Forecasting the dynamics of decommissioning nuclear power plants

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Abstract. The forecast of the dynamics of the nuclear power plants decommissioning, taking into account the duration of operational period, is given in the article. This forecast reflects the volume of markets for decommissioning nuclear power plants in the world by region. The amounts of spent nuclear fuel arising from the shutdown of reactors and fuel overloads of operating reactors are calculated and compared. Additionally, the costs of decommissioning and construction of reactors to replace retired facilities are estimated.

1. Introduction

The life cycle of any nuclear power plant (NPP) begins with construction planning, then goes through the construction and operation stages and ends with its decommissioning.

The lifetime of an NPP is limited by changes in the mechanical properties, homogeneity of the material and violation of the geometric shape of the reactors’ structural elements because of radiation. Most of the currently operating reactors (II generation reactors) were designed for 30 years operation, but there is the possibility of extending their operational period to 60 or even 80 years. This solution was recognized by operators and regulatory bodies as the most efficient and economically viable, as evidenced by a large number of programs to extend the licenses for the operation of NPPs. Reactors of generations III and III+, which are now actively developing, are initially designed for a longer operational period [7-10].

Longer operational period postpones the issue of NPP decommissioning in the future. Nevertheless, the life cycle management of NPPs has attracted increasing attention in the last decade, since effective management of aging systems, structures and components is a key element to ensure safe and reliable long-term operation of NPP and its decommissioning. Therefore, forecasting the dynamics of NPP decommissioning is important and necessary for assessing the size and volume of this market.

2. Modelling of NPP decommissioning market volume

For each of the currently operating reactors, the date of commissioning is known, as well as the design lifetime. For some of them periods of renewal are also known. According to PRIS (IAEA) [1], the construction of power units has so far been uneven (figure 1). To 2018, the number of operating reactors is 451, and 166 nuclear reactors have been shut down. 67% of all operating reactors have been in operation for 30 years or more. The oldest reactors are 49 years old (figure 2).
Knowing the number of reactors connected to the network in a given year, and their design and extended operational periods, the number of reactors, that will be decommissioned in the future, can be determined. Thus, calculations of the number of reactors that will be stopped in each particular year were made using the inner formula in MS Excel (figures 3-6).

At the design operational period of the reactors, most of the reactors will be shut down in 2020–2040, while as the life of the reactor is extended, these dates shift to 2040–2050.

According to the annual report of ROSATOM in 2016, the volume of the global market for decommissioning nuclear and radiation hazardous facilities amounted to ~$7.2 billion. The market will gradually grow, as in the coming years a large number of old reactors will be removed out of service. As follows from figures 3-4 over the next 20 years (until 2037), more than 5-10 reactors with a peak of 37 reactors in 2025 will be stopped annually (according to the project).
Figure 3. Forecast of the dynamics of the number of reactors decommissioned annually after the expiration of the design life

Figure 4. The forecast of the dynamics of the number of reactors decommissioned annually after the expiration of the design life, cumulatively

If we assume that all operating power reactors in the world will receive licenses to extend the operation period to 60 years, then the dynamics of reactors’ shutdown will shift to the right along the time axis. In this case, in the next 10 years (until 2028) there will be a “temporary pause”: the power reactors will not be stopped or decommissioned. All existing reactors built before March 2018 will be stopped only by 2078 (figures 5-6).
Figure 5. Forecast of the dynamics of the number of reactors decommissioned annually while extending the design life to 60 years

Figure 6. The forecast of the dynamics of the number of reactors decommissioned annually with the extension of the design life to 60 years, cumulative

By 2050, almost 400 reactors will be shut down, of which more than 60 are Russian-designed reactors (built in Russia and abroad, figures 7-8). That is, the global “order book” for NPP decommissioning may amount to about 220 reactors by 2030, and about 400 by 2050. Of these, the “order book” for decommissioning Russian-designed reactors in Russia and abroad may be 30 reactors by 2030 and about 60 reactors by 2050.
Thus, in the next decade, a capital-intensive market for NPP decommissioning will be formed, moreover, it is very heterogeneous in terms of the distribution of its volumes between individual states and groups of countries. The most promising are the markets for decommissioning NPPs in the USA and Europe, where the largest number of reactors are operating (about 100 and more than 160, respectively), and in Asia (excluding China).

Of the 447 power reactors operating in the world at the end of 2017, 74 Russian-designed power reactors (16.5%) operated in 11 countries of the world, including 39 reactors outside Russia (17 VVER-440 reactors and 22 VVER-1000 reactors). Apparently, this is Russia’s future “order book” for decommissioning.

3. Forecast of spent nuclear fuel accumulation
To assess the prospects of the market for spent nuclear fuel (SNF) treatment, it is necessary to know the indicators of market volume (mass). The amount of SNF generated annually includes two sources: the total mass of the cores of all reactors stopped in the year \( t \) and the unloaded fuel during refuelling of all remaining operating reactors:
\[ M(t) = \sum_i M_i + \sum_j \frac{Q_j}{B_j}, \]  

\( M(t) \) – mass of SNF generated in the year \( t \);
\( M_i \) – mass of fuel in the cores of reactors stopped in the year \( t \);
\( Q_j \) – thermal capacity of the \( j \) reactor;
\( B_j \) – burnout depth of the \( j \) reactor.

Knowing the date of commissioning of the reactor, its thermal capacity and burnout, it is possible to calculate the amount of SNF accumulated to the current moment as a result of the operation of reactors. These results are presented in figure 9.

At present, about 400 kilowatts of SNF are accumulated in the world, with the majority in the United States and France.

The mass of fuel in the core in different reactors varies from 40-42 tons (in PWR-300 in Pakistan and VVER-440 of Russian design) to 192 tons (in RBMK-1000). The vast majority of reactors with a capacity of 1000–1400 MW have about 90–110 tons of fuel in the core. When all \( \approx 440 \) reactors built before 2018 are decommissioned, the amount of SNF will increase by \( 440 \times 90 \approx 40 \) kilotons, which is an order of magnitude less than the amount of SNF accumulated at the current time as a result of fuel reloading.

Figure 10 shows the amount of SNF calculated as the sum of SNF arising due to fuel overloads in reactors and the mass of fuel in the core of the shutdown reactors.

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As follows from figures 11-12, the annual formation of SNF during the decommissioning of NPPs (i.e., the mass of fuel in the core of the shutdown reactors) does not exceed 2.7 kilotons per year, which is significantly less than the mass of SNF generated annually during reactor overload.

![Figure 11. Mass of fuel in the core of reactors annually decommissioned upon expiration of the design period](image1)

![Figure 12. Mass of fuel in the core of reactors annually decommissioned upon expiration of the design period (cumulative)](image2)

The total mass of fuel in the cores of shutdown reactors built up to 2018 is approximately 35 kilotons, which is several times less than the total mass of the SNF generated because of overloading of operating reactors (figure 13). The largest contribution to the accumulation of SNF will be made by OECD countries.
The main source of SNF accumulation is fuel reloading. To a much lesser extent, SNF accumulation is associated with NPP decommissioning. Therefore, when extending the operational period, the amount of SNF will be even higher (figure 14).

According to ROSATOM’s estimates, it is expected that up to 2030 the market for spent nuclear fuel recycling, reprocessing and disposal will be the most dynamic segment of the final stage of the nuclear fuel cycle market with average annual growth rates near 5.9%. In 2016, the volume of this market was $4.4 billion. In 2020, the market volume will reach $5.9 billion, and by 2030 - $9.9 billion. The main players in this market are ROSATOM, Orano (AREVA), SKB, Holtec, GNS and Skoda.

4. Estimated costs of NPP construction and decommissioning

Figure 15 reflects the dynamics of reducing installed electrical power of the reactors that remain in operation until the shutdown (assuming that from 2018 new reactors are not being built). The forecasts of the nuclear power industry development made by the World Nuclear Association (WNA) [2, 6] in three scenarios make it possible to judge the appropriate rates for the construction of new reactors compensating the facilities that are under decommissioning. The difference between the forecast and the capacity of the remaining reactors built before 2018 indicates a capacity deficit that needs to be filled with new reactors.
Figure 15. Forecast of reducing the capacity of operating reactors built up to 2018 as a result of decommissioning with a design life extended to 60 years, and WNA (2017) forecasts for the development of nuclear power at upper (kW = 1.7% / year), reference (kW = 1.7% / year) and lower (kW = -0.57% / year) scenarios.

The number of new reactors that need to be connected to networks in particular year to fulfill a specific scenario for the development of nuclear energy can be calculated. Thus, the number of reactors built before the start of the forecast period (t = 0) and remaining in operation in the year t should be subtracted from the predicted value of the total number of operating reactors (or their installed capacity, or electricity generated) in the year t. The results of this calculation are shown in figure 16. At the designed operational period the recommended number of reactors to be commissioned is more than at an extended operational period. Regardless of the service life it is expected that the installed electrical power level of the remaining reactors will be approximately 50 GW (e) by 2066, which is 8 times less than in 2018.

Figure 16. Forecasting the start-up dynamics of new reactors to ensure a given scenario for the development of global nuclear power with a high rate (k = 2.6% / year) and a low rate (-1.3%) until 2040, with the planned decommissioning of reactors built before 2018 of the year. The annual reactor start-up is given only for the upper scenario.
As can be seen, due to the planned shutdown of 327 old reactors by 2040, even with a decreasing development scenario of world nuclear power (reducing the total number of operating reactors), it is necessary to build 232 new reactors to 2040 (more than 10 reactors per year), and with the upper scenario it is necessary to build 673 new reactors for the remaining 22 years. That is, 30 reactors per year, which seems unlikely. It can also be noted that the “order book” for the construction of NPPs (the number of new reactors on a cumulative basis) grows over time almost linearly (figure 16). For the next decade, the situation with the construction of new reactors may soften as a result of extending the period of operation of old reactors. However, this process only postpones the problem of fast commissioning of new reactors for the near future (by ≈10 years), since after extending the rate of decommissioning of old reactors will accelerate (see figure 15). Currently, 58 reactors with a total installed capacity of about 60 GW are under construction.

Now it is important to compare the costs arising from the construction and from decommissioning of NPPs. Suppose that new reactors will be built only to recover outgoing capacity. The costs of decommissioning and construction of various types of reactors will be considered averaged (construction $3 billion per 1 GW [3]; withdrawal of various types of units from operation in million $/GW [4, 5]: PHWR - 360; PWR - 320; VVER - 330; BWR - 420; GCR - 2 500). If the reactor is shut down in a given year, we consider the costs of its decommissioning, as well as the costs of building a reactor of the same type and capacity to replace the outgoing one. The results are presented in figures 17-18.

![Costs of decommissioning and construction of new NPPs to replace the outgoing capacity](image)

**Figure 17.** Costs of decommissioning and construction of new NPPs to replace the outgoing capacity (extension to 60 years operation)
Construction costs far exceed decommissioning costs, i.e. in the short term, it is more profitable to prolong the operation than to close the NPPs and build new ones instead. However, in this case, there will be a sharp increase in costs for both decommissioning and the construction of new reactors. This means that the extension of operation for a longer period (in particular, from 60 to 80 years) in the absence of construction of new power stations will result in the need to finance a large number of projects for NPP decommissioning and high investments in the construction of new NPPs to replace retired facilities. Therefore, despite the current tendency to extend the life of an NPP, it is nevertheless necessary to limit the term of renewal and combine it with the construction of new stations to finance future projects for NPP decommissioning by generating electricity. This will also help to avoid the risks associated with the loss of operational documentation for 80 years of operation.

5. Conclusion
Calculated number of reactors to be decommissioned in the next decade defines the largest NPP decommissioning markets. The most promising are the markets for decommissioning NPPs in the USA, Europe and in Asia (excluding China). Additionally, the calculation gives an opportunity to see Russia’s future “order book” for decommissioning as number of Russian-designed reactors is also known.

The analysis shows that the main source of SNF accumulation is not an NPP decommissioning, but fuel reloading. That is why the amount of SNF will be higher when extending the operational period of an NPP. Moreover, longer operational period without construction of new NPPs is the reason of the necessity of very high investments in both construction and decommissioning in the near future. Therefore, it is important now to balance the lifetime of existing NPPs and commissioning of new ones.

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