Joint recommendations for the nuclear energy future

Released by the three Academies

Chinese Academy of Engineering
National Academy of Technologies of France
French Academy of Sciences

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Foreword

In the later part of the year 2016 the Chinese Academy of Engineering and the French Academies (National Academy of Technologies of France and French Academy of Sciences) set up a joint Franco-Chinese study group. Its general objective was to prepare a common position paper to distil policies and technology options, including safety and waste management, for making nuclear power generation a component of future energy mixes in countries with the appropriate potential for implementing this energy.

Context

Regarding overall civil nuclear activities, France and Russia may, at this time, be considered the leading countries in the world. However, China is making impressive breakthroughs in setting up nuclear power plants and appears as one of the potential leaders in the future.

Both France and China are convinced that nuclear energy can effectively contribute to the reduction of fossil fuel consumption and consequently to a notable reduction in emissions of CO_2 in the atmosphere. They face similar issues with respect to the role of the foreseen new nuclear technologies and public acceptance. In the context of COP21, targeted at a “low-carbon” world, the three academies have agreed upon a common message addressed to other countries regarding nuclear issues, including mainly scientific, technological, industrial but also economical and societal aspects.

This common message is the outcome of the joint Franco-Chinese study group.

Content and target audience

This report covers many aspects of nuclear energy and attempts to provide an objective overview of many aspects (position of nuclear energy in the future energy mix, benefits, strengths and weak points of nuclear energy, research and development perspectives, technology and safety, engineering etc.) and of societal issues (education, training, risk perception, public awareness etc.) but it is admittedly far from being exhaustive. For example, the important question of the life-time of nuclear power plants and the possible extension of their operation as well as questions pertaining to power plant decommissioning, as well as economic aspects of nuclear energy are not addressed. The report also does not attempt to deal comparatively with all the methods of energy production and with their respective merits and weaknesses.

Although the expert group is attentive to the problems encountered in some current nuclear power plant projects, these issues are not specifically considered in the present study and no attempt is made to examine these difficulties. It is considered that they will be overcome and that this joint report should focus on methods and tools that could improve the development and completion of future projects in particular those relying on digitalisation. There is also no intention whatsoever to interfere with on-going business, governance, financial issues or commercial discussions.

The study is aimed at developing common declarations between the partner academies, which are documented in the present report, whereas the visions and dynamics in China and France are not strictly the same.

Furthermore, this report is not primarily aimed at the general public. The target audience of the study is the "professional" public of countries considering the development of nuclear energy in their energy mix, and in particular the world nuclear community at the annual meeting of the IAEA. On certain issues, the expert group is conscious that more work needs to be done to improve the current state of the matter. This is true in particular for societal issues, where much more is required to inform the public about energy issues and about the extraordinary difficulties that will be encountered when trying to replace fossil fuels, finding other, essentially carbon free, sources of energy that can be mobilized and assuring a stable production responding to demand. To get a better understanding of public concerns will require further efforts, a point that is underlined but that will still need innovative approaches. Progress in this area will depend on the public’s involvement in the discussions about these issues and their solutions. This debate goes, however, beyond the purpose of the present report and will need additional evidence-based experience and further technical innovations.

Presentation at the September 2017 IAEA meeting in Vienna

The three partners are bringing their joint work to a conclusion when exposing their common views to the world nuclear community, including policy makers, at a side event during the annual General Assembly of the International Atomic Energy Agency (IAEA), scheduled on September 20, 2017. The presentation will highlight the present partnership between the Chinese and French academies and it is hoped that it will allow putting into perspective some of the difficulties that are encountered in current Western projects by providing a broader, more long-term viewpoint.

Synthesis and recommendations

France and China are countries with large and lasting nuclear power plant capacities. France has a long experience in operating nuclear reactors and all the facilities of a closed fuel cycle. China is the country where the increase in nuclear power is foreseen to be the largest in the world for the coming years. Both countries are engaged in an electrical transition phase to optimise their "energy mix" and both have Research and development (R&D) programmes to prepare the next generation of nuclear systems.

In line with their interest in sustainable energies and acting as independent bodies, the three Academies (Chinese Academy of Engineering, French Academy of Technologies and French Academy of Sciences) have analysed some issues and challenges raised by nuclear energy. They came to the following considerations and recommendations.

1. Decarbonising the energy system raises difficult issues that should not be underestimated. It is generally considered that this will require an increase in the contribution of the electric vector (terrestrial mobility, industry, urban uses, etc.). Nuclear energy constitutes one of the most realistic options for supplying electrical energy. The latest generation of nuclear power plants (NPPs) constitutes a highly realistic option for supplying electrical energy in a safe, efficient and clean way and simultaneously solving environmental and climate change problems. They can reliably provide dispatchable electricity and complement renewable energy sources (like wind or solar photovoltaic) that are mostly intermittent with a fluctuating production independently of the demand and are not easy to dispatch to respond to demand.

2. As nuclear energy is highly concentrated in large NPPs, it has a smaller footprint (requires a smaller amount of land) in comparison with more dilute energy sources. NPPs are capable of delivering the energy that is needed by the present megacities and by those that will arise in the future. Nuclear energy uses uranium, which is an abundant resource, without any cartel manipulating its availability on the market, thus ensuring security of supply.

    - In the foreseeable future, there will be no solutions able to economically store large quantities of electricity. Other means of compensating for intermittent productions are therefore necessary to ensure that even more fluctuating demand can be met with large response reactivity and deployment, and thus satisfied at all times; however, the goal of decarbonisation would be missed if fossil fuels were to provide the necessary back-up.
    - There are technical and economic limits to the share of intermittent energy in large electric networks (network–stability, recovery plans in case of large scale black-outs, etc.)

3. Nuclear power is still a relatively young technology in continuous progress

    - Major accidents have been analysed; return of experience and lessons learned have led to significant changes in the design and operation of reactors.

- The latest generation of reactors (Gen-III) that is now under construction has been designed to make sure that there will be essentially no significant radiological consequences beyond the boundary of the nuclear site, even in case of a severe accident with fusion of the reactor core.

4. Other paths of progress are anticipated and their development should be encouraged:

   - Gen-IV reactors, including Sodium-cooled Fast Reactors (SFRs), which have the capacity to make full use of uranium and allow multi-recycling of spent fuel and transmutation of very long-lived radioactive elements present in radioactive waste.
   - Small Modular Reactors (SMRs) that are adapted to small electric networks. Their modular construction allows to alleviate the complexity of large construction sites.

5. Accordingly, it is important to maintain ongoing R&D efforts targeted at reducing cost and risk, which should include:

   - Sharing of human resources and research infrastructures.
   - Consolidating and developing education and training programmes for designing, constructing and operating nuclear reactors at all levels.

6. The proper development of nuclear energy requires competent and independent safety authorities

   - They can rely on Technical Support Organisations (TSOs), which equally must be competent and independent.
   - There must be a technical dialogue between these authorities, operators, and vendors to ensure that safety requirements take into account the evolution of scientific and technical knowledge, and are based on an objective assessment of risks.
   - The convergence of safety requirements among State regulators is a prerequisite for the standardisation of reactor models. This standardisation would in itself improve safety. In the present situation, safety authorities differ in the definition of the level of safety required, some implementing a cost-benefit approach, which is rejected by others: harmonisation is essential. The Academies recommend a «Risk informed» approach which balances new safety requirements with their benefits.

7. The main challenges of the nuclear industry are (1) waste management, (2) control of costs, and financing of new projects, and (3) conveying the message that security improvements of nuclear operations have attained such a high level that social acceptance should follow suite.

   7.1. Low and medium level waste management is being implemented industrially with proven and accepted solutions. High-Level Long-Lived Waste (HL-LLW) conditioning technologies (with or without reprocessing of the spent fuel) exist. The scientific and technical community has not identified any major obstacle for the disposal of the conditioned HL-LLW in carefully selected deep geological layers. The characterisation of disposal sites needs to be pursued.

   7.2. The nuclear industry must intensify its efforts to control the cost and duration of nuclear projects.

- A non-complacent analysis of the difficulties faced by some recent projects must be undertaken by the owners and vendors; the Academies recommend that the conclusions of these analyses be made public.

- The Academies recommend that the nuclear industry accelerate the implementation of digital technologies, the use of which proves very beneficial in other industries. These technologies have helped to significantly reduce project costs and delays, while improving quality; three areas are of special importance:
  - ✓ Use and further development of simulation models and their coupling with design
  - ✓ Digitalisation of the instrumentation and control systems
  - ✓ Use of a digital platform (PLM - Product Lifecycle Management) with a unique data base encompassing 3D-design, construction, operation and lifecycle management.

- The introduction of these technologies requires cooperation with the safety authorities, and harmonisation of regulations, particularly in the area of cyber security.

- Nuclear power is an industry with long lifecycles and requires significant up-front investment. It is important for it to receive adequate funding by international investment banks

7.3. The nuclear industry cannot develop if it is not socially accepted, and supported by Governments:

- Safety aspects must be fully addressed and current and past improvements of nuclear operations clearly explained to the public.
- Since the energy debate addresses complex technical and economic matters it can only be handled with well-structured information and reliable data.
- The need for full and objective information is paramount. Non-governmental associations must be listened to, but so must operators, designers, safety authorities and experts in nuclear engineering and in economy. Governments should request expert opinions, including the expertise of their national Academies.

8. Nuclear industry could be shared with emerging countries through international and bilateral cooperation. Countries that have built a nuclear infrastructure, such as China and France, should help politically stable emerging countries to develop nuclear energy in a safe and effective way. In parallel, the nuclear community should foster this development by making progress in two directions:

- Standardisation and stabilisation of the licensing and regulatory processes
- Generalisation of long-term electric power purchase agreements (PPAs), with governmental guarantees.

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Section 1. Introduction: the necessity of nuclear power in the future energy mix and challenges to overcome

As a source of social and economic development, energy is essential to human life, health and welfare. Meeting world energy demand, and reducing global emissions of greenhouse gases (GHG) raises fundamental challenges for the future of the planet.

Since the 1950s, the peaceful use of nuclear power has become one possible option for providing energy without resorting to fossil fuels like coal, oil or gas. In recent years nuclear energy has also been considered as a sustainable and reliable low-carbon source of energy, that guarantees energy supply, allowing global economic development while reducing emissions of greenhouse gases. Although nuclear energy has become one of the three pillars of global electricity supply its development traverses a critical period. The Fukushima nuclear accident in Japan has had an enormous impact, raising public concerns about safety. This and some other reasons have led a few countries to abandon nuclear energy and terminate operation of existing nuclear plants. Return of experience and lessons learnt from the Fukushima accident have led to important safety enhancement plans of existing nuclear reactors and to further improvements of future installations so that the development of nuclear energy is being continued in many countries.

To obtain a noticeable reduction in greenhouse gas emissions in relation with climate change, diminish pollutant emissions of nitric oxides, unburned hydrocarbons and particulates, improve the atmospheric environment in the medium and long term, and achieve a sustainable development of human beings, requires a global energy system that will better respect the environment and that will use minimal amounts of fossil fuels. In the present situation where much of the electrical energy production is based on fossil fuels and more specifically on coal, nuclear power constitutes one of the most realistic options for supplying energy in a safe, efficient and clean way and simultaneously solving environmental and climate change problems.

Because it is a stable source of energy, it can reliably provide base load electricity and complements renewable energy sources like wind or solar PV that are mostly intermittent and are not easy to dispatch to respond to demand. In this respect, it is generally considered and supported by recent experience that the total share of intermittent renewable energies in the electricity mix in most countries, cannot exceed 30 to 40% without inducing unacceptable costs of electricity and leading to an increase in greenhouse gas emissions or a risk to the security of supply of electricity. The main cause of this limitation is the unavailability of electric energy storage, for which there is today no sign of a coming breakthrough. As it uses large concentrated power plants and requires lesser amounts of land in comparison with more dilute energy sources, it is capable of delivering the energy needed by the present megacities and by those that will arise in the future.

However, the development of nuclear power still raises many challenges and issues with regard to safety, management of radioactive waste, development and deployment of advanced nuclear energy systems, economics, public acceptance, etc. As two of the main countries with large capacities of nuclear power plants (NPPs), both China and France attach great importance to the peaceful use of nuclear energy in the world, and have the responsibility and willingness to help emerging nations in their development of NPPs and in their wish to resolve the challenges they will face.

In the continuation of COP21 and COP22 aimed at 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) believe that their initiative to shed light on some of the complex issues related to nuclear electricity generation could send a strong and valuable message to other countries' academies, decision makers and society in general.

The present report reflects positions of the three academies acting as independent bodies, and shall not be construed as positions of industrial actors in the nuclear power plant field or positions of either the French or Chinese governments.

In this report, the contributing academies aim at outlining the history and perspectives of nuclear energy, and address the key issues to be considered in order to make nuclear energy even safer and affordable for the benefit of developed and emerging countries.

Although this report touches on many issues, it is not intended to be comprehensive. It synthesises reflections and discussions carried out over a period of six months.

The present report comprises a set of seventeen sections and a synthesis. The next two sections (2 and 3) give a brief account of the history, problems and challenges of nuclear development and address issues concerning the deployment of Gen-III NPPs. The next three sections (4 to 6) deal with scientific aspects including promises and challenges of future reactor designs and specifically consider the Gen-IV situation and new small modular reactor (SMR) concepts. Technological issues are addressed in sections 7, 8 and 9 and include the safety issues and the need for Technology Support Organisations (TSO), advances and challenges in digitalisation and in novel design tools. The importance of nuclear research, facilities and infrastructures is underlined in section 9.

Section 10 is concerned with the question of education and training of manpower. One important aspect is that of attracting young graduates from higher education in the nuclear industry. Another is the training of employees in the utilities to give them the proper scientific background and the culture of safety management. In that respect, the role of simulators is underlined.

The next two sections (11-12) deal with engineering issues including that of managing nuclear projects, questions of handling safety requirements while controlling costs and complexity. Section 13 considers the pertinence of international support of nuclear projects in emerging countries.

The last four sections (14-17) deal with societal issues. An assessment is provided of the impact of global nuclear activities on human health during the last fifty years. Since safety is a central issue in the operation of nuclear power plants, it is necessary to examine (section 15) the perception of risk and its relation with real hazards. Section 16 underlines the need to improve public awareness and considers the governance needed for that purpose. The reasoning is pursued in section 17 that is devoted to the organisation and roles of the different stakeholders. This section also discusses the need to improve public understanding to limit the risks of increasing regulations that would complicate the development and operation of nuclear facilities.

Section 2. History, current situation, problems and challenges of nuclear development

Recommendations

Some major recommendations for allowing nuclear energy to play an effective role as source of low- carbon energy and as a part of the future energy mix in various countries can be made at this stage:

- Industry should make great efforts to keep nuclear projects in-line with their planned schedule and costs if public confidence in the capacity of nuclear players to master complexity is to be restored. To reach this objective, it seems necessary to explicitly understand the reasons of the poor performance of the recent construction of several Gen-III+ nuclear power plants in some "Western" countries, while at the same time identical construction in China is progressing according to schedule. This analysis should involve the stakeholders of these projects: owners, regulatory organisations, designers, engineering teams, contractors and subcontractors.
- Efforts should be made to bring SMR designs to the market as soon as possible to enhance the vision of a more flexible nuclear capacity that can also be used in regions with limited capacity grids or in emerging countries.
- Mechanisms for financing nuclear projects need to be re-examined jointly by governments of nuclear countries and by financial market players.

Civil nuclear energy represents one of the greatest technological challenges mankind has ever had to face because it features an unequalled number of facets all requiring a high level of knowledge and demanding approaches such as tolerant failure modes: safety, design, construction, commissioning, project management, legal and regulatory issues, waste management and decommissioning, financing, security and non-proliferation issues, health physics, environmental impacts, public acceptance, etc.

The complexity of nuclear engineering did not stop increasing since its origin in the 1940s and 1950s when science and technology, and the industrial capacity to build the designed « objects » were the only challenges to overcome.

Since that time, the mainstream of civil nuclear energy has progressed through a steady evolution of the technological reactor designs and of other supporting nuclear facilities: research reactors, laboratories, fresh fuel manufacturing and reprocessing facilities. Three generations of nuclear power plants have appeared successively with some overlapping without any major difficulty regarding the designs, each of them increasing safety by a factor of at least 10.

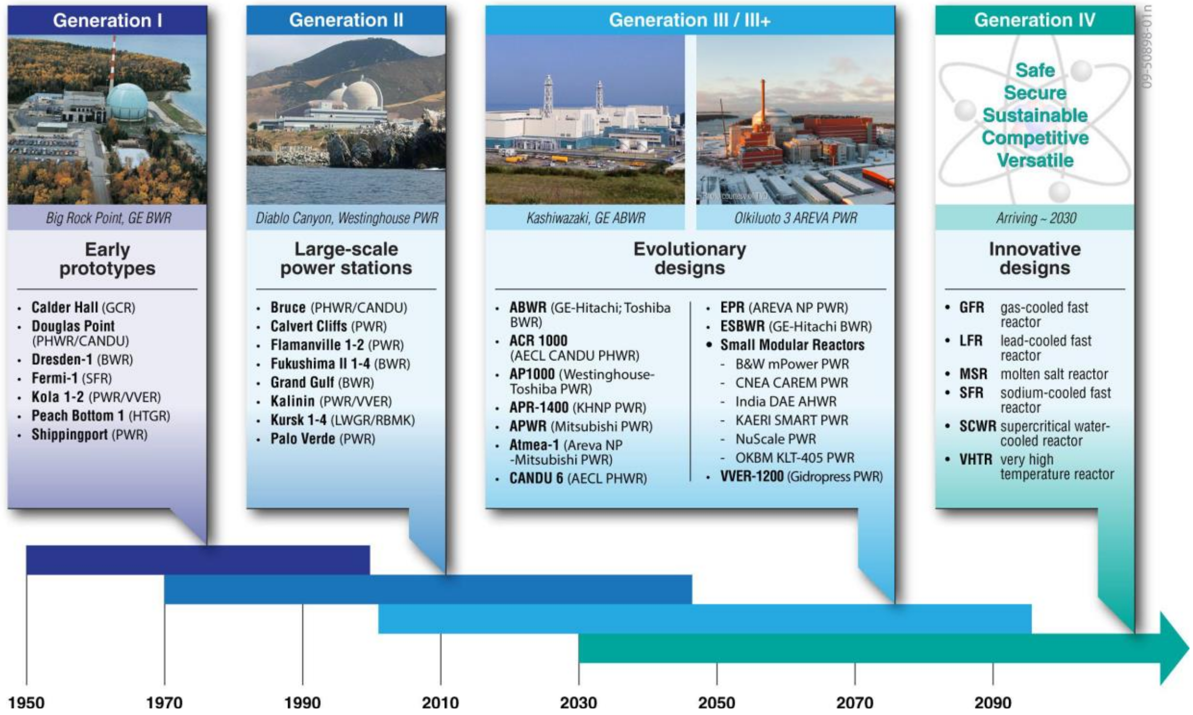

Figure 1. The successive generations of nuclear power plants. Reproduced from the Generation-IV International Forum (www.gen-4.org) - Not shown in this diagram are the following Generation-III/III+ Chinese Reactors: HPR1000 CNNC PWR and CAP1400 SNPTC PWR, and the ACP100 CNNC SMR PWR.

As a result of lessons learned from three major nuclear accidents (TMI, Chernobyl, Fukushima) and the 9-11 terrorist attacks, Generation III+ must satisfy high expectations and standards on nuclear and radiation safety. This has led to cost increases that have reduced the competitiveness of nuclear energy.

The fourth generation is already under preparation and its deployment is expected after 2030. It specifically addresses the economics of fissile nuclear materials and the question of closing the fuel cycle.

In Western countries, the period from about 2003 to 2016 of the above-mentioned mainstream has been preceded by a kind of freezing of the nuclear sector, following the Chernobyl accident, when virtually no new construction project was launched, accompanied by a limited renewal of technical staff. This has not been without serious consequences for the development of generation-III and -III+ projects that combine notably enhanced safety features with an increased safety design and licensing complexity.

Fortunately, two factors came into play to mitigate this difficult conjunction:

- Investments made by some vendors geared at modularity of construction and reactivation of reliable supply chains,
- The arrival of new clients/vendors such as South Korea and China having a huge potential of a trained and skilled nuclear workforce with « fresh eyes » and enthusiasm.

Inside the mainstream, decade after decade, the pressurised water reactors have commercially outperformed their competitors, first marginalising the heavy water reactors and then, after the Fukushima accident, the boiling water reactors, despite specific strengths of these two designs.

Much like the mainstream reactors, the design and construction of fuel cycle facilities and more generally the front-end and back-end industries did not, until today, experience any major difficulty and have not seen fundamental changes in their operation, except for the introduction of centrifugation technologies in enrichment facilities. One must also mention that industrial processes and technologies for partitioning /transmuting major actinides but also minor actinides have been validated at the R&D level; their deployment at industrial scale is only considered in conjunction with generation-IV dedicated reactors or accelerator driven systems.

Current problems and challenges are mainly linked to the specific environment of nuclear projects. They can be summarised by a set of three issues, each one having serious and direct consequences slowing-down nuclear development and strongly interacting with each other, making it impossible to solve one without dealing with the other two! These issues are:

- Diminishing public confidence, nearly everywhere in the world, for large projects but especially nuclear ones, and consequently a demand for tougher safety requirements
- A trend in many countries to ever increasing complexity of licensing and control processes
- A growing difficulty to find public and private financing for initial nuclear investments, due to increasing costs and increasingly prudent banking rules

With respect to these issues, some decision-makers, especially in Europe, consider that only government-owned vendors or utilities are able to handle nuclear activities. One might wonder if this is the best configuration for finding solutions for the transition to a de-carbonated energy system or if a competition between private actors might not yield a more optimal result in terms of safety and cost.

A crucial technological issue remaining partially pending is the long-term management of high-level long-lived nuclear waste. This has been a subject of considerable attention in various countries. On the basis of research carried out in France within the framework of two laws (1991 and 2006), it is believed that solutions exist that should help reducing the amount of waste. Such solutions stipulate the construction and operation of fast neutrons reactors, which could transmute minor actinides into fission products, the lifetime of which is about 300 years; far less than those of minor actinides. It is thus possible to be more optimistic about future nuclear waste, once reprocessed. However, at this point in time the most realistic solution is to dispose of existing waste or spent fuel in deep geological repositories. The few examples of such repositories under construction raise only few technological problems and those that remain are in the process of being resolved, but they also give rise to issues of public acceptance that need considerable attention.

A key to improving future public confidence in nuclear power will be to demonstrate the feasibility of decommissioning generation-I and -II nuclear plants and other nuclear facilities in an increasing number of countries; increasing competencies on the technological and safety levels are certainly required, but even more important for public confidence will be the construction of nuclear projects on-time and within foreseen budgets.

Conclusions

It is of foremost importance to explain to decision-makers and to the public that nuclear energy effectively contributes to the limitation of global warming and that this is one of the most effective ways to provide abundant, safe and reliable base load electricity with demonstrated results.

It is similarly important to compare safety levels reached by nuclear activities with other human activities that imply a specific level of risk and explain how, in the nuclear domain, that risk has been reduced to a very large extent. Safety engineering with generation-III and post-Fukushima enhanced generation-II nuclear power plants has eliminated the need for countermeasures in case of severe accidents. In other words, these reactors will not entail major radiological consequences in case of severe accidents as all possible discharges will be contained within the reactor building.

It is worth recalling that most western generation-II reactors will come to the end of their life somewhere before mid-century and that this will require a renewal of the nuclear power plant fleet.

Section 3. The feasibility and challenge for near and mid-term deployment of GEN-III nuclear power plants

Recommendations

The economic competitiveness of GEN-III/III+ power plants must be further enhanced through optimising reactor designs including digitalisation, modular and standardised construction, as well as innovative financial solutions and more supportive regulations. The French standardisation strategy of Gen-II+ reactors contributes to safety enhancement while reducing the construction cost. China has made great strides in digitalisation of design and engineering and in nuclear project management. Sharing the experience gained by these two countries would be beneficial for the future nuclear industry worldwide.

The current nuclear reactors connected to the grid in the world mainly belong to 2nd generation (Gen-II) and improved 2nd generation (Gen-II+) reactors. Their basic design was completed before the TMI-2 accident occurred; however, most of them were back-fitted with additional safety features, taking into account lessons learned from this accident (reactor safety valves; man-machine interface, etc.) and also from the Chernobyl accident (In-containment Hydrogen Recombiners; Filtered Containment Venting systems). Before and after the Fukushima accident, Gen-II reactors were also back-fitted to take into account Station blackout (SBO) with additional passive or active systems, and loss of Ultimate Heat sink. It is worth noting that those back-fits were essentially not implemented in Japan; on the other hand, when back-fitted, these second-generation reactors can be qualified as Gen-II+, and their safety level can be considered to be close to that obtained by later designs.

In the early 1990s, starting in Germany and France, safety authorities required that newly built reactors should meet the following safety objectives with respect to internal events:

- Accidents with core melt that would lead to early or large releases of radioactivity had to be practically eliminated.
- For severe accidents where the possibility of core melt could not be totally eliminated, design provisions had to be taken so that only limited protective measures in area and time were 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 provision had to be made that sufficient time was available to implement these measures.
- INSAG, a high-level advisory group to the IAEA general director, recommended fairly similar safety objectives in its INSAG-12 document (1999), well before the Fukushima accident[1]. Although IAEA Fundamental Safety Principles[2]did not include such requirements, they became part of the IAEA Safety Standard "Safety of Nuclear Power

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[1] INSAG - Basic Safety Principles for Nuclear Power Plants – A 1999 revision to INSAG-3 Rev. 1 (1975)

[2] IAEA – Fundamental Safety Principles – Safety fundamentals – SF-1 - 2006

Plants: Design[3], in line with WENRA safety objectives[4].

With respect to external events, regulators now tend to require consideration of an intentional airplane crash[5], with the need to demonstrate that safe shutdown can be achieved. Also, beyond design external hazards (earthquake, flooding), have to be considered, in order to demonstrate that no cliff edge effect would greatly impair nuclear safety.

In addition to safety improvements back-fitted in GEN-II+ reactors, Gen-III+ reactors include devices to collect the corium in the reactor cavity (core catcher), or systems to prevent melting of the reactor pressure vessel, In-Containment (or In-Reactor) water storage capacity (IRWST) to cool the molten core and a set of backup power sources. Mitigation of an airplane crash such as that corresponding to the September 11, 2001 attack requires a double containment building with adequate cooling systems.

The combination of all these features leads to reducing the frequency of a high-pressure core melt by a factor far greater than ten with respect to Gen-II+ reactors and to essentially control all safety functions in case of an accident. Human error is reduced by implementation of a long-term operator intervention strategy. As a result, radiological consequences of a severe accident are drastically diminished, so that the objectives of “no permanent relocation, no need for emergency evacuation outside the immediate vicinity of the plant, limited sheltering, no long-term restrictions in food consumption” are achieved.

From an operational standpoint, the neutron flux reaching the reactor vessel is reduced, which will allow substantial life extension. Finally, collective dose to workers is decreased by a convenient choice of materials and equipment, easy to clean and maintain. Gen-III reactor nuclear waste should be substantially reduced compared to Gen-II per TWh.

American and European Utilities have translated regulatory requirements into more practical specifications (URD in the USA, and EUR in Europe). Several designs have been developed that comply with these requirements such as AP600/1000, EPR, VVER1000/1200, HPR1000, CAP1400, APR1400, APWR1500, ABWR, ESBWR, etc.

Reactors meeting these requirements and qualified as GEN-III+ are ready for industrial implementation. Two ABWR units have been under commercial operation since 1996. There are eight AP1000 units under construction or commissioning in China and the USA with the leading project in Sanmen, China; four EPR units in Finland, France, and China, the first of which in Taishan is planned for operation by the end of 2017. China also started construction in 2015 of four HPR1000 units, which are scheduled to begin operating in 2020. The GEN-III+ would be the main fleet for near and mid-term massive deployment of nuclear power.

Due to the enhancement of safety and complexity of the first engineering implementations, nearly all the GEN-III demonstration projects were delayed or postponed with over-budget and financial pressure due to increased cost, except so far, for the HPR1000.

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[3] IAEA - Safety of Nuclear Power Plants: Design - Specific Safety Requirements - SSR-2/1 (Rev. 1) - 2016

[4] WENRA – Western European Nuclear Regulators’ Association - Report on Safety of new NPP designs (2013)

[5] WENRA – id.

Due to significant efforts devoted to safety, the economic competitiveness of GEN-III/III+ power plants must be further enhanced by optimisation of reactor design, utilisation of modern information technology, bulk procurement, modular and standardised construction, global supply chain partnerships, and innovative financial solutions along with more supportive regulations and supervision to minimise the construction duration, improve the thermal efficiency and the reactor utilisation, and consequently the safety and competitiveness of nuclear power.

The French standardisation strategy of Gen-II+ reactors features some important contributions to safety enhancement while reducing the construction cost. This strategy could also be used to reduce Gen-III cost and maintain electro-nuclear power as the most competitive of all sources of base load electricity. A plan to progressively replace part of the French fleet with Gen-III reactors is under consideration.

China has made a great plan to develop nuclear power, and along with the 30-year continuous construction of NPPs, a strong infrastructure has been set up, including development of competencies in R&D, design and engineering, manufacture, construction and erection, project management, commissioning and operation capacity. On this basis, China envisages strategic cooperation with related parties.

Conclusions

Most nuclear reactors connected to the grid are of the second-generation type (Gen-II) with a high percentage improved to Gen-II+, i.e. back-fitted for satisfying more stringent safety requirements. Gen-III+ reactors include devices for collecting the corium in case of core melt and other safety features, which reduce the frequency of high-pressure core melt by a factor larger than 10. Human error tolerance is increased through an operator intervention strategy leaving sufficient time for action so that the population in the wider vicinity of the plant need not be evacuated or worry about food consumption. Similar progress has been made at the front of neutron flux to the reactor vessel and reduction of exposure to radiation of workers. Such reactors are now ready for industrial implementation. However, such safety enhancements have a price and have led to substantial delays and budget overruns and loss of competitiveness.

Section 4. Promises and challenges of new and innovative future reactor designs, the 4th generation reactors

Recommendations

In order to be ready in time to launch commercial Gen-IV Sodium-Cooled Fast Reactors (SFRs) and Very High Temperature Reactors (VHTR), the Academies recommend constructing and operating, during the coming decades, Gen-IV technological demonstrators of such reactors, including the facilities for the associated fuel cycle. Launching and operating SFR requires reprocessing of spent fuel to multi-recycle plutonium and uranium. Thus, special emphasis should be given to SFR fuel cycle. According to present technologies, SFR are a promising technology to provide electricity on the basis of fissile/fertile nuclear material accumulated since the beginning of the hitherto fission-based nuclear energy. VHTR have the potential to provide high temperature heat for multipurpose industrial use. According to the present national energy strategies, deployment of Gen-IV SFR and VHTR are expected after 2030.

A central issue in electronuclear energy is to extract the maximum amount of energy from nuclear fuel while at the same time maximising safety. To do this, one uses fissile and fertile isotopes of uranium (U) and plutonium (Pu). A fertile isotope such as ^{238}U gives fissile isotope such as ^{239}Pu by nuclear processes induced by thermal or fast neutrons.

Present situation

Today worldwide nuclear electricity is produced (with the exception of a few units) through thermal neutron reactor types (TNR) fuelled with natural U oxide enriched in ^{235}U (UOX fuel). The energy released from the fuel comes from ^{235}U (around 70 %) and ^{239}Pu fission, the latter isotope being produced in situ in the fuel from ^{238}U.

Some TNR reactors are partially fuelled with a mixed U-Pu oxide (MOX fuel). Plutonium is recovered from spent UOX fuel by reprocessing and U is the depleted uranium that remains after natural uranium has been enriched**.** The energy in MOX fuel originates from Pu fission (90%). Recycling plutonium from the UOX spent fuel saves consumption of natural uranium and diminishes SWU (Separation Working Unit) operation, but Pu can be recycled easily only once in appropriate TNRs.

A TNR does not use the total potential nuclear energy of natural uranium because nearly all the ^{238}U isotopes remain in the spent fuel. On the other hand, for safety reasons, the burn-up of fuel in TNR is limited to typically 50 GWd/t (GigaWatt day per ton) with a temperature of the coolant around 300°C.

The only way to fission ^{238}U and to transmute it into ^{239}Pu, with a good yield, is to use fast neutrons. Fast neutron reactors (FNR) are designed to take advantage of such neutron properties. The energy originates from the fission of all isotopes of U and Pu. In FNR the burn-up of MOX fuel can reach values of up to 140 GWd/t (or more) and the temperature of the coolant can reach 500 °C.

At this point in time, only a few FNR units are connected to the grid in Russia**.**

Major expected change

Fifteen years ago, the Generation-IV International Forum (GIF) initiated a joint research effort on the nuclear systems of the future. This has given rise to an active partnership between China, France, Korea, Japan, Russia, USA and the EU. The technical goals and related evaluation index were defined by GIF in six areas: sustainability, economics, safety and reliability, waste minimisation, proliferation resistance and physical protection. Six most promising nuclear systems were selected, two of them were Gas (helium) Cooled Reactors, another two were Liquid Metal (sodium and lead alloy) Cooled Reactors, one was Super-Critical Water-Cooled Reactor and the last one was a Molten Salt Cooled Reactor.

Among the previous selection, the advanced, MOX fuelled Sodium-cooled Fast Reactor (SFR), was considered to come closest to commercial status during this century by nearly all the GIF partners. The VHTR (Very High Temperature gas cooled Reactor) system is being actively developed by China, Japan and Korea following developments in the US, Germany and South Africa. France has a limited contribution to the development of VHTRs but had initiated research on the GFR (Gas Cooled Fast Reactor).

SFRs are mainly devoted to electricity production and benefit from more than 400 reactor-years of operating experience since 1951. The VHTR is primarily dedicated to the cogeneration of electricity and hydrogen production, the latter being extracted from water by using thermo-chemical, electro-chemical or hybrid processes. Its high outlet temperature makes it attractive also for the chemical, oil and iron industries. Operating experience with VHTRs has been gained since 1963.

Both SFRs and VHTRs have potential for inherent safety and are designed to exclude any release of radioactive fission products into the environment under all operating or accidental conditions.

France is actively developing a 600 MWe Gen-IV SFR, based on its experience with operating SFRs, on spent MOX fuel reprocessing and on Pu recycling. China has plans to develop a 600 MWe demonstration SFR based on the CEFR experience. Japan has also experience in operating SFRs. Russia has FNRs connected to the grid and long-term plans for further developments. The civil nuclear program of India, based up to now on thorium, includes the launching of a MOX fueled SFR.

China follows a detailed long-term R&D plan related to VHTRs.

Promises of Gen-IV SFR and VHTR

At present the Gen-IV SFR reactors look promising in many ways. One important aspect is that nearly all the isotopes of uranium, plutonium, and heavier nuclei submitted to a flux of fast neutrons can undergo fission. This means that the depleted uranium, as well as the uranium and plutonium present in the spent fuels, can be multi-recycled in a FNR. Thus, a FNR can generate its own MOX fuel provided the spent fuel is reprocessed shortly after being unloaded from the reactor. In SFR MOX fuel, 15 % of ^{238}U (from depleted U (DU) after enrichment process or U from reprocessing) is converted into plutonium. The energy extracted from natural uranium with a FNR is only limited by the industrial possibilities of recycling the spent fuel. The resource in fissile materials is therefore nearly unlimited with a fast neutron technology.

High burn-up allows leaving the fuel in an SFR twice as long as in a TNR and the minor actinides content is lower. This allows more economical operation of SFRs than of TNRs and opens the perspective of better waste management. The high-level radioactive waste from SFRs contains less long-lived radio nuclides compared to those originating from TNRs. This point is addressed in the section devoted to nuclear waste management.

Various configurations of SFRs are conceivable as they may be designed to produce less, exactly as much, or more Pu as they use. In the iso-generation configuration, the amount of Pu in an SFR park remains stable, in the “burner” configuration the stockpile of Pu can be strongly reduced. That reduces proliferation and allows to safely plan for the end of nuclear power generation should this be decided at one point in the future. An SFR can also be designed to transmute trans-plutonium elements such as americium.

Before launching of a new generation of SFRs one has to resolve various scientific and technological issues in laying out such reactors and in mastering the corresponding closed fuel cycle.

According to the GEN-IV Roadmap updated in 2014, the VHTR can supply nuclear heat and electricity over a range of core outlet temperatures between 700 °C and 950 °C, and potentially more than 1000 °C in the future. The core outlet temperature refers to helium temperature, i.e. primary coolant temperature while the temperature of water steam depends on specific design features. R&D on the VHTR focuses on the fuel and the fuel cycle, materials, hydrogen production, computational methods for simulation, validation and benchmarking, components and high-performance turbomachinery, system integration, and assessment.

Gen-IV commercial reactors should have at least the same level of safety as Gen-III TNRs. This requires many innovations with respect to the components of classical FNR reactors. Technological demonstrator designs of such reactors are under progress in France and China according to the GIF roadmap. SFRs should be considered as part of any future development of nuclear energy. This technology has the potential for providing a nearly endless source of dispatchable electricity by transmuting/fissionning all uranium isotopes and not only the 0.7% of ^{235}U in natural uranium. SFRs provide also a tool to control the plutonium inventory and to transmute long-lived actinides, which could facilitate the management of long lived nuclear waste. France was a pioneer in this technology and is actively developing a half-scale technological demonstrator of a commercial reactor (Astrid – 600 MWe) incorporating operation feedback of past reactors and important innovations. China successfully operates a prototype reactor (20 MWe) of this kind since 2011 and plans to start construction of its CFR600, also a half-scale demonstrator, in the very near term. Construction of the first commercial Chinese SFR could start as soon as 2035. France foresees the deployment of commercial SFR reactors later in this century.

Conclusions

In summary Gen-IV SFRs and VHTRs are the most promising reactors to support the future of nuclear energy producing respectively electricity and both electricity and high temperature fluids/gases. At the present stage of development, where electronuclear energy is produced mainly based on TNRs, the increasing production of electricity augments the ^{239}Pu stockpile worldwide, at a rate of around 75 t/year, as well as other nuclear materials. This increase of large amounts of Pu stockpile induces numerous issues: non-proliferation, disposal of it as spent fuel if spent fuel is considered as a waste, or use of man-made fissile material in TNRs if it is considered as a resource. The quantity of Pu still produced in many countries and in the years to come, offers the prospect of launching in a few decades enhanced safety Gen-IV SFRs, providing energy for hundreds of years. But this implies drastically changing the present reactor system, setting up a novel nuclear fuel cycle and focusing R&D on the long-term use of nuclear energy.

Appendix A

Generation-IV initiatives in France

Since 2010, the CEA is in charge of the Astrid project (Advanced Sodium Technological Reactor for Industrial Demonstration), a project consisting of two parts (i) The reactor design, (ii) The design of installations to produce its first specific MOX fuel, and then to recycle Pu and to test the transmutation of Am. Astrid must also prove that burning of Pu is achievable. The project gathers many industrial partners from the nuclear and non-nuclear fields and benefits from 40 years of Phenix and Superphenix FNR operation.

The Astrid reactor will be a 600 MWe pool type SFR loaded with MOX fuel, a power level that qualifies this system as an industrial demonstrator. It is designed to have four loops in the primary circuit and one steam generator or one nitrogen gas generator, depending on the design version, for each sodium loop of the secondary circuit. The tertiary circuit is a single line water-steam system or a two lines nitrogen system. Steam and nitrogen gas parameters are around 15 MPa and 500°C. Two shutdown systems and one supplementary independent shutdown system are designed for reactivity control. Several decay heat removal systems are connected with the hot pool or the vessel.

Innovations in the safety area focus on the control of the core reactivity in cases of sodium loss, and the cooling and confinement of radioactivity in all circumstances. CEA has patented a new heterogeneous core with a near zero-negative void coefficient, a major advance in FNR technology. It needs specific MOX fuel sub-assemblies. None of the in-service SFRs feature such an intrinsic stability core. The main chemical risk of water-sodium reactions is under control thanks to improved steam generator (SG) design. Alternatively, a sodium-nitrogen exchanger, that eliminates any contact between sodium and water, is presently under testing. This exchanger associated with a nitrogen turbine, would be the second major innovation.

New detection methods of sodium leakage have been patented by the CEA. In the case of a complete core fusion the corium is recovered. The residual power removal is ensured by several passive systems. Finally, double containment buildings and air-tightness systems should prevent any release of radioactivity into the environment should an accident occur.

Innovations in the operability domain relate to new in-service inspection systems and repair of reactor components. Special systems for handling of sub-assemblies for refuelling are being designed to save time.

The process for fresh MOX fuel fabrication for the Astrid reactor is industrially operational. The main problem to overcome is the industrial reprocessing of MOX SFR spent fuel, highly concentrated in plutonium, with a short turn-over of a few years. Thousands of tons of UOX spent fuel have been reprocessed in France.

Despite major advances in SFR design over the last twenty years, Astrid still needs to be improved with further R&D in the area of, for example, materials for reactor components and fuel cladding. It is of special interest to develop steels for cladding allowing an increase of the burn-up to a level of 200 GWd/t.

The decision to launch Astrid construction will not be taken before 2024. The French strategy for future nuclear energy consists of setting up a strategic reserve of Pu through the storage of un-reprocessed MOX TNR spent fuel and of other nuclear materials, such as depleted uranium. This should allow the progressive launching, beyond 2050 in the best case, of a self-sustaining park of SFRs, with, possibly, the transmutation of the americium that they will generate.

It is also possible to launch TNRs using the fertile mono-isotopic ^{232}Th, with ^{235}U or Pu as fissile isotopes. Fissile ^{233}U is produced in the fuel by nuclear processes on the ^{232}Th. ^{233}U has attractive fissile properties and it can be, or could be, produced in TNR by irradiation of ^{232}Th. Some prototypes of Th reactors operated more or less successfully. India experiments a “Th cycle”. A modern version of a fast neutron molten salts reactor (FRMSR) considered in France features a high operating temperature (600 to 700 °C), where molten salts (Th, Li and Be fluorides) act simultaneously as fuel and coolant. This system produces small quantities of heavy actinides, but fission products must be extracted periodically from the fuel, through batch or online pyro-chemical processes. Extraction of ^{233}U is also needed to maintain a stable flux of fast neutrons. Such reactors can transmute actinides online.

Many problems still need to be resolved in such systems. Although the use of liquid fuel is attractive, it raises issues of cooling for residual power, corrosion, containment of radioactivity, radiological protection against high-energy gamma rays, and management of new waste types. The MSR has balanced advantages and disadvantages but its development is not foreseen in France for commercial electricity production, at least unless massive fertile nuclides would become massively necessary.

The contribution of France to the VHTR development has been limited to materials and to hydrogen production. The CEA made significant efforts from 2000 to 2008 to design a prototype of a GCR as part of the GIF studies. This Allegro project was planned as a 75 MWth power system, helium cooled at 75 bar 850 °C, a start-up core with a MOX fuel (30% Pu in stainless steel cladded pins) and in the long-term a UPuC carbide core with the same content of plutonium in silicium carbide cladded pins. In 2005 the CEA gave priority to R&D for Astrid while Allegro projects continued as part of a European programme with a reduced power level of 40 MWTh since qualified carbide fuel is not yet available and further R&D is needed on materials.

Generation IV initiatives in China

SFR

As the second step of the Chinese “TNR- FNR- Fusion Reactor” nuclear strategy, the main objective of FNR development is to meet the energy demand and mitigate the possible shortage of natural uranium resource. Another goal is to allow for transmutation of long-lived nuclides.

The demonstration SFR, namely CFR600, will be built in China before 2025. The purpose of the CFR600 is to demonstrate the closed fuel cycle and establish the standards and rules for large size SFRs.

Technical choices made for the CFR600 are based on the following objectives:

- Meet safety design criteria of national nuclear power safety design regulations revised after the Fukushima accident.
- Use inherent safety characteristics and the in-depth-defence principle. Try to fit the reliability and safety requirements of the GEN-IV system.
- Adopt mature and technically proven components. All the innovative design should be fully certified by different methods.
- Try to raise the economic target compared with CEFR and other SFR projects.

The CFR600 is a pool type fast reactor loaded with MOX fuel. Its thermal power is 1500 MWth, for an electric power of 600MWe. There are two loops in the primary circuit and 8 modular steam generators for each loop of the secondary circuit. The tertiary circuit is a typical water-steam system installed with one turbine. Steam parameters are 14 MPa and 480°C. Two independent shutdown systems and a supplementary hydraulic shutdown system are designed for reactivity control, and a passive decay heat removal system is connected to the hot pool. The primary and secondary containments are specifically designed for the reactor. The preliminary design of CFR600 was completed in 2016. The First Concrete Drop (FCD) is planned at the end of this year.

VHTR

The R&D Chinese programme for the high-temperature gas-cooled reactor (HTGR) began in the mid-1970s, and the construction of the HTR-10 test reactor was achieved in the 1990s. China is now moving forward to develop the high-temperature gas-cooled reactor pebble-bed module - HTR-PM - demonstrator project as a technical leader in the industry. In February 2008, the 200 MWe HTR-PM demonstration plant was approved as part of the National Major Science and Technology Projects. According to the roadmap report of the project, the prospects for HTR-PM development in China are its potential for highly efficient nuclear power technology as a supplement to pressurised water reactor (PWR) technology, in particular in the area of nuclear process heat. HTR-PM development will also contribute more generally through innovation in advanced nuclear technologies. The HTR-PM consists of two pebble-bed reactor modules coupled with a 210 MWe steam turbine. The helium temperatures at the reactor core inlet/outlet are 250/750 °C, and steam at 13.25 MPa/567 °C is produced at the steam generator outlet. The first concrete of the HTR-PM demonstration power plant was poured on December 9, 2012, in Rongcheng, Shandong Province. The construction of the reactor building was completed in 2015 and two reactor pressure vessels were installed in 2016. Other main components are currently being installed. According to its planned schedule, the plant will start power generation in 2018.In 2005, a prototype fuel-production facility was constructed at INET with a capacity of 100 000 fuel elements per year. After that, a fuel-production factory with a capacity of 300 000 elements has been constructed in Baotou, Northern China. Fuel production for the HTR-PM demonstration power plant started in 2016.Following operational demonstration, commercial deployment of HTR-PMs based on batch construction is foreseen, and units with more (e.g. six) modules are under design. It is also envisaged to develop units with multiple standardised reactor modules coupled to a single steam turbine.

Section 5. Promises and challenges of new innovative reactor concepts and technologies: Small Modular Reactors; advanced technologies

Recommendations

Light-Water Reactors are a young technology which offers a huge potential for improvements.

- The development of Small Modular Reactors should be encouraged and financially supported, as they offer a flexible means to address the requirements of a low carbon economy. International cooperation, in the framework of the IAEA, should be further enhanced, to develop new regulatory regimes adapted to their transportability from country to country.
- Promising results are expected from Research and Development, applicable to all Light Water Reactors. R & D funding of nuclear-specific technologies should be kept at a significant level. Transfer of technologies from other sectors should be systematically promoted. Following the initiatives by the IAEA and by the US NRC, regulators should review new features and technologies taking into account the experience gained with such technologies in other sectors.

In the context of the energy transition, market requirements have generated renewed interest in small modular reactors (SMR). They may find their place in a time of low-carbon economy. SMRs can become the source of stable and clean distributed energy.

As demonstrated by the development of SMRs, the Light Water Reactor technology is not frozen. Research and Development is ongoing, and its results will be used to simplify nuclear reactors design and operation – whatever their size - while improving their safety.

1. Small modular reactors

➢ <u>Research and development background</u>

Since the 1970s, the industrial development of Nuclear Power Plant based on conventional loop type reactor was accompanied by a continuous increase of reactors' generating capacity, up to more than 1500 MWe for the latest models, mainly for economic reasons.

Furthermore, research and development into innovative small or medium sized reactors (50 – 300 MWe) was also promoted for multi-purpose applications: isolated locations, small and medium-sized electricity grids not connected to neighbours; old coal-fired unit replacement; cogenerations to use waste heat in heating networks (district heating and process heating supply); seawater desalination; island development; progressive introduction of a nuclear electricity programme for a newcomer country.

It is obvious that despite often promising market and design studies, these SMRs have not yet been able to demonstrate their practicality for general application, mainly for slow development progress and economic reasons (installation, decentralisation and training costs), but also location and implementation delay.

- Renewed Interest

For a number of years, mainly at the initiative of the DOE in the USA, there has been renewed interest in SMRs on the account of advanced nuclear energy leadership and major ongoing developments in the energy landscape and nuclear technology. The SMR is a game changer which may provide a different nuclear power co-generation solution with high safety level.

On the energy side, four reasons can be mentioned: (1) The need to reduce the use of fossil fuels; (2) Decentralisation of electricity generation (renewable energies, smart networks, energy storage); (3) The need for operators to be agile and flexible, and finally (4) The problem of financing long-term investments.

On the technology side, SMRs include a large variety of designs and technologies, such as: Integrated PWRs which can be employed at near term; Small-size Gen-IV reactors with non-water coolant/moderator which can be employed at medium-long term; converted or modified impact loop type SMRs, including barge mounted floating NPP and seabed-based reactors. Three major developments have repositioned the competitiveness and attractiveness of SMRs:

(1) The possible use of the concept of passive safety for smaller reactors, which satisfies increasing safety requirements and at the same time allows design simplification;
(2) The emergence of in-factory modular construction capacities which should reduce overall costs and building-time on location.
(3) Like the "plug and play" concept, the power station is built entirely in the factory, transported and connected to the grid; the only significant local operation is to connect the station to the electricity network.

Among the many SMRs concepts being studied in the USA, Russia, China, South Korea, Japan, UK, Argentina and also France, two generic models emerge: terrestrial and transportable SMRs.

- Terrestrial SMRs aim at nuclear island modularity and need to be installed at a specific location with civil engineering and additional ancillary facilities, turbine-generator unit, network connections.
- Transportable SMRs, completely decoupled from the operation-site, providing agility, flexibility and reversibility while at the same time reducing overall acquisition time to a minimum for a newcomer.

As a typical terrestrial SMR, ACP100 is a 125MWe small modular reactor developed by China National Nuclear Corporation (CNNC). ACP100 adopts proven and practical light water reactor technologies with five significant technical features: integral reactor, inherent safety features, fully passive safety system, underground arrangement, and twin unit sharing one 250MWe turbine generator.

Several transportable SMRs are being build or developed:

- A concept on a barge proposed by Russia and China; a first Russian unit is being finalised while China is rapidly developing ACP100S (125MWe) and ACPR 50S(50MWe)

Fig. 2-ACP100S floating NPP developed by CNNC

Fig. 3 – Seanergie: an immersed SMR

- A submerged concept Seanergie studied in France capable of providing more power (160MWe). An alternate onshore option is also studied.

- *SMR challenges and solution SMR*

Industrialisation of those models requires proof of their competitiveness, public acceptability, and a regulatory framework for the transportable reactors that IAEA is working on.

To comply with actual market requirements, new SMRs have to be developed with truly innovative concepts and surely not as a downsizing project of present Gen-III reactors.

The economic competitiveness of SMRs can obviously be improved by innovative design. Economically, SMRs can be competitive with intermittent wind power, solar power, gas power generation and diesel generators for particular applications.

If solutions similar to plug and play, with a design completely independent of the installation site, are confirmed, they may be best placed to fully comply with market requirements and thereby contribute to a realistic energy transition.

2. *Innovative technologies to be implemented in large reactors*

Commercial nuclear technologies are only a few decades old. Because of stringent safety requirements, innovations are only slowly flowing into the reactor designs. Therefore, a huge potential of improvements is lying ahead, by either implementing technologies already applied to other sectors, or specifically developed for nuclear applications. Both SMRs and large commercial Light Water Reactors will benefit from such technologies. Nuclear-specific technologies, or technologies transferred from other sectors:

Nuclear specific developments

- High performance fuels
    - Increased burn-ups with limited swelling and fission gas releases
    - Tolerant fuels withstanding higher temperature without melting, and preventing or limiting hydrogen generation in case of accident
- Improved In-core instrumentation with better accuracy, allowing less conservatism in design analysis and operation
- Improved understanding of corium behaviour, to optimise In-vessel fuel retention in case of accident
- Implementation of up to date simulation methods, coupling thermohydraulic and neutronic calculations in real time substantially enhance design and operation capabilities

Technologies transferred from other sectors

- Digitalisation of design, procurement, construction and project management of nuclear facilities (see Section 8 in this report)
- New composite materials to replace steel for low pressure circuits
- Advanced concrete with high mechanical properties, and leak-tightness

A high priority should be given to R&D in these fields; international cooperation should be encouraged, when Intellectual Property issues are not at stake.

Conclusions

Nuclear energy is a relatively young technology, with a huge potential of improvements, including Gen. IV reactors, and also small modular reactors. Technological bricks such as accident tolerant fuel would enhance safety and simplify the system in order to increase the competitiveness of all Light Water Reactors. Highly innovative SMRs could offer new solutions to further develop flexibility and decentralised production. They also allow smooth ramp up in financing and in local nuclear skills development for newcomer countries and rapid access to nuclear electricity.

Section 6. Radioactive waste management status and outlook for the future

Recommendations

Safe management of radwaste (RW) is a key issue for expanding nuclear energy. All nuclear countries are faced with this problem and have to develop the administrative and technological tools to deal with the corresponding issues. Main hurdles are to be overcome in order to dispose of the ultimate long-lived RW. There is general agreement to site repositories for such RW in deep geological rocks. The Academies recommend to intensify scientific and technological research and development for managing all types of RW with special attention to the qualification of host rocks for disposal of high-level long-lived wastes. The Academies also consider that international cooperation on this topic needs to be promoted.

Safe management of radioactive waste (RW), which is produced in every stage of the nuclear fuel cycle, is an important contribution to demonstrating that nuclear energy can be managed in a safe and sound manner. This issue has a great significance in the peaceful, sustainable, and scalable development of nuclear energy and strengthening of public confidence. Radioactive waste is categorised according to activity and half-life of the main radionuclides contained therein. Another criterion is heat generation and the categorisation of RW depends on the classification system of individual countries according to their national radwaste policy. The management of medium and high activity long-lived RW is an ongoing and difficult task, due to the necessary heavy radiological protection measures and to heat generation from the most radioactive waste.

1. Fuel cycle strategy and RW characteristics

Nuclear fuel cycles fall into two categories, a once-through fuel cycle (also designated as open cycle) and a closed fuel cycle, in which the spent fuel is reprocessed to recycle uranium (U) and plutonium (Pu). These cycles reflect political decisions on the disposal of Pu as waste or use as nuclear fuel material. In a once-through fuel cycle, the spent fuel will be disposed of, as an ultimate high-level RW, after a long-term temporary storage to allow thermal power decay of the sub-assemblies. Final repositories are nuclear installations constructed in deep geological rock formations. According to safety analysis, the host rock shall isolate and confine radioactivity over hundreds of thousands of years.

In a closed fuel cycle, spent fuel is reprocessed, yielding ultimate short and long-lived "*processing*" and "*technological*" RW. The long-lived *processing* RW, containing all the radionuclides present in the spent fuel, except U and Pu, is highly radioactive. All the long-lived spent fuel RW, initially stored in facilities, will be sent to a final deep geological repository as stipulated in the open cycle option. Most nuclear power countries, including France and China, have adopted for a closed fuel cycle. Indeed, the closed fuel cycle is the cornerstone of a sustainable nuclear energy system, where U and Pu are multi-recycled in FNR as France and China intend to do. The closed fuel cycle improves the efficiency of natural fissile resource consumption and reduces the toxicity of the ultimate waste since it does not contain Pu.

However, Pu has to be managed in the fuel cycle until the end of the recycling process. The total volume of ultimate waste is slightly reduced.

2. Progress on RW management

RW management involves controlling, collecting, sorting out and processing waste. These actions are then followed by conditioning different RW into appropriated packages to avoid dispersion of radionuclides. Packages are further transported to storage and are finally disposed of. The disposal step is regarded as the core objective and ultimate management target. The next sections focus on the current situation of RW management (excluding very short-lived RW or RW emanating insignificant radiation doses that are subject to exemption and/or clearance practices, where they exist).

Very-low level waste (VLLW)

Whatever the radionuclides contained in VLLW, their activity is so low that this waste can be disposed of in surface installations like shallow landfills. These account for the largest volume of nuclear RW. Indeed, dismantling of nuclear facilities can give rise to large quantities of VLLW, with a proportion of 50 to 75% of all decommissioning RW. It can thus be predicted that the bulk of VLLW production will occur in the future. Above and beyond the positive development of volume reduction technology, the construction of large VLLW disposal facilities is imperative.

Low and Intermediate Level Waste (LILW)

If only short-lived radionuclides are concerned, the final management issues of LILW can be solved by constructing and operating surface/sub-surface disposal facilities, including shallow trenches, near-surface concrete structures, underground rock caverns or tunnels, vertical large diameter boreholes. Practice and experience of LILW in waste conditioning, transportation of packages, reception on site, disposal of packages and safety assessment is available.

Low-level long-lived RW, produced in large quantities, is a special category of waste that is difficult to manage. If sub-surface disposal is selected it must be proved that long-lived radionuclides will remain isolated from the biosphere for a long time due to their long half-life and radiotoxicity.

High Level Waste (HLW)

HLW is a mixture of toxic and hazardous materials containing large amounts of long-lived radionuclides. Examples are sub-assemblies of spent fuel or packages of vitrified fission products and minor actinides. HLW has to be stored during decades for cooling before being transferred to a centralised deep geological repository. Countries around the world have made extensive efforts to select sites and design repositories for HLW. Belgium and France selected sites in clay layers, Finland and Sweden site their HLW waste disposal in relatively homogenous granites. Germany, USA, UK and many others countries are still in the process of selecting sites in an appropriate host rock, having so far abandoned salt domes and volcanic rocks. China is now studying both granite and clay rock for siting a HLW repository. The choice of a site takes several decades and requires experiments in Underground Research Laboratories (URL), which appear unavoidable. Up to now only Finland has obtained permission to go ahead with the construction of a HLW repository in 2015. Based on extensive research work on the selection of host rock and preliminary disposal design (including the sealing of the repository), one can expect that HLW will be isolated in safe ways.

Conclusions

The international management of radioactive waste has clear goals. It asks for the safe deployment of continuously improving solutions for the various types of waste (VLLW, LILW, and HLW). This requires experience in resolving connected conflicts through information transparency, public understanding of issues and participation. For the future development of RW management, the following points need to be considered.

National policy should pay permanent attention to management of radioactive waste issues.

Decisions at the national level are the primary driving forces to carry a safe management programme relying on a firmly based legal system, well founded scientific studies and technical solutions, detailed and coordinated planning and adequate fund investment.

Research and development on science and technology of RW management should be intensified

RW management requires advanced science and technology in the treatment and disposal of waste to achieve safety. The construction of a deep geological repository constitutes a central issue and a considerable challenge. Each component and control system must be operational during more than a century and its closure must ensure that the waste is totally isolated. It is important to intensify research and development in the underlying scientific disciplines and encourage technological innovations to effectively reach breakthroughs in key issues of waste management.

International cooperation and broad prospects in the future should be promoted

The management of RW is an important issue that needs permanent attention by all those engaged in the nuclear industry. It is important to develop international cooperation and share knowledge, information and technology in this domain.

Appendix B

For each nuclear country, the characteristic features and trends of RW management depend on many factors. The main driving factor is the national choice on an open or a closed fuel cycle. Radioactive waste management in France is typical for ~~of~~ a country aiming at a closed fuel cycle.

French RW management

Today 90 % of the RW is produced by the electronuclear industry in the operation of facilities dedicated to manufacturing, using, recycling and storing nuclear fuel. This figure is not expected to change, according to the French energy policy with regard to spent nuclear fuel. All the unloaded sub-assemblies of UOX spent fuel of the current fleet (58 PWR- and 1 EPR-systems, 62 GWe, 420 TWh/year) will be reprocessed to recycle only once Pu and U in MOX and URE fuels. The sub-assemblies of spent MOX fuel will be stored as a strategic stockpile of Pu for the future. The figures correspond to a reactor life-time supposed to be 50 years. All other non-electronuclear spent fuels will also be reprocessed.

The French system identifies five families of RW according to the criteria of radioactivity levels and decay time of such waste, corresponding to a pragmatic view of management, corresponding to so called "radwaste channels". Table 1 presents the 2013 volumes and the expected total figures for 50 years of reactors life-time. Figure 1 illustrates the French electronuclear nearly-closed cycle. At each step, the size of the surface of the circle is proportional to the amount of RW produced in 2013.

Table 1. Radioactive waste volumes.

Radioactive waste (m3)	Abbreviation	Volume up to year 2013	Activity relative to total activity in %	Total volume up to 50 years lifetime
High-Level Long-Lived	HL-LLW	3200	~98 %	10000
Intermediate Level Long-Lived waste	IL-LLW	44000	~2 %	72000
Low-Level Long-Lived Waste	LL-LLW	91000	0.01 %	180000
Low and Intermediate Level short lived waste	LIL-SL	880000	0.02 %	1900000
Very-Low Level	VLLW	440000	<0.000004 %	2200000
Total		1460000	100 %	4300000

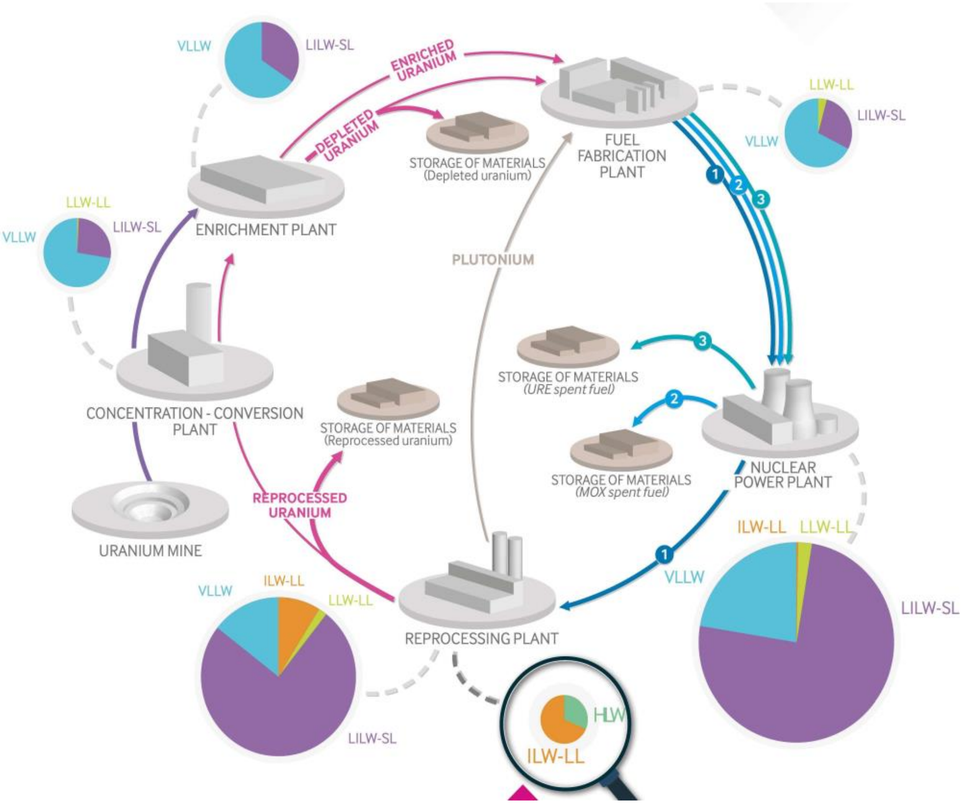

Figure 1. French electronuclear near-closed cycle (From Andra). 1: UOx fuel; 2: MOx fuel; 3: recycled Uranium. Dashed line: running and dismantling waste.

Legacy - and dismantling RW of nuclear facilities are included in the total amount. The most active RW from reprocessing (5000 packages of HL-LLW and 170 000 of IL-LLW), to be disposed of, do not contain Pu or U (except for losses from the Purex process). Furthermore, it should be noticed that, in comparison to an open fuel cycle, a closed fuel cycle with recycling of Pu leads to reducing the production of packages of HL-LLW by a factor of ten (0.8 against 8 m^3/TWh) but to an increase of IL-LLW (0.6 against 0.08 m^3/TWh).

The next sections focus only on the management of long-lived waste and VLLW, which are at the root of the main problems. Some indications will also be given on the management of other waste: LL-LLW, IL-SLW, uranium tailings and *Technologically enhanced naturally occurring radioactive materials* (*TENORM*), which are solved or in progress.

French Institutional Framework.

Andra is the nuclear operator in charge of the RW. ASN in addition to its control role provides safety guidelines for Andra and for radioactive waste producers such as CEA, EDF and Areva. The law n° 2006-739 of June 28, 2006 defines the French management policy of the various kinds of radioactive matter and RW and (1) sets the research areas, milestones and targets to be reached, taking into account societal requirements, (2) establishes a Management Plan (elaborated by ASN and the Ministry of Industry) including interim storage/disposal of RW and partitioning/transmutation of long lived radionuclides. It provides a coherent framework for the global management system and takes dispositions to continuously improve a safe management of RW, (3) establishes a new National Assessment Board (CNE2), in charge of evaluating progress in research and studies dealing with the management of RW.

The 2006 law follows the law n° 91-1381 of December 31, 1991, which was devoted to research to be done regarding partitioning, transmutation, geological disposal, and long term storage.

Progress and challenges

Progress in RW management has been continuous, from conditioning to final disposal. Associated problems are addressed through long-term planning of R&D. One major achievement has been the selection, by Andra, of a site in clay for the disposal of HL-LLW and IL-LLW and the design of the facilities for a deep geological repository named Cigéo.

Cigéo repository for HL & IL-LLW

The 2006 law stipulates that the HL and IL-LLW disposal facility will be reversible for at least one century. It is considered that reversibility is the ability, for successive generations, either to continue the construction and further exploitation of the successive steps of storage, or to re-assess the choices made previously and to change the management scheme. This includes the possibility of recovering packages of waste already stored in a manner and for a period consistent with the strategy of operation and closure of storage.

Callovo-Oxfordian clay has been chosen as host bedrock. Cigéo will be launched quite soon at Bure, a location near the underground laboratory LMHM (Laboratoire de Meuse Haute-Marne) operated by Andra over a period of 15 years. The clay layer, 130-meter-thick, 500-meter-deep, and located in the East of the Paris Basin, shows a remarkable lateral continuity and a good homogeneity in composition and structure. Investigations on regional and local geology, hydrogeology and geochemistry show no faults or connection with convective flow between the upper and lower aquifers through the clay. Clay pore water has a very long residence time. Water composition and diffusion coefficients of the fastest diffusive radionuclides have been measured in situ in the LMHM. The data show that clay is an efficient ultimate barrier to stop radionuclide migration up to a million years. Mechanical properties allow the building-up of underground facilities designed to separately dispose HL-LLW and IL-LLW in specific cells and to last more than a century during the operation of the repository. On site investigations and design of Cigéo began in 1991.

LL-LLW

The LL-LLW is formed by materials containing Ra and its daughters, large or small pieces of graphite containing ^{36}Cl and ^{14}C, packages of slugs in bitumen containing trace amounts of actinides. They are stored in various places waiting for disposal. Andra is looking for a dedicated sub-surface site in clay. Disposal of such waste in such a place is a challenge due to the long-lived radionuclides to be confined so close to the biosphere. R&D is conducted to see if processing of some LL-LLW could help in disposing of this category of waste. The LL-LLW will amount to around 200 000 m^3.

LIL-SLW

The IL-SLW, mainly originating from electricity production (1.9 10^6 m^3), is and will be packaged and disposed of in the CSA (Centre de stockage de l'Aube, Soulaines-Dhuys) centre, open since 1992 and foreseen to be in operation up to 2100 (capacity of 10^6 m^3). The previous repository, CSM (Centre de Stockage de la Manche, Digulleville), open in 1969 (0.5 10^6 m^3) has been closed and is under monitoring since 1993.

VL-LLW

VL-LLWis currently disposed of in a special centre: the Cires (Centre Industriel de Regroupement et de Stockage, Morvilliers). Its authorised capacity is 650,000 m^3. It could be extended to 900,000 m^3 and should be full by 2030. In addition to the extension of capacity of Cires, another high-capacity centre needs to be opened to cope with the disposal of VL-LLW, originating from dismantling activities.

VL-LLW raises many problems due to the large foreseen quantity (estimated to be 2.2 10^6 m^3) because the French system of RW management defines no clearance level. For a few years, research organisations, industry and the authorities have been developing innovative methods for the management of dismantling-derived materials also classified as waste, although they contain little or no added radioactivity. In order to do so, one has to develop methods for measuring very low radioactivity levels in large batches of materials that could be used to support an innovative VLLW management strategy. Andra and waste producers are looking first to all the possibilities for drastically reducing VLLW production, for instance by recycling large streams of metallic components. Concerns about recycling are numerous and require at least the definition of thresholds to be reached in decontamination before reuse.

Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM)

Up to now Tenorm waste, originating from non-nuclear industries were managed in technical centres for industrial waste, equipped to detect radioactivity above fixed thresholds. This management is under reconsideration, particularly with regard to their quantities and their activity. This raises concerns similar to those pertaining to LLW.

Other waste

Uranium has been mined in France. About 50 Mt of U radwaste (tailings) are disposed of ***in situ,*** in 17 sites, near the place of their production in old open-air mines, basins or bottom valley closed by dams. The sites are monitored and submitted to specific regulations to take care of radon migration and daughter products. A large amount of radwaste from processing of yellow cake, which are more or less similar to mining radwaste, is stored in Malvesi.

In conclusion, France has set up under the control of ASN a safe radioactive waste management system to support its nuclear activities according to the strategy of reprocessing/recycling all spent fuel. The Cigéo project of a deep geological disposal will be launched in a few years' time. Management of VLLW is aimed at reducing the large volumes resulting from dismantling of reactors and nuclear facilities and at defining a new high capacity disposal site. From several debates between all stakeholders, including the public, it has become clear that people want to be "secured" and not "reassured". The major question is: how can one have confidence in the management of such long-lived radwaste. Reversibility of disposal of radwaste, as stipulated by the law, reconciles ethics and transmission of duties to next generations. It helps making public acceptance a reality. The next step will be to set up the governance of repository reversibility, which by law must involve the public.

Section 7. Technical support organisations (TSO) related to safety

Recommendations

- Technical expertise of regulators, either built in-house or provided by Technical Support Organisation is essential to secure a high level of nuclear safety.
- Independence and transparency of TSOs should be kept at the highest possible level, and not be compromised.
- Competences of Technical Support Organisations should be ever increased on a continuous basis, for them to be able to assess new, multiple, and innovative technologies, including Gen IV reactors
- International cooperation between TSOs should be strengthened to better harmonise requirements, and assessment methodologies and criteria.
- TSOs of nuclear-developed countries should assist and support emerging countries, to build up their national safety expertise.

All nuclear related activities are deeply regulated (Ref. IAEA General Safety Requirement - Governmental, Legal and Regulatory Framework for Safety - Series No. GSR Part 1 (Rev. 1))

Throughout the lifetime of a nuclear facility, the owner/operator has the prime responsibility for safety; but the regulator shall be fully empowered to control the owner/operator.

Beyond the administrative and legal tasks of issuing a construction, first fuel loading, operation or dismantling license for any specific facility, the regulator needs to be supported by a strong technical expertise/organisation. Such expertise/organisation will be used to develop safety rules, regulations, and requirements in a coherent fashion, to assess and evaluate the licensees' compliances and non-compliances.

Many organisational schemes exist for a regulator to access nuclear expertise. It can be built in-house by the regulator, or contracted to external parties. And when safety expertise is subcontracted, a preferred specialised agency is often considered, referred to as the Technical Support Organisation (TSO – also the Technical and Scientific Support Organisation).

In the US, the NRC owns the expertise to develop nuclear safety regulations and Regulatory Guides, and to assess compliance with its very prescriptive requirements. In France, the Regulator (Autorité de Sûreté Nucléaire - ASN) develops general guidelines, and owns a strong expertise in the field of integrity of the primary and secondary circuits, supplemented with contracts to universities and research institutes in this specific field; but relies on the Institut de Radioprotection et de Sureté Nucléaire (IRSN) for specialised nuclear engineering expertise. IRSN is a spin-off of the former safety division of the French Atomic Energy Commission, later merged with the Radiophysics division of the Ministry of Health. Essentially all technical safety assessments, among other tasks, are assigned by ASN to IRSN, the French TSO.

In China, the Regulator (National Nuclear Safety Administration – NNSA) issues nuclear safety rules and guides, prepares and promulgates nuclear safety regulation, controls their implementation, establishes principles and policies of nuclear safety. All civil nuclear facilities are regulated by NNSA. China atomic Energy Agency (CAEA) is in charge of national nuclear emergency.

Most of the nuclear expertise is accessed by NNSA from several TSOs: 1) Nuclear and Radiation Safety Centre (NSC) of Ministry of Environmental Protection which provides most of technical support work needed by NNSA. 2) Radiation Monitoring Technical Centre (RMTC) of Ministry of Environmental Protection; its main duty is to provide national radiation monitoring support. 3) Suzhou Nuclear Safety Centre (SZNSC) which provides technical support in the field of Quality Assurance, Mechanical Equipment and Research Reactors. 4) Nuclear Equipment Safety and Reliability Centre (NESRC), which participates in reviewing nuclear pressure retaining components. 5) Beijing Review Centre of Nuclear Safety (BRCNS), the first founded TSO in Beijing Institute of Nuclear Engineering (BINE); its main duty is to provide technical support in the field of nuclear engineering not designed by BINE. All safety assessments are subcontracted to these TSOs, and supplemented with contracts to universities and research institutes in specific fields, such as Tsinghua University, China Institute of Atomic Energy, China Institute for Radiation Protection, etc.

When reviewing international experience in this field, there is no evidence for claiming that any organisational model is superior to others; many models work, provided they 1) fit the technical history and administrative organisation of each country, 2) channel the best available expertise to the nuclear Regulator and 3) foster the development of such expertise.

However, a few basic principles generally applicable to nuclear safety expertise can be drawn up, inter alia:

1. Independence: the expertise body (TSO) shall not undertake work likely to compromise its neutrality or likely to lead it to assess its own work. If the expertise body works for several clients, including the safety authority, potential conflicts of interest should be identified and prevented.
2. Transparency: the TSO should be organised to enhance independence and transparency of its operation, including full disclosure of its reports (except when serious confidentiality issues are at stake).
3. Quality assurance: the expertise body should comply with a stringent Quality Assurance Programme, ensuring the assessment of the competence of its experts, the traceability of its expertise, from task acceptance to provision of deliverables

The expertise body can provide training services, and manage its own R&D programmes, which are means to enhance the qualification of its staff.

TSOs should not work in an isolated manner. Although nuclear safety is a sovereign issue for any State, experience and best practices should be shared. Owners/operators are sharing their experience on a daily basis in the frame of the World Association of Nuclear Operators (WANO), and organise peer reviews on a regular basis. The IAEA and OECD provide fora for safety authorities to meet and cooperate, in the frame of working groups or peer-reviews as requested by the Nuclear Safety Convention. No such forum exists for TSOs; however, major TSOs in the world took the initiative under an IAEA umbrella to hold regular meetings, the last one having taken place in Beijing in 2014; such exchanges should be encouraged. Although safety requirements are left to each State, sharing experience and expertise between TSOs can only benefit each of them.

The development of nuclear energy in emerging countries raises specific issues with respect to their access to safety expertise. When nuclear technology is imported, a “reference plant” is generally considered. Clients should be given access to safety expertise from the origin country of this technology, and to the safety case of the reference plant, provided the requirements of independence and transparency are complied with. Furthermore, TSOs of more advanced countries should help and assist newcomers to set up and develop their own safety expertise, to the maximum extent possible.

When looking back to more than fifty years of commercial nuclear development, the invaluable role of TSOs cannot be overestimated. Analysis of nuclear incidents or accidents demonstrates that the absence of an independent and transparent TSO, implementing strict Quality Assurance programmes has had serious consequences. In the future TSOs should continue serving the global nuclear community. Some key challenges lying ahead are:

- Keep and increase their competences to be able to assess new, multiple, and innovative technologies, including Gen IV reactors
- Strengthen international cooperation to better harmonise requirements, and assessment methodologies and criteria
- Support safety authorities and TSOs of emerging countries, to build up their national safety expertise

Conclusions

Nuclear regulators need to rely on a strong technical expertise, which they can build in-house, or contract from a Technical Support Organisations; there is no evidence that any organisational model is superior to others.

TSOs should comply with stringent requirements of independence, neutrality, transparency, and quality. While they would largely benefit from international cooperation and exchange of experience, there is, as yet, no dedicated forum for cooperation and peer review. Notwithstanding, TSOs of advanced nuclear countries can and should play an important role in assisting newcomers to develop their own safety expertise.

Section 8. Challenges for the future, including digitalisation and novel design methodologies.

Recommendations

The nuclear industry shall take full benefit of digitalisation at all stages of its development.

- More accurate design codes simulating reactor operation in normal and accidental conditions can take advantage from progress in IT including fast increase in the speed and storage capacity of computers. They pave the way for implementing new methodologies that need to be licensed through positive interactions with safety regulators.
- Digitalisation of instrumentation and control systems is a reality; but safety requirements are not harmonised between regulators, leading to different solutions to fulfil the same functionality, depending on the country. Regulations and rules coping with new threats, like cyber security are also not harmonised and progress in these fields should be made at the international level.
- Many industries take full advantage of new digital technologies for design and project management (CAD tools, Project Life Management). The nuclear industry will greatly benefit from these tools. Sharing of experience in this field is encouraged.

Nuclear energy must deliver low carbon and competitive electricity by reducing cost and construction time of new nuclear power plants, without affecting safety, and by better controlling outage times of existing plants.

To cope with these challenges, nuclear energy needs to make the best use of the available tools stemming from digital technologies, and above all “Industry 4.0”, PLM (Product Lifecycle Management), 3D scan for numerical twin of an existing facility, Big Data and Internet of Things, virtual and augmented reality, 3D Printing, etc.

Furthermore, nuclear energy is developing in an open and global economy, with focus to “One belt and one Road” in China, and open competition in Europe.

Digital transformation of nuclear engineering will help achieving competitiveness and provide economic gains, while improving safety; it should also significantly enhance and improve efficiency and benefit the working organisations, which must adapt to digitalisation.

At stake:

- Increased control of construction schedules of new nuclear plants,
- Increased availability factors of existing plants, by better planning, scheduling and controlling outages,
- Lifetime extension of installed base,
- Increased competitiveness of 3rd generation nuclear power plants.

- 1 – For the **installed base**, which has not benefited so much from a numerical model at the design stage and updated during operation, creating a "numerical twin" thanks to a 3D scan, and sharing it with subcontractors, will allow time-saving for maintenance operation, testing accessibility for maintenance, and facilitate training of operators, up to the dismantling phase. The numerical model also provides tools to minimise workers' exposure to radiations.

- 2 - For **new projects**, considering the long lifetime of a nuclear project (typically 60 years) and the very high level of safety requirements, it is critical to use Data Management tools for managing in real time the reactor configurations, covering specifications, design, construction, operation and dismantling.

Such tools as for example PLM (Product Lifecycle Management) - exist and are routinely employed in the aerospace sector.

Lack of complete control over data is a major source of delays during construction phase and cost-overruns due to rework.

For a successful implementation of a PLM numerical platform, a change in industrial organisation is mandatory. This requires:

- System engineering with "architects" (chief engineers) fully responsible for the whole system (Nuclear Island, Conventional Island, Pumping Station, ...) from design to construction and commissioning.
- A strict data governance, with a process to authorise a change of configuration when needed; data are no more dispersed in paper documents but embedded in a single PLM numerical platform with a unique management, and made available to each project stakeholder.

It also allows checking design completion before starting construction, and interactive numerical simulation of construction or maintenance sequences, to assess accessibility and optimise construction methods.

Major project stakeholders should be connected to the PLM numerical platform (civil works, conventional island, nuclear island, subcontractors) allowing a unified data management system, offering a novel design methodology and significantly reducing the project duration.

Digitalisation of the manufacturing chain, in particular replacement of paper documents, will also improve data traceability, components specifications and data sheets archiving and retrieving, and globally improve quality insurance, with a single source of data.

Intelligent design methodologies are of paramount importance to improve nuclear engineering, throughout the lifetime of nuclear projects, from cradle to grave.

Early in the process, at the conceptual design stage, key decisions structuring the project have to be made, including plant output, heat sink arrangement, general layout of the site, main features of the buildings (structure, large openings, etc.). All these aspects have to be jointly optimised, which is usually done in successive steps. 3D CAD tools should be used at the earliest stage possible in this design process, to accelerate the optimisation and assessment of alternative solutions...The seamless achievement of this step-by-step optimisation requires a high level of digitalisation, including static and dynamic calculations.

As a lesson learned, it appears that simplicity and limpidity of the design, from any point of view, is the main objective of this conceptual design phase. Progress remains to be made in this field; software providers should consider the specific functionalities needed at these early stages of the design.

At the basic design stage, better optimisation and therefore improved competitiveness can be achieved by means of innovative numerical simulations. Qualified reliable simulation models, validated by experiments, can both be used to guide the optimisation process of designing, and to provide feedback to the design engineer. But they still require to be licensed by Safety Authorities, which sometimes proves to be highly demanding and may become a limiting factor of innovation.

Virtual/Augmented Reality technology aims to integrate the three-dimensional design models into a unified software environment, and capture all the geometrical characteristics of the different components into a full-scale digital 3D model. This allows a better optimisation of the reactor and auxiliary systems layout, and their interface with civil works. Improvement of industrial performance throughout the lifetime of a project, from design to decommissioning of a NPP can be achieved thanks to valorisation of data, as is being recognised in other industrial sectors: Predictive maintenance can be improved, using Big Data technologies to analyse and sort the huge volume of data collected by nuclear power plants.

Nuclear projects imply the management of a considerable amount of data, far greater than what is currently implemented in the automobile or aircraft industries. However similar PLM methodologies coupled with CAD tools prove to be very effective in improving data quality and streamlining project management. These processes will provide better traceability of the projects and benefit Quality assurance and safety. Important gains are still accessible which need cooperation of all stakeholders including safety authorities.

Furthermore, digital simulation should be used to animate full-scale simulators for training purposes, and to improve emergency preparedness and severe accident response capacity.

For more than twenty-five years, Instrumentation and Control systems of nuclear power plants have made extensive use of digital technologies, However, many challenges are still lying ahead in the application of these technologies to the nuclear industry, including the qualification of both hardware and software for meeting safety requirements. Taking science and technology to market is key for nuclear energy competitiveness, but requires involvement of Industry and Regulators. Work remains to be done to develop codes and standards applicable to key software, when they are safety relevant. Besides, there are no international regulations and laws in the field of prevention and detection of incidents like hostile cyber-attacks of NPPs. Thus, an effort should be made to strengthen the establishment of certain legislation, and simultaneously attention should be given to relevant safety protection techniques relying on physical separation, firewalls, and effective management measures.

Conclusions

The nuclear industry would greatly benefit from full digitalisation at all stages from conception through construction, operation and maintenance up to decommissioning of reactors. Product Lifecycle Management, which is a tool for doing just that, is widely and successfully used in the aerospace industry. Other tools include numerical simulation, 3D CAD, and Virtual/Augmented Reality. As a result of using these tools, performance would go up substantially, construction delays and cost increases would be avoided and competitiveness would be augmented.

Use of simulation tools (neutronic, thermohydraulic, etc.) at the design stage, is quite promising. For many years, digital Instrumentation and Systems have been used in nuclear power plants. In these two areas, a coordinated approach by safety authorities worldwide is needed.

In any case, utmost attention must be given to cyber security in order to detect and prevent cyber-attacks in a timely manner.

Section 9. Importance of nuclear research facilities and infrastructures

Recommendations

Two recommendations can be formulated covering the missions of nuclear research organisations in established as well as in emerging nuclear energy countries:

- In a globalised world, and taking into account the increasing cost of nuclear research facilities and their relatively low utilisation rate (at least for some of them), it is recommended to explore the mutualisation of large and/or heavy and/or specific nuclear facilities; research reactors, hot labs, irradiated materials labs, simulation and computation centres. This is valid for existing facilities and even more so for new ones.
- To allow nuclear emerging countries to have access to R&D facilities at acceptable cost, it is recommended that the R&D organisations and equipment makers in well-established nuclear countries make available low-cost laboratory facilities to address specific as well as general needs for experimentation and research in the nuclear field, including front-end and back-end activities.

The nuclear infrastructure in nearly all industrialised countries has originated from national Atomic Energy Commissions, themselves strongly marked by an academic and research culture. In addition to their own nuclear research and education centres, these institutions have also been the ultimate source of most of the national nuclear safety authorities as well as of technical support organisations (TSOs) for safety, of waste management agencies, and of a part of the nuclear industry.

At an early stage, military applications, where they existed, have been separated from civil applications, both in terms of programmes, infrastructure and human resources so as to ensure confidentiality and non-proliferation. With this caveat, civil nuclear research remains - to a large extent - non-secretive, obeying IAEA transparency rules, and exposed to a globalised world.

Very early-on, a separation appeared between the nuclear reactor industry and the fuel cycle industry. The former quickly became engaged in a competitive market, with some of the main actors originating from their national energy commissions, while others, such as Westinghouse, emerging independently from these agencies, designing, proposing and building power plants, supported by the massive streams of cash earned from the operation of reactors. Westinghouse, a brilliant success in this field, has strongly influenced the nuclear power industry in France, Japan, Korea and China. In the Generation-II and -III market segments, the role of nuclear research centres has often been, but by no means always, limited to case-by-case support, especially for high-level unexplained problems encountered during the operation of reactors by vendors or utilities.

Nuclear reactor fuel performance continues to be investigated at some of these centres while research on reactor life extension is also carried out by National laboratories. In almost all cases there is a need for specific facilities located in the nuclear research organisation (research reactors, test facilities, etc.). In France, research facilities are shared between by EDF and CEA.

As can be concluded from the above, the fuel cycle industry remains more closely linked to nuclear research organisations. The companies acting downstream in that domain have often been formed as “spin offs” of such research organisations. They became standalone companies, even when the founding research organisations kept a strong capital share, developing tight cooperative research programmes, and using more of the common innovation capacities (reprocessing or waste management, etc..). In this field, a close connection was needed to cope with the requirements of nuclear materials control. On the other hand of the fuel cycle, the enrichment business is mostly in the hands of private companies doing their own research.

During the last fifteen years, several issues have had a strong impact on nuclear research organisations and, in the following context, their role or at least their way of operation had to be re-defined:

- Lifetime extension for the most advanced generation-II reactors
- Arrival of the generation-III designs,
- Preparation of the generation-IV designs,
- Access of emerging countries to nuclear power or their desire to access,
- Severe accidents
- Global increase of nuclear costs, largely consequences of increasing safety requirements
- “Phasing out of nuclear” by some large industrialised countries
- A huge need of nuclear educated manpower to replace the “generation-II staff” in conjunction with a relative disaffection of young people for scientific and technical jobs, at least in Western countries (cf. Section 10)
- Strong increase of the decommissioning programmes and the associated feed-back
- And last but not least, the emergence of the SMRs paradigm

In the absence of evident and declared private financing, a good solution to house and manage an innovative nuclear project (or programme) might be the nuclear research organisations, where they still exist. Their experienced teams are capable of coping with short-term studies – while leaving time to select or build industrial actors – as well as with mid- or long-term studies such as those related to the fuel cycle (Examples: Generation-IV, SMRs).

However, in many emerging countries, the R&D organisations are managed by universities, professors and academic staff. This provides an acceptable basis to start activities but it should rapidly be supplemented by more industrial or at least more technological profiles in order to bring technical expertise and added value to the industrial actors of the nuclear programme when it is launched.

This should not however preclude to take into account disruptive innovations which originate most frequently from universities and academic research. Building efficient partnerships between academic teams and industrial companies is always helpful.

Conclusions

An emerging nuclear country, even if it has chosen to make a comprehensive appeal to external competences (which is the case when facilities are contracted under a Build Own Transfer (BOT), or Build Own Operate model (BOO)), shall have a minimum of technical competences to manage the relationship with the utility and to fulfil its responsibilities to ensure the safety of its operations vis-à-vis its population and the worldwide nuclear community. This role of “national owner’s engineer” especially for safety issues should ideally not be sub-contracted. However, the support of foreign TSOs can be helpful and the experience gained with them in other countries could be shared.

In this framework, the role of a NEPIO (Nuclear Energy Programme Implementing Organisation) as defined by IAEA could be complemented with R&D missions, in support to the construction programme implemented by the NEPIO or by another national organisation.

Section 10. Challenges for education and training

Recommendations

The academies consider that it is mandatory to consolidate education to satisfy the need for adequately trained engineers and technicians and to reinforce the attractiveness of the nuclear industry through more intense interaction between science and technology, industry and universities, and the prospect of interesting careers. They recommend to

- Improve teaching methodologies, integrate modern IT, such as simulation, multimedia, e-learning, and virtual reality in courses for engineers and technicians, but also diversify courses to include a wider range of skills and competences such as PLM as well as cultural heritage,
- Enhance cost-effectiveness *and* safety of nuclear power plants, integrate the use of digitalisation for construction, operation, and maintenance in student courses,
- Take full advantage from available experience and help providing better training services to third countries, start cooperation in this area between France and China.

The context for education and training has deeply changed during these last ten years.

1. The engineers, scientists and technicians graduating between 2020 and 2030 will be working until between 2065 and 2075 respectively. Those working for the nuclear industry will have to:

- Operate, maintain and modernise the installed nuclear fleet, but also dismantle part of it,
- Build new “Generation-II, -II+, -III”, plants and then operate and maintain them,
- Conceive new plants, “Generation-IV”, SMR….,
- Develop advanced fuel cycles, including waste management.

In France, even though the percentage of nuclear engineers is now superior to what it was 20 years ago, the nuclear industry is still in need of technicians (Professional baccalaureate, baccalaureate +2 years professional training and education and baccalaureate+3 years professional training and education), making up around half of the employees.

China keeps constructing nuclear power plants for more than 30 years. Especially after 2005, when the construction of a new cohort of NPPs was started, more and more universities in China were setting up nuclear technology courses, trained qualified personnel in highly valued competences for the industry. However, at present, their professional skills are still insufficient - employers have to systematically train staff for long periods and provide on-the-job practising to get them to the stage where they are authorised to effectively take on responsibility.

2. The development environment of the nuclear industry is very different from what it was in the 80s; the nuclear power industry is at a crossroad now. Firstly, the necessity of dealing with climate change has become a global consensus. Green energy and low-carbon transition policy provide further opportunities for the development of nuclear power in

China and for Sino-French cooperation in developing a nuclear power market in third countries.

Secondly, as the technology of wind and solar energy improves rapidly, their operational costs decrease rapidly, but with more stringent safety requirements for nuclear power after the Fukushima nuclear accident, the needed investments for new NPP projects and for safety improvements of the existing NPPs are increasing significantly. As a result, the relatively strong competitiveness of nuclear power is weakening.

Thirdly, as the public is more concerned about nuclear safety, the continued strong development of the nuclear industry faces challenges, such as how to communicate with stakeholders and win their support.

Fourthly, due to more unstable power capacity and deregulation of the electricity market, sustained revenue from NPPs becomes uncertain.

3. Safety issues have become extremely important for the nuclear industry; conservatism is encouraged while innovation is discouraged. For example, the "digitalisation" of the nuclear industry is lagging behind the digitalisation of other industries such as the aviation industry. But with the technology development of the Internet, big data, artificial intelligence and others, more digital and intelligent technology will be applied in such areas as data management, product life-cycle management (PLM) and digital simulators (DCS). The required knowledge in these areas has to be taught to many employees in the nuclear industry and to government regulators, now and in the future. It is a precondition for its sustainability.

4. Due to the complexity of nuclear safety issues, all nuclear industry employees should have a wide range of professional knowledge, skills, experience and cultural heritage. So, we must establish adequate knowledge management and personnel training systems for new employees to provide full training, to have competent teachers, and to promote more efficient intergenerational institutionalised cooperation. This applies to all employees, at all levels.

The responsibility to deal with the four preceding factors is shared between the Nuclear Industries and the "Educational Ecosystems" (Universities, Engineering Schools, Research Institutes and technological Institutes) of our countries:

- For the educational ecosystem, it is the responsibility to refocus student's curricula to include PLM, environmental issues, interdisciplinary and systemic issues, modern instrumentation, etc. and not only, as in the past, fundamental sciences (e.g. neutronics, thermal-hydraulics, strengths of materials, structural mechanics, etc.) and/or basic engineering and classical project management.
- For the nuclear industry, it is the responsibility to recruit employees with more diverse backgrounds, thus taking into account new ideas and ideas from "outside", fostering actively and steadily innovative engineering approaches.
- To promote nuclear safety culture and comprehensive quality management, the cooperation in personnel training in the concerned nuclear industry sector should be strengthened, training resources should be shared, and training standards should also be unified.

- Between the two, it should be made possible that scientists and engineers from industry work part-time or for a few years in education and, symmetrically, that professors/researchers work a few years in the industry.

It should be mentioned here that China and France have a number of common international cooperation initiatives regarding training of nuclear industry personnel, such as the promising experience with the young IFCEN, the Sino-French Institute for Nuclear Energy, part of the Sun Yat Sen University of Guangzhou. IFCEN delivered the first 80 engineering degrees in June 2016 with an innovative curriculum implemented by a Sino-French team.

With the support of IAEA, the Chinese government continues to train nuclear professional masters and doctors for emerging countries in the Harbin Institute of Technology. In order to support the nuclear industry training programme for students from emerging countries at the Tsinghua University, the Chinese Ministry of Education provides scholarships to 30 international students every year. Customised training for the nuclear industry is popularised at Chinese universities; the training of talents for nuclear power applications is speeding up. Based on the win-win training cooperation between university and enterprise, graduates get employment opportunities and enterprises get trained personnel. Training cooperation increases graduates' education in skills, accelerates their formation according to responsibility standards, and improves the level of the personnel teaching courses.

Foremost, the nuclear industry must evaluate its needs, taking into account the age pyramid of its current staff. This difficult task has already occurred once in France, 15 years ago, when the retirement of the "baby-boomers" post-World War-II after around the year 2000 had to be anticipated. Nowadays, in France, we need to anticipate the wave of retirements linked to the large number of recruitments made during the short period of accelerated construction of the majority of the French nuclear fleet.

When training the current employees at the different professional levels of companies and for the different types of jobs, we have to take into account not only the evolution or even outright replacement of systems, the upcoming of new software - which has always been the case - but also an altogether different education of the workforce. For example, the mindset, the values, and the learning habits of the new generation of employees in the nuclear industry; all of this is changing. The increasing performances of the IT world allows the use of multimedia, videos, e-learning, virtual reality to educate the employees at all levels - not only the staff and the engineers! Therefore, nuclear industry regulators should adapt, promote and support new training techniques to be applied in the nuclear industry.

For example, simulators have been used for a long time for the training of plant operators. With the progress of modelling, simulation and computer-power, simulators are becoming more powerful, in particular for simulating post-accidental situations, which leads to better training possibilities for plant operation. Moreover, the progress in the area of simulation, of virtual reality, etc. opens possibilities for differently and more efficiently training maintenance operators working in the field, especially those who have to intervene in areas where radiation imposes short intervention times. Here again, what is done in other industries, may be applicable and of help for the various operators working in the nuclear industry. The training centre of CGN innovated in a variety of simulation training courses and tools, integrated learning, teaching, training and research progress, and formulated multilevel training systems and facilities. They have developed stand-alone versions and portable simulators; "door-to-door training" and "learning while practicing" is becoming a reality; these innovations enhance the quality of training.

To succeed, the nuclear industry has also to keep current talents and attract new ones. Indeed, the nuclear industry is no longer regarded as the most high-tech industry, nor is it seen as the most desired industry. Renewed interactions with sciences and technologies, through up-to-date training of present employees and education of future employees are key.

Those countries that desire to develop and use NPP technology should encourage the cooperation in personnel training for the nuclear industry, especially the identification and training of talents for international projects needed for promoting the development of nuclear power programmes at the international level. Furthermore, the development and application of international nuclear standards, of local regulations and technical standards, as well as of the technical knowledge and competence for NPP design, construction and operation should be accelerated. As China and France have built a good nuclear professional teaching system, have a good international professional training basis, both countries would like to cooperate in this area and provide better training services for third countries.

Conclusions

In both France and China, there is a need for better education and training of more nuclear engineers and technicians. Furthermore, in about 20 to 25 years’ time, there will be a second wave of retirements in the nuclear industry in France, leading to the need for accelerated recruiting. This situation needs to be anticipated. Attracting new talents would be helped by renewed interaction with science and technology. Professors/researchers would benefit from opportunities to work in industry whilst industrial scientists and engineers working part-time in education would enrich training programmes. Training programmes would also benefit from modern IT, allowing cost-effective training through simulation and other teaching methods. Furthermore, the training programmes should encompass a wider and more diverse range of skills and competences. While technologies for wind and solar energies improve rapidly, reducing their costs, the nuclear industry is suffering cost increases due to more stringent safety requirements. In order to counteract such cost increases, today’s students need to be familiarised with the digitalisation of all phases and elements of nuclear power plant construction, operation, and maintenance.

Section 11. Engineering and Managing Nuclear Projects

Recommendations

- Nuclear projects are complex. The Academies recommend using the most modern tools to alleviate this complexity.
- Risk assessment should be performed throughout project implementation.
- Because changes in the safety regulations during project implementation brings major engineering uncertainties, these regulations should be fully validated and frozen before starting a project
- A proper use of up-to-date management tools allows to cope with the engineering challenges of such large projects.

The size and complexity of nuclear power plants is exceptional: not including sub-components, several hundred thousand objects have to be designed, manufactured, erected, tested and commissioned, which is usually one or two orders of magnitudes more than projects developed by the aerospace or automotive industry. In addition, complex safety requirements, and quality classifications are to be complied with. For these main reasons, project schedules span over five years or more, not including site preparation, procurement of long lead items, and development of all basic and most of the detailed design. Therefore, controlling nuclear projects is a challenge, and insufficient control may lead to dramatic consequences. As an example, after the TMI accident (1979) new safety requirement were developed; therefore, on-going constructions were stalled pending the enforcement of these requirements. Consequently, schedules of many projects were doubled, and many projects were cancelled. More recently, recent Western projects faced difficulties due to insufficient completeness of the design before the start of construction, and lack of recent experience throughout the supply chain. On the other hand, many Chinese and other Asian projects provide evidence that the inherent complexity of nuclear projects can be overcome, and that implementation of appropriate design and project management methodologies result in well controlled project implementations.

The risks are even greater for FOAKs (first of a kind reactors). For these projects, R&D and technical verifications at the design phase are the key of risk control. In general, active and effective measures to ensure that R&D results are available at the design stage are paramount. Therefore, the R&D of new technologies needs to be integrated within the project schedule. Furthermore, licensing of FOAK generally proves to take time, as the regulator requires evidence of the effectiveness of new features. Therefore, FOAK projects require far greater attention, and construction should not start before new concepts are suitably validated and licensed.

When a nuclear project is based on a reference plant, the main difficulties and risks faced during its implementation relate to the quality and stability of the design, the performance of the supply chain, the delivery of all components at site in time and according to schedule and the proper coordination of all site activities.

Experience gained with recent projects proves that at least 70% of the detailed design must be completed before starting construction of any nuclear building, which requires that procurement activities are well advanced in order to get all input data needed for static and dynamic analysis, definition of anchors, construction plates and openings, etc. Only the definition of small items with no influence on the civil works and piping and electrical layout may be left behind. Design work must be fully and seamlessly integrated between the architect engineer and the contractors and suppliers, using the same CAD tools and data bases (refer to Section 8). Stability of the licensing requirements is a prerequisite, and regulators should understand that "combined construction and operation" licenses (COLs) provide the frame for better safety and quality.

Procurement activities and the strength of the supply chain are another key factor of success of nuclear projects. China and France are used to the owner's own model; in this model, the owner has its own design and project management in-house capacities; this model proves successful, so long as the skills, methods and tools are kept up to date, making use of the best tools and experience available on the market.

Coordination of all activities during design, procurement, erection and commissioning requires sophisticated project management tools, combining a huge component data base, a scheduling tool, a documentation control system etc. Such coordinated tools (Project Life Management) exist; stringent procedures have to be defined and enforced to fully benefit from their powerful capacity (Section 8).

Finally, strong controls need to be put in place, encompassing quality, safety, scheduling, and cost. To the maximum extent possible, they need to be independent of project management itself, and to have their own reporting line to the highest level in the organisation.

In order to guarantee the quality and schedule of nuclear power projects, necessary measures need to be taken to reduce construction costs, while strengthening the cost control. It allows reducing the project cost and improve cost efficiencies of the nuclear power project. Cost linkage management can benefit from earned value evaluation. Earned value management can predict progress and cost deviations and propose measures to ensure that project objectives are achieved.

Appendix C provides a more detailed presentation of project risks; sound design and project management has the common result of better controlling and alleviating these risks.

Conclusions

The complexity of nuclear projects needs to place a maximum of attention in the design quality, the robustness of the supply chain, the control of the consistency and schedule of the project with use of modern CAD and PLM tools.

Recent experience shows that nuclear projects, if properly controlled, can be delivered in time and within budget, while coping with stringent safety and quality requirements.

Methodologies, often implemented in other industries, are available and should greatly benefit the nuclear industry.

Appendix C - Main risks of nuclear power project construction

1) Financing Risk

Nuclear power projects belong to investment in the fixed assets, in which steady cash flow is the priority of success when executing. The proportion of debt capital to equity capital depends on the balance of the fund cost and acceptable risks. In general, project financing risk covers all the risks of the project. Specifically, the significant project financing risks are debt paying ability; investment ability, refinancing, and financial risk (e.g. interest risk, exchange rate risk, etc.).

The project financing risk might be seriously influenced by duration in nuclear power plant project. Delay does not only cost more, but also leads to a series of legal problems if the power plant is not ready for commercial operation when the first loan instalments are due.

2) Design Risk

Generally speaking, design risk of proven technology is relatively low, but the possible design change and documentation and drawing delay is still a bigger challenge to the project if the design work is not organised well on the basis of integrated project schedule. For FOAK (first of a kind reactor), R & D and technical verification at the design phase are the key of risk control. The key of new technology risk control is to take active and effective measures to ensure the rational coherence of R&D, design improvement and construction. At the same time, the R&D of new technologies needs to be matched within the construction progress schedule.

3) Purchasing Risk

Developing procurement schedule should consider manufacturing cycle, required time of interface information for design. For long lead equipment, experienced manufacturers are needed. For the high-risk equipment, redundant procurement is recommended (the additional equipment can be used in next projects or increased cost is acceptable). Equipment with new supplier, new techniques and technology constitute the main risk sources for delay of design interface and equipment delivery procurement management. Mock negotiation simulating execution process is an effective method of risk identification including technology, schedule, cost, quality etc. And then targeted measures can be taken. Demand of localisation is acquired during the development of nuclear power in many countries. The risk of equipment localisation should be well assessed.

4) Construction Risk

Large NPPs projects bear multiple construction risks, such as design changes, late drawings and instructions, lack of resources (especially qualified workers), accidents, equipment commissioning, etc. They must be accurately assessed, and impacts of quality and safety requirements on construction schedules shall not be underestimated.

Section 12. Assuring safety while keeping costs and complexity under control

Recommendations

- The Fundamental Safety Principles set forth by the IAEA are paramount to the development of the nuclear industry. According to these principles, nuclear safety requirements shall consider the latest state of science and technology. However, IAEA remains fairly general in defining any adequate level of nuclear safety, and the question remains: “how safe is safe enough?” The Academies recommend that IAEA reach a clearer view on this complex issue.
- Nuclear safety, for a very long time, will be regulated at national levels. However, the French and Chinese Academies recommend that safety requirements be harmonised at a worldwide level; such harmonisation which happened more than eighty years ago in the aerospace industry is a prerequisite to industrial standardisation. The first step in this direction would be to reach a consensus on safety targets.
- Academies recommend a “Risk-Informed” approach, as implemented by large nuclear countries, where safety requirements are balanced versus their benefits; Academies question any approach requiring that “the best technology which is available” be systematically implemented, independently of its merits.
- While the Academies acknowledge that operating reactors should be regularly back fitted to always be “state of the art”, they recommend that safety requirements be frozen during plant construction, and until commercial operation. Nuclear safety has to be seen in a comprehensive way therefore any change with even improved technologies may not necessarily have an overall positive impact.

From the onset of nuclear energy development, safety has been of overwhelming importance. The main concepts of nuclear safety (ultimate responsibility of the operators, independent safety authority, justification of facilities and optimisation of protection, prevention of accident by means of defence in-depth, mitigation by means of multiple and independent barriers, emergency preparedness and response) have been established at the early days of the industry. They are enshrined in the fundamental safety principles issued by the IAEA, and lastly revised in 2006.

Therefore, there is a broad consensus that proper nuclear safety requirements are the precondition for nuclear power development. It is also acknowledged that these requirements have to evolve overtime as a result of operation feedback, progress in science and technology and social demand for increased protection. Therefore, safety is a developing concept, and a relative issue. However systematically pursuing higher safety targets whatever the additional complexities that they imply is questionable.

Nuclear risk or safety levels should be considered in comparison with the other societal risks and be contained within a reasonable range. It is not appropriate to pursue higher safety blindly. While there was to a large extent, a common view worldwide on safety requirements of Generation II reactors, inspired by the prescriptive objectives issued by the US-NRC, the development of Gen-III reactors reopens two main questions: (1) "How safe is safe enough?", or "is there an appropriate safety level, to which all countries could agree? And (2) Is it possible to develop a single set of safety requirements acceptable to all countries? It is easy to understand that a positive answer to question (1) is a prerequisite to question (2). When comparing recent evolutions of safety requirements in different countries, it appears that regulators are not converging on these major issues.

Acknowledging that absolute safety cannot exist, and that a "residual risk" will always remain in the nuclear industry as in any other industry, it is necessary to have a clear methodology to decide upon the acceptable safety level.

This is answered by the IAEA Safety Objectives and Principles, with the optimisation principle under which "*The safety measures that are applied to facilities and activities that give rise to radiation risks are considered optimised if they provide the highest level of safety that can reasonably be achieved throughout the lifetime of the facility or activity, without unduly limiting its utilisation*". However, if it is assumed that a zero risk should be pursued, or that there is never enough safety, optimisation means maximisation, which could lead to an endless process.

For sure, the nuclear industry must consider state of the art science and technology, but also ensure a better design optimisation, and not systematically add features and increase complexity. To introduce more rationality in the process, the "Risk-Informed approach" should be followed, as developed initially by the US-NRC, and formalised by the IAEA. Under this approach, new requirements are systematically analysed inter alia by means of probabilistic assessments, to make sure that they add safety.

Best estimate analysis when considering beyond design basis accidents is more realistic and avoids over conservative approaches. More realistic design methodologies relying on a good understanding of the physical phenomena should be accepted, as overdesign does not only induce direct costs but may also lead to delays and difficulties in implementation.

Conclusions

Nuclear energy should not be looked at through the glasses of a risk analysis only. It should be considered using both a risk- and benefit-analysis and then weighing the risks against the benefits.

Nuclear safety is an ever-improving process; its progress has been impressive. After many years of development and integration of return of experience, the nuclear industry has reached a high level of safety and, in addition, nuclear energy is also Low-carbon.

In order to improve competitiveness of the nuclear industry there is a need to implement methodologies relying on physical understanding and on qualified simulation models validated experimentally to avoid overconservative solutions. Interactions on technical matters with safety regulators are required to get these methodologies licensed.

It would be good and timely to pursue and deepen the harmonisation of safety regulations on a worldwide basis.

Section 13. Pertinence of international approaches to supporting the preparation of projects in emerging countries

Recommendations

To better support emerging countries nuclear energy programmes by vendor countries, progress should be made in two directions:

- Standardisation and stabilisation of the licensing (and regulatory) processes,
- Generalisation of long-term contracts for electricity purchasing guaranteed by the concerned governments.

Most emerging countries have an urgent need for stable and reliable base load electricity, to develop their infrastructures, their industry, and to cover the needs resulting from the accelerating growth of large cities. The nuclear energy option offers a potential answer to these requirements, supplemented by renewable energy sources, which may appropriately cover part of the needs of the population at the local scale.

At present, there are more than 50 countries positively considering developing nuclear power, most of which are emerging countries, that lack experience in nuclear power construction and feature an infrastructure in nuclear power that is underdeveloped. Therefore, IAEA has established a guide for the construction of nuclear power infrastructure in emerging countries (NG -G.3.1 document « Milestones in the Development of a National Infrastructure for Nuclear Power »). This guide points out three phases that emerging countries usually experience when they introduce the first nuclear power plant, and 19 infrastructure issues that need to be considered more specifically. Combined with the international experience, each emerging country can use this guide to choose its nuclear power development pattern which best suits the domestic specificities.

Furthermore, the philosophy of the international nuclear community, throughout IAEA, is that every country may have access to civil nuclear energy while respecting its proper timeline and situation to fulfil the conditions for maintaining, first of all, the high level of nuclear safety reached by the international nuclear community. The interdependence of all nuclear countries with respect to the prevention of accidents is undoubtedly a constraint. It shall also be an asset when the “old” nuclear countries help the “new” ones to overcome the difficulties and develop their projects. The cases of China and UAE illustrate two different but pertinent tracks.

China has chosen a nuclear power development pattern of introduction, absorption, innovation and substantial planning corresponding to its very large internal market. During the self-reliant design and construction of the Qinshan Nuclear Power Plant in the 1980s, China introduced the nuclear island technology from France and the conventional island technology from UK, and eventually built the Daya Bay Nuclear Power Plant. During the next 20 years, China has gradually formed its own technology system by means of introduction, absorption and innovation and has achieved standardised and mass construction. On this basis, China has introduced third generation nuclear power technology from the USA, France and Russia, from which the advanced design concept was adopted. Combined with proven experience in the domestic construction and operation of nuclear power plants, China has formed its third-generation nuclear power technology-HPR1000 with fully independent intellectual property rights. In this process, China has made great progress in its nuclear power infrastructure, and has gained the ability of a complete nuclear industry exporter.

UAE has chosen a nuclear power development pattern of comprehensive introduction. UAE has adequate reserves of capital and a concrete planning of nuclear power. To rapidly build up the nuclear power system, UAE has chosen a comprehensive introduction pattern corresponding to its lack of experience in nuclear energy research and relevant technology resources. The first nuclear power plant in UAE relies on the Korean nuclear power technology. The design and construction of the nuclear power plant was outsourced to South Korea, and the nuclear fuel supply was outsourced to France and Russia. With regard to human resources, the UAE nuclear energy agency hires experienced talents directly from overseas to take charge of the supervision of nuclear in UAE. Furthermore, UAE has established the International Advisory Board (IAB) formed by renowned nuclear experts from different countries, so as to promote the development of its nuclear power infrastructure.

More generally a « nuclear newcomer » country faces difficulties at three levels:

- Management
- Industrial
- Financial

The first *management difficulty*, results from the lack of nuclear competences in the emerging country, even if it is – and this need is all too often underestimated – only to play an ownership role. These owner-competences have either to be built mainly on a national basis. This has been the case for China, or to be in-sourced by making appeal to foreign competences or experts, like for example the United Arab Emirates (UAE).

The second *management difficulty* is the lack of familiarity with the specificities of nuclear projects; but this can easily be overcome with the help of IAEA or nuclear advisory companies.

The third *management difficulty* is due to the fact that a nuclear project is a programme involving the whole country, which is generally not the case with a classical engineering project. This is perfectly described in the IAEA NG guide.

However, among the 19 items of the « milestones process », and with feedback from recent programmes, three issues appear to be of utmost importance:

- A safety and regulatory national system
- A robust financing scheme
- A long-term and reliable strategy to cope with spent fuel and other nuclear waste

One can easily understand from these considerations that the ability and the long-term commitment of the government of the emerging country are mandatory.

The *industrial difficulties* are mainly related to the fact that an emerging country has in general a relatively weak industry or is at least not familiar with the nuclear specificities and the very high level of requirements in terms of quality, traceability, auditing and control processes. On the other hand, the government generally wishes to reach as rapidly as possible a significant local share of the total project work.

Financing difficulties arise more and more often when the preparatory work of the NPP project arrives at the crucial stage of building the owner company with its shareholders, its governance, its financing means and the ways for return on investment to the shareholders. These items are related to one or several of the following issues:

- The high level of investment required (several G€),
- The limited capacities of the host country,
- The constraints burdening the potential lenders as a consequence of Basel I, II and III accords regulating the banking industry
- The reluctance of the host country governments to guarantee a purchasing price of electricity at rewarding conditions for the owner company on a long-term basis.

Only international approaches seem pertinent to support the emerging country decision-makers and overcome all these difficulties.

Regarding the *management difficulties*, bilateral governmental agreements and solutions by « twinning » appear to be the most adapted for appropriately putting in place a safety authority and a regulatory framework, for organising education and training to build up a human capacity, and for mobilising – on a long-term basis – a capacity of technical support such as research reactors, hot labs or waste labs. Site selection studies could also be added to this list, although the vendor consortium more and more frequently does the characterisation of the site.

The building-up of a first stage of national industrial companies, capable of taking in charge- with the required level of quality- specific work-lots of nuclear projects, is often a shared mission between ministries and industry associations or trade and industry chambers. The most efficient approach seems to be the creation of joint undertakings between the pre-selected national companies and foreign companies that are already experienced with nuclear contractors, or at least setting up a twinning consortium with these companies.

Financing difficulties have until now been overcome mainly by an important involvement of the vendor country(s) and its industrial companies:

- Through equity by the nuclear utility leader of the future operations, and sometimes of the reactor vendor
- Through debt with lenders or through export credit agencies

The use of Build-Own-Operate (BOO) and Build-Operate-Transfer (BOT) contractual schemes, such as those employed in Turkey, is a real novelty in the nuclear domain, although it is currently used in other types of power production schemes.

As a counterpart, long-term contracts for electricity purchasing are mandatory to assure the return on investment. But this system is reaching some limits. Even Russia, who was the most important player in that game, is now facing financial constraints. Moreover, in most countries an excessive confidence in pricing of electricity by the free market reduces the ability of governments to establish long-term contracts, despite the remarkable example given by UK with its feed-in tariffs.

The standardisation and stabilisation of the licensing processes all over the world would give confidence to investors in the NPP projects scheduling.

Generalisation of long-term contracts for electricity purchasing guaranteed by the government would also enhance investors' confidence in the reliability of the forecasted return of investment. Both of these improvements rely on an international cooperation for which a forum to establish the above does not yet exist.

Lastly *Small Modular Reactors*, developed by all the nuclear "vendor" countries could represent a complementary solution in a near future, as they can significantly lower the cost of the initial investment, and simplify and accelerate the implementation. They would probably require an increased level of cooperation between the vendor country and the emerging country especially in terms of regulations, waste, and insurance.

Conclusions

When developing nuclear power, different countries should choose the development pattern which best suits their domestic conditions, and gradually improve their ability in nuclear power development through international cooperation. International approaches and bilateral cooperation turn to be unavoidable for supporting emerging countries in introducing civil nuclear power in their energy mixes. Only they can help solving the management, industrial and financing difficulties arising on the way.

Out of consideration of the security of global nuclear industry as a whole, countries that have gained the ability of nuclear industrial chain supply, such as China and France, should take the initiative to serve the global community by sharing their nuclear energy resources and helping emerging countries to develop nuclear power in a safe and effective way.

Section 14. Human health assessment over fifty years of nuclear power activities

Recommendations

- Fifty years of normal operation of commercial nuclear reactors demonstrate that their radiological impact is extremely low, and well below the level of natural radiation. This fact should be better communicated to the public. It would also be important to report on the health effects resulting from fossil fuels like coal combustion to provide a proper perspective.
- Lethal radiological consequences from severe accidents like Chernobyl and Fukushima were limited; however large territories had to be evacuated for long periods of time. It is therefore important to retrofit Gen-II reactors to further improve the prevention of such accidents, and mitigate their consequences so that no countermeasures would be required except in the close vicinity of the plants and for a limited period of time. In that respect, the safety level of Gen-II reactors should be improved to bring that level as close as possible to that implemented in Gen-III reactors, as was done in France and China.

Since the nineteen fifties, the impact of nuclear electricity production on the health of operators and the public living around NPPs (nuclear power plants) has been the subject of numerous studies. Radiological impacts of exposures during normal operation of the nuclear fuel cycle, as well as in case of accidents have been thoroughly estimated. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) scientific reports, among others, periodically summarise results of these investigations. The concerns about exposure to radiation are covered below. A short explanation about the dose levels and their health effects of radiation exposure is provided in Appendix D.

1. Radiation exposure from normal operations

The annual dose due to natural radiation is around a few mSv/y. The impact of NPPs for individuals living in the vicinity is extremely small, between 1‰ and 1% of the natural radiation and is well below accepted ICRP standard which limit additional exposure to 1 mSv/y. The average annual dose to the workers of the worldwide nuclear fuel cycle (from uranium mining through fuel fabrication and reactor operation to reprocessing) in the period 2000-2002 reported by UNSCEAR is about 1.2mSv, while the occupational exposure limit defined by ICRP for workers is 20 mSv/y.

Regarding uranium mining for example in Canada, the second largest uranium producer worldwide, no increase in radon beyond normal background levels can be observed in the vicinity of uranium mines and the average dose for workers at uranium mines and mills is about 1 mSv/y, significantly below the regulatory limit of 50 mSv/y in Canada.

Indeed, any type of electricity generation, may increase the radiation exposure of the public and workers from activities in the life cycle from mining, construction, operation and decommissioning. An important exposure pathway is the discharge of natural radionuclides (radon and its progeny) from the soil and from geological formations. For example, to obtain the materials for construction of an electricity generation plant of any type, mining activities are needed especially for collecting metallic ores. The UNSCEAR 2016 report contains a comparison of radiation exposures from the different types of electricity generation and their upstream and downstream activities.

It is estimated that the coal cycle contributed more than half to the total collective dose (individual doses times the people exposed). The collective dose is the consequence of all discharges due to a single year's global electricity generation. That estimate was based on the assumption that the discharges are those of modern coal plants. The nuclear fuel cycle including electricity generation, on the other hand, contributed less than one fifth of this collective dose. It is counter intuitive to note that under normal operations, the coal cycle gives rise to a higher collective dose per unit of electricity generated than the nuclear cycle, and a significantly higher dose per unit of electricity produced than the other technologies evaluated, with the exception of geothermal power.

2. Casualties and health effects evaluation of accidents at NPPs

Since the beginnings of nuclear energy to produce electricity, the world has experienced a few significant accidents, involving NPPs entailing the fusion of the nuclear core with large release-consequences:

The Three Mile Island (TMI) accident in March 1979 led to a partial meltdown of the core and resulted in the release of radioactive gases including radioactive iodine (0.55 PBq) into the environment. According to the American Nuclear Society, using the official radioactivity emission figures, "The average radiation dose to people living within ten miles of the plant was 0.08 mSv, and no more than 1 mSv to any single individual." A variety of epidemiological studies have concluded that the accident has had no observable long-term health effects.

The Chernobyl NPP accident in April 1986 led to a total core meltdown and resulted in the release of radioactive gases (1760 PBq of radioactive iodine, 85 PBq of radioactive caesium) and materials into the environment.

One hundred and thirty-four emergency workers suffered 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 leukaemia 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 radioiodine during the early stage of the accident. The thyroid cancer is a rare disease and its prognosis has been improved to a great extent. During the period 1991-2005, more than 6000 cases were reported around Chernobyl in contaminated areas, of these, 15 cases had proven fatal.

Apart from the thyroid cancer from exposure in childhood, the excess occurrence of any other solid cancer and leukaemia in residents of contaminated areas has not been observed. The UNSCEAR committee indicated that "most area residents were exposed to low levels of radiation comparable to, or a few times higher than, the annual natural background radiation levels", "not likely to lead to substantial health effects in the general population" but that “the severe disruption caused by the accident has resulted in major social and economic impact and great distress for the affected populations.”

The Fukushima NPP accident in March 2011 was the result of an earthquake followed by a tsunami. This led also to the melting of three cores of the 6 NPPs installed on the shore of the Fukushima site and the release of radioactive gases (less than 500 PBq of radioactive iodine, less than 20 PBq of radioactive caesium) and materials into the environment.

No acute health effects (including deaths) was encountered directly from radiation. During the first year after accident, the average doses for workers involved in the mitigation of the accident and adults living around areas were about 12 mSv and 1-10 mSv, respectively, and about twice as much for infants. The doses incurred over the first 10 years are estimated ~~up~~ to be twice those induced during the first year. The UNSCEAR report (2013) and white paper (2015, 2016) have reviewed the relevant studies since the accident. The committee considered “a theoretical possibility that the risk of thyroid cancer among the group of children most exposed to radiation could increase. However, thyroid cancer is a rare disease among young children so that statistically no observable effects in this group are expected.”

The UNSCEAR Committee also “noted that the most important health effects that had been observed among the general public and among workers were considered to be on mental health and social well-being”.

That statement would be valid each time large releases of radioactivity would occur. Therefore, a priority was to back-fit Gen-II reactors in order not only to reduce the probability of core melt even further, but also to allow a controlled release of fission products in case of containment overpressure, by means of filtered containment venting systems and other engineering features. The safety level of these reactors, after back-fitting is now as close as possible to the safety level of Gen-III reactors. If such systems had been considered in Japan, no long-term evacuations in and around Fukushima plants would have been needed; such systems are implemented in China and France.

Conclusions

Over the last 50 years of NPPs operations, the feedback from experience of severe accidents show that they do not have any or only a very limited radiation impact on humans if fission products are contained. On the other hand, in case of dissemination, large territories may have to be evacuated. Health consequences to the public from NPPs accidents are also limited: health effects from ionizing radiation depend on the doses received and as shown above, such doses have been low. But the social consequences in terms of mental health and well-being at the local level near the accident sites have been important. This explains why considerable efforts are made to enhance safety in all current and future reactors with the objective of preventing release of radioactivity in any circumstances. Under normal operations of nuclear electricity activities, the levels of radiation exposure to public are very low and even lower than those induced for example by coal-fired electricity (coal naturally contains traces of radioactive elements such as U, Th, Rd, etc., which escape into the atmosphere when coal is burnt in coal-fired electric power plants).

Appendix D. Dose levels and health effects of radiation exposure

People use and are exposed to non-ionizing radiation sources every day. This form of radiation is not sufficiently energetic to ionize atoms or molecules. Examples for such non-ionizing radiations are the electromagnetic fields in the neighbourhood of microwave ovens, radio sets or mobile phones. Some types of radiation, generically designated as ionizing radiation have enough energy to knock electrons out of atoms, upsetting the electron/proton balance of matter and leaving positive ions.

Humans are continuously exposed to ionizing radiation from natural sources ever present in the environment and artificial sources due to radiation application. The global average annual dose to an individual is estimated about 3 mSv (Table 1). About 20 per cent of the exposure is from artificial sources, mainly from medical applications, for example, the dose from one computed tomography (CT) scan of the abdomen is about 10 mSv.

Table 1. Global annual doses of average public exposure by radiation sources (*Radiation Effects and Sources*, UNEP, 2016)

Total natural sources	**2.42 mSv**	**Total artificial sources**	**0.65 mSv**
Food	0.29 mSv	Nuclear power plants	0.0002 mSv
Cosmic rays	0.39 mSv	Chernobyl accident	0.002 mSv
Soil	0.48 mSv	Weapon fallout	0.005 mSv
Radon	1.26 mSv	Nuclear medicine & Radiology	0.65mSv

The energy of ionizing radiation can damage living tissue by killing cells or modifying cells. These health effects are dependent on the dose of radiation exposure. In UNSCEAR reports, the dose is described as high when it exceeds 1000 mSv, it is defined as moderate when it is between 100 mSv and 1000 mSv and it is low when it is less than 100 mSv.

If the number of cells killed by radiation exposure is large enough, it may result in tissue reactions and even death, e.g. loss of hair, skin burns and acute radiation syndrome. The severity of these effects increases with the dose when a certain threshold is exceeded. For example, a dose of more than 1000 mSv could cause acute radiation syndrome. The dose thresholds of possible harmful human tissue reactions are above 100 mSv. Such effects are observed in radiation accidents or in radiotherapy.

If the modification of cells irradiated is not repaired, it may result in cancer or heritable disease affecting offspring. These effects are stochastic, and the probability of their occurrence depends on the radiation dose received. The UNSCEAR 2010 Report indicated that “There is strong epidemiological evidence that exposure of humans to radiation at moderate and high levels can lead to excess incidence of solid tumours in many body organs and of leukaemia”. For example, 10423 survivors of the atomic Hiroshima and Nagasaki bombings died from cancers (solid tumour in addition to leukaemia) up to December 2000, of which 572 cases (about 5%) could be attributed to the radiation exposure from the bombing. However, there is no clear evidence of excess heritable effects of radiation exposure in humans.

Section 15. Risk perception relative to real hazard

Recommendations

- More efforts should be made to promote and implement the nuclear safety culture, and improve a two-way interactive communication to help the public viewing the nuclear risks in rational and objective ways.
- More efforts should be directed towards explaining in simple terms what measures have been taken after Fukushima to strengthen the safety of the existing Generation-II NPPs and improve the designs of the Generation-III and -III+ NPPs. With respect to the severe nuclear accidents, it should be especially emphasised firstly: the implementation of prevention features which reduce by an order of magnitude the probability of occurrence of such accidents, and secondly the limitation of any radiological consequences of such accidents to the close vicinity of the plant, and for a limited time period only.

Every time that a new technology emerges, two logics, almost metaphysically confront each other. One logic is reduced to the evaluation of the costs/benefits balance, the logic of operating and industrial players, who must innovate to remain competitive. The other logic pays attention to the negative consequences of the technological innovation and attempts to re-build an approach whereby « rationality » would impose limits to the conclusions from such costs/benefits estimations by taking into account other, more ethical, qualitative or indirect considerations.

Following this line of thought engineers and scientists are enjoined to focus all their efforts at avoiding – at any price – not only the catastrophe but also the shadow of a possible catastrophe! From evidence in most countries in the world, one can say that nuclear activities are supporting this goal and are therefore an obvious illustration of this observation.

Hence, it is necessary to recall that if the existence of a risk requires the existence of a danger, risk should not be confused with danger: risk is the multiplication of the exposure by the danger. If there is no exposure to a danger, there is no risk.

One can imagine that risk perception corresponds to the correct assessment of the risks themselves as soon as they are objectively proven. But this is a utopian dream, which can be analysed from three perspectives:

- Psychological
  Risk perception does not only rely on non-rational factors. Everybody builds his/her own “basket of risks” and manages it with a certain level of rationality. For example, some risks are accepted according to the compensation they provide; this is for instance the case for the inhabitants around a nuclear power plant or facility.
- Sociological
  The perception of risks strongly depends on culture, country and history.

Moreover, risks selected by an individual are not dreaded in the same way than risks experienced collectively. Nuclear energy is a mode of production of electricity that has not been explicitly chosen by most of those who could be affected by its drawbacks.

- Communication
  The subjects of communication affect risk perception and risk value judgment of the public. Since nuclear energy is highly scientific and technical and most members of the public do not have much experiential knowledge on it, one expects that the media will perform a strong heuristic role in shaping public perceptions on nuclear risk a role that has become more pervasive in the current era of Web based media.

Analysis of risk perception regarding nuclear energy from the perspective of psychology

Psychology surmises that the individual perceives risks through cognitive psychological mechanisms. The risk-related cognitive deviation is linked to the individual's cognition and judgment. The causes of risk-related cognitive deviation include: subjective factors such as individual personality traits, knowledge and experience, "loss" or "expectation of risk”, and objective factors such as the nature of risk, size, degree of control and comprehension factors. Hence, for different kinds of people there are differences in their understanding of risks related to nuclear energy; for professionals, identifying the risk is usually based on technical evaluations weighing the pros and cons; on the other hand, the public tends to perceive its own interests closely related to safety and health, ignoring the benefits of nuclear energy, giving rise to the NIMBY[6] syndrome directed at nuclear facilities.

The public usually regards potential catastrophe, uncontrollable and unknown as the intuitive characteristic of nuclear energy, which was aggravated by the TMI, Chernobyl and Fukushima accidents. The public is not usually aware that the radiation effects of normal operation of nuclear facilities are much lower than those of the coal industry and that new Gen-III and Gen-IV reactors are designed to prevent release of radioactivity in any circumstances. However, the public still believes that nuclear risk is much higher than that induced by other industries.

Results of a survey conducted by government departments, researchers, and the media of public acceptance of nuclear energy in China indicate that:

- The public disposes of limited information sources on nuclear energy and is in lack of basic knowledge,
- A majority of the public worries about the development of nuclear energy is mainly caused by low public participation, lack of information transparency and apprehension about nuclear safety. As a result, only 40% of the public supports the development of nuclear power in China,
- The Fukushima nuclear accident has had the consequence that the public has become more sensitive to the possible development of nuclear energy projects, and is opposing such projects, especially near their homes.

In France, the main findings of the « IRSN 2016 Barometer on risks and security perception by the French public » are:

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[6] Not in my backyard

- Terrorism has become the first worry,
- More than one French in two declares that they have more confidence in science than ten years ago and also that they trust experts and technical and scientific organisations when intervening in the nuclear domain,
- The majority is in favour of giving the public access to the results of expertise,
- Although 46 % of the respondents think that all precautions are taken to assure a very high level of safety in the French NPPs, about 90% think that an accident in a nuclear power plant would have very serious consequences.

Analysis of risk perception regarding nuclear energy from the perspective of sociology

The perception of risk of an individual is not just based on individual psychological cognition, but is also associated with the social organisation or social system. The individual risk perception is affected by social position, community influence, and social background. Disaster events interact with psychology, society, system and cultural status, which can profoundly influence risk perception. This is known as the social chain effect of risk perception: when fear is more frequently mentioned in conversation or in the media, the public pays more and more attention to the related information, and finally “perceives” (imagines) a risk, which is an actual strong deviation from the factual risk. For example, after the Fukushima nuclear accident in Japan, the United States, France, Germany and some other countries, the consequences of this deviation manifested themselves in the phenomenon of buying iodine tablets. In Malaysia, the Philippines and Russia, the phenomenon appeared in the form of buying iodine tincture, in South Korea it was seaweed product snapping, and in China buying of iodized salt. More importantly there are examples where nuclear projects have been brought to a halt because of public protest, a situation which needs to be carefully investigated to find better ways of managing such societal crises.

Analysis of risk perception regarding nuclear energy from the perspective of communication

The subject of risk-related communication involves national government agencies, scientific experts and scholars, the public, the media, non-governmental organisations and so on. Different subjects of communication will affect the different risk transmission effects, especially the public risk perception and risk value judgment. After the Chernobyl accident, the various reports from the government, the media and organisations on casualties caused by the accident differed in a notable manner, leading to a situation where the public was no longer able to make the correct judgment regarding the real impact of the accident.

The public is highly sensitive to the acquisition and trust of risk information. As a result of incomplete risk information, such as government avoidance measures or ambiguous attitudes towards risk handling, the public’s fears of risk tend to increase leading to a loss of confidence in the information provided. Media coverage and qualification of the "hydrogen explosion" in the Fukushima nuclear accident as a "nuclear explosion", also tended to promote public panic.

China is dedicated to improving its national nuclear safety system, enhancing nuclear safety capabilities and boosting nuclear safety culture. In 2014, nuclear safety was formally incorporated into the Chinese national security system.

The problems, challenges and difficulties of nuclear risk perception

Risks are both objective and influenced by media communication, individual perception and judgement, and by social, institutional and cultural factors. With the emergence of nuclear power plant construction and accidents in the world, and the changes and development of nuclear power policies in various countries, the public's cognition of nuclear power has also changed, indicating a high degree of attention to this matter, a limited degree of acceptability and cognition, and subjective and irrational characteristics of attitudes. How to improve public awareness, regulate the dissemination of information and reduce public panic: these are the challenges and difficulties of global nuclear energy development.

To have a better understanding of what could be done to improve public awareness and in the light of the above considerations, it is of utmost interest to recall two major discrepancies between real hazard and risk perception in nuclear activities.

- *The real hazard* is that accidents at Generation-III+ nuclear power plants will not entail major radiological consequences in case of severe accidents (and will only require limited countermeasures).

  The *subjective public perception of the Risk* is, however, that in case of airplane crash or a severe accident damaging the reactor core, sizable quantities of radioactive products would still flow out of the containment building.

- *The real hazard* is that the noxiousness of low radioactive levels and doses is still an important subject for biology studies, without clear conclusions for the time being. But the return of experience on populations living in regions with « high levels » of natural radiation (Kerala, Britanny, etc..) show no perceptible long-term effects.

  The *subjective public perception of the Risk* is, however, that the « first Becquerel » originating from a nuclear power plant or facility is dangerous for human health. But if that Becquerel is linked with radiography at a dentist or at a hospital, it is not.

Conclusions

The policies of full transparency and information of the public about the results of scientific and technological studies dedicated to nuclear issues and projects seem to be fruitful. They strongly contribute to reducing the gap between real hazards and risks perception by the public. However, the public generally overestimates the real hazards of nuclear energy because of limited scientific and technical knowledge. Work remains to be done to make the public aware of the huge progress in safety due to the post-Chernobyl and post-Fukushima measures put in place on all the reactors around the world: by means of adequate prevention features, the estimated probability of accidents with core melt has been reduced by a factor of ten, both for the existing fleets in France and China, and for Gen-III reactors. Also mitigating features have been back-fitted in existing reactors, or implemented in the design of new reactors which would drastically reduce radiological consequences of such accidents; thus, no countermeasures would be needed, except in the close vicinity of the plant, and for a limited time only.

Section 16. Improvement of Public Awareness and Governance Requirement

Recommendations

- Countries developing nuclear energy must share information and arguments to explain the driving advantages and weaknesses of nuclear energy and remedies to enhance public awareness. The role of nuclear energy as a stable and reliable source of dispatchable electricity free of greenhouse gas emissions needs to be emphasised.
- Nuclear operators and stakeholders should have a positive communication strategy on the successful operation of NPPs and be transparent on disclosing events.
- Beyond the shared arguments and messages, communication strategies should take into account the different development rates of those countries that massively introduce intermittent renewable energies. There is no reason that such massive introduction be conflicting with nuclear energy if renewables serve to replace fossil fuel plants and not to reduce the already carbon free nuclear electricity.

For both Industrialised and Emerging, Western and Asian countries and more generally on a worldwide scale, the driving advantages of nuclear energy are:

- No emission of greenhouse gases, supporting the fight against climate change
- Large power operated as base load, assuring the stability of the network and allowing the development of industry and heavy infrastructure at the level of a country
- A today abundant and secure availability of low-price electricity compared to other sources
- No need for storing electricity, which strongly penalises intermittent energies

On the other hand, the driving weaknesses are:

- The burden of high-level long-lived radioactive waste disposal, admittedly with relatively limited volumes but during hundreds of thousands of years
- The effects of severe accidents on large areas and significant populations

In all these countries, the basic efforts to improve public awareness will consist in providing accessible information on each of these items, with special attention to quantifying the issues, and discussing solutions.

What distinguishes countries and requires a differentiated treatment, is the trend in electricity growth. In China and more generally in rapidly developing economies, the fast increase in electricity demand allows a progressive and substantial introduction of intermittent renewable generating capacity that does not oppose the simultaneous development of a strong nuclear energy sector. The situation is quite different in Europe, where the perspectives of electricity consumption are relatively flat (but might be on the rise again if fossil fuel consumption were to be replaced by electricity). Therefore, while a major and rapid introduction of intermittent carbon-free renewable energy (solar and wind) requires large investments, the main consequence will be to reduce the demand for nuclear generation. However, this has very limited impact on CO_2 emissions, as nuclear energy is equally carbon-free. Furthermore, it has also very limited effects on the installed nuclear capacity, which has to be kept in place to provide the necessary back-up for the intermittency of renewable energies.

The fashionable belief that the development of intermittent energies “allows to take steps in imagining the world of the future” together with more or less philosophical ideas like those of the “theory *of negative growth*” compounds the difficulty in Europe requiring new arguments and further efforts to enhance less emotive public awareness.

Further arguments and details related to the five items mentioned previously can be found in other sections of this report. In particular, issues related to the management of radioactive waste are considered in Section 4, where it is shown that disposal of the long-lived radwaste in deep geological repositories is feasible. Accidents involving nuclear power plants and other installations are reviewed in Section 12 together with the considerable improvements that were accomplished at current installations and included in the design of Generation-III systems. However, additional considerations are useful for a better understanding of the present situation in Europe.

Currently, and probably in the coming decades, climate change issues will not be sufficient to convince public and political bodies to welcome new NPPs without the strong governmental support that one finds for example in Finland and the United Kingdom. Such governmental support must be available in the short- and medium-term during the decision phase (5 to 10 years) and the construction phase (5 to 10 years) but also in the long-term e.g. during the operational lifetime of the plant (at least 60 years).

If the contribution of nuclear energy to the reduction of CO_2 emissions is known to the public (but more or less denied by several anti-nuclear NGOs!), its value is not fully appreciated. The economic benefits (once again at least in Europe) in terms of generation costs are being questioned in a context where more stringent safety requirements have led to rising production prices, while photovoltaic production costs have significantly decreased.

Today, the technological, industrial and economic culture of politicians, media and the public in general is relatively limited and short-term oriented. Industrial assets and economic considerations are all-too often underrated in the balance with political or even philosophical arguments in some major decision-making processes.

Fortunately, there are political decision-makers who take in consideration economic objectives and technological constraints. This is the case with many of the members of the French Parliament belonging to OPECST (the Parliamentary Office for the Evaluation of Scientific and Technical Choices). This office carries out well-informed investigations and delivers high quality reports that are often ignored by the pubic and by the media but that deserve to be taken into account when deciding about complex issues in the energy field.

But in almost all these countries, the major misunderstanding lies in the pace of the “energy transition”. There is no reason requiring a substitution of nuclear electricity by intermittent renewables in less than 50 to 100 years if this intermittency then requires back-up through fossil fuel fired electricity generation! This is the central additional message that must be offered to the public.

Public Awareness and Governance Requirements are very much influenced by Communication Strategies of nuclear operators but also of anti-nuclear NGOs. Utmost attention must be given to preventing that messages of nuclear operators be completely turned upside-down with respect to their initial meaning. As an example, the EDF motto “Safety First” has been interpreted by many people as “The EDF nuclear power fleet is currently unsafe” and needs urgent modifications. This interpretation is especially associated with the enormous amount of the investments required by the so-called “Grand Carénage”.

In order to start building new nuclear facilities on “green field” sites, strong governmental support is needed and long and well adapted procedures are mandatory. This is mainly not due to local opposition but to professional international opponents and – at least in France – to a complex network of environmental laws, such as the Law on water, the Law on coastlines, the Law on biodiversity. Even the extension of existing sites may become problematic. In China, some inland projects are still on hold since the Fukushima accident.

Conclusions

The benefits of nuclear energy and in particular its stable and massive production of electricity with low emissions of greenhouse gases are not sufficiently publicised. The need for base-load production of electricity is not well understood by the public and there is an insufficient appreciation of the remarkable services provided by the electrical network, its stability and its relatively low sensitivity to meteorological conditions. It is necessary to bring more reality into the debate about the energy mix. In particular it must be emphasised that the intermittency of renewable energy needs to be compensated for: when renewables do not produce electricity because there is no sun or wind, then back-up capacity must be brought on line, as electricity storage facilities are not available, and may not be available for many years. If the conventional back-up capacity is then based on combustion of fossil fuels, it will induce emissions of GHG. In addition, when the amount of renewable energy generating capacity exceeds a critical level, there will be severe stability issues concerning vast swathes of interconnected grids. This is due to the necessity for conventional generating capacity to operate in a highly intermittent fashion, which may not be technically or economically sustainable.

It is worth explaining these fundamental issues to the public and showing that nuclear energy is needed to safely and continuously produce electricity in large connected electricity networks responding to the growing demand of an urbanised society. Because positions about the energy mix are often influenced by emotional arguments, there is a need for enhancing the level of understanding in terms of technological constraints and fundamental economic objectives and to provide further information on safety issues and on progress made to deal with accidents in a safe manner. This might be achieved with better communication strategies and improved education in energy matters so that people understand the issues without falling victim to misleading arguments and developing an opinion based on a rational analysis of facts.

It is also important to take into account countries’ different development rates, which in cases of slow economic development may create conflicts between the massive introduction of intermittent renewable energies and nuclear energy, while in cases of rapid economic development they may not.

Section 17. Organisation, methodologies and roles of the different stakeholders to improve public understanding

Recommendations

To improve public acceptance, it is recommended that actions be taken at three different levels.

- On the technical level, it is important to take full account of experience drawn from major accidents to operate current power plants in a safe and efficient manner.
- On the organisational level, central governments should formulate their energy strategy and strive to carry it out. A clear separation is needed between operators on one hand, and safety authorities and their safety support organisations on the other hand. All actions at the local level to positively establish an accessible dialog platform for the public will improve confidence.
- On the communication level, it is important to make these efforts known to the public at large: organise access to transparent, exact and structured information. In order to take due account of social acceptability, it is important to develop education on energy issues, essential technical and economic factors, environmental impact and risks, and improve public understanding of fundamental energy challenges.

Experience drawn from the major accidents of Three Mile Island, Chernobyl and Fukushima, has led to reconsider the risk factors that must be taken into account in order to be better prepared in the event of having to face a large release of radioactivity into the environment and have stressed the need for independently and transparently informing the public on nuclear issues. This requires different types of action.

The *first type of action* is essentially technical and consists in making constant progress in plant operation in terms of efficiency and safety and integrating the return from this experience into the current fleet of nuclear plants and into the engineering design of future power plants. In order to manage risk factors effectively, they need to be rationally analysed and prioritised. This has led to third-generation reactors that have considerably improved characteristics of resistance to accidents and to various aggressive acts.

The *second type of action* is organisational and involves three levels of stakeholders:

- Central governments and their functional departments of energy, education, communication, health, etc.;
- All stakeholders of the nuclear industry, which includes supervision departments, operators, safety authorities, independent technical supporting organisations, industry associations, etc.;
- Local authorities and the public in the areas where nuclear projects are located.

At each of these stakeholder levels, different responsibilities and potential for actions can be identified:

1. Central governments should harmonise their national framework in order to formulate their national energy development strategy, including for the development of nuclear energy. Then they should strive to pursue its implementation, and coordinate their subordinate functional departments to commit to the national energy strategy.

2. All stakeholders of the nuclear industry have to structure the nuclear sector in a rigorous manner clearly defining their respective roles so that they engage and practice a safety culture. This is defined by the IAEA guidelines as "*the assembly of characteristics and attitudes in organisations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance.*" To implement this culture, it is appropriate to spell out the roles of the different actors:

- The responsibility of safety relies primarily on the operators of the nuclear reactors.
- The operations are placed under the administrative authority of an independent public safety agency, which controls all the civil nuclear installations. In France, its independence is guaranteed by the fact that its members are nominated for a six years irrevocable mandate. This agency organises regular, mandatory inspections of nuclear sites and equipment, delivers the authorisation for operations and has the power of interrupting them under all circumstances when it considers that this is necessary.
- The administrative agency needs to rely on a strong technical expertise; it can develop it in-house, or be backed by one or several Technical Support Organisations (refer to Section 7).

3. At the local level, different situations can be encountered with respect to the type of decentralisation of the country. For example, in France, the local representative of the Central government (the ”Préfet”) is the only interlocutor of the operator. Local authorities are committed to consult and inform the public in the areas where nuclear projects are located: projects related with nuclear energy are formulated through complete decision-making procedures. After projects are approved and construction needs to be prepared, local authorities should, together with operators, positively establish accessible dialogue platforms for the public as well as transparent information disclosure mechanism. In addition, local authorities should actively explore ways to seek integrated development of nuclear projects and local economic and social progress including support in the form of financial contributions from the nuclear project and local employment.

In some cases, in France, public consultation of citizens needs to be organised prior to decisions, in order to better understand the source of fears. This was done for instance for the planned deep repository of nuclear wastes project named CIGEO.

The *third type of action* is to make these efforts known to the public by enhancing its awareness and understanding.

However, the lack of a basic education on radioactivity and the invisibility of radiation, the association in many minds of nuclear energy with nuclear weapons, leave much space for fears. Even for the most obvious benefits of nuclear physics, such as the irradiation of tumors to cure cancers, the use of nuclear magnetic resonance in medical imaging, the understanding of the history of our planet through radio-isotopes, the adjective “nuclear” is banned from the vocabulary as too scary. It has become clear that the future of the nuclear industry will depend to a great extent on public understanding and acceptance of this technology. This is illustrated in Europe by countries such as Italy that now refuses any nuclear industry, or like Germany that has decided after Fukushima to close its nuclear power plants by 2022. It is thus important to explain the safety measures that have been included in the new designs by assuring the transparency of information, providing the necessary education, and responding to growing demand for information from the public at large. It is also timely to improve the way we inform the public and communicate on accidents and incidents, be they natural or man-made. In France, at the national level, a high-level committee for the transparency and information on nuclear safety (HCTISN) guarantees that exact and accessible information on the civil nuclear operations is available to the public.

Conclusion

Beyond the many actions taken to insure the safety of operation of nuclear power plants, it is important to spell out the roles of the different stakeholders and provide transparent, exact and structured information. This constitutes the best response to different negative attitudes towards the development of nuclear energy. It is also important to underline the benefits of nuclear energy as a safe, clean and effective electrical energy and as an asset of economic development.

Glossary

ABWR: Advanced Boiling Water Reactor

APWR: Advanced Pressurised Water Reactor

ASN: Autorité de Sûreté Nucléaire (France)

BOO: Build Own Operate model

BOT: Build Own Transfer

BWR: Boiling Water Reactor

CAD: Computed Aided Design

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

CEFR: China Experimental Fast Reactor

CGN: China General Nuclear Power Corp.

CNNC: China National Nuclear Corporation

COP: Conference of Parties to the United Nations Framework on Climate Change

DOE: Department of Energy, US

EDF: Electricité de France (French Utility)

EPR: European Pressurised Water Reactor

ESBWR: Essentially Simplified Boiling Water Reactor

EUR: European Utilities Requirements

FNR: Fast Neutron Reactors

FOAK: First of a kind

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

GIF: Generation-IV International Forum

HL-LLW: High level Long-lived waste

HLW: High Level Waste

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

IAEA: International Atomic Energy Agency
ICRP: International Commission on Radio Protection
INSAG: International Nuclear Safety Advisory Group (advising the IAEA general director)
IRSN : Institut de radioprotection et sûreté nucléaire (France)
IT: Information technology
LL: Long-Lived (Waste)
LLW: Low Level waste
LWR: Light Water Reactor
MOX: Mixed Uranium-Plutonium oxide
MSR: Molten Salt Reactor
NEPIO: Nuclear Energy Programme Implementing Organisation
NGO: Non-Governmental Organisation
NNSA: National Nuclear Safety Administration (China)
NPP: Nuclear Power Plant
NRC: Nuclear Regulatory Commission (USA)
PLM: Product Lifecycle Management
PPA: Power Purchase Agreement
PWR: Pressurised Water Reactor
R&D: Research and Development
RW: Radioactive waste
SBO: Station blackout
SFR: Sodium-cooled Fast Reactor
SG: Steam generator
SMR: Small Modular Reactor
SWU: Separation Working Unit
TMI: Three Miles Island
TNR: Thermal Neutron Reactor
TSO: Technical Support Organisation
UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation
URD: Utility Requirement Document (developed in the United States)
VHTR: Very High Temperature Reactor

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Chinese working team

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In the present situation where much of the electrical energy production is based on fossil fuels and more specifically on coal, nuclear energy constitutes one of the most realistic options for supplying electricity in a safe, efficient and clean way and for simultaneously solving environmental and climate change problems. Because it is a stable and massive source of energy, it can reliably provide dispatchable electricity and can complement renewable electrical energy sources (like wind or solar) that are mostly intermittent and are not easy to mobilise to respond to demand.

The development of nuclear energy still raises many challenges and issues with regard to safety, management of long lived radioactive waste, development and deployment of advanced nuclear reactors, economics, public acceptance, etc. As two of the main countries with large capacities of nuclear power plants (NPPs), both China and France attach great importance to the peaceful use of nuclear energy in the world, and have the responsibility and willingness to help emerging countries in their development of NPPs and in their wish to resolve the challenges they will face.

In the continuation of COP21 and COP22 aimed at 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) believe that their initiative to shed light on some of the complex issues related to nuclear electricity generation could send a strong and valuable message to other countries' academies, decision makers and society in general.

The present 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. In this report, the contributing academies aim at outlining the history and perspectives of nuclear energy, and address the key issues to be considered in order to make nuclear energy even safer and affordable for the benefit of developed and emerging countries. Although this report touches on many issues, it is not intended to be exhaustive. It synthesises reflections and discussions carried out over a period of six months.

The report comprises a synthesis and a set of seventeen sections. Two sections give a brief account of the history, problems and challenges of nuclear development and address issues concerning the deployment of Gen-III NPPs. Two sections deal with scientific aspects, including promises and challenges of future reactor designs and specifically consider the Gen-IV situation and new small modular reactor (SMR) concepts. One deals with nuclear waste management. Technological issues are then addressed and safety issues are discussed pointing the need of Technology Support Organisations, advances and challenges in digitalisation and in novel design tools. The importance of nuclear research, facilities and infrastructures is underlined. The question of education and training of manpower is examined. One objective is that of attracting young graduates from higher education in the nuclear industry. Another is the training of employees in the utilities to give them the proper scientific background and the culture of safety management. Two sections deal with engineering issues including that of managing nuclear projects, questions of handling safety requirements while controlling costs and complexity. The pertinence of international support of nuclear projects in emerging countries is examined.

Societal issues are considered in the last four sections. An assessment is provided of the impact of global nuclear activities on human health during the last fifty years. Since safety is a central issue in the operation of NPPs, it is necessary to the perception of risk to be analysed compared with the real hazards. The report underlines the need to improve public awareness and considers the governance needed for that purpose and the organisation and roles of the different stakeholders to improve public understanding and limit the risks of increasing regulations that would complicate the development and operation of nuclear facilities.