Assessing Operational Performance Before and After LTO in a Nuclear Power Plant

Ki Sig Kang[a], Se Youl Won[b]

[a]Dept., NPP Engineering. KINGS (KEPCO International Nuclear Graduate School), 658-91, Haemajiro, Seosaeng-myeon, Ulju-gun, Ulsan, 45014, Republic of Korea. Kisigkang4@outlook.com,
[b]Continued Operation Technology Group, Central Research Institute, Korea Hydro Nuclear Power Co. 70, Yuseong Daero 1312 Beon-gil, Yuseong-gu, Daejon, 34101, Republic of Korea. wonsy1310@khnp.co.kr

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Abstract

Long-term operation (LTO) of nuclear power plants (NPPs) has become an important strategy for enhancing energy security, supporting low-carbon electricity generation, and maximizing the economic value of existing nuclear assets. This study evaluates the operational performance, reliability, and safety of NPPs before and during LTO using key performance indicators derived primarily from the IAEA Power Reactor Information System (PRIS), including capacity factor, operational reliability, and unplanned outages and trips.

The analysis indicates that the chronological age of an NPP does not inherently lead to a decline in operational performance. Although capacity factor may temporarily decrease during the transition to LTO at approximately 40–42 years of operation, a clear recovery is observed thereafter. Capacity factors increase from approximately 75–80% at 40–42 years to 85–90% by 45–47 years, reaching 90–95% for some of the oldest operating units. This trend suggests that NPPs successfully transitioning into LTO can recover and potentially improve their operational performance following major LTO-related preparation and investment programmes.

1. Introduction

Analysis of the IAEA Power Reactor Information System (PRIS) indicates that nuclear power plants (NPPs) operating under Long-Term Operation (LTO) can maintain high-capacity factors, often exceeding those observed during their early years of commercial operation. PRIS performance indicators also suggest that mature nuclear units can achieve lower unplanned capability losses and sustained electricity production during extended operation. These trends should not be interpreted as evidence that physical ageing itself improves plant performance. Rather, they reflect the combined effects of continuous modernization, component replacement, strengthened ageing management programmes, optimized maintenance and outage management, and accumulated operating experience.

2. Materials and Methods

2.1. Data Sources

This study used historical operational performance data for commercial NPPs to investigate changes in plant performance and reliability over extended periods of operation, with particular emphasis on the transition to LTO. The analysis focused primarily on operating NPPs in the United States and the Russian Federation, where a substantial number of reactor units have accumulated extended operating experience beyond their original or initial design and licensing periods.

The dataset consisted of annual reactor-level operational performance indicators collected over the available operating history of each NPP. The analysis included key indicators related to plant availability, and unplanned operational losses, including Load Factor (LF), Forced Loss Rate (FLR), and Unplanned Capability Loss Factor (UCLF), where available in the source data.

2.2. Data Processing

The collected operational data were reviewed and processed to establish a consistent structure for statistical analysis. Reactor operating age was determined relative to the beginning of the available operating history for each reactor unit.

For age-based analysis, reactor-year observations were classified into six operating-age groups: 0–10, 11–20, 21–30, 31–40, 41–50, and >50 years. The grouping was selected to characterize changes in operational performance over the plant lifetime and, in particular, to examine performance patterns around approximately 40 years of operation, when many NPPs begin or prepare for extended operation beyond their original licensing or design basis.

2.3. Key Performance Indicators

The impact of extended operation was evaluated using operational performance indicators that reflect plant utilization and equipment reliability. The principal key

indicators considered in this study were LF, FLR, and UCLF.

Load Factor (LF) represents the ratio of the electrical energy actually generated during a specified period to the energy that could have been generated if the plant had operated continuously at its reference power during the same period.

Forced Loss Rate (FLR) represents the proportion of potential generation lost as a result of forced outages or forced power reductions.

Unplanned Capability Loss Factor (UCLF) represents the percentage of maximum potential generation that was not produced because of unplanned energy losses, including unplanned outages and power reductions..
The indicators were evaluated collectively rather than independently when assessing overall plant performance. In particular, a sustained or increasing LF combined with decreasing FLR and UCLF was interpreted as evidence of improved or maintained operational reliability.

2.4. Statistical Analysis

Statistical analyses were conducted at both the descriptive and inferential levels. For each performance indicator and operating-age group, the mean, median, standard deviation (SD), and 95% confidence interval (CI) were calculated. The mean was used to characterize average fleet performance, while the median was included to reduce sensitivity to extreme observations and to provide additional information when distributions were skewed. The SD was calculated to characterize the variability of reactor performance within each age group.

3. Practical Cases Studies from USA and Russian Federation NPP fleet

3.1. Global Capacity Factor Trends by Reactor Age

The figure 1 illustrates the relationship between reactor age and capacity factor, with particular relevance to the transition from the original design operating period to LTO. Although the capacity factor fluctuates throughout the operating life of an NPP, a notable pattern can be observed around the period preceding and following approximately 40 years of operation.

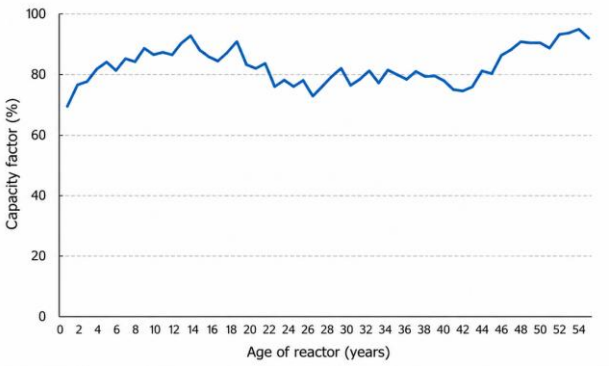


Figure 1. Mean capacity factor as a function of reactor operating age (2019–2024. (2)

During the period between approximately 35 and 40 years of reactor age, the average capacity factor remains relatively stable at around 80%, with a modest declining trend toward the late 30s of reactor age. One possible explanation is that this period often coincides with intensive preparation for LTO. As an NPP approaches the end of its original design or licensing period, the operator typically undertakes comprehensive ageing management reviews, plant condition assessments, safety evaluations, periodic safety reviews, and equipment qualification activities.

After approximately 40 years of operation, however, the figure 1 shows a clear recovery and subsequent improvement in capacity factor. The capacity factor increases from approximately 75–80% at around 40–42 years to approximately 85–90% by 45–47 years, and eventually reaches around 90–95% for some of the oldest operating units. This trend suggests that NPPs successfully entering LTO may achieve improved operational performance after completing major LTO-related preparation and investment programmes.

3.2. Analysis of the Impact of LTO on the Performance and Reliability of USA NPP Fleet

The historical trends in LF, FLR, and UCLF for the U.S. NPP fleet, the three indicators show a clear long-term pattern. While the U.S. NPP fleet matured and many reactors moved beyond their original operating periods, LF increased and remained at a high level, whereas FLR and UCLF declined substantially.

3.2.1. Load Factor: Sustained High Performance during the LTO

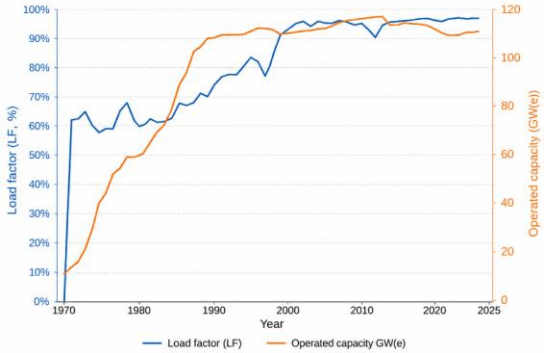


Figure 2, Historical trend of load factor for the U.S. nuclear power plant fleet (1970–2024)

The LF trend shows a substantial long-term improvement in the operational performance of the U.S. NPP fleet. During the 1970s and early 1980s, LF fluctuated considerably and remained at relatively moderate levels. From the late 1980s through the 1990s, however, a clear upward trend emerged, and by approximately 2000s the fleet had reached a consistently high level of performance.

Since the early 2000s, the LF shown in the figure 2 has generally remained close to the upper end of the historical range, despite the fact that the U.S. NPP fleet itself has become progressively older. At the same time, total operated nuclear capacity has remained broadly stable at around 100 GW(e), indicating that high generation performance has been sustained largely through improved utilization and reliability of the existing reactor fleet rather than through substantial additions of new capacity.

3.2.2. Forced Loss Rate: Strong Improvement in Equipment Reliability

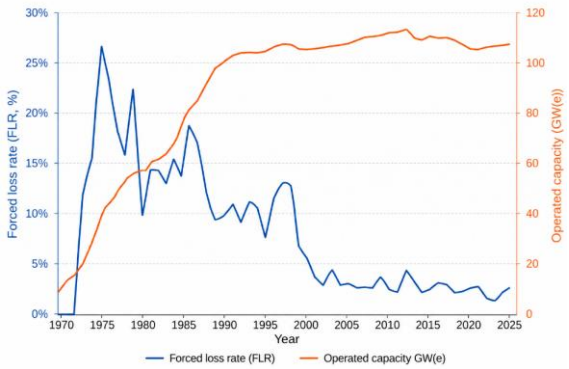


Figure 3. Historical trend of forced loss rate for the U.S. nuclear power plant fleet (1970–2024).

The FLR provides an important indication of losses associated with forced outages and unexpected plant shutdowns. The figure 3 shows that FLR was relatively high and volatile during the early decades of U.S. NPP operation. During the 1970s and 1980s, values frequently reached double-digit percentages, reflecting a period in which the NPP fleet was expanding rapidly and operating experience, equipment reliability programmes, and maintenance practices were still developing.

A significant improvement becomes evident from the 1990s onward. The FLR declines sharply during the late 1990s and early 2000s and subsequently remains at a very low level, generally around only a few percent. This reduction is particularly noteworthy because it occurred while a large portion of the U.S. NPP fleet was ageing and entering the period associated with LTO.
The very low FLR achieved by the mature U.S. NPP fleet therefore supports the conclusion that well-managed plant life management can maintain and enhance operational reliability even as chronological plant age increases.

3.2.3. Unplanned Capability Loss Factor: Reduction in Unplanned Production Losses

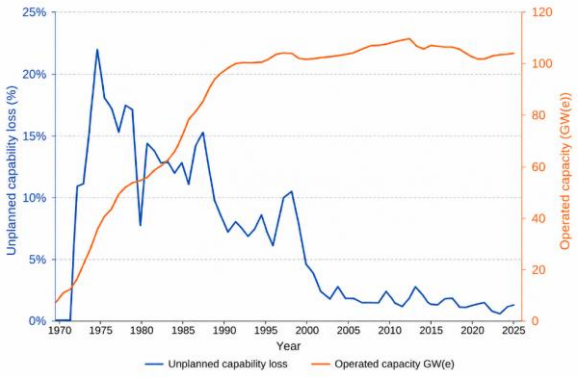


Figure 4. Historical trend of unplanned capability loss factor for the U.S. nuclear power plant fleet (1970–2024).

As shown in figure 4, The UCLF trend closely follows the overall pattern observed for FLR. During the earlier decades of NPP operation, UCLF was relatively high and subject to significant fluctuations. From the late 1980s and particularly after the late 1990s, however, UCLF declined substantially.

Since approximately 2000, unplanned capability losses have generally remained at a low level, mostly within a few percentage points. This period also broadly corresponds to the time when an increasing number of U.S. NPP fleet were preparing for operating under extended operating licences. The sustained reduction in UCLF indicates a significant decline in energy losses resulting from unplanned outages and unplanned power reductions.

3.2.4. Relationship Between LTO and Operational Performance

When the three indicators are considered together, a clear long-term relationship emerges: higher LF, lower FLR and lower UCLF. The U.S. NPP fleet has achieved this combination while its average operating age has steadily increased. This observation is highly relevant to the assessment of LTO. The transition to extended operation generally requires substantial technical and financial investment.

Ageing management programmes are strengthened to ensure that degradation mechanisms such as corrosion, fatigue, thermal ageing, radiation embrittlement, wear, erosion, and cable ageing remain within acceptable limits. Consequently, a plant entering LTO may, in some respects, have a more systematically monitored and modernized equipment base than it had during the later years of its original operating period.

3.3. Analysis of the Impact of LTO on the Performance, Safety, and Reliability of Russian Federation NPPs

The figure 5~7 present the historical trends in LF, FLR, and UCLF for operating NPPs in Russia, together with the growth in the number of operating reactors or total operated capacity. When considered collectively, these indicators provide useful evidence that the ageing of the Russian NPP fleet has not been accompanied by a systematic deterioration in operational performance or reliability. On the contrary, the long-term trends indicate substantial improvements in plant availability and reductions in unplanned production losses, despite the increasing average age of the reactor fleet and the continued operation of many units under LTO programmes.

Beginning in the late 1990s, the LF recovered steadily, increasing from approximately 60% to over 80%. The gradual increase demonstrates that plant performance improved substantially after modernization rather than deteriorating with age. Since approximately 2010 to present, the average load factor has remained consistently between 85% and 90%, while the number of operating reactors has remained relatively stable.

3.3.1. Analysis of Load Factor by Reactor Operating Age

Figure 5 presents the statistical distribution of LF across four reactor-age groups: 0–10, 11–20, 21–30, and 31–40 years. The results show a substantial improvement in operational performance as the reactor progresses from its initial operating period to mature operation.

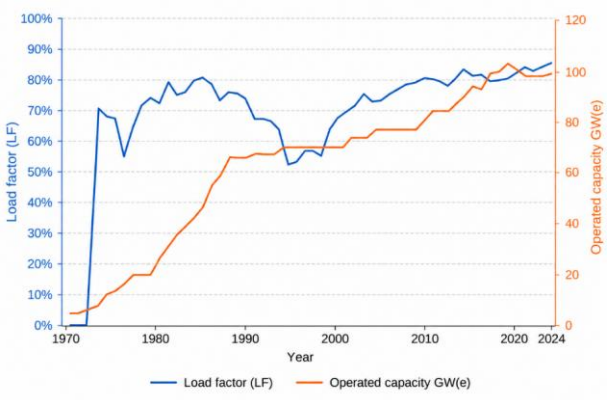


Figure 5. Historical trend of load factor for the Russian Federation nuclear power plant fleet (1970–2025).

The long-term trend in the LF of Russian NPPs shows a substantial improvement in fleet-level operational performance despite the progressive aging of the reactor fleet and the expansion of nuclear generating capacity. Following relatively high but fluctuating LF values during the 1970s and 1980s, the fleet experienced a noticeable decline during the 1990s, reaching approximately 52–58% in the mid-1990s. Since the late 1990s, however, the LF has shown a sustained recovery, exceeding approximately 70% in the early 2000s and reaching around 80% by 2010. During the 2010–2024 period, the LF remained relatively stable at approximately 78–85%, with the most recent values approaching the upper end of this range.

This trend is particularly relevant from the perspective of LTO. As an increasing number of Russian NPPs entered extended operating periods, the fleet-level LF did not exhibit a systematic deterioration associated with plant aging. Instead, operational performance generally improved or remained at a relatively high level. This observation is consistent with the potential benefits associated with LTO preparation and implementation.

Nevertheless, the observed correlation should not be interpreted as direct evidence that LTO alone caused the improvement in load factor. Fleet-average LF is also influenced by the commissioning of new units, retirement of lower-performing units, power uprates, outage management, and broader improvements in operational and maintenance practices.

3.3.2. Analysis of Forced Loss Rate by Reactor Operating Age

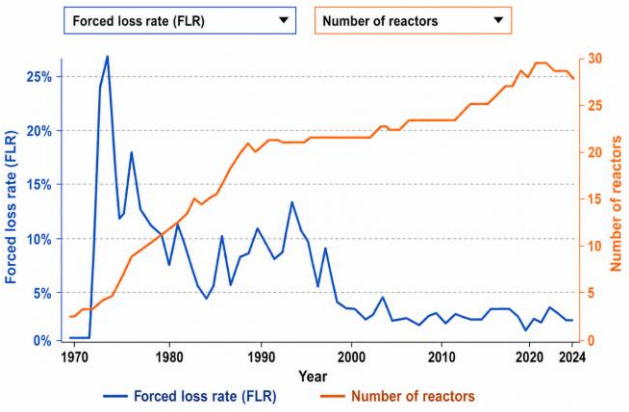


Figure 6. Historical trend of forced loss rate for the Russian Federation nuclear power plant fleet (1970–2025)

The historical trend in the FLR of Russian NPP fleet demonstrates a substantial long-term improvement in operational reliability. During the early period of NPP development in the 1970s and 1980s, the FLR was relatively high and exhibited considerable year-to-year fluctuations, occasionally exceeding 20%. During the 1990s, the FLR generally remained in the range of approximately 8–13%. A significant improvement occurred around the late 1990s and early 2000s, when the FLR declined sharply to below approximately 5%. Since the early 2000s, the FLR has remained consistently low, generally within the range of 2–4%.

This declining trend in FLR is particularly relevant to the assessment of LTO. Despite the progressive aging of the Russian NPP fleet and the increasing number of units operating beyond their original design or licensed operating periods, no systematic deterioration in fleet-level forced loss performance is evident.

The FLR trend also complements the observed improvement in LF. The simultaneous decline in forced generation losses and increase in LF suggests that improved equipment reliability and reduced unplanned production losses have contributed to enhanced fleet-level operational performance.

3.3.3. Analysis of Unplanned Capacity Loss Rate by Reactor Operating Age

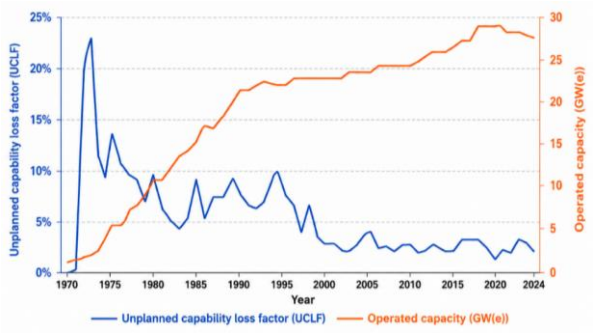


Figure 7. Historical trend of unplanned capability loss factor for the Russian Federation nuclear power plant fleet (1970–2025).

The long-term trend in the UCLF of Russian NPP fleet indicates a substantial improvement in fleet-level operational reliability. During the early stage of nuclear power development in the 1970s, UCLF exhibited considerable fluctuations and temporarily exceeded 20%. Although the indicator generally declined thereafter, relatively large year-to-year variations persisted through the 1980s and 1990s, with UCLF typically ranging between approximately 4% and 10%.

A notable improvement occurred from the late 1990s to the early 2000s, when UCLF declined substantially to approximately 2–4%. Since then, it has remained at a relatively low level despite the progressive aging of the Russian NPP fleet and the increasing prevalence of LTO. This sustained reduction in unplanned capability losses suggests an improvement in equipment reliability and plant availability over time.

When considered together with the increasing trend in LF and the substantial reduction in FLR, the declining UCLF provides complementary evidence of improved operational performance and reliability across the Russian NPP fleet. In particular, the simultaneous occurrence of higher LF and lower FLR and UCLF during the period in which LTO became increasingly prevalent suggests that plant aging has not resulted in a systematic deterioration of fleet-level performance. Rather, effective aging management and modernization measures implemented in support of LTO appear to have mitigated potential age-related degradation and contributed to maintaining reliable operation.
However, these fleet-level trends should not be interpreted as direct causal evidence that LTO alone resulted in the observed improvements.

4. Conclusions

This study examined the relationship between LTO and the operational performance and reliability of NNPs, with particular emphasis on the U.S. and Russian NPP fleets. The results indicate that increasing reactor age does not necessarily lead to deterioration in plant performance. In both countries, NPPs operating for extended periods have generally maintained high levels of operational performance, demonstrating that ageing effects can be effectively managed when LTO is supported by systematic ageing management, plant modernization, equipment refurbishment or replacement, and optimized maintenance and reliability programmes.

Overall, the experience of the U.S. and Russian NPP fleets demonstrates that well-managed LTO is

compatible with sustained, and in some cases improved, operational performance and reliability. When supported by rigorous regulatory oversight, effective ageing management, modernization, and targeted investment in plant systems and components, NPPs can continue to achieve high levels of availability and reliability beyond their original operating periods. These findings support LTO as a technically viable strategy for maximizing the long-term value of existing nuclear assets while maintaining the plant condition necessary for continued safe operation.

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