Chapter 2

Survey on Nuclear Capacity Factor and Related Troubles

September 2020

This chapter should be cited as

ERIA team (2020), 'Survey on Nuclear Capacity Factor and Related Troubles', in Murakami, T. and V. Anbumozhi (eds.). *Improving Nuclear Safety and Use: An International Analysis.* ERIA Research Project Report FY2020 no.10, Jakarta: ERIA, pp.3-27.

Chapter 2

Survey on Nuclear Capacity Factor and Related Troubles

This chapter investigates the trend of capacity factors in nuclear power generation. Focusing on the periods when the trend increased or decreased, the study identified troubles that occurred during these periods, classified these troubles, and extracted representative events. Using the extracted representative events, the study team analysed the communication between the regulator and operators that impacted the capacity factor.

The factors necessary for improving nuclear safety and the capacity factor have been developed in respective countries over many years. Therefore, the IEEJ selected countries subject to the investigation with the reasons below.

Amongst countries for which data are available for all years from 1970 to 2018 in the IAEA's PRIS database, those that continue to promote nuclear power generation were selected as 'major nuclear power generation countries'. Canada, France, Japan, the UK, and the US fall under this category. The countries that mainly adopt light-water reactors (LWRs) (hereinafter referred to as 'major LWR countries') are France, Japan, and the US. The LWRs are the current mainstream of nuclear power generation around the world.

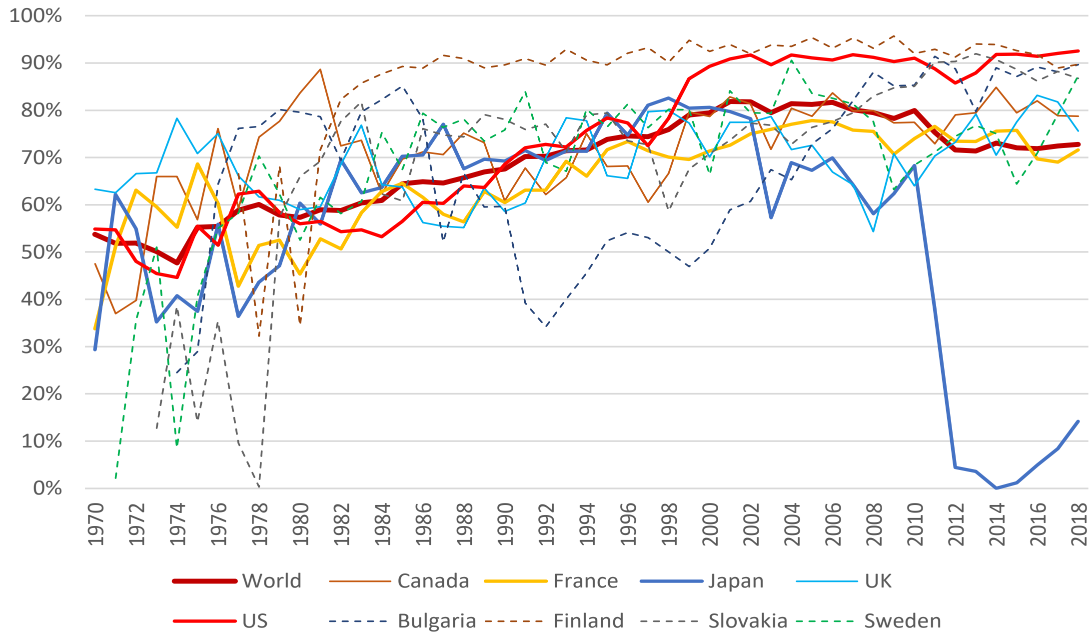
Meanwhile, countries for which data are not available for all years from 1970 to 2018 in the PRIS database, those with a capacity factor exceeding 85% in 1 of the last 2 years – 2017 or 2018 – and for which data are available from the 1970s were selected as 'high capacity factor countries'. Bulgaria, Finland, Slovakia, and Sweden were extracted for this category.

1. The Trend of Capacity Factor

1) Status in the world

To obtain a general picture before studying in detail the trends in individual countries, the IEEJ investigated the transitions in the capacity factor of nuclear power generation in the world and in the subject countries (Figure 2.1)

Figure 2.1: Changes in Capacity Factor of Nuclear Power Generation in the World



UK = United Kingdom, US = United States.
Sources: Authors.

The world average of capacity factor remained low at 50%–60% in the 1970s and gradually increased to nearly 80% from the 1980s through the 1990s. It then stayed around 80% in the 2000s but fell to about 70% in the first half of the 2010s and has since remained unchanged.

The capacity factor varied widely from country to country in the 1970s, but it started to show similar values in the 1980s. Focusing on the major LWR countries shown in bold solid lines in Figure 2.1, in the 1980s, Japan showed high values whilst the US had low values. Amongst the high capacity factor countries shown in narrow broken lines in the figure, Finland has been showing constantly high values. In the 1990s, the capacity factors are much closer amongst the countries. In all major LWR countries, the capacity factor was almost the same as the world average. Amongst the high capacity factor countries, whilst Finland remained at high values, the capacity factor in Bulgaria dropped sharply. In the 2000s, amongst the major LWR countries, the capacity factor in the US remained high, whilst that in Japan dropped. In the 2010s, the capacity factor in Japan plummeted whilst the values in other countries stayed equivalent to or higher than the world average, including the major nuclear power generation countries other than the major LWR countries, which are shown in narrow solid lines in the chart. In general, the capacity factor in France transitioned at levels similar to the world average.

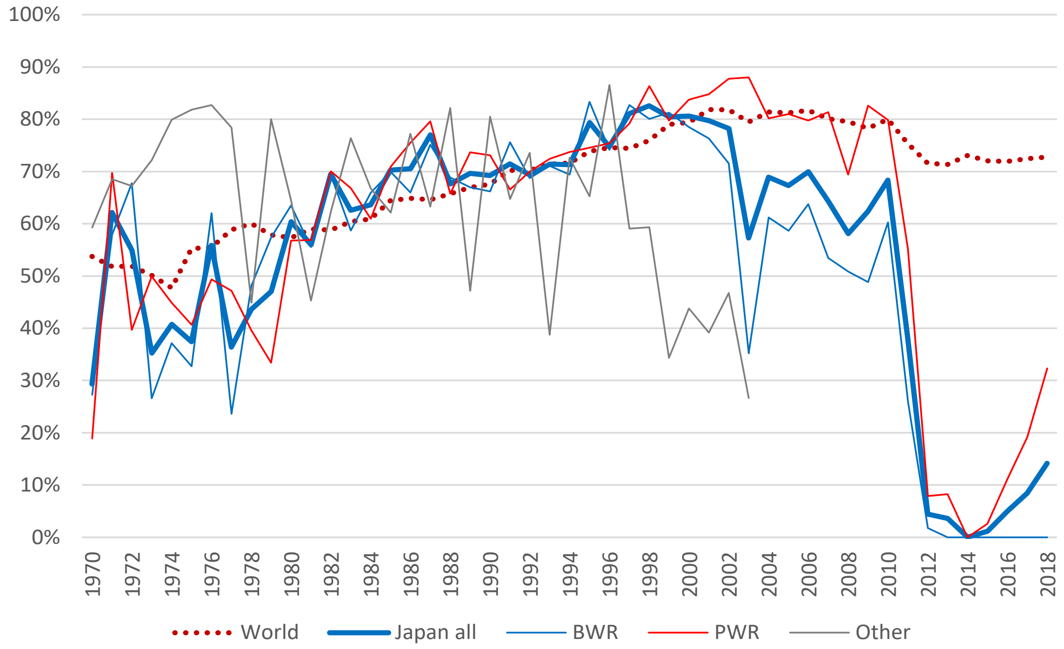
Considering the general trend above, the next section first discusses the status in Japan, which has been leading the world in the 1980s, and in the US, which has been leading the world since the 2000s, amongst the major LWR countries, followed by the status in other countries.

2) Status in Japan

Japan's first commercial nuclear power generation started in 1966 at the Tokai Nuclear Power Plant (NPP) that housed a gas-cooled reactor (GCR) built through technology imported from the UK. In 1970, Japan introduced the LWRs from the US, and expanded construction of the LWRs to supplement its low-energy self-sufficiency rate. Japan then propelled domestic production of the LWRs in the 1980s and promoted their construction in the 1990s. Until the Fukushima Daiichi accident in 2011, 54 NPPs were operating, and nuclear power accounted for roughly 30% of total power generation in Japan. However, as of 2019, the ratio of nuclear power generation to total power generation was only around 8%. At present, only nine NPPs are in operation.

Figure 2.2 shows the transition of capacity factor in Japan.

Figure 2.2: : Changes in Capacity Factor of Nuclear Power Generation in Japan



BWR = boiling water reactor, PWR = pressurised water reactor.
Sources: Authors, IAEA (n.d.).

In the 1970s, the capacity factor in Japan was slightly lower than the world average in general. This period was the dawn of nuclear power generation in Japan, and the low capacity factor was a result of troubles caused by equipment failure at the initial stage, which is inevitable when utilising new technologies. Meanwhile, in the 1980s, as mentioned above, the capacity factor was higher than the world average, notably amongst the major LWR countries, indicating that Japan had quickly overcome troubles from equipment failure. Then, in the 1990s, the capacity factor transitioned at world average levels.

In the 2000s, the capacity factor of boiling water reactors (BWRs) dropped amongst the LWRs, which dragged down the overall capacity factor in Japan. The capacity factor plummeted in 2003, when the falsification of voluntary inspection records by the Tokyo Electric Power Company Holdings, Inc. (TEPCO) was brought to light (FEPC, 2003). This is referred to hereinafter as the 'TEPCO issue'.

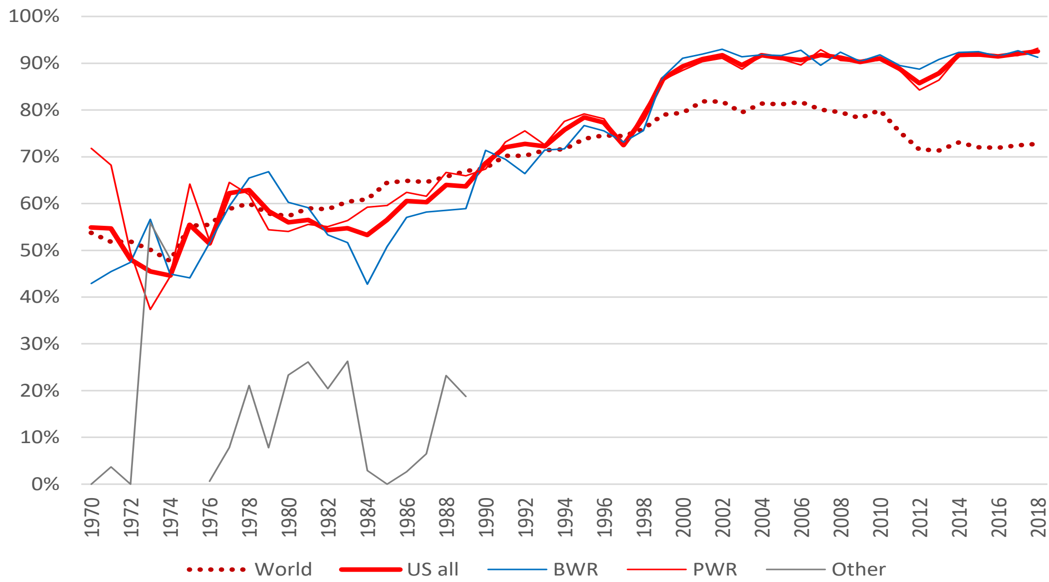
In the 2010s, all NPPs in Japan stopped operating after the Fukushima Daiichi accident in 2011. As a result, the capacity factor significantly dropped and reached zero in 2014. The impact was particularly significant on the BWRs. Whilst a small number of pressurised water reactors (PWRs) resumed operation one by one after the accident, no BWRs have resumed operation to date.

3) Status in the United States

The construction of NPPs rapidly expanded in the US from 1957, when the Shippingport Atomic Power Station commenced operation, through the 1970s. However, the accident in reactor no. 2 of the TMI NPP in 1979 sparked public distrust of nuclear power. Along with the reduced cost of thermal power generation and downward correction of power demand forecast, the US stopped construction of new NPPs altogether. Then, triggered by the California electricity crisis in 2001, concerns over the necessity of a stable supply of electricity and soaring natural gas prices rose, and the move to construct new NPPs began in earnest. As of 2019, nuclear power accounted for about 20% of total power generation in the US. At present, 95 NPPs are in operation, and two reactors are being constructed at the Vogtle.

Figure 2.3 shows the transition of capacity factor in the US.

Figure 2.3: Changes in Capacity Factor of Nuclear Power Generation in the US



BWR = boiling water reactor, PWR = pressurised water reactor, US = United States.
Sources: Authors, IAEA (n.d.).

In the 1970s, the capacity factor in the US was similar to the world average in general. However, in the 1980s, the values were below the world average. It is symbolic that the TMI unit no. 2 accident occurred in 1979, the year between these two periods.

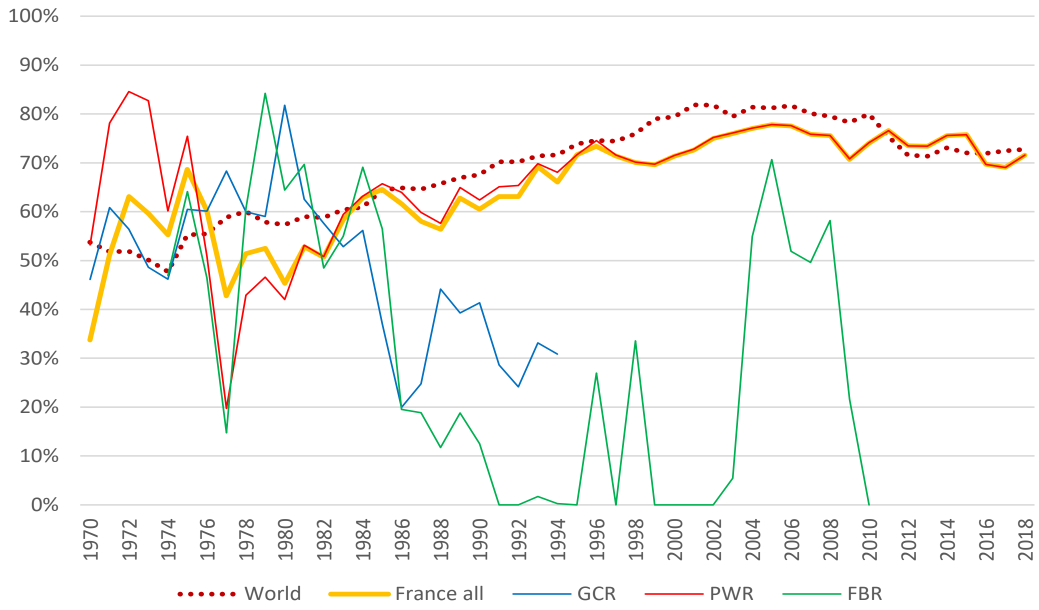
After that, unlike the capacity factor in Japan that stagnated in the 1990s after its predominance in the 1980s, that in the US steadily increased, exceeded the world average by about 10% in the 2000s, and remained high. However, the steady increase fell in 1997, the year between the 2000s when the capacity factor started to greatly exceed the world average and the preceding 1990s. In 1996, the previous year, the media extensively reported the Millstone Nuclear Power Station (hereinafter referred to as the 'Millstone issue') as not meeting design basis.

4) Status in France

After the oil crisis in the 1970s, France accelerated development of nuclear power for its relatively low natural resources compared to neighbouring countries. In the early stage, France adopted the GCRs but had been solely using the PWRs, the technology of Westinghouse, US amongst the LWRs, since units no. 1 and 2 of Fessenheim NPP started operations in 1977. France had developed a next-generation European pressurised water-type LWR with higher output jointly with Siemens, Germany and has been constructing them in recent years. As of 2019, nuclear power generation accounted for about 71% of total power generation in France. At present, 57 NPPs are in operation, and one NPP is under construction at Flamanville.

Figure 2.4: Figure 2.4 shows the transition of capacity factor in France.

Figure 2.4: Changes in Capacity Factor of Nuclear Power Generation in France



FBR = fast-breeder reactor, PWR = pressurised water reactor.
Sources: Authors, IAEA (n.d.).

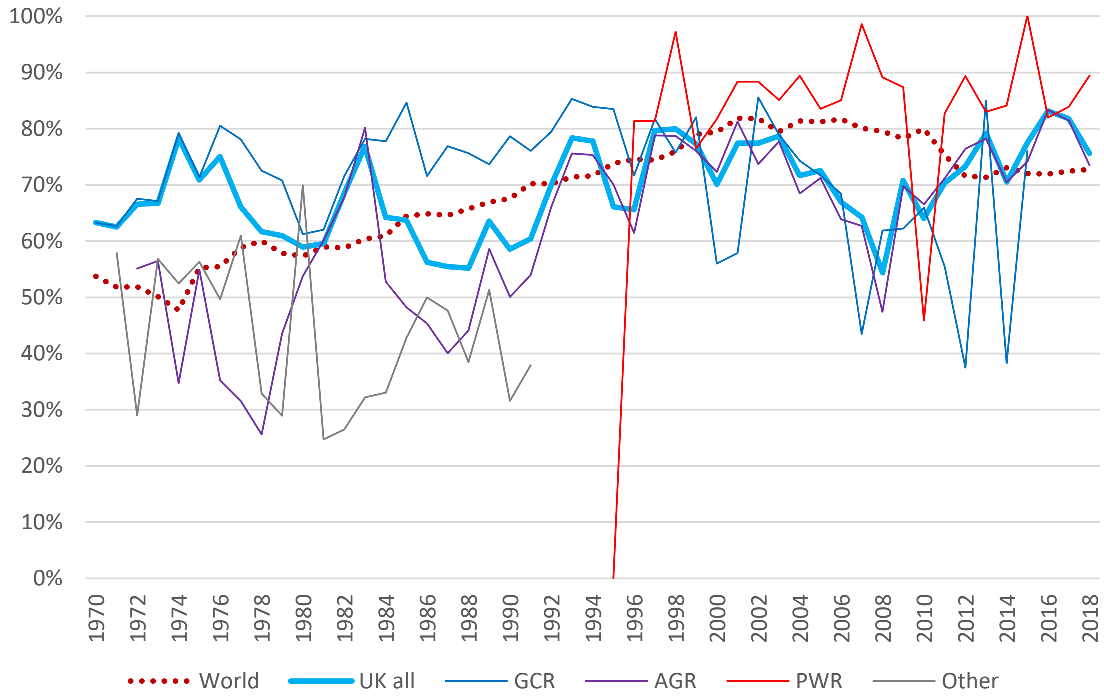
In the 1970s, the capacity factor in France was roughly the same as the world average, albeit somewhat fluctuating. The reason the capacity factor dropped significantly for the PWRs in 1977 was that full-fledged introduction started this year. As for fast breeder reactors, Superphénix started operating in 1986 but its capacity factor remained low until it was closed in 1998. Since the 1980s, the capacity factor of mainstay PWRs has mostly constituted the overall capacity factor in France that transitioned at levels near the world average.

5) Status in the United Kingdom

The UK has been a pioneer in nuclear power generation since the Calder Hall Unit no. 1 started commercial power generation in 1956. Whilst promoting the development of nuclear reactors based on their unique GCRs through trial and error, the UK introduced the LWRs in the 1990s. Though it has closed the GCRs one after another since the second half of the 1980s, the UK has promoted the construction of new LWRs in recent years to address depletion of North Sea gas fields, realise stable energy supply, and achieve its greenhouse gas emissions reduction target. As of 2019, nuclear power generation accounted for about 18% of total power generation in the UK. At present, 15 NPPs are in operation, and two NPPs are being constructed at the Hinkley Point C.

Figure 2.5 shows the transition of capacity factor in the UK.

Figure 2.5: Changes in Capacity Factor of Nuclear Power Generation in the UK



AGR = advanced gas-cooled reactor, GCR = gas-cooled reactor, PWR = pressurised water reactor, UK = United Kingdom.
Sources: Authors, IAEA (n.d.).

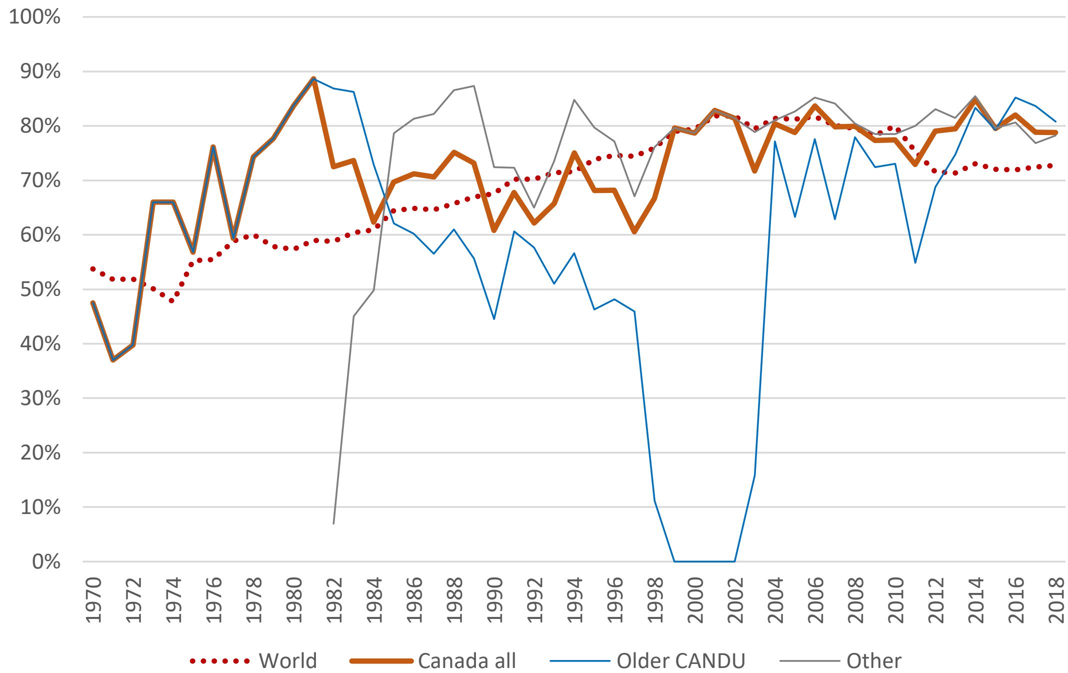
In the 1970s, the capacity factor was high for the GCRs, which had been used for more than 10 years after introduction, resulting in a higher overall capacity factor than the world average. Meanwhile, the 1980s saw the dawning of advanced gas-cooled reactors (AGRs). The capacity factor in the UK was about the same as the world average because of the AGRs' dragging down the excellent performance of the GCRs. From the 1990s onwards, the capacity factor of the AGRs that has become the mainstay of nuclear power generation in the UK has constituted most of the overall capacity factor in the country. Notably, the capacity factor dropped in the 2000s. During this period, an issue related to the AGRs occurred: there was concern over the deterioration in the state of the pressure barrier of a steam generator, a structure specific to the AGRs. In the 2010s, the capacity factor in the UK returned to the levels nearly the same as the world average.

6) Status in Canada

To put its abundant uranium resources to use, Canada has been promoting independent development and construction of Canadian deuterium uranium (CANDU) reactors that operate using natural uranium as fuel. The first generation using a CANDU reactor goes back to the power generation performed at Rolphton in 1962. From 1995, Canada had stopped old plants that started operations in the 1970s since their economic efficiency was falling. However, some of them have then been repaired and have resumed operation. In the 2000s, Canada developed the next-generation CANDU reactors with much higher output. Canada places nuclear energy as an important source of power in the fight against global warming. As of 2019, nuclear power generation accounted for about 15% of total power generation in Canada. At present, 19 NPPs are in operation.

Figure 2.6 shows the transition of capacity factor in Canada.

Figure 2.6: Changes in Capacity Factor of Nuclear Power Generation in Canada



CANDU = Canadian deuterium uranium.
Sources: Authors, IAEA (n.d.).

In the 1970s, the capacity factor was high due to older reactors introduced in the early period, exceeding the world average. In the 1980s, modified reactors were introduced and, in contrast to what happened in the UK, exhibited high capacity factors. However, old-type reactors often stopped due to troubles like damage to pressure tubes, a structure specific to CANDU. The country's overall capacity factor was similar to the world average.

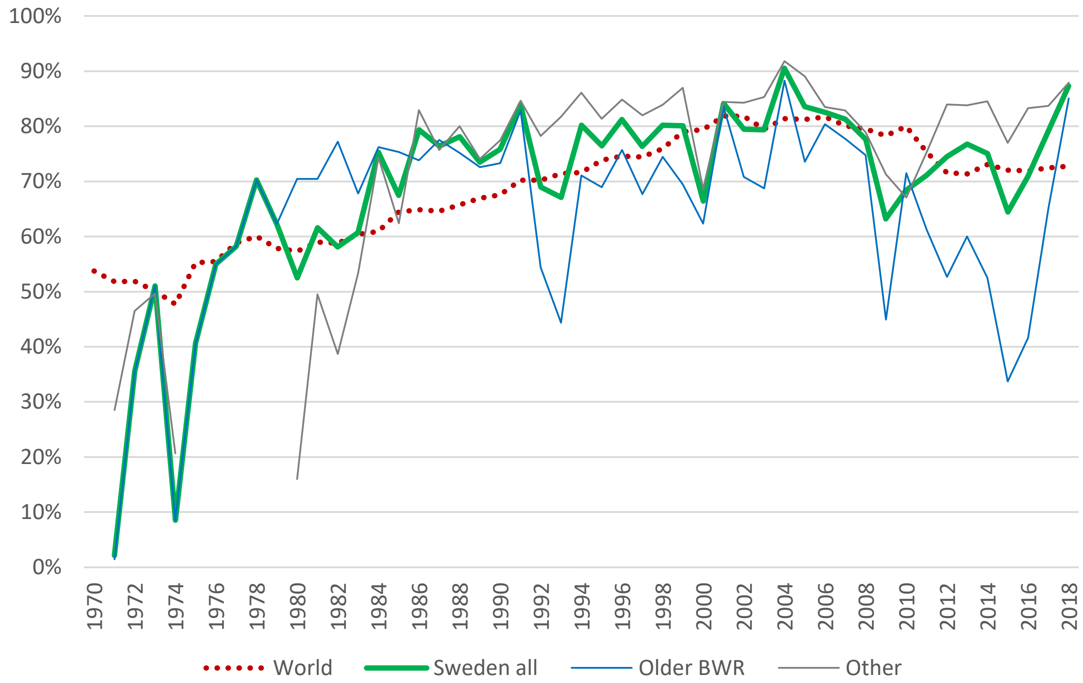
This trend continued into the 1990s. In the second half of the 1990s, older reactors required upgrading to address safety issues but they were stopped because of economic inefficiency, and their capacity factor reached zero at a certain period. Then, in the 2000s, some older reactors were finally upgraded and resumed operation, and the capacity factor in Canada exceeded the world average in the 2010s.

7) Status in Sweden

Sweden lacks electricity resources other than hydraulic and has promoted nuclear power generation to counter the uncertainty in oil prices. This policy was proven to be correct by the oil crises. Sweden initially developed nuclear reactors that use natural uranium as fuel, but then developed its own boiling water–type LWRs. Sweden also introduced pressurised water–type LWRs as imported from Westinghouse, US. After the TMI accident in 1979 and the Chernobyl disaster in 1986, Sweden committed itself to policies to phase out nuclear power. As of 2019, nuclear power generation accounted for about 34% of total power generation in Sweden. At present, seven NPPs are in operation.

Figure 2.7 shows the transition of capacity factor in Sweden.

Figure 2.7: Changes in Capacity Factor of Nuclear Power Generation in Sweden



BWR = boiling water reactor.

Sources: Authors, IAEA (n.d.).

The 1970s saw the dawn of nuclear power in Sweden and the capacity factor was lower than the world average. However, the values started to exceed the world average in the 1980s, with that trend continuing into the 1990s. In 1992, the strainer of a containment vessel spray pump was clogged; heat-insulating materials around a safety valve inside the containment vessel was damaged by steam that was ejected due to the malfunctioning of the safety valve, which clogged the strainer. As a result, the capacity factor of older BWRs dropped. In the 2000s, the capacity factor was roughly the same as the world average. The same trend was observed into the 2010s but the capacity factor of older BWRs fell due to mass repair for modernisation.

8) Status in Bulgaria, Finland, and Slovakia

Since the number of reactors at the NPPs in Bulgaria, Finland, and Slovakia is less than five, their capacity factors are discussed in this section together.

Bulgaria promoted research and development of nuclear power as it lacked electricity resources except lignite. It introduced four old-generation Soviet-type reactors and started operating them one after another from 1974. Bulgaria then introduced two next-generation reactors whose performance is equivalent to Western reactors. After that, to address a safety concern triggered by the Chernobyl disaster, Bulgaria implemented safety measures in the 1990s but decided to stop the four first-generation reactors in the 2000s before it became a member of the European Union. Bulgaria sought to build new reactors as an alternative source of power to the closed reactors, but to no avail. As of 2019, nuclear power accounted for about 38% of total power generation in Bulgaria. At present, two NPPs are in operation.

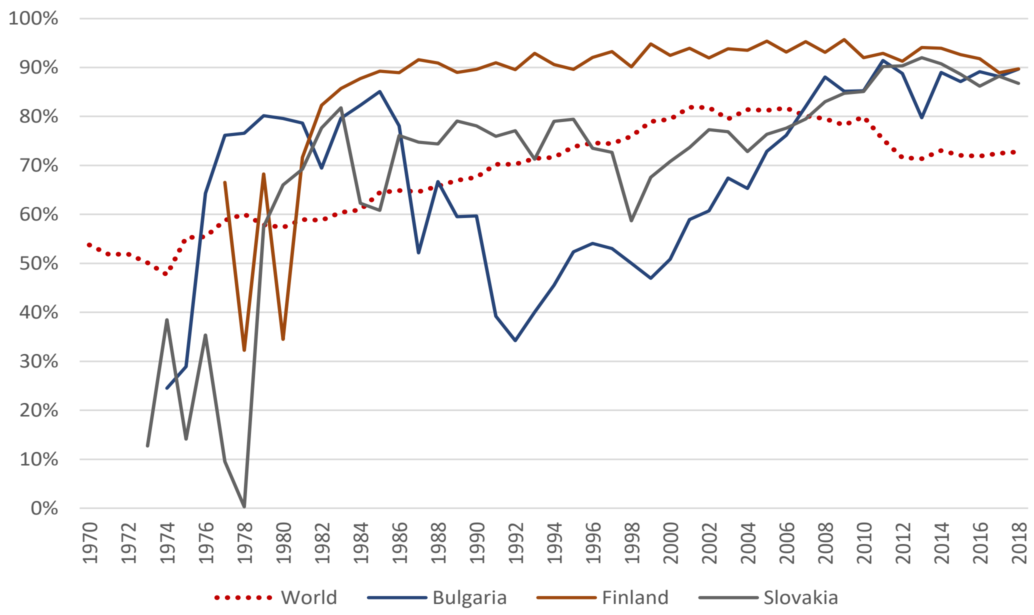
Finland has promoted nuclear power development to resolve the excessive dependence on fossil fuel from Russia, triggered by the oil crisis in the 1970s. Amidst the Cold War, Loviisa units no. 1 and 2 that started operation in 1977 and 1981, respectively, were using technology from the former Soviet Union (currently the Russian Federation). Olkiluoto units no. 1 and 2 that started operation in 1979 and 1982 were built using Western bloc technology. The new construction projects that followed the initial introduction were suspended due to the Chernobyl disaster in 1986, but they resurfaced to reduce chronic electricity import and reduce greenhouse gas. As of 2019, nuclear power accounted for about 35% of total power generation in Finland. At present, four NPPs are in operation, and one NPP is being constructed at the Olkiluoto.

Slovakia built pressurised heavy-water reactors that operate using natural uranium as fuel in the era of its predecessor Czechoslovakia and started operating these in 1972 to use domestic uranium resources. However, they were closed in the late 1970s due to an accident. Slovakia then introduced two old-generation and two next-generation Soviet-type reactors and started operating them one after another from 1978. Slovakia worked on upgrading them in the 1990s, but it stopped the two old-generation reactors in the 2000s before it became a member of the European Union. After achieving independence in 1993, Slovakia introduced two more next-generation Soviet-type reactors and started operating them one after another from 1999. As of 2019, nuclear power accounted for about 54% of total power generation in Slovakia. At present, four NPPs are in operation, and two NPPs are under construction at the Bohunice.

Figure 2.8 shows the transition of capacity factor in Bulgaria, Finland, and Slovakia.

Figure 2.8: Changes in Capacity Factor of Nuclear Power Generation in Bulgaria, Finland,

and Slovakia

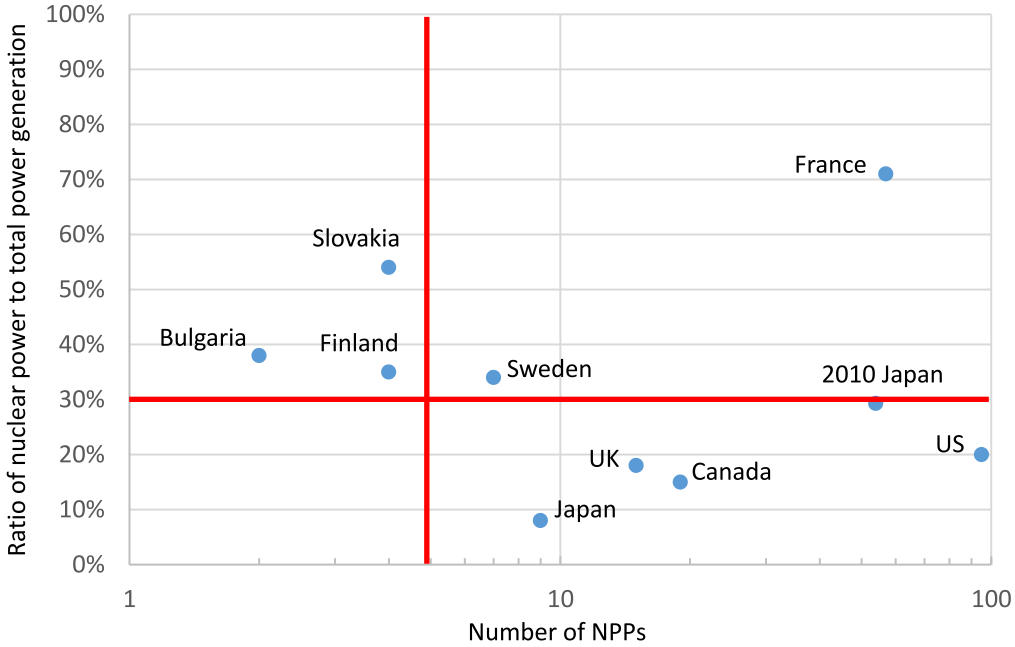


Sources: Authors, IAEA (n.d.).

The 1970s saw the dawning of nuclear power generation, and the capacity factor varied amongst these countries. In the 1980s, their capacity factors started to go above the world average. However, in the 1990s, Bulgaria and Slovakia started to show values lower than the world average, compared to Finland which was maintaining extremely high values. In this period, Bulgaria and Slovakia worked on upgrading Soviet-type reactors. In the 2000s, the capacity factor in Bulgaria and Slovakia started to improve, and the values in these three countries surpassed the world average by a large margin in the 2010s.

Figure 2.9 shows the relationship between the ratio of nuclear power to total power generation and the number of NPPs.

Figure 2.9: Ratio of Nuclear Power to Total Power Generation and Number of NPPs



NPP = nuclear power plant, UK = United Kingdom, US = United States.
Sources: Authors, IAEA (n.d.).

Bulgaria, Finland, and Slovakia are all located in the top left of the quadrant in Figure 2.9. Whilst the ratio of nuclear power to total power generation exceeds 30%, the number of NPPs is below 5. This means a single NPP contributes to more than 6% of domestic power generation on average and suspending the use of even one NPP may seriously impact electricity use in the country. One possible reason for their high capacity factors is the sense of pressure. When the IEEJ asked experts in the industry from such countries, 'What do you think is the reason the capacity factor is high in your country?', some answered 'market pressure', which supports this hypothesis.

2. Troubles that Affected the Capacity Factor

In the preceding section, the IEEJ investigated the transition of capacity factor in subject countries and pointed out some issues that occurred in the period the values changed. These troubles can be classified into several groups and representative troubles are discussed in detail in this section.

First, a series of equipment failure was observed in the 1970s, the dawn of the LWRs, and in the initial period of introducing new type reactors specific to the respective countries. In this category, Japan's initiatives from the 1970s through the 1980s stand out – although the capacity factor was lower than the world average initially, it then improved ahead of the rest of the world. This is to be selected as the first representative trouble.

Second, troubles caused by human and organisational failure more than by equipment failure were observed. The Millstone issue in the US in the second half of the 1990s and the TEPCO issue in Japan in the first half of the 2000s are such troubles. They are also to be selected as representative troubles.

Third, accidents are a manifestation of risks. The accident to a pressurised heavy-water reactor that occurred in Slovakia falls under this category. The problem of strainer closure in Sweden may be classified as equipment failure. It could also be regarded as one step short of becoming a safety-threatening accident. However, these are covered by the TMI and Fukushima Daiichi accidents, the most representative accidents in the LWRs.

Events that affected the capacity factor include reactor type–specific concerns, safety upgrades, and sense of pressure arising from the energy mix of the country as mentioned at the end of the preceding section. However, these events did not necessarily directly link to the troubles that occurred in relevant countries. Those that directly linked to troubles are included in equipment failure, human and organisational failure, or accidents. Therefore, they are excluded from the discussion in this section.

The selected troubles and the relevant actions taken by the regulator and the operators are described below in chronological order.

1) Equipment failure and prevention of abnormal operation and failure

According to the Japan Atomic Energy Commission, one reason for the low capacity factors in Japan in the 1970s was initial failure troubles, such as stress corrosion cracking and damage to steam generator tubes. Japan addressed such issues through the following efforts like those below, which are likely the reason its capacity factor improved in the 1980s.

In the aspect of designing, nuclear plant manufacturers strive to develop and establish frameworks and methods for checking so that high-quality materials and highly reliable systems are exhaustively and assuredly reflected on design specifications, drawings, etc. of plants that consist of a huge number of components and systems. As such, efforts to improve the quality are made in the design stage.

In the aspect of operation, operators constantly monitor the systems for any abnormality through frequent walk-around checks. They also perform start-up and functionality tests for important equipment systems to check their reliability and integrity for prevention and early detection of abnormalities.

As for maintenance, periodic inspections about once a year according to the relevant laws and regulations are conducted. Operators perform these based on the concept of preventive maintenance to avert the occurrence of abnormalities during operations after repair. An example of preventive maintenance is periodically replacing consumables within their service life regardless of their status with or without abnormality, not just paying attention to repair work itself.

As a result of these efforts, the prevention of abnormal operation and failure that corresponds to the first layer of 'defence in depth' improved drastically, and operation with less stoppage due to troubles, etc. except for periodic inspection was realised in the 1980s.

2) TMI Unit no. 2 accident and Systematic Assessment of Licensee Performance (SALP), application of risk-informed decision-making methods (hereafter 'risk-informed').

The sequence of events pertaining to the TMI NPP Unit no. 2 accident that occurred in the US and the restart of Unit no. 1, both handled by the same operator, is shown below (Table 2.1)

Table 2.1: The Sequence of Events of the TMI NPP Accident

March 1979	An accident occurred in Unit no. 2 of the TMI NPP. (Although a safety valve was left open after the reactor stopped and the coolant was lost, the water supply stopped because of the false water level gauge. As a result, the core was damaged.)
July 1979	The Nuclear Regulatory Commission (NRC) ordered maintaining the suspended state of Unit no. 1 (which was already suspended).
August 1984	The NRC staff reported improved operator performance after the officer was replaced.
May 1985	The NRC approved the restart of Unit no. 1.

MPP = nuclear power plant, TMI = Three Mile Island.
Source: Nuclear Regulation Authority of Japan (2017).

The troubled Unit No. 2 was decommissioned later. Unit no. 1 was stopped because it was handled by the same operator, although it did not have an accident. It was not restarted for 6 years, from 1979 to 1985, until the Nuclear Regulatory Commission (NRC) recognised improvement in the performance of the operator.

In response to this accident, in 1980, the NRC introduced a system to assess the long-term performance of operators (Systematic Assessment of Licensee Performance [SALP] programme), instead of a case-by-case evaluation that had been adopted until then. However, Japan's Nuclear Regulation Authority (NRA) reported that this system had shortcomings like those listed below. Such shortcomings remained unresolved until the introduction of a new system (Reactor Oversight Process) in 2000.

- Assessment is subjective, objective indicators are barely considered important, and assessment results lack consistency.
- Focus is often placed on compliance with regulatory requirements, rather than safety.
- The indications are backward-looking, instead of providing forward-looking information.

- Assessment investigates the causes of the problem at hand, which may lead to failure to notice potential problems.
- In some cases, problematic power plants are not found quickly.
- Assessment results get out of control and are misused to adversely affect the management of the relevant operator.

Meanwhile, WASH-1400, the pioneer PRA issued by the NRC before the accident, pointed out a small-scale loss-of-coolant accident, the cause of the accident of TMI unit no. 2, as one major risk factor. This fact led to support the application of risk-informed, such as the PRA, later. Examples in the 1980s are safety goals and backfitting (requesting existing facilities to comply with new regulations). The sequence of relevant major events is shown in Table 2.2.

Table 2.2: The Sequence of Events of Application of Risk-Informed in the 1980s

1981	The Nuclear Regulatory Commission (NRC) started a study on safety goals to indicate the tolerable level of risks.
1982	The operator avoided backfitting by providing the NRC with cost–benefit analysis for risk reduction.
1986	The NRC issued a policy statement on safety goals.
1988	The NRC clarified the relation with safety improvement and cost considerations in backfitting. The NRC itself studied whether to backfit the stations blackout (SBO) rule.

Source: Jackson et al. (2017).

It is apparent from Table 2.2 that independent studies and analyses by the regulator and the operators in the first half of the 1980s led to the making and clarification of NRC's regulations in the second half of the 1980s. The judgement on whether to backfit in the clarified backfit rule consists mainly of two stages: safety goal evaluation and value impact assessment. Safety goal evaluation is related to performance goals, such as core damage frequency (CDF, $<10^{-4}$/year), that are linked to safety goals. According to a regulatory document issued by the NRC (NUREG-1776), the NRC assessed their stations blackout (SBO) rule then as below, and the rule was implemented:

- The CDF is estimated to be reduced from 4.2×10^{-5}/year to 1.6×10^{-5}/year by applying the regulation.
- The public dose is estimated to be reduced by 1,450 person-Sv by application of the rule (using the NRC's dose-cost conversion coefficient 0.2 million $/person-Sv, this value becomes $290 million as cost.).
- The burden on operators and the NRC by implementing the rule is estimated at $61.5 million.

Additionally, the NRC enacted the Maintenance Rule on NPPs from the second half of the 1980s through the 1990s because ineffective maintenance was adversely affecting the entire NPPs associated with equipment failure, which Japan overcame in the 1980s. The sequence of relevant major events is shown in Table 2.3.

Table 2.3: The Sequence of Events of Application of Risk Information on the Maintenance Rule

July 1991	The National Regulatory Commission (NRC) promulgated the Maintenance Rule.
July 1996	The Maintenance Rule came into effect.
July 1999	The NRC promulgated the revised Maintenance Rule.
November 2000	The revised Maintenance Rule came into effect.

Source: Ministry of Economy, Trade and Industry (2003).

The requirements of the Maintenance Rule – the first performance-based regulation in the US – are stated in Title 10, Chapter I, of the Code of Federal Regulations 50.65. Some of them are extracted as follows:

- Shall monitor the performance or condition of structures, systems, or components.
- When the performance or condition of a structure, system, or component does not meet established goals, appropriate corrective action shall be taken.
- Performance and condition monitoring activities and associated goals and preventive maintenance activities shall be evaluated at least every refuelling cycle, provided the interval between evaluations does not exceed 24 months.

After that, concern was raised over operators increasing the amount and frequency of maintenance whilst operating, i.e. online maintenance (OLM), without fully assessing the safety in operations after the Maintenance Rule came into effect, and the following clause was added in 1999: 'shall assess and manage the increase in risk that may result from the proposed maintenance activities'.

Technical specifications that prescribe the minimum requirements during operations provide allowed outage time (AOT), etc., a period when facility outage is safely acceptable. However, in many cases, the AOT is conservative because it is decided by design basis engineering judgement under a deterministic method. Using qualitative engineering judgement, the deterministic method is more conservative than applying a quantitative risk-informed technique. The OLM to be performed can be completed within the AOT. If the AOT of each equipment could be prolonged by applying risk-informed in the revised Maintenance Rule, the range of the OLM can be widened reasonably whilst paying attention to safety.

No method is specified for risk assessment in such an occasion, but operators in the US mainly use the PRA.

The combination of risk-informed technical specifications and revised Maintenance Rule was never before epoch-making in associating the application of risk-informed by the PRA with effective regulations. It also improved the ability of risk analysis because of frequent use of the new clause of the revised Maintenance Rule for OLM.

3) Millstone issue and reactor oversight process

In the 1990s, whilst establishment and revision of the Maintenance Rule were ongoing, many NPPs in the US were on long-term suspension triggered by the trouble found at the Millstone Nuclear Power Station. The sequence of relevant major events is shown in Table 2.4.

Table 2.4: The Sequence of Events of the Millstone Issue

1993	It was found that all fuel of the core of Millstone Unit no. 1 was moved to the fuel pool. (By design, the cooling capacity of a pool was for only one-third of fuel in the core.)
March 1996	Media reported the issue above. => Many similar issues were found.
October 1996	The Nuclear Regulatory Commission (NRC) requested all nuclear power plants (NPPs) to provide information on adequacy and availability of design bases information.
1996–1998	Many NPPs were put into long-term suspension due to similar measures taken and tightened regulations. (In 1997, 11 NPPs were stopped for a year, and 8 NPPs could operate at less than 50% of the capacity.) => Five NPPs, including Millstone Unit no. 1, were stopped permanently.

Sources: Japan Atomic Industrial Forum, Inc. (2011); Smith and Wallen (2007).

Related to the above, the following was stated in the testimonies of the US General Accounting Office at the public hearing of the US Senate (1998):

- NRC assumes plants are safe if they operate as designed and follow NRC's regulations.
- NRC reasoned that these plants were still safe because the many safety features and systems built into a plant's design provide an adequate margin of safety.
- Ambiguity over 'how safe is safe' arises because NRC does not have an effective way to quantify the safety of plants that deviate from their approved designs.
- NRC's regulatory approach needs to be anchored in goals and objectives that are clearly articulated, and performance measures that hold NRC managers as well as licensees accountable.

At the public hearing, as a nuclear industry trade association in the US, the Nuclear Energy Institute claimed:

- 'This is the safety regulatory process and the requirements that are imposed that really do not directly relate to public health and safety.
- That is why I think it is essential that this committee and you, Mr. Chairman, participate and support these changes that are necessary to correct these underlying cultural and fundamental issues that exist within the process.
- I'd like to make three recommendations in this regard. First, we believe that this committee should reauthorise the agency's budget in 1 year increments until this committee and the appropriations committees are satisfied that these changes are being brought about. My second recommendation, the NRC should regularly report to Congress, and you should continue to have oversight hearings. The last thing, there needs to be an independent review of the NRC's activities. There needs to be an external look at how the agency does its business and how it can improve its efficiency and effectiveness and how it can carry out its important role in regulating the safety of nuclear power today and into the future' (US Senate, 1998, p.30).

According to the Institute of Applied Energy (2006), whilst some NRC staff doubted the SALP programme, other groups insisted on maintaining the rules, resulting in opposing opinions inside the NRC about regulatory reform. However, the demand for regulatory reform kept rising. An influential lawmaker who had the authority to decide on the budget of the NRC summoned its chair and stated that the budget of the NRC will be halved if NRC's activities are not be improved (Institute of Applied Energy, 2006).

Amidst such a situation, one executive director of the NRC who had been having doubts about the SALP programme held conferences from the spring to summer of 1999 and introduced a colour-coded safety level identification system. This system was to visualise the safety of NPPs, and met the request of interested parties (example: ΔCDF [/year] … Green < 10^{-6}, 10^{-6} < White < 10^{-5}, 10^{-5} < Yellow < 10^{-4}, 10^{-4} < Red). The reactor oversight process introduced in 2000 had this system and prioritised the following based on transparency:

- objectivity: performance based,
- predictability: can predict regulatory action to an event occurred, and
- safety: risk informed.

4) TEPCO issue and quality management system (QMS)

In the first half of the 2000s, dishonesty pertaining to records of voluntary inspection by an operator (TEPCO) was found in Japan. The sequence of relevant main events is shown in Table 2.5).

Table 2.5: The Sequence of Events of the TEPCO Issue

July 2000	The regulator received the accusation that the operator falsified voluntary inspection records at the nuclear power plant.
October 2001	The regulator requested the enterprise in charge of work pertaining to voluntary inspection to cooperate.
April 2002	The enterprise in charge reported to the regulator the possibility of falsification of multiple voluntary inspection records.
August 2002	The operator reported the possibility of dishonest acts in multiple voluntary inspection records.
September 2002	The operator reported the modification of records to the regulator and announced it to the public. The operator voluntarily stopped its plants one after the other to conduct inspection relevant to the modified records.
May 2003	The operator gained understanding by the local government about restarting its plants.

Source: Cabinet (2002).

How to address this issue was discussed at the Subcommittee to Study the Regulatory System for Nuclear Safety composed of knowledgeable persons that was established by the regulator. At the subcommittee, opinions like those below were exchanged, stating that there was no safety issue:

- The act by the operator was not a violation of law and there was no safety issue.
- It is wrong to apply the concept of not accepting defects in design and manufacturing standards to the maintenance of equipment as well. The basis of the issue is that no agreement has been made on standards about the relationship between defect and availability.
- Without such an existing agreement, the operator exchanged opinions on whether inspection results would cause safety issues and decided after making a certain level of assessment.
- Three years ago, the Japan Society of Mechanical Engineers prepared the Maintenance Standards covering defect evaluation with operators playing core roles. If the regulator endorsed and authorised these standards, such an issue would not have occurred.

Also, at the subcommittee, opinions on the sense of safety amongst citizens were exchanged, like those below:

- This issue will not be resolved by specialists one-sidedly presenting technical reasons for safety.
- Even if the regulations are unreasonable, it is important to go through a process to disclose information and gain the understanding of the general public, no matter how inefficient it could be, so that people can feel safe and have a sense of trust.
- We need to come up with a means to spread value amongst the operators that it is important to establish a process to disclose information and make people fully

understand because nuclear power always comes with the issue of public risk acceptance.

- Operators should keep in mind that they must provide information for the general public to fully understand the concept that creating a situation where society feels safe about nuclear power is part of quality assurance.

As a result of addressing this issue, Japan introduced mainly the regulations as follows:

a) Voluntary inspection
   - Voluntary inspection as 'periodic operator's inspection' in the law;
   - 'Evaluation of equipment integrity' to predict and evaluate the progress of cracking or other troubles found by voluntary inspection;
   - 'Periodic safety management review' to review the system of voluntary inspection.

b) Quality assurance
   - Quality assurance activities by an operator were included in 'operational safety programmes'.
   - Regarding safety activities by an operator, minimum requirements were identified and specified as requirements of quality assurance.

However, according to the Japan Society of Maintenology (2012), the introduced QMS had the following problems:

- The Study Group on Inspection Practices that studied the introduction of the system initially intended to shift the focus from conventionally practiced inspection of individual facilities to checking the implementation status of safety activities by an operator. However, the regulator continued to perform conventional inspection after the TEPCO issue, and it ended up with a form of the QMS system simply being added on. (Additionally, voluntary inspection was included in the relevant laws and regulations, and periodic safety management review was added).
- Neither society nor the public but regulation was defined as the client of QMS, which caused operators to misunderstand that all they should do is satisfy the regulatory requirement.
- Safety was defined as the service of the QMS, which caused regulators to misunderstand that safety can be ensured just by a strict inspection of plan-do-check-act (PDCA) cycle activities. As a result, regulators failed to think about a possible loss of integrity in the relationship between the system, QMS, and safety.
- The implementation status of all PDCA activities performed according to quality assurance requirements was made subject to inspection. That led to dispersion of the regulator's resources and difficulty in placing a focus on safety issues.
- Conformance to minute details was checked whilst the implementation status of all PDCA activities performed according to relevant requirements on quality assurance was made subject to inspection, which hindered the autonomous activities of operators.

It appears that, in the end, this tightening of regulations merely kept both the regulator and the operators exhausted throughout the 2000s and contributed little to bolstering ‘safe nuclear power’, namely, improving the safety of the NPPs and spreading the sense of safety of nuclear power in society.

5) Fukushima Daiichi accident and a long-term moratorium under the safety assessment, along with the new regulatory requirements

The sequence of main events relating to the accident at the Fukushima Daiichi Nuclear Power Station in the 2010s and the restarting of reactors thereafter in Japan is shown in Table 2.6.

Table 2.6: The Sequence of Events of the Fukushima Daiichi Accident

March 2011	An accident occurred at the Fukushima Daiichi Nuclear Power Station due to earthquakes and tsunamis beyond its design basis.
May 2011	The Government of Japan (GoJ) ordered the Hamaoka NPPs to be shut down because of the risk of strong earthquakes.
July 2011	The GoJ asked a stress test to be implemented before restarting all NPPs in Japan because of insufficient understanding by the people. (After that, the operators submitted the test results one after another.)
January 2012	The GoJ submitted a nuclear regulation reform bill to the National Diet of Japan (regulators are administrative agencies under the Ministry of the Environment).
April 2012	Political parties submitted a nuclear regulation reform bill to the National Diet of Japan (regulators are independent administrative commissions).
June 2012	The GoJ agreed to restart two units of the Ohi NPPs for stress test results were completed.
June 2012	The National Diet of Japan drafted a bill establishing the Nuclear Regulation Authority (NRA), which was approved by a majority.
July 2012	Two units of the Ohi NPPs were restarted (electricity crisis in Western Japan was averted).
September 2012	The NRA was inaugurated.
December 2012	A change of government occurred after the general election. The new government party stated that safety will be left to the expert judgement of the NRA.
February 2013	The NRA started a procedure for receiving public comments on the draft new regulatory requirements.
March 2013	NRA committee members agreed with the chair’s personal view that the judgement based on the safety assessment is to be made before the next restarting.
June 2013	The NRA decided on the new regulatory requirements.
July 2013	The new regulatory requirements came into effect.
August 2015	The first NPP that was confirmed to conform with the new regulatory requirements was restarted after its shutdown for 4 years.

Source: House of Councillors (2013).

These events can be roughly divided into three stages: (i) initial inquiry by the Government of Japan (GoJ) (until June 2012), (ii) inauguration of a new regulatory body associated with the establishment of a new law by the National Diet of Japan (until September 2012), and (iii) decision and implementation of new regulatory requirements by the new regulatory body. The latter two stages are discussed below.

The Act for the Establishment of the Nuclear Regulation Authority (NRA) decided by the National Diet of Japan includes the following contents as a partial amendment to the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors, in addition to provisions on the establishment of the NRA:

- Obligation to take measures against severe accidents
- Introduction of a backfit system for when the latest findings are taken up into regulations
- Limitation of operation period to 40 years (which can be extended once by no longer than 20 years).

Amongst them, measures against severe accidents and taking up the latest findings (e.g. 'back-check in Japan' of seismic safety) had ever been addressed since as part of voluntary measures by operators. As for the newly established limitation of operating period that directly links to the long-term use of facilities, opinions at the National Diet of Japan show various evaluations to the 40-year-period rule, according to the minutes:

- That number (40 years) may be political.
- It is not a number determined based on scientific findings either.
- The opinions of the NRA (i.e. new regulatory body) shall be respected.
- It is a comprehensive judgement including not only scientific and engineering views but also ethical, economic, and social views.
- The judgement should be left (to the new regulatory body).

Regarding the future prospect of the issues above, supplementary provisions of the act establishing the NRA stipulate that with regard to the revised provisions, the government shall review them promptly whilst considering the status of their enforcement. When it finds it necessary, it shall take necessary measures based on the results thereof.

As a result of the December 2012 election for the House of Representatives, immediately after the inauguration of the NRA, the government party changed. The campaign promises made by the major parties concerning nuclear energy at the time of election are shown in Table 2.7.

Table 2.7: Nuclear Energy–Related Promises of Major Political Parties at the December 2012 Election

Democratic Party (in power before the election)	**Liberal Democratic Party** (in power after the election)
• As for the NPPs, the three principles below will be observed. - The 40-year operation limit will be strictly applied. - Only those confirmed safe by the NRA will be restarted. - No NPPs will be expanded or newly built. • Every possible political resource will be used to realise zero NPP operation in the 2030s. 'Zero NPPs' will be achieved absolutely.	• As for the safety of nuclear power, expert judgement by the NRA will be prioritised over any circumstances. • At least within the next 10 years, the 'best energy mix' will be established. In making judgement thereof, the basic concept will be to ascertain whether new technical measures judged safe by the NRA are applicable or not.

NPP = nuclear power plant, NRA = Nuclear Regulation Authority,
Sources: Democratic Party of Japan (2012), Liberal Democratic Party (2012).

From the above, the revision of the operation limit in the future will be left to the NRA under the current administration.

Regarding backfitting, in March 2013, when invitation for public comments on the draft of new regulatory requirements was about to be closed, the NRA summarised the confirmation of compliance of existing reactors with requirements in the future as follows:

a) As of the enforcement of the new regulations in July 2013, the NPPs would be requested to have all functions necessary as measures against design basis and measures against severe accidents (including those caused by large-scale natural disasters and terrorism activities). Compliance with requirements is to be confirmed before the operator runs the facility the next time.

b) Backup measures for improving the reliability of measures against severe accidents and against terrorism activities would be requested to be realised within 5 years after enforcement.

At that time, regarding the enforcement of new regulations (1 above) that had a short grace period, opinions were exchanged as shown below. Though what was added by law were measures against severe accidents, it shows a serious concern over the fact that the accident occurred due to an event that was well beyond the design and concerns a boundary that determines whether an event leads to a severe accident or not. An example is a tsunami with a height of 15 metres (m) hit, whilst the licence issued for the design is to withstand a tsunami with a height of 3 m:

- What needs to be clear also is: is what is requested here for a certain level of safety or reduction of risk as defined in a)? Or is it that a) is a measure that can be done immediately, and b) is what will take a long time?
- Those that will take time (for taking measures) are included. Design basis ground

motion and tsunami that involve the design basis events all fall under a). Earthquake ground motion that exceeds the design basis ground motion shall not be observed frequently.

A severe or serious accident was newly defined by the NRA as a significant damage to a core, or a fuel assembly, or spent fuel stored in a nuclear fuel material storage facility. As for the serious accidents, the new regulatory requirements provided that the specific progress of accident will be studied using the PRA method. As such, the new regulatory requirements were groundbreaking in incorporating risk assessment into effective regulations for the first time in Japan.

For example, in assessing the risk of tsunamis (one of the natural hazards), the following can be estimated for a certain plant through hazard curves.

1) Under the former regulatory requirements
   - Design basis tsunami occurs at a rate of 10^{-2}/year.
   - The operator addresses accidents that occur at a rate of 4×10^{-3}/year, conservatively, as measures against design basis.
2) Under the new regulatory requirements
   - Design basis tsunami occurs at a rate of 4×10^{-5}/year.
   - The operator addresses accidents that occur at a rate of 4×10^{-6}/year, conservatively, as to take measures against design basis.

The CDF evaluation value for tsunamis over sea wall level, which a certain operator of a plant sets up under the new regulatory requirements, is 4×10^{-6}/year, assuming there are no measures against severe accidents. The frequency of such tsunamis and the CDF are likely near under this assumption. This value is by design basis alone far below 10^{-4}/year, the value of the safety goals studied by the NRA along with the new regulatory requirements. The value will become far smaller when an operator takes more conservative measures. The regulatory requirement for resilience against tsunamis seems too conservative, considering that hundreds of people die by natural disasters in Japan every year.

The problem was not only that the new regulations are too conservative. The operations of all NPPs were suspended, not only the operator that caused the Fukushima accident. The first NPP that was confirmed to conform with the new regulatory requirements was restarted after its shutdown for 4 years. During that period, the capacity factor of nuclear power generation substantially dropped, and Japan is still feeling its effect now. Japan is the first and only country that stopped all NPPs during the backfitting to the new regulation. The case of Japan after the Fukushima accident should be carefully reviewed – whether it can be a model for balancing the safety and effective use of the NPPs. Suspending the operation of all existing NPPs was not an effective use of nuclear power nor did it result in safety improvement.

Through the literature survey, facts about the efforts of operators, enhanced regulations by the regulator and government, improvement of regulations by the regulator, and communication on safety improvement between the operator and the regulator have been found to be crucial factors for effective use of nuclear power.