# Challenges and constraints related to the final stage of the SMR fuel cycle in the light of plans to implement SMR technology in Poland.

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**Abstract**

In Poland, it was decided that to diversify energy sources, and to reduce carbon dioxide and sulfur emissions, the country should move to introduce nuclear power. Poland has plans for both large and small nuclear reactors. Recently, there is great interest to use small modular reactors. However, this implies the need to carry out a number of works aimed at checking the feasibility of implementing SMR technology in Polish conditions. Among others, there is a necessity to conduct in-depth analyses concerning the final stage of the fuel cycle. The paper presents a analysis of the possibility of deployment of SMRs in Poland including an initial selection of SMR technologies most suitable for use in Polish condition as well as the fuel cycle options for selected technologies. Challenges and constraints related to the management of spent nuclear fuel and ways to counteract them are also taken into account. Additionally, possible ways of management of spent fuel from SMR including the possibility of using innovative methods of reprocessing, including solvent extraction for the separation of actinides has been considered.

## INTRODUCTION

The technology of small modular reactors (SMR) is a innovative solution, which can be a recipe for the high costs of building large nuclear power plants. According to the current assumptions, SMRs are to be reactors with a capacity of up to 300 MW (small) or 300-700 MW (medium); they can be single units or components of a large systems. The concept of SMR appeared over a decade ago in the USA, where numerous advantages of such a solution were noticed. These include: short construction time, increased safety and low investment and operating costs. SMRs are delivered as ready-made modules, allowing for easy scaling up. They can be installed close to the recipients, which reduces network and transmission costs. With their introduction, the philosophy of nuclear safety is changing, which until now required locating nuclear reactors far from human settlements. SMRs can use various technologies that are already known from large nuclear power plants, such as:

* LWR – Light Water Reactor;
* PWR – Pressurized Water Reactor,
* BWR – Boiling Water Reactor,
* HTR – High Temperature Reactor,
* FNR – Fast Neutron Reactor,
* MSR – Molten Salt Reactor.

Technical parameters e.g. reactor power, the temperature of generated steam and fuel properties are very important when choosing a nuclear technology. Depending on the technology chosen, the appropriate nuclear fuel is used; the way of dealing with spent fuel should also be different.

There are many issues related to management of spent nuclear fuel (SNF) from SMRs which need to be solved before the implementation of this new technology. An important factor that ought to be considered is the volume of spent fuel produced, its characteristics and management methods that can be applied in a specific case. How SMR spent fuel is handled during storage, transportation, reprocessing and final disposal may impact not only to the nuclear safety of the whole process of SMR implementation, but also with its economics. The choice of fuel cycle is one of the crucial challenges in this process. As for the fuel cycle back-end, the first assessment suggests that the direct disposal of spent fuel is a reasonable solution, especially since construction of fuel elements for new reactors guarantees inherent safety and limits the release of radionuclides through the use of various types of protective coatings/layers.

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However, due to the lack of deep geological repositories (DGRs), which are considered the final and rational solution for spent nuclear fuel and high-level waste, it seems that postponed disposal could be replaced by interim storage, while maintaining all safety rules. Interim storage, of course, should only be treated as a temporary solution until the widespread implementation of DGR technology. Though, like all solutions in the nuclear industry, it requires a lot of attention, building additional facilities and safety systems. This situation is difficult, particularly in countries with early-stage nuclear programs that lack sufficient experience in spent fuel management and adequate storage facilities.

The other strategy is to use innovative separation methods for reprocessing the fuel with recovery of actinides. Such an option is also tested for TRISO fuel, which reprocessing is a real challenge. The solvent extraction methods used for reprocessing result also in creation ~~arge volumes of~~ high-level waste which need to be treated before disposal. The volume of high-level waste is relatively small, most nuclear waste is low-level and intermediate-level waste. Nevertheless, the majority of the radioactivity produced in nuclear power generation comes from high-level waste, which is mainly generated in actinide separation processes during spent fuel reprocessing.

 Regardless of whether spent nuclear fuel from SMRs will have to be directly disposed, it is extremely important to develop waste acceptance criteria (WAC) for the disposal as they help to define a waste management strategy.

## National context

The Polish power sector is based mainly on fossil fuel combustion, of which more than 70% represent hard and brown coals. Current climate policy foresees a significant decrease of CO2 emission to the environment implicating the need for transformation of Polish power industry into a low-carbon sector. To meet this goal, the reduction of the share of hard and brown coal-based power industry in entire energy mix is crucial.

The strategic document of the Energy Policy of Poland until 2040 (PEP2040), setting the framework for the energy transformation in Poland, states that the decarbonisation of the energy sector will be possible thanks to the implementation of nuclear energy and offshore wind energy. There is consensus that nuclear power plants provide stable energy generation with zero emissions into the air.

Poland has plans to implement both large and small nuclear reactors. The Energy Policy of Poland until 2040 (EPP2040) states that the country’s first nuclear power reactor with a capacity of 1-1.6GW will be commissioned in 2033. Further reactors will be commissioned every 2-3 years up to a total of six. In parallel to the development of conventional nuclear energy (“big atom”), interest in the use of SMRs has been growing very quickly in recent years in the country. Nearly 10 energy, chemical and metallurgical companies in Poland are planning or considering the construction of small nuclear reactors. It is expected that SMRs will provide energy for power generation and for district heating

The first decisions regarding the implementation of nuclear energy in Poland, i.e. decision-in-principle, have already been issued. The decision-in-principle is the first decision in the process of administrative permits for investments in nuclear power facilities in Poland that an investor may apply for. First of all, Poland's Ministry of Climate and Environment has issued decisions-in-principle for the construction of two large nuclear power plants: one for a 3750 MWe plant in Pomerania using Westinghouse's AP1000 technology, the other for a plant comprising two South Korean-supplied APR1400 reactors in the Patnów-Konin region. The ministry has also issued a decision-in-principle (in July last year) on copper and silver producer KGHM Polska Miedź SA's plan to construct a NuScale VOYGR modular nuclear power plant with a capacity of 462 MWe consisting of six modules, each with a capacity of 77 MWe. In December, the ministry issued decisions-in-principle also to Orlen Synthos Green Energy for the construction of power plants based on GE Hitachi Nuclear Energy's BWRX-300 SMR in six locations. A total of 24 BWRX-300 reactors are planned at the sites. Moreover, Polish Ministry of Climate and Environment has approved also plans for Rolls-Royce SMRs construction, submitted by Polish industrial group - Industria in December last year. The application concerns the construction of a nuclear power plant using Rolls-Royce SMR technology - a 470 MWe design based on a small pressurised water reactor and a used nuclear fuel storage facility as an integral part of the power plant.

The potential to use high-temperature reactors (HTRs) has been also noticed, which, not being an alternative to large-scale light-water nuclear power plants, could in the future be used mainly as a source of process heat for industry [1]. Confirmation can be found in the reports of the GOSPOSTRATEG project “Preparation of legal, organizational and technical instruments for implementation of the HTR nuclear reactors” (a part of Polish Strategic Program "Social and economic development of Poland in the conditions of globalizing markets) developed by consortium of the National Center for Nuclear Research with the Institute of Nuclear Chemistry and Technology with the Ministry of Climate and Environment as a content partner. The project resulted in the contract for the implementation of design work for a High Temperature Gas Cooled Reactor (HTGR) signed in 2021 by the National Center for Nuclear Research and the Ministry of Education and Science. The agreement assumes that within three years the conditions for the construction of a high-temperature research reactor in Poland will be prepared.

The list of SMR’s types [2] scheduled for deployment in Poland is presented below (Table 1).

TABLE 1. LIST OF SMRS CONSIDERED FOR IMPLEMENTATION IN POLAND.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| SMR | Design organisation | Thermal Power (MWth) | Outlet Temperature (°C) | Spectrum (thermal/fast) | Fuel type | Fuel |
| BWRX-300 | GE-Hitachi | 870 | 287 | Thermal | UO2 pellets | LEU |
| VOYGR | NuScale Power | 250 | 321 | Thermal | UO2 pellets | LEU |
| HTGR-PM | INET | 500 | 750 | Thermal | TRISO pebble | HALEU |
| Rolls-Royce SMR | Rolls-Royce SMR Ltd | 1358 | 325 | Thermal | UO2 pellets | LEU |
| PWR-20 | Last Energy | 60 | 300 | Thermal | UO2 pellets | LEU |
| CMRS | Seaborg Technologies | 250 | 670 | Thermal | Molten salt | LEU |

## Back-end waste from SMR

The operating cycle of the SMR and HTR reactors, just like other types of reactors, is associated with the generation of radioactive waste, in particular spent nuclear fuel, which must be changed every few years. Large amounts of used fuel must be properly secured after removal from the reactor and must also be protected for storage and final disposal in deep storage facilities for a long time.

Much of the research on SMRs focuses almost exclusively on the technology and economics of these reactors, while very little attention is paid to the amount and characteristics of the nuclear waste that different types of SMRs will generate. However, it is important to understand how these new reactors may impact nuclear waste production rates and related nuclear waste management practices in the future. This work concerns the so-called “back-end” waste, i.e. wastes arising from the spent nuclear fuel (SNF), and decommissioning waste.

Conducting a reliable assessment of nuclear waste generated at nuclear power plants requires a wide range of information. They include: the fuel cycle type (once-through or recycling), reactor power level, thermal efficiency, design reactor lifetime and capacity factor, fuel type, the chemical form of the coolant, fuel burnup level, post-irradiation cooling time of discharged fuels, etc. Dimensions and materials of all reactor components and buildings, neutron spectrum, flux distribution, and the quantity and lifetime of structural materials near the active core are also needed to evaluate the activation levels and identify the nuclear waste classifications.

To investigate the waste characteristics of specific reactor technologies, a set of appropriate indicators must be selected for analysis and comparison. There is a wide range of potential waste metrics, and those relating to back-end waste include[3]:

* SNF mass (t/GWe-year) – The initial heavy metal mass of fuel discharged from the reactor and destined for geologic disposal;
* SNF activity at five points between 10 to 100,000 years after discharge (Ci/GWe-year) – A measure of the radioactivity of the fuel at various time after discharge, calculated by reactor and fuel specific irradiation conditions and isotopic content;
* SNF decay heat at 10 and 100 years after discharge (kW/GWe-year) – A derived metric from the SNF activity details;
* SNF ingestion radiotoxicity at 10,000 and 100,000 years after discharge (Sv/GWe-year) – A derived metric from the SNF activity details;
* SNF volume (m3/GWe-year) – The volume of the discharged fuel including structural components.

To assess the amount and characteristics of waste from various types of SMR reactors they can be compared with those of the large reference reactor, for example PWR. Such a comparative analysis is shown in Table 2 [3].To facilitate comparison across reactors of different sizes, all metrics are normalized per unit of electricity produced (waste per GWe-year).

TABLE 2. COMPARISON OF NUCLEAR WASTE METRIC VALUES FOR SELECTED NUCLEAR REACTORS [3]

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | PWR(reference) | VOYGR | Xe-100 |
| Power, MWe | 1175 | 77 | 80 |
| Thermal efficiency, % | 34 | 31 | 40 |
| Burnup, GWd/t | 50.0 | 49.5 | 169 |
| Uranium enrichment, % | 4.5 | 4.95 | 15.5 |
| Fuel form | UO2 | UO2 | TRISO |
| SNF mass, t/GWe-year | 21.7 | 23.9 | 5.41 |
| SNF volume, m3/GWe-year | 9.6 | 10.4 | 118 |
| SNF decay heat, kW/GWe-year* After 10 years
* After 100 years
 | 40.69.76 | 42.210.3 | 32.26.36 |
| SNF radiotoxicity, 108 Sv/GWe-year* After 10 000 years
* After 100 000 years
 | 1.210.086 | 1.270.091 | 0.410.041 |

As can be seen from the above table, the VOYGRTM generates 1.1 times the SNF mass and 1.1 times the SNF volume of the reference large PWR due to relatively lower burnup and thermal efficiency. VOYGRTM SNF has slightly higher activity, decay heat and radiotoxicity. When it comes to the Xe-100, the SNF mass and 100-year decay heat are lower by 75% and 35% respectively, again due to much higher burnup and higher thermal efficiency. Normalized activity is initially ~20% lower and continues to drop as the fission products decay. The SNF radiotoxicity is reduced by 66% at 10,000 years as plutonium and minor actinides are minimized. However, the SNF volume is higher by a factor of 12.3 due to the fuel design which includes large amounts of graphite moderator and non-fuel matrix/coating materials.

### Factors influencing the characteristics of SMR back-end waste

Although SMR developers tend to describe their waste production in terms of HLW or SNF mass and total radiotoxicity, repository design and postclosure safety analysis depend more on the solubility, environmental mobility, and sorption properties of specific radionuclides and the decay power or heat generation rate of the packaged wastes as well as the recriticality potential of the fissile materials that they contain. These parameters correlate to the waste stream radiochemistry and bulk chemical composition, which in turn, depend on the initial fuel composition and enrichment, discharge burnup, and in-core neutron energy spectrum, which are different for SMRs than for “large” PWRs [4].

An important issue affecting the characteristics of waste is neutron economy, specifically the loss of neutrons across the fuel boundary, which can activate structural materials that surround the fuel assemblies. The probability of neutron leakage is a function of the reactor dimensions and the neutron diffusion length, the latter of which is determined by the neutron scattering properties of the fuel, coolant, moderator, and structural materials in the reactor core [5]. The neutron diffusion length will be the same in reactors that use similar fuel cycles and fuel–coolant–moderator combinations; thus, the neutron leakage probability will be larger for an SMR than for a larger reactor of a similar type. For thermal-spectrum reactors, the neutrons undergo elastic scattering with the moderator. With a view that neutron diffusion lengths are short relative to the core dimensions, neutron leakage grows quadratically with decreasing core radius and reactor size. Small increases in neutron leakage have a substantial effect on core criticality and power output and will lead to reduced SNF burnup, unless compensated for by design changes to the reactor and/or fuel. It can be achieved by [4]:

* using a fuel enriched to >5 wt % initial 235U or 239Pu to increase the initial fissile loading and the probability of neutron absorption by a fissile element
* introducing a neutron reflector to redirect a fraction of leaked neutrons back into the core,
* foregoing a neutron moderator or using graphite rather than water.

Most of the SMR designs listed in the IAEA database [2] incorporate one or all these strategies to improve the core neutron economy. However, these changes affect the volume and composition of SNF and finally also with its geologic disposal.

## fuel cycle options

Methods of handling spent nuclear fuel discharged from the reactor are related to the implemented nuclear fuel cycle strategy. In this time, there are considered three main strategies of nuclear fuel cycle.

* the once-through fuel cycle, OTC called open fuel cycle.

The spent fuel after discharge from reactor is stored and then directly disposed in a deep geological repository (DGR).

* the twice-through cycle, TTC called partially closed fuel cycle.

The used fuel is reprocessed and uranium and plutonium are recovered and then recycled into mixed oxide fuel (MOX)

* the fully-closed cycle (FCC), in which spent fuel is reprocessed and fissile materials are usually recycled in a fast reactor (FR) multiple times to maximise the energy value of the fuel components, also referred to as plutonium multi-recycling.

The third strategy is not used anywhere but is under intensive studies. The main goal is to minimize the amount of minor actinides loaded into the DGR, thus the long-term hazard. In result, the time needed to decrease of the radiotoxicity of the HLW below the radiotoxicity level of the original uranium ore level (LOMBT) will be also much shorter. LOMBT of LWR SNF coming from the open fuel cycle is about 150 000 years. This waste consists of long-lived isotopes of U, Pu, MA, and FPs. The LOMBT of the spent fuel obtained from PBMR is lower than 50 000 years. This waste contain Am, Cm and FPs and that corresponds to a TCC cycle [6 ].

SMRs will also generate spent nuclear fuel that will require to be managed either in open or closed fuel cycles. The short-lived low level- and intermediate level waste (LLW and ILW, respectively) that are produced at each of the stages of the fuel cycle are acceptable for disposal in the near surface facilities.

According to the National Plan for the Management of Radioactive Waste and Spent Nuclear Fuel [7], accepted by the Polish Council of Ministers in December 2015 and notified to European Commission, it is recommended an open fuel cycle with the temporary storage of the spent fuel and with no further processing. It is justified both by the technical and economic reasons. However, global trends in this area will be constantly monitored and, if necessary and justified, appropriate changes will be introduced in the proposed solutions. The fuel cycle will be analyzed again after the first Polish nuclear power plant is launched. Though direct disposal relies to be the most reasoned option for the country just coming on nuclear way, conducting studies on the reprocessing seems important, given the economic and environmental determinants of the future and circular economy demanding the recovery of nuclear resources and decreasing significantly the volume of disposed waste.

Pursuant to the Atomic Law Act [8], the decision regarding the classification of spent fuel as waste or raw material for further processing will rest with the operator of nuclear power plants, who will have to cover the processing costs from his own funds. The NPP operator is responsible for the storage of spent nuclear fuel and must ensure the possibility of storing spent nuclear fuel from the entire period of operation of the nuclear power plant. After a cooling phase in the process pool, lasting approximately 3–5 years, the spent nuclear fuel is transported to a storage facility outside the reactor (dry or wet). In the case of Poland, it can be considered building one common storage facility for several power plants or several - for each power plant separately. After several dozen years of storage this fuel can be transferred to the storage.

The National Plan of Radioactive Waste and Spent Fuel Management (the National Plan), which adopts for the Polish law the Directive No 2011/70 of the Council of the European Union Community points out the need of work on the deep disposal for high-level waste. The issue of building the geological repository for spent nuclear fuel was also considered for the needs of the first nuclear program in Poland (Żarnowiec NPP). Then, a number of studies were carried out to select the location of the repository in the frames of the Strategic Government Program "Management of radioactive waste and spent nuclear fuel" implemented in 1997-1999. As a result of the work, 44 rock structures were identified in which the deep repository for spent nuclear fuel can be located. Amongst them, there are five localizations in the North-East part of Poland: clay deposit in Pogorzel and the magmatic formations in Krasnopol, Tajno, Kruszyniany and Rydzewo. Moreover, there were also found four other localizations in the Central and Western Poland: three in the salt deposits in Damasławek, Kłodawa, Łanięta and one in the clay deposit – Jarocin.

According to the National Plan, the construction of a deep repository should be preceded by intensive research carried out in an underground laboratory. Various concepts for the foundation of such a laboratory were envisaged as part of the Polish Underground Research Laboratory PURL initiative [8].

## SMR SNF: THE possibility of the reprocessing

 Management of spent nuclear fuel from SMR, HTR, and other reactors generally includes the following activities: characterization, conditioning, storage with the possibility of the selective recovery, storage and reprocessing, final disposal, or complete reprocessing. All these areas of activities must be thoroughly related to safety, radiological, and legal protection, and must be preceded by economic and technical analyzes of the entire fuel cycle with simultaneous information and acceptance by the public. Research and scientific organizations worldwide have accumulated vast experience in handling and repurposing spent nuclear fuel throughout the years. The management and recycling of spent nuclear fuel can be developed more efficiently through collaborative solving the problem and sharing practices.

Currently in Poland it is envisioned the implementation of SMRs operating mainly on uranium oxide fuel. Moreover, work on the HTGR reactor is carried out in parallel. While the reprocessing of spent oxide fuel used in water reactors is relatively well mastered, this process in the case of TRISO fuel still requires much research.

This does not mean, however, that research on the reprocessing of oxide fuel has been abandoned. The next steps in the reprocessing of spent nuclear fuel are its controlled dissolution in appropriate solutions of mineral acids, then cleaning and extraction of the main mass of uranium and plutonium, selective isolation of transuranium elements and fission products, including lanthanide fission products and corrosion products, using hydrometallurgical solvent extraction methods. Currently, the recovery of uranium and plutonium is carried out, for example, in the PUREX process (Plutonium - Uranium - Redox - EXtraction), which is a standard hydrometallurgical method for the recycling of spent nuclear fuel using tributyl phosphate in kerosene as an organic diluent. The PUREX process consists of several individual stages, such as: fuel dissolution, waste gas treatment, chemical separation, uranium and plutonium recovery, conversion of fission products and small amounts of actinide waste into a vitrified product [9, 10].

The use of the process of selective separation of long-lived actinides from spent nuclear fuel significantly influences the choice of storage method and shortens the storage time of nuclear waste. Therefore, for safety purposes and to simplify segregation and further storage of remaining waste, e.g. fission products, it is so important to eliminate long-lived and highly radioactive minor actinides.

The PUREX process and its complementary processes ( e.g.: DIAMEX, r-SANEX, 1c-SANEX, i-SANEX, and EXAm) used for recycling actinides from spent nuclear fuel constitute the so-called heterogeneous recycling of actinides, is been replaced by the Group ActiNide Extraction - GANEX process (in research) aimed at homogeneous recycling of actinides by extraction of transuranium elements, while ensuring full closure of the fuel cycle [11, 12]. All those complementary processes to PUREX are still at the research level and can be applied only for multirecycling of Pu and burning of MAs in appropriate reactors such as FRs (Fast Reactors) and FRs+ADS (Fast Reactors plus Accelerator-Driven Systems).

In order to choose appropriate recycling methods, it is necessary to follow global research in this field. In accordance with the guidelines contained in the National Plan, the task of Polish research teams is monitoring the progress of work on the implementation of technology enabling the separation of minor actinides and their use as fuel for fourth generation fast reactors or their nuclear transmutation in subcritical systems driven by accelerators. The international cooperation in the field of management of spent fuel and long-lived radioactive waste and consistent updating of knowledge about programs in this area can be helpful in making decisions about the choice of future fuel cycle for Polish reactors.

In our research we will also focus on a literature review concerning research, syntheses, characterization and description of existing knowledge regarding lanthanide and actinide complexes formed from N and O donor ligand used in liquid-liquid extraction processes for recycling metals from spent nuclear fuel from various types of reactors. Particularly important are the cognitive values related to the mechanisms of formation of lanthanide and actinide complexes with various ligands, as they will be used to explain the selectivity of individual extractants to the metals and the stability of metal compounds. This type of information is also required for the appropriate methodology to the design of a brand new extractants in future.

### The reprocessing of TRISO spent fuel

The unique features of TRi-structural ISOtropic particle (TRISO) fuel used in the HTGR reactors caused that they are very safe. As long as coating layers are not damaged, there will be no release of fission products from the TRISO particles. The tight TRISO coatings reduces the need for additional barriers. Moreover, this fuel is designed to reach very high burnup and to ensure a full detaining of any gaseous fission product in every case of reactor operation, under any normal and abnormal conditions. In the aim of the long storage of spent TRISO fuel is necessary to turn this fuel into a form suitable for long-term disposal. There are currently considered few methods of preparing to storage. One of them is the storage of a whole block of spent fuel. However, the storage of the entire graphite blocks of spent fuel is associated with the storage of the enormous volume of high-level waste that requires huge storage space and the need to ensure safety for a long time.

An optional solution is detachment of the particles of spent fuel from the graphite block. This conception has been studied in the United States and in France. In the beginning, the large blocks containing TRISO spent fuel were mechanically removed from the installations. It is necessary to notice that it was not observed the damage of the TRISO fuel coating. Then, the graphite-containing pellets were effectively separated using an electric field and directly moved to the aqueous solution in the reactor. The separation of the TRISO particles from the graphite matrix effects of great reduction of volume of the high-level waste intended for storage in a geological repository [13]. The graphite matrix can be finally disposed as a medium or low level-waste.

In the case of spent TRISO fuel, the kernel has to be liberated from the silicon carbide and pyrolytic carbon layers at first. It is the big challenge because of enormously hard and highly refractory coat of the TRISO fuel particle. Nevertheless, when the fuel kernels will be released from the silicon carbide and pyrolytic carbon layers, the well-known technologies that are used for LWR SNF may be used.

Various methods of release TRISO kernels from coatings has been examined. Among them there were mechanical methods like crushing and combustion, jet stream method, different mills have been also applied. Nowadays, the non-mechanical methods seem to be the most promising method for removal of the graphite and silicon carbide coatings of TRISO. The Summary of tested technologies for processing TRISO SNF and assigned TRL [14, 15] are presented in Table 3. TRLs runs from level 1 – basic technology research through to level 9 – system operated in the environment for which it was designed.

TABLE 3. SUMMARY OF TESTED TECHNOLOGIES FOR PROCESSING TRISO SNF.

|  |  |  |
| --- | --- | --- |
| Method used | The goal to achieve | Technology Readiness Level |
| Block and compact deconsolidation | Pyrolytic carbon breach | Silicon carbide breach |
| Combustion | - | × | - | 3 |
| Acid intercalation | × | - | - | 2 |
| Electrolytic Constant Current | × | - | - | 2 |
| Electrolytic – Pulsed Current | × | × | × | 2 |
| Thermal shock | × | × | × | 1 |
| Acoustical | - | × | × | 1 |
| Hot Chlorine Gas | - | × | × | 1 |
| Pyrometallurgical | - | × | × | 1 |

##  CONCLUSIONS

Currently, in Poland there is a great interest in the use of small modular reactors to reduce CO2 emissions from industry and energy. This growing interest implies the need to carry out a number of works and develop many procedures aimed at enabling the implementation of SMR technology in Polish conditions. The operating cycle of the small modular reactors, just like other types of reactors, is also associated with the generation of radioactive waste, in particular spent nuclear fuel. Great amounts of used fuel must be properly secured after removal from the reactor and must also be protected for storage and final disposal in deep storage facilities for a long time.

According to the National Plan for the Management of Radioactive Waste and Spent Nuclear Fuel, an open fuel cycle with the temporary storage of the spent fuel and with no further processing is recommended when implementing nuclear energy in Poland. Though direct disposal relies to be the most reasoned option for the country just coming on nuclear way, conducting studies on the reprocessing seems important, given the economic and environmental determinants of the future and circular economy demanding the recovery of nuclear resources and decreasing significantly the volume of disposed waste.

Regardless of the fuel cycle chosen, some challenges with the back-end of the fuel cycle will arise. In case of HTR the challenge may be both the management of large amounts of spent fuel, such as TRISO fuel, as well as its reprocessing hindered by the exceptional durability of the fuel pellets. In case of liquid fuel based on the molten salts the challenging can be appropriate processing methods of this reactive fuel, including its treatment, conditioning and packing, ensuring its safe geological disposal. The management of spent nuclear fuel seems to be relatively least problematic in the case of LWR SMR reactors. The range of burnup and fuel technologies used indicate that the fuel from these reactors should be susceptible to processing methods used in the case of SNF from traditional large Generation III+ nuclear reactors.

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