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NEA News

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NUCLEAR ENERGY AGENCY

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The Nuclear Energy Agency (NEA) is an intergovernmental organisation established in 1958. Its primary objective is to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes. It is a non-partisan, unbiased source of information, data and analyses, drawing on one of the best international networks of technical experts. The NEA has 31 member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Russia, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The NEA co-operates with a range of multilateral organisations including the European Commission, the International Atomic Energy Agency and others.

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Another nuclear crossroads

It seems that every few years since the 1970s, one respected expert or another has penned an article or spoken to a gathering interested in nuclear issues and declared that nuclear power was at a crossroads. Generally, this was meant as a clarion call to industry and government proponents that unless various actions were taken, the future of nuclear power would be in question. With the actions proposed, one path would lead to a greater use of nuclear energy; without action, the alternative path would be a bleak one with a lingering trail of ageing plants, ageing infrastructure, slow decline and inevitable oblivion.

Today, once again, nuclear power is certainly at a crossroads; but this time the roads before us are very different from the paths those respected experts saw before them in past decades. Based on analyses collected in various NEA and International Energy Agency studies and the realities on the ground, the question about whether the world will expand its reliance on nuclear energy appears to have been resolved. As highlighted in an article featured in this edition of *NEA News*, "Nuclear new build: Financing and project management," there are more nuclear power reactors under construction today than at any time in history. There are more countries building, planning and preparing for new nuclear plants than in any previous era, and many are taking paths and approaches never before attempted. There are many more technological options than ever before – including a diverse array of new light water reactors of various capacities, small modular reactors and even a floating reactor. There is a wider array of vendors offering new designs under a great variety of contract and financing terms – most with significant governmental support – than has been seen before. These elements, taken together, appear to point to a future in which the world as a whole will become increasingly reliant on nuclear energy.

The crossroads we face, therefore, is not one that will see the world choose between the decline of nuclear energy and its increased use; it is a crossroads that challenges us to consider what kind of nuclear future we will have.

The diversity of technologies, suppliers and customers has brought a new vitality to the discussion about nuclear energy, but has also raised important questions about what approaches might be needed to assure high levels of nuclear safety in the future; how strong safety cultures, adequacy and pedigree of components and parts, and appropriate operational practices, will be assured. Even old questions such as "what technologies will the future rely upon?" and "how will we ultimately address used nuclear fuel?" appear more difficult to analyse and answer. New questions are being asked about how countries with limited technological infrastructures will build and operate large nuclear plants, what role small modular reactors will play and how markets will be shaped to support efficiently high capital cost and low-emitting technologies such as nuclear and wind power in an era of inexpensive gas.

As is the case in so many other areas of life today, the future of nuclear energy is at once more complex than ever before and a creature of our interconnected world. Whether countries choose to build many plants or phase out the plants they currently operate, the global expansion of nuclear energy is a reality that will impact us all. What kind of nuclear future do we want?

William D. Magwood, IV
NEA Director-General

Nuclear new build: Financing and project management

by J.H. Keppler and M. Cometto*

A considerable number of nuclear reactors continue to be built around the world. Since the year 2000, construction has begun on 77 new reactors and 47 new reactors have been connected to the grid.[1] To assist policy makers, vendors, investors and electricity producers alike in drawing the appropriate lessons from recently concluded or ongoing projects and integrating these experiences, a new NEA study, *Nuclear New Build: Insights into Financing and Project Management,* analyses a wide range of new build projects from three different perspectives. The first is from the point of view of the management of long-term electricity price risk in co-operation with electricity market regulators and governments. The second is from the perspective of the structure of financing, the composition of investors and the allocation of financial risks during the investment phase. And lastly, the study provides analyses from the perspective of project management and the structure of the supply chain during construction, as well as the integration of overall best practices. It also combines quantitative modelling with economic analysis for each of these areas, as well as empirical results from recent projects, identifying wherever possible factors that have contributed to successful nuclear new build projects.

New build overview

The beginning of the 21st century has seen a renewed interest in nuclear power, in particular in economies with fast-growing electricity demand such as China and India. Despite a reduction in planned projects following the Fukushima Daiichi accident, a substantial number of nuclear plant construction projects remain active around the world. The World Nuclear Association database shows 68 nuclear power plants under construction and 159 currently planned (see Table 1).

The largest single market is China, with 56 reactors planned and 27 under construction, followed by Russia and India. Compared with the current operating fleet of 435 reactors worldwide, this represents a geographical shift from the United States and Europe towards Asia. The total value of planned new build is estimated at approximately USD 1 200 billion, and opportunities for the supply chain are worth some USD 575 billion.

Table 1: **Reactors currently under construction or planned**

Region	Under construction	Planned
Europe	4	19
Russia and Former Soviet Union	11	30
China	27	56
Remainder of East Asia	10	10
West Asia (Middle East)	2	8
South Asia	7	24
Southeast Asia	–	4
Africa	–	1
North America	5	7
South America	2	–
TOTAL	68	159

Source: World Nuclear Association.

Long-term solutions for electricity price stability and financing

Electricity market risk, and in particular uncertainty in the long-term evolution of electricity prices, is an important element of the financial risk that developers of new nuclear projects face. Capital-intensive technologies such as nuclear energy and renewables are more vulnerable to changes in the long-term level of electricity prices than dispatchable technologies such as coal or gas-fired power plants, which are characterised by lower specific investment costs.

Because of their high fixed costs, low-carbon technologies such as new nuclear power plants would therefore benefit from a stable, guaranteed level of electricity prices over a substantial period. Indeed, such stability is important for nuclear energy

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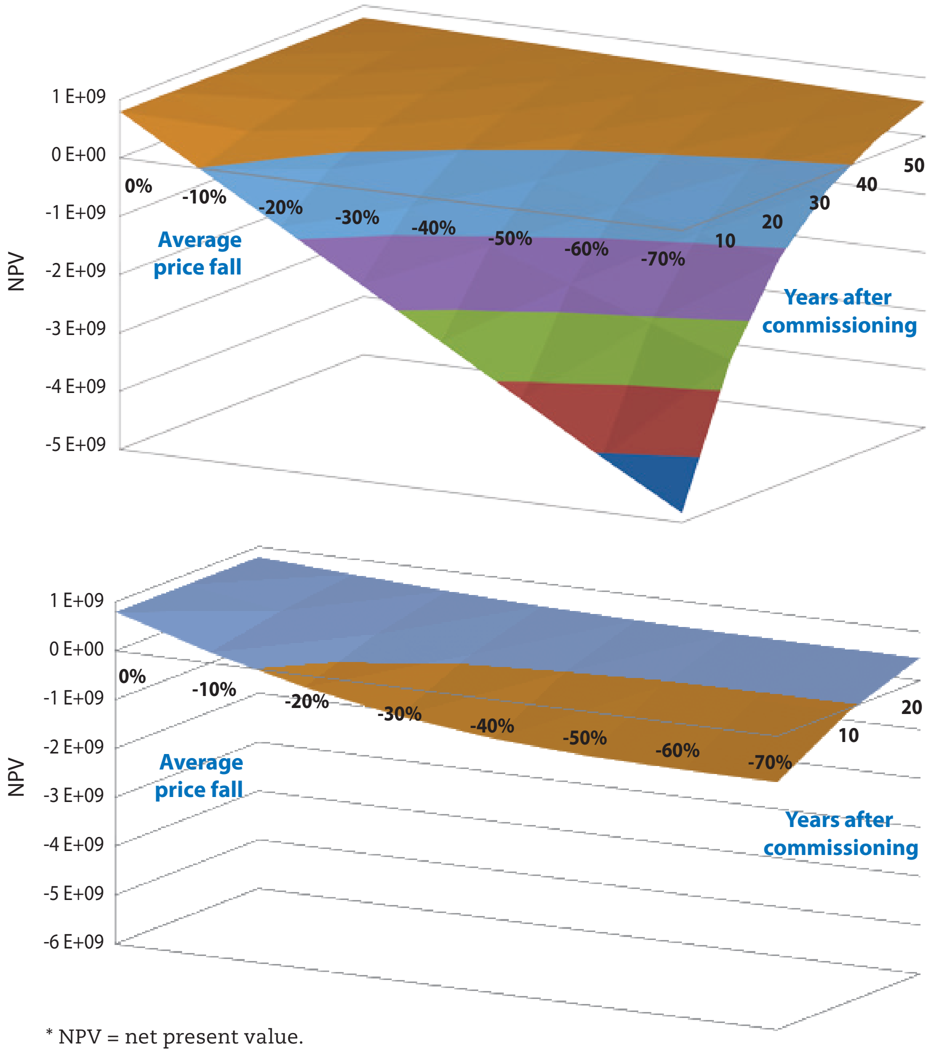
Figure 1: NPV* sensitivity to long-term declines in electricity prices for a gas plant (top) and a nuclear power plant (bottom)



* NPV = net present value.

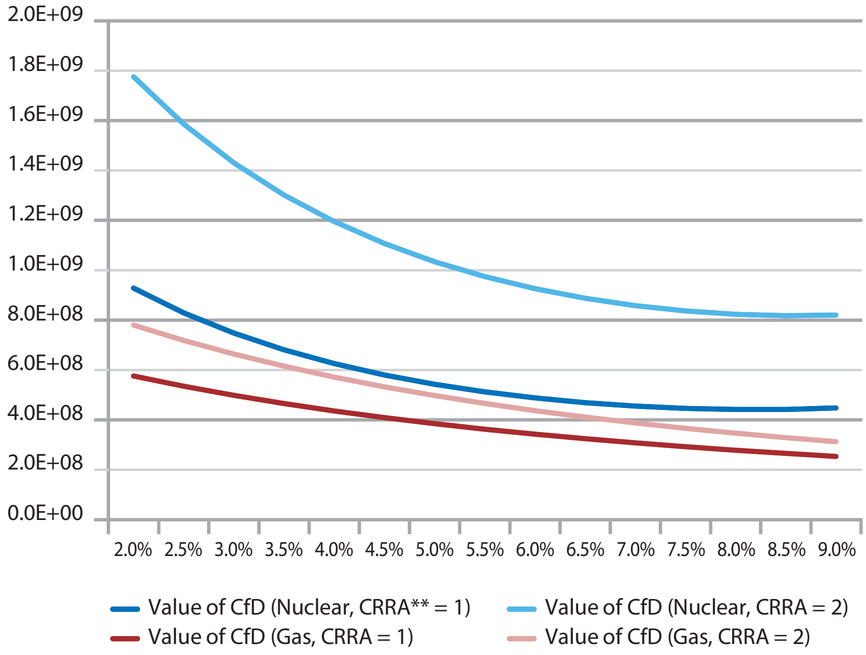
to compete against other baseload technologies such as coal-fired power plants or combined-cycle gas turbines. It is exceedingly difficult for investors to absorb long-term electricity price risk when two-thirds or more of total lifetime costs are due before the date of commissioning.

In a first step, the economic and financial analysis of the study compares the respective exposure of gas-fired and nuclear power generation to electricity price uncertainty and examines the option of leaving the market in the case of a permanent fall in electricity prices. In a second part, the study more specifically addresses the financial risk associated with the development of a new nuclear project, taking into account not only uncertainty about the future evolution of prices but also about the cost of construction and operations, as well as the implications of different ratios of fixed cost to variable cost for bondholders and equity investors.

The first objective of this analysis is to compare the profitability of a nuclear power plant with that of a gas-fired plant under different scenarios of electricity price decline. This quantitative analysis is based on real daily prices for gas, carbon and electricity in European markets over the period 2005-2010 so as to establish the net present value (NPV) of two alternative power generation projects of 1 000 MW, a nuclear plant and a gas plant. In order to allow for a meaningful comparison of the potential exposure of these two technologies to price, the NPVs of the two plants under price stability were normalised. The results are presented in Figure 1 for a real discount rate of 5%. The horizontal axis shows different levels of price declines, the depth axis shows different years for the onset of the price decline and the vertical axis shows the NPV.

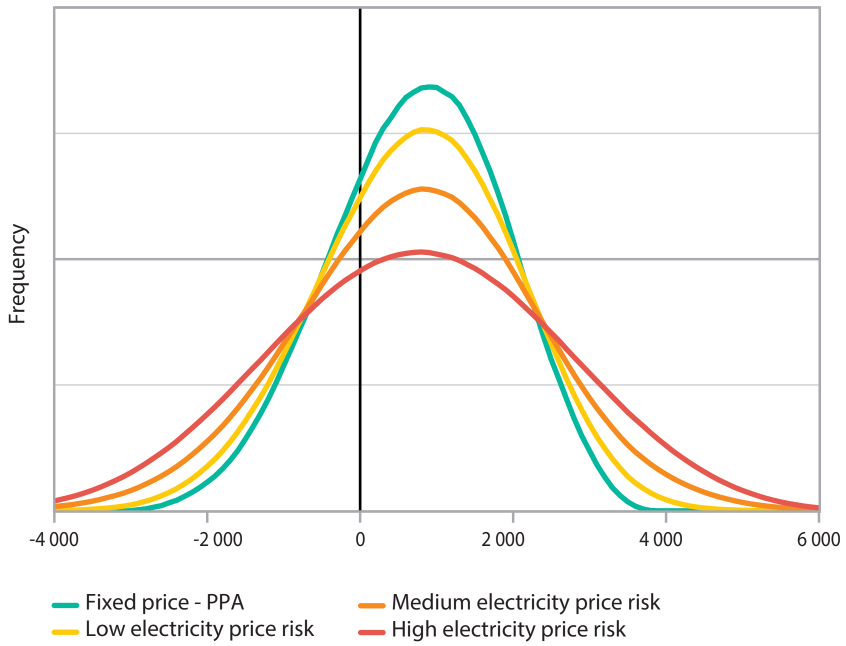
The graph demonstrates the behaviour of NPVs for the two technologies as electricity prices fall. Gas power plants limit the impact on profits by exiting the market, ceasing production when prices become too low. Given that most of their costs consist of expensive fuel, there are large savings to be made

Figure 2: Value of a CfD* for nuclear and gas at different degrees of risk aversion



* CfD = contract for difference. ** CRRA = constant relative risk aversion.

Figure 3: NPV distribution of different cash flows (million EUR)



by halting production. While gas power plants may never recover their fixed costs, these costs were never very high to begin with. Nuclear power plants, on the other hand, will continue producing with their relatively low variable costs but will have to bear a large fixed cost, which drags down their net present value. It is very unlikely that electricity prices would fall below the variable cost of nuclear power, and thus cause the shutdown of a nuclear plant. The option to leave the market therefore has little value for the nuclear plant. Such an analysis underlines the much stronger dependence of nuclear energy on the stability of electricity prices when compared with a gas plant of the same size. Intuitively, the greater the difference between nuclear and gas in terms of the steepness of the decline in NPV following a fall in prices, the more valuable the option to exit the market is for gas.

One measure to limit the exposure of nuclear power and other low-carbon technologies to long-term price declines is to provide long-term guarantees such as the contracts for difference (CfD) currently proposed by the government of the United Kingdom for the construction of two new nuclear plants. The analysis outlines a case where a CfD pays EUR 55 per MWh with certainty (the average electricity price from 2005 to 2010). This case is then confronted with a risky scenario, in which there is an even chance of either a 30% rise or 30% fall in electricity prices over the lifetime of the plants. In conceptual terms, the value of a CfD corresponds to the maximum amount an investor would be willing to pay for an insurance that would guarantee price stability in a market environment characterised by the risk of either a 30% fall or a 30% rise in electricity prices. Risk aversion was modelled with the help of a constant relative risk aversion (CRRA), a standard notion based on utility functions with declining marginal utility of income.

Figure 2 shows the value of a fair CfD for risk-averse investors, in blue for nuclear and in orange for gas. This value increases with the degree of risk aversion. It is also higher for nuclear than for gas since the exposure of nuclear to changes in the price level is considerably higher than that of gas. At realistic levels for the cost of capital, the value of such a CfD to a normally risk-averse investor is slightly below EUR 500 million, translating to about 11% of the overnight investment cost of a nuclear power plant.

In addition to electricity price risk, other important sources of risk in relation to a nuclear new build project, for example construction risk and load factor risk, are addressed via a Monte Carlo simulation. The uncertainty in relation to overnight cost (construction risk) is represented by a normal distribution with a mean value of EUR 4 000/kW. The correlation between overnight cost and construction duration is introduced to reflect the fact that delayed projects tend to go over-budget. Electricity market risk is treated in detail via a two-stage model that takes into account the short-term volatility of electricity prices as well as long-term changes in the electricity price trend. Short-term variability of electricity market prices is modelled via a mean reversion model with parameters derived from real data observed in European markets from 2005 to 2010.

Distribution of cash flows are plotted in Figure 3 for the four scenarios considered (with and without electricity market risk). With low electricity market risk, total financial risk is dominated by the uncertainties during the construction phase. For scenarios with more variable electricity prices, both construction and electricity market risks are important parts of the total financial risk of a nuclear project.

Two standard financial measures of investor risk are considered in the study: standard deviation, which measures the dispersion of net cash flows, and shortfall. Shortfall risk is the probability that the NPV of the project is negative or that the rate of return obtained in the project does not meet the investor's requirements. From this perspective, the benefits of long-term fixed-price arrangements are significant: long-term contracts reduce the spread of possible financial outcomes as well as their variability. For instance, the maximal spread and the standard deviation of NPVs are reduced by a factor of two in comparison with the scenario having very high electricity market risk (see Table 2).

Table 2: **Standard deviation of NPVs in nuclear projects**

	Standard deviation	
	(million EUR)	(%)
Fixed price (CfD)	980	17.9
Low electricity market risk	1 160	21.2
Medium electricity market risk	1 470	26.9
High electricity market risk	1 780	32.6

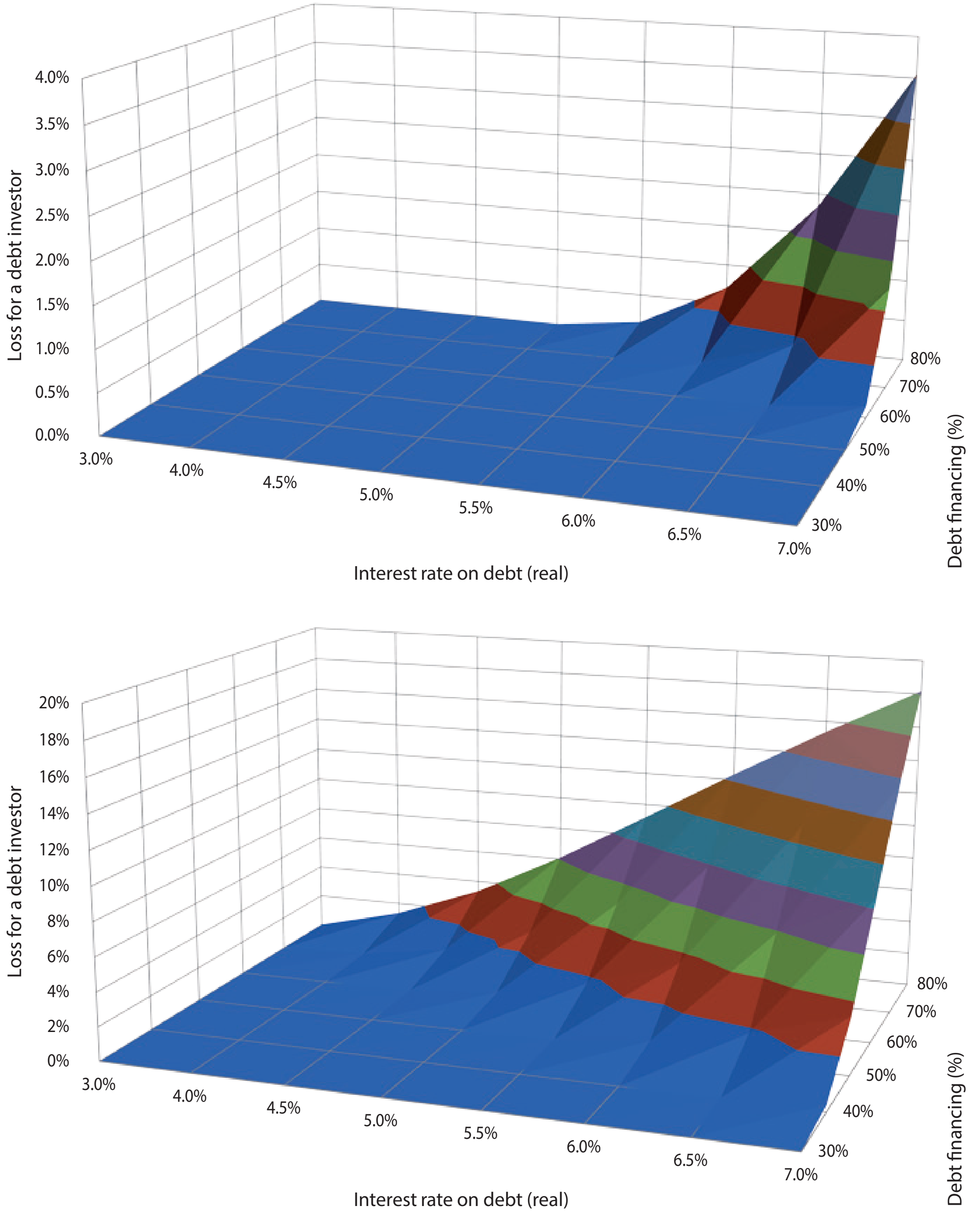
The benefits of long-term contracts are even more evident when considering only the negative outcomes from the investor viewpoint. For all projects that are financially viable (those with a expected positive NPV), long-term price arrangements significantly reduce the probability of having a negative financial outcome, as well as the average extent of the financial loss (average shortfall). Clearly such significant reductions in shortfall risk reduce the risk premium required for investment in nuclear projects and thus facilitate their realisation.

The last part of the study looks specifically at the financial characteristics of a nuclear project from the viewpoint of debt holders. The objective is to quantitatively assess the risk of debt holders being unable to recuperate their investment in the case of an unfavorable evolution of electricity market prices. When electricity prices sharply fall, nuclear plant owners will experience a shortfall in their expected revenue. However, in all but the most extreme cases, a nuclear plant will continue to operate, owing to its low variable cost. In almost all cases, therefore, nuclear plants will continue producing some cash-flow that can be recuperated by debt holders.

The metric for risk in terms of the loss for bond-holders (see Figure 4), is expressed in percentage terms as the difference between the NPV of the committed capital and the NPV of the paid off debt. Thus, an average loss of 0% would mean that the cash-flow going to debt holders is sufficient to repay the committed capital and accrued interests. A loss of 5% would mean that the repayment to debt holders covered 95% of the committed capital and interest. Figure 4 provides the results for declines in electricity prices of 30% and 50% respectively.

Decreases in long-term electricity prices of less than 20% of the base case do not have any impact on the expected payoff for debt holders. Debt holders may incur financial loss only in the case of a combi-

Figure 4: Average loss for a bondholder in the case of a 30% decrease (top) and 50% decrease (bottom) in the electricity market price



nation of high leverage (≥70%) and high interest rate (≥6.5%). Even then, however, financial risk remains limited. For all other financial arrangements, the nuclear project would be able to service its debt fully in all the simulated situations. In the case of more significant decreases in electricity prices between 30% and 40%, the financial risk for debt holders becomes significant for a larger range of financial arrangements. However, even in such adverse market conditions, the debt holders are fully repaid for debt ratios up to 50%. Potential losses for debt holders increase substantially when long-term electricity prices decrease further. If electricity prices decline 50% from their initial level, bond holders must expect losses even with a gearing of 50%, except at ultra-low rates.

At debt ratios below 60%, the risk for a debt investor in a nuclear project is limited even for large and permanent electricity price falls. Under such conditions, the risk premium required for investing in a nuclear project would be rather limited. Due to the financial structure of nuclear new build projects, equity holders, who shoulder the residual risk most exposed to electricity price changes, are therefore in far greater need of protection.

Project and supply chain management in nuclear new build

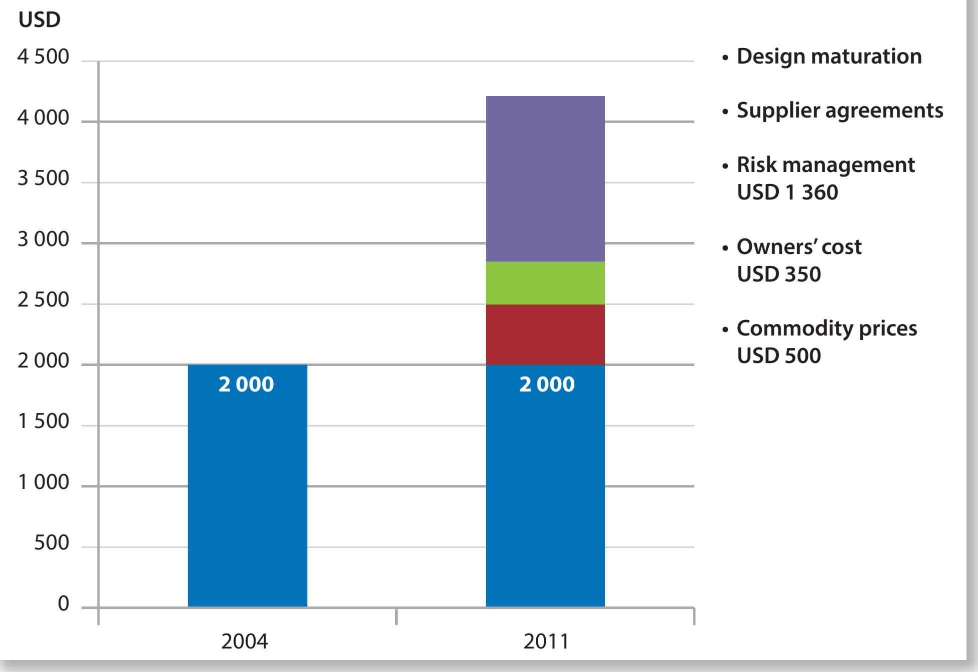
In the management of new build projects and their supply chains, the nuclear industry is undergoing a number of important developments that will shape the future of nuclear new build. Massive and discontinuous technological change is underway as generation II nuclear power plants (NPPs) are substituted by larger and more complex generation III/III+ plants. The loss of skill and human capital as engineers of the nuclear building boom of the 1970s and 1980s retire must also be factored in. In addition, there is the reconfiguration of the global supply chain, which is driven both by new possibilities in data management, externalisation and logistics, and a secular shift of activity from the United States, Japan, Europe and Korea to China, Southeast Asia and the Middle East.

Construction of a nuclear power plant is a highly complex undertaking requiring the co-ordination of a wide range of activities, including the development of a design according to detailed technical assessments and regulatory requirements, procurement of equipment, civil engineering and construction, testing and installation of components, commissioning of the power station, as well as the co-ordination of numerous contractors and sub-contractors. The way in which the project is procured and the relationships with contractors have a significant impact on the development of the supply chain. While there exists a wide spectrum of different options for sharing the responsibilities between the project manager of a nuclear power plant and its principal suppliers, the NEA and the International Atomic Energy Agency (IAEA) nevertheless distinguish routinely between three main categories of contracts that are used for the construction of new nuclear power plants.

- a turnkey approach, where a single contractor or a consortium of contractors take(s) the overall responsibility for the construction work;
- a split-package approach, where the overall responsibility is divided between a relatively small numbers of contractors, each coping with a large section of the plant;
- a multi-contract approach, where the owner or its architect/engineer assumes the overall responsibility for detail engineering and construction of the plant.

An important question is how to find the right balance between vertical integration and competitive procurement. The former is the traditional model for integrated vendors close to national authorities that in some cases are even able to include long-term fuel supply, maintenance and the removal of radioactive waste in their offerings. Competitive procurement under an architect-assembler or a turnkey approach with an engineering, procurement and construction (EPC)-contractor model is an alternative that holds promise but has yet to provide a sufficient number of compelling success stories. There is also at least some evidence that EPC contracting could be contributing to increased costs, as contractors as well as several layers of subcontractors hedge their respective exposure, thus "pancaking" margin on margin (see Figure 5).

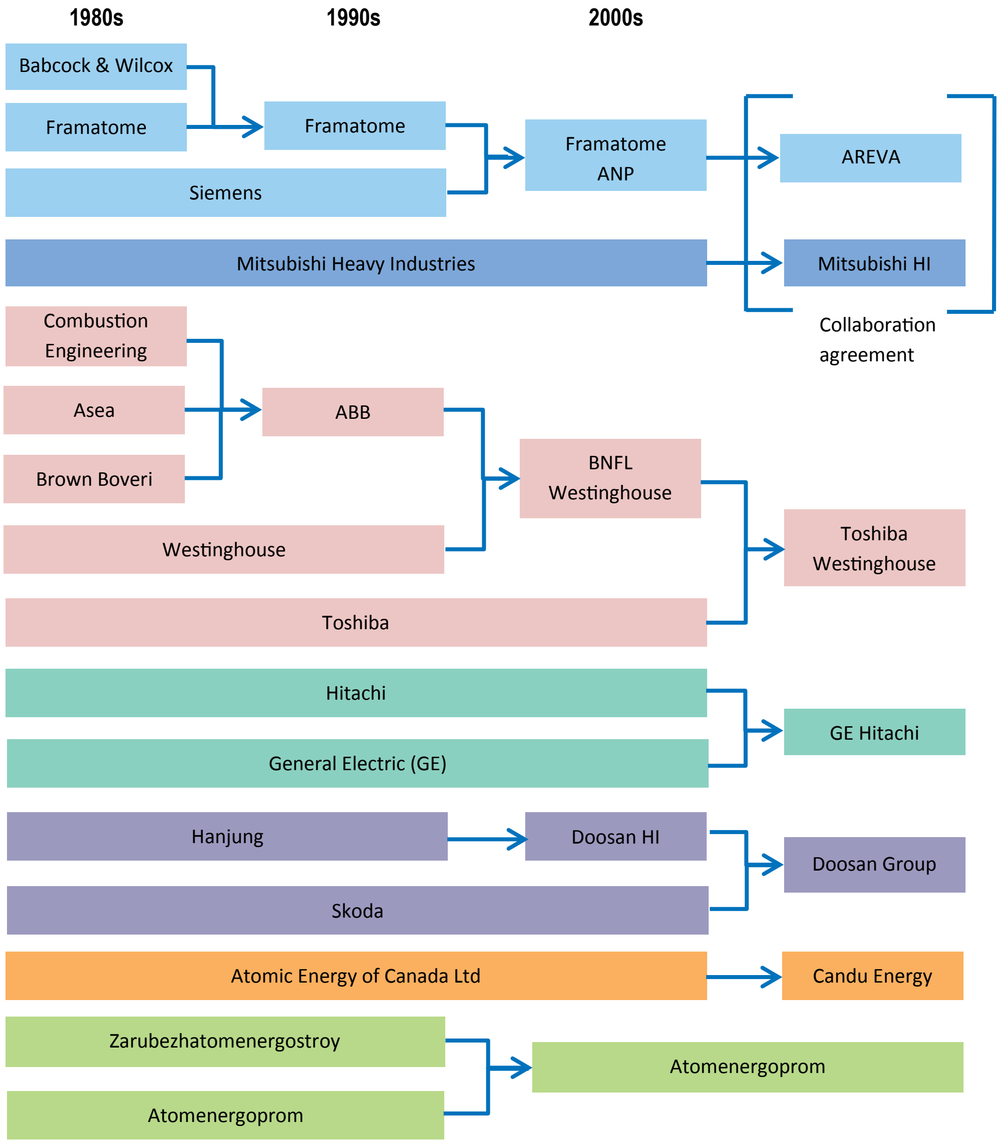
Figure 5: Factors for increases in overnight capital costs
(Overnight costs, USD/kW)



With respect to the supply chain, most areas of equipment supply for a new nuclear plant are relatively open to competition and new entry, and there is great diversity in the range of companies in the market. There are only a few specific items, mainly in the nuclear island, where the technological and manufacturing capability required constitutes a significant barrier to entry, namely the reactor pressure vessel, reactor coolant pump and steam generator (in a pressurised water reactor) and the associated very large forgings. The supply of these critical components is restricted to a few companies in the world with manufacturing facilities on the necessary scale and the required experience in the nuclear market. Reactor vendors will typically take responsibility for supplying these items themselves or will procure them from strategic partners. Vendors are also likely to take responsibility for the assembly of reactor internals, and instrumentation and control equipment, although most of the components can be supplied by a somewhat wider range of companies both locally and internationally.

In the early days of nuclear power development, the design and construction of NPPs was led by consortia built around the makers of the reactor pressure vessel on the one hand and electrical turbine-generator manufacturers on the other. These consortia evolved over time into integrated reactor vendors. According to the World Nuclear Association, there were in these early years 32 such companies active in nuclear plant construction in 10 countries. By the 1970s, a process of industrial restructuring had reduced the number of these companies, with more focus on nuclear plant engineering. Further consolidation occurred from the 1980s, in part because of the slowdown in nuclear plant construction, with a series of mergers and partnerships developing. This reconstruction

Figure 6: Consolidation in nuclear reactor manufacture



took on an increasingly international pattern, with significant mergers and partnering between the American, European and Asian companies to take advantage of economies of scale and sharing of technology. At this time, former UK and Swiss/Swedish champions were absorbed by other players (see Figure 6). The resulting consolidated groups of AREVA, Toshiba/Westinghouse, GE Hitachi and Atomenergoprom are responsible for 222 of the 434 nuclear plants currently operating globally and 27 of the 56 plants built since 2000 or currently under construction.

Another major issue for the structure and efficiency of the global nuclear supply chain is the convergence and standardisation of industrial codes and quality standards. There are currently a number of private or public initiatives under way, such as the Nuclear Quality Standard Association in Europe, the Nuclear Procurement Issues Committee, which created the NSQ-100 standard, or the CORDEL initiative of the World Nuclear Association. Despite these initiatives, unification remains elusive and the two big groups of codes – RCC-M/E and ASME – continue to exist in parallel. This co-existence impedes the emergence of a competitive global nuclear industry as it limits the scope of externalisation and co-operation between different companies. It also hinders benchmarking and an easy transferability of best practices across suppliers, which would constitute important stepping stones to reduce construction costs in a significant manner.

Several international initiatives aim to foster collaboration between regulators and industry so as to harmonise regulatory requirements and to promote the convergence of regulatory criteria and safety objectives across countries. Examples of such initiatives include the NEA Multinational Design Evaluation Programme (MDEP), the aforementioned CORDEL initiative, and the Western European Nuclear Regulators' Association (WENRA) and International Nuclear Information System (INIS) initiatives in Europe.

While awaiting a global harmonisation of engineering and safety codes, the nuclear industry has nevertheless been adopting a number of technological and managerial improvements. Traceability of all components, 3-D modelling or automatic-welding are part of a number of incremental improvements that are nudging the industry towards higher levels of efficiency. On the management side, early involvement and training of suppliers, attention to the management of culturally diverse teams and explicit change management to prepare for unforeseen and unforeseeable mishaps are now part of the industry standard. Design completion before the start of production is also an important component of successful projects.

Conclusions

Today, nuclear new build is in a state of technical, geographical and structural transition, with a number of general lessons beginning to emerge. If heeded, these lessons should allow for an improvement in the prospects of nuclear new build in the coming decades. On the financing side, capital-intensive projects require the long-term stabilisation of electricity prices through tariffs, power purchase agreements or CfDs. Electricity-market designs are not technologically neutral and if significant reductions in carbon emissions continue to be the objective of the electricity industry, there will need to be a general rethink of how to finance capital-intensive, low-carbon generation technologies.

In construction, where the emergence of a competitive, global supply chain is not yet ensured, the convergence of nuclear engineering codes and quality standards remains a key step to promote both competition and public confidence. In parallel, a number of smaller technological and managerial improvements keep the industry moving forward. During a time of major shifts, it is important that the global nuclear industry maintains a dynamic of continuous technological, logistical and managerial improvement at the level of the construction site, while preserving the essential financial and regulatory stability at the level of the overall project. While it may be too soon to tell how things will turn out, there are a sufficient number of promising developments underway to justify expectations for a new business model for financially and economically sustainable nuclear new build to emerge in the coming years.

Note

1. Construction began as early as the 1990s for some of the latter reactors, resulting in a wealth of experience.

Nuclear liability amounts on the rise for nuclear installations

by X. Vásquez-Maignan, J. Schwartz and K. Kuzeyli[*]

The NEA Table on Nuclear Operator Liability Amounts and Financial Security Limits (NEA "Liability Table"), which covers 71 countries, aims to provide one of the most comprehensive listings of nuclear liability amounts and financial security limits. The current and revised Paris and Brussels Supplementary Conventions ("Paris-Brussels regime"), the original and revised Vienna Conventions ("Vienna regime") and the Convention on Supplementary Compensation for Nuclear Damage, newly entered into force in April 2015, provide for the minimum amounts to be transposed in the national legislation of states parties to the conventions, and have served as guidelines for non-convention states. The following paragraphs examine in more detail increases in the liability amounts provided for under these conventions, as well as examples of non-convention states.

Liability amounts under the Paris-Brussels regime

The 1960 Paris Convention on Third Party Liability in the Field of Nuclear Energy ("Paris Convention") provides for an operator's minimum liability amount of 5 million Special Drawing Rights (SDR)[1] (EUR 6.3 million) and a maximum liability amount of SDR 15 million (EUR 19.1 million).[2] However, in 1990, the NEA Steering Committee for Nuclear Energy recommended that Paris Convention states provide, if possible, the maximum liability of the nuclear operator at not less than SDR 150 million (EUR 191 million), which most of the 16 Paris Convention states have agreed to do.

The majority of these states recognised at a very early stage that operator funds under the Paris Convention might not be adequate to compensate victims for nuclear damage suffered in the event of a large nuclear incident. As a result, they established a supplementary compensation scheme under the Brussels Convention Supplementary to the Paris Convention ("Brussels Supplementary Convention"),[3] which calls for the establishment of additional state intervention that, in principle, requires public funds.

The current Paris-Brussels regime provides for a three-tier system of compensation, under which the first tier is provided by the operator in accordance with the Paris Convention; the second tier is the difference between the first tier and SDR 175 million (EUR 222 million) and is paid by the state in whose territory the liable operator's installation is situated or by the liable operator, in part or in full; and the third tier is up to SDR 125 million (EUR 159 million), paid for by contributions from all Brussels Supplementary Convention states. The total compensation currently available under the Paris-Brussels regime is thus SDR 300 million (EUR 382 million).

1960 Paris Convention (PC)	SDR 15 million maximum SDR 5 million minimum NEA Steering Committee recommendation of a maximum liability of not less than SDR 150 million minimum
1963 Brussels Supplementary Convention (BSC)	First tier *(operator)*: SDR 5 million minimum Second tier *(installation state/ operator)*:between first tier and SDR 175 million Third tier *(BSC parties' fund)*: SDR 125 million Total amount available: SDR 300 million
2004 Paris Protocol	EUR 700 million minimum
2004 Brussels Protocol	First tier *(operator)*: EUR 700 million minimum Second tier *(installation state/operator)*: between first tier and EUR 1.2 billion Third tier *(BSC parties' fund)*: EUR 300 million Total amount available: EUR 1.5 billion

The 2004 Protocols amending these two conventions, which are anticipated to come into force in 2017, significantly increase these amounts of compensation. The 2004 Paris Protocol requires operators of nuclear installations to be liable for not less than EUR 700 million in the event of a nuclear incident (which corresponds to the first tier under the Brussels Supplementary Convention); the 2004 Brussels Protocol requires that the second tier be fixed at an amount between the first tier and

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EUR 1.2 billion, and the third tier at an amount between EUR 1.2 billion and EUR 1.5 billion. Thus the total compensation amount available once the 2004 Protocols enter into force will be EUR 1.5 billion (if no other state adheres to the convention), which will more than triple the amount provided for under the current Paris-Brussels regime.

While nuclear installations comprise more than just nuclear reactors, the latter constitute the vast majority of such installations. Currently, there are 437 nuclear power reactors in operation worldwide. The Paris Convention's liability regime applies to 113 reactors in operation located in 9 states: Belgium (7), Finland (4), France (58), Germany (8), Netherlands (1), Slovenia (1), Spain (7), Sweden (10) and the United Kingdom (16). Once the 2004 Paris Protocol enters into force, five Swiss nuclear reactors will also fall within the scope of this liability regime.[4]

Operator liability amounts within states party to the Paris Convention range from SDR 15 million to unlimited liability, with some countries (such as Belgium and the Netherlands) having set liability amounts to EUR 1.2 billion.

Those Paris Convention states that have imposed unlimited liability regimes upon their operators, such as Finland, Germany and Switzerland, require that they maintain financial security for an amount that is at least equal to the minimum liability amount of EUR 700 million required under the 2004 Paris Protocol. In the case of Germany, for example, the financial security limit has been set at EUR 2.5 billion, considerably above the minimum liability amount. In Finland, the application of unlimited liability is exclusively reserved for nuclear damage suffered within Finnish territory. If a nuclear incident occurs in Finland for which a Finnish operator is liable and which causes transboundary damage, the operator's liability for such damage would be SDR 600 million (EUR 764 million).

Liability amounts under the Vienna regime

In 1963, member states of the International Atomic Energy Agency (IAEA) adopted the Vienna Convention on Civil Liability for Nuclear Damage ("Vienna Convention"). Its 40 contracting parties originate from all geographical regions, except Oceania. In contrast to the Paris-Brussels regime, the Vienna Convention does not provide for a supplementary funding mechanism.

Vienna Convention (VC)	Minimum USD 5 million, based on USD gold value on 29 April 1963 (USD 170 million or EUR 154)
1997 Vienna Protocol	SDR 300 million minimum

The Protocol to amend the Vienna Convention was adopted in 1997 ("1997 Vienna Protocol"). There are currently 12 contracting parties. The Vienna Convention and the 1997 Vienna Protocol, together referred to as the "Vienna regime", exist concurrently.

The Vienna regime covers 75 nuclear reactors in operation. Most are located in states party to the 1963 Vienna Convention, with only five located in the 1997 Vienna Protocol states. The first group includes Argentina (3), Armenia (1), Brazil (2), Bulgaria (2), Czech Republic (6), Hungary (4), Mexico (2), Romania (2), the Russian Federation (34), the Slovak Republic (4) and Ukraine (15), whereas the second group mainly covers states with no reactors or with reactors under construction (such as Belarus and the United Arab Emirates).

The NEA Liability Table illustrates that almost all of the Vienna regime states with nuclear capacity have established limited nuclear liability schemes. For these states, nuclear liability amounts range from MXN 100 million (EUR 5.8 million) in Mexico and BGN 96 million (EUR 49 million) in Bulgaria to SDR 150 million in Ukraine, EUR 300 million in the Slovak Republic and SDR 300 million in Argentina and Romania. On the other hand, Russia – the Vienna regime state with the highest number of reactors in operation – has established an unlimited liability scheme.

Liability amounts under the Convention on Supplementary Compensation for Nuclear Damage

During the 1997 Vienna Protocol deliberations, negotiating states decided to establish a mechanism for mobilising supplementary funds to compensate nuclear damage, in addition to the funds that would be provided by operators under the Paris and Vienna Conventions or by operators of nuclear installations in specified non-convention states. The resulting system comprises funding at both national and international levels, modelled in part on the Brussels Supplementary Convention, and is reflected in the 1997 Convention on Supplementary Compensation for Nuclear Damage ("CSC").

The CSC provides for a two-tier compensation system: the first tier is provided by the operator and, if necessary, the state where the nuclear installation is located; and the second tier is provided by CSC states collectively. As of 30 June 2015, the CSC has seven contracting parties.[5]

Convention on Supplementary Compensation for Nuclear Damage (CSC)	First tier *(installation state/operator)*: SDR 300 million minimum
	Second tier *(CSC parties' fund)*: SDR 74.5 million (EUR 95 million) - *Amount expected: SDR 300 million**
	Total amount available: SDR 374.5 million (EUR 477 million)

** This assumes that all major nuclear power generating states join the convention.*

Despite its limited number of parties, the CSC now covers 147 reactors in operation, with 43 of them located in Japan and another 99 in the United States.[6]

Examples of non-convention states: China, India and Korea

China

China has one of the largest nuclear power programmes, currently operating 27 nuclear reactors and constructing 24 new reactors. As a non-convention state, its position on nuclear liability since 2007 entails limiting operators of nuclear installations to up to CNY 300 million (EUR 44 million). Where nuclear damage exceeds this amount, an additional state indemnity of up to CNY 800 million (EUR 118 million) will be provided. While these amounts may not be impressively high, they are a significant increase over the previous amounts established in 1986, which were only CNY 18 million (EUR 2.6 million) for operators with a state indemnity of up to CNY 300 million.

India

Another country that has a considerable share of the world's nuclear energy production is India, with 21 reactors in operation and 6 under construction. India has signed but not ratified the CSC and provides in its national legislation that the maximum liability in the case of a nuclear incident is SDR 300 million: the operator paying a first tier up to INR 15 billion (EUR 216 million) and the state paying the difference between this amount and SDR 300 million.

Korea

Korea is another non-convention nuclear power generating state, with 24 nuclear reactors in operation and 4 more under construction. Korea's nuclear liability amounts have also increased over time, from KRW 1.5 billion maximum (EUR 1.1 million) until 1975, when the operator's liability amount doubled, and from KRW 3 billion (EUR 2.3 million) until 2001, when the liability limit jumped to SDR 300 million. The financial security amount of nuclear power reactors per site was only KRW 50 billion (SDR 31 million or EUR 40 million); this amount has been recently increased to equal the nuclear liability amount of SDR 300 million.

Further information on operator liability amounts and financial security limits in effect in specific countries around the world can be found in the NEA Liability Table.

Notes

1. A Special Drawing Right is a unit of account defined by the International Monetary Fund (IMF) based upon a basket of key international currencies. The current value is available at www.imf.org/external/np/fin/data/rms_sdrv.aspx.
2. All the conversion rate calculations in this article are approximate and are based on the May-June 2015 rates provided on the following website: XE Currency Converter www.xe.com/currencyconverter/ (last accessed on 15/07/2015).
3. The Brussels Supplementary Convention is only open to Paris Convention states. All contracting parties to the Paris Convention (except for Greece, Portugal and Turkey) are party to the Brussels Supplementary Convention. The status of ratification of the Paris Convention is available at www.oecd-nea.org/law/paris-convention-ratification.html and of the Brussels Supplementary Convention at www.oecd-nea.org/law/brussels-convention-ratification.html.
4. On 9 March 2009, Switzerland deposited its instrument of ratification of the 1960 Paris Convention as amended by the 1964, 1982 and 2004 amending Protocols; on 11 March 2009, Switzerland deposited its instrument of ratification of the 1963 Brussels Supplementary Convention as amended by the 1964, 1982 and 2004 Protocols. However, the Paris-Brussels regime will only enter into force for Switzerland once the 2004 Paris and Brussels Protocols have themselves entered into force.
5. The CSC states are Argentina, Japan, Montenegro, Morocco, Romania, the United Arab Emirates and the United States, www.iaea.org/Publications/Documents/Conventions/supcomp_status.pdf. To calculate the contributions of the CSC sates to the second tier, see calculator available at: http://ola.iaea.org/ola/CSCND/Calculate.asp.
6. The nuclear reactors in Argentina (3) and Romania (2) are included in this calculation as well as in that for the Vienna regime.

References

All conventions cited in this article are reproduced at the following address www.oecd-nea.org/law/legal-documents.html.

All Decisions, Recommendations and Interpretations regarding the Paris Convention are available at www.oecd-nea.org/law/paris-convention-dec-rec-int.pdf.

For more information on compensation in Japan, see "Japan's Compensation System for Nuclear Damage" (NEA, 2012), available at www.oecd-nea.org/law/fukushima/7089-fukushima-compensation-system-pp.pdf.

The NEA Liability Table can be found at www.oecd-nea.org/law/2014-table-liability-coverage-limits.pdf.

Gas generation in deep geological repositories

by G. Kwong*

Experts worldwide agree that the disposal of long-lived radioactive waste in engineered geological repositories is the most efficient and feasible waste management solution. Deep geological disposal repositories are expected to achieve adequate long-term safety without reliance on continuing institutional controls. While geological repositories will continue to evolve over time, in order to effectively contain and isolate emplaced radioactive waste from the environment, most will use backfill materials such as bentonite, crushed rocks or cement as engineered barriers against groundwater infiltration and radionuclide transport. Gases generated within the repository will not pose any major concern during the operational phase as repositories are ventilated, and airborne wastes are removed by high-efficiency particulate air (HEPA) filters. However, after closure, geological repositories are prone to potential gas build up, which may result in the loss of integrity of the engineered barrier system (EBS) and the disposal system. This article examines the significant issues of concern in relation to gas generation and migration from radioactive waste disposal repositories. It is based on a more detailed position paper (NEA, 2015) recently issued by the NEA Integration Group for the Safety Case (IGSC).

Gases generated in the repository

Within a sealed geological repository, gases are generated mainly from anaerobic metal corrosion, microbial degradation of organic waste and radiolysis of water and waste. The gases that are expected to be more predominant are hydrogen (from anaerobic metal corrosion and radiolysis of water and waste), carbon dioxide and methane (from microbial degradation of organic waste). Radioactive gases such as carbon-14, iodine-129 and krypton-85 (^{14}C, ^{129}I and ^{85}Kr) may also be present, although in smaller amounts depending on the waste types, the emplaced waste and continuous radioactive decays. Gas generation from high-level waste (HLW) and spent fuel (SF) is primarily due to radiolysis and anaerobic corrosion, while microbial processes play a more dominant role in low- and intermediate-level waste (LILW). There are essentially two possible effects as gases build up in a repository: i) a physical effect caused by the pressure increase, which may create physical pathways for radionuclides to escape into the geosphere, and ii) a chemical effect which could adversely affect the geochemical conditions in the surrounding geosphere.

SKB, Sweden

View of the Lasgit experiment conducted at the Äspö Hard Rock Laboratory.

Anaerobic metal corrosion and radiolysis

Hydrogen gas, produced mainly from anaerobic metal corrosion and radiolysis, is a concern due to its potentially significant quantity as the metal inventory present in a repository is usually considerable. Potential hydrogen upsurge not only poses a threat to the integrity of the surrounding engineered barriers or disposal system, it also imposes restrictions on the canister designs due to the number of hydrogen-related degradation mechanisms for steels (e.g. hydrogen-induced cracking, hydrogen cracking of welds, loss of ductility). Hydrogen evolution is driven by the amount of water and the quantity of corrodible metals available in the environment.

To restrict water access, unsaturated buffer materials are placed in emplacement boreholes or cells so as to limit the electrochemical corrosion processes and the mass transport of dissolved and gaseous species to and from the waste. Note that hydrogen generation is also controlled by the availability of water, and the pressure build-up as gas evolves could potentially reduce the flow of water into the repository. The accumulation of gas within the pore space of the engineered barrier system could therefore reduce the access of water to the waste, thereby diminishing the rate of gas generation.

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Microbial degradation of organic waste

Microbes have shown remarkable versatility even in the harsh environments of geological repositories (Shaw, 2013). Indigenous micro-organisms metabolise organic compounds such as paper, wood, tissues, plastics (in low- and intermediate-level waste) as energy sources under both aerobic and anaerobic conditions, using nitrate and sulphate as electron acceptors. As a result, a variety of gases such as hydrogen, nitrogen, hydrogen sulphide, carbon dioxide, nitrous oxide and methane (H_2, N_2, H_2S, CO_2, N_2O and CH_4) may evolve, with the quantities depending on the availability of electron donors or acceptors, moisture and nutrients. These types of reactions are significantly affected by temperature, pH, redox potential Eh, radiation and the presence of toxic compounds.

In addition to the possible presence of significant quantities of such gases, carbon dioxide and methane could also contribute to other potentially adverse effects on the long-term integrity of geological repositories. The presence of carbon dioxide can lower pH (and the redox potential, Eh), increase the solubility of actinides or change the ionic state of radionuclides, thus enhancing radionuclide transport or releases into the environment. Methane gas, as in the case of hydrogen, poses a flammability hazard due to its explosive nature.

Radioactive gases released from waste and radioactive decay

In addition to the generation of non-radioactive gases, radioactive gases may also evolve from the disposed waste, although in relatively smaller amounts. Depending on the type of waste, significant quantities of ^{14}C and tritium (^{3}H) can be captured within the fuel elements. These ^{3}H and ^{14}C atoms can replace the hydrogen and carbon atoms in non-radioactive hydrogen, carbon dioxide and methane, resulting in releases of radioactivity. Microbial biodegradation may also produce other tritiated and ^{14}C gaseous waste in the form of methane, while volatile radionuclides such as radon-222 (^{222}Rn), ^{85}Kr and ^{129}I can either be released continuously from the waste or can form in radioactive decay.

Tritium and most noble radioactive gases (i.e. ^{222}Rn and ^{85}Kr) do not pose a long-term safety concern due to their short-lived nature. The common practice of treating contaminated gases through HEPA filters is considered adequate in removing radioactive components from gaseous effluents during the operational period. Radioactive ^{129}I, however, has a long half-life of 15.7 million years and can be dispersed in air and water. Yet its relatively small volume and its "organic fixation" property – it combines easily with organic materials in soil – allows its movement to be retarded and trapped in the surrounding sealing buffer.

Gas transport and migration in deep geological repositories

Gas accumulation within a disposal system affects the hydraulic state of a repository. In repository closure, disposal systems are often backfilled with unsaturated sealing materials. In an unsaturated disposal system (i.e. one not immersed in water), evolved gas will dissolve in the available moisture and be carried away by diffusion. The diffusivity of the dissolved gases depends on various factors such as the composition or the solubility of the gas, availability of moisture or the temperature. When gas generation exceeds the diffusive flux, pore-water will become over-saturated and a free gas phase will form, resulting in an advective gas flux. Similarly, the advection rate is affected by surrounding conditions such as temperature or the permeability of the environment. Many studies have shown that evolved gas is unlikely to travel sufficiently fast to avoid the formation of a separate gas phase in a repository (King and Stroes-Gascoyne, 2000), particularly in low permeability media (e.g. clay or highly compacted bentonite). Excessive pressure build-up, if higher than the local stress of the surrounding buffer, can form mechanical deformations and create pathways for contaminant releases. In addition to these potential pathways, the excavation damaged zone (EDZ) resulting from repository construction, as well as the interfaces between the engineered barriers and the host rock, also provide permeable conduits for gas migration.

As fractures inevitably exist in host rock formations, it is important to prevent radionuclide releases into the biosphere. The ultimate implication of gas migration on repository safety is the radiological impact. A suitable host rock is one means of helping to prevent such releases, complemented by the proper design measures including appropriate canister or packaging materials, drying of wastes, selection of backfill materials that absorb gas (e.g. magnesium oxide or cement), and design vaults to facilitate steady gas release. These are all effective means to reduce gas generation, as well as to control the movement of radionuclides. To better understand the long-term behaviours of gases in geological repositories, gas transport characteristics in three common host rocks, namely clay, crystalline and rock salts, are briefly summarised below.

Gas transport in clay

The NEA Clay Club, a working group formed in 1990 under the auspices of the NEA Integration Group for the Safety Case (IGSC), has examined the characteristics of various argillaceous media for more than 25 years. Its studies concluded that clay not only exhibits the capabilities to chemically and physically retard radionuclide migration, its homogeneity with few hydraulically active fractures, along with a propensity for plastic deformation and self-healing over time, are also key attributes for hosting radioactive waste geological repositories. Numerous laboratory and modelling studies have been performed on clay, with consistent results continuously reported. Results to date have indicated that gas migration in clay formations is only possible if a fracture or specific pathways exist and remain available. More recent data presented at the International Conference on the Fate of Repository Gases (Shaw, 2013) further support this "self-healing" capability and the dilatant behaviour of clay. In cases where fractures occur in the host rock, they are most likely formed in a direction perpendicular to the direction of the lowest *in situ* stress. Gradually, these fractures will close or discontinue after the pressure gradient is removed. Gases that have evolved in a clay formation will likely migrate through a cycle of opening and closing pathways, regulated by the pressure level in the system. The closing of fracture apertures is driven by increased pressure, as well as precipitation of minerals within the fracture. The time required for self-sealing apparently depends on the clay's mineralogy and geologic history. Plastic clays have been reported to heal relatively quickly (i.e. within a few months), whereas indurated argillaceous rocks may take significantly longer to heal (i.e. in the order of years). Most importantly, these studies observed that, over time, fractures in clay deposits become less conductive and hydraulically insignificant.

More information on the key attributes of clay for hosting geological repositories can be found on the NEA Clay Club webpage at www.oecd-nea.org/rwm/clayclub/.

Gas transport in crystalline rocks

Crystalline rocks are often described as strong igneous or metamorphic rocks, for example granite or consolidated tuffaceous rocks. Such rocks typically have low porosities, and groundwater is present predominantly in discontinuities or fractures within the rock matrix. Through many international studies (e.g. at Aspo Hard Rock Laboratory in Sweden, Grimsel-FEBEX in Switzerland and Stripa in Sweden), it is generally thought that the discontinuity network has sufficient transport capacity to accommodate the gas flux from the radioactive wastes without mechanical disruption to the surrounding rock mass. Most crystalline repository concepts control gas generation issues by using corrosion-resistant materials (e.g. copper canisters to protect the inner steel container) and clay or cementitious engineered barriers to retard or retain radionuclides dissolved in groundwater. The physical properties of the rock mass – in particular the porosity, pore size distribution, tortuosity of the diffusional path and retardation or retention properties – will affect the speed at which the gas and hence the radionuclides are transported. The excavation disturbed or damaged zone (EDZ) formed during excavation will also alter the mechanical, hydraulic and geochemical properties of the rock, depending on the excavation method used. For these reasons, detailed characterisation studies must be carried out to fully understand the transport mechanisms and gas behaviours when developing geological repositories in crystalline rock. Despite the general consensus that gas migration in a typically discontinuous crystalline host is likely to proceed without the development of an excessive overpressure in the repository, the system design must nonetheless take into account whether cement was used as a backfill or to grout fractures, since the resulting interactions may lower the surrounding permeability and could impede gas migration.

Gas transport in rock salt

Several countries (e.g. Germany, the Netherlands, the United States) are considering rock salt repositories for their high-level and long-lived waste due to its favourable characteristics. Positive attributes for salt disposal include *inter alia* extremely low water content, low porosity and permeability, high thermal conductivity and the ability of salt to anneal after fracturing. Salt has unfavourable characteristics as well, such as its high dissolution and its low propensity to adsorb radionuclides. These factors may adversely affect rock salt's suitability for hosting repositories and require individual investigations during site selection.

Temperature also has a pronounced effect on the physical behaviour of salt. Salt deformation is dominated by plastic behaviour at elevated temperatures, as observed in underground research laboratory experiments at waste isolation pilot plants (Matalucci, 1988). Higher temperatures result in enhanced creep of the host salt, but could cause thermally induced fracturing and thermally driven flow of brine. Temperature limits may therefore need to be established such that the performance of the waste forms or the disposal canisters and waste packages are more predictable during the operational phase of the repository.

References

King, F. and S. Stroes-Gascoyne (2000), "An Assessment of the Long-term Corrosion Behaviour of Carbon Steel and the Impact on the Redox Conditions Inside a Nuclear Fuel Waste Disposal Container", Ontario Power Generation Nuclear Waste Management Division Report No. 06819-REP-01200-10028, Toronto.

Matalucci, R.V. (1988), "In-situ Testing at the Waste Isolation Pilot Plant", SAND87-2382, Albuquerque, NM. Sandia National Laboratories, Albuquerque.

NEA (2015), "Relevance of Gases in the Post-closure Safety Case", OECD, Paris. This paper can be downloaded at www.oecd-nea.org/rwm/igsc/.

Shaw, R.P. (Ed.) (2013), *Gas Generation and Migration, International Symposium and Workshop*, 57 February 2013, Luxembourg, Proceedings, FORGE Report.

The NEA benchmark study of the accident at the Fukushima Daiichi NPP

by T. Koganeya*

Following the Fukushima Daiichi nuclear power plant accident in March 2011, the Japanese government established a research and development (R&D) plan to support decommissioning. This plan, the "Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station", includes an analysis of the accident progression and the current status of the reactors. Severe accident (SA) analysis codes had been developed in a number of NEA countries since the Three Mile Island accident in 1979, and these codes are being used to analyse the Fukushima Daiichi accident. In November 2012, the NEA, under the aegis of the Committee on the Safety of Nuclear Installations (CSNI), initiated a joint research project called the Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station (BSAF).

Objectives of this project include supporting Fukushima Daiichi decommissioning by analysing accident progression and the current status of the reactors, such as fuel debris distribution in the reactor pressure vessels and primary containment vessels in preparation for fuel debris removal. A second objective of the project is to improve SA analysis codes through comparisons with data from the Fukushima reactors. So as to enhance communication between analysts and those involved in decommissioning activities, participants in the project – France, Germany, Japan, Korea, Russia, Spain, Switzerland and the United States – have been discussing the remaining uncertainties in relation to understanding the accident and the data needs from the viewpoint of the analysts.

Since the accident sequences at the Fukushima Daiichi site include a wide range of phenomena, a phased approach is being applied in this benchmark exercise while awaiting more detailed information on debris examination and other factors. This article provides an overview of the project as well as an outline of the project's next phase that begins in June 2015.

Project scope

The wide array of phenomena exhibited during the Fukushima accident poses a significant challenge for current SA integral codes to reproduce. Information on the accident progression, including operator actions and safety system performance, is only partially available. While more information should be obtained during the decommissioning phase, it is likely to be incomplete. Thus, a phased approach has been applied in this project, with the range of analysis in the first phase set as follows:

- conduct full scope analyses of Fukushima Daiichi nuclear power plant (NPP) Units 1 to 3, using currently available SA integral codes;
- use a time span of analysis for accident events of about six days from the occurrence of the earthquake;
- analyse in full scope the following phenomena:
  - initial transient from rated condition to core heat-up;
  - core heat-up;
  - core melt;
  - behaviour of core internals (core shroud);
  - core status, including debris behaviour;
  - molten debris-coolant interaction in the lower plenum (if necessary);
  - reactor pressure vessel (RPV) failure;
  - primary containment vessel (PCV) thermal-hydraulics;
  - molten core concrete interaction (MCCI);
  - hydrogen generation (excluding hydrogen explosions).

Input data and boundary conditions

In order to conduct a full scope analysis of the accident progression, the Tokyo Electric Power Company Incorporated (TEPCO) and other Japanese nuclear vendors jointly prepared a common information database, consisting of plant specifications, timeline plant operation data and measured data during the accident. A web portal (https://fdada.info/) was also established to share this information among project participants. The portal is open to the public and provides access to technical information on accident analysis and decommissioning activities at the Fukushima Daiichi NPP, though proprietary information is protected and restricted to participants.

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Information on in-reactor conditions, operation of equipment, status of valves and effects of emergency measures is limited or is difficult to quantify specifically. However, it was essential to fix initial conditions and boundary conditions for the execution of the analysis. A set of boundary conditions was therefore prepared by the Institute of Applied Energy (IAE) of Japan and discussed among the participants.

Participants

A total of 17 participating institutions from 8 countries are involved in the project. The table below outlines the computer codes used by the different participants.

List of computer codes used by participants

Country	Institutes	Codes
France	CEA	Analytical study
	IRSN	ASTEC V2.0 rev3 p1
Germany	GRS	ATHLETE/COCOSYS
Japan	CRIEPI	MAAP 5.01
	IAE	SAMPSON-B 1.4 beta
	JAEA	THALES2/KICHE
	NRA (S/NRA/R)	MELCOR 2.1
Korea	KAERI	MELCOR 1.8.6
Russia	IBRAE/ROSATOM	SOCRAT/V3
Spain	CIEMAT/CSN	MELCOR 2.1-4803
Switzerland	PSI	MELCOR 2.1-4803
United States	EPRI	MAAP 5.01
	NRC/DOE/SNL	MELCOR 2.1-5864

Analytical approach

Common case

Due to the large uncertainties in boundary conditions and in plant behaviour, the results of the analyses by the participants show a wide range of predictions. It was therefore decided that a "common case" should first be analysed with a common set of boundary conditions, determined with a simplified mass and energy balance. The common case analysis was considered to be useful to identify differences in assumptions and physical modelling among the SA codes and analysts.

Best estimate case

Based on the insights gained from the common case results, the next step in the project was to perform a best estimate analysis. In this analysis, the participants adjusted uncertain boundary conditions according to their expert judgment (i.e. they were not constrained by the simplified mass and energy balance).

TEPCO, Japon

Spent fuel removal at the Fukushima Daiichi NPP site.

The main outputs from the best estimate analysis concern:

- coolant level, including the time to reach the top of the active fuel (TAF);
- hydrogen generation;
- initiation and progress of fuel rupture and melt;
- initiation and progress of control blade deformation and melt;
- timing and mechanism for leakage from the reactor primary cooling system;
- core plate failure;
- RPV failure due to relocation of molten materials;
- distribution of the molten and solidified materials at three locations (above core plate, on the lower head of RPV and out of the RPV);
- composition of molten and solidified materials;
- progress of the MCCI.

The best estimate calculation results also show a wide range of predictions. However, by comparing the results, the project has determined the most probable accident scenarios for each unit and has predicted reactor status and debris compositions. This information provides valuable insight into the long-term decommissioning activities at the Fukushima Daiichi NPP, most importantly in relation to the identification and specification of R&D needs for fuel debris retrieval and planning for fuel debris retrieval strategies.

BSAF phase 2

Although phase 1 of the project has provided information on the most probable accident progression and current status inside RPVs and PCVs, the significant uncertainties in relation to the boundary conditions, and the limitations in currently available information, would imply a certain degree of inaccuracy in the results. It is expected that more detailed and wider ranges of information will be obtained as decommissioning activities progress. As a result, further benchmark studies are necessary for a better understanding of the accident progression and the current status of the reactors, as well as for further improvements to SA codes and analysis.

BSAF phase 2, beginning in June 2015, has a more challenging scope of work and is expected to be more closely connected with Fukushima Daiichi decommissioning activities. BSAF phase 1 focused on thermal-hydraulics in the RPVs and PCVs for the first six days after the accident. In contrast, phase 2 will be expanded to include source term and fission product behaviours in reactor buildings, and the time span has been extended to about three weeks (up to the end of March 2011). Workshops will be held during phase 2, where updated decommissioning information and progress on the project will be shared and discussed with an increased number of experts. The first project meeting will be held in late June 2015 in Japan with the eight initial participating countries (France, Germany, japan, Korea, Russia, Spain, Switzerland and the United States) plus three new participating countries (Canada, China and Finland).

Conclusions

The NEA Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station (BSAF) Project was established in November 2012. Seventeen organisations from eight countries participated in phase 1 which focused on calculating the thermal-hydraulic behaviour of the Fukushima Daiichi reactors with severe accident integral codes for a time span of about six days from the occurrence of the earthquake. The calculated results submitted by participants were compared and evaluated to estimate the accident progression and status inside the reactors. The output of the project includes a thorough review of the remaining uncertainties and data needs, which is then communicated to actors in the decommissioning process.

While it is very difficult to predict the accident progression at the Fukushima Daiichi NPP, particularly with the extent of damage and uncertainty in boundary conditions, computer codes are nevertheless valuable tools to estimate the status inside the contaminated reactors that are difficult to access. In order to ensure accuracy and obtain more reliable results for decommissioning, boundary conditions and models will need to be updated based on information and data from the Fukushima Daiichi NPP and related studies.

While BSAF phase 2 will have a more challenging scope of work, it will also contribute to a better understanding of the Fukushima accident and further improvements to SA codes, which will ultimately be more supportive to Fukushima Daiichi decommissioning activities.

Assessing high ionic strength solutions: A new activity of the TDB Project

by M.E. Ragoussi, M. Altmaier and D. Reed*

For the past 30 years, the Thermochemical Database (TDB) Project has been actively building a database of chemical thermodynamic values for the most significant elements related to repository performance assessments in the field of radioactive waste management. Thus far 13 major reviews and a large set of selected values have been published in dedicated volumes. An electronic database that follows the modelling guidelines of geological repositories has also been populated. One of the more unique characteristics of the TDB project is that data from existing primary experimental sources are critically reviewed by experts from universities and research institutes. The selected data are characterised for their accuracy, self-consistency and traceability so as to develop an international high-quality reference in the field.

The fifth phase of the project (TDB-5) was initiated in 2014 for a period of four years. During this phase, state-of-the-art reports will also be produced that consist of literature surveys and assessments aiming to analyse and systematise current methods and techniques for the study of waste disposal. These reports are a less formal departure from previous TDB reviews that focused on the selection of accurate thermodynamic values. Notably, the new TDB-5 programme of work envisages the preparation of a state-of-the-art report that will assess the modelling of and experimental approaches used to describe high ionic strength solutions. The report will build on previous TDB work *(Modelling in Aquatic Chemistry, 1997)* to address high ionic strength systems ($I > 3$ M), where the Pitzer formulation rather that the SIT approach is usually applied.

The pronounced interest of the nuclear community in high ionic strength systems is reflected in the number of publications that have appeared in the field since 2000 (see the figure). More importantly, a significant amount of the recent literature has not yet been fully integrated into the existing models. The driver for this increased level of attention to radioactive waste management has been the growing role of salt repository concepts for the permanent disposal of radioactive waste. Understanding and properly assessing current experimental approaches for measurements and modelling of actinide solubilities and associated brine chemistry in brine-intrusion scenarios will thus be indispensable.

The focus of this state-of-the-art report will be on radioactive waste disposal aspects that apply to repository concepts in bedded and domed salt formations, which could also be relevant to other geological disposal concepts where high ionic strength aqueous conditions exist. The overall objective of the report will be to identify the strengths and weaknesses in the existing Pitzer parameter data, assess and provide guidance for the collection and measurement of these data, provide assistance in the calculation and extrapolation methods used, and identify the data gaps and needs that will guide ongoing and future studies. The review will focus on the Pitzer parameters for binary and ternary species for the main components of brine, broadly referred to as "oceanic" species; key radionuclides and actinides that are important in the repository safety case; and key species in the low-pH process chemistry that, in many cases, directly or indirectly support radioactive waste disposal options.

This new TDB activity will serve not only as a means of undertaking critical analyses of current experimental data and techniques available for Pitzer modelling, it will also be a key step towards developing a single, self-consistent Pitzer database for radioactive waste repository applications for the international community. Today, the TDB provides an authoritative database for low to intermediate ionic strength conditions, with the recommended values being evaluated against well-documented, traceable and scientifically convincing guidelines. In terms of Pitzer-based modelling, however, there is no thermodynamic database of comparable transparency and consistency. The growing need to work towards this goal has also been recognised officially by the NEA Salt Club, which envisages setting up a working group to develop concepts for a future Joint International Pitzer Database (JIPD). The proposed JIPD will continue where the TDB state-of-the-art report leaves off, and will constitute a key activity of international relevance in the context of thermodynamic databases and Pitzer modelling.

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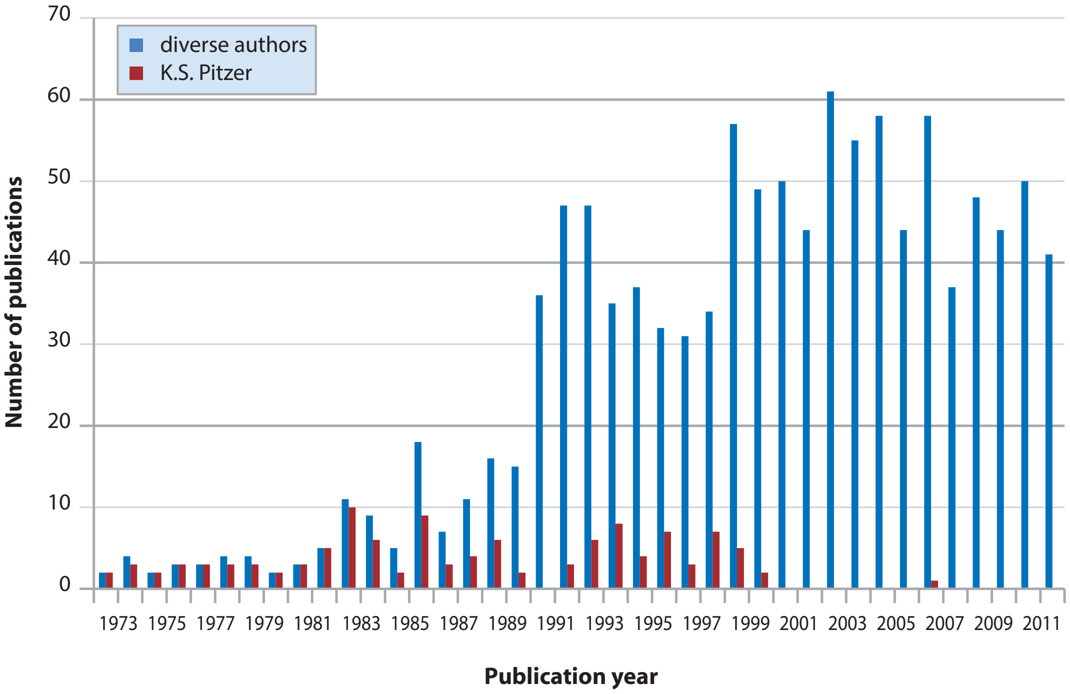
Publications that centre on the experimental measurement or modelling of Pitzer data since the development of the Pitzer approach in 1973



The funding of this report comes from the TDB-5 participating organisations together with a significant in-kind contribution from Los Alamos researchers through the United States Department of Energy Environmental Management programs (workers at the Waste Isolation Pilot Plant [WIPP]) and Advanced Simulation Capability for Environmental Management (ASCEM) and the Karlsruhe Institute of Technology – Institute for Nuclear Waste Disposal (KIT/INE) researcher through the Helmholtz Association of German Research Centres (HGF) Radioactive Waste Management, Safety and Radiation Research Helmholtz Programme (NUSAFE) programme. The review team consists of eight experts, currently active in the field and with high scientific standing, from Germany (KIT/INE, the Technical University of Freiberg and Global Research for Safety [GRS]), the United States (Los Alamos National Laboratory), as well as independent reviewers. Completion of the state-of-the-art report is expected by the end of 2016, with publication planned for 2017.

References

The Thermodynamic Database (TDB) and its publications are available at www.oecd-nea.org/dbtdb/.

Further information on the NEA Salt Club is available at www.oecd-nea.org/rwm/saltclub/.

Altmaier, M. and D.T. Reed (Eds.) (2015), "Proceedings of the Third International Workshop on Actinide and Brine Chemistry in a Salt-Based Repository (ABC-Salt III)", Los Alamos National Laboratory Report LA-UR-15-21114, Los Alamos.

NEA, Allard et al. (Eds.) (1997), *Modelling in Aquatic Chemistry*, 724 pages, OECD, Paris. Available at www.oecd-nea.org/dbtdb/pubs/modelling-aquatic-chem.html.

Multi-physics experimental data, benchmarks and validation

by J. Dyrda, J. Gulliford, P. Finck, T. Valentine and U. Rohatgi*

Computational analysis methods continue to evolve in many nuclear power countries to meet the needs of designers, operators and safety regulators, to increase predictive accuracy and to evaluate complex situations that could have only been addressed by experimental means or simple bounding calculations in the past. As a result of these developments, computational methods targeted at multi-physics and multi-scale simulations are beginning to be used in different settings. These codes are capable of modelling highly complex scenarios at a very high level of spatial, phenomenological and/or temporal resolution. They also enable rigorous modelling of coupled behaviours between, *inter alia*, reactor physics, thermal-hydraulics, fuel performance, materials and chemistry.

The increasing fidelity of such analytical tools does not, however, eliminate the need for suitable validation via comparison to experiments. In fact, in order to be used to their full potential, these tools may likely require a more complex array of validation tests as a result of multiple length and time scales, as well as the number of physical phenomena being simulated. However, the ability to conduct validation experiments has either progressed very little or in some cases significantly regressed. Recognition of this divide has led research and industry experts from across the NEA nuclear science community to form a new Expert Group on Multi-physics Experimental Data, Benchmarks and Validation (EGMPEBV). The aim of the group is to provide member countries with guidelines and recommendations for validating and improving their novel multi-physics simulations.

Validation of multiple physics models requires a wide variety of experimental data, which emphasises the importance of maximising the use of historically accumulated data to avoid the significant cost of performing similar experiments today. The preservation, evaluation and dissemination of such legacy validation data represent a cost-effective path forward to validate modern codes. Identification and prioritisation of key legacy data relevant to modern requirements is therefore one of the group's primary goals. A review and evaluation of the data by experts, both current and contemporary to the experiments in question, will also be undertaken. The target end product will be evaluated and independently reviewed benchmark datasets with quantified uncertainties, which are of significantly greater value to users than the "raw" documentation.

One such set of experimental data is from the former Loss-of-Fluid Test (LOFT) facility in the United States where an NEA international project was conducted between 1983 and 1989. LOFT data are particularly unique in that they originate from the only large-scale multiple-phenomena test facility that employed a nuclear powered core. NEA members from the United States have therefore made it a priority to collect, analyse and re-model these data so as to re-evaluate the uncertainties and the sensitivity of the measured data for use in multi-physics benchmarks. The EGMPEBV will build upon efforts being made by other expert groups, such as the Expert Group on Uncertainty Analysis in Modelling (EGUAM), to develop methodologies and recommendations for uncertainty propagation.

At the same time, while historical data are undoubtedly of great value, they may also be limited by several factors, usually related to past experiments' targeting the validation of older codes and the application of those codes. As a result, these data can often exhibit limitations including a lack of measurement accuracy in the experimental techniques; an absence of measurements for some critical parameters, an obscuring of relationships between individual physics phenomena owing to the output data resolution or simply the inability to allow for a detailed reinterpretation of the experiments based on the documented information.

Part of the EGMPEBV's role will therefore be to help identify gaps in the experimental data, where the scarcity of information is detrimental to the validation efforts of stakeholders. By comparing similar needs, efforts to fill such gaps may be coordinated across member countries. Where data

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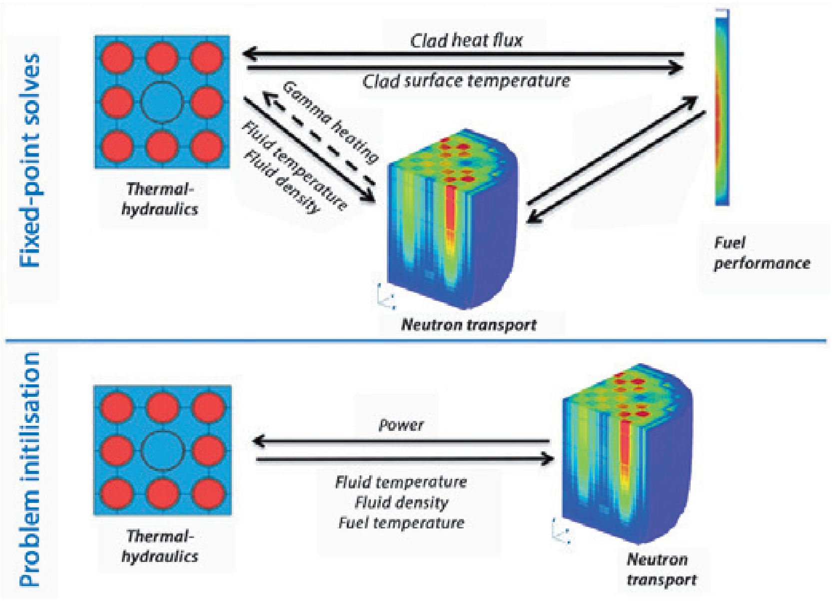
High fidelity modelling of a nuclear reactor using multi-physics applications coupled via the Tiamat Code



The Tiamat code was used to coupled neutronics (Insilico), thermal-hydraulics (Cobra-TF[CTF]), and fuel performance (Peregrine) to model components of a nuclear reactor with cutting edge fidelity. Insilico generates a fission rate within the fuel throughout the problem; the fission rate is a heat source for an independent Peregrine model of every fuel pin; convective heat transfer draws the heat from the fuel pins (Peregrine) into the coolant, and out of the reactor core, which is modelled with CTF. The temperature distribution within the fuel pin and coolant, along with the coolant density, effect the neutron cross sections and alter the power distribution from Insilico. The images demonstrate that this is a very multiscale problem that spans the internal temperature distribution of an individual fuel pin (Peregrine image), the flow distribution around individual fuel pins (CTF), and the power distribution that accounts for core-wide (Insilico) features such as control rod banks. CASL Technical Report: CASL-I-2013-0165-000.

Source: Roger Pawlowski (SNL), Consortium for Advanced Simulation of Light Water Reactors (CASL), Oak Ridge National Laboratory, US Department of Energy.

does not exist, suitable experiments, facilities and measurement techniques may be designed and developed to address those specific needs. The benefit of this international effort is the leveraging of experimental capabilities that are likely to go beyond any single country's ability to achieve the desired results – a true representation of cost efficiency for all partners involved.

Establishing consensus guidelines for the application of validation data is essential in light of the developing multi-physics code systems. The EGMPEBV will aim to establish standards for evaluating experimental data and determining how these data should be applied to the specific codes and applications in question. The resulting output, along with appropriate phenomena identification and ranking tables (PIRT), could help guide users on the applicability of particular experimental data to reactor phenomena or scenarios of interest.

Finally, guidance for performing robust validation analyses is also important, including for methods to extrapolate uncertainties beyond the validation domain and for estimates of the degree to which stakeholders can rely on the results. This is closely related to the issue of scaling, or when factors must be applied to experimental results because of the extrapolation from the experimental configuration to a full-size application. To compile and make available such recommendations will thus be of significant benefit to the scientific community. The composition of the group is therefore diverse as it will draw upon experience from multiple nuclear science and safety fields of expertise.

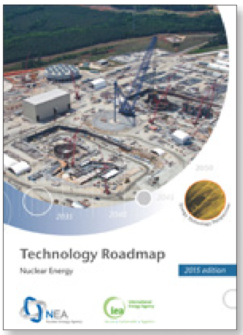
It is clear that the tasks of the EGMPEBV will be very demanding and require significant effort. However, the participants remain confident and committed to the ultimate aim, which is for the nuclear industry to realise the potential benefits of novel methods over traditional ones.

Reference

For more information on the LOFT Programme, see www.oecd-nea.org/jointproj/loft/.

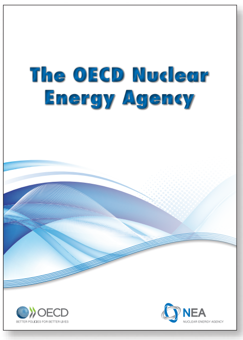
New publications

General interest



Technology Roadmap: Nuclear Energy

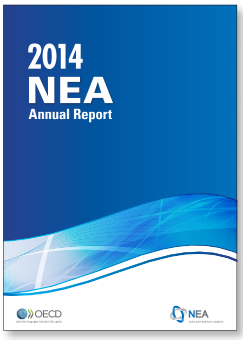
NEA No. 7257. 64 pages.



The OECD Nuclear Energy Agency

8 pages.

Also available in French.

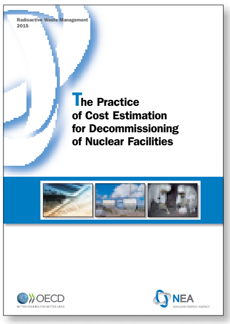


2014 NEA Annual Report

NEA No. 7238.
60 pages.

Also available in French.

Radioactive waste management

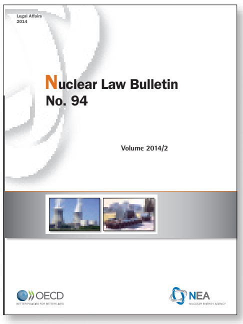


The Practice of Cost Estimation for Decommissioning of Nuclear Facilities

NEA No. 7237. 89 pages.

Decommissioning of both commercial and R&D nuclear facilities is expected to increase significantly in the coming years, and the largest of such industrial decommissioning projects could command considerable budgets. Several approaches are currently being used for decommissioning cost estimations, with an international culture developing in the field. The present cost estimation practice guide was prepared in order to offer international actors specific guidance in preparing quality cost and schedule estimates to support detailed budgeting for the preparation of decommissioning plans, for the securing of funds and for decommissioning implementation. This guide is based on current practices and standards in a number of NEA member countries and aims to help consolidate the practice and process of decommissioning cost estimation so as to make it more widely understood. It offers a useful reference for the practitioner and for training programmes.

Nuclear law



Nuclear Law Bulletin No. 94

Volume 2014/2

NEA No. 7183. 185 pages.

The *Nuclear Law Bulletin* is a unique international publication for both professionals and academics in the field of nuclear law. It provides subscribers with authoritative and comprehensive information on nuclear law developments. Published twice a year in both English and French, it features topical articles written by renowned legal experts, covers legislative developments worldwide and reports on relevant case law, bilateral and international agreements as well as regulatory activities of international organisations. Feature articles in this issue include "Facilitating the entry into force and implementation of the Amendment to the Convention on the Physical Protection of Nuclear Material: Observations, challenges and benefits"; "The legal status of nuclear power in Germany"; "Challenges facing the insurance industry since the modernisation of the international nuclear third party liability regime"; "Draft Federal Act of the Russian Federation, 'The Civil Liability for Nuclear Damage and its Financial Security'".

Nuclear science and the Data Bank

International Handbook of Evaluated Criticality Safety Benchmark Experiments

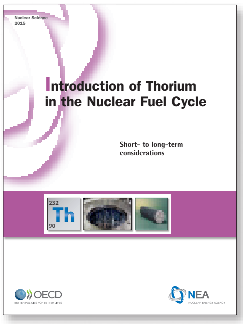
NEA No. 7231. DVD (limited distribution).

The Criticality Safety Benchmark Evaluation Project (CSBEP) was initiated in October 1992 by the United States Department of Energy. The project quickly became an international effort as scientists from other interested countries became involved. The International Criticality Safety Benchmark Evaluation Project (ICSBEP) became an official activity of the NEA in 1995. This handbook contains criticality safety benchmark specifications that have been derived from experiments performed at various critical facilities around the world. The benchmark specifications are intended for use by criticality safety engineers to validate calculation techniques used to establish minimum subcritical margins for operations with fissile material and to determine criticality alarm requirements and placement. Many of the specifications are also useful for nuclear data testing.

International Handbook of Evaluated Reactor Physics Benchmark Experiments

NEA No. 7258. DVD (limited distribution).

The International Reactor Physics Experiment Evaluation (IRPhE) Project was initiated as a pilot in 1999 by the Nuclear Energy Agency (NEA) Nuclear Science Committee (NSC). The project was endorsed as an official activity of the NEA in 2003. While the NEA co-ordinates and administers the IRPhE Project at the international level, each participating country is responsible for the administration, technical direction and priorities of the project within their respective countries. The information and data included in this handbook are available to NEA member countries, contributors and to others on a case-by-case basis. This handbook contains reactor physics benchmark specifications that have been derived from experiments that were performed at nuclear facilities around the world. The benchmark specifications are intended for use by reactor designers, safety analysts and nuclear data evaluators to validate calculation techniques and data.

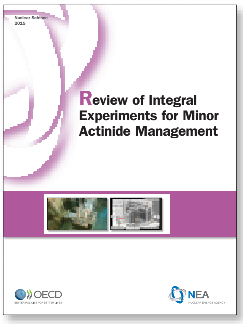


Introduction of Thorium in the Nuclear Fuel Cycle

Short- to long-term considerations

NEA No. 7224. 133 pages.

Development of innovative fuels such as homogeneous and heterogeneous fuels, ADS fuels, and oxide, metal, nitride and carbide fuels is an important stage in the implementation process of advanced nuclear systems. Several national and international R&D programmes are investigating minor actinide-bearing fuels due to their ability to help reduce the radiotoxicity of spent fuel and therefore decrease the burden on geological repositories. Minor actinides can be converted into a suitable fuel form for irradiation in reactor systems where they are transmuted into fission products with a significantly shorter half-life. This report compares recent studies of fuels containing minor actinides for use in advanced nuclear systems. The studies review different fuels for several types of advanced reactors by examining various technical issues associated with fabrication, characterisation, irradiation performance, design and safety criteria, as well as technical maturity.



Review of Integral Experiments for Minor Actinide Management

NEA No. 7222. 137 pages.

Spent nuclear fuel contains minor actinides (MAs) such as neptunium, americium and curium, which require careful management. This becomes even more important when mixed oxide (MOX) fuel is being used on a large scale since more MAs will accumulate in the spent fuel. One way to manage these MAs is to transmute them in nuclear reactors, including in light water reactors, fast reactors or accelerator-driven subcritical systems. The transmutation of MAs, however, is not straightforward, as the loading of MAs generally affects physics parameters, such as coolant void, Doppler and burn-up reactivity. This report focuses on nuclear data requirements for minor actinide management, the review of existing integral data and the determination of required experimental work, the identification of bottlenecks and possible solutions, and the recommendation of an action programme for international co-operation.

Also available

2014 GIF Annual Report

124 pages.

www.gen-4.org

This eighth edition of the *Generation IV International Forum* (GIF) *Annual Report* highlights the main achievements of the Forum in 2014, and in particular progress made in the collaborative R&D activities of the eleven existing project arrangements for the six GIF systems: the gas-cooled fast reactor, the sodium-cooled fast reactor, the supercritical-water-cooled reactor and the very-high-temperature reactor. Progress made under the memoranda of understanding for the lead-cooled fast reactor and the molten salt reactor is also reported. In May 2014, China joined the supercritical-water-cooled reactor system arrangement; and in October 2014, the project arrangement on system integration and assessment for the sodium-cooled fast reactor became effective. GIF also continued to develop safety design criteria and guidelines for the sodium-cooled fast reactor, and to engage with regulators on safety approaches for generation IV systems. Finally, GIF initiated an internal discussion on sustainability approaches to complement ongoing work on economics, safety, proliferation resistance and physical protection.

Multinational Design Evaluation Programme Annual Report 2014-2015

38 pages.

www.oecd-nea.org/mdep

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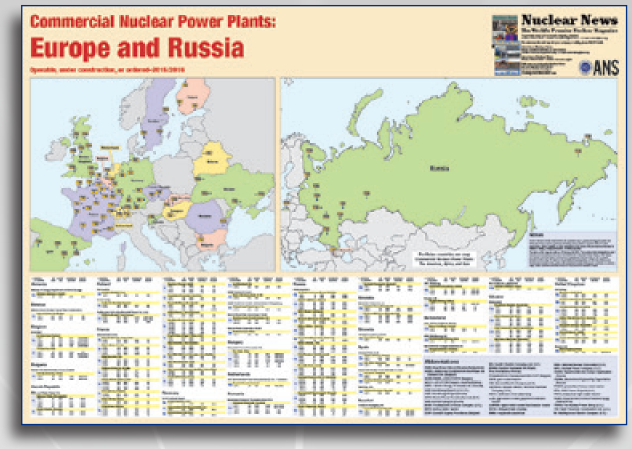
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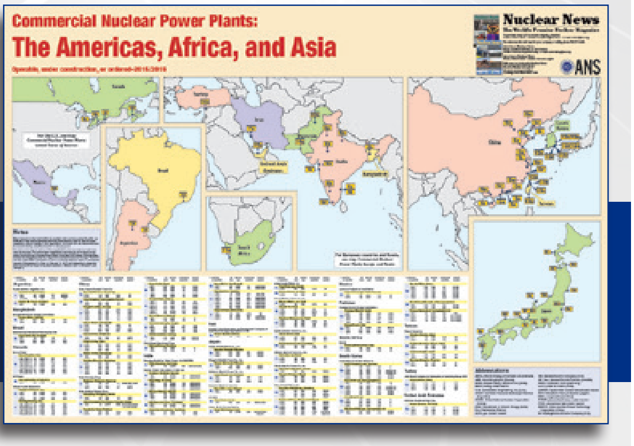
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