such ash and slag are mainly mixed to be used as the main material for housing walls, generating 2.6×10^{3} man-Sv/GWa of normalized collective dose to the public (average from the year of 2003 to 2010), accounting for 99.9% of normalized collective dose to the public in the life cycle of coal power, higher than the sum of others by nearly three orders of magnitude and considerably higher than that of other power sources. Thus, research results indicate that improving the energy structure and developing nuclear and renewable power could greatly reduce the public exposure.

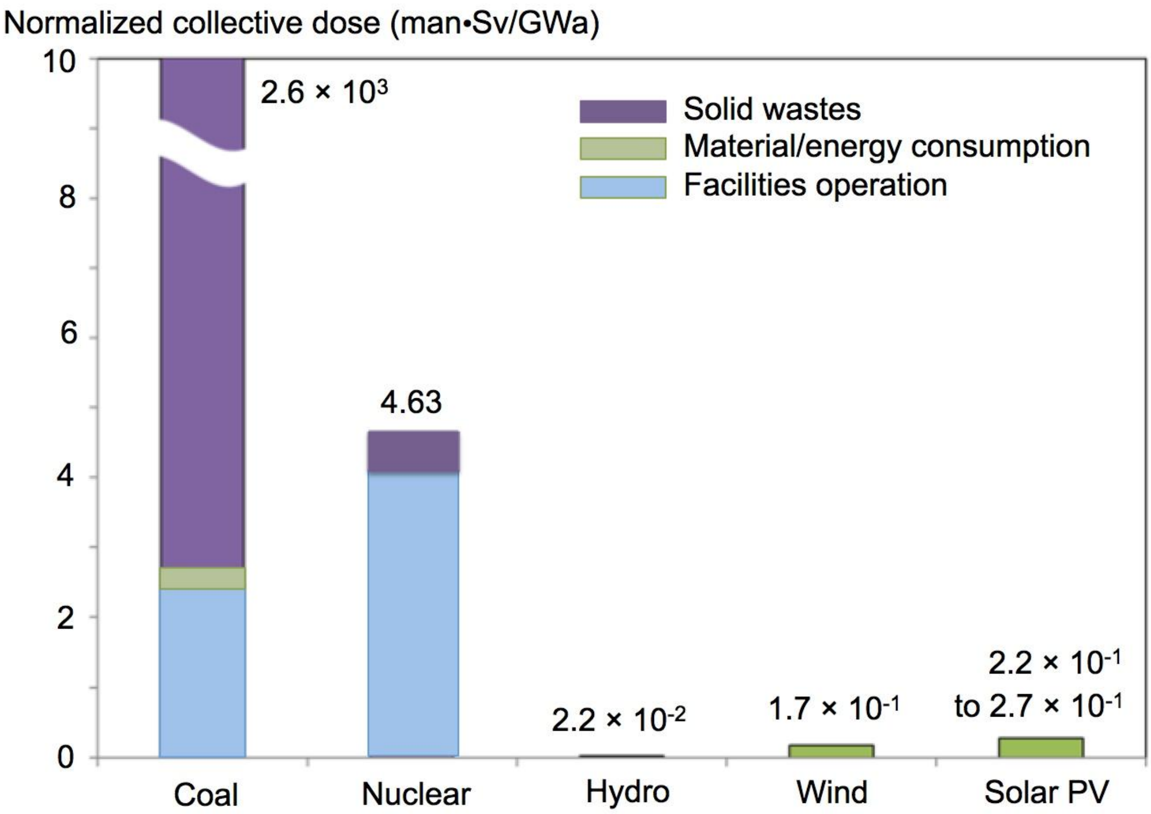

Figure A2-2 Public normalized collective dose from different power sources during the life cycle in China.

Note: in terms of coal power, “Solid waste” refers to the application of coal ash and slag on the main walls of houses; in terms of nuclear power, “Solid waste” refers to the disposal of solid waste.

Appendix 2-2: Large scale epidemiological studies around nuclear sites (examples and results)

As releases of radioactivity around nuclear facilities are quite low, their impact on life and health of the surrounding populations can be evaluated only by means of epidemiological studies, which require probabilistic assessments. They analyze the cases presented or the mortality rate caused by radioactivity induced diseases, as well as the factors that influence their development. The studies are done in the natural environment of the observed individuals, and their life habits are taken into consideration as far as possible.

Since World War II, hundreds of epidemiological studies have been carried out within the environments of nuclear sites and contaminated areas all over the world.

Conducting epidemiological studies is not easy. This requires a good preparation, a precise identification of all the interfering parameters and their interrelations, a detailed and in-depth study of the environmental conditions that might influence the research, a prolonged observation time, orderly and thorough data collection, adequate means and properly trained specialists to correctly interpret and handle the data, the methods used, and the results obtained.

Here are some of the reasons which complicate the analysis of radiation consequences at low doses:

- Given their low incidence, the effects might be masked by causes other than ionizing radiation, which, at greater frequencies, could produce similar effects in an isolated or simultaneous way.
- From the methodological and statistical viewpoint, and due to this low incidence, it is necessary to study very large population samples throughout several generations and along with very large contrasted population samples (control samples) with similar environmental factors and which have not been exposed to the ionizing radiations.
- Humans are being continuously subject to natural ionizing radiation (such as cosmic radiation and radiation from radioelements in the atmosphere and in the earth's crust) as well as from artificial radiation (medical or industrial uses of nuclear radiations) or non-ionizing soft radiation (such as radiation from television, computers...). Therefore, it is not easy at all to discern the effects produced by one or the other source of radiation.

In this respect one may mention a few international epidemiological studies:

a. The 2006 to 2010 study "Possible radiological impacts of nuclear and radioactive sites on human health", carried out in Spain by the Ministry of Science and Innovation, the Carlos III Health Institute, and the Nuclear Safety Council. *This study concluded that nuclear sites do not affect the risk of cancer for the population; the estimated accumulated doses that the population would have received in the analyzed areas are* *very low, on an average 300 times lower than the natural background radiation around the sites.*

b. The 2008 to 2010 study carried out by the University of Berne in Switzerland at the request of the Swiss medical *authorities showed that there is no relationship between juvenile cancer and Swiss nuclear reactor sites*.

c. In 2008, the French IRSN published a detailed report (Ref. 28) which synthesizes the results of all the epidemiological leukemia studies around nuclear sites (of all types) done in the world. The main conclusion is the following:" *At the local level, excess of acknowledged childhood leukemia cases exists in the UK near the Sellafield and Dounreay reprocessing facilities and in Germany near the Kruemmel NPP. Nevertheless, all the multisite studies available today, including France, do not show an increase of the frequency of leukemia among young people (0-14 years or 0-24 years) around the nuclear sites.*

d. A German study shows an excess of leukemia among the (0-4 years) around 16 German NPP (Ref. 11); but the authors caution the readers that their findings are unexpected given the very low observed levels of radiation and they state that the cause of childhood leukemia remains unexplained and may be due to uncontrolled confounding or pure coincidence. Today such an observation is not confirmed by the studies carried out in other countries, including France.

Numerous studies have tried to explain the excess of leukemia observed around some nuclear sites by looking at multiple potential risk's factors. But the determination of the causes is limited by the lack of knowledge about risk factors of childhood leukemia, especially on potential effects of ionizing radiation exposure in utero and during early childhood. Large scale investigations would be necessary, at national and international levels.

Epidemiological studies are often done once a nuclear facility is already in place. They cannot reveal changes if there is no reference to the situation prior to the construction of the nuclear facility. Therefore, one would need studies before and after the installation of a nuclear facility.

It appears that, in order to study health effects, epidemiologic studies around nuclear sites are more appropriate when carried out after releases of radioactivity during accidents than regular investigations, which cannot easily reveal the very small impact of facilities during normal operation. Nevertheless, the latter are interesting as background for comparisons.

CHAPTER 3 - Spent fuel and radwaste management

Recommendations

The present analysis indicates that radwaste management under present practices has very low local and global impacts on health and the environment. Nevertheless, improvements of the various processes, which lead to the release of radioactivity outside of nuclear facilities and radwaste packages, are always desirable.

The Academies recommend that the methodology to evaluate all environmental impacts (radiological and chemical) the associated risks be refined considering waste arising from the front and back-end of nuclear fuel cycle and taking into account time scale.

To support this general recommendation the Academies propose that:

a. The best available technologies (BATs) be used to confine radionuclides at every step of the processes;
b. The process of safe disposal of radwaste be accelerated, so as to ensure intergenerational equity and to avoid undue burdens on future generations;
c. R&D programs be developed aimed at a better understanding of the radiological and chemical impacts on ecosystems (reversibility, resilience, bio-availability of elements of interest...) and quantitative parameters be defined to characterize the hazards linked to radwaste in order to better face environmental issues;
d. Comprehensive and responsible systems, visible to the public, be used to protect the environment (including legislation system, competent bodies, funding system...).

Introduction

A specificity of the nuclear industry is that it uses fuel that does not disappear when “burned”. The nuclear industry cannot manage waste in the same way as the fossil fuel industry does, i.e. according to standard waste disposal channels in the form of greenhouse gas emissions into the atmosphere on one hand and accumulation of solid residue deposits on the other. Fission and other nuclear processes inside the nuclear fuel produce around a hundred of short- or long-lived radionuclides, i.e. radioactive isotopes which encompass two thirds of the elements of the periodic table. The chemical properties of all these radionuclides are drastically different. The nuclear fuel radioactivity increases, from a kBq/cm^3 (fresh fuel) to 10^{10} or 10^{11} Bq/cm^3, when it is downloaded from reactors (spent fuel). All electronuclear radwaste contain higher or lower amounts of these radionuclides. Management of radwaste is then a part of the nuclear fuel cycle. Today industrial channels for radwaste management are operated in all nuclear countries. The great majority of radwaste (the less radioactive and more abundant) is finally disposed of in surface/sub-surface repositories; the remainder (the more radioactive and less abundant) is kept in storage pending the launching of deep geological repositories. Despite of the high level of care taken in such operations, sorting out fissionable material still held in spent fuel (essentially Plutonium), and nuclear waste leads to the immediate release of a few radionuclides into the environment. In a long-term future (from centuries up to thousands of centuries) one may expect the return to the biosphere of some radionuclides from disposed-of radwaste in the geosphere. However, in all cases, measures are taken today to keep the radiological impacts within the normal variations of natural sources of radiation irrespective of geography and timescale.

This chapter focuses on the environmental impacts associated with the management of radwaste.

3.1. Principles, strategies and framework of radwaste management to prevent environmental impacts

The following principles and strategies reflect the international situation but are mainly drawn from several decades of French return of experience.

3.1.1. Principles of radwaste management

The first basic principle is the inter-generational equity (i.e., our generation should not leave the burden of our technical decisions to future generations). The environment is the common property of all generations. Leaving a clean environment to the next generations is a major duty of the present one, particularly with respect to restraining addition of radioactivity to the natural radioactivity. The second is the inter-generational right of access to information so that each generation remains informed about the practices of radwaste management at national and international levels. Keeping the memory, as long as possible, of the location of radwaste having possibly an impact on the environment is the duty of national and international organizations in charge of radwaste management.

To restrain releases of radionuclides to the environment, operators have to implement the BATs (Best Available Technologies) for radwaste management in all nuclear facilities, to minimize radwaste production. This is already current practice as shown in the following.

3.1.2. Strategies of radwaste management

The global strategy defining radwaste management is to 1) maximize in-reactor burning of radioactive materials, 2) concentrate and confine radionuclides and toxics and 3) finally dispose of ultimate radwaste in repositories. These engineered infrastructures are designed to isolate radwaste from the biosphere in such a way that the time of return of radionuclides to the living world be as far-off as possible: in terms of centuries or thousands of centuries. Dilution strategy is avoided. Thus, radwaste management basically differs from the management of conventional waste. It requires a high level of scientific and technical competence and strong support. The principle of “safety first” should be implemented, even if at the detriment of economy.

Except for radwaste produced in very large quantities such as in uranium mining/milling or low/very low level radwaste, crude waste produced at each stage of the fuel cycle is - as soon as possible - either processed to confine/isolate radionuclides or stored in facilities to prevent any contact with the public and the environment, waiting for further processing. The objective is to produce primary waste packages that are handled in all the steps leading to their final disposal. Packages used for high-level waste rely on the best technology design concepts either for conditioning fission products and minor actinides when spent fuel is reprocessed or for encapsulating spent fuel assemblies when spent fuel is not reprocessed (see section 2.1). Radionuclides cannot escape from these packages (except under highly hypothetical circumstances). For other radioactive waste, that are less radioactive by several orders of magnitude, packages are not necessarily sealed.

When repositories, are not immediately available, the packages of whatever radwaste are stored in specially designed facilities, pending final disposal. For high-level radwaste packages, storage in such facilities is mandatory to allow a decrease of their thermal power before being disposed-of.

Short/medium-term impacts to the environment originate from processing and packaging. Under normal operation of the facilities where crude waste is processed and where the packages are stored, the releases to the environment are below the authorized limits as is the case for all nuclear facilities. Long-term impacts come from packages that have been disposed-of, because a time comes when the containers corrode, and radionuclides/toxics are slowly released. During uranium mining and disposal of non-packaged radwaste from processing of uranium ores both types of impacts (short- and long-term) have to be considered.

Radwaste is disposed of in several ways including surface, subsurface, or will be disposed of in deep geological repositories, depending on their characteristics. Whatever they are, the decision to open a repository, which is a nuclear facility, relies on a safety case analysis, requiring preservation of public health and avoidance of environmental pollution. This safety case analysis considers both short/medium and long-term impacts.

For short/medium term in all circumstances, hazardous impacts on people and the environment must be well below legal thresholds and in compliance with current regulations.

For the long-term, potential impacts are assessed by making use of simulation based on the present up-to-date information, data and scenarios. Discharges of radioactive gaseous or liquid effluents to the environment lead to the dispersion of radioactivity and to their deposition at a more or less distant location from their emission source. Finally, radionuclides enter the biogeochemical cycles. The immediate radiological and chemotoxic impacts of these fall-outs can be calculated from *in situ* measurements. This is not the case for the long and very long-term impacts of radionuclides returning to the biosphere from contaminated soils or waters or from radwaste packages disposed-of in geological formations. Scientists have to model the space-time migration of radionuclides through many natural or exogenous materials from the place of their emission to the outlets of the formations before to estimate the impacts through scenarios. Time duration to be considered in safety case analysis goes from ten thousand years for quantitative estimates of doses to a million years for qualitative estimates, well beyond usual theoretical and practical considerations in the field of technology and stability of society.

The long-term modeling depends on the understanding of effects due to the complexity of the microscopic and/or macroscopic convection/or diffusion phenomena. Convection phenomena occur in fractured engineered or geological materials. The transport of solutes in large homogenous materials without connected fractures is under the dependence of concentration gradients leading to theoretical diffusion laws in $t^{1/2}$. The behavioral laws of the materials used for their ability to withstand degradation like packages of High Level/ Long Life Waste are, in the final analysis, the result of microscopic diffusion phenomena. In total the long-term models incorporate low-power empirical laws in relation to time: t^n, n being less than 1, meaning that consequences are decreasing over time. Sciences which support the models belong to the fields of earth science, science of matter and life science. Each field has accumulated many data.

Earth sciences are familiar with the mechanisms of thermal, hydro-geological, mechanical and chemical (THMC) evolutions of geological layers up to a million years and have local models for earthquakes, hydrogeology and climate. The astronomical cyclical changes that affect the climate are included as part of a global climate model. Future events and their consequences can be included on these bases over a few hundred thousand years.

Material sciences can model the fate of rocks, solid components of waste packages and storage structures, taking into account all knowledge derived from natural or anthropogenic analogues and experimentation. The same is true for the migration of elements. The importance of geochemistry is of a crucial importance. Thus, a deep reducing environment (Eh $\ll 0$) allows a substantial limitation of the solubility of actinides and thus of their potential migration. This is also true for many fission products. The only long-lived radio-elements that are not susceptible to redox conditions are essentially ^{36}Cl or ^{129}I, which largely dominate the outfall inventories predicted in normal and degraded scenarios. The majority of radionuclides remains trapped on the spot in near field.

Models are constructed on the basis of experiments carried out over decades and results of brutal, mild, repeated disturbances aimed at accelerating environmental aggressions. The results obtained generally allow for the identification of mechanisms at the appropriate scale. The models can be tested by simulation and blind validation in which information is initially masked. Uncertainties can be reduced by repeating the experiments. The limits of extrapolation in the different domains are known.

In material science, temporal modeling can be based on well-founded mathematical models. In life sciences modeling is less easy because of the complexity of metabolism. In human sciences historians work over a few centuries while sociologists consider a few decades, and the use of formalization and logic are less systematic, so that temporal models are, less advanced, or non-existent.

There is some uncertainty about future environmental impacts as in all cases where long-term simulations are being considered mainly because scenarios require many assumptions. However, all simulations, even those corresponding to worst scenarios, indicate that radiological impacts are well below the impacts of natural radioactivity (or of the same order in the case of human intrusion in disposal).

3.1.3. Framework of radwaste management with respect to the environment

The frameworks of radwaste management are defined at the international level by:

a. the Common Convention (IAEA, INFCIRC/546, December 24, 1997) on the safety of management of spent fuel and radioactive waste. This convention is the result of broad discussions between 1994 and 1997 following the Convention on nuclear safety (IAEA, INFCIRC/449, July 15, 1994). It includes a section on protection of the environment against ionizing radiations. It calls for periodic reports from contracting nuclear countries about how they accomplish their obligations with regard to the dispositions of the convention. Today 43 countries report each three years to IAEA,
b. the recommendations of ICRP (IAEA, Safety series 115-I, Vienna, 1994) which are taken into account by all countries.

European countries have also to consider the European Council Directive 2011/70/Euratom which requires that each country develop a waste management policy protecting human beings and the environment.

In addition, there are, under the IAEA authority (and European Commission), international regulations dealing with the transportation of radwaste packages which require robust canisters to protect the public and the environment.

The implementation of the commitments of the Common convention is a key item. This is why the IAEA follows the three years update of the contracting parties.

Both China and France are parties to the Common Convention on the safety of the management of spent fuel and radwaste, and they have established a relatively comprehensive legal and organizational framework for the effective and safe management of spent fuel and radwaste.

The French Constitution acknowledges the precautionary principle. This applies to all activities and aims at protecting the environment. It implies to take proportionate measures as soon as there is a presumption of serious and irreversible environmental impact. It involves new researches to better understand the fear phenomena (section 5 of the 2004 Environment Charter, incorporated in the French Constitution).

In France the management of radioactive waste is governed by two laws: the 1991 law (focused on researches) and the 2016 law (focused on implementation of decisions). The Ministry of Ecology Transition and Solidarity develops the policy and implements the Government's decisions. Several nuclear operators are involved: EDF which operates 58 nuclear reactors, Orano-Cycle and Framatome which operate the facilities of the front and back-end of the nuclear cycle, CEA which leads R&D on nuclear energy and Andra which is in charge of the long-term management of radwaste. The safety authority ASN assures, on behalf of the French state, the control of nuclear safety and radiation protection so that people and environment are protected from risks related to nuclear activities. IRSN is the technical support of ASN for safety case analysis. It carries out its own researches on the noxiousness of radwaste and on environmental impacts of radwaste management. Finally, there is a High committee for transparency and information on nuclear safety. This committee formulates recommendations to improve the transparency and the quality of information for the public.

In France all researches and investigations dealing with radwaste management are indexed in a National Plan (PNGMDR: Plan National de Gestion des Matières et Déchets Radioactifs) issued every three years by ASN and the Ministry of Ecology and of Solidarity in connection with a pluralistic working group including environmental protection associations. This constitutes a strategic tool to implement the waste management policy and to inform the public. It identifies the needs, sets the objectives, makes recommendations to all stakeholders and asks for mandatory reports. It is evaluated by a Commission in charge of the environment. The Plan is transmitted to the Parliament and submitted to a public consultation.

A complete inventory of all radwaste and nuclear materials is published by Andra every three years gathering the declarations of producers. It comprises radwaste categories, quantities, geographic location at the time, and for the next decades, according to several scenarios of evolution of the domestic nuclear fleet. Any change has implications on the nature and quantities of waste and possibly on the impacts on environment.

Each year an independent Committee set up by law (CNE: Commission Nationale d'Evaluation) reports to the Parliament about results of research carried out on this topic.

In China a legislative framework for governing the safety of spent fuel management and the safety of radwaste management is established and maintained, that incorporates a comprehensive set of relevant national laws, administrative regulations, departmental rules, management guides and reference documents, as well as the licensing regime of spent fuel and radioactive waste management activities. The laws applicable to the management of spent fuel and radioactive waste are: a) the Law on Prevention and Control of Radioactive Pollution (LPCRP), enacted by the NPCSC (National People's Congress Standing Committee） in 2003, and b) the Act of Nuclear Safety, enacted by the NPCSC in 2017.

In China the Ministry of Ecology and Environment/National Nuclear Safety Administration (MEE/NNSA) is responsible for the regulatory control of the spent fuel and radioactive waste management, and the China Atomic Energy Authority (CAEA) is the competent body for the spent fuel and radwaste management.

In China the generator of radwaste shall bear the overall safety responsibility for radwaste management and implement the management of radwaste in terms of their classification.

3.2. Specific characteristics and classification of radwaste

Nuclear countries have adapted the classification of nuclear radwaste to their national industrial channels and the ensuing management practices of radwaste categories may differ to some extent but there are many commonalities. The Academies have discussed this topic in their first report according to activity and life of radionuclides contained in radwaste. In the following the traditional denominations used are as follows: Very low-level waste (VLLW), Low level-long lived waste (LLW-LL), Low and intermediate level-short lived waste (LILW-SL), Intermediate level-long lived waste (ILW-LL), High level-long lived waste (HLW).

Before proceeding, it is mandatory to recall that the type of highest activity radwaste (ILW-LL and HLW) depends on the decision made by nuclear countries with regard to the spent fuel cycle.

3.2.1. Spent fuel or reprocessing radwaste.

The management of radwaste from electronuclear reactors deals with:

a. spent fuel (when spent fuel is considered as radwaste) and radwaste originating from reprocessing and recycling of spent fuel (when spent fuel is considered as a source of fissile materials),

b. all other radwaste produced by reactors or facilities of the nuclear fuel cycles.

As already indicated, there are two types of nuclear fuel cycles:

- Open nuclear fuel cycle where the spent fuel is not reprocessed but stored under wet or dry conditions, pending the transfer to a final disposal after adequate conditioning and packaging as HLW packages of encapsulated spent fuel to be disposed-of are designed to be unfailing during thousands of years,

- Closed fuel cycle where the spent fuel is reprocessed, valuable materials (U and Pu) extracted and the remaining material conditioned in the form of nuclear glasses and packaged mainly as HLW and ILW-LL. Packages of nuclear glasses to be disposed of are designed to be unfailing during thousands of years.

The radioactivity of spent fuel and nuclear glass is roughly the same, but the latter does not contain plutonium and uranium.

Each nuclear country in the world has chosen one or the other of these fuel cycle options, according to the national political, economic, technical or diplomatic contexts. France and China have chosen the closed fuel cycle scheme, allowing a sustainable nuclear energy policy. In Europe the 28 countries of the European Union (including UK) have not all adopted the same strategy. Some countries consider that their choice is not final and could change with respect to the evolution of technology and return of experience of the more advanced nuclear countries in recycling fissile radionuclides; some countries have no electronuclear facility.

According to the characteristics of the packages of spent fuel and nuclear glasses to be disposed of, little difference is to be expected regarding the long-term environmental impact, if any. The same would apply to storage under monitoring in spite of the differences in the conditions of storage (sub-assemblies of spent fuel in pond or in dry cask, nuclear glasses in dry facilities). In contrast, reprocessing, which needs chemical separation of radioactive elements from spent fuel, has a local impact on the environment that is higher than the no-reprocessing option.

In this chapter, for the sake of simplicity, we shall generically consider the main trends in radwaste management independently of the nuclear fuel cycle option, with the objective of examining phenomena that could lead to environmental impacts.

3.2.2. Specific characteristics of radwaste versus the environment

Nuclear energy produces much smaller amounts of waste per MWh compared with fossil energies. This is linked to the energy density of nuclear fuel, thousands of times higher than that of fossil fuels, depending on burn-up of the nuclear fuel and on the reactor type. Radwaste is generated by a relatively small number of NPPs and fuel cycle facilities when compared to the gaseous and solid residue output of the many fossil fuel fired power plants. This condition makes radwaste management easy to control by Safety and Environmental authorities, in compliance with strict regulations, which are accepted by nuclear countries and derive as already indicated from recommendations of international agencies. Streams and characteristics of radwaste are the best documented of all waste streams. In those nuclear countries that have also legacy radwaste, produced by the early electronuclear reactors and by military applications, the corresponding stockpiles are well identified.

The main environmental impacts that one can expect from radwaste management are linked to public exposure to ionizing radiation and to modifications of the quality of aquatic and terrestrial ecosystems, possibly leading to a loss of biodiversity. They are due to liquid or gaseous releases of radioactive substances during severe accidents. Other impacts are those encountered in any supply-dependent operating facilities, involving important and continuous transportation of materials (resulting in heavy traffic, noise, …).

The doses (external and internal) due to release of gases or liquids containing radioactive or toxic substances are estimated according to tested methods and the results are submitted to international scrutiny (Round Robin tests). Phenomena involved in the various processes are well understood and open databases are used to feed simulation models. Similar methods are used to estimate the impacts, if any, from toxic chemicals with reference to the recommendations of the World Health Organization (WHO).

It is less easy to quantify the impacts of radioactivity and toxics on other ecosystems because data on the non-human biosphere is still lacking. Usually, human beings are more sensitive to radiation hazards compared to other species. The non-human species would be suitably protected when human beings are adequately protected against radiation.

In both cases, the main knowledge-gap relates to the bioavailability of elements that carry radioactivity, i.e. the radioactive chemical species that can be transferred to living beings. In this respect, speciation of elements is of primordial importance. Radionuclides in the environment are at tracer scale and their physicochemical behavior cannot be inferred from the behavior of the element of which they belong at usual concentrations. Radionuclides species do not control chemical systems, on the contrary they undergo the constraints imposed by the species in weighable quantities. The chemical identity of the radioactive elements is lost. In principle [2] radioactive monomeric species could exist but they are often sorbed on natural colloids and appear as radioactive pseudo-colloids. In contrast the behavior of radionuclides in packages is that of any element at usual concentration. Solubility phenomena limit their releases, a point that needs to be underlined. Many national and international research programmes have been set up to clarify basic phenomena involved in the transfer of radioactivity to living material. This topic should be included in the numerous trans-disciplinary investigations aimed at understanding the human impact on the environment. Ecotoxicology of radionuclides has been studied since several decades, but progresses are slow.

Other energy industries generate various non-radioactive waste containing toxic and hazardous material. A special treatment and/or disposal in landfill could be required but, as the concentration of chemicals before having a toxic effect is much higher than that of radionuclides causing radiological hazards, confinement of conventional disposal sites for chemicals may be less effective than that of radwaste repositories. It is then apparent that radwaste repositories designed to confine radionuclides also effectively confine toxic material usually encountered in classical waste.

3.2.3. Classification of radwaste versus the environment

Spent nuclear fuel is periodically removed from NPPs and replaced by fresh fuel. As indicated, spent fuel assemblies are either reprocessed or stored before being disposed-of as high-level radwaste. For the reprocessing route, spent fuel rods are cut open, thus allowing the chemical separation of Pu and U through recycling. Today all other radionuclides resulting from recycling are dissolved in nuclear glasses and packaged. The resulting packages are initially as radioactive as the original spent fuel but with very small content of uranium and plutonium. The reprocessing and manufacturing processes generate additional streams of radwaste, more or less contaminated with long-lived radionuclides present in spent fuel. The operation of NPPs also generates radwaste. Finally, large quantities of various categories of radwaste, but mainly of low-level radioactivity, are expected from future massive decommissioning of reactors and facilities.

Regarding the environmental impact, a distinction between short-lived and long-lived waste is crucial. Indeed, the former is generally disposed-of in surface/sub-surface facilities and its environmental impacts can logically be of direct concern to our generation. Long-lived waste will be disposed-of in deep geological repositories, down to several hundred meters, and its expected environmental impacts are seen as possibly occurring in the far future. Notwithstanding, both strategies are a subject of careful investigation.

An additional distinction considers the origin of radionuclides present in radwaste: natural (U, Th and daughters) or man-made (actinides, fission products, tritium, etc.). Radwaste containing only uranium originates from the front-end nuclear cycle. Those linked to the back-end of the nuclear cycle contain in addition many other radionuclides.

Releases of radionuclides or toxic substances can occur during the operation of the facilities/repositories and even after their closure. The operational procedures and equipment for dropping-off the packages as well as the daily and periodic monitoring of radioactivity (and sometimes of chemical pollutants) permit the detection of any malfunction affecting normal operation. Thus, local environmental impacts need to be evaluated according to the selected domains where they might occur. The occurrence and extent of releases of radionuclides and toxics, long time after the closure of repositories, depends on the robustness of packages and the capacity of manufactured and natural barriers to prevent migration of elements to the biosphere. As already indicated, near- and far-field impacts can only be modelled. In France the classification of radwaste follows the classical approach implemented in the option of an open fuel cycle. There are channels to dispose-of all the radwaste except the LLW-LL and ILW-LL and HLW (see Appendix 3). For the former, Andra geological investigations are in progress to site a sub-surface repository in clay. For the latter, Andra plans to ask ASN to license Cigeo as soon as 2019. Cigeo will be a deep repository sited in a clay layer at 500 meters depth and 130 m thick designed to accept all the radwaste which cannot be disposed-of in sub-surface repositories. Radwaste to be considered are those produced and to be produced by all the reactors and facilities of the present nuclear fleet and fuel cycle, whatever the future energetic choices that will be made by the government. The present choice is to recycle once plutonium and uranium from UOX spent fuel and to store MOX spent fuel as valuable nuclear matter for launching fast neutron reactors. It is assumed that all UOX spent fuel will be reprocessed.

The sorting of radioactive substances into radwaste and nuclear matter with added value and available for later use, is the responsibility of the producers.

In China the system of radwaste categorization is developed on the basis of IAEA safety standards of radwaste classification and the current version is the adoption of the equivalent of the Classification of Radioactive Waste (GSG-1) issued by IAEA in 2009 (Ref. 30). The classification of radwaste is similar to that of France, which is set up according to the disposal strategy. The major differences are that the low-level radwaste in China corresponds to low and intermediate short-lived waste plus low-level long-lived radioactive waste with lower specific activity in France, and the low-level long-lived radioactive waste with higher specific activity in France corresponds to the intermediate radioactive waste in China.

3.3. Processing and discharge of radwaste

3.3.1. Minimization of radwaste

The risk that the management of radwaste leads to environmental impacts is lowest when the amount of crude radwaste to be processed is the lowest. The minimization of the quantities of radwaste starts by sorting out the radioactive substances produced in all facilities. It allows to eliminate those characterized by a radioactivity that is at the detection limit or under clearance level, if they exist. The next step is the packaging of radwaste to reduce the dispersion of radionuclides in transport operations and storage. There are many packaging techniques for finding the economic optimum between any immediate environmental impacts due to packaging and storage and delayed environmental impacts due to geological disposal. In all cases BATs are generally implemented.

Nearly all countries have clearance levels or detection limits of radwaste, which lead to the de-categorization of potential radwaste in non-radioactive material. Such releases of materials for public uses can result in a substantial reduction of the most abundant VLLW. They concern the concepts of exemption and of clearance of radioactive materials. The first concept relies on the definition of activity concentration (Bqg^{-1}or $Bqcm^{-2}$ or total activity) for limited quantities of matter (1 ton for instance) below which no control is necessary to assure radiological protection or that environmental impacts are negligible when for instance recycled materials are used. The second concept relies also on the consideration of the activity concentration (Bqg^{-1} or $Bqcm^{-2}$ or total activity less than, or equal to, those for exemption) for possible re-use of decontaminated materials. Universal clearance levels are such that for any pessimistic scenario the radiological impact is less than 0.01 mSv per year (recommended dose by IAEA -safety rule RS-G-1.7- and Euratom - directive 96/29). Such low doses cannot have an impact on the environment.

The other way to minimize radwaste quantities is the recycling of LLW like metallic materials. They can be melted in such a way that the processes lead to their decontamination. Melting is the only process which leads to radioactivity homogenization of the material for recycling, later facilitating their monitoring.

It seems impossible to reduce the quantities of other radwaste produced along the fuel cycle by recycling.

France does not practice the release of VLLW. The French Nuclear Safety Authority (ASN) considers that every material which has possibly been in contact with a radioactive contamination or which has been activated by radiation is a VLLW subject to regulation. The main reason claimed by ASN for not applying exemptions and clearances is the difficulty of the application of these concepts so that the limit of 0.01 mSv/year is ensured for the added dose to an individual. ASN considers that, against the advantages of clearance, it is impossible to consider all possible scenarios; they point out that parameters of safety analysis are subject to discussion, protocols of measuring radioactivity are difficult to implement at industrial scale and finally that there is a risk to make artificial radioactivity as ubiquitous, as natural one. This position is not coherent with international recommendations and some practices in Europe, and it is presently being reviewed. Nevertheless, some exceptional authorizations of clearance could be given (conditional clearance) for special cases in which the addition of radionuclides to solid materials (except products in contact with human beings) could be monitored. It might also be possible to recycle in the nuclear industry special materials only contaminated at very low level of radioactivity and that can be monitored. Cases are submitted to ASN for specific approval.

For several years, the waste producers, Andra, IRSN and ASN have been studying the conditions for creating a release threshold for VVLLW (Very, very low-level waste). EDF and Orano are looking to the technological and economic conditions to recycle by melting large quantities of metallic radwaste.

The safety guide on radioactive waste minimization is in place in China. The newly constructed NPPs comply with the requirements of this safety guide. NPPs under operation have taken practical measures to implement the principle of radioactive waste minimization.

3.3.2. Discharge of effluents

Gaseous or liquid releases to the environment are the main sources of immediate environmental impacts, as already indicated. In the case of waste management, it is the question of the effluents associated with the packaging of primary waste. Gaseous discharges are decontaminated by filtration and/or by washing with appropriate aqueous solutions, if necessary. This leads to solid secondary waste and decontaminated gases. These gases are released to the atmosphere according to regulatory requirements.

The liquid effluents originating from the processes implemented in nuclear facilities are treated locally to produce decontaminated liquid solutions which are released to the environment in compliance with the authorizations, that produces solid radwaste and concentrated radioactive liquid, which are converted to a solid form.

In China both the radioactive gaseous waste and radioactive liquid waste need to be properly treated to make their radioactive levels as low as reasonably achievable while meeting the discharging requirements. All emissions of gaseous and liquid effluents are monitored and controlled to ensure that no accidental releases occur. The liquid effluent is discharged, and the appropriate discharging point is properly selected to optimize dilution in receiving water, and meet the near zero emission requirement for inland site NPPs.

3.4. Disposal of radwaste

3.4.1. Very low-level waste (VLLW)

For radwaste with a low/very-low activity (less than $10^2 Bqg^{-1}$), even containing trace amounts of long-lived radionuclides (like uranium), the landfill disposal concept (on surface or sub-surface) is generally adopted by most nuclear countries around the world. In fact, as radioactivity is low, the half-life of radionuclides is not a determining factor. In general, there are large quantities of such radwaste. The difference with disposal of short-lived radwaste is that it requires only light packaging and a rather limited engineered infrastructure. Packages, if any, have no function of confinement of radionuclide or toxic material. Regulations defined for short-lived radwaste also apply to this category**:** control of radwaste (packages, big-bags, materials, etc.), control of filling of facilities according to predefined capacities, control of releases, control of the environment. There are many types of disposal facilities around the world for technological radwaste, radwaste originating from processing of yellow-cake only containing natural radionuclides as well as radwaste produced through uranium enrichment. IAEA recommend surface/subsurface management by trenching.

France will have to dispose-of around more than 2 billion cubic meters of VLLW which exceed by a factor 4 to 5 the capacity of the present sub-surface repository. The major part of VLLW will come from dismantling of reactors and nuclear facilities. Andra will extend the capacity of the present repository. Andra, radwaste producers, ASN and IRSN are looking for a new management approach of VLLW: addition of a new central disposal, possibly decentralized disposal centers, recycling of metallic radwaste and concrete, conditions for releasing VVLLW.

As indicated previously France does not practice the release of VLLW.

There are four landfill facilities operated for VLLW disposal in China. Around 10,000 m^3 of VLLW have been disposed of so far.

3.4.2. Low and intermediate short-lived waste (LILW-SL)

Short-lived radwaste (10^2-10^6Bq/g) mainly originates from NPP operations. Some contain very small amounts of long-lived radionuclides. Packages of short-lived waste are in general disposed-of in specifically engineered surface/subsurface facilities. The depth of sub-surface facilities could be of several tens of meters. Packages take the form of steel or concrete drums or large containers, sealed or not. Safety and environmental authorities define the radiological capacity, and the capacity for each radionuclide or toxic material, that can be accepted up to the closure of the repository. These capacities depend on the characteristics of the site, the structures designed to host the packages and the engineered barriers. The capacity limitations for surface disposal facilities consider the perspective that they could return to a greenfield status after several hundred years when short-lived radionuclides will have disappeared, but not the long-lived ones. The authorized releases of gas and liquid effluents are also regulated and controlled, and the environment is monitored. All authorizations are set in accordance with the safety analysis of the disposal site/facility.

During operation, which may cover several decades, the main vector of transfer of chemical species from packages to the environment is rainwater or subsurface water flows. Rainwater is collected and processed if necessary. Ground water is monitored at the outlets of the site if this is needed. There is also the possibility that some gases escape the packages, like tritium in the form of tritiated hydrogen and tritiated water and this is why tritium capacity of the repository is limited.

Siting, operating and monitoring of repositories for short-lived radwaste enables the testing of new technologies to improve the confinement of radionuclides, thus reducing immediate or long-term releases of radioactivity into the environment and becoming a reference for surface/subsurface radwaste management.

When the disposal site will be returned to greenfield status, impacts are expected to be limited to those evaluated in the safety case analysis.

Waste containing large amounts of tritium is kept in storage facilities waiting for a decrease of tritium activity and is then managed according to the industrial channel adapted to its classification.

France will have to dispose-of around 1.5-2 billion cubic meters of LIL-SLW coming from the present nuclear fleet. The capacity exists. The return of experience from 25 years of operation of a closed LIL-SLW repository (0,5 billion cubic meters, closed 20 years ago) indicates that tritium is difficult to confine but that the impact on the public is less than a fraction of one µSv/a (see Appendix 3).

The low-level radwaste mainly contains short-lived radionuclides and limited number of long-lived radionuclides in China. This type of waste can be disposed of in near surface disposal facilities, which corresponds to Low and intermediate short-lived waste in France. China has disposed of about 20,000m^3 of radwaste in two near-surface disposal facilities (Ref. 31).

3.4.3. Low-level long-lived waste (LLW-LL)

This radwaste (10 to 10^5Bq/g) cannot be accepted in repositories for LILW-SL or LLW because it contains some radionuclides such as ^{36}Cl or ^{14}C, which are difficult to confine by engineered or natural barriers and, in addition, are present in quantities that are too large to be deposited in deep geological repositories. If a sub-surface disposal is considered, the site has to be selected according to the requirement of confining these radionuclides for a very long time. Therefore, the depth of disposal must be sufficient in order to guarantee a well-functioning natural barrier of adequate thickness.

The total amount of LLW-LL expected from the present nuclear fleet is around 190 000 cubic meters. Andra is continuing to characterize a potential site in clay according to two sub-surface disposal-of concepts. A preliminary concept should be ready in a few years from now. The absence of a repository leads to prolonged storage of radwaste and slows down dismantling.

There is no low-level long-lived waste in the classification system of radwaste in China. The waste (10 to 10^5Bqg^{-1}) containing long-lived radionuclides at lower levels of activity concentration than the upper limit of low-level waste belongs to low-level radioactive waste and can be disposed-of in near surface disposal facilities. The waste containing long-lived radionuclide at higher levels of activity than the upper limit of low-level waste would be categorized to intermediate-level radioactive waste and be applicable to intermediate-depth disposal.

3.4.4. Intermediate level long-lived waste (ILW-LL) and High-level waste

According to nuclear experts, the isolation of ILW-LL (10^6 to 10^9Bq/g) and HLW (10^9Bq/g and more) from the environment and confinement of radionuclides can be assured in deep geological formations combined with multiple engineered barriers. Such formations must have been stable for hundreds of millions of years and feature favorable geochemical properties like limitation of water circulation and retention of chemical elements. The basic reason for choosing geological disposal for high-level waste comes from sociological considerations about the stability of society that cannot be assured for more than a few centuries. It is then more rational to entrust geology in keeping this waste away from the biosphere for a very long period of the order of geological times.

Whatever the nuclear fuel cycle option chosen, after a long interim storage period (for example in cooling ponds or in dry storage) allowing a decrease of their thermal radiation, packages of HLW and ILW-LL will be disposed-of in deep geologic formations. To this purpose, special surface facilities are designed to accommodate the reception of such packages until their further handling. Primary packages are then placed in an over-package before being disposed-of. Environmental impacts during storage as well as during the dropping of packages into the repositories are the same as those encountered during normal or incidental operation of nuclear facilities, particularly with regard to authorized releases.

As already indicated a deep repository is designed to accept all the radwaste that cannot be disposed of in surface/subsurface repositories. There is no limitation of its capacity with respect to activity of radionuclides.

There are several concepts for deep repositories depending on the geological rock formation chosen for siting them, for instance clay or granite. Clay slows down and finally stops the migration of all radionuclides present in spent fuel because of its high capacity to catch them by various mechanisms. This is why clay is used as a buffer if the selected rock is granite. Extensive and detailed investigations have been carried out and are still underway in countries that need to find a site for their deep repositories.

Up to now only Finland has drilled shafts in granite to establish an underground spent nuclear fuel repository (Onkalo) down to about 450 m. Sweden is close to do the same. Spent fuel will be encapsulated in copper canisters and deposited surrounded by bentonite rings in wells drilled in the granite of the Scandinavian shield (KBS3 concept). All galleries and shafts will be filled with bentonite before the repository is sealed off. France is ready to apply for the license to install a repository in clay at 500 m in a few years from now for ILW-LL and HLW produced by reprocessing. In France over-packed nuclear glasses will be deposited in horizontal tunnels and over-packages of ILW-LL will be deposited in large cavities both excavated in the (vertical) center of an extended horizontal clay layer 130 m thick (Callovo-Oxfordian clay). All engineered structures as well as galleries and shafts will be sealed with special concrete/bentonite plugs. Such engineered structures are expected to confine radionuclides (and toxics) over a very long period of time (tens to hundreds of centuries) that will prevent any impact on the biosphere.

Ten other nuclear countries are more or less in an active preparation stage for several decades. They hope to open a repository during the next decades. Implementation of geological repositories spans long periods of time owing to the extensive processes of site characterization, analysis and final selection, involving large scale scientific studies as well as political and public participation in the decision-making process. All countries have produced numerous reports on their national programs to site an underground repository. International organizations (EU, OCDE-NEA, AIEA), have set up joint international research projects in that direction. These programs aim at the understanding of basic phenomena controlling migration of radionuclides and at testing engineered barriers.

It is expected that operation of a deep geological repository will last more than one and half century, as planned for instance in France. During this period of time, environmental impacts may be due to an accidental situation despite the measures taken to prevent them. The impacts on the environment can be anticipated by simulation and compared to conditions prevailing at present. The environment is also monitored during a long period of time prior to the opening of a repository.

The simulation of the long-term evolution of the components of a repository after its closure is the main issue of the safety case analysis. Despite their capacity to isolate and confine radionuclides, packages of ILW-LL and HLW will progressively be corroded and release of radioactivity will subsequently occur. The migration of radionuclides and other elements will then slowly start by diffusion. According to numerous leaching experiments and natural analogues, the life of nuclear glass or uranium oxide packages is estimated to be over hundreds of thousands of years. Results of numerous simulations demonstrate that migration of actinides could not be more than ten meters in clay and the time of mobile fission products to reach the biosphere would be so long that their activity would be drastically decreased.

Simulations of the migration of radionuclides into the environment enable the calculation of concentrations of long-lived radionuclides at the outlets of the site. Then, according to scenarios of land and water use, doses to people can be derived according to standard methods in use today.

Several simulations for periods of up to a million years or more showed that, owing to the efficiency of radwaste packages, of natural and engineered barriers in deep repositories, such release of radionuclides will lead to doses at ground surface that will not exceed one tenth of a percent of the exposure to natural background radioactivity (see section 3.1.2)

The file presented to the nuclear safety and environmental authorities to obtain a license to open a geological repository contains all the data, results of experiments and of simulations. It includes the safety case evaluation of the repository.

According to the present fuel cycle strategy it is expected that around 72,000 cubic meters of ILW-LL and 12,000 of HLW will need to be placed in the repository. These waste are in storage pending for the commissioning of Cigeo.

As specified in the current radwaste classification system in China, the Intermediate level waste is defined as waste that contains long-lived radionuclides in quantities that need a greater degree of containment and isolation from the biosphere than is provided by near surface disposal. Disposal in a facility at a depth of between a few tens and a few hundreds of meters is considered for ILW. Disposal at such depths has the potential of providing a long period of isolation from the accessible environment if both the natural barriers and the engineered barriers of the disposal system are properly selected. In particular, there is generally no detrimental effect of leaching at such depths in the short to medium term. Another important advantage of disposal at intermediate depth is that, in comparison to near surface disposal facilities suitable for LLW, the likelihood of inadvertent human intrusion is greatly reduced. Consequently, long term safety for disposal facilities at such intermediate depths will not depend on the application of institutional controls.

An underground research laboratory (URL) and a geological repository are planned to be constructed around years of 2020 and 2050, respectively (Ref. 32). At present, the general program of R&D of geological disposal was completed in China. The Beishan in Gansu province has been defined as the primary pre-selected site region for geological disposal of high-level radwaste. The material of buffer and backfill for geological disposal has been developed and research on radionuclides migration and safety assessment is in progress. The site and preliminary construction programme of URL have been determined and the construction of URL is expected to start in 2019.

3.4.5. Radioactive waste containing only natural radionuclides from the front-end of uranium fuel cycle (uranium mining)

Large quantities of uranium radwaste from uranium mining consist of tailings and waste residues from ore processing (to get the yellow-cake) and additional technological waste. This radwaste contains uranium and all its non-volatile daughters as well as other chemicals (^{226}Ra is the only one present in a sizable amount).

The refining of yellow cake and its transformation to gaseous fluoride to be enriched in ^{235}U yield large quantities of radwaste containing only natural radionuclides.

Mining

In France uranium mining has been operational during 50 years at 250 sites producing 80,000 tons of uranium from 52 million tons of ores, and is now discontinued. Mining radwaste accounts for 166 million tons of excavated rocks including tailings and 52 million tons of mining residues. The orders of magnitude of uranium content and radioactivity levels usually associated with materials and residues on mining sites are shown below (Ref. 33).

	Uranium Content (g/t)	**^{226}Ra activity concentration (Bq/kg)**	**Overall activity concentration (Bq/kg)**
Average of soils and rocks in France	A few	A few tens	A few hundreds
Granitic rocks	A few tens	A few hundreds	A few thousands
Ore	About thousand	A few tens of thousands	A few tens of thousands
Steriles	A few tens to hundreds	A few hundreds to a few thousands	A few thousands to a few tens of thousands
Residues	A few hundreds	A few tens of thousands	A few hundreds of thousands

Table 3-1: Uranium content and radiation in uranium mining activities and natural rock formations.

Mining waste is disposed-of in-situ in large excavations and at closure covered with a layer of natural material to prevent radon emanation and direct gamma exposure. Monitoring concerns radon emanations, uranium and toxic releases in rainwater and underground water at the facilities' outlets. Water is processed and after decontamination released to the environment, only featuring traces of uranium and radium. Accumulation of these radionuclides in the environment is monitored and periodical remediation follow if necessary. Considering the various uranium fuel cycle steps, mining, milling and leaching the ores are the most polluting steps.

In France residues and tails are stored in 17 ICPE-classified repositories. The residues (clay sands or blocks of ores leached by H_2SO_4) are placed on a geo-polymer basement and are under cover (2 m of steriles, 0.4 m of soil). The percolation water is treated (6000 m^3 / year) either before discharge or to recover part of the uranium. Feedback from monitoring and analysis of core samples in residues indicates a certain stabilization of residues after alteration by water and diagenesis. In addition, U and Ra are trapped by some mineralogical phases. The uranium is adsorbed on clay minerals and oxy-hydroxides of Fe (III) and also forms insoluble U(VI)/U(IV) mixed phosphates. The radium co-precipitates with $BaSO_4$ and is also adsorbed on the clay minerals. Modelling of the behavior of U and Ra has been achieved. In total, U and Ra are not very mobile. All the information gained from environmental monitoring and in-situ periodical analysis may be used to model the migration of these elements in the long-term.

The French experience at home (and in Niger) indicates that the main problem still requiring attention is the possible re-use of tailings and mining waste as rocks in construction or ballast materials (and in the case of Niger also the re-use of contaminated scrap iron). In France restoration of radiological standards with regard to the dispersion of sterile tailings is applied when the local impact is greater than 0.6 mSv/year. All tailings and mining waste rock are now in repositories. The impact is most significant for buildings erected on tailings and mining waste rock as the induced individual doses are in the range 0,5 to 1 mSv/year and the radon concentrations yield 1,000 Bq/m^3. In France health regulations have laid down the limit for the public at 1 mSv/year and that 300 Bq/m^3 of radon is the limiting value for this dose rate. Frequenting areas ballasted with tailings still in place, induces significantly lower doses (at least one order of magnitude) and is consequently not a problem.

Eighty sites for uranium mining have been constructed in China and about thirty of them have been decommissioned. Mining radwaste accounts for 34 million tons of excavated rocks, including tailings and 11 million tons of mining residues (Ref. 34).

Orano operates uranium enrichment in France. The radwaste are managed on the site.

Radwaste from refining Yellow cake

Orano conversion facilities are sited at Malvesi in southern France. The radwaste produced up to now have been left on site, the fresh aqueous nitrate effluents in large ponds (70,000 cubic meters) and the others are stored (around 280,000 cubic meters) in sub-surface deposit. The solid nitrates collected from nitrates effluents in “evaporation ponds” will be processed to become VLLW and ILW-LL, included in the present inventories. A new facility has recently been commissioned. The future radwaste coming from a new process will be managed in line as VLLW and LLW-LL.

3.5. Open/closed nuclear fuel cycle

Environmental impacts due to waste management are linked to the radionuclides released from reactors and facility operations (including mining) and to the quantities of radwaste produced. These indicators enable comparisons between nuclear fuel cycles. The estimates from the French CEA (Ref. 35) for open fuel cycle (OFC) and closed fuel cycle with single-recycling of Pu (CFC) actually operated in France are shown in §2.4.1.This section draws attention to the fact that reprocessing in CFC releases noticeable quantities of noble radioactive gases and tritium (5.5 10^{11}Bq/TWh) into the atmosphere as well as some slightly radioactive liquids to the sea (2.24 10^{10}Bq/TWh) but without significant radiological impact. For the two fuel cycles, the production of LLW and LILW-SL is not significantly different, however, CFC produces 4 times more ILW-LL (1,18 m^3/TWh versus 0,32 m^3/TWh) than OFC and it is the reverse for HLW (0,36 m^3/TWh versus 1,17 m^3/TWh).

The local environmental impacts, due to the operation of repositories, are facility specific. Operators report annually to safety and environmental authorities. Regarding radiological impacts, public doses are estimated to be less than a tenth of a µSievert. The objective for long-term impacts is to comply with the present radiological target of less than 1 mSv/year in all cases.

Taking into account, for a CFC, that the present reactors are replaced by Gen-III reactors (typically EPR), the production of radwaste will be reduced by 20-35 %, depending on the type; these results are due to the better performances of Gen-III rectors in terms of thermodynamic efficiency, higher burn-up and in-service life. But liquid releases increase by about 20 % mainly due to reprocessing and reactor operation, but their radiological consequences will remain low compared to natural radiation.

3.6. New technologies

If electricity were produced by SFR, or more generally Gen IV fast neutrons reactors, this would lead to a drastic reduction of releases and waste production due to the elimination of all the operations of the front-end cycle. Another significant improvement in the reduction of long-lived radwaste impacts would be the extraction of minor actinides (Am, Cm, Np) from the spent fuel during the reprocessing, with the use of Gen IV fast reactors or hybrid reactors for burning them. Theoretically this additional step in spent fuel reprocessing would permit to shorten the length of time for hazards from HLW from several hundreds of thousands of years to only hundreds of years. In France, the demonstration of the feasibility of such an extraction of minor actinides has been demonstrated at the pilot level on a kilogram scale. The extension to the industrial scale would become possible if and when Gen-IV fast reactors will come to maturity. It has been shown that transmutation of minor actinides produced by an SFR fleet is only possible if all the SFRs of the fleet are able to transmute actinides. That requirement implies a drastic change in nuclear electricity production: new SFRs, new closed fuel cycle, new extraction methods, new fuel fabrication…. Regarding the environment, the more radioactive matter is submitted to chemical processes the greater is the risk of radionuclides release.

In addition, it is obvious that for economic reasons, transmutation of minor actinides could not be applied to material that has already been packaged in nuclear glasses.

Another way of transmutation of minor actinides is under investigation using an Accelerator-Driven-System (ADS). The most advanced project is Myrrha in Belgium. There is only prospective information about the impacts, if any, of ADS-transmutation on environment. Whatever the performance of ADS might be, it will be necessary to prepare the transmutation targets and probably recycle them to get a good transmutation yield. Separation of radioactive material always leads to a limited, but unavoidable, release of radionuclides to the environment.

During the last ten years, France has developed an ambitious research programme to be ready to launch a first commercial SFR in the frame of GenIV around 2040 but this target is now reconsidered.

The ambition of China is to have a first commercial SFR around 2035 and to deploy large-scale construction around 2050.

A project on Accelerator-Driven-System (ADS) for the partition and transmutation has been initiated in China and the demonstration project is planned to be constructed around 2050.

3.7. Conclusion

Environmental protection constraints are basically taken into account at each step of radwaste management - isolation/confinement in packages, storage, and disposal in facilities adapted to each type of radwaste. All measures benefit from top technological developments and are supported by continuous R&D on the behavior of radionuclides/toxics in engineered barriers and the geosphere.

Monitoring is carried out during all operations from production of radwaste up to their disposal in repositories which isolate radwaste packages from the biosphere. The background level is permanently monitored around these facilities. Normal releases do not have an impact on the environment greater than that authorized by safety and environmental authorities when the facilities were licensed. Feedback from experience shows that such releases are far smaller than initially expected. Unusual releases are promptly detected.

The main environmental impacts are induced by the front-end of the nuclear fuel cycle.

The assessment of radiological and chemical impacts on people is the responsibility of radiation protection and health protection authorities. They are based on reliable scientific data and tested models of irradiation and incorporation of radionuclides. However, the R&D continues to reduce uncertainties on the data and to improve the models and this effort needs to be maintained.

Estimates of ionizing radiation impacts on ecosystems are less well supported, and R&D effort on this subject needs to be increased.

After closure of the repositories, monitoring will continue during a test period; then safety will change from active to passive. Most radionuclides will decay in the repositories, those that might return to the biosphere will do so at a time so long that their radiotoxic impact will be negligible.

As of today, the WIPP repository is in operation in USA, New Mexico. It has been designed in a deep salt formation, to accommodate transuranic radioactive waste left from the research and production of nuclear weapons. No deep geological repository accommodating HLW from commercial nuclear power is in operation yet. Three projects are presently at licensing stage, in Finland, Sweden and France. Licensing requires excavation of deep laboratories to get all data for modelling transportation of radionuclides. These laboratories will be later used as the starting point of the repositories themselves.

In terms of society it is important that the proven or potential impacts of radioactive waste management on environment be brought to the public's attention in a transparent manner.

Appendix 3

French Side

It is instructive to consider the feedback of measures taken in France with respect to the environmental impact of radwaste management. This information originates from the monitoring of three types of repositories: the first one that is now closed, the second one that is currently in operation and the third one that is to be constructed.

CSM

The surface repository for LILW-SL called CSM (Centre stockage de la Manche) was in operation for twenty-five years (1969-1994) and the construction of a provisional multi-barrier cap lasted six years. The repository is sited near the sea on a basement of gneiss rock. A total of 1 470 000 packages (530 000 m^3 of waste) have been deposited over 15 ha. Several civil engineered structures to host packages have been experimented. Since the year 2000, CSM is under monitoring (tests of confinement of the cap and structures, tests on surface and underground water yield relying on 10 000 measurements per year). This facility will be closed after completion of a definitive cap, expected to take place around 2050/60. Monitoring will continue up to the time when passive safety is reached. Feedback of CSM monitoring is that tritium is difficult to confine. Maximum radiological impact on the environment is 0.20 µSv/year for the full use of the water stream flowing in the near vicinity of this repository.

CSA

The CSA (Centre de stockage de l'Aube) surface repository for LILW-SL is in operation since 1992 with a surface area of 95 ha. It is sited near Soulaines-Dhuys (Aube department) on layers of sand and clay. This center is designed for the disposition of 10^6 m^3 of radwaste. Exposition to radiation of the most exposed group of people at and around the site shall not exceed 0,25 µSv/a. Management of CSA benefits from the feedback from CSM (see above). Standardized packages are placed in engineered structures sheltered from rainwater. When structures are full, packages are drowned in concrete to form a monolith. CSA is monitored in terms of radiological, physico-chemical and ecological parameters (15 000 checks per year). According to the measured release of several radionuclides to the environment, the radiological impact is around $1x10^{-3}$ µSv per year. Tritium is not detected neither on nor around the site, or in the underground water.

Cigeo

In the coming years, France will open the deep geological repository Cigeo for ILW-LL and HLW near Bure (Meuse/Haute Marne departments). Packages will be deposited in engineered structures constructed in a clay layer 130 m thick at 500 m below the surface. Surface facilities will receive and condition packages to be transported underground. Operation of Cigeo is expected to last 150 years. The environment of Cigeo will be monitored; Andra operates since 2007 an Environmental Permanent Observatory (EPO) extending over 900 km^2 with a reference sector of 250 km^2 around the Cigeo facilities (with a meshing of 1.5x1.5 km). The objective is (a) to understand all the impacts on air, water, soils, flora and fauna through measurement of the physico-chemical exchanges between them with respect to human activity and (b) to record and retrieve these data. The EPO is associated with a facility to preserve samples. There are 2500 observation points, collecting 2 500 samples and 85 000 data samples per year.

Chinese side

Northwest disposal site

The Northwest disposal site is located in Gansu Province, north western China. It receives and stores and disposes of low level and intermediate level radioactive solid waste for near-surface disposal. The construction of the northwest disposal site began in 1995 and was completed in 1998. In 2011, it was approved for operation. The planned disposal capacity for this Site is 200,000 m^3. The disposal capacity for the first phase is 60,000 m^3, consisting of seventeen disposal units. To date, six units have been built, the capacity of which is 20,000 m^3. The site is located in the cohesive soil and sandy soil interbed with a thickness of approximately 50 meters. The concept of the disposal unit is a reinforced cement structure. Sandy soil is back filled between waste drums and between waste drums and disposal unit wall. The disposal unit will be poured with reinforced cement to form top plate when it is full. After closure, the top of each disposal unit will be finally covered with a two-meter-thick cap. During the disposal facility construction, reinforced bottom plate (slab) was added for higher safety. The safety-assessment for the unintentional intrusion scenarios during institutional control after closure includes the dwelling, drilling and water well-digging on the disposal site. Results of the analysis indicate that the exposure dose received by the unintentional intruder for these scenarios is not more than 0.1 mSv/a, which is much lower than the national limit of 1 mSv on annual effective dose to the general public.. The Northwest disposal site received a total of about 15 km^3 low level solid radwaste.

CHAPTER 4 - Severe nuclear accidents

Recommendations

- It is necessary to continue research and development on the mechanisms leading to severe accidents and provide support for their mitigation. It is suggested that further studies on measures of maintaining the integrity of containment and development and application of advanced technology (such as ATF) should be carried out.

- It is necessary to further accumulate experience in the implementation of severe accident management guidelines and to pursue the development of mitigation measures aimed at coping with large-scale damage in NPPs, multi-units' accidents and to strengthen emergency response capacities.

Introduction

Since the peaceful use of nuclear power in 1950s, after years of development, nuclear power, coal-fired power and hydro- power have been known as the three main sources of electricity. The integral safety situation of the world 454 nuclear units is good (according to data from IAEA PRIS), and more than fifty years of normal operation of commercial nuclear reactors proves that the radiation impact of nuclear reactors is extremely low and much lower than the natural background radiation level (cf. the joint report of the three Academies about the future of nuclear power). However, the accidents at Three Mile Island (TMI), Chernobyl, and Fukushima Daiichi NPPs accidents have had a major impact on the development of nuclear energy and on the world view of nuclear generation of electricity. It is at this stage important to review the above nuclear accidents, and to summarize the design improvements and measures taken by the nuclear industry to reduce the severe accident frequency and limit any post-accident consequences, and consider return of experience.

This chapter begins with a review of severe accidents and an account of their impacts as well as of lessons learned from them (section 4.1). The measures taken to avoid such events through a continuous improvement in technology and management are described in section 4.2. Conclusions are given in section 4.3. In addition, in order to further clarify the technical and policy consideration for severe accidents in China, three specific items are included at the end of this chapter. Appendix 4-1 introduces dedicated prevention and mitigation measures for severe accidents of Gen-III NPPs. Appendix 2 introduces the safety issues of inland NPP sites, and Appendix 4-3 introduces emergency management after severe accidents in China.

4.1. Severe accidents

Three accidents have had a notable impact on nuclear industry worldwide. These accidents took place at the Three-Mile Island reactor in the United States in 1979; at the Chernobyl nuclear power plant in the former Soviet Union in 1986; and at the Fukushima Daiichi nuclear power plant in Japan in 2011. The former was ranked at level 5 on the IAEA INES (International

Nuclear Event Scale System) with no or limited consequences on the environment. The latter two accidents, qualified as severe, have been rated at level 7 based on the IIAEA INES; they have had serious consequences on the environment.

The causes of these accidents, their impacts on the environment and the lessons learned differ in most respects but these severe accidents have substantially promoted progress in nuclear safety technology and augmented nuclear safety level. The new safety features and dispositions are aimed at reducing the environmental impact even in case where such an accident might happen again, and this may hopefully diminish people's worries. Today, the designs of new reactors around the world have been significantly improved giving rise to Gen-III NPPs. Moreover, with the accumulation of operating experience, the management ability of nuclear units has been effectively improved, so that even in the worst situation, the risk of radioactive material release to the environment is decreased to a very low level. In parallel safety authorities have published guidelines for emergency in case of accident as well as for remediation. Regulations have also moved to reinforce the obligation of operators to apply these guidelines.

This section analyses the three accidents and the changes that they have induced on the technical and management levels and in terms of regulations. Each accident is documented with a focus on information related to improvements of the impacts of nuclear energy on the environment.

4.1.1. Three-mile Island accident (Ref. 36)

Cause of accident

The TMI NPP employed pressurized water reactors developed at an early stage in the United States. The cause of the accident was equipment failure, inadequate interpretation of the state of the system by the operators and subsequent inappropriate decisions. As a result, the reactor core melted, and a large amount of fission products entered into the containment. Fortunately, the containment maintained its integrity and confined the major part of radioactive substances produced in the accident.

Impact on the environment

The accident produced a limited release to the environment. The maximum dose to the surrounding public was ten times less than the doses from the annual natural background. No casualties were caused and there was no mid-or long-term impact on the environment.

Lessons learned

Although the Three-mile Island accident only brought minor radiological consequences to the environment and the public, and caused no casualties, the direct economic losses were huge. It sounded the alarm for the entire United States nuclear industry and regulatory authorities and has had far-reaching implications for the development of the world's nuclear industry. The TMI accident also had a notable impact on the nuclear industry that was in rapid development at the time in the US, Europe and in other countries.

The TMI accident proved the overall soundness of the safety concept based on defence in depth, but also revealed weaknesses and deficiencies in design, management and safety studies. It showed that small details that had not been considered before were capable of producing serious consequences. The accident indicated that management aspects (e.g., operator training, emergency procedures, organization and coordination) had no lesser importance than technological aspects (e.g., equipment design, construction, qualification, and safety analysis).

After the TMI accident the nuclear industry made substantial improvements in man-machine interactions, monitoring, control and training of plant operators. A significant move took place in the safety analysis under accidental conditions where nuclear companies and regulatory agencies acted in concert to shift their focus from reactor research targeting DBA (Design Basis Accident) to research on severe reactor accidents, and initiated large scale research projects on severe accidents. As a watershed, safety analysis turned from studies on LBLOCA (Large Break Loss of Coolant Accident) to studies on SBLOCA (Small Break Loss of Coolant Accident) and transients. The WASH-1400 report adopted a probabilistic risk assessment (PRA) methodology demonstrating scientific capabilities surpassing those of more traditional deterministic analysis techniques. One outcome of the TMI accident was a strengthened interest for PRA. It their viability and merits during decades that followed.

4.1.2. Chernobyl accident

Cause of accident (Ref. 37)

One of the causes of the Chernobyl NPP accident was linked with the stability characteristics of the RMBK reactors. The reactor was a graphite-moderated water-cooled core featuring a positive void coefficient with the potential risk of prompt super-criticality. There was no-containment vessel to confine radioactive substances in an accidental situation. Erroneous interpretation of the reactor state led to inadequate actions by the operating team resulting in a prompt super-criticality event. The sharp power increase led in turn to the explosion of the reactor. Large radioactive leaks occurred, which resulted in a sizable radioactive release into the atmosphere. The Chernobyl accident was primarily due to flaws in the management of NPP operation and to an insufficient nuclear safety culture.

The Chernobyl reactor was one of the seventeen RBMK reactors that were designed and constructed by the former USSR; it has been deployed in the Soviet Union only, and the concept was abandoned after the accident.

Impact on the environment

Major releases from unit 4 of the Chernobyl nuclear power plant continued for ten days, and large areas of Europe were affected to some degree by the Chernobyl releases. Much of the release comprised radionuclides with short physical half-lives; long lived radionuclides were released in smaller amounts (Ref. 38).

One hundred and thirty-four emergency workers suffered an acute radiation syndrome, of which 28 died from radiation. Among the recovery operation workers exposed with moderate doses, there are some evidences of a detectable increase in the risk of leukemia and cataract. The occurrence of thyroid cancer among those exposed during childhood or adolescence has significantly increased due to the drinking of milk contaminated with radioactive iodine during the early stage of the accident (Ref. 39, 40 and 41).

Construction of the shelter was aimed at environmental containment of the damaged reactor, reduction of radiation levels on the site and the prevention of further release of radionuclides off the site (Ref. 38). The radioactivity is continuously monitored, and periodic international reviews assess the evolution of the situation. Natural life is re-developing, and studies are now in progress to assess whether there are genetic effects on plants and wild animals.

Lessons learned

The Chernobyl accident and its post processing have set a great financial burden to the former Soviet Union states, Ukraine, Belarus and Russia, and have had a huge impact on local population and activities, and on the nuclear industry worldwide. The accident raised issues of public safety and public concern about safety, affecting the planning of the nuclear energy infrastructure. The depth and scope of this accident had an impact that was far beyond that of the TMI accident.

Lessons learned within nuclear industry have been again quite substantial:

a) after the accident, the nuclear industry essentially abandoned core design concepts featuring positive feedback characteristics, ending graphite moderated reactors development. Inherent reactor safety features were augmented;

b) reactor protection systems were improved, and operators in main control rooms were subjected to more restrictions to effectively reduce the possibility of improper operations associated with human errors;

c) containment buildings as the last safety barrier were adopted by the whole industry further reducing the possibility of large radioactive releases to safeguard public health and environmental safety;

d) safety culture came into being and received greater attention from the nuclear industry across the world. Awareness of nuclear safety was extended widely, from NPP operation to design, manufacturing, construction, supervision and control, playing an important role in preventing nuclear accidents;

e) ideological isolation in nuclear technology that flourished under the context of the Cold War was essentially waved out. The IAEA developed and implemented the Nuclear Safety Convention which calls for International peer reviews of regulators. International organizations such as WANO were established, to encourage operators to improve operational safety and foster the concept of “borderless nuclear safety”.

Although the consequences of the Chernobyl accident were quite serious and far-reaching, follow-up studies of the accident indicated that nuclear safety is guaranteed as long as safety guidelines are observed, safety awareness is enhanced, and safety design is constantly optimized. When all these items are considered, they ensure that new nuclear power plants have a higher level of safety and that nuclear power remains a safe source of energy.

4.1.3. Fukushima Daiichi accident (Ref. 42 and 43)

Cause of accident

Fukushima in Japan is located near the "subduction zone" of the Eurasian plate and the Pacific plate, which witnessed frequent earthquakes in the past geological history. The Fukushima Daiichi NPP adopted a boiling water reactor type of the earliest commercial reactor technology developed in the United States. Its design and construction were completed prior to the Three-mile Island nuclear accident when serious accidents had not been experienced and complex accidental sequences were not foreseen.

The triggering event of the Fukushima Daiichi accident was a super earthquake and subsequent tsunami with an amplitude that by far exceeded the design standard. Severe damage caused by the magnitude 9 earthquake and subsequent tsunami to infrastructure such as transportation and power systems in the surrounding areas deferred recovery of offsite power for 9 days after the earthquake, a time period that far exceeded design considerations. The four reactors damaged by the accident (out of the six reactors of the Fukushima Daichi NPP) were located near the sea shore, to minimize the length of the cooling circuit. In addition to the increased exposition to tsunamis, this also had the effect of exposing diesel generators required in case of a loss of offsite power. The lack of tightness of diesel generator rooms, and the flooding of their air intakes ended up with a station black out and a disastrous loss of core cooling. It has also been pointed out that the lack of passive hydrogen recombiners led to explosions which sent radioactive materials in the atmosphere. In addition to the reactors the loss of cooling of spent fuel pools posed a serious threat of additional emission of radioactive materials to the atmosphere.

Finally, failure to evacuate residual heat from three operating units and spent fuel storage pools caused core melting, hydrogen generation and accumulation leading to explosion, and release of radioactive material in the environment. Lack of prevention and mitigation measures in case of severe accidents in NPP design had serious consequences.

Impact on the environment

Fukushima Daiichi accident resulted in the release of radioactive gases (less than 500 PBq of radioactive iodine, less than 20 PBq of radioactive cesium) and materials into the environment. Although dose rates exceeded some reference values in the early phases of the accident, no impact on animal and plant populations and ecosystems is expected. Long term effects are also not expected as the estimated short-term doses were generally well below levels at which highly detrimental acute effects might be expected and dose rates declined relatively rapidly after the accident.

People within a radius of 20 km from the site and in other designated areas were evacuated, and those within a radius of 20–30 km were instructed to shelter before later being advised to voluntarily evacuate. Evacuation resulted in the loss of farms and businesses. The Japanese government has undertaken heavy restoration works to clean the area so that the population could progressively re-occupy their land.

Lessons learned

Lack of prevention and mitigation measures for severe accidents in NPP design is also attributable to the accident. Its design and construction were completed prior to the TMI accident when there were no clear understanding of serious accidents and complex accident sequences. In these early reactor systems, there were design deficiencies of preventive safety features.

Experience and lessons learned from the accident have served as references to improve the design of new NPPs and to enhance the operational management of operating NPPs. Feedback from the Fukushima nuclear accident has concerned a number of items:

(a) External events beyond design basis require more attention in NPP design and operation. Evaluations of natural disasters should be more conservative and for this it is important to consider scenarios of their occurrence, in a sequential or in a simultaneous mode and analyze their combined impacts on NPPs;
(b) The Fukushima accident has outlined the specific needs for absolute tightness of the emergency pumps;
(c) It also put a spotlight on the protection of spent fuel pools in terms of structure and requirement for permanent cooling;
(d) Safety of NPP needs to be assessed on a regular basis to incorporate knowledge updates, necessary corrective actions and compensation measures that are to be immediately implemented;
(e) It is necessary to ensure that instrumentation and control systems will maintain their functions in DBA allowing to monitor basic safety parameters of NPPs and to facilitate operation. Residual heat removal requires robust and reliable cooling systems that are capable of functioning both in DBA and BDBA (Beyond Design Basis Accident) conditions;
(f) Training, drills and exercises need to include hypothetical scenarios of serious accidents to ensure that operators are fully prepared and ready to take the best decisions.

After the accident, the IAEA established a direct link with the Nuclear and Industrial Safety Agency (NISA), Japan's official liaison for the accident through emergency arrangements, and shared information that was continuously updated and released to member states, relevant international organizations and the public in general.

Although it is still hard to clearly measure the extent of the damage and its impact on the global environment, the Fukushima accident, as the Chernobyl accident, induced a shock straining the world, raising concern about nuclear radiation and enhancing public worries about environmental disasters that could be caused by nuclear power. This led many countries to reassess the nuclear safety of their domestic NPPs.

After inspections and assessments, many countries confirmed their position to pursue the development of nuclear power and adopted measures to improve safety of existing installations and enhance their emergency response capacities. Although the Fukushima accident slowed down the development of the world's nuclear energy, it has also promoted progress and improvement of nuclear safety and management.

4.2. Improvements to make nuclear energy free of environmental impacts in case of accident

To summarize, we can say that after the TMI accident there has been a series of major improvements in equipment reliability, operator training, and man-machine interface for Pressurized Water Reactor (PWR) nuclear power plants in the world. After the Chernobyl accident, several countries have undertaken extensive research to improve the safety of NPPs, and to develop advanced nuclear power technologies on this basis. After the Fukushima Daiichi accident, various countries organized nuclear power safety inspections.

4.2.1. Improvements in reactor technologies

Taking into account the lessons learned from the above accidents, the nuclear industry has implemented many important technical improvements to Gen-II PWR nuclear power plants for those under operation and those under construction. At the same time, the concept of Gen-III PWR nuclear power plant has been put forward based on the requirements of improving safety, availability and reliability of NPPs, in order to practically eliminate large radioactive release after severe accidents.

The concept of practical elimination was first proposed by Europe and was later adopted by the International Atomic Energy Agency (IAEA) and agreed upon by China's nuclear industry. According to this concept, if some conditions are physically impossible or extremely unlikely to occur with high confidence, the occurrence possibility of such conditions can be considered to be practically eliminated. New nuclear power plants built in China will strive to achieve the possibility of practical eliminate large radioactive release in design, a goal that is clearly defined in relevant planning documents on prevention and control of nuclear safety and radioactive pollution.

The Gen-III PWR has adopted the concept of defence in Depth, that multiplicity, diversity, and physical isolation design principles are included to improve accident response in case of an accident and mitigation capabilities, to practicality eliminate large radioactive release after severe accidents. The particular goals of preventing and mitigating severe accidents include:

(a) preventing meltdown,
(b) maintaining the integrity of the reactor pressure vessel (RPV),
(c) maintaining the integrity of the containment,
(d) preventing radioactive release of spent fuel.

The Gen-III PWR are equipped with advanced large containment buildings capable of enduring external natural disasters such as earthquakes, tornadoes, and the destructions due to human induced accidents such as fires and explosions, as well as intentional or accidental crash of a large commercial aircraft or other terrorist acts. They are able to withstand environmental conditions such as high internal temperatures; high pressures and high radioactive transfer caused by a severe accident, and maintain integrity, avoiding the release of radioactive substances to the environment. Appendix 4-1 explains the countermeasures and special improvements introduced by the Chinese nuclear industry to prevent massive release of radioactive substances.

Nuclear power industries in France and China have both developed their own Gen-III PWR technology, which are materialized in the EPR and the HPR1000. A first EPR is already connected to the grid, while the first HPR1000 project progresses well.

In addition, nuclear industry in China has made specific technical improvements to the safety of "inland nuclear power plants" which is of particular concern to the public, such as "Near Zero Emission" of radioactive liquid effluent under normal operation and treatment of radioactive liquid waste under severe accident conditions; and their safety level meets the highest safety requirements implemented worldwide. See Appendix 4-2 for more details.

In order to improve the safety of nuclear power plants, especially for PWR, nuclear industry has actively developed new technologies, like the new generation of accident tolerant fuel (ATF), to minimize the possible hydrogen production under accidental conditions, and to eliminate the possibility of hydrogen explosion. The technique of In-vessel retention after severe accident has also been considered by nuclear industry and many research institutes have carried out relevant work on enhancing heat transfer and increasing critical heat flux (with for example an application of nanofluids).

4.2.2. NPP Action after Fukushima Daiichi Accident

After Fukushima Daiichi accident, self-inspection was actively carried out by all NPPs operators in China, as well as in western countries. According to the technical requirements from the regulatory bodies, many technical improvements have been implemented, including increased resistance to external flooding, improvements of emergency core cooling system and related equipment; addition of (a) transportable back-up power supply, (b) spent fuel pool monitoring, (c) hydrogen monitoring and control, (d) implementation of an emergency control center, (d) radiation environment monitoring and emergency response, and (e) external natural hazards response, etc.

Taking the improvement of flood control capability of NPP as an example, the nuclear power flooding is re-evaluated, the maximum water depth of the plant is calculated by considering conditions of design basis flood plus once-in-a-century situation. The maximum water depth of an NPP site is determined as design basis of waterproof plugging for relevant structures and buildings. Combining with the evaluation of the potential flooding of NPP, the inspection is carried out for waterproof plugging measures for galleries, doors and windows, pipe trenches and penetrations of nuclear relevant building, so that the weaknesses have been strengthened. By increasing waterproof plugging function of holes, plugging the interface between the galleries and the nuclear island, the ability of NPP resistance to external beyond design basis flooding has been further strengthened by ensuring that protection requirements of external flooding design criteria are being met.

The implementation of the above technical improvements enhances the ability of coping with beyond design basis accidents, including multiple failures, to prevent accidents similar to Fukushima Daiichi accident.

The French Nuclear Safety Authority (ASN) issued technical requirements for additional safety reviews of nuclear facilities throughout the country in accordance with the requirements of the French government, focusing on the following items: flooding, earthquakes, loss of power and loss of cooling, accident management, technical assessments and on-site verifications.

4.2.3. Severe Accident Management

In addition to improvements in operational management of NPPs, two series of Guidelines have been set up both at international and national levels, to deal with severe accident mitigation and emergency.

Severe Accident Management Guidelines (SAMG)

Nuclear power suppliers have developed guidelines for different types of power plant designs. The first was issued by Westinghouse, U.S. in 1994 and based on results of an extensive research programme on severe accidents phenomena and on the Technical Base Report (TBR) developed by EPRI to propose the Westinghouse Owner Group (WOG) SAMG. This document summarizes research carried out on severe accidents management in typical PWRs in the United States. Due to its advanced technological basis and logical structure, it has been widely recognized and followed internationally.

In 2009, the IAEA issued the Safety Guide No. NS-G-2.15 dealing with « *Severe Accident Management Guidelines* » which focuses on the requirements for the development of management procedures for preventing severe accidents and mitigating their consequences and proposes requirements for the development of guidelines for the management of severe accidents.

Since the first edition WOG SAMG has been continuously improved in its contents, guidelines, as well as application. A brand-new system PWR WOG SAMG was introduced more recently in 2016 combining the latest research results and engineering experience in the field of severe accident management for more than twenty years and making it convenient and widely applicable.

The French EDF developed the GIAG Guidelines for severe accident management, which is mainly directed at the second generation of PWR nuclear power plants in France. Framatome has also developed the corresponding guidelines OSSA for severe accident management for the EPR design. The OSSA guidelines cover all the power plant stages including full power operation, low power shutdown, and nuclear fuel storage in spent fuel pools.

In China the SAMG guidelines have been implemented during the last period beginning in the year 2000 in all NPPs operating or under construction. The current domestic guidelines for severe accident management are based on the WOG SAMG guidelines, except for the Taishan Nuclear Power Joint Venture (EPR OSSA developed by Framatome). After the Fukushima accident, the guidelines have been expanded to include full power operation, low power shutdown, and spent fuel storage facilities. Differences in design have resulted in different framework structures.

Since 2013, the China Nuclear Energy Association is entrusted by the China National Nuclear Safety Administration (NNSA), to organize and conduct peer reviews of SAMG at various NPPs, including Unit 1 and 2 of Tianwan NPP, LingAo Nuclear Power Plant, and Fangjiashan Nuclear Power Plant and Qinshan Phase III. At the request of NNSA, NPPs carry out SAMG training incorporating a comprehensive implementation of SAMG into their regular exercise plan and special severe accident practice.

Assessments by peer experts, and special practice conducted at NPPs among other efforts have effectively improved the management capacity and emergency response level of China's NPPs, and have greatly enhanced operational safety. However, these improvements were implemented in a relatively short period of time and more efforts are needed on some issues including mutual cooperation, single and multi-units' accident-handling, and verification.

Extensive Damage Mitigation Guideline (EDMG)

Extreme damage needs to be envisaged in relation with conditions such as fires and explosions caused by terrorist attacks. These may induce extensive damage, leading to the failure of conventional accident management procedures. A possible aggression that has to be considered might be of the kind of the September 11, 2001, a terrorist destruction of the World Trade Centre towers in New York, After that event, the U.S. Nuclear Regulatory Commission (NRC) required nuclear power plants to develop accident management strategies and guidelines for damage of this type with the objective of maintaining containment integrity and restoring reactor core and spent fuel pool cooling.

To comply with the federal regulations requirements of 10CFR50.54 (hh), the United States nuclear power plants have established Extensive Damage Mitigation Guidelines (EDMG). In this framework, it is assumed that the main control room is not accessible and that the remote shutdown station has lost the ability to control the state of the nuclear power plant, so that EOP and SAMG cease to be operational. Licensees have developed and implemented strategies to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities under the circumstances associated with loss of large areas of the plant due to explosions, fire, airplane crash, etc."

Europe has conducted "stress tests" on nuclear power plants, to primarily assess the impact of extreme external events on nuclear facilities. These tests focus on security threats and reactor accidents caused by malicious or terrorist activities. This assessment led EDF to propose the development of FARN ("the fast-acting nuclear force"), under which national-level professionals and equipment form an emergency rescue team that can be quickly brought to the accident site and has the capability of simultaneously intervening on multiple units. FARN rescue needs to clarify its start-up criteria, potential tasks, configuration of emergency professionals and emergency resources, requirements for personnel training and also corresponding management procedures in NPPs. Nuclear power plants in South Africa and Spain have already established EDMG; South Korea is also researching and developing EDMG to deal with the extensive damage that might be caused by extreme external disasters.

Research institutes in China have also been, in recent years, actively engaged in the development of severe accidents mitigation guidelines. Nuclear power plants, such as Hongyanhe and Fangjiashan, have already completed the development of EDMG. Other nuclear power plants, such as Fuqing Nuclear Power Plant Units 5 and 6 are actively engaged in this development. As already indicated, one considers in this framework that the main control room and remote shutdown station lose the ability to control the state of a NPP and that EOP and SAMG cannot function. Numerous conferences organized by NNSA have been held to discuss the development and implementation of EDMG as well as its impact on nuclear power plant emergency plans. In general, China has made useful progress in the development and implementation of EDMG but the implementation experience has to be consolidated and their integration within existing emergency response systems needs to be pursued.

4.2.4. Insights on similar severe accidents in future

Among the three severe nuclear accidents that have occurred, the Chernobyl and Fukushima accidents have had serious consequences.

The Chernobyl accident was caused by flaws in design and repeated violations of safety procedures by operators which left the reactor out of control giving rise to super prompt criticality, resulting in reactor explosion due to sharp power increase. After the accident, the nuclear industry abandoned core design concepts with positive feedback. Inherent safety of reactor was improved.

The Fukushima nuclear accident was the first NPP accident in history induced by external disaster with a high amplitude earthquake plus an accompanying tsunami. It was also the second nuclear accident in human history after the Chernobyl nuclear accident that was rated as 7th on the INES scale.

After the Fukushima accident, China carried out an extensive safety analysis on coastal NPPs' resistance to earthquakes and tsunamis.

China is in the Eurasian continental plate, and its tectonic structure is in the inner part of the plate. The main destructive seismic activities are shallow earthquakes within the continental plate and inside the earth crust. The energies of such earthquakes are much lower than those of earthquakes in a subduction zone, and the deformation and displacement as a result of such earthquakes are far from those that can trigger a tsunami. In addition, China enjoys a broad continental shelf along its seaside, in which the water depth is not conducive to the accumulation of tsunami energy. Coastal conditions of China thus differ from those prevailing in Japan, both in terms of earthquake magnitude levels and high amplitude tsunamis. This is also the case for France where such extreme natural disasters have never been observed for thousands of years.

Several causes which made the Fukushima nuclear accident so severe (the flooding of the emergency pumps, the lack of catalytic hydrogen recombiners) have also been eliminated.

In conclusion, accidents such as the Chernobyl and Fukushima nuclear accidents that caused large radioactive releases are now unlikely in China and France given the reactor design, the low probability of natural disasters, the enhanced safety measures and emergency response capacities that have been implemented.

4.3. Conclusions

Environmental risks in the event of a severe accident that might occur in the future have been substantially reduced. Nuclear power plants both under operation and construction are endowed with mitigation measures, which would control the radioactive source term release and limit the impact of such accidents when they occur. These are meant to drastically reduce the area affected, so that there would be no need for permanent relocation, or emergency evacuation beyond the immediate vicinity of the plant, a limited sheltering, and no long-term restrictions in food consumption.

Comprehensive protection and mitigation measures for severe accidents contribute to a higher level of safety in Gen-III reactors. Gen-III PWRs are equipped with advanced large containment vessels capable of resisting external hazards such as earthquakes, tornadoes, aggressions by fires and explosions induced by humans, as well as accidental or intentional crashes by large commercial aircraft. These vessels are also able to withstand harsh internal conditions such as augmented temperature, increased pressure and radiation after accidents, and maintain their integrity, thus avoiding radioactive release to the environment.

Given the design of the nuclear power plants, the low exposure to natural disasters and the enhanced safety guidelines now implemented by NPP operators, the probability of a nuclear accident such as Chernobyl and Fukushima Daiichi, which have caused large radioactive releases, has been considerably reduced in China and France.

But an accident is precisely unpredictable. In general, any future accident would differ from previous ones. A rationale way to control the risks is to consider that accidents are possible following unexpected scenarios. Therefore mitigation features should be enhanced, to minimize potential offsite consequences, even more than is done for other human activities.

Appendix 4-1: Dedicated Prevention and Mitigation Measures for Severe Accidents of Gen-III NPPs

In response to various severe accidents, Gen-III PWR NPPs have set up a series of severe accident mitigation measures to maintain the integrity of the containment and prevent massive release of radioactive substances. Currently, the major potential causes that could threaten the integrity of containment of pressurized water reactor nuclear power plants have been identified and the corresponding countermeasures have been designed as follows:

(a) Direct Containment Heating (DCH) caused by high-pressure core melt, is avoided by a special quick safety valve generally set on the regulator,

(b) Hydrogen elimination systems in the form of catalytic combiners to control accumulation of this combustible gas in the containment,

(c) The reliability and redundancy of the heat-removal system is augmented to avoid the risk of overpressure in the containment. This is implemented by increasing the number of spraying points in the vessel, ensuring a reliable source of water, and using a passive heat-extraction system,

(d) to avoid steam explosion outside the pressure vessel, dry pit design or measures for external cooling of the reactor pressure vessel are generally used to prevent melt-through. The former eliminates the water needed for steam explosion, while the latter prevents the melted core from being released, which can fundamentally eliminate the possibility of steam explosion,

(e) In order to avoid the MCCI (Molten Core Concrete Interaction) and subsequent floor penetration, melt retention in the heap and a core melt trap may be used. The former avoids pressure vessel penetration, while the latter collects and cools the core melt after it has melted through the pressure vessel,

(f) For the failure of containment bypass, the current electric power plants are designed to increase isolation reliability and pressure of the low-pressure system. In order to reduce the amount of release, in case of a severe accident caused by the interface LOCA, it is imperative that the system required in normal operating conditions for the reactor coolant, be located within a containment-enabled building. For the bypass of SGTR (Steam Generator Tube Rupture) release, one has to take the necessary measures to prevent the SGTR steam generator from overflowing.

In particular, in the event of a severe accident with a failure of mitigation measures, with the pressure in the containment continuing to rise, the filtration and exhaust system should be able to decompress and discharge the containment in a safe and controlled manner ensuring that the pressure does not exceed the load limit. The filtering system installed on the pressure relief pipeline is designed to withhold radioactive material in the exhaust gas with a filtration efficiency that reaches 99.9% ensuring that only inert gas and a small amount of volatile substances be discharged into the environment.

Appendix 4-2: Safety of inland NPP in China

Nuclear power plant can be built near sea (costal) or inland (riverside and lakeside). Except for engineering availability requirements of each plant site, nuclear power plants around the world implement unified nuclear safety assessment standards and comply with unified rules for construction and operation, so that there should be no controversy about inland nuclear power plants. At present, more than half of the nuclear power units are located in inland areas, among which, 74% of USA total 99 nuclear power units under operation are inland, 70% of French total 58 nuclear power units under operation are inland. However, China mainland now still has temporary management problems for inland nuclear power.

The nuclear and radiation safety regulation and standard in China are formulated in accordance with IAEA safety standards, for maintaining, improving and enhancing NPPs to keep pace with international standards. In-land nuclear power construction based on current nuclear safety regulations in China, can meet current international highest requirement for nuclear power construction.

The definition of design basis earthquake of siting for China inland NPP has adopted strict international standards, that take into account extreme earthquakes effect and once-in-a-thousand-year seismic fortification standards. At present, the peak value of seismic acceleration at fully demonstrated inland site is less than 0.15g, while the design standard for seismic design of Gen-III PWR is 0.3g, which indicates that the seismic robustness of Gen-III PWR at these sites is significantly enhanced. In addition, inland nuclear power plants adopt the siting concept of “dry plant site”, which ensures avoiding of flooding impacts. In terms of cooling water, closed circuits with wet cooling towers are used for inland plant site, so that the withdrawal of water is low and “thermal pollution” due to discharges water is prevented.

The site selection of inland nuclear power plants must strictly comply with existing nuclear safety regulations and meet the relevant requirements for gas and liquid effluents, and population distribution. In particularly, liquid effluent standards of inland NPPs are stricter than those of coastal areas, that their concentration limits are one order of magnitude lower than those of coastal areas. Nuclear power plants adopt the design of controlling the generation of radioactive waste from the sources, applies the best feasible technology to treat radioactive effluents, and realizes “Near Zero” radioactive fluid effluents discharge through comprehensive measures such as strict radioactive waste monitoring, optimized discharge management and strengthened environmental monitoring.

As mentioned in Section 4.2.1, Gen-III PWR technology adopted by China inland NPP has intact severe accident prevention and mitigation measures, which effectively prevent the occurrence of severe accidents and mitigate the consequences of severe accidents. Against the problem of radioactive waste water treatment after severe accidents, nuclear industry in China has carried out extensive research. Even under extreme accidental conditions, the total maximum radioactive waste water can be generated designed for Gen-III NPP is around 70000~10000 cubic meters. In order to prevent surrounding environmental water body from being polluted by these radioactive waste water, a series of measures are adopted in design, including, radioactive waste water storage in reactor building and nuclear auxiliary building; a number of waste liquid storage tanks and temporary waste liquid storage pools with large capacity to act as supplement or backup of safety building waste liquid storage capacity; setting of water inhibitor to prevent leakage, radioactive waste inhibitor and zeolite filters, to realize radioactive waste water sealing and isolation from surface water body under emergency conditions; reserving spaces in the site area to ensure that mobile emergency waste liquid treatment devices can be installed in time when waste liquid is produced. Through above measures, even in extreme conditions, the “storage, treatment, blockage and isolation” of radioactive waste liquid can be realized, to ensure that even in an extreme accident situation, radioactive release to the environment is under control, and environmental safety can be guaranteed.

In summary, at present, nuclear and radiation safety standards adopted for China NPPs meet the highest international safety standards, and nuclear technology implemented is in accordance with Gen-III safety standards. The site safety of inland nuclear power plants in China is guaranteed, as long as nuclear safety regulations and standards are followed strictly, and reasonable and effective engineering measures are adopted. The impact on public and environment under normal operating conditions is within natural background levels, which is acceptable, and the environmental risk of nuclear power plant can be controlled under severe accident condition (with no permanent relocation, no need for emergency evacuation outside the immediate vicinity of the plant, limited sheltering, and no long-term restrictions in food consumption).

Appendix 4-3: Emergency Management after Severe Accidents in China

According to the *National Emergency Plan for Nuclear Accidents (2013)*, in case of a severe accident, nuclear emergency organizations at all levels shall implement all or part of the following response actions in light of the nature and severity of the accident:

(a) Accident mitigation and control;
(b) Radiation monitoring and evaluation of consequences;
(c) Personnel protection from radiation;
(d) Decontamination, cleansing and medical treatment;
(e) Control of entrances and port;
(f) Market supervision and regulation;
(g) Maintenance of public order;
(h) Information reporting and dissemination;
(i) International notification and request for assistance.

Monitoring of radioactivity will be carried out on the site of the accident and in the surrounding environment (including air, land, water, atmosphere, crops, food, drinking water, etc.), and doses of radioactivity will be monitored for emergency staff and the public exposed to radiation. Furthermore, real-time meteorological, hydrological, geological, seismic and other observation (monitoring) measurement and forecast are carried out as well as accident conditions diagnosis and source investigation. Identification and monitoring of accident evolution, evaluation of radiation consequences, determination of the extent of affected areas, and provision of technical support for emergency decision-making are mandatory.

Three level nuclear emergency system in China:

The National Nuclear Accident Emergency Coordination Committee is composed of experts from nuclear engineering, nuclear safety, radiation monitoring, radiation protection, environmental protection, transportation, medicine, meteorology, oceanography, emergency management, public propaganda, who provide advice and suggestions for important decisions and plans of national nuclear emergency work and for nuclear accident response work.

The government at the provincial level shall establish a provincial nuclear emergency committee, which is composed of responsible persons from relevant functional departments, relevant cities, counties and operating units of nuclear facilities, to be responsible for nuclear accident emergency preparedness and emergency treatment tasks, and to uniformly direct nuclear accident off-site emergency response actions, within its jurisdiction. The provincial nuclear emergency committee establishes an expert group to provide decision-making advice, and establish nuclear accident emergency office to undertake the daily work of provincial nuclear emergency committee. Besides, the provincial nuclear emergency front command department is established to give decision-making support.

The nuclear emergency command department of nuclear installation operators is responsible for organizing on-site nuclear emergency preparedness and treatment task, uniformly commanding nuclear emergency response action of its own, assisting off-site nuclear emergency preparedness and response task, and providing suggestions for entering off-site emergency state and taking off-site emergency protection measures.

Nuclear emergency monitoring system:

National Nuclear Accident Emergency Command Department or National Nuclear Accident Emergency Coordination Committee shall organize national emergency forces to carry out radiation monitoring, depending upon the actual situation, which organize and coordinate national and local radiation monitoring forces to carry out radioactive monitoring in areas where is already or possibly affected by nuclear radiation (including air, land, water, atmosphere, crops, food and drinking water, etc.).

The government at the provincial level and nuclear accident emergency department of nuclear power plant should ensure radiation monitoring work after accidents, and provide support for taking emergency countermeasures and emergency protection measures for nuclear accidents.

The provincial environmental protection department has an environmental monitoring group, including land, sea, air, food, and drinking water monitoring groups. The provincial radiation environment monitoring and management station has communication, data collection and transfer devices, who is responsible for organizing and coordinating off-site emergency monitoring after nuclear accident for provincial environmental monitoring group, and for collecting and summarizing all monitoring data, analyzing the possible radiation impact of accidents on environment and public, providing monitoring data for provincial emergency evaluating center, and providing decision-making basis for provincial nuclear emergency command department.

The emergency response group of operating units coordinates and implements emergency radiation monitoring and environmental sampling to ensure that emergency radiation monitoring can be started short after accidents. The emergency response group includes monitors, samplers, people who guide and coordinate monitors and samplers and people who analyze data, sample and other information provided by monitors and samplers. There is at least one trained monitoring group per day on-site who can start emergency radiation monitoring at any time, to carry out emergency radiation monitoring. One emergency radiation monitoring group can undertake monitoring and sampling duties independently and simultaneously.

At present, the state has set up China’s nuclear emergency rescue team, consisting of 6 sub rescue teams, about 320 people, which are established within the national emergency framework and rely on existing nuclear emergency forces from army and nuclear industry, who undertake the task of sudden rescue and emergency treatment task for NPP severe accident under complex conditions, effectively controls the source of nuclear accidents, searches and rescues of trapped people in time, stops the spread of the accidents with all strengths, minimizes the consequences of the hazards and supports treatment actions for nuclear facilities.

A multi-level coordinated command to be in place of the emergency command system, a unified decision-making, a multi-sector coordination after a severe accident, and a rapid deployment of emergency resources shall be present. After a severe accident, the data and information channels shall remain unobstructed, and decision-making means shall be diversified, to allow effective decision-making and support in all circumstances.

CHAPTER 5- Nuclear safety and the environment

Recommendations

As the main goal of environmental protection is to eliminate the possibility of large radioactive releases, it is recommended that owners of nuclear facilities:

- Test the resilience of the existing nuclear facilities to external events higher than considered in the design basis,
- Upgrade existing nuclear facilities to meet the same safety objectives as set for new facilities, as reasonably achievable,
- Implement the risk-informed defence in depth, including "beyond design basis" conditions, for all facilities,
- Perform internal and independent reviews of their safety management systems, and not exclusively rely on the reviews performed by the safety authorities.

As environment protection is a major sensitive issue for people, it is recommended that nuclear regulatory agencies:

- Establish a transparent supervision of nuclear safety through transparent communication,
- Initiate a permanent dialog with local authorities and the public.

As digitalization of the nuclear industry has been progressing at a fast pace, special attention should be given to protect software and data bases used at design, construction and operation stages. Nuclear Operators should identify a Chief Security Officer (CSO), and set up, under the responsibility of the CSO, an organization dedicated to the development and implementation of a digital security policy.

Introduction

The fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation (Ref. 44). This is primarily achieved by controlling the radiation exposure of workers and the release of radioactive material to the environment during normal operation of NPPs and fuel cycle facilities. The smaller the nuclear facilities release of radioactive substances, the smaller their impacts on the environment. Releases are continuously monitored and controlled as shown in Chapter 2; their consequences on the environment are well below the level of natural radiation. Furthermore, they are kept as low as reasonably achievable, and records show that releases have been steadily reduced over time, to reach an asymptote at an extremely small fraction of authorizations granted by safety and environmental agencies. In France for instance, the average radiological consequences of liquid releases are in the range of 10^{-6} Sv/a, which is a factor of one thousand below the authorized level (10^{-3} Sv/a - (Ref. 45), which itself is 30 times less than natural radioactivity. Long-term deferred releases of radioactivity from radwaste disposed of in geological formations are also expected to lead to radiological exposition, however, much smaller than natural radioactivity as discussed in Chapter 3.

Therefore, the first section of this chapter addresses the two other objectives of nuclear safety: restricting the likelihood of nuclear accidents and mitigating the consequences of such accidents should they occur. The following three sections emphasize a few specific issues which tend to be of increasing importance nowadays, including:

- Siting in relation to safety;
- Responsibility for safety and role of the Government;
- Nuclear safety and public acceptance.

Appendix 5-1 presents the architecture of the safety regulation system.

5.1 The safety of nuclear power plants and their environmental impact

From the onset of commercial nuclear energy, safety requirements have been set up to prevent accidents and limit their consequences. Historically, the safety analysis of Nuclear Power Plants was based on the identification of a “Design Basis Accident” (DBA). It was to be demonstrated to the Regulator that such accident, and any accident having a higher probability of occurrence, would result into fairly limited releases to the environment. To achieve this goal, a dual approach is taken, i.e.: (a) all safeguard systems mitigating nuclear accidents less or as severe as the DBA have to be provided with adequate redundancy and diversity; and (b) multiple barriers have to be set up in order to drastically limit radioactive releases to the environment. This approach, known as deterministic defence in depth has to be systematically enforced, with special attention to the independence of the safeguard systems and of the barriers (see § 5.1.2 Risk-informed defence in depth); in earlier designs, accidents with core melt were not considered.

Overtime, this deterministic approach was supplemented with probabilistic safety analysis, following the WASH-1400 analysis.

5.1.1. Severe accidents and their external consequences

When the first Generation 1 and 2 reactors (Gen. 1 and 2) were designed and build, a simple reference scenario including a DBA was considered to design their safety systems and containment, typically the Loss of Coolant Accident (LOCA), limited to the consideration of a “double ended guillotine break” of the primary circuit in PWRs and BWRs. However, probabilistic assessments made as early as 1975 (Ref. 46) and, unfortunately, severe accidents with core melt (such as those at the Three Mile Island NPP (1979), the Chernobyl NPP (1986) and the Fukushima Daiichi NPP (2011)) provided evidence that DBAs did not encompass all situations to be considered by nuclear safety. Lessons learned from these accidents resulted in back fittings of existing plants, and revisions of safety objectives.

The quantitative safety goals of NPPs have been assigned after the Three Mile Island NPP accident, such as the two “one thousandth” rule[2].

---

2 a. for normal individuals next to a NPP, the risk of immediate death due to a reactor accident should not exceed one thousandth of the total risk of immediate death caused by other accidents faced by social members; b. for the population in the vicinity of a NPP, the risk of cancer death due to the operation of the NPP should not exceed one thousandth of the total risk of cancer death caused by other causes.

The Probabilistic Safety Assessment made in NUREG-1150 concluded that:

Average probability of an individual early fatality per reactor per year:

- NRC Safety Goal: 5×10^{-7}
- Typical PWR: 2×10^{-8}

Average probability of an individual latent cancer death per reactor per year:

- NRC Safety Goal: 2×10^{-6}
- Typical PWR: 2×10^{-9}

These results could appear as quite satisfactory. However, both the Chernobyl and the Fukushima Daiichi accident evidenced that nuclear safety should not only consider lethal consequences of nuclear accidents, but environmental consequences which could require evacuation and relocation of population, even living at some distance from the plant (up to 30 km).

New safety objectives, including consideration of severe accidents are now formalized in the regulations of several countries. They have been summarized by the Western Association of Nuclear Regulators (WENRA) as follows (Ref. 47):

- Accidents with core melt which would lead to early or large releases **have to be practically eliminated;**
- For accidents with core melt that have not been practically eliminated, design provisions have to be taken so that only limited protective measures in area and time are needed for the public (**no permanent relocation, no need for emergency evacuation outside the immediate vicinity of the plant, limited sheltering, no long-term restrictions in food consumption**) and that sufficient time is available to implement these measures.

Severe accidents (i.e. with core melt) can be triggered either by external events, and/or by the malfunction of engineered safety systems and hypothetically by a terrorist attack.

It is of utmost importance that operators check the resilience of their facilities to external events (Flooding, earthquakes, hurricanes, etc.) more severe than the environmental conditions taken as design basis, and demonstrate that there is no “cliff edge” effect as encountered at the Fukushima Daiichi NPP. After this accident, the European Union promoted the performance of “stress tests” for all European sites, the results of which were made publicly available. These stress tests achieved two important benefits: (a) they helped identifying weaknesses in the design of some facilities, and address them; and (b) being made publicly available, they provide evidence to all stakeholders and the public that safety issues were thoroughly reviewed. So far, the IAEA provides no guidance on the performance of similar stress tests at all NPP; issuing a Safety guideline on this matter would help promoting their regular and systematic implementation.

With respect to engineered safety systems, and as recommended by the Western European Nuclear Regulators’ Association, it is necessary to supplement the outdated DBA approach with the consideration of other, or extended conditions, beyond DBAs. This is achieved by a comprehensive Risk-informed defence in depth.

It is recommended to implement similar safety principles to existing plants and improve their safety levels according to the same objectives as set for new plants (practically eliminate large or early releases). In that respect, WENRA has provided guidelines which may be used as a reference (Ref. 48). All French reactors are presently being upgraded as part of the large retrofit program ("Grand Carénage"), to meet the requirements applied to Gen-III reactors as closely as possible. And the Chinese government has taken provisions to enhance nuclear safety to prevent large releases of radioactive substances in case of severe accident (see Appendix 5-2).

5.1.2. Risk-informed defence in depth

It is advisable to "practically eliminate" (WENRA wording) any scenario inducing large or early releases, to drastically limit the residual risk, by such measures as increasing safety margins, adopting supplementary safety measures, and strengthening defence in depth.

Design and setup of supplementary measures should be based on the principle that nuclear safety needs be as high as reasonably achievable and ensure that such measures do not induce negative effects. To this end, various factors including the probability and the consequences of the residual risks should be comprehensively taken into consideration, and the adverse effects on response functions dedicated to normal operation, anticipated operational occurrences (AOO), DBAs and design extension conditions (DEC) should be prevented.

Risk-informed defence in depth system (RDIDS) is illustrated in Table 5-1. RDIDS employs engineered safe features (ESF), additional safety features and supplementary safety features:

At Level 3, engineered safe features are dedicated to DBAs, and should be implemented in accordance with the requirements of safety-grade systems and equipment.

Additional safety features dedicated to DECs are introduced at Level 4; as an example, a rapid pressure relief valve is added to the pressurize relief system to practically eliminate High Pressure Core Melt (HPCM), and the catastrophic early containment failure HPCM would induce. From a risk-informed perspective, additional safety features are not required to be safety grade (redundancy, qualification, etc.). Their design criteria should be defined on the basis of a specific analysis of the function they have to perform; therefore, deterministic design rules (such as redundancy, seismic qualification) which apply to engineered safety features coping with Level 3 do not apply, and a probabilistic assessment of the additional safety features may be used to support their safety case. As an example, the fire protection system may be considered at Level 4 to refill spent fuel pools, although this system is not safety-grade: considering the extent of time left before such refilling action would be needed, alternative means can be considered, lowering the reliability required from additional safety features.

At Level 5, supplementary safety features are used to prevent and mitigate the residual risk under extreme conditions. Such features include containment filtration and venting system, off-site emergency plans, mobile power sources for mitigating extensive damage consequences in NPPs, mobile pumps, water tanks, and mobile devices provided by nuclear power group and national institutions for support of emergency response in and around NPPs. In principle, supplementary safety features have not to be safety-grade, their reliability is proven, and their availability is regularly checked.

Levels of RDIDS	Objective	Basic measures	Conditions of NPP
Level 1	Prevention of abnormal operation and failures	Conservative design, and high-quality construction and operation	Normal operation
Level 2	Control of abnormal operation and detection of failures	Control, restriction and protection of systems and monitoring facilities	Anticipated operational occurrences
Level 3	To restrict accidents within design basis	Engineered safety features and accident response procedures	Design basis accident (to assume a single postulated initial event)
Level 4	To control severe conditions, including prevention of severe accidents(4a) and mitigation of consequences (4b)	Additional safety features and accident management	Design extension conditions, including multi-failures(4a) and severe accidents (4b)
Level 5	Engineering rescue under extreme conditions; mitigation of consequences of radioactive releases	Supplementary safety features, guidelines for management of extensive damage condition and off-site emergency response	Residual risks

Table 5-1: Risk-informed defence in depth system.

Under the framework of RDIDS, the Level 4 requires including additional features dedicated to DECs in NPP design, consider their adequacy and reliability, and achieve a better balance between accident prevention and mitigation. Relevant NPP safety analysis should demonstrate that under severe accident conditions, containment can maintain its integrity and no large radioactive release to the environment would occur. Depending on the results of a plant-by-plant analysis, the installation of a containment filtration and venting systems shall be decided, if the integrity of the containment cannot be demonstrated.

At Level 5, it is assumed that the additional Level 4 of defence in depth failed, and although the objective was to practically eliminate large radioactive releases, such releases occur. It remains therefore necessary to prepare for emergency (implementation of off-site emergency preparedness to alleviate the consequences).

5.1.3. New safety threats

When assessing nuclear safety of operating and new plants, special considerations should be given to new threats such as cyber-attacks, and terrorism.

Cyber-attacks are not specific to nuclear plants, and protections should be implemented in a similar way as done for any large facility providing vital services, or having potential environmental impacts. Digitalization of the nuclear industry has progressed quite rapidly at all stages (design, construction, operation, and maintenance), and special attention should be given to protect software and data bases used at any level.

Operators should assign a CSO, and set up, under the responsibility of the CSO, a dedicated organization to develop and implement a digital security policy at all level of its organization (Ref. 49). The role of this organization should include the review of provisions taken by subcontractors in this field. A special care should be given to the Instrumentation and Control systems (I&C), now digitalized in modern plants, and especially to the Safety I&C system. Since this system is vital for ensuring the safety of the facility, including its safe shutdown when needed, its protection requires special attention. It should not be connected to external networks, and changes and updates of this system should be subject to strict procedures, controls and re-qualification.

Terrorism, unfortunately, is also not specific to nuclear facilities. From the onset of civil nuclear industry, and under the auspices of the IAEA, considerable efforts have been drawn to prevent uncontrolled dissemination and use of nuclear material (Ref. 50). Over the years, this system has proven to be efficient, and should be supported with determination. However, direct attacks of nuclear facilities have to be considered, as 09/11 attacks demonstrated the vulnerability of our modern world to new forms of terrorism. This topic is confidential by nature, and it is essentially impossible to publicly discuss the approaches that are implemented in different countries. In principle, the same concept of defence in depth applies to this specific hazard. By design (earthquake resistance, robustness of a containment design to withstand a significant overpressure), nuclear facilities have the capacity to resist some external aggressions, but additional engineered features may be added to protect safety buildings, and withstand high frequencies vibrations induced by airplane crashes. What is more important, a national agency should be assigned for the responsibility to identify the safety threats to be considered; the operator shall build prevention and mitigation measures to cope with them, in cooperation with forces in charge of national security (police, army, etc.). Although the details cannot be provided, transparency calls for the concepts to be explained, and more specific information should be provided to certified members of parliament or regulatory agencies.

5.2. Siting NPPs

NPP siting should not only take into account power demand and plant layout, but also consider suitability of the site from a safety perspective, in all its aspects namely, (a) site safety, (b) environmental protection and (c) emergency preparedness, as provided for by the international consensus on elementary requirements for siting of nuclear facilities. Emergency preparedness remains an important factor of a risk-oriented defence in depth.

At first, the three following aspects should be considered:

(a) The impact of external events (these events may be natural or artificially induced) on the area where the site is located;

(b) The site and its environment characteristics that may affect the release of radioactive substances to people and the environment;

(c) Site factors that may affect implementation of emergency preparedness & responses.

The safety assessment of a nuclear site may be split into the following eight indicators: (a) geology and earthquake characteristics; (b) atmospheric dispersion; (c) restricted areas and low-populated areas; (d) population distribution; (e) emergency plans; (f) safeguard guidelines; (g) hydrology; and (h) industrial, military and transportation facilities.

If the assessment using the above criteria qualifies a site as not being suitable and that its deficiencies cannot be compensated through design, site protection measures or administrative procedures, then the site must be excluded without further consideration (Ref. 51).

In order to preclude external safety hazards, NPP siting shall consider geological factors in depth to avoid geologically unstable areas such as seismic faults, areas that may be subjected to landslides, and volcanoes. It is also necessary to investigate factors such as climate and hydrology to protect NPPs from threats induced by typhoons, tsunamis, tides, floods, etc. It is also important to ensure that NPPs will always have sufficient heat sink capacity to remove the residual heat.

Moreover, issues such as the transport infrastructure to ship large equipment to the site, the local economy, and public acceptance also need to be considered in siting, although they are not safety related.

There is no difference in safety requirements for NPPs at inland sites and coastal sites, but factors that may be considered (such as typhoons, tsunamis, or dam collapse) may vary. Scenarios of extreme natural disasters facing inland NPPs may include earthquakes and landslides, ground fissures/faults, subsidence; floods and dam break; earthquake and dam break.

With regard to the issue of how to prevent radioactive waste water from affecting ground water after accidents in the inland NPPs, abundant research has been carried out in China, resulting in the formulation of four principles for treating radioactive waste water in the containment after accidents. The four principles for ensuring that the radioactive waste water can be “stored”, “blocked”, “treated”, and “isolated”, are suggested to be used as supplementary safety measures for the safety design of NPPs, enhancing defence in depth of NPPs and further ensuring safety of nuclear power.

Similar Research and Development has been carried out in France, resulting in solutions adapted to each site and facility, and regularly reviewed. Exchanges between the French and Chinese institutes in charge of those matters should be encouraged.

After the accident at the Fukushima Daiichi NPP, development of nuclear power in China encountered some challenges, especially for inland NPPs. Due to the shortage of “good” coastal sites, some “not so good” coastal sites (especially with higher earthquake risks) are reassessed and considered as appropriate for Gen-III NPP. Building NPPs in regions with higher seismic risks requires special attention from each party and an in-depth analysis, inclusion of safety margins, to allow for conservative decisions compatible with the required safety level.

In France, the suitability of sites is reviewed every ten years, before granting authorization to continue operation for the next ten years. For several sites, (Cadarache, Fessenheim as examples), the seismic design criteria were increased during the lifetime of the facilities; however, it could be proven that designs had sufficient margins to cope with these increased requirements without impairing safety.

5.3. Responsibility for Safety and role of the Government

5.3.1. The prime responsibility of the operator

There is no safety without a well identified organization responsible for ensuring safety and provided with adequate resources to discharge its duties. "**The prime responsibility for safety must rest with the person or organization responsible for facilities and activities that give rise to radiation risks" (Ref. 52)**. On a legal standpoint, this person is the nuclear licensee; through contractual arrangements, he may delegate operation and maintenance, in part or as a whole; but it is essential that the licensee – sometimes called "the owner/operator" - keeps full responsibility for controlling safety and demonstrates that he has enough resources for ensuring this role.

The complex structures of ownership of NPPs in the future, customized to accommodate financial constraints, may lead to situations where one facility has several owners, with operation delegated by contract to one of them. In such cases, a clear line of responsibility shall be established with respect to safety. The Regulator has to make sure that the owner/operator organization is clearly identified, which should be a condition to the award of a nuclear license.

To fulfil these responsibilities, nuclear operators should have adequate technological and financial resources allowing them to perform and manage nuclear safety activities. Those activities may be carried out by a considerable number of staff members within the organization, or subcontracted. To control and monitor safety related activities, it is common practice to establish safety departments or safety divisions, independent from the operational and maintenance divisions. In complex organizations (multiple sites; multiple units at one site), it is recommended for such safety departments or divisions to have a dual reporting line, operationally to the operational management at its level (unit, site, corporate), and functionally to the upper level of the safety organization. Furthermore, it is important that each employee working for the operator or any subcontractor be entitled to confidentially report any safety violation he might witness or be aware of, to a point of contact well identified within the organization and independent of the management line, without running any risk of sanction (whistle-blower). In very large organizations, it is also recommended to set up an independent inspection department, reporting to the top management within the organization, and performing audits of the system and self-inspections of the facilities without relying exclusively on regulatory safety authority to conduct their own regular inspections.

Whatever the safety organization is, it is of utmost importance that a strong safety culture, emphasizing the principle "Safety first", be disseminated at all levels of the organization and its subcontractors, from the top management to the laypersons.

The IAEA has rightly reminded the prime responsibility of the nuclear operator to achieve nuclear safety. It would be helpful that, in connection with the World Association of Nuclear Operators, it makes basic recommendations on the best practices to be implemented by the operators to fully take in charge their duties.

5.3.2. The role of the Government and the regulator

The role of the Government is to protect people and the environment. It shall establish a legal and governmental framework for safety, including an independent regulatory body. In turn, the regulatory body grants construction and operating licenses in accordance with nuclear regulations. To check compliance with the license, the regulator performs supervision and inspections on the operator/licensee.

But these supervision and inspections do not prejudice the responsibility of the operator for taking full responsibility of nuclear safety, whatever the controls of the regulators are.

To implement these principles, China promulgated the "National Security Law of the People's Republic of China" on July 1st, 2015, putting nuclear safety in the national security system together with political security, homeland security, military security, economic security, cultural security, social security, science & technology security, information security, ecological security, resource security etc. and the responsibility of each party is clarified by the “Nuclear Safety Law of the People's Republic of China", which was enacted on January 1st, 2018. In France, these principles are included in the Environmental Code (articles L591-1 and sq.) and consequential decrees.

5.4. Nuclear Safety, and Public understanding

Due to the complexity of nuclear power and external consequences of large accidents such as the accident at the Fukushima Daiichi NPP, the public is still haunted by “nuclear panic” and raises doubts about peaceful use of nuclear power. The not-in-my-back-yard (NIMBY) syndrome has reached an acute level for nuclear power and there is an escalating resistance and opposition to NPP projects. Public acceptance has become a bottleneck and hinder the development of nuclear power, whatever its merits with respect to cost and CO_2 emissions. There is a long way to go for better communicating with the public on nuclear safety.

Improving nuclear safety, to better prevent and mitigate the consequences of severe accidents is a prerequisite to further acceptance of nuclear energy. But it is also important that the public is aware, and understands these improvements. It is an important part of a healthy nuclear development to improve public communication and raise public confidence in nuclear energy. Good public communication requires effective and transparent information, active public involvement and a permanent dialogue with local authorities and the public. Better education for the public in technical matters – starting with teachers and educators, and as soon as elementary school – should be a target of education systems.

Nuclear regulatory agencies have an important role to play in their handling of an open and transparent supervision and management of nuclear safety, and in establishing a public communication mechanism comprising “central government supervision, local authorities’ leadership, enterprise implementation and public participation”. It is not the role of nuclear regulatory agencies to promote nuclear energy; but they should explain to the public how they handle their role, and why they are confident that nuclear licenses can be granted. Governmental websites, as information disclosure platforms, should be improved to release relevant documents such as reports on environmental impact of nuclear projects, results of national radiation monitoring and information on project licensing. Public opinions should be widely listened to and engaged in the process of policy formulation and in the environmental evaluation of nuclear projects.

Experience indicates that openness is the basis, information disclosure and public participation the prerequisite, and sharing of benefits the key. If there is no benefit-sharing, it will be hard to solve the problem of NIMBY even with increasing awareness and an improved perception of risks of nuclear power.

Generally, there is no problem in public acceptance of existing NPP site expansion, probably because the local public (including local authorities) is fairly acquainted with nuclear energy and its benefits in promoting local economic and social development, while feeling no safety risk of nuclear power on the neighboring communities. Public acceptance of new NPP sites, however, may be more challenging as they have to be accepted without previous local experience.

5.5. Conclusion

As described in Chapter 4, the Gen-III reactors have special prevention and mitigation measures for severe accidents, which could achieve the control of environmental risks and fully meet the requirements of nuclear safety regulations. However, it is important to explain that nuclear safety is an area of continuing learning, updating, and improvement with good experience-feedback systems.

Safety of nuclear facilities has been effectively improved through in-depth analysis of all types of incidents, internal and external, domestic and foreign, and even by borrowing best practices from other industries facing risk issues. By considering root causes of previous accidents and taking appropriate measures, potential safety risks are reduced to a large extent. After the accident at the Fukushima Daiichi NPP, the problem of public acceptance of nuclear power has become more important and even has become a bottleneck in the development of this energy. It is therefore important to explain the many additional safety measures that have been implemented to reduce the risks, eliminate large radioactive release and protect the population and the environment.

Appendix 5-1: Nuclear safety principles

The development and utilization of nuclear energy has brought new impetus to human development. At the same time, development of nuclear energy is also accompanied by safety related risks and challenges. As consequences of nuclear accidents may not be limited to one Region or one country, the transnational nature of nuclear energy has to be acknowledged, and appropriate international cooperation be promoted.

The nuclear safety regulation system is like a building that needs to systematically construct its foundation and support. A typical management system, as shown in Figure A5-1 below, consists in four cornerstones and eight pillars (also known as four crossbeams and eight pillars).

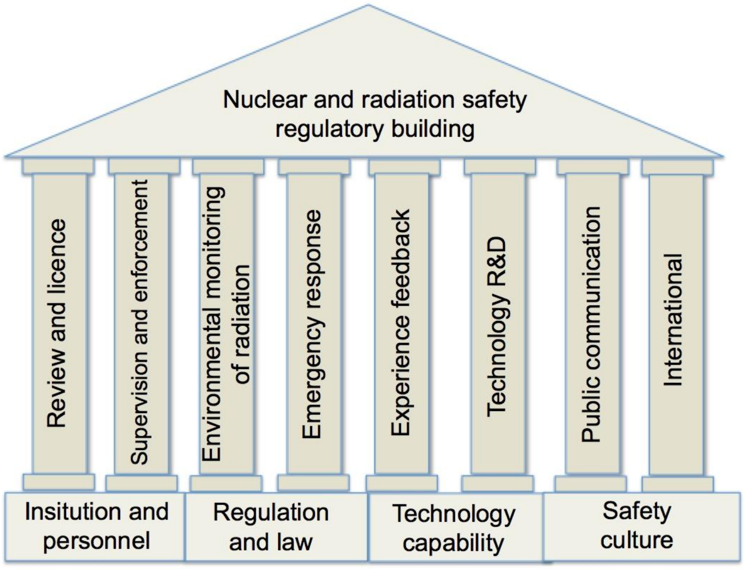

Figure A5-1: Schematic diagram of a nuclear and radiation safety regulatory building.

The four cornerstones are Laws & Regulations, Institutional structure, Technology capability and Safety Culture. It is generally considered that it is necessary to cement the four cornerstones as following proposals:

(a) **Regulation and Law:** to improve top-down design of the nuclear laws and regulations based on a “Law of Atomic Energy” and/or a “Nuclear Safety Law”;
(b) **Institution and Personnel:** to establish competent nuclear safety regulatory agencies independent from development departments of nuclear energy;
(c) **Technology Capability:** to build platforms for independent analysis and experimental verification, information sharing, exchanges and training;
(d) **Safety Culture:** to popularize nuclear safety culture, strengthen risk awareness, and adhere to the principle of "safety and quality first.

The eight pillars are Review and License, Supervision and Enforcement, Environmental Monitoring of Radiation, Emergency Response, Experience Feedback, Technology R&D, Public Communication and International Cooperation. Based on the 4 cornerstones and 8 pillars, the nuclear safety authority should build a robust and effective management system for nuclear power safety regulation.

Appendix 5-2: Actions taken in China

The Chinese government promulgated the "National Security Law of the People's Republic of China" on July 1, 2015, putting nuclear safety in the national security system.

In addition, the Chinese government clearly required in the "***12th Five-Year Plan for Nuclear Safety and Radioactive Pollution Prevention & Control and Vision for 2020***" issued in 2012 that: new nuclear power units being or to be constructed during the period of 13th Five-Year Plan and beyond strive to achieve the goal in design to practically eliminate the possibility of large radioactive release. In the "***13th Five-Year Plan for Nuclear Safety and Radioactive Pollution Prevention & Control and the Vision for 2025***" released in 2017, it is clearly stated that newly-built nuclear units will maintain international advanced level and achieve in design the goal to practically eliminate release of large amount of radioactive substances.

China National Nuclear Safety Administration released a new version of "***Safety Regulations for Nuclear Power Plant Design (HAF102-2016)***" in October 2016. HAF102-2016, as one of the important documents in China's nuclear safety regulation/law system, specifies binding requirements for design, specification and arrangement of structures, systems, and components important for safety of NPPs, as well as requirements for conducting comprehensive safety assessment.

HAF102-2016, with reference to the IAEA document "Nuclear Power Plant Safety Design (SSR2/1, Rev.1)", also incorporates relevant requirements published by regulatory bodies and organizations such as the United States Nuclear Regulatory Commission (NRC) and the Western European Nuclear Regulators' Association (WENRA), such as protection against malicious impact by commercial aircraft.

The 12th and 13th Five years plans state that:

(a) Under the condition of design basis accident (DBA) and/or design extension condition (DEC), accidents in nuclear power plant will not result in significant release of radioactive substances and,
(b) Under extreme conditions, there will be no large-scale release of radioactive substances to protect people, society, and the environment from hazards, and in particular, accident scenarios similar to the Fukushima accident which caused lasting serious pollution on the surrounding environment. The new safety goal of "practically eliminating large radioactive release" is not intended to abolish off-site emergency plan because the Fukushima nuclear accident has proved importance of the off-site emergency response. Here, the term "large amounts of radioactive release" refers to radioactive release scenarios similar to that of the Fukushima nuclear accident.

The HAF102-2016 regulation lays equal emphasis on the following three issues:

(a) Prevention of both internal events and external events,
(b) Prevention and mitigation of severe accidents and,
(c) Deterministic and probabilistic analysis.

Major upgrades introduced in HAF102-2016 require to:

(a) Strengthen prevention of radiological consequences unacceptable to the public and the environment;

(b) Avoid early release and long-term pollution on the surrounding environment by taking measures for severe accident mitigation;

(c) Prevent severe accidents through NPPs design, including strengthening the fourth level of defence in depth, considering impact of external events and maintaining sufficient safety margin;

(d) Strengthen reliability of ultimate heat removal;

(e) Consolidate emergency power supply;

(f) Enhance safety of fuel storage to avoid water-uncover of fuel;

(g) Provide interfaces to facilitate uses of mobile devices where necessary;

(h) Strengthen performance of emergency response facilities.

CHAPTER 6- Conclusion

The present report is a continuation of the work carried out previously by experts from the three Academies (Chinese Academy of Engineering, National Academy of Technologies of France and French Academy of sciences).

The report published in 2017 by these Academies essentially focused on recommendations about the future of nuclear energy. The present report more specifically deals with the impact of nuclear energy on the environment considering all operations from uranium mining to radioactive waste disposal. It addresses the four major environmental issues associated with nuclear power generation:

- Evaluation and control of the radioactivity released by nuclear installations under normal operation,
- Management of long-term radioactive spent fuels and radioactive waste, notably those that will be disposed of in geological repositories,
- Management of severe nuclear accidents and their radioactive releases,
- Improvement of nuclear safety as a way to limit environmental impacts and to contribute to public acceptance of nuclear energy.

On the one hand, nuclear power has many benefits, in particular that of providing an on-demand source of electrical energy and/ or heat with extremely low levels of GHG emissions. In the context of global warming, nuclear energy with its near absence of GHG emissions, features a unique capacity to massively generate electricity. Furthermore, in contrast to fossil fuel plants that emit, through combustion, important quantities of air pollutants such as particles, nitric oxides, sulfur oxides, heavy metals, nuclear power plants do not generate air pollutants. On the positive side also, nuclear energy requires a relatively limited use of land. Nuclear energy production is also flexible enough to be used for compensating a large proportion of intermittent renewable energy sources.

By summarizing these positive features, one may conclude that nuclear power constitutes one of the most appropriate sources of energy for accompanying the necessary energy transition. Without nuclear power the objective of GHG emission reduction seems to be difficult to attain.

On the other hand, nuclear energy may have potential adverse effects on the environment that need to be assessed, and this constitutes the focal point of this report.

It is first indicated that under normal operation, the impacts of nuclear energy on the environment are well documented and that measurements of the concentration of radionuclides in the environment are easy to do. This allows independent monitoring of such installations. The radioactivity levels of the releases are regulated in all nuclear countries according to safety rules for radiation protection. The actual releases only reach a few per cent of the authorized levels, which themselves are well below the impacts of natural radiation. This is why the report concludes that the impact of nuclear power plants under normal operation is negligible or quite limited in terms of radioactivity.

The question of cooling water is then considered. Nuclear power plants are frequently built near the seashore and sea-water is used to ensure cooling requirements. The temperature of such sea water increases slightly in heat exchanger devices before being released to the sea without any consequence.

In other cases, nuclear power plants are sited near large rivers and the condenser is cooled either by a once-through cycle (the cooling water is returned to the river) or with cooling towers. Operation of inland-sited NPPs under the first solution may face more limitations due to "thermal pollution" (increased water temperature) downstream the facility. Cooling towers drastically limit any thermal impact to the river but to the detriment of water withdrawal. The public should be better informed about measures taken to control water temperature and limit water withdrawals when one considers siting of new NPPs along large rivers.

Protection of the environment requires to be considered at each step of radwaste management:

- isolation/confinement in packages,
- storage, and disposal in near surface or deep geological facilities adapted to each type of radioactive waste.

Solutions rely on top level engineering technology developments and are supported by continuous R&D on the behavior of radionuclides/toxics in engineered barriers and in the geosphere and benefit from a large international cooperation.

Monitoring is carried out during all operations from production of radwaste to their disposal in repositories, where radwaste packages are isolated from the biosphere. The background level is permanently monitored around these facilities. Feedback from their operation shows that operational releases are less than initially expected and authorized by safety and environmental authorities when the facilities were licensed.

After closure of the repositories, monitoring will continue during a test period; then safety will change from active to passive. Most radionuclides will decay in the repositories, those that might return to the biosphere will do so at a time so long that their radiotoxic impact will be negligible. While available data from analytical laboratories and underground rock laboratories are short term data, *natural analogues* provide valuable support to waste repository modeling and safety assessment: this is for example the case for natural nuclear reactors at Oklo, Gabon, that confine actinides and fission products during millions of years, or for Mediterranean archaeological glasses having resisted to erosion and leaching during thousands of years.

The main issue considered in the report pertains to environmental impacts of severe accidents that have marked the history of nuclear energy development. Issues raised by these past accidents need to be considered in a fully transparent, independent and balanced assessment. These impacts are well documented for what concerns the three severe accidents of nuclear reactors (TMI, Chernobyl, Fukushima); less well documented for the few important accidents concerning nuclear fuel cycle facilities and an effort should be made to present the feedback of these latter events. The present report indicates that on the one hand, the accidents ranked to level 7 on INES (Chernobyl and Fukushima) have had a large impact on the environment and have reduced public confidence in the nuclear energy generation system. On the other hand, the return of experience has led to important improvements in many aspects including reactor design and operational management as well as in the development of severe accident management guidelines and this has proved to be quite valuable.

The environmental risks in the event of a severe accident that might occur in the future have been substantially reduced. Nuclear power plants that are operating or under construction are endowed with prevention and mitigation measures that will limit the impact of such an accident if it occurs. These are meant to drastically reduce the area affected, limiting pollution and the need for a long term and large-scale evacuation of people.

One aspect that is still not settled is that of the long-term effects of low and very low dose rate exposures. There is no consensus within the scientific and nuclear communities, even though the large majority of epidemiological studies around the world converge to demonstrate that they are not harmful.

Comprehensive prevention and mitigation measures for severe accidents contribute to a higher safety level of Gen-III reactors which are equipped with additional systems to prevent core melt, and large containment buildings capable of resisting external hazards and maintaining their integrity in case of sever accidents, thus avoiding radioactive releases to the environment.

The return of experience has led to upgrade existing NPPs and to improve the design of new reactors together with the safety guidelines now implemented by NPP operators. It drastically reduces the probability of occurrence of a nuclear accident such as Chernobyl and Fukushima. In case of such an accident, radioactive material releases would be minimized and would not require large or long evacuations of people. It would be valuable if a global assessment by IAEA or WANO could demonstrate that a high level of upgrading has been implemented all over the world for operating NPPs.

Considering that safety management is essential to environmental protection, the report underlines that:

- The risk-oriented defence-in-depth system constitutes an improved and more complete safety methodology comprising five levels that significantly reduces the residual risks and probability of a severe accident and this in turn has an important influence on the environmental impact.
- NPP siting should not only take into account power demand and plant layout, but should also consider suitability of the site from a safety perspective, in all its aspects namely, site safety, environmental protection and emergency preparedness, as provided for by the international consensus on elementary requirements for siting of nuclear facilities.
- Safety Authorities play a major role in the dynamics of safety improvement and its control but the full responsibility rests on nuclear operators. Both should be engaged in a positive dialog to assure the highest level of environmental protection.

In summary, this report is aimed at providing a balanced assessment of the impact of nuclear energy on the environment. On the one hand nuclear energy has positive effects in providing energy with a very limited level of greenhouse gas emissions without emissions of air pollutants or solid nano- or micro- particles as it is the case for energy systems using fossil fuels. This is an essential asset in the current situation where climate change induced by human activities has become one of the most difficult challenges facing humankind and where air pollution has become a major problem in many countries. On the other hand, nuclear power raises local and more global environmental issues that pertain to radioactive waste management and to the multiple consequences of severe accidents. Considerable efforts have been devoted to defining a sustainable management of high-level radioactive waste leading to their final disposal in geological formations. Lessons learnt from the three main severe accidents have served to improve nuclear reactor design, reduce the probability of occurrence of the release of radioactivity and make sure that the consequences to the environment remain limited if one such accident occurs.

References

1. World Energy Outlook 2018 – International Energy Agency.
2. http://www.french-nuclear-safety.fr/Information/Publications/ASN-s-annual-reports/ASN-Report-on-the-state-of-nuclear-safety-and-radiation-protection-in-France-in-2017 pages 144 -145.
3. NCRP. Ionizing Radiation Exposure of the Population of the United States. NCRP Report No.160, 2009.
4. Pan Ziqiang, Liu Senlin, et.al. RADIATION LEVEL IN CHINA. China Atomic Energy Publishing and Media Co.Ltd. 2011.
5. UNEP. Radiation Effects and Sources. Pages 29 and 54, 2016.
6. G. Brookins, Douglas. (1982). Migration and retention of elements at the Oklo natural reactor. Environmental Geology. 4. 201-208. 10.1007/BF02380513.
7. http://www.french-nuclear-safety.fr/Information/Publications/ASN-s-annual-reports/ASN-Report-on-the-state-of-nuclear-safety-and-radiation-protection-in-France-in-2017 page 53.
8. "Assessment on Radioactive Environmental Impact from Both Nuclear Power Chain and Coal Power Chain" group. Assessment on radioactive environmental impact from different power sources, 2017.
9. WHO, World Health Organization, 2004. Guidelines for Drinking-Water Quality. Vol.1. Third Edition. Geneva, Switzerland.
10. Le tritium dans l'environnement - Synthèse des connaissances IRSN Rapport DEI 2009 -05 - https://www.irsn.fr/FR/expertise/rapports_expertise/Documents/environnement /IRSN_DEI-2009-05_Tritium-environnement-synthese-connaissances.pdf
11. Actualisation des connaissances acquises sur le tritium dans l'environnement - IRSN - https://www.irsn.fr/FR/expertise/rapports_expertise/surveillance-environnement/Documents/IRSN_Rapport-Tritium-2017_PRP-ENV-SERIS-2017-00004.pdf
12. Tritium and the environment –IRSN – August 2012 – July 2017 - https://www.irsn.fr/EN/Research/publications-documentation/radionuclides-sheets/environment/Pages/Tritium-environment.aspx
13. http://www.french-nuclear-safety.fr/Information/Publications/ASN-s-annual-reports/ASN-Report-on-the-state-of-nuclear-safety-and-radiation-protection-in-France-in-2017 pages 144 -145.
14. 2014: Annex III: Technology-specific cost and performance parameters. In: Climate Change 2014: Mitigation of Climate Change. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf page 1335.
15. Global land outlook working paper energy and land use https://global-land-outlook.squarespace.com/s/Fritsche-et-al-2017-Energy-and-Land-Use-GLO-paper-corr.pdf
16. DoE quadrennial technology 2015 https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter10.pdf see note 47 page 390 and 410 for reference publications.

17. https://thebreakthrough.org/index.php/programs/energy-and-climate/ nuclear-has-one-of-the-smallest-footprints.
18. Centrales nucléaires et environnement - Prélèvements d'eau et rejets - EDP Sciences Page169.
19. Life cycle water use for electricity generation: a review and harmonization of literature estimateshttps://doi.org/10.1088/1748-9326/8/1/015031.
20. Revue Générale Nucléaire | SFEN – 08/01/2019.
21. Synthèse de l'étude thermique du Rhône - Agence de l'eau Rhône-Méditerranée - Corse, ONEMA, Agence Régionale de Santé Rhône-Alpes, Agence de Sûreté Nucléaire, CNR and EDF.
22. Le Quéré, C. et al. (2013). The global carbon budget 1959-2011 - Earth System Science Data Discussions 5, no. 2 (2012): 1107-1157.
23. IEA Statistics © OECD/IEA 2014.
24. IEA Energy Technology Perspectives 2017.
25. Nuclear Energy Agency – OECD - Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles – 2002.
26. Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles. - Ch. Poinssot, S. Bourg, N. Ouvrier, N. Combernoux, C. Rostaing. Elsevier Energy 2014.
27. "Research on Key Issues of Greenhouse Gas Emission from Different Power Sources" group. Greenhouse gas emission from different power sources in China, Beijing, China Atomic Energy Press, 2015.
28. Les études épidémiologiques des leucémies autour des installations nucléaires chez l'enfant et le jeune adulte : revue critique - Dominique LAURIER, Marie-Odile BERNIER, Sophie JACOB, Klervi LEURAUD, Camille METZ, Éric SAMSON, Patrick LALOI– IRSN – 2008 - https://www.irsn.fr/FR/Larecherche/publications-documentation/aktis-lettre-dossiers-thematiques/RST/RST-2008/Documents/CHO3-4-Epidemio-Leuc.pdf
29. Spix C, Schmiedel S, Kaatsch P, Schulze-Rath R, and Blettner M, 2008. Case-control study on childhood cancer in the vicinity of nuclear power plants in Germany 1980-2003. European Journal of Cancer 44(2): 275-284.
30. Classification of radioactive waste, 2017, China.
31. Fourth national report for the joint convention on the safety of spent fuel management and on the safety of radioactive waste management, China, section D.4.
32. Research and Development Planning Guide for High-level Radioactive Waste Geological Disposal (2006), China.
33. Synthèse de l'étude thermique du Rhône - Agence de l'eau Rhône-Méditerranée - Corse, ONEMA, Agence Régionale de Santé Rhône-Alpes, Agence de Sûreté Nucléaire, CNR and EDF.
34. Report on the Key Consulting Project of China Academy of Engineering: Strategic Research on Radioactive Waste Management in China, 2018.
35. Assessment of the anticipated environmental footprint of future nuclear energy systems. Evidence of the beneficial effect of extensive recycling. J. Serp, Ch. Poinssot, S. Bourg. Energies 2017.

36. Report of The President's Commission on the Accident at Three Mile Island, Washington, D.C.1979.
37. IAEA. INSAG-1: Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident. 1986.
38. IAEA. Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience. 2006.
39. IAEA, WHO, UNDP, et al. Chernobyl’s Legacy: Health, Environmental and Socio-Economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine, Second revised version [R]. 2006.
40. UNSCEAR, Health effects due to radiation from the Chernobyl accident, 2011.
41. Pan Ziqiang. How much impact of Chernobyl and Fukushima nuclear accidents on human health. China Nuclear Power, 2018(1).
42. International Atomic Energy Agency. The Fukushima Daiichi Accident - Report by the Director General. 2015.
43. The National Diet of JAPAN, Fukushima Nuclear Accident Independent Investigation Commission. The Official Report of the Fukushima Nuclear Accident Independent Investigation Commission. 2012.
44. Fundamental safety principles: safety fundamentals. – Vienna: International Atomic Energy Agency, 2006. Chapter 2.
45. EDF – Annual public information report for the PENLY NPP – Electricité de France – 2017.
46. Rasmussen, Professor Norman C.; et al. (October 1975). "Reactor safety study. An assessment of accident risks in U. S. commercial nuclear power plants. Executive Summary." WASH-1400 (NUREG-75/014). Rockville, MD, USA: Federal Government of the United States, U.S. Nuclear Regulatory Commission. WASH-1400 was later superseded by the document NUREG-1150 "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants", published December 1990 by the Nuclear Regulatory Commission (NRC).
47. Safety of new NPP designs - Study by Reactor Harmonization Working Group RHWG - WENRA -March 2013.
48. Safety Reference Levels for Existing Reactors - WENRA - 2014.
49. Computer Security at Nuclear Facilities - IAEA Nuclear Security Series No. 17 - 2011.
50. The International Legal Framework for Nuclear Security IAEA International Law Series No. 4.
51. Site Survey and Site Selection for Nuclear Installations – IAEA - No. SSG-35 (2015) and Managing Siting Activities for Nuclear Power Plants IAEA -No. NG-T-3.7.
52. Fundamental safety principles: safety fundamentals. – Vienna: International Atomic Energy Agency, 2006. Principles 1 and 2.

Glossary

ADS: Accelerator Driven System

AI: Artificial Intelligence

ANCCLI:Associaion nationale des CLIs (national association of CLIs)

Andra: Agence National pour la Gestion des Déchets Radioactifs (French Nuclear Waste Agency)

AOO: Anticipated Operational Occurrences

ASN: Autorité de Sûreté Nucléaire (French Nuclear Safety Authority)

ATF: Accident Tolerant Fuel

BAT: Best Available Technology

BDBA: Beyond Design Basis Accident

BWR: Boiling Water Reactor

CA: Control Area

CAE: Chinese Academy of Engineering

CAEA: Chinese Atomic Energy Authority

CCGT: Combined Cycle Gas Turbine

CCS: Carbon Capture and Storage

CEA: Commissariat à l'Energie Atomique (French atomic energy commission)

CEFR: China Experimental Fast Reactor

CFC: Close Fuel Cycle

CIAE: China Institute of Atomic Energy

Cigeo: Centre Industriel de stockage Géologique (French underground waste facility)

CLI: Commission local d'information (local commission delivering information to stakeholders)

CNE: Commission Nationale d'Evaluation (National Evaluation Commission of the waste strategy and R&D)

CNNC: China National Nuclear Corporation

CNPE: China Nuclear Power Engineering Corporation

CSA: Centre de Stockage de l'Aube (Low activity storage – Aube Department)

CSM: Centre de Stockage de la Manche (Low activity storage – Manche Department)

CSO: Chief Security Officer

CSP: Concentrating Solar Power

DBA: Design Basis Accident

DCH: Direct Containment Heating

DEC: Design Extension Conditions

DOE: Department of Energy, USA

EDF: Electricité de France (French Utility)

EDMG: Extensive Damage Mitigation Guideline

EPO: Environmental Permanent Observatory

EPR: European Pressurized Water Reactor

EPRI: Electric Power Research Institute

ESF: Engineered Safe Features

EU: European Union

FARN: Force d’action rapide (the fast-acting nuclear force)

FR: Fast Neutron Reactors

GCR: Gas Cooled Reactor

Gen-II, Gen-III, Gen-IV refer to the second, third and fourth Generations of nuclear reactors presently operated or under development. The first generation were prototypes, which are now decommissioned

GFR: Gas Cooled Fast Reactor

GHG: Greenhouse gas

GIAG: Severe Accident Intervention Guide

GIF: Generation-IV International Forum

GSG: General Safety Guide

GWa or GWy: Energy produced by one GW during one full year

HBRA: High Background Radiation Area

HL-LLW: High level Long-lived waste

HLW: High Level Waste

HPCM: High Pressure Core Melt

HPR1000: Advanced Pressurized Water Reactor developed in China (also named Hualong One)

HWR: Heavy Water Reactor

IAEA: International Atomic Energy Agency

I&C: Instrumentation and Control

ICRP: International Commission on Radio Protection

ICPE: Installation Classée pour l'Environnement (Facility regulated as sensitive to the environment)

IEA: International Energy Agency

ILW-LL: Intermediate Level-Long Lived Waste

INES: International Nuclear Event Scale System

IRSN: Institut de radioprotection et sûreté nucléaire (French Technical Safety Organisation)

LBLOCA: Large Break Loss of Coolant Accident

LCA: Life Cycle Analyses

LFR: Lead-cooled Fast Reactor

LILW-SL: Low and Intermediate Level-Short Lived Waste

LLW: Low Level waste

LLW-LL: Low Level-Long Lived Waste

LOCA: Loss of Coolant Accident

LPCRP: Law on Prevention and Control of Radioactive Pollution

LWR: Light Water Reactor

MCCI: Molten Core Concrete Interaction

MEE: Ministry of Ecology and Environment

MOX: Mixed Uranium-Plutonium oxide

MSFR: Fast spectrum Molten Salt Reactor

MSR: Molten Salt Reactor

NIMBY: Not-In-My-Back-Yard

NISA: Nuclear and Industrial Safety Agency

NNSA: National Nuclear Safety Administration (China)

NPCSC: National People's Congress Standing Committee

NPP: Nuclear Power Plant

NRC: Nuclear Regulatory Commission (USA)

NRSC: Nuclear and Radiation Safety Center

OECD: Organization for Economic Co-operation and Development

OFC: Open Fuel Cycle

OTC: Once Through Cycle

PNGMDR: Plan National de Gestion des Matières et Déchets Radioactifs (Multi-annual plan for disposal of radioactive waste)

PRA: Probabilistic Risk Assessment

PRIS: Power Reactor Information System

PV: Photovoltaics

PWR: Pressurized Water Reactor

R&D: Research and Development

RDIDS: Risk-informed Defence In Depth System

SAMG: Severe Accident Management Guidelines

SBLOCA: Small Break Loss of Coolant Accident

SFR: Sodium-cooled Fast Reactor

SGTR: Steam Generator Tube Rupture

TBR: Technical Base Report

THMC: Thermal, Hydrogeological, Mechanical and Chemical

TMI: Three Mile Island, Pa, US

TTC: Twice Through Cycle

UNEP: United Nations Environment Program (UNEP)

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation

UOX: Uranium Oxide

URL: Underground Research Laboratory

PV: Photovoltaic energy or technology

VLLW: Very Low-Level Waste

VVLLW: Very, Very Low-Level Waste

WANO: World Association of Nuclear Operators

WENRA: Western European Nuclear Regulators' Association

WHO: World Health Organization

WOG: Westinghouse Owner Group

Authors

National Academy of Technologies of France

http://www.academie-technologies.fr/en/members

Alain BUGAT (*Study co-leader), Yves BAMBERGER,* Pascal COLOMBANI, Bernard ESTEVE, Gerard GRUNBLATT, Patrick LEDERMANN, Philippe PRADEL, Bruno REVELLIN-FALCOZ (*International coordinator)*, Bernard TARDIEU, Dominique VIGNON

Academy of Sciences, France

http://www.academie-sciences.fr/en/Members/members-of-the-academie-des-sciences.html

Edouard BREZIN, Sebastien CANDEL (*Study co-leader)*, Robert GUILLAUMONT

Chinese Academy of Engineering (CAE)

http://en.cae.cn/en/Member/Member/

ZHAO Xiangeng (*Study co-leader),* YE Qizhen (*Assistant co-leader*)

Chinese Working Team

LEI Zhengguang (CNNC)(*Team leader*), LIU Senlin (CIAE)(*General editor*)

JIANG Ziying (CIAE) (*PIC of Chapter 1*); CHEN Xiaoqiu (NSC) (*PIC of Chapter 2*), YANG Duanjie (NSC), ZHANG Yanqi (CIAE); LIU Xinhua (NSC) (*PIC of Chapter 3*), ZHANG Zhentao (CIAE), WEI Fangxin (NSC); CHEN Qiaoyan (CNPE) (*PIC of Chapter 4*), XUE Na (CNPE), YU Xinli (CNPE), WANG Hui (CNPE); CHAI Guohan (NSC) (*PIC of Chapter 5*), LI Jingjing (CIAE)

Technical and Support Team

Wolf GEHRISCH (NATF) (*Technical secretary)*, Jean-Yves CHAPRON (NASF) *(Technical secretary),*WANG Zhenhai (CAE),TIAN Qi (CAE), ZONG Yusheng(CAE),LIU Wei (CAE), PENG Xianke (CAE), XIE Guanghui (CAE), ZHANG Ning (CAE), WANG Haowen (CAE), ZHOU Yalin (CAE), XU Lin (CAE),), LI Yanjie (CAE), QIAN Tianlin (CNNC), LIU Zhonghua (CNNC), ZHOU Mi (CNNC), YU Hong (CIAE), YIN Zhonghong (CIAE), ZHANG Xupu (CIAE), XIA Yun (CIAE), XIA Mengdie (CIAE)*,* WANG Xinyan (CIAE)

Acknowledgments

The authors wish to thank Yves BRECHET (AS), Antoine DANCHIN (AS), Jean-Claude DUPLESSY (AS), Marc FONTECAVE (AS), Guy LAVAL (AS), Olivier PIRONNEAU (AS), Jean SALENÇON (AS) ; Jean FRÊNE (AT), President of the Reviewing Committee and all members of this Committee, Pierre LAMICQ (AT), Bernard PAYEN (AT), Pierre TOULHOAT (AT) for their careful reading of the initial version of this report and for their many helpful comments.

The authors would also like to express their gratitude to DU Xiangwan (CAE), PAN Ziqiang (CAE), XU Mi (CAE), CHEN Niannian (CAE), LI Guanxing (CAE), YU Junchong (CAE), Hou Lian (CAE), NIU Xinqiang (CAE), DENG Jianjun (CAE), ZHANG Huazhu (CNEA), CHENG Huiping (CNNC), ZHANG Jintao (CNNC), MAO Yawei (CNPE), HUO Xiaodong (CNPE), REN Xiaona (CIRP), ZHOU Lianquan (CIAE), YANG Yong (CIAE), REN Yi (CIAE), CHEN Yanxin (CIAE) for providing valuable comments and remarks.

Biographical notes (More information to be found on Academies Web Sites)

National Academy of Technologies of France

Alain BUGAT (†) was Honorary President of the Academy of Technologies. He was former Head of the Commissariat à l'Énergie Atomique (CEA) and co-founder and President of NUCADVISOR

Yves BAMBERGER is Member of the Academy of Technologies and former Director of Research and Development at EDF

Pascal COLOMBANI is Member of the Academy of Technologies. He is Senior Advisor of A.T. Kearney Paris, and member of the Board of TechnipFMC, former Head of the Commissariat à l'Énergie Atomique (CEA), former Chairman of the Supervisory Board of AREVA

Bernard ESTEVE is Member of the Academy of Technologies and former Nuclear Counsellor for Total. He is currently President of B.E. Consult

Gerard GRUNBLATT is Member of the Academy of Technologies. He is former Head of superconductivity applications at ALSTOM

Patrick LEDERMANN is Member of the Academy of Technologies and former Managing Director of ALSTOM India limited

Philippe PRADEL is Member of the Academy of Technologies and Vice-President of ENGIE Nucléaire, France

Bruno REVELLIN-FALCOZ is Member and Honorary President of the Academy of Technologies. He is former Vice-President Director-General of Dassault Aviation

Bernard TARDIEU is Member of the Academy of Technologies and Honorary President of COYNE and BELLIER

Dominique VIGNON is Member of the Academy of Technologies and of the World Nuclear Academy, former Chairman and Chief Executive Officer of Framatome, former member of the International Safety Advisory Group to the IAEA and Past President of the French Nuclear Energy Society

French Academy of sciences

Sébastien CANDEL is past-President of the French Academy of sciences. He is a specialist in Engineering Sciences, University Professor Emeritus at Centrale Supélec, University Paris-Saclay. He has recently been appointed Chairman of the Scientific council of EDF.

Edouard BREZIN is Member and Past President of the French Academy of sciences. He is a specialist in Statistical and Particle Physics and Professor Emeritus at Ecole Normale Supérieure.

Robert GUILLAUMONT is Member of the French Academy of sciences. He is a specialist of Radiochemistry, Honorary Professor at the University of Orsay and Member of the « Commission Nationale d'Evaluation ».

Chinese Academy of Engineering

ZHAO Xiangeng is Member of CAE and Former president of CAEP and vice president of CAE. He is member of the standing committee of National People's Congress (NPC) of P.R. China and Vice chairman of the environment and resources protection committee of NPC

YE Quizhen is Member of the CAE. He is a specialist in the field of Nuclear Reactor and Nuclear Power Generation Technology. He was Chief Design Engineer of the Qinshan Nuclear Power Project

Chinese working team

Members of this team work for CNNC (China National Nuclear Corporation), NRSC (Nuclear and Radiation Safety Center), CNPE (China Nuclear Power Engineering Corporation), CIAE (China Institute of Atomic Energy)

Back cover

Mid-2017, and in the wake of COP21 and COP22 committing to a significant worldwide reduction of greenhouse gas emissions, the three Academies (Chinese Academy of Engineering, the French Academy of technologies and the French Academy of sciences) presented a comprehensive review of the potential role nuclear energy could play to progressively replace fossil fuels. Its merits as a reliable and dispatchable source of electricity were outlined, and recommendations were made in the field of project management, education and training, research and technological development, to further improve the acceptance of this technology.

However potential environmental consequences of nuclear energy are a strong concern for the public, which the Academies decided to specifically address in this second report. It considers a Life-Cycle Assessment of nuclear energy including uranium mining, reactor operation dismantling, accident consequences.

It is found that radiological consequences of nuclear operation, including the fuel cycle, are a small fraction of natural radiation, most of the stemming from uranium mining. Recommendations are made to further reduce these consequences. A comparison of the environmental foot print of nuclear generation compared to other sources is made, which shows the merits of nuclear with respect to land, or material used. A specific emphasis is made to water withdrawal and consumptions which may be an issue at some river sites but can be alleviated with a proper design of the cooling systems.

Waste management is comprehensively discussed. The present waste management policies based on the latest technologies for waste confinement, including disposal of long-lived highly radioactive waste in deep underground repositories, are analysed. Safety analysis are summarized which show that even after thousands or millions of years, the possible additional radioactivity from the potential migration of radionuclides through the confinement barriers including the repositories themselves, the additional radioactivity will remain below about 1% of natural background radiation. Some further developments are however recommended.

Several accidents with core melt which happened at several sites in the world (Three Miles Island, Chernobyl, Fukushima) raise understandable questions from the public. Lessons learned from these accidents are presented. Safety requirements applicable to new facilities are presented. They include prevention and mitigation features to drastically reduce external consequences beyond site boundary and avoid the need for long-term evacuation of population. It is recommended that existing facilities be upgraded to meet these requirements as closely as possible.

Improvements in safety analysis are presented, which include an extension of the traditional defence in depth to consider severe accidents with core melt both in the design and operation of reactors, to meet the “no-evacuation” goal even in the most unlikely scenarios.

Public acceptance of nuclear energy is discussed. Although it is a country specific issue, it is outlined that a transparent information to a well-educated public is paramount.

This report reflects positions of the three Academies acting as independent bodies, and shall not be construed as positions of industrial actors in the NPPs field or positions of either the French or Chinese governments.