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MODERN LIGHT WATER NUCLEAR REACTORS OF GENERATION III+ AND SMALL MODULAR REACTORS: CHALLENGES AND SOLUTIONS IN THE FIELD OF NUCLEAR FUEL AND MANAGEMENT

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Abstract: This paper discusses light water cooled reactors (LWR) Generation III+ and small modular reactors (SMR) from the perspective of nuclear fuel characteristics and reactivity control systems. Technological advancements in reactor design have led to improved safety, efficiency, and reliability, particularly through the introduction of passive safety systems and optimization of fuel cycles. Special attention is given to the types of nuclear fuel used in new-generation reactors, including standard UO2 fuel, MOX (mixed oxide fuel composed of plutonium and natural or depleted uranium), and HALEU (high-assay low-enriched uranium with ^{235}U enrichment between 5% and 20%), along with an analysis of their technical advantages. The section on reactor management addresses the concepts of active and passive safety systems, as well as reactivity control strategies under normal and accident conditions. A comparative analysis of several leading reactor technologies (EPR, AP1000, VVER-1200, NuScale) provides insight into different technical solutions regarding safety systems and fuel cycle management. The paper concludes with an overview of key challenges and future perspectives, with a focus on safety aspects.

Keywords: LWR, Generation III+, SMR, nuclear fuel, burnable absorbers, nuclear safety

INTRODUCTION

In recent decades, nuclear energy has undergone continuous technological advancement aimed at achieving higher levels of safety, reliability, and economic viability. A significant step in this direction is the development of modern light water reactors (LWR) of Generation III+ (Gen III+) and small modular reactors (SMRs), which represent engineering responses to current energy and climate challenges. The technical solutions implemented in these systems include enhanced safety concepts through the extended use of passive safety systems, as well as more flexible approaches to nuclear fuel utilization.

This paper focuses on examining the solutions and challenges in the field of nuclear fuel and excess reactivity management in modern LWRs, including Gen III+ designs and SMR-type reactors. Special attention is given to the application of burnable absorbers and the regulation of boron concentration in the primary coolant, including concepts that eliminate the use of soluble boron (SBF - Solution Boron Free), in addition to technical solutions related to the selection and development of advanced nuclear fuel.

The paper analyzes four representative reactor technologies - EPR, VVER-1200, AP1000, and NuScale - in the context of their different approaches to reactivity control and safety enhancement, with an emphasis on their design philosophy and integration of fuel and safety features. The aim is to present the current state of technological development and identify future trends in the evolution of modern nuclear power systems.

1. KEY CHARACTERISTICS OF LWR REACTORS: GEN III+ AND SMR DESIGNS

The development of Gen III+ LWR reactors and SMR concepts has been accompanied by continuous improvement of design and safety solutions, aimed at achieving a higher level of nuclear safety, energy efficiency, and operational reliability. The technical features that define these systems include the implementation of passive safety systems, advanced materials and components, modernized control systems, and enhanced resilience to extreme events [1].

1.1. Generation III+ Reactor Designs

Gen III+ reactor designs have been developed to significantly reduce the probability of severe accidents

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by incorporating additional physical barriers, multiple independent safety systems, and the capability for passive removal of residual heat without reliance on external power sources. Technologies within this generation include:
EPR - a French-origin reactor featuring highly redundant active safety systems, designed with core melt retention capability and integrated passive hydrogen recombiners inside the containment structure [2];
AP1000 - a U.S.-designed reactor characterized by the predominant use of passive safety functions and a modular construction approach [3];
VVER-1200 - a Russian reactor design that combines active and passive safety systems, the use of advanced materials and components, and integrates hydrogen recombiners and a core catcher for molten core retention [4].

1.2. Small Modular Reactors (SMRs)

Small Modular Reactors (SMRs) represent an innovative approach to nuclear energy development, based on lower unit power, modular construction, and transport flexibility. This allows deployment in remote or infrastructure-limited areas, as well as integration into decentralized power systems. Although a significant number of SMR concepts are still in the development or licensing phase, the potential benefits of these designs include:

- lower initial capital investment and shorter construction time;
- high levels of inherent safety due to simplified systems and reduced plant power;
- potential for flexible integration into lower-capacity power grids.

The modular approach entails factory fabrication of components designed for efficient transport and on-site assembly, enabling reduced construction time and streamlined installation processes. The full potential of this concept can only be demonstrated through the implementation of a larger number of projects under real-world conditions. So far, the only SMR plant based on LWR technology in operation is a floating nuclear power plant equipped with two KLT-40S reactors, conceptually derived from those used in icebreakers. In China, commissioning is expected soon for the demonstration facility with the ACP100 (Linglong One) SMR, while in Russia, construction is underway for a new generation of barge-mounted plants featuring compact RITM-200 reactors.

One example of an SMR system based on LWR technology is the NuScale design, which integrates the reactor core, steam generator, pumps, and pressurizer into a single compact pressure vessel. This eliminates the need for external piping between major components and significantly reduces the risk of loss-of-coolant accidents (LOCA). Despite design progress and regulatory approvals in certain countries, construction of nuclear power plants based on this system has not yet begun.

In addition to the above-mentioned technical advantages, Gen III+ and SMR concepts are accompanied by specific challenges related to the use of new-generation fuels, integration of burnable absorbers, and different approaches to safety system design, all of which will be discussed in the following chapters.

2. NUCLEAR FUEL IN MODERN LWR REACTORS

In modern LWRs, the development objectives for nuclear fuel include increased efficiency, reduced waste volume, extended fuel cycles, and enhanced safety characteristics. The pursuit of long-term sustainability and reliability has led to the development of advanced fuel types that differ from standard UO_2 in composition, structure, and thermo-mechanical properties.

These reactors primarily utilize low-enriched uranium (LEU) with a ^{235}U content ranging between 3% and 5%, in the form of uranium dioxide (UO_2) fuel pellets. UO2 fuel is characterized by a high melting point, chemical and thermal stability, and resistance to radiation and high pressures, enabling safe operation under demanding thermohydraulic conditions. However, due to its relatively low thermal conductivity, modern designs aim to improve these properties through fuel material modifications.

To improve safety and long-term fuel performance, various concepts have been developed under the umbrella of accident-tolerant fuels (ATF). These include modifications to fuel pellets and cladding to improve mechanical resistance, enhance thermal conductivity, and reduce fission product release under normal, transient, and accident conditions. A prominent example within the ATF framework is ADOPT (Advanced Doped Pellet Technology) fuel, developed to increase reliability and extend the fuel cycle. By adding chromium oxide (Cr_2O_3) and aluminum oxide (Al_2O_3) to UO2 fuel, higher fissile material density is achieved, as well as reduced pellet-clad interaction (PCI) effects and lower fission product release during transients [5].

In parallel, fuel concepts with enhanced thermal conductivity are being investigated, notably CERMET (CERamic METal) fuels. These consist of UO_2 ceramic fuel dispersed in a highly conductive metallic matrix (e.g., molybdenum or chromium), comprising 5–10% of the pellet volume. This configuration provides improved thermal management, reduces internal temperature gradients, and increases safety margins under both normal and accident conditions. The metal phase also aids in retaining gaseous fission products, thereby improving overall fuel safety [5].

In addition to ATF developments, modern reactors are also exploring the use of fuel with higher enrichment, known as HALEU (High-Assay Low-Enriched Uranium), containing between 5% and 20% of ^{235}U (Figure 1). The use of HALEU enables the design of longer fuel cycles, increases core power density, and supports more compact reactor configurations, which is particularly important for SMR technologies. Over half of SMR concepts currently in development plan to use HALEU fuel. However, its broader adoption depends on establishing the necessary infrastructure for production, processing, transport, and regulated storage. Presently, only a limited number of countries, including Russia, China, and the United States (via pilot facilities), have the capacity for commercial-scale HALEU production. Introduction of this fuel requires new regulatory frameworks, specialized transportation containers, and significant investment in the supply chain, necessitating institutional support during the initial commercialization phase [6].

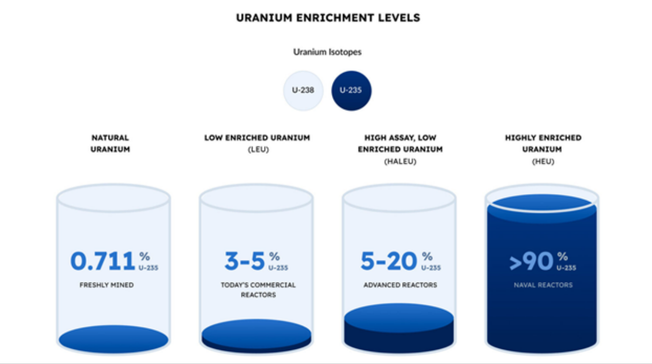

Figure 1: Uranium enrichment levels expressed as percentage of the ^{235}U isotope. Adapted from [7].

Another option is the use of fuel derived from reprocessed spent nuclear fuel-specifically MOX (Mixed Oxide) and REMIX (Regenerated Mixture) fuels. MOX fuel contains plutonium blended with either natural or depleted uranium and allows for a closed fuel cycle, reducing consumption of natural uranium and minimizing waste containing long-lived radionuclides. In some Generation II reactor configurations, MOX fuel is used in up to 30% of the core assemblies (in some cases up to 50%), while in Gen III+ reactors, the design allows for higher MOX fuel fractions, including full-core loading, provided adequate optimization of core neutronics and control systems is implemented. Such configurations are technically feasible and have been demonstrated in various studies and prototype analyses, but are not yet deployed as reference designs in current operations [8].

REMIX (Regenerated Mixture) fuel represents another innovative closed-cycle concept developed within the Russian nuclear program. It consists of a mixture of plutonium and uranium obtained through spent fuel reprocessing, without their separation, supplemented with newly enriched uranium. Unlike MOX, which uses plutonium mixed with depleted uranium, REMIX fuel can be reused in thermal reactors through multiple cycles-up to five times-with appropriate reprocessing between uses. Like MOX, REMIX enables a reduction in natural uranium consumption by about 20-30% per reuse cycle compared to an open fuel cycle [9].

Modern closed fuel cycle strategies also include concepts that combine thermal and fast reactors to maximize utilization of fissile material and minimize waste containing long-lived radionuclides. One such approach is the dual-component nuclear power system, wherein plutonium from spent nuclear fuel of thermal reactors is used to produce MOX or REMIX fuel for fast reactors (e.g., BN-1200). After use in fast reactors, the resulting spent fuel has a more favorable isotopic composition suitable for reuse in thermal reactors, thereby enabling a closed-cycle use of plutonium [10].

Figure 2 provides a schematic representation of material flows in a dual-component nuclear power system, enabling a closed fuel cycle through plutonium and uranium recycling between thermal and fast neutron reactors.

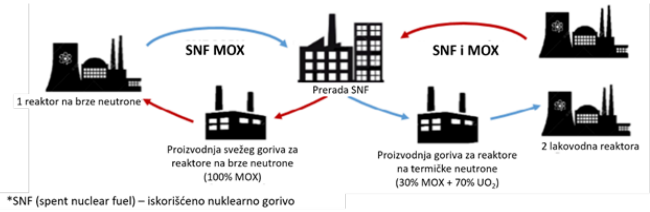

Figure 2: Structure of a dual-component nuclear energy system. Adapted and modified from [10], Fig. 1.

3. REACTIVITY MANAGEMENT USING BURNABLE ABSORBERS AND SOLUBLE BORON

The management of excess reactivity in nuclear reactors represents a key aspect of safe and efficient operation throughout the fuel cycle. Reactivity control is achieved through a combination of neutron-absorbing mechanisms, including variable concentrations of boric acid dissolved in the primary coolant, the positioning and effectiveness of control rods, and the application of burnable absorbers integrated within the fuel matrix. In fuels with higher enrichment levels, such as HALEU, the use of soluble boron requires particular caution due to its influence on reactivity temperature coefficients. Consequently, alternative strategies relying on integral burnable absorbers are increasingly investigated. For this reason, in Gen III+ reactors and SMR concepts, growing emphasis is placed on absorbers directly incorporated into the fuel structure or applied as coatings on fuel rod cladding.

In large-power reactors such as AP1000, EPR, and VVER-1200, reactivity management typically relies on a combination of soluble boron concentration control throughout the cycle and burnable absorbers for fine shaping of the reactivity distribution. The most commonly used burnable absorber is gadolinium oxide (Gd_2O_3), which is introduced either directly into fuel pellets or in the form of dedicated absorber rods within fuel assemblies, owing to its very high thermal neutron absorption cross section. A known limitation of gadolinium is its relatively rapid depletion, which necessitates careful optimization of its concentration and spatial distribution within the core.

In Western nuclear fuel development, current research is focused on improving Gd_2O_3 application technologies through advanced solutions, such as combinations with aluminum oxide additives and configurations in which gadolinium is placed in the interior region of UO_2 fuel pellets. These concepts provide more uniform absorber depletion, enabling extended fuel cycles and allowing core designs with lower initial soluble boron concentrations in the primary coolant. Further integration of higher Gd_2O_3 concentrations directly into the fuel matrix contributes to smoother reactivity evolution during the cycle and reduces reliance on control rod movements [11]. However, increased Gd_2O_3 content may adversely affect the thermal conductivity of the fuel, requiring a careful balance between effective reactivity control and acceptable thermal performance of the fuel matrix [12].

In certain reactor designs of Russian origin, erbium oxide (Er_2O_3) is applied as a burnable absorber, supported by several decades of operational experience in RBMK reactors [13]. Erbium is characterized by a more gradual depletion rate and more stable absorption behaviour, which enables a smoother reactivity profile and improved fuel utilization. Ongoing research investigates the application of Er_2O_3 in solution-boron-free (SBF) concepts, aiming to reduce dependence on soluble boron and simplify reactivity control systems.

In addition to oxide-based absorbers, more recent concepts also consider the application of ZrB2 (zirconium diboride), deposited as a coating on fuel rod cladding. This approach enables localized neutron absorption without altering the internal structure of the fuel matrix [14].

For AP1000, EPR, and VVER-1200 reactors, reactivity control strategies combine soluble boron regulation and burnable absorbers to ensure precise control during normal operation and transient conditions. In parallel, primary coolant pH control strategies are employed to maintain chemical stability and support neutron balance. In the VVER-1200 design, the use of hexagonal fuel assemblies further enhances neutron flux homogeneity within the reactor core.

Figure 3 illustrates the variation of the infinite multiplication factor (kinf) as a function of fuel burnup for different Gd_2O_3 concentrations, based on results reported in reference [15]. Higher Gd_2O_3 content significantly reduces initial excess reactivity, while the absorber effect gradually diminishes with burnup due to gadolinium depletion. Increased Gd_2O_3 concentrations also influence the overall reactivity evolution during the cycle, including lower end-of-cycle multiplication factors.

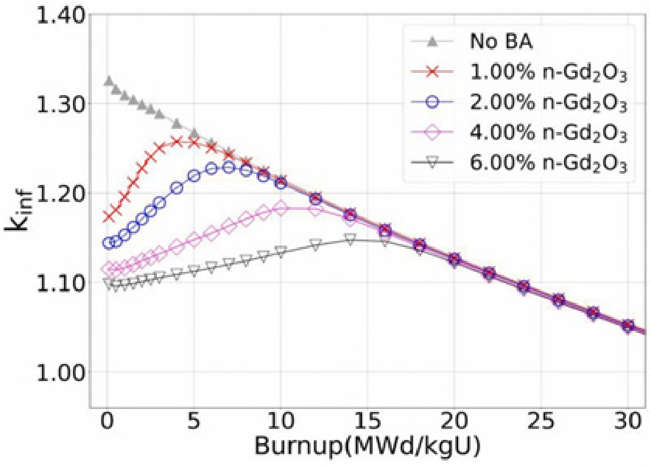

Figure 3: Variation of the multiplication factor as a function of burnup for fuel elements with different mass fractions of gadolinium oxide (Gd_2O_3) burnable absorbers and without burnable absorbers (No BA). Reproduced from [15], Fig. 1.

By comparison, data related to Er_2O_3 application indicate a more moderate reduction of initial reactivity and a smoother evolution over the entire fuel cycle. Due to its slower depletion and reduced absorption oscillations, erbium enables a more stable distribution of reactivity and temperature, contributing to more uniform reactor operation and potentially improved fuel utilization [16].

In certain SMR concepts, such as NuScale, a complete elimination of soluble boron from the primary coolant, referred to as the solution-boron-free (SBF) approach, is under consideration [17]. In this case, reactivity control relies exclusively on burnable absorbers and control rods. This approach reduces dependence on boron-related systems, simplifies chemical control, and contributes to more stable core behaviour. In addition, the generation of radioactive waste associated with soluble boron removal during the cycle is eliminated.

Figure 4 presents the evolution of the effective multiplication factor (keff) during the fuel cycle for two SBF SMR core concepts: one employing burnable absorbers (a combination of Gd_2O_3 and B_4C) and another without burnable absorbers. As shown in reference [18], the application of burnable absorbers effectively suppresses excess reactivity at the beginning of the cycle, maintaining the multiplication factor close to critical throughout operation, albeit with a slightly earlier transition to subcriticality compared to the reference core. These results demonstrate the suitability of burnable absorbers in boron-free SMR designs for stabilizing neutron behaviour and simplifying reactivity management during operation.

The SBF approach requires precise spatial distribution of burnable absorbers and appropriately designed control rods, while ensuring a negative temperature coefficient of reactivity throughout the entire cycle. Detailed fuel

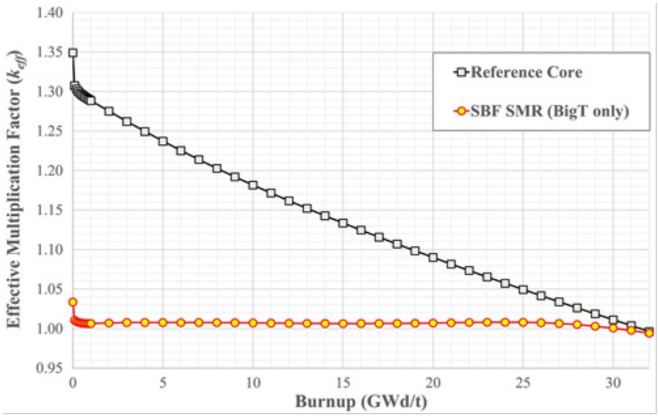

Figure 4: Comparison of multiplication factor evolution during the fuel cycle for two solution-boron-free SMR core concepts: one employing burnable absorbers (Gd_2O_3 and B4C - BigT only) and one without burnable absorbers (Reference Core). Reproduced from [18], Fig. 4.

depletion modelling and analysis of its impact on core neutron parameters are necessary to meet safety criteria under normal, transient, and accident conditions.

Regardless of the use of soluble boron, all modern reactor designs must ensure sustainable excess reactivity control, adequate safety margins, and extended fuel cycles. The selection of burnable absorber type, chemical form, spatial arrangement, and interaction with other core parameters must be consistent with the neutron characteristics and anticipated operating conditions. Current research directions also include the development of composite fuel forms, such as UO2 mixed with uranium diboride (UB2), which combine the function of burnable absorbers with improved thermal properties of the fuel [12].

4. SAFETY APPROACHES AND FUEL SOLUTIONS

Among contemporary Gen III+ reactors and SMR concepts, the EPR, AP1000, VVER-1200 and NuScale technologies represent different conceptual approaches to the design of safety systems and fuel solutions, aimed at increasing reliability, resistance to accident conditions, and efficiency in fuel utilization.

With regard to safety systems, EPR reactors rely predominantly on active safety systems, featuring multiple physically separated and functionally redundant safety trains for coolant injection, reactivity control, and removal of residual heat. Such redundancy, combined with additional protection levels such as a core melt retention system and passive autocatalytic hydrogen recombiners within the containment, provides a high degree of protection even in severe accident scenarios. Owing to the large number of active and independent systems, the EPR design requires careful engineering integration during the design and construction phases, as well as detailed planning of power supply and control infrastructure. The complexity of this approach is the result of an explicit design philosophy aimed at ensuring multiple layers of protection through functionally and physically separated safety mechanisms [19].

The VVER-1200 concept combines active and passive safety systems. In addition to multiple active safety trains for control and cooling, passive systems for residual heat removal are implemented, including heat exchangers located outside the reactor building and cooled by natural air circulation, as well as water tanks pressurized by inert gas and gravity-driven water injection systems based on elevation differences relative to the reactor vessel. Safety is further enhanced by the installation of a core catcher and passive hydrogen recombiners, which reduce the risk of forming explosive hydrogen concentrations within the containment-features shared with the EPR design [20].

The AP1000 represents a technology predominantly based on the use of passive safety systems under accident conditions. In the event of a complete loss of power supply or system depressurization, natural circulation, gravity, and condensation processes ensure removal of residual heat from the core and cooling of the containment without the need for electrical power or operator intervention for a minimum duration of 72 hours [20]. The spatial integration of these systems and the reduced number of active components contribute to a lower probability of component failure and simplified maintenance requirements [21].

In the NuScale SMR design, the lower reactor power enables the application of passive safety systems under both normal and accident conditions. Owing to the integral configuration, with all primary system components housed within a single compact vessel, the possibility of large-break LOCA events is effectively eliminated. Passive residual heat removal systems, such as the Decay Heat Removal System (DHRS) and the Emergency Core Cooling System (ECCS), ensure system stability without external power supply or operator intervention for periods exceeding 30 days. Additional advantages include the compact modular design, underground installation, and low thermal power per module, which enable deployment in infrastructure-limited regions [22].

In terms of fuel, all considered technologies employ low-enriched uranium (LEU) fuel with enrichment levels up to 5% ^{235}U. To improve fissile material utilization and reduce the quantity of radioactive waste, Gen III+ reactors have demonstrated the capability to accommodate higher fractions of MOX fuel compared to previous generations, as well as REMIX fuel, which allows multiple recycling cycles of uranium and plutonium recovered from spent fuel. For advanced systems, particularly within the SMR framework, the use of HALEU fuel is foreseen, enabling longer fuel cycles, increased core power density, and reduced specific waste generation per unit of produced energy. In parallel, fuel concepts tolerant to accident conditions (Accident-Tolerant Fuels, ATF), such as ADOPT and CERMET, are being developed to achieve improved thermal conductivity, enhanced structural stability, and reduced fission product release under accident conditions. A comparison of the analyzed solutions indicates that there is no uniform approach to the selection of safety systems and nuclear fuel solutions. EPR reactors emphasize extensive redundancy of active safety systems; the VVER-1200 employs a combination of active and passive systems; the AP1000 relies on passive systems under accident conditions; while SMR concepts such as NuScale rely on passive systems across all operational regimes. In the fuel domain, while conventional LEU remains the standard, emerging strategies include the use of MOX and REMIX fuels to support closed fuel cycle concepts, as well as the prospective deployment of HALEU and ATF concepts to enhance both economic performance and operational safety. The core damage frequency (CDF) for Gen III+ reactors is on the order of 10-6 to 10-7 per reactor-year, representing a reduction of two orders of magnitude compared to Generation II reactors, whereas for SMR technologies it is projected to be on the order of 10-8 or lower, indicating significant progress in risk reduction and technical advancement.

To provide a concise overview of the key differences and distinctive characteristics of the analyzed technologies, Table I presents a summary of selected technical parameters related to fuel type, reactivity management strategies, and the application of passive and active safety systems for the EPR, AP1000, VVER-1200, and NuScale reactors.

5. CONCLUSION

The Gen III+ and SMR nuclear power technologies examined in this paper demonstrate a high level of alignment with post-Fukushima safety requirements, alongside continuous advancements in fuel management strategies aimed at improving the long-term sustainability of nuclear energy. The observed differences in technical approaches - ranging from highly redundant, predominantly active safety systems in the EPR design, through combined active and passive safety solutions in the VVER-1200, to largely passive safety concepts implemented in the AP1000 and NuScale - illustrate the breadth of engineering options available for tailoring reactor safety architectures to specific design philosophies and regulatory environments.

From the perspective of reactivity management, the use of burnable absorbers such as gadolinium and erbium, together with optimized control rod arrangements and management of soluble boron concentration in the primary coolant, enables effective control of excess reactivity throughout the fuel cycle. In this context, concepts such as the SBF approach, which eliminates reliance on dissolved boric acid, are particularly attractive for SMR applications, offering the potential for simplified plant operation, improved neutron economy, and a reduction in secondary radioactive waste streams.

The demonstrated technical maturity of these solutions, along with their flexibility with respect to grid integration and site-specific constraints, makes them relevant not only for established nuclear programs but also for countries that are in the early stages of developing nuclear infrastructure. Accordingly, further investigations addressing the influence of reactor design choices on operational economics, as well as long-term evaluations of advanced fuel cycle strategies, represent essential elements for informed planning and the sustainable deployment of future nuclear energy systems.

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Table I: Selected technological parameters of EPR, AP1000, VVER-1200 and NuScale reactors

Parameter	EPR	VVER-1200	AP1000	NuScale (SMR)
Fuel	LEU / MOX (up to 50%) - optional	LEU / MOX optional / REMIX under development	LEU / MOX (up to 50%) - optional	LEU / HALEU under consideration
Burnable absorber	Gd_2O_3 (in fuel rods)	Gd_2O_3 / Er_2O_3 under testing	ZrB_2	Gd_2O_3 (in fuel pellets)
Presence of soluble boron in the coolant	Yes	Yes	Yes	Yes, SBF concept under investigation
Application of passive safety systems	Limited; predominantly active systems	Combination of passive and active systems	Passive system for accident conditions	Fully passive (normal and accident conditions)

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BIOGRAPHY

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