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FACTORS LIMITING LIFETIME OF NUCLEAR POWER PLANTS WITH PRESSURIZED-WATER REACTORS

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ABSTRACT

The objective of this paper is analysis and overview of factors currently or potentially limiting future lifetime of operated nuclear power plants (NPPs) with pressurized-water reactors (PWR) including Russia designed PWRs, also known as WWERs (water-water energy reactors).

Current perspectives of operation lifetime of PWR reactors in individual countries operating PWR reactors are discussed and analyzed.

Factors limiting lifetime of NPPs are divided into categories 1) 'Technical reasons' covering 'Accidents or serious failures' and 'Attainment of design lifetime, 2) 'Safety requirements' and 3) 'Other reasons' covering 'Economic reasons', 'Political decisions' and 'Environmental reasons'. Each reason/ factor potentially limiting lifetime of NPPs is described, relevant examples provided as well as a summary of historically occurred cases for each reason/ factor separately.

Technical factors which can potentially limit lifetime of PWR reactors in future are then discussed in detail with focus on technical factors which might be more important in future with growing age of units in operation. It means particularly attainment of design lifetime, which is closely connected with physical ageing of equipment and technological obsolescence. Components and structures which have capacity to limit lifetime of PWR reactors in future like irreplaceable structures and components and component 'difficult to replace' are then discussed considering separately 40, 60 and 80 years of operation.

INTRODUCTION

The purpose of this paper is analysis and overview of factors currently or potentially limiting future lifetime of operated nuclear power plants (NPPs) with pressurized-water reactors (PWR) including Russian designed PWRs, also known as WWERs (water-water energy reactors).

It provides an overview of current perspectives of operation lifetime of PWR reactors (intended operation period, formally confirmed or only considered as an option) in countries operating PWR reactors. It also summarizes the most important factors currently limiting lifetime of PWR plants leading to permanent shut-down. Last chapter discusses technical factors which can potentially limit lifetime of PWR reactors in future.

Paper provides updated information based on author`s doctoral thesis [1] finalized in 2018 and paper published in Nuclear Engineering and Design [2] in 2020.

CURRENT PERSPECTIVES OF OPERATION LIFETIME OF PWR REACTORS

Twenty eight countries currently operate nuclear power plants (NPPs) with PWR reactors (Armenia, Belarus, Belgium, Brazil, Bulgaria, Czech Republic, China (including Taiwan), Finland, France, Germany, Hungary, Iran, India, South Africa, South Korea, Japan, the Netherlands, Pakistan, Russia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, UAE, USA and United Kingdom). Some of them operate also other types of reactors. Only 4 countries operate exclusively reactors of other than PWR designs (Argentina, Canada, Mexico and Rumania) (source: https://www.iaea.org/PRIS).

PWR reactors are also the most common design of units under construction. New units with PWR reactors are currently (as of February 2022) in construction in 16 countries already operating PWR reactors - Belarus, Brazil, China, Finland, France, Hungary, India, Iran, Pakistan, Russia, Slovakia, South Korea, UAE, Ukraine, USA and United Kingdom but also in 3 countries operating no PWR reactors yet - Argentina, Bangladesh and Turkey (source: https://www.iaea.org/PRIS).

Current operation targets differ among countries operating PWR reactors and are influenced by political situation in each country. The future of NPPs has become a political instrument of some political parties in some countries which leads to unstable (or even missing) long-term national strategies for exploitation of nuclear energy for electricity and heat production.

The government of Germany approved a phase-out law with a plan to gradually phase-out all nuclear units by 2022. This plan is to a large extent already implemented with last three PWR units scheduled for permanent shutdown in 2022.

The government of Belgium decided to phase-out all seven PWR units in the country by 2025. Belgium single operator Electrabel obtained license for LTO from 40 to 50 years for Doel and 2 and Tihange 1 which is currently valid until 2024 (Doel 1) and 2025 (Doel 2 and Tihange 1). LTO for other units is not foreseen and are planned to be phase-out after 40 years of operation in 2022 (Doel 3 and Tihange 2) and in 2025 (Doel 4 and Tihange 3). This would mean that Belgium would lose app. 6000 MWs by 2025 which represents more than 50% of its consumption.

The government of Spain announced phasing-out three units by 2030 and last four units by 2035. Several operators in Spain currently operate six PWR units and one BWR unit. If current phase-out plan comes into power, all PWR units in Spain will be phase-out before they reach 50 years of operation.

An extreme earthquake followed by tsunami waves in Japan in March 2011 led to an accident with core melting of three reactors at Fukushima-Daiichi site. Since this accident, majority of reactors in Japan are suspended from operation, implementing safety measures which should improve robustness of the design to withstand extreme external events. Licensing process of NPPs to comply with new regulatory requirements is still in progress. As of February 2022, ten PWR units have restarted and six other PWR units have submitted applications and are waiting for regulatory authority decision. No BWR plans has been restarted yet despite of eleven applications submitted. From the perspective of long term operation (LTO) or operation beyond original design lifetime of 40 years, regulations in Japan allow extension for maximum 20 more years but with very strict conditions (source: https://world-nuclear.org).

Legislation in other countries basically allows LTO of reactors and typically provides conditions on different level of detail. Technical conditions for LTO also significantly vary among countries. Many regulators require fulfilment of International Atomic Energy agency (IAEA) Safety Standards for LTO such as [3-6].

USA is probably the most advanced in this process. As of February 2022, USA has in operation 93 units (more than 10 units recently decided to phase out from economic reasons), with more than two thirds of PWR reactors. US legislation allows extension of lifetime from 40 to 60 years. License extended for 60 years has already been awarded to 85 units in USA. US regulations allows second extension of license from 60 to 80 years of operation. Applications for 15 units (including 13 PWRs) have already been submitted to the US regulatory authorities. 4 PWR has received license for 80 year. Fifty-five units were identified in a recent NEI survey as interested in license renewal to 80 years.

US model with original operational license of 40 years and then extension to 60 years is applied with various modifications and conditions in many countries operating PWR reactors, for example already mentioned Japan, China, the Netherlands, Slovenia, South Africa, South Korea and Spain. It is a consequence of similar design with original design lifetime of 40 years but also of publicly accessible and practically proven US legislation written in English. Nevertheless, none of these countries currently officially considers extension beyond 60 years of operation.

Other important group of countries has unlimited operational license. Continuous operation is typically regulated by operational permission, usually for 10 years, conditioned by periodic or continuous assessment and fulfilment of regulatory body requirements. The most important conditions are typically conduct of periodic safety review (PSR) [6] and compliance with other relevant IAEA Safety Standards such as [3-6]. It applies to countries like Belgium, the Czech Republic, France, Sweden, Switzerland. Nevertheless, operation in Belgium, Sweden and Switzerland is also significantly impacted by political decisions.

Operated Russian designed PWRs (WWERs) are of two basic series of WWER 440 with design lifetime of 30 years and WWER 1000 with design lifetime of 40 years. Generation III WWER 1100 designs which are in operation in Russia and Belarus less than 10 years are not being discussed from the perspective of lifetime expectations in this paper. In case of WWER 440 reactors, operators extend the lifetime from 30 to 50 years using US approach (Hungary, Finland), or from 30 to 45 years followed by extension from 45 to 60 years (Russia, Ukraine). Some countries even decided to extend the lifetime directly from 30 to 60 years of operation (Bulgaria, Slovakia). Loviisa NPP in Finland extended license from 30 to 50 years (to 2027 and 2030 respectively) and considers extension license to 70 years. Similarly, Paks NPP in Hungary extended license of all four units from 30 to 50 years (to 2032-2037) and considers extension license to 60 years. Other WWER countries extend operating permissions by 10 years in connection with successful PSR (Armenia, the Czech Republic).

Some other countries, considering the age of their PWR units, have not decided yet which way they will proceed with their PWR units (Belarus, Iran, India, Pakistan, UAE, UK).

All countries operating PWR plants use either PSR approach, licensing renewal approach or their combinations for LTO justification. Officially, they all consider 60 years of operation as maximum timeframe. Only USA has already formalized rules for license beyond 60 years and Finland took some technical actions.

Outside the PWR world, only lifetime of some CANDU (heavy water reactors) units in Canada has been extended beyond 60 years to 76 years.

Currently, it looks that 60 years of operation is maximum considered timeframe for most of the PWR units outside the USA. As of February 2022, more than 30% of all units already exceeded 40 years of operation (source: https://www.iaea.org/PRIS), more operators can still seek for operation beyond 60 years.

Electricity prices has been constantly increasing in last decade in most of the developed parts of the world. Electricity wholesale prices in period of 2016-2021 increased by 100% to up to 500% of original prices, depending on the region and country [7]. Energy pricing models and EU response to the 2021 surge in wholesale energy prices were further exacerbated by the Russian invasion of Ukraine in February 2022 (source: https://ec.europa.eu/eurostat). In the wake of the Russian invasion of Ukraine early 2022, which further amplified the market price difficulties that started in 2021, the European Commission and EU countries started to work on a plan to make Europe independent from Russian fossil fuels well before 2030. This situation can also lead to reconsidering nuclear phase-out in some European countries like Belgium, Spain and Germany, encourage LTO, including LTO beyond 60 years (e.g. the Netherlands) and speeding up new builds in other European countries (e.g. the Czech Republic, Poland).

As of March 2022, Belgium government has announced to reconsider decision on whether to extend the life of Belgium's nuclear reactors beyond 2025. On contrary, there is so far no official information from Germany about reconsidering phasing-out last nuclear units. There is also no official indication from Spain government about changes in phase-out law but there is still reasonable time to do so, if needed.

FACTORS LIMITING LIFETIME OF NPPS

To better describe complete range of potential causes of permanent shutdown of NPPs, this chapter will also use examples of non PWR units. It will help to more thoroughly analyze potential threats relevant also to PWRs in future. NPPs are currently being permanently phased out from several main reasons:

1. Technical reasons
   a) Accidents or serious failures
   b) Attainment of design lifetime
2. Safety requirements
3. Other reasons
   a) Economic reasons
   b) Political decisions
   c) Environmental reasons

Accidents or serious failures as a reason for NPPs permanent shutdown

Based on analysis of NPPs incidents and failures from joint IAEA/OECD-NEA database International Reporting System for Operating Experience (IRS) and other available sources summarized in [1], we can conclude that only several units were phased out as a consequence of incident or failure. For the purpose of this paper, we can divide accidents and failures into two categories, 'caused by ageing of equipment' and 'other' (design, operation misconduct, operation problems, human errors, etc.)

The most important accidents in category 'other' are PWR unit Three Mile Island 2 in USA in 1979 (human errors of operating personnel, combination of various equipment failures), RBMK unit Chernobyl 4 in Ukraine in 1986 (combination of human errors of operating personnel and design deficiencies) and BWR units Fukushima-Daiichi site in Japan in 2011 (combination of design deficiencies, unexpected natural disaster and poor preparedness for accident management). These three accidents are the most important in a history of peaceful utilization of nuclear energy because they resulted in core melting and large scale (Chernobyl) or small scale (Three Mile Island and Fukushima Daiichi) radioactivity release into environment and caused permanent shut down of the units. Fortunately, there were very few accidents leading to permanent shut down of the unit (A1 heavy-water gas cooled reactor in Jaslovske Bohunice, Slovakia in 1977 phase out after partial core melting due to operational and design issues probably the only one worth mentioning).

Phasing out of two FBR units Phenix and Superphenix in France due to persistent operational issues and frequent malfunctions and failures belongs also to this category.

Regarding category 'caused by ageing of equipment', we can conclude that there are very few, if any, PWR units which were phases out up to 2020 due to equipment ageing degradation. Some ageing effects contributed to permanent shut down (e.g. PWR unit Crystal River 3 in USA due to delamination of containment concrete after temporary removal of containment tendons for aged steam generator replacement) but most of them have been resolved by equipment replacement, repairs, additional inspections, monitoring and analyses. It is worth to mention several examples of serious ageing degradations which were eventually managed. PWR unit Davis-Besse in USA – reactor pressure vessel head was seriously damaged by boric acid corrosion and finally replaced. PWR unit Indian Point Energy Centre 2 in USA – steam generator heat exchange tube rupture due to stress corrosion cracking led to replacement of all steam generators. PWR unit Mihama 3 in Japan – high energy pipeline rupture due to flow-accelerated corrosion in secondary circuit led to improved management of flow-accelerated corrosion worldwide. PWR units Koeberg 1 and 2 in South Africa – large-scale delamination and cracking of containment concrete and corrosion of carbon steel rebars induced by sea water chloride penetration led to large-scale repairs of concrete buildings surface but it does not prevent repeated damage. Ultimate solution is not in place yet. PWR unit Seabrook 1 – alkali-silica aggregates reaction caused swelling and microcracking of concrete reactor building. Ageing management programme was implemented and other mitigating actions are is in preparation.

Attainment of design lifetime as a reason for NPPs permanent shutdown

As of 2020, we can conclude that attainment of original design lifetime is not the actual reason for permanent shut down of nuclear units. Nevertheless, in connection with approaching end of original design lifetime, operators have to take major decisions on investments to equipment replacement and modernization due to attained equipment lifetime or increased safety requirements. In combination with other factors such as unclear national nuclear strategies, needs for massive investments and low electricity prices, some operators decided to permanently shut down units while reaching original design lifetime (e.g. CANDU NPP Point Lepreau in Canada).

Safety requirements as a reason for NPPs permanent shutdown

As a consequence of technology development, development of diagnostic, inspection and monitoring methods and primarily with increasing experience from operation, ageing and accidents, safety requirements for operated units design, operation and maintenance are gradually increasing. Vast majority of countries operating NPP (with exception of USA where alternative arrangements exist) performs every 10 years Periodic Safety Review [6] which is based on comparison of the plant status against the latest national and international requirements, codes and standards. Conclusions of this review typically lead to improvement of processes, procedures and organizational arrangements but also to major modernizations and safety improvements of original plant design. Other source of major modernizations and safety improvements are direct requirements of national regulators as corrective actions after major accidents (e.g. after Chernobyl or Fukushima Daiichi accidents) or based on operating experience or enhanced safety analyses.

There requirements for modernizations and safety improvements of original plant design are associated with significant financial resources and extended outages which may lead to operators' decisions to permanently phase out units. This was, in connection with economic aspects, reason for shut down of four units in Sweden in 2015-2020 (PWR and BWR 1 and 2 units at Ringhals NPP and BWR units 1 and 2 at Oskarshamn NPP).

Economic reasons of NPPs permanent shutdown

In early years of peaceful utilization of nuclear energy, many prototype units of small electric output were phased out as they became not profitable. Reactors of various early designs were phased out particularly in countries developing own reactors such as Canada, Czechoslovakia, France, Germany, Japan, Russia, Sweden, Switzerland. UK and USA. Except of early design units, several standards series units were recently phased out due to changes in energy market. It was caused by increased competitiveness of other energy sources (e.g. shell gas production in USA and Canada), subsidizing renewable energy and increased taxes on nuclear energy production in Europe (units in Sweden discussed earlier).

Political decisions causing NPPs permanent shutdown

Political decisions typically follow major nuclear accidents. After accident in Chernobyl in 1986, all nuclear units in Italy were phased out. Germany decided on gradual phase out of all nuclear units until 2022 after Fukushima-Daiichi accident in 2011.

Sweden permanently shut down 2 BWR units of Barseback NPP built not far from Denmark capital Copenhagen in 2005 and 2010 respectively as a consequence of political pressure from Denmark.

After unification of Germany in 1990, Germany decided to phase out all Russian design PWR plants (WWER) in east Germany. As a part of EU access agreements, several east European countries had to permanently shut down Russian design units of older designs such as WWER 230 (Jaslovske Bohunice units 1 and 2 in Slovakia; Kozloduy units 1-4 in Bulgaria) and RBMK (units 1 and 2 at Ignalina, Lithuania).

Unclear national political strategy and associated unsure return on investments led to permanent shut down of BWR plant Muhleberg in Switzerland.

Political aspects can have very significant impact on future investments and operation of NPPs. In March 2015, EU supreme court decided that tax from utilization of nuclear fuel or tax from spent nuclear fuel are compatible with EU constitution. This legalized introduction of special taxes and fees on NPPs (e.g. tax from utilization of nuclear fuel in Germany, tax from installed nuclear capacity in Sweden), increase of existing fees, changes in insurance conditions, etc. Political decisions also impacted profitability of potential LTO with increased taxes and increased payments for decommissioning and radioactive waste processing. Political decisions are in many cases results of public opinion. From this perspective, open and transparent public approach is of paramount importance for future operation of NNPs.

Environmental reasons of NPPs permanent shutdown

Global warming, changing environmental conditions, population and demographic development can have major impact on feasibility of LTO in individual countries. Decisions to phase out NPP or to not allow LTO from environmental reasons are mostly closely related to political decisions. But primary reason can be environmental.

Many NPP use cooling water from surrounding rivers or lakes, either in open circuit (without cooling towers) or in closed circuit (with cooling towers). Some areas have been experiencing significant decrease of average or minimum water flow which can lead to operation restrictions and ultimately to permanent shut down or prevention of LTO. This issue is being closely investigated in several countries in connection with LTO from 60 to 80 years.

Other example from this area is fast demographic development in some areas. 8 CANDU reactors were commissioned at Pickering NPP site since 1971, at that time approximately 30 km from Toronto city center in Canada. Fast city growth in recent decades moved the city boundaries to 5 km from the plant. Future development towards the plant is expected which led to decision of permanent shut down of all units at the end of original design lifetime and not going for LTO.

POTENTIAL TECHNICAL FACTORS LIMITING LIFETIME OF PWR REACTORS IN FUTURE

As summarized in previous chapter, permanent shut down of PWR units was until 2020 mainly from economic and political reasons. This chapter summarizes based on [1] technical factors which might be more important in future with growing age of units in operation.

As discussed in previous chapter, accidents or serious failures causes permanent shut down of only very few units until 2020. Nevertheless, future accidents or serious failures may definitely lead to permanent shut down of units in future. Important contributor to increased probability of accident or failure is physical ageing of equipment but also non-physical ageing (also called obsolescence) of technology. This will be thoroughly discussed in this chapter but there are also other contributors to potential impact of future accidents and failures such as quality of operational and accident procedures, personnel preparedness for abnormal and accident scenarios, human factors during operation and abnormal and accident scenarios, safety culture in operating organizations, resistance of the plant to external hazards like extreme weather conditions, airplane crash, terroristic attack.

This chapter will also discuss potential attainment of design lifetime, which is closely connected with physical ageing of equipment, and technological obsolescence, which can lead to loss of fitness for service of safety equipment.

Physical ageing is a general process in which the physical characteristics of SSCs gradually deteriorate with time or use owing to physical degradation or chemical or biological processes (i.e. degradation mechanisms) [5].

To discuss components and structures which have capacity to limit lifetime of PWR reactors in future, we need to distinguish for the purpose of this paper between operation for 60 and 80 years.

As of 2020, there are very few technical or safety issues caused by physical ageing which could limit lifetime of PWR reactors. Irreplaceable structures and components such as reactor pressure vessels or concrete containment structures show in case of good maintenance and ageing management capacity for safe operation for 60 years in vast majority of PWR plants. From PWR components categorized as ‘difficult to replace’, replacement of many primary circuit components was successfully performed (steam generators, pressurizers, reactor pressure vessel heads). Status of other primary circuit components is usually good, but more information will be needed for ageing management of internal reactor parts and primary circuit pipelines. Cable systems are important issue for many PWR plants, particularly for WWER plants. Equipment qualification of safety cables is theoretically well managed, but it is not completely implemented in many countries. Ageing management of non-qualified safety cables and non-safety cables is in initial phase in most of the plants. Current situation can lead to the need of extensive cable systems replacements even before reaching 60 years of operation. I&C systems are also susceptible to physical ageing, but main issue is technological obsolescence which will be separately discussed later on.

For 80 years of operation, there are many more potential issues from the perspective of physical ageing. Regarding irreplaceable structures and components, not all reactor pressure vessels will have sufficient safety margins without additional calculations and measures. Enhancing reactor pressure vessel surveillance programmes and using ‘Master Curve’ approach appears to be of key importance for some of them. Further development and application of advanced inspection and test methods (e.g. time of flight-diffraction and phased array ultrasonic methods) will be important. As a last option, reactor pressure vessel annealing can be used. Annealing was used for several WWER reactor pressure vessels. Nevertheless, the effect of annealing on material properties development during further irradiation is still subject of research. Current status of knowledge does not allow to confirm capacity of all concrete reactor building structures for 80 years. Further research, inspections and calculations will be needed for these structures.

For 80 years of operation of components categorized as ‘difficult to replace’, primary circuit pipelines and reactor pressure vessel internals are currently the most problematic primary circuit components from the perspective of adequate information for their ageing management and potential replacement. Substantial work will also have to be done for successful requalification of safety cables for 80 years of operation. In many NPPs, partial or complete (due to current requirements for segregation and separation) replacement of qualified safety cables may be necessary. Non-qualified safety cables and non-safety cables status, even with appropriate ageing management, have to be partially or completely replaced in some plants. This is a very complex task which can lead to extremely long outages, costs and it can also cause unit phase out.

Technological obsolescence of components is defined as a lack of spare parts, technical support, suppliers and industrial capabilities leading to declining plant performance and safety due to increasing failure rates and decreasing reliability [5]. Systematic identification of useful service life and anticipated obsolescence of components, provision of spare parts for planned service life, timely replacement of parts, long term agreements with suppliers and development of equivalent structures or components are relevant actions to manage technological obsolescence.

Technological obsolescence has become an issue for many NPPs. This topic has been addressed since 2005 using several commercially developed solutions. A modern approach to proactive technological obsolescence management was implemented in USA and Canada. In the last decade, this issue is being solved also in other parts of the world, mostly using similar approaches (e.g. Argentina, Belgium, Brazil, France, Hungary, Sweden). International cooperation is of a key importance to identify and quantify current and future needs of individual operators and jointly motivate manufacturers and suppliers to produce, supply and provide maintenance services for existing equipment.

Technological obsolescence is important particularly for instrumentation and control (I&C) and electrical equipment, both safety and non-safety. I&C systems are typical example, but their obsolescence is frequently combined with physical ageing. I&C refurbishments are regularly performed and are both from technical and safety side well managed. But regulations in some countries (e.g. USA) still does not allow routine shift from analogue to completely digital safety I&C systems. This can eventually lead to the situation when the units could be phased out due to lack of maintainability of I&C systems. Other important aspect is high financial costs of I&C refurbishment (investment costs, extended outages, tests).

It is important to mention also other type of obsolescence - obsolescence of knowledge, knowledge retention and transfer of knowledge from old to young generation. Lack of relevant knowledge of research staff, manufactures, suppliers and operators can also lead to lack of capability to address technological obsolescence issues and physical ageing issues and consequently to permanent shut down of NPPs.

CONCLUSIONS

As of 2022, permanent shut down of operated NPPs is in vast majority from reasons other than attainment of structures and components design lifetime, namely from political and economic reasons. PWR (including WWER) plants have been from technical reasons (accidents and failures or attainment of structures or components design lifetime) permanently shut down only exceptionally. Current oldest reactor units are in operation for more than 50 years and large number of reactor units has already obtained license (or operating permission) for 60 years. Some reactor units already obtained license for operation up to 80 years and others are in preparation.

For operation of PWR reactors for up to 40 years, reasons for permanent shutdown are typically economic or political. No PWR reactor has been shut down only due to technical reasons.

In case of operation of PWR reactors up to 60 years, economic and political reasons remain the main contributor for phase out decisions. Nevertheless, safety reasons and increasing safety requirements become also very important contributor. We can expect higher portion of NPPs permanently shut down due to attained lifetime of major structures and components or lack of adequate safety margins. Nevertheless, there are no known technical issues which would prevent operation of PWR reactors for 60 years in general.

Operation for up to 80 years is currently in phase of preparation of scientific and technical basis. First licenses for 80 years of operation were awarded in USA in 2020 and 2021. For PWR reactors, besides the economic, political and safety reasons, environmental reasons and technical reasons will play more important role for operation up to 80 years. Attainment of the lifetime will become an important factor for many units.

More information on topics related to current status of preparation for long term operation of current fleet of NPPs can be also found in papers [8-11].

REFERENCES

[1] Krivanek R. (2018). “Factors Limiting Life Time of Nuclear Power Plants with Pressurized-water Reactors”, Doctoral Thesis, Brno: University of Technology Brno, Faculty of Mechanical Engineering.

[2] Krivanek R. (2020). “Factors limiting lifetime of nuclear power plants with pressurized-water reactors”, *Nuclear Engineering and Design,* 370 110872, doi: 10.1016/j.nucengdes.2020.110872.

[3] International Atomic Energy Agency (2016). “Safety of Nuclear Power Plants: Design”, Specific Safety Requirements No. SSR-2/1 (Rev.1), Vienna: IAEA.

[4] International Atomic Energy Agency (2016). “Safety of Nuclear Power Plants: Commissioning and Operation”, Specific Safety Requirements No. SSR-2/2 (Rev.1), Vienna: IAEA.

[5] International Atomic Energy Agency (2018). “Ageing Management and Development of a Programme for Long Term Operation of Nuclear Power Plants”, Specific Safety Guide No. SSG-48, Vienna: IAEA.

[6] International Atomic Energy Agency (2013). “Periodic Safety Review for Nuclear Power Plants”, Specific Safety Guide No. SSG-25, Vienna: IAEA.

[7] International Energy Agency, Electricity Market Report, January 2022.

[8] Krivanek R. (2014). “Long term operation of nuclear power plants – IAEA SALTO peer review service and its results”, *Nuclear Engineering and Design,* 280, 99–104, doi: 10.1016/j.nucengdes.2014.09.021.

[9] Krivanek R., Havel R. (2016). “Long term operation of nuclear power plants – IAEA SALTO missions observations and trends”, *Nuclear Engineering and Design,* 305, 64–67, doi: 10.1016/j.nucengdes.2016.05.023.

[10] Krivanek R., Fiedler J. (2017). “Main corrective measures in an early phase of nuclear power plants’ preparation for safe long term operation”, *Nuclear Engineering and Design,* 316, 125–130, doi: 10.1016/j.nucengdes.2017.03.002.

[11] Krivanek R., Fiedler J. (2017). “Main deficiencies and corrective measures of nuclear power plants in ageing management for safe long term operation”, *Nuclear Engineering and Design,* 323, 78–83, doi: 10.1016/j.nucengdes.2017.07.035.