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Optimized Capacity: Global Trends and Issues 2014 edition

A Report by the World Nuclear Association's
Capacity Optimization Working Group

Contributors

2014 (3rd) edition

Michael Baron (Chair), Global Nuclear Associates
Alexander Puhrer, Alpiq
Wolfgang Denk, Alpiq
Steven Lau, CGNPC
Thomas Paffrath, E.On
Ken Barry, EPRI
Johan Danielsson, GE Hitachi
Jiri Mandula, IAEA
Daniel Westlén, Vattenfall
Michael Lövgren, Vattenfall
Ulf Johansson, Vattenfall
David De Novellis, Westinghouse
David Hess (staff director), World Nuclear Association

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Foreword

The World Nuclear Association is the organization that represents the global nuclear industry. Its mission is to promote a wider understanding of nuclear energy among key international influencers by producing authoritative information, developing common industry positions and contributing to the energy debate.

As part of its commitment to facilitating cooperation, the World Nuclear Association working groups are formed of experts drawn from the global nuclear industry who address topics of shared interest. Working group members meet on average three times a year and engage in an open exchange of information and opinions – continuing the well-established tradition of the sharing of knowledge and best practice within the industry.

Working group reports present the consensus views of these expert members on important specific issues. To this extent they provide a voice for the global nuclear industry; however the views of working groups do not necessarily reflect the views of the World Nuclear Association's individual member companies.

This report reflects the research of the World Nuclear Association's Capacity Optimization Working Group. The group was constituted to identify means by which nuclear operators worldwide can maximize the performance of their plant. In order to progress towards this goal, this report establishes a status baseline and undertakes high-level analysis to understand at what point the global industry currently stands and what the dominant issues in utilization of the installed capacity base are.

This is the third edition of the *Optimized Capacity: Global Trends and Issues* report. The first was published in April 2010 and contained data drawn from the IAEA Power Reactor Information Service (PRIS) for the two years up to the end of 2008. A second edition was published in 2012 which included PRIS data up to the end of 2010. This edition, contains PRIS data to the end of 2012 as well as new sections exploring some of the factors affecting capacity in more detail.

Executive summary

This report draws upon data collected in the International Atomic Energy Agency's (IAEA) Power Reactor Information Service database to present a snapshot of the performance of the world's operating nuclear power reactors as well as a breakdown of the principal causes of capacity loss for the period 2010-2012.

While the idling of the Japanese fleet resulted in a decrease of the global average capacity factor to 72% in 2012 (down from 77% in 2010) the global median capacity factor remains at about 84%. There is however a range of performance levels around that median with a long tail of reactors showing clear potential for improvement. Best performing units still regularly achieve greater than 90% – an industry benchmark. The potential for >90% capacity factors does not appear to be limited by reactor age and can be achieved by any of the major reactor types. This serves as testimony to the general robustness of existing nuclear technology and the commitment of the organizations involved.

The main findings of the report include:

- The vast majority of energy loss is within plant management control.
- Combined maintenance and refuelling outages are the single biggest cause of planned energy loss. Improving outage performance is key to achieving a high capacity factor.
- Best performing nuclear units manage to minimize scrams and achieve both productivity and safety.
- A strong safety record is a pre-requisite to a high capacity factor.
- An increasing number of plants have been put into long-term shutdown for regulatory reasons or because of component issues related to upgrades. Preventing similar occurrences is an industry-wide priority.
- Regardless of plant performance, policy and market forces have led to premature retirements in certain countries, and are putting other units under pressure. Action is needed to prevent the further loss of clean, reliable and low-cost nuclear energy in these places.

1 Introduction

In 2012 the world's operating nuclear reactors supplied 2,346 TWh of electricity at an average capacity factor of 72.2%. This number was down compared to the 2011 figure of 2,518 TWh (average capacity factor of 77.4%) due largely to the progressive idling of reactors in Japan which followed the accident at Fukushima Daiichi. For 2011, total global supply was 22,202 TWh[1], meaning that nuclear-generated electricity accounted for 11.3% of the total.

The best performing reactors in the world regularly exceed capacity factors of 90%. There is thus great scope for improvement in the performance of the global reactor fleet, not only through the restart of the Japanese fleet but also through the improvement of day-to-day operations. If an industry-wide average capacity factor of 90% were to be achieved then, based on the 369 GWe of available capacity at the end of 2011, this would:

- Result in about 2,900 TWh of baseload electricity generation per year, an amount equivalent to ~13% of total global demand in 2011, without the addition of any extra capacity.
- Prevent the emission of about 2.8 billion tonnes of carbon dioxide per year[2] and numerous other atmospheric pollutants.

The performance of the nuclear fleet should therefore be of interest to a wide range of stakeholders. Among these are the plant operators who stand to make financial gains through more efficient operations, but also included are policymakers, regulators and the general public, who are primarily concerned with the adequate supply of affordable, reliable and clean electricity.

This third edition is intended as a broad overview of the global trends influencing reactor performance with emphasis on the period 2011-2012. In keeping with the previous editions, the primary focus of the report will be on plant capacity factors and analyzing them in terms of region, technology age and other criteria. The methodology remains mostly the same, however since the time period covers the accident at Fukushima Daiichi and the subsequent idling of the Japanese fleet, some adjustments have been made. Several new sections have been introduced which examine in detail some of the

Figure 1: Plant maintenance

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[1] From IEA *Electricity Information 2013*

[2] Estimated if coal had been used as a direct replacement at 963 grams of CO_2 per kWh

factors which lead to capacity loss – specifically outages and maintenance, plant engineering projects, and regulatory and market factors.

1.1 Issues in review 2010-2012

The third edition of this report covers the period of the March 2011 accident at the Fukushima nuclear plant in Japan. The accident and its repercussions continue to influence the nuclear industry worldwide. In Japan the Fukushima Daiichi nuclear accident led to a progressive idling of the country's fleet of 50 operable reactors as they were stopped for refuelling and maintenance and subsequently not permitted to restart[3]. A long period of uncertainty followed before it was finally determined that a new regulatory agency would be formed and new operating requirements drawn up before operators could apply to restart.

The fate of nuclear power in Japan was at times in serious doubt, with several prime ministers in quick succession expressing different preferences over a phase-out and the speed with which that should occur. In September 2012 the Liberal Democratic Party under Shinzo Abe won the national election on what can best be described as the least anti-nuclear platform with a stated intention to work towards restarting most reactors as soon as possible. At the time this report was going to press only one Japanese reactor had been restarted.

The accident also had a profound impact on Germany. Massive public backlash led the Merkel government to order the final closure of eight reactors without any supporting case from the country's regulator. A phase-out policy for the remaining reactors was introduced that would see them all close by 2022. A similar phase-out had only just been removed from policy at the end of 2010.
The accident also affected nuclear policies for operating reactors in Switzerland and Belgium, although in a less severe fashion than in Germany. In Belgium, a case was introduced to limit reactor lifespans to 40 years if 'alternative' generation could be found. In Switzerland, a policy to prevent replacement of reactors has been discussed although not formally adopted.

North America

The further rapid exploration and discovery of shale gas deposits has continued to reduce North American energy import dependency and power market prices. It has also had an impact on the competitiveness of nuclear plants at a time when many units have been operating 25-35 years and are undergoing upgrades to ensure safe long-term operation for a period of 60 years or longer. The increasing use of shale gas for power has decreased consumption of coal in the US, freeing up large amounts for export to Europe or China and affecting markets there. Some US reactors have experienced serious technical problems, which coupled with market conditions and regulatory requirements, eventually resulted in their permanent shutdown earlier than expected. Crystal River unit 3 was offline since 2009 after delamination was discovered in the containment, leading to eventual permanent closure in 2013. The two-unit San Onofre plant was idled at the beginning of 2012 as a result of rapid wear and degradation of tubes in replacement steam generators. The plant was also closed in 2013.

In Canada, Gentilly 2 was permanently shut down at the end of 2012 as the regional Quebec government deemed refurbishment of the 30 year-old unit to be too expensive. It was the only reactor in the province.

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[3] Two of the Ohi reactors were allowed to operate for longer than others due to a severe power shortage in the Kansai region

[4] For more information consult *Development And Integration Of Renewable Energy: Lessons Learned From Germany*, Finadvice, July 2014

[5] The amount has since been reduced as some nuclear units were closed and is now closer to €1.5 billion

Europe

Large subsidies and support for wind and solar generation in Germany and neighbouring countries are reducing European power prices on the spot market, while simultaneously increasing the price paid by customers[4]. As a result, European utilities are facing major unplanned asset devaluations, balance sheet write-downs and depressed outlooks. This is tightening budgets and restricting the ability of utilities to invest in new generating capacity. Gas plants exhibiting high marginal cost are being hit particularly hard. The growing intermittent capacity base is increasing the need for load following in both German and neighbouring reactors, with huge peaks in photovoltaic generation and wind energy occurring with increasing frequency.

In Spain, a generous renewables incentive saw a large-scale uptake of the technology, particularly wind energy, leading to spiralling power costs. New tax laws introduced in 2012 placed the burden of market recovery on all generators. This, coupled with re-licensing concerns, resulted in the owner of the Garoña nuclear power reactor not filing for licence renewal in 2012, with operations ceasing in 2013.

The period also saw a dramatic escalation of nuclear taxes in some European countries. A reactor-fuel tax was introduced in Germany and controversially kept following the country's nuclear policy turnaround. The tax netted the government approximately €2 billion per year[5]. An existing reactor tax in Belgium was effectively doubled in 2011, netting the government an estimated €550 million per year.

In general plant performance in other major European nuclear power fleets were satisfactory but availability was affected by ongoing backfitting programmes such as the replacement of nuclear and conventional island systems and components prolonging outages in countries such as France, Switzerland, the UK and Sweden.

Asia

Japan, China and South Korea have all embarked upon reforming their nuclear regulators. One of the most frequently heard lessons of the Fukushima accident is that the Japanese regulator was not sufficiently independent. These countries have responded to this while at the same time increasing their regulator's resources. A new and expanded Japanese regulator – the Nuclear Regulatory Authority – was formed and placed under the Ministry of Environment. In structure this body resembles the US regulatory system where staff report to a five-person commission. In South Korea the Nuclear Security and Safety Commission was launched in 2011, effectively replacing the Korea Institute of Nuclear Safety (KINS) in this role. KINS continues to exist as a technical advisory body. In China a review of the regulator resulted in a suspension of licences for new-build projects that lasted until the end of 2012.

Overview

2011 and 2012 have been some of the most challenging years for the global nuclear power plant fleet. Many of these challenges are expected to remain or even intensify during the upcoming years. Market price pressures drive the need to optimize plant performance for economic operation, and to maximize production in order to increase financial returns. In the future, plant capacity factors are expected to come under pressure by subsidized intermittent electricity generation in many countries, which may result in base-load plants needing to curtail output. Nuclear power plant closures in these markets are a real possibility unless governments take steps to preserve disptachable low-carbon capacity or to incentivise flexible nuclear operations.

2 Reactor performance

The balance between available and unavailable capacity is determined by the following factors: operations, outages, maintenance and equipment reliability, engineering, fuel performance, environment, regulation and market, organizational factors and human performance, safety, finances, supply chain processes.

Figure 2 shows the model that has been adopted to assess data values collected from nuclear power plants. The reference unit power is the maximum (electrical) power of the unit under reference ambient conditions. It is based on design values and is expected to remain constant unless certain design changes are made to the unit. As shown, it can be split into two components – 'available capacity' and 'unavailable capacity'.

'Available capacity' can be broken down into what is, and what is not, supplied to the grid. Similarly 'unavailable capacity' can be broken down into elements that are, or are not, under plant management control. Two additional important concepts can be defined using this model: 'availability' is the sum of the 'generation supplied' and 'available but not supplied'; 'capability' is the sum of the 'generation supplied' and 'available but not supplied' the element of unavailable capacity which is 'not under plant management control'.

In order to determine performance measures, the concept of reference energy generation (REG) is applied. This is a theoretical maximum value for annual electricity production that is calculated by multiplying the reference unit power by the reference period. By dividing the components at the lowest level of Figure 2 by REG, we derive a set of indicators that are used across the nuclear fleet. The relationship between values and indicators is shown in Figure 3.

Performance indicators allow for meaningful statistical analysis of current and historic data held on the nuclear fleet. Of particular interest for this report is the 'capacity factor' indicator that relates to the 'generation supplied' as discussed above. This is what generates revenue.

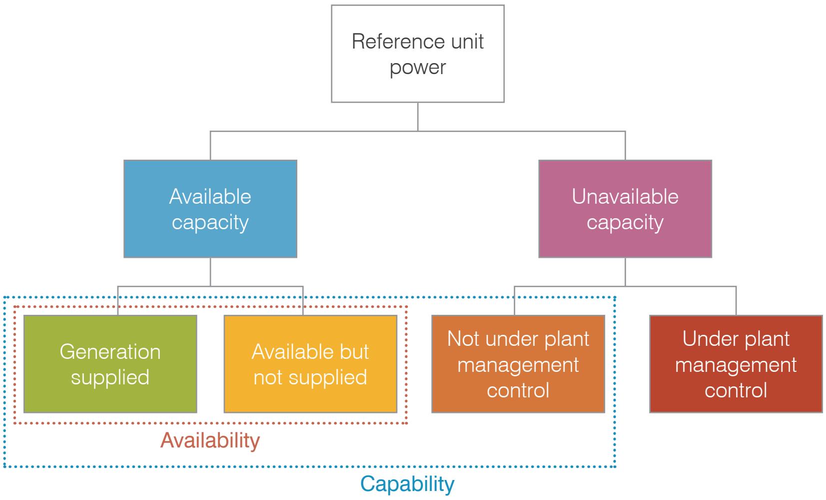

Figure 2: Data model

Where the data comes from
Note: The data model, performance indicators and data used in this report are drawn from figures held in the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) www.iaea.org/pris/ which constitutes the most complete and authoritative technical data bank on nuclear power reactors in the world. The same terminology is also applied, with the exception of the capacity factor which the IAEA refers to as ‘load factor’. More detailed definitions of these performance values and indicators can be found in Appendix 2 of this report.

To highlight the current limits of achievable performance, a distinction is drawn between the entire global fleet of nuclear reactors (All reactors) and the top performing 10% (best performers) as determined by their energy availability factor averaged over five years. Other performance indicators are then derived separately for these two groups. Availability is used instead of capacity factor to determine best performers so as not to discriminate against units which load follow or are subject to other grid limitations.

Several distinct time periods are discussed throughout the report. A snapshot of performance over one year is presented for 2012. However most plant operating cycles are longer than this, meaning that some indicators should be derived over a longer period in order to be meaningful – five years was the period chosen (1 January 2008 - 31 December 2012). A ten-year period is also used to allow comparison over the longer term (1 January 2003 - 31 December 2012). It should be noted that the individual units which comprise the best performers category remain the same across these time periods. However they may change between editions of this report.

Most of the analysis presented here makes use of median capacity factors rather than averages, effectively removing weighting due to long-term shutdowns or chronically underperforming plant. The report is designed to address factors affecting everyday operation – rather than highlight units which are shutdown for long periods due to regulatory reasons or major refurbishment.

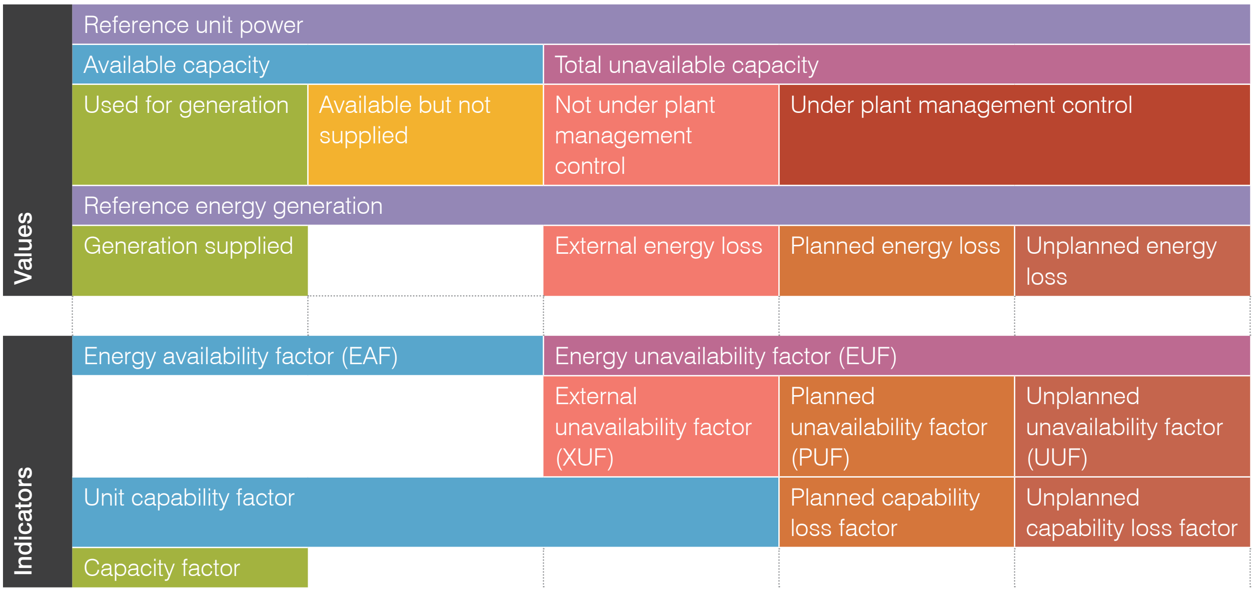

Figure 3: Performance indicator derivation

Impact of the Fukushima nuclear accident on report statistics
For this edition of the report the Japanese reactors are excluded from most figures and statistics. Were these reactors to have been included, this would have prevented any meaningful comparison being made between different editions of this report. The exceptions are Figures 4, 5 and 6 which seek to demonstrate the effect of the shutdown.

2.1 The global picture

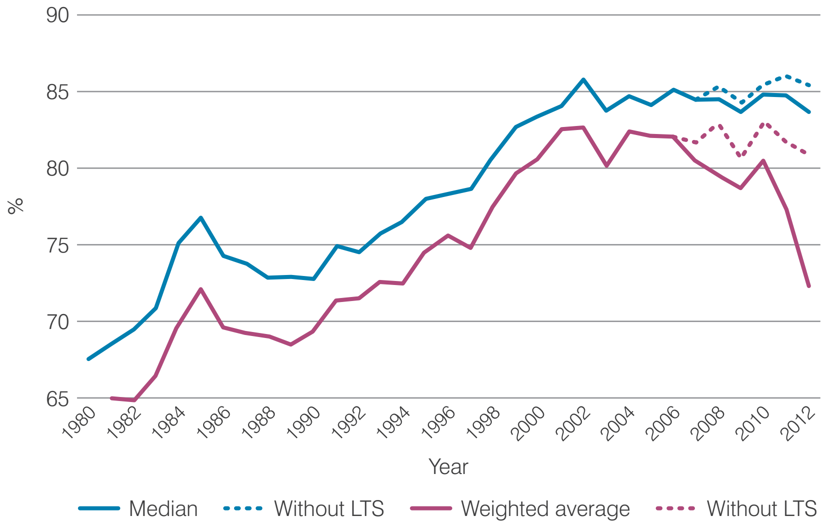

Figure 4: Global capacity factor over time

While the Fukushima Daiichi nuclear accident and resulting reactor shutdowns in Japan and Germany have had profound effects on the global nuclear industry, operating performance in the rest of the global fleet does not appear to have suffered. The solid lines in Figure 4 shows the impact of the Japanese reactor shutdown, while the dashed lines provide an indication of what the global fleet capacity factor would have been if a typical value for the Japanese fleet were included. Judging from the dashed lines, it seems that the Fukushima accident may even have overshadowed a slight rise in the global median capacity factor over the last two years. Whether or not this is the case[6] it is evident that overall the trend in the median global reactor performance has been mostly flat for the past decade with most of the improvement taking place through the 1990s.

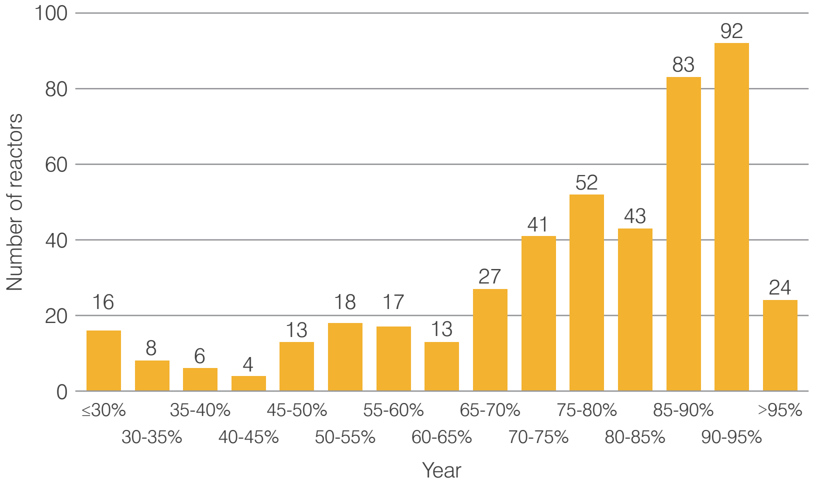

Figure 5: Histogram of individual plant capacity factors 2008-2012

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[6] It can only be confirmed over subsequent years to see if the trend persists

Figure 6: Number of reactors not operated for the entire year, or for less than 10% of the year

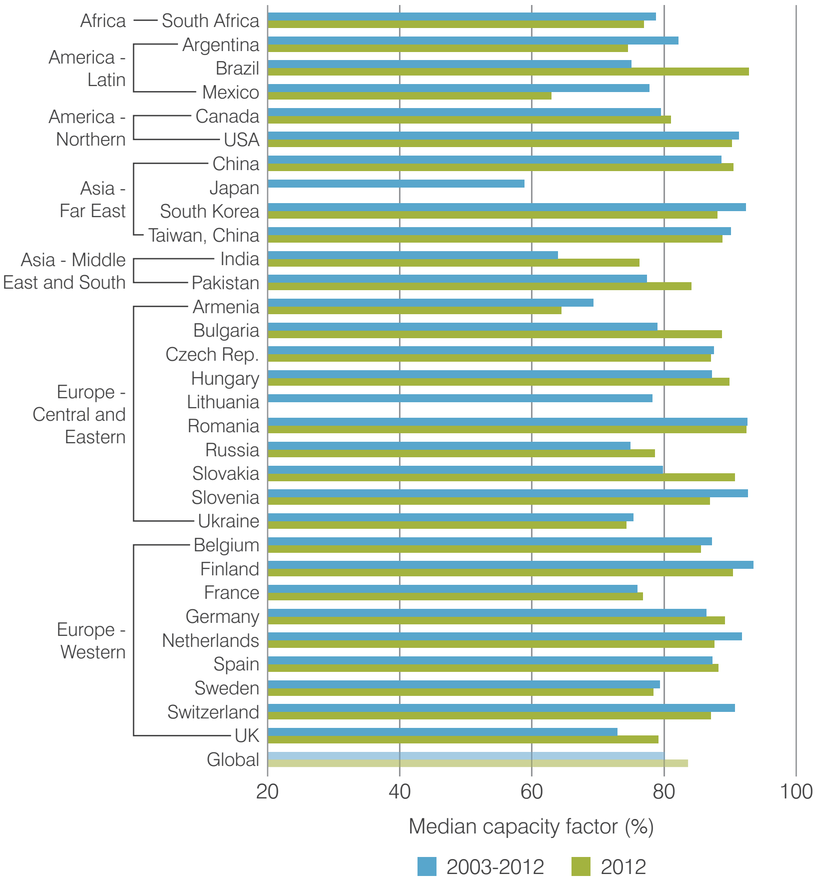

Figure 7: Long and short term capacity factors by country

The Figure 5 histogram contains a long tail of reactors that have experienced lengthy shutdowns and energy loss. Improving the performance of these could result in substantial extra nuclear generation and drive up the average global capacity factor; however this would have a smaller effect on the median value.

Cases where a reactor is shut down for longer than a year, or has delivered less than 10% of its reference energy generation, are indicated in Figure 6. In 2012 we see a large jump in the number of these reactors as the entire Japanese fleet is progressively idled in the months following the Fukushima nuclear accident.

Figure 5 illustrates that the capacity factor of individual plants in some cases varies widely from the global median. There are a large number of reactors which have no technical barrier to achieving industry best performance levels of >90% capacity factors. By contrast all the reactors in Figure 6 have a unique story to tell. They face major engineering, regulatory and/or political obstacles specific to their individual circumstances.

As Figure 7 demonstrates, there is a wide spread of capacity factors between regions and also between countries within the same region. Local conditions can be seen to come into play more directly (for example fuel supply issues, seasonal demand variations, load following). While reactors in a given country will always face similar conditions such as politics and regulation, companies and workforces are becoming increasingly international over time and efforts are ongoing towards harmonizng codes, standards and regulatory approaches. If this trend towards globalization of the nuclear industry continues it may reduce the importance of where a reactor is based in determining performance.

Figure 7 also reveals the consistently high performance of the Belgian, German and Swiss reactors. All three countries experienced a negative backlash following the Fukushima accident which imposed reactor lifespan limitations and considerations of phase-out policies despite this excellent operational record. In the case of Germany, following the accident the government immediately forced the closure of eight units without any safety basis. Since then the country has increased its reliance on coal-fired generation.

The biggest impact of the Fukushima accident was the subsequent idling of the 50 remaining operable Japanese reactors. This has had profound economic impacts on the country as it has switched to more expensive coal, gas and fuel oil imports. It has also adversely affected the vendors and fuel cycle companies in the nuclear industry through a sudden and substantial reduction in market size. However the Japanese plant capacity factors have not been high historically, thanks largely to a regulatory requirement for a mandated annual 60-day outage and inspection. It is for this reason that the removal of the Japanese reactors from the global statistics has had little impact on the median capacity factor and may even have caused it to rise when the idled reactors are not accounted for.

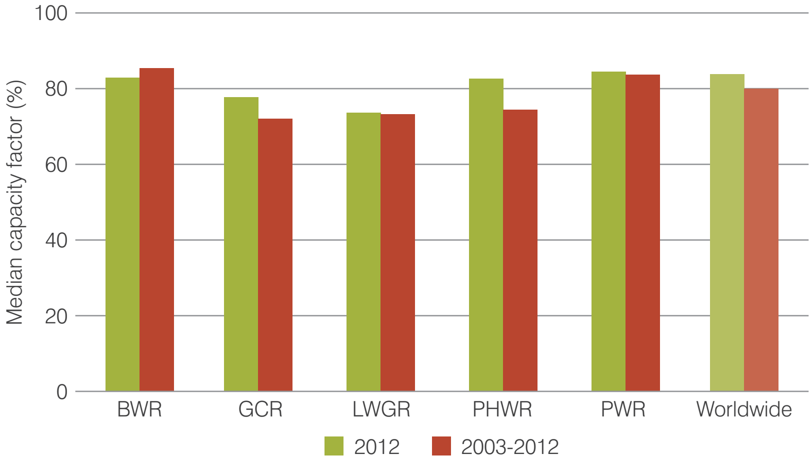

Figure 8: Long- and short-term capacity factors by reactor type (excluding Japanese reactors)

PWR:	Pressurized water reactor (including VVER) – 68% of installed global capacity
BWR:	Boiling water reactor (including ABWR) – 20%
PHWR:	Pressurized heavy water reactor (including Candu) – 7%
GCR:	Gas-cooled reactor (the vast majority of these are the UK’s AGR fleet) – approx. 3%
LWGR:	Light water graphite reactor (also known as RBMK) – approx. 3%

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[7] On 7 October 1994 Pickering 7 commenced an outage after generating continuously for 894 days

Figure 8 shows the median capacity factor recorded by the different main reactor types. For most types the 2012 capacity factor is higher than the 10-year average, indicating that long-term performance may improve in the future for these types. Only BWRs saw a performance decrease for 2012, however it is worth noting that Japan is home to 24 BWR reactors which now sit idle – a significant fraction of the 82 operational BWRs worldwide. All of the operable reactors in Japan are either PWRs or BWRs, but the performance of both reactor types continues to be strong globally. The 10-year capacity factors for PWRs and BWRs have not changed much since the last edition of this report.

It is the LWGRs that have exhibited the clearest performance gain in the last two years. The 10-year average has improved by about 4% since the last report edition, a respectable achievement for a reactor type that now exists only in the Russian Federation and which is expected to be phased out over the coming decade.

Figure 9: Long- and short-term capacity factors by reactor age (excluding Japanese reactors)

Both GCRs and PHWRs exhibited strong performance in 2012, well above the 10-year average. The GCR is another reactor type which is expected to disappear within 15 years as the UK closes them down and gradually replaces them with new LWRs. Major upgrades are not expected for the AGRs and the plans for long-term operation are modest, with most reactors expected to shut down in the 2020s achieving an average life span of 45 years.

The PHWR is a technology that continues to be actively marketed via the Candu 6 and ACR-1000, with indigenous designs under construction in India. With the benefit of a mid-life refurbishment the intended operating life of these designs can been extended up to 60 years. PHWRs are capable of the same performance levels as light water alternatives. The design can be refuelled online, meaning that maintenance and inspections rather than refuelling determines the length of the operating run. It also means that PHWR units hold the title for the longest uninterrupted period of generation[7].

It is evident that technology selection, at least for all major types available today is not a fundamentally limiting factor for operating performance. In fact increasing experience and focus on improvement continues to yield positive results across the different reactor types. This is a significant achievement and stands as a benchmark that any future reactor design – PWR, BWR, PHWR or an advanced reactor concept – must seek to match.

Only one fast breeder reactor (FBR) is currently operating and has therefore been omitted from statistical analysis in this report. The Russian designed BN-600 at Beloyarsk 3 has achieved a lifetime capacity factor to date of 74.1%, a promising result for this design and future fast reactors.

In general, no significant global age-related trend in capacity factor can be detected from Figure 9. This is good news for older plants, which can maintain historic output levels, and also for newer plants, which do not appear to require any 'run-in' time, suggesting that good practice in operations is being passed on.

What is not looked at here is the cost of keeping older plants performing at historic levels, and whether this cost is comparable with the cost of operating younger plants. It is also important to remember that capacity factor is different from output – older plants tend to have significantly lower reference unit power.

3 Available capacity and energy loss

This section explores the causes of energy loss in the global reactor fleet. The differences between an average reactor – as represented by the median value derived for all reactors – and a hypothetical best performer (median of the top 10% of reactors) are compared, revealing characteristic profiles for each.

Figure 10 shows that best performers maximize their availability and minimize the amount of unavailability compared with other units. They reduce both planned unavailability and unplanned unavailability, demonstrating that long outages are not strictly necessary for problem-free operation. For best performers then, planning for success and being able to stick to that plan is important. Outage scope does not have to be cut, and risk does not have to be transferred onto the operating cycle. It follows that there are clear efficiency gains to be made by poor performing units in this area.

The best capacity factor performers represent a range of technologies[8], vendors, regions[9] and countries, suggesting that performance is somewhat independent of these choices. Best performers achieved a median capacity factor of 94.4%.

Figure 11 shows that globally about 95% of unavailable capacity is within plant management control. Planned losses are most significant, followed by unplanned losses. Accounting for only 5% are factors which are not under plant management control. This includes environmental and grid limitations.

In this figure unplanned losses have been split into two components, demonstrating the importance of unplanned extensions to planned outages. Clearly planned outages and reductions are most important, but unplanned causes should also be addressed – especially since they tend to entail extra economic consequences to operators such as the need to purchase replacement power and to perform unexpected corrective maintenance. They also disrupt power system planning.

3.1 Planned energy loss

Figure 12 shows the amount of energy lost per reactor year due to different planned causes[10] and therefore provides some level of insight into the financial impacts on operators. Combined maintenance and refuelling outages are the dominant cause of planned energy loss across both best performers and 'all reactors', however, best performers lose only half the energy in these planned outages compared with the average of all reactors.

Units undergoing major modernization, or backfitting,

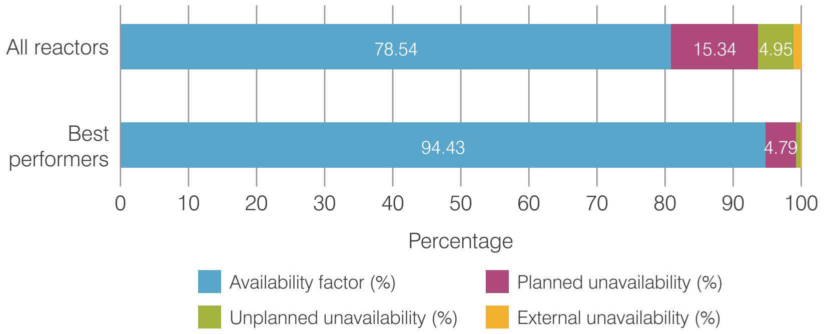

Figure 10: Availability of reactor units (2008-2012)

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[8] PWR, BWR and PHWR all appear in the list of best performers

[9] North America, East Asia and Europe all appear in the list of best performers

[10] This is a break with the two previous editions of this report, which showed the relative percentage of energy loss incidents per reactor year by cause

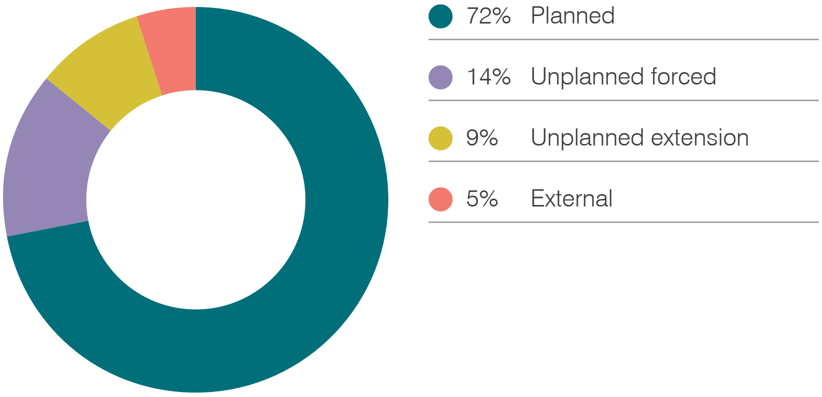

Figure 11: Energy loss distribution (2008-2012)

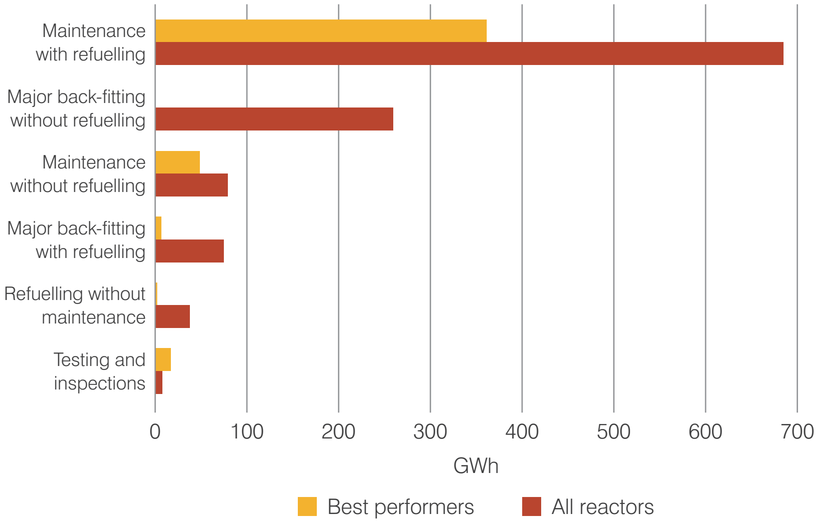

Figure 12: Planned energy loss by cause (2008-2012). Averaged per reactor in each category

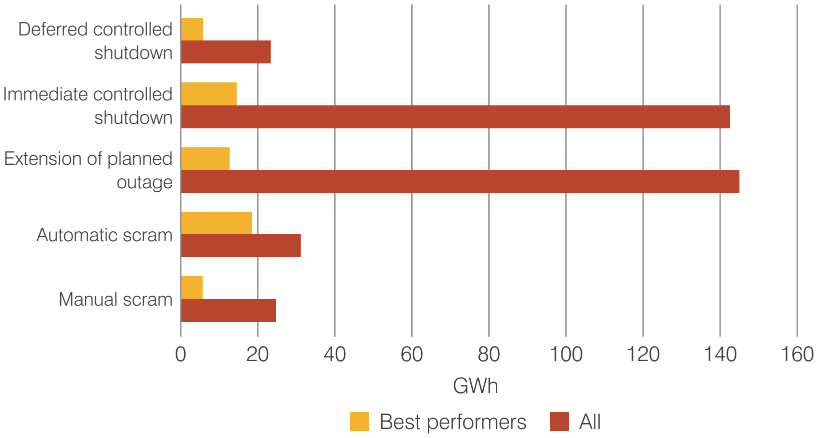

Figure 13: Unplanned energy loss by outage type (2008-2012). Averaged per reactor in each category

are missing entirely from best performers for the reason that this has a large impact on availability, enough to knock these units out of the best performing category for the time period covered. Of course modernization and major engineering work provides other benefits such as greater life expectancy, long-term reliability and potentially increased reference unit power. Modernization is often required by the regulator in order to permit continued operation.

3.2 Unplanned energy losses

Figure 13 looks at the various causes of unplanned losses for all reactors and best performers. As with Figure 12, the x-axis of the graph represents energy loss per year due to unplanned causes. This allows a direct comparison between the figures, and reinforces the fact that greatest energy loss across the global fleet is due to planned outages rather than unplanned ones.

Also clear is the big influence of unplanned outage extensions on most reactors. Better planning of scheduled outages and especially improved contingency management are the keys to reducing this type of energy loss. Scrams have become less frequent over recent years, but unplanned controlled shutdowns is another area where most operators can improve.

Figure 14 shows that the direct cause of unplanned energy loss is overwhelmingly attributable to equipment problems and failure. While a direct cause is the immediate initiator for an unplanned loss event and therefore useful to know about, it would be even more valuable to understand root causes which may in theory lead to similar events or indicate an underlying problem. Information for this however is not usually publicly available and can be hard to find.

Root cause
The root cause is the initiating event (or omission) in the chain of events which leads to the unplanned loss. It is suspected that a root cause analysis for unplanned energy loss events would reveal a very significantly higher proportion of human factor-related causes, as well as attributing some responsibility to maintenance strategy, design or ageing.

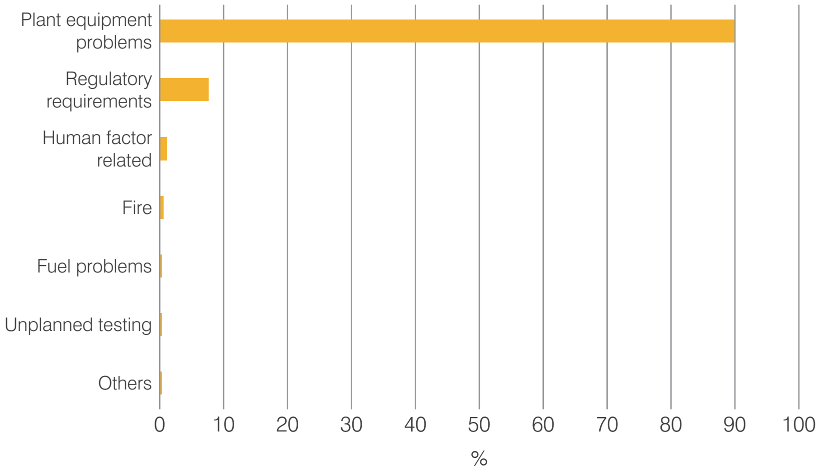

Figure 14: Unplanned energy loss by direct cause (2008-2012)

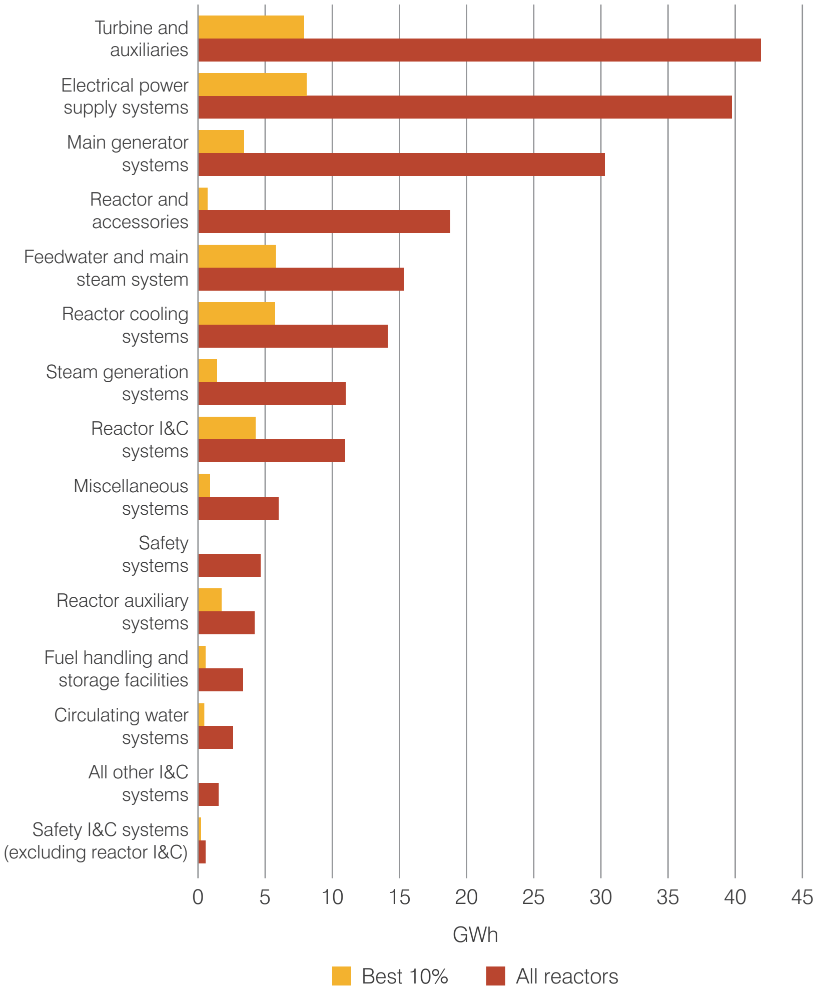

Figure 15: Unplanned energy loss by system (2008-2012)

Figure 15 shows the causes of unplanned energy loss due to individual component systems. It is ranked in order of importance with respect to the 'all reactors' class although the profile is similar for best performers. Unsurprisingly, best performers experience less energy loss across all component systems; however it is interesting to note the comparative size of the difference for some systems.

As with previous editions of the report, the turbines, generators and electrical power supply systems lead to the greatest unplanned energy loss. In fact if all the other systems were to be combined, they would account for less energy loss than those three in the 'all reactors' class. Focusing on these areas in particular, be it through improved maintenance or system replacement, and sharing of operating experience and other relevant information, could lead to improved capacity factors globally.

It is noteworthy that the safety systems only represent a limited share of the lost production. This suggests that the focus on nuclear safety has concrete benefits. Safety systems are maintained in such a manner that they are rarely unavailable and thus rarely cause production losses.

Of interest is the amount of energy loss due to the electrical power supply system. That so much loss can be attributable to a system which is common to so many other forms of infrastructure is somewhat surprising and further research is warranted.

3.3 Factors affecting availability

The list below sets out the factors that have been identified as affecting availability. The following sections of this report investigates the first four factors – outage down to regulation & market – in more detail.

1) Outage
    a) Duration
    b) Frequency
    c) Scope
    d) Management
    e) Cost
    f) Planning

2) Maintenance and equipment reliability
    a) User interface
    b) Lifecycle management, (asset management)
    c) Predictive maintenance
    d) Online maintenance
    e) System redundancy
    f) Component failure
    g) System diagnostics
    h) Culture of operations
    i) Digital controls

3) Engineering
    a) Power uprates
    b) Plant modernization
    c) Design change processes (lifecycle management)
    d) Ageing – longer-term management
    e) Thermal performance
    f) Grid issues

4) Regulation & market
    a) Licences/licensing
    b) Working regulations
    c) Market conditions
    d) Baseload versus load following
    e) Greenhouse gas emission abatement schemes
    f) Public relations
    g) Fuel availability
    h) Surveillance extensions (component level)
    i) Mandated outage operations requirements
    j) Long-term operation

5) Fuel
    a) Design
    b) Reliability
    c) Front and back end (limiting factor)
    d) Fuel loading cycles (12, 18, 24 months)

6) Environment
    a) Ultimate heat sink
    b) Severe weather
    c) Earthquake
    d) Tsunami/flooding

7) Organizational factors and human performance
    a) Human resource availability
    b) Training and education requirements
    c) Safety culture
    d) Knowledge management
    e) Governance (centralized/decentralized)
    f) Financial decision making – financial steering model
    g) Worker satisfaction – strikes

8) Safety performance
    a) Scrams
    b) Controlled shutdowns
    c) Limited condition operation

9) Finance
    a) Cost benefit
    b) Investment analysis

10) Supply chain processes
    a) Contract management
    b) Partnerships and alliances
    c) Procurement

4 Outages and maintenance

Outages are a period of time in which a nuclear power plant shuts down (stops producing power) in order to perform routine or required maintenance, replacements, and/or refuel the reactor[11]. They are periods of intense activity at nuclear plants and the aim is usually to get on-line again as quickly as possible.

4.1 Types of outage

Depending on their management models, utilities may have several different designators for outage type, however all usually employ the three main categories: refuelling, maintenance or forced.

The main purpose of a refuelling outage is to replace fuel that is depleted of fissile isotopes (most importantly uranium-235). Using the refuelling duration as a guideline, other maintenance can be performed in the outage time window. This is a good rule of thumb for the creation of a baseline outage schedule. Maintenance activities can be performed on equipment that is not usually accessible when the reactor is running or fuelled, or equipment that supports the primary system function during reactor operation or shutdown activities. It also creates opportunities to perform periodic inspections and refurbishments, allowing longer run cycle times. Refuelling outages (with some maintenance) typically span 17 to 120 days in length and are performed every 12, 18 and 24 months depending on licence requirements and technical specifications – especially fuel performance.

No refuelling takes place in a maintenance outage, rather activities concentrate on equipment repair that can be executed with fuel in the core of the reactor. This type of outage is usually scheduled and is performed as result of maintenance requirements, surveillance, and backlog management. If a unit experiences an unplanned outage, a maintenance outage may follow based on management decision and root cause analysis of the event. Some utilities use maintenance outages to shorten their refuelling outage and will perform a short maintenance outage during the run cycle. Maintenance outages are more common for reactor types capable of online refuelling such as Candus and AGRs.

As in all well-executed projects, a strict timetable must be adhered to or the sum of the duration of the refuelling and maintenance outages will subtract from the unit run-cycle efficiency and drag down the overall capacity factor.

A forced outage can be defined as emergent or unforeseen, based on degradation of safety or key equipment. An emergent shutdown can initiate a forced outage that is administratively based. New industry issues, surveillance or committed corrective actions can also initiate a forced outage. Work control organizations usually compile lists of equipment that can be worked on if a forced outage situation should occur. The key to minimizing the impacts of a forced outage is to be prepared and execute the required work in the most efficient time possible.

Several factors can affect timing and outage duration, such as location, regulatory and market environment, and conduct of maintenance approach. Most operators, especially of PWRs and BWRs, use refuelling outages to also conduct necessary maintenance for the reasons outlined above, with the aim being to then run breaker-to-breaker – *i.e.* without stopping or reducing the licensed power output for any reason until the next refuelling outage. This means

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[11] In the IAEA's PRIS database, a 'partial' outage refers to any power reduction. A full outage refers to a shutdown. This difference does not affect the figures shown in this report

[12] Guidance for optimizing nuclear power plant maintenance programmes

[13] A minimum of two classes – critical and non-critical – but three or four is typical, with one being run-to-failure

that outages are regularly spaced and timed to occur at a period of low energy demand, or perhaps when human and tooling resources are available for fleet operators. Some operators will engage in refuelling-only outages, where little or no maintenance is conducted. This strategy has been demonstrated to be effective but creates the need for additional maintenance outages, and so does not necessarily result in greater overall availability.

Outage management is a key factor for safe and economic nuclear plant performance. It involves the coordination of diverse factors such as operational strategy, available resources, nuclear safety, regulatory and technical requirements and includes all activities and work hazards both in the lead-up to and during the outage itself. A competitive market environment for electricity generation has significant implications for nuclear power plant operations and has been one of the major drivers for more efficient outages.

It can be seen in Figure 16 that the best 10% have less than half the average outage duration. Clearly a short refuelling duration is a key feature of best performance. While the shortest outage time of 9.3 days is a remarkable achievement, it is a refuelling-only outage.

4.2 Maintenance and equipment reliability programme

Every nuclear operator should aim to maximize availability while ensuring that critical safety-related systems and components are well-maintained. The key to achieving this is to introduce a programme of maintenance optimization, a process which can best be summarized as "the right work on the right equipment, at the right time"[12].

To help determine the best maintenance approach, each system, structure or component should first be categorized according to its safety significance[13]. This judgement should be based on three factors: 1) impact of failure (economic and safety); 2) risk of occurrence; and 3) detectability. Highest maintenance priority should be given to safety-related components where the risk of occurrence is high and the failure is not detectable until the component is called on to perform.

The ideal maintenance approach then depends on the ageing-related degradation mechanisms for systems and components. There needs to be a detailed technical evaluation of the maintenance history, both preventative and corrective. Precisely how this evaluation is performed may vary but it is important to include the operator's own experience as well as that of others, and to be aware of existing industry best practice.

Not all equipment issues are resolved by maintenance optimization. Obsolescence and replacement or redesign of a component system must be addressed by a lifetime management programme. Nuclear plants worldwide are at different stages of plant life management initiatives. Some are seeking greater availability in the near term, while others are optimizing over the longer term and considering power uprates and life extension. It is important to ensure that lifetime management plans are in line with the business needs of the company.

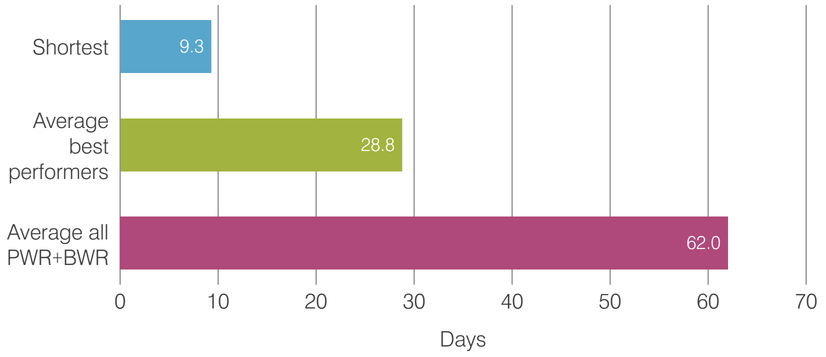

Figure 16: Refuelling outage durations for BWR and PWRs (2012)

5 Engineering impacts on operation

There are times in a plant's operational life where engineering work can have substantial impacts on capacity factors and sometimes require shutdown for lengthy periods. Two such events are life extensions and power uprates.

5.1 Long-term operation

In most countries nuclear plants were originally licensed for a set period that related to estimates of how long it would take to amortise the costs of construction. There was, and still is, no technical concept of an engineering 'end of life' for a nuclear plant as this is determined by how components age (something the designers couldn't know with certainty) and the cost of replacing them. Many research programmes have been developed to look at the viability of long-term operation (LTO) especially in countries with large reactor fleets. Of note are the R&D programmes carried out by EPRI in the USA, similar programmes in France, the PLiM[14] concept in the IAEA and other international associations (such as the Nuclear Energy Agency of the OECD).

The main power reactor types in the world today – the PWR, BWR and PHWR – can all benefit from LTO. There are examples of reactors approved for 60 years in each and it appears possible that they could operate for longer than this. Other reactor technologies such as the AGR (operating only in the UK) and RBMK (operating in the Russian Federation) face specific technical issues related to ageing and units are not expected to reach 60 years.

In principle, LTO should be an economically attractive prospect. A nuclear power plant is characterized by high initial capital costs and low fuel costs, with operation and maintenance (O&M) costs varying according to individual operator efficiency and national regulatory requirements. Well-managed plants with low O&M costs and a limited need for retrofitting can produce electricity at very low cost.

An important part of successfully preparing for LTO is the lifetime management programme and a key part of this is the technical programme, which includes:

- Safety upgrades necessary to meet regulatory requirements.
- An ageing management plan and its effective implementation for critical life-limiting components.
- Major replacements of structures, systems and components.
- Major refurbishment of structures, systems and components.
- Technological upgrades (safety and non-safety related equipment).
- Enhancement of spent fuel storage capacity.
- Implementation of post-Fukushima recommendations and requirements.

Typical examples of upgrade work to be done to qualify for LTO includes the replacement of steam generators, turbines and transformers; complete redesign and renewal of the control rooms and associated instrumentation and control (I&C) systems; the addition of new emergency equipment (diesel generators, pumps); reinforcement of buildings against seismic events, storage tanks, civil works and general repairs (cooling towers, pumping stations), etc. Such an extensive work programme may lead to lengthy outages and energy loss over a couple of run cycles, however it should lead to a much longer period of operation and greater reliability over the longer term.

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[14] Acronym stands for 'Plant Life Management'

[15] The text of this section has been adapted from the NRC website

[16] Oskarshamn 3 in Sweden has achieved a 30% uprate over its original licensed power

5.2 Power uprates

An uprate is a process by which the reference unit power of a reactor is increased so that it becomes capable of producing additional electricity. This comparatively cheap form of capacity addition typically involves changes to the plant's components, operating, maintenance and accident response procedures as well as a corresponding licensing effort. The larger the uprate, the more work is required in all of these areas.

Most nuclear uprates to date have taken place in the USA. The US Nuclear Regulatory Commission (NRC) – has devised a three tier classification system[15] which is well-known and used internationally.

Measurement uncertainty recapture power uprates

Measurement uncertainty recaptures are uprates of less than 2%, achieved by implementing enhanced techniques for calculating reactor power. This involves improved feedwater flow measurements, which are used to calculate reactor power. More precise measurements reduce the degree of uncertainty in the power level, which is used to predict the ability of the reactor to be safely shutdown under postulated accident conditions.

Stretch power uprates

These are typically up to 7% and are within the design capacity of the plant. The uprate level achieved is plant-specific and depends on the operating margins included in the design. Stretch power uprates usually involve changes to instrumentation setpoints but do not involve major plant modifications.

Extended power uprates

These are greater than stretch power uprates and have been approved for increases as high as 30%[16]. These uprates require significant modifications to major balance-of-plant equipment such as the high pressure turbines, condensate pumps and motors, main generators, and/or transformers.

Uprating can have substantial impacts on plant availability in the short term as longer outages may be required for component replacements, especially for stretch and extended power uprates. Since large uprates typically involve older 'Generation II' plants and require substantial capital investment, they often take place as part of LTO work. A success criterion for an uprate is typically that it has a net zero, or even net positive impact on plant availability over the longer term.

6 Regulatory, policy and market factors

Even if a unit is technically safe and sound, it cannot always operate at full reference unit power. Nuclear power facilities are subject to intense scrutiny that often results in conditions imposed on operation. Any safety or security related concerns which do emerge can result in additional maintenance costs, shutdowns and less income as well as possible financial penalties.

A nuclear plant functions within a balanced environment that integrates power generators and consumers – the energy market. All parties within this system have to adhere to rules – including grid codes designed to ensure a certain quality of electricity supply, and market rules set by national or regional energy policy (*e.g.* payment structure, support and subsidy schemes). Plants operating in privatized markets have to remain profitable within these rules, or else risk closure. Unlike for fossil plant, nuclear plant owners seldom have the option to 'mothball' units until economic conditions improve.

Non-energy related politics may also have an impact on nuclear operations. Geo-political events may leave a plant cut off from international fuel and component supply markets in rare instances. Severe public backlash may cause additional costs and lead to political reaction, possibly forcing plants to suspend operations even if they are operating fully within their licence conditions[17].

6.1 Regulatory shutdown

Regulators can demand shutdowns or power restrictions due to safety or security concerns. Extra worker time and effort will be required to address these issues and demonstrate that the plant is safe to restart. An example of a regulatory shutdown can be found in the two Belgian units (Doel 3 and Tihnage 2) that were shut following the discovery of suspected flaws in their reactor vessels[18]. The associated outages took nearly 10 months to perform with over 10,000 maintenance tasks and other checks carried out before restart was eventually permitted. The units have since been shut down again as new information caused the regulator to re-evaluate the seriousness of the flaws.

6.2 Nuclear and intermittent renewable energy forms

Modern energy policy aims to deliver low-carbon, secure electricity and encourage energy efficiency measures – in addition to the fundamentals of affordable and reliable supply. To achieve this, many countries have chosen to financially support and prioritise renewable energy sources. In recent years the amount of intermittent capacity in the European market has expanded considerably. This is creating the need for additional grid balancing measures and upgrades. It has also driven the electricity market price down during periods of high renewable production, in some cases even resulting in short periods of negative pricing – a particular problem for base-load generators. For some countries the amount of intermittent renewable generation has reduced operating hours of base-load plants on some days. In Germany at least this situation has forced operators to change from base-load operation mode to load following.

6.3 Load following operations

Load following is technically possible for most nuclear reactors and takes place routinely in several countries, such as those shown in Figure 17. Variations of up to 5% of nominal

[17] This was demonstrated in Germany following the Fukushima accident

[18] These were discovered when the operator employed a new and more sensitive measuring technique

[19] See Bruynooghe *et al., Load-following operating mode at Nuclear Power Plants (NPPs) and incidence on Operation and Maintenance (O&M) costs. Compatibility with wind power variability*, European Commission Joint Research Centre, 2010 (ISBN 978-92-79-17534-3)

power per minute can be permitted for the primary response of the plant to grid frequency fluctuations. However, the increased effect of cyclic thermal and mechanical loads on equipment induced by such flexible operation mode can lead to higher wear and tear on components and accelerate material ageing processes. This increases the need for planned outages and associated cost of maintenance, especially on the chemical and volume control system (for boron adjustment in PWRs) and the control and safety rod system. Investigations have determined that load-following operations increase overall maintenance costs.[19]

Of far greater importance is the lost generation income. If a nuclear plant operates in a market that does not somehow reward flexible load-following operation (*e.g.* through capacity payments), the economic burden from underproduction might make plants unprofitable.

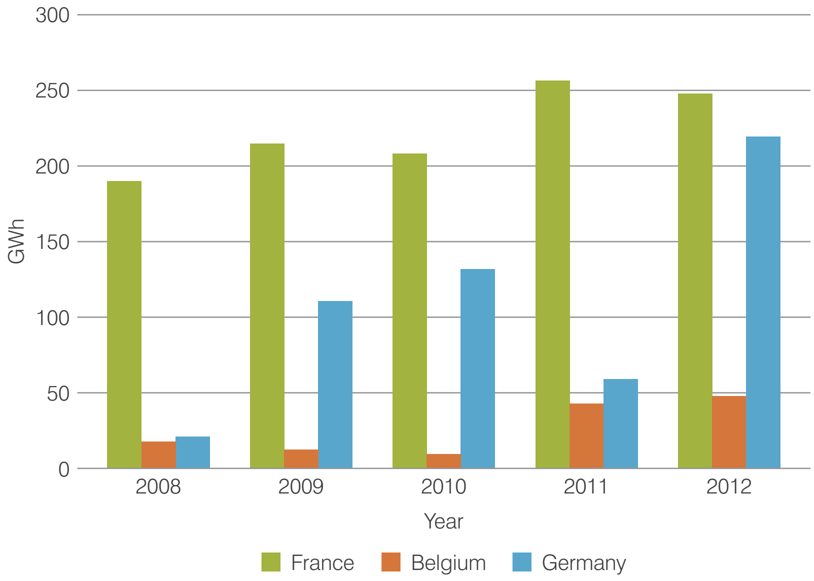

Figure 17: GWh per reactor-year spent load following by fleet

7 Safety performance

The 'automatic scram rate per 7,000 hours critical' indicator relates to plant safety as it provides a measure of undesirable and unplanned thermohydraulic and reactivity transients requiring reactor scrams. It also provides an indication of how well a plant is being operated and maintained and indeed, it can be seen that there is a correlation between plant safety and performance. A higher capacity factor is linked to lower numbers of automatic scrams. This is not to say that units which undergo scrams are unsafe. Scrams are caused by a wide range of issues including equipment problems and human performance issues as well as issues relating to nuclear safety. They are one of a reactor's primary lines of defence against a possible accident condition. Nevertheless, best performers manage across these operational issues to minimize scrams and achieve both productivity and safety.

The World Association of Nuclear Operators (WANO) tracks nuclear plant safety performance as part of its mission to maximise the safety and reliability of nuclear plants globally. WANO's industrial safety accident rate tracks the number of accidents among employees that result in lost work time, restricted work, or fatalities. This has fallen dramatically since 1990 but has levelled off since at least 2005. WANO notes that the nuclear industry continues to be one of the safest industrial work environments.

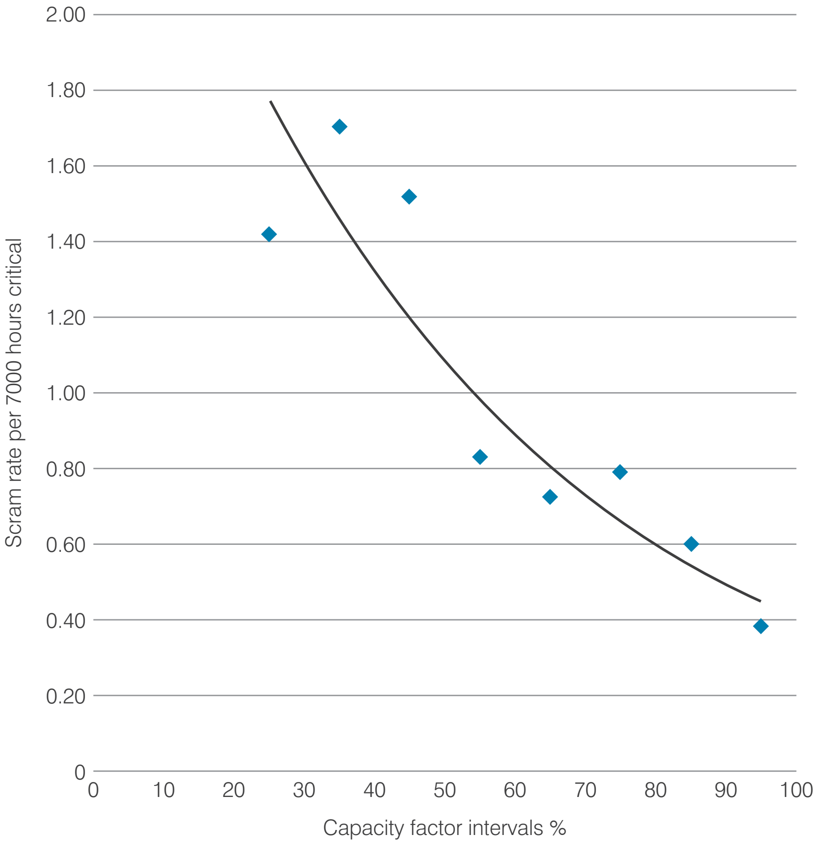

Figure 18: Average number of automatic scrams for capacity factor intervals (2008-2012)

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[20] The industrial safety accident rate tracks the number of accidents among employees that result in lost work time, restricted work, or fatalities. See WANO's annual *Performance Indicators* online publication, www.wano.info/en-gb/library/performanceindicators.

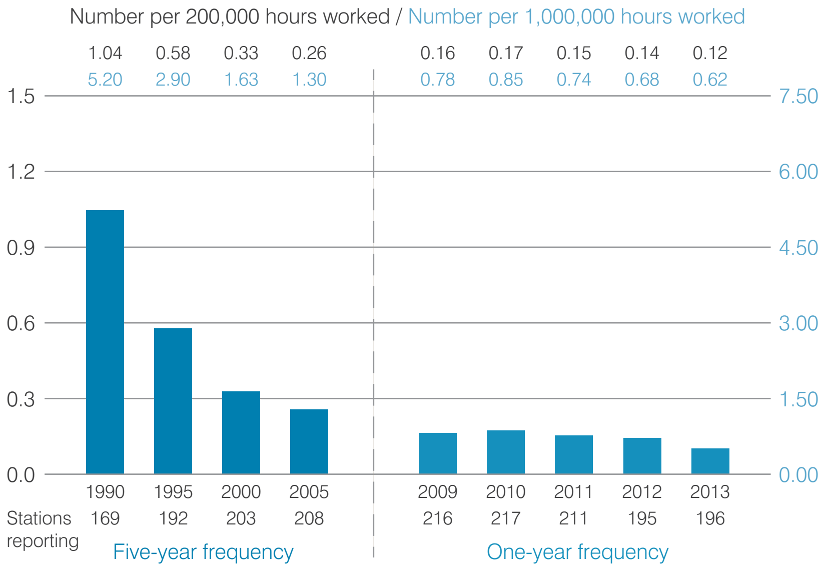

Figure 19: The industrial safety accident rate - image courtesy WANO[20]

8 Conclusions

Analysis of the data reveals that the March 2011 accident at Japan's Fukushima Daiichi nuclear plant has not led to any significant changes to the conclusions of the two previous editions of this report, namely:

- The industry's steady progress in raising capacity factors has mostly halted in recent years.
- Age does not, generally, have a significant effect on capacity factor.
- Technology choice between the predominant reactor designs does not have a significant effect on capacity factor.
- Best performers have lower planned unavailable capacity than other reactors.
- The vast majority of energy loss is within plant management control.
- Planned losses are the biggest contributor to energy loss (except in the case of GCRs).
- Combined maintenance and refuelling outages are the biggest cause of planned energy loss – this is more pronounced for the best performers, which comparatively reduce other causes of loss.
- One of the biggest causes of unplanned energy loss is an extension to a planned outage – suggesting not only short outages but also well-planned and executed, predictable outages are beneficial.
- Plant equipment problems and failure is the largest direct cause of unplanned energy loss, with the turbine and auxiliary systems and electrical power supply systems responsible for the highest proportion of this.
- Plants with higher capacity factors have lower numbers of automatic scrams.

All of this suggests that most operators are capable of improving operating performance if they introduce good practice in areas such as outage management and maintenance optimization. Improved performance should result in clear economic and safety gains.

However, over recent years regulation, policy and market factors are taking an ever greater toll on the global reactor fleet. With a large number of units in long-term shutdown, many others are witnessing a decline in revenue due to the impacts of other generators (often subsidized) and all plants are facing upgraded safety/design requirements. In some notable countries governments have introduced a nuclear phase-out. These are worrying developments which operators cannot mitigate by simply improving day-to-day performance. A different approach is necessary if the benefits of clean, affordable and reliable nuclear energy are to be maintained in these areas.

For most nuclear plants around the world, long-term operation is a viable prospect. There is no reason to believe at this stage that plants operating for longer than their original license period will result in reduced performance levels. Uprates remain a good way to add new generating capacity at a very competitive price.

By far the most important event facing the global industry in the immediate future is the restart of the idled Japanese units. It is not yet clear whether Japan's new regulations will remove the mandatory outage and inspection requirement that prevented Japanese nuclear units from reaching the capacity factors of operators in Europe and North America. This would cause capacity factor figures to improve within the country, and could even improve support for nuclear energy.

Appendix 1 | Definitions

For more detailed definitions and descriptions of accepted measurement techniques for the following values and performance indicators please refer to either the IAEA PRIS database or the World Association of Nuclear Operators' Performance Indicator Program Reference Manual

Values

Reference unit power (RUP)

The maximum power capability of the unit under reference ambient conditions. Reference ambient conditions are environmental conditions representative of the annual mean (or typical) ambient conditions for the unit. The reference unit power remains constant unless permanent modification or permanent change in authorization that affects the capacity is made to the unit.

Reference energy generation (REG)

The energy that could be produced if the unit were operated continuously at full power under reference ambient conditions. The reference energy generation is determined by multiplying the reference unit power by the period hours.

Available capacity (P)

The maximum net capacity at which the unit or station is able or is authorized to be operated at a continuous rating under the prevailing condition assuming unlimited transmission facilities.

Energy loss (EL)

The energy which could have been produced during the reference period by the unavailable capacity. It is comprized of PEL, UEL and XEL.

Energy generated (EG)

The net electrical energy supplied during the reference period as measured at the unit outlet terminals, *i.e.* after deducting the electrical energy taken by unit auxiliaries and the losses in transformers that are considered integral parts of the unit.

External energy losses (XEL)

The energy that was not supplied due to constraints beyond plant management control that reduced plant availability.

Planned Energy Loss (PEL)

The energy that was not supplied during the period because of planned shutdowns or load reductions due to causes under plant management control. Energy losses are considered to be planned if they are scheduled at least four weeks in advance.

Unplanned energy loss (UEL)

The energy that was not supplied during the period because of unplanned shutdowns, outage extensions or load reductions due to causes under plant management control. Energy losses are considered to be unplanned if they are not scheduled at least four weeks in advance.

Indicators

Capacity factor (CF)

The ratio of the energy which the unit produced over the period, to the reference energy generation over the same time period
CAPACITY FACTOR (%) = (EG/REG) x 100
This indicator reflects the actual energy utilization of the unit for electricity and heat production.
(Note: this is sometimes known as load factor.)

Energy availability factor (EAF)

The ratio of the energy that the available capacity could have produced during this period, to the reference energy generation over the same time period.
EAF (%) = [(REG–PEL–UEL–XEL)/REG] x 100
This indicator reflects the unit's ability to provide energy.

Energy unavailability factor (EUF)

The ratio of the energy losses during the period due to unavailable capacity to the reference energy generation over the same time period.
EUF (%) = (EL/REG) x 100 = 100–EAF = PUF+UUF+XUF
This indicator reflects all the unit's energy losses.

Unit capability factor (UCF)

The ratio of the energy that the unit was capable of generating over a given time period considering only limitations under plant management control, to the reference energy generation over the same time period.
UCAPACITY FACTOR (%) = [(REG-PEL-UEL)/REG] x 100
This indicator reflects the unit's energy production reliability.

Planned capability loss factor (PCLF)/Planned unavailability factor (PUF)

The ratio of the planned energy losses during a given period of time, to the reference energy generation over the same time period.
PCLF/PUF (%) = (PEL/REG) x 100
This indicator reflects planned activities that cause energy loss such as refuelling and maintenance.

Unplanned capability loss factor (UCLF)/unplanned unavailability factor (UUF)

The ratio of the unplanned energy losses during a given period of time, to the reference energy generation over the same time period.
UCLF/UUF (%) = (UEL/REG) x 100
This indicator reflects outage time and power reductions that result from unplanned equipment failures or other conditions.

External unavailability factor (XUF)

The ratio of the external energy losses during a given period of time, to the reference energy generation over the same time period.
XUF (%) = (XEL/REG) x 100 = UCAPACITY FACTOR-EAF
This indicator reflects energy loss caused by events beyond plant management control.

Forced loss rate (FLR)

The ratio of all unplanned forced energy losses during a given period of time to the reference energy generation reduced by energy generation losses corresponding to planned outages and unplanned outage extensions of planned outages during the same period.
FLR (%) = FEL/[REG-(PEL+OEL)] x 100
where FEL is unplanned forced energy losses and OEL is unplanned outage extension losses.
This indicator reflects the plant's ability to maintain systems for safe electrical generation when it is expected to be at the grid dispatcher's disposal.

Automatic scram rate per 7,000 hours critical (UA7)

The number of unplanned automatic scrams (reactor protection system logic actuations) that occur per 7000 hours of critical operation. This indicator reflects plant safety (the number of undesirable and unplanned thermal-hydraulic and reactivity transients requiring reactor scrams).

Appendix 2 | Tables of reactor performance by type

Median	CF	PUF	UUF	XUF	FLR
Totals:	**81.11**	**10.69**	**1.96**	**0.19**	**1.58**
BWR	83.48	10.13	1.86	0.06	1.24
FBR	58.11	35.76	5.56	0.45	6.53
GCR	70.96	11.43	16.74	0.01	14.77
LWGR	76.08	17.19	1.88	0.17	1.86
PHWR	74.09	7.47	3.12	0.53	3.00
PWR	84.27	10.72	1.42	0.21	1.18

Figure 20: Performance indicator by reactor type, all reactors (2008-2012)

Best Quartile	CF	PUF	UUF	XUF	FLR
Totals:	**90.06**	**6.93**	**0.63**	**0.00**	**0.57**
BWR	90.54	6.13	0.53	0.00	0.52
FBR	77.92	22.26	0.91	0.04	0.81
GCR	80.77	9.62	8.91	0.00	7.19
LWGR	82.81	13.98	1.04	0.00	0.77
PHWR	89.71	5.53	1.71	0.12	1.71
PWR	90.55	7.67	0.59	0.00	0.53

Figure 21: Best quartile performance indicator by reactor type (2008-2012)

World Nuclear Association
Tower House
10 Southampton Street
London WC2E 7HA
United Kingdom

+44 (0)20 7451 1520
www.world-nuclear.org
info@world-nuclear.org

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