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Small modular reactors: Simpler, safer, cheaper?

Jasmina Vujić [a], Ryan M. Bergmann [a,*], Radek Škoda [b], Marija Miletić [c]

[a] University of California, Berkeley, CA, USA
[b] Texas A&M University, College Station, TX, USA
[c] The Czech Technical University, Prague, Czech Republic

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ABSTRACT

Nuclear energy can play a very significant long-term role for meeting the world's increasing energy demands, while simultaneously addressing challenges associated with global climate and environmental impact. Many nations of the world, particularly the Asia/Pacific Rim countries, are actively engaged in a major expansion of their nuclear energy complex. The degree to which nuclear energy can address long-term energy needs, either globally or regionally, will be dictated by the pace and adequacy of technical and policy solutions for waste, safety, security, and non-proliferation issues, as well as the capital cost of construction. Small Modular Reactors (SMRs) could successfully address several of these issues. SMRs offer simpler, standardized, and safer modular design by being factory built, requiring smaller initial capital investment, and having shorter construction times. The SMRs could be small enough to be transportable, could be used in isolated locations without advanced infrastructure and without power grid, or could be clustered in a single site to provide a multi-module, large capacity power plant. This paper summarizes some of the basic features of SMRs for early deployment, several advanced SMR concepts, and points out the benefits and challenges in regulatory, economical, safety and security issues.

1. Introduction

For efficient economic and social development, prosperity, health, education, and security of a people, a basic necessity is access to affordable energy. In addition to food and water, electricity in particular is a major factor in quality of life. In the last decade, the world population has increased by more than 12% and is expected to rise from todays 6.8 billion to 9 billion people by 2050. At the same time, with the population growth, the primary energy consumption has increased by 20%, and electricity consumption has increased by 31.5% [1]. Electricity demand in the world is projected to grow at an annual rate of 2.5% until 2030 [1]. Global population growth in combination with rapid industrial development might lead to a doubling of electricity consumption by 2030. In order to meet these demands, many countries have been developing diverse energy strategies, including many non-fossil based energy sources in their mix. The objective of this paper is to point out that the SMRs with powers smaller than 300 MWe could be an appropriate option for the energy demands in many countries. The figures and specifications presented have not been re-evaluated in the paper, they are taken at face value from the referenced authors.

The development of small reactors began in the early 1950s for naval propulsion (as power sources for nuclear submarines). Over the years, several countries have been continuously working on the development of SMRs. The following table lists some of the current SMR designs [2,3] that could be broadly classified as integral PWRs, marine derivative PWRs, BWRs/PHWRs, gas-cooled, lead and lead–bismuth cooled, sodium-cooled, and various non-conventional designs (Table 1).

Another possible classification subdivides SMRs into two broad groups those for early deployment based on a proven light water reactor (LWR) technology, and those for longer-term deployment, based on other, more advanced designs.

In this paper, emphasis is placed on assessing the technical viability of recent design concepts, including further research that might be required for successful development. As far as the licensing and regulatory issues are concerned, the most important aspects of the SMRs assessment are reactor safety (including seismic safety), radiation protection, and power plant security. Since the SMR design concepts are outside of the traditional nuclear regulatory body experience, work has begun to address these issues in advance in order to simplify licensing procedure and reduce

* Corresponding author.
E-mail addresses: vujic@nuc.berkeley.edu (J. Vujić), rmb@berkeley.edu (R.M. Bergmann), rskoda@ne.tamu.edu (R. Škoda), miletmar@fjfi.cvut.cz (M. Miletić).

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Table 1
Current SMR designs.

	US	Russia	Japan	France	India	S. Korea	Argentina	China	Italy
Integral PWR	IRIS NuScale mPower		IMR	SCOR		SMART	CAREM		
Marine derivative PWR		ABV KLT-40S VBER-300 VBER-150		NP-300					
BWR/PHWR		VKR-MT	CCR		AHWR				MARS
Gas-cooled	GT-MHR	BGR-300	GT-HTG-300					HTR-PM	
Lead/Pb–Bi cooled	ENHS STAR/SST AR	BREST SVBR-100 SVBR-75	LSPR						
Sodium-cooled	PRISM ARC-100	BN-GT-300	4S RAPID			KALIMER			
Non-conventional	AHTR Hyperion TWR	MARS	MSR-FUJI		CHTR				

licensing time. The following must be addressed when applying for design license: implementation of defense-in-depth, use of probabilistic risk assessment, key component and system design technical issues (redundancy, accident selection, containment, etc.), security and safety requirements, feasibility of the projects, financial and economic issues, and competitiveness, etc.

SMRs small size could be beneficial in providing electric power to remote areas that are deficient in transmission and distribution infrastructures, but they could be also used to generate local power for larger population centers. Small reactors are ideal for providing the electricity to countries with small, limited, or distributed electricity grid system as well as for countries with limited financial resources for investment in large nuclear power plants. Most of the proposed designs offer combined electricity and process heat for industrial complexes, water desalination, and district heating. Overall, we can point out the following advantages of SMRs: (1) Power generating systems for areas difficult to access or without infrastructure for transportation of fuel; (2) Modular concept that reduces the amount of work on-site, makes it simpler and faster to construct; (3) Long-life cycle and reduced need for refueling (perhaps every 10–15 years); (4) Design simplicity; (5) Passive safety; (6) Expanded potential siting options since more sites are suitable for SMRs; (7) Smaller nuclear island and footprint of the whole nuclear power plant; (8) Low operation and maintenance costs; (9) Lower initial costs and risks; and (10) Proliferation resistance.

However, the following disadvantages of SMRs must be overcome if the SMRs are to be deployable in the near future: (1) Economics of SMRs needs more analysis in order to show possible advantages over large LWRs; (2) Spent nuclear fuel from small reactors could be located in remote areas which will make its transport more difficult. Also, spent fuel will be spread across many more sites while currently it is congregated at a limited number of locations; (3) Public acceptance of new concepts; and (4) Obtaining design certification and licensing may take longer than expected.

This paper summarizes the most important issues associated with the development, deployment and competitiveness of the small modular reactors (SMRs), and discusses the type of solutions the SMRs could provide for radioactive waste, safety, security, and non-proliferation issues. The issue of the initial capital investment, economy of scale and overall cost of construction will also be discussed. Most of the materials presented in this paper are based on the presentations at the 4th Asia-Pacific Forum on Nuclear Technology: Small and Medium Reactors, which was held at the University of California at Berkeley from June 17–19, 2010 and organized by the Berkeley Nuclear Research Center [18].

2. Small modular reactor designs

There are three major groups of small modular reactor designs which are actively being developed in the USA, Japan, China, Korea, Russia, France, and other countries. The first group of SMRs is based on the design concepts of proven and widely utilized light water reactors, namely Pressurized Water Reactors (PWRs). The second group consists of gas-cooled SMRs. The third group of SMRs that will be included in this paper are advanced SMRs that are cooled either by liquid metal or liquid salt. The SMR design concepts that belong to the third group are expected to be the most difficult to license, since there is not much experience in operating such reactors or available test facilities for verifying new designs.

2.1. Light water concept

International Reactor Innovative and Secure (IRIS) is a 335 MWe reactor in conceptual design stage which will use conventional pressurized light water with 5% enriched fuel rods in 17×17 bundles (see Fig. 1). Even though it is based on light water reactor design, this concept has integral reactor vessel (which means that the steam generators will be inside the reactor vessel) and some smaller designs offer natural circulation versus typical active circulation by convection in PWRs. The probabilities of steam line breaks and steam generator rupture accidents are minimized by having the steam generator operate at the same design pressure and temperature as the reactor vessel [4]. The integral design also eliminates the need for large piping between the pressure vessel and the steam generators, greatly reducing the demands on the containment structure. Therefore, IRIS would have a much smaller plant footprint even though the pressure vessel itself is bigger than the pressure vessels traditional PWRs. IRIS also features natural circulation emergency cooling systems and gravity-fed water injection systems [23] (Fig. 1).

The small Russian reactor KLT-40 (Russian acronym) is a similar concept to IRIS, but is mainly based on the nuclear steam supply system used in Russian icebreakers. It is a small portable PWR system, representing a floating nuclear power plant intended mainly for electric power generation, but could be also used for desalination or heat production [8]. In all emergency modes, this

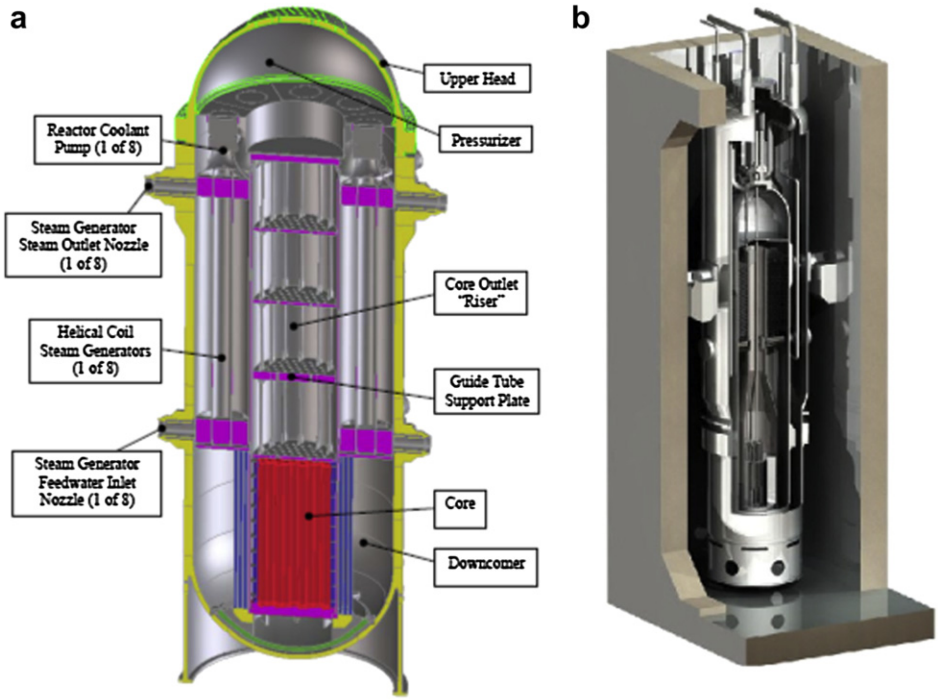

Fig. 1. 335 MWe Westinghouse IRIS [29] and NuScale concepts [30].

reactor relies on natural convection even though it is normally cooled by forced circulation. A major challenge is the reliability of steam generators and associated equipment, which is much less accessible when inside the reactor pressure vessel. A smaller version of this reactor, KLT-20, is a two-loop modification of the KLT-40S, and is designed to have a refueling interval of 8 years and no on-site refueling [21]. The longer refueling interval is achieved by using the uranium enrichment of less than 20 weight percent (Fig. 2a shows MRX, a similar sized Japanese marine propulsion PWR design) [7,21].

The VBER-150 (another Russian acronym) is a 110 MWe Russian reactor which is a two-loop version of the VBER-300 reactor with a 6-year refueling interval and a modular design. The reactor pressure vessel, two once-through steam generators, and two main

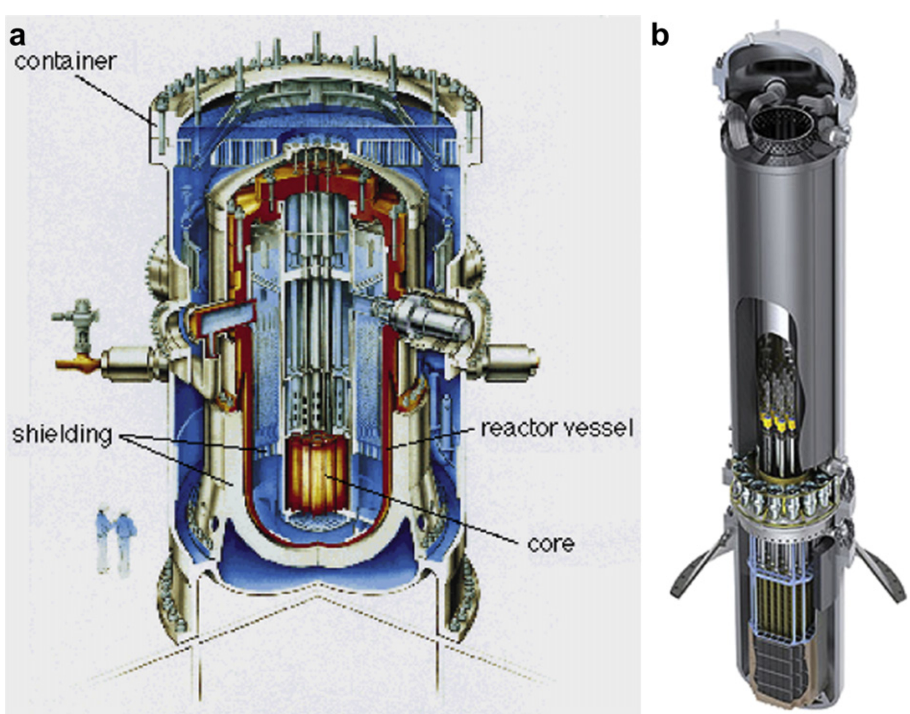

Fig. 2. Marine reactor MRX (100 MWt) and mPower reactor [10].

circulating pumps are integrated into a single vessel system by short welded coaxial coolant pipes. Both VBER-300 and VBER-150 are based on decades-long operating experience of Russian marine propulsion reactors, and are designed for a floating (barge-mounted)-type of Nuclear Power Plant (NPP) [3,22].

The NuScale Power Reactor is a 45 MWe reactor based on a PWR design. A 540 MWe power plant could be comprised of 12 independent 45 MWe modules, each with its own dedicated steam generator. This innovative design has been developed initially through the US DOE funds at Oregon State University, where a world class integral system test facility called APEX was also built [11]. This design is similar to IRIS, but has natural circulation. Also, new design enhances safety and security since it is positioned below the ground.

NuScale is an integrated module, factory manufactured, transportable by rail, truck or barge, with dimensions of 15 m by 4.5 m, and the weight of 400 tons. It also has a robust seismic design, with its structure composed almost entirely out of concrete, with well arranged shear walls and diaphragms which provide high rigidity, it is mostly below grade, partially supported by bedrock, and it also has large pools filled with water that help dampen seismic forces. An application for US design certification is expected in 2014 and there are hopes for a first operating unit in 2020 [11].

The Babcock & Wilcox designed mPower reactor (see Fig. 2b) is similar to NuScale and IRIS in that it is a small, rail-transportable, conventionally-fueled, integral PWR design, but it has a slightly higher power of 125 MWe. Multiple units can be built at one site to increase the installed capacity. mPower has a slightly more advanced construction schedule than NuScale, as its licensing process is expected to be started in late 2012 [9].

Integral primary system configuration in these reactors enhances their robustness by eliminating major classes of accidents, such as large pipe break. In addition, it simplifies design by eliminating unneeded safety systems, large piping and external vessel, allowing for compact containment and small plant footprint, thus enhancing economics and security. However, having many components integrated into the reactor vessel could also make maintenance more difficult should one of them fail.

2.2. High-temperature gas-cooled reactors

The GT-MHR (Gas Turbine Modular Helium Reactor) by General Atomics is a 285 MWe reactor, which will be built as modules of up to 600 MWt. The annular core consists of 102 hexagonal fuel element columns in graphite blocks with channels for helium coolant and control rods. Graphite reflector blocks are both inside and around the core. HTRs can potentially use thorium-based fuels, such as highly enriched uranium (HEU) with thorium, uranium-233 with thorium, and plutonium with thorium. Areva is working on a version of this reactor called ANTARES (A New Technology Advanced Reactor Energy System), a 285 MWe (600 MWt) prismatic helium cooled design. ANTARES has the same characteristics as GT-MHR, but uses indirect-cycle gas and steam-turbines using intermediate heat exchangers. A smaller version of the GT-MHR, the 10–25 MWe Remote-Site Modular Helium Reactor (RS-MHR), has been proposed by General Atomics. The RS-MHR, presented in Fig. 3, uses uranium oxide fuel contained in very small spherical particles approximately 1 mm in diameter and would have a refueling interval of 6–8 years [9].

Since graphite reacts with oxygen, one of the vulnerabilities for gas-cooled, graphite-moderated reactors is a possible entry of air or water into the primary coolant system. The only time such air entry causes a significant problem for a graphite reactor is if sufficient natural circulation flow of air through the reactor core can occur. The RS-MHR minimizes this probability by locating the coaxial coolant pipe below the level of the reactor core. Establishing air flow by natural circulation through the core following breakage of this pipe would be difficult, thus increasing the level of safety.

The Pebble Bed Modular Reactor (PBMR) is under development by PBMR (Pty.) Ltd. It is a 165 MWe reactor cooled by helium and moderated by graphite, with a core consisting of a half million fuel pebbles. Each pebble consists of 12,000 microspheres (fuel kernels) composed of low-enriched (9%) uranium dioxide (UO_2) coated with a fission-product-retaining tri-structural isotropic (TRISO) coating. This reactor is designed to operate for up to 30 years without refueling. This type of reactor is also considered with gas turbine (i.e. direct cycle) which will significantly reduce the number of components and the overall size of the plant. This model is limited by the requirements for passive safety. The design requires that the decay heat could be removed without any active cooling system below 1600 °C since above this temperature the ceramic coating of the fuel particles does not provide adequate barrier for fission products. The largest development uncertainty is the unique power conversion systems being purposed for PBMR and GT-MHR. Both concepts use direct cycle helium turbines to drive vertically-oriented generators

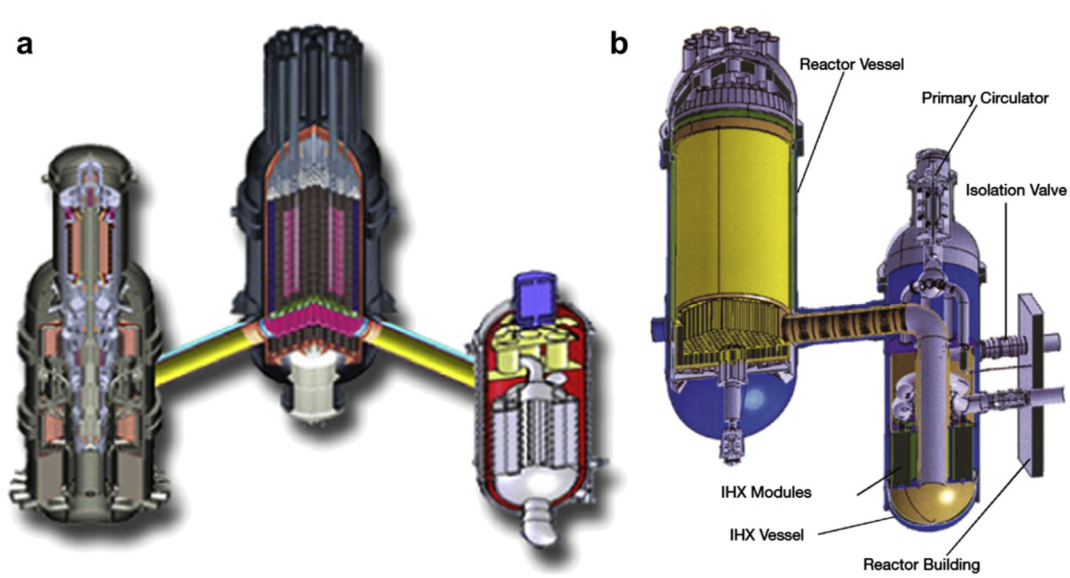

Fig. 3. GT-MHR (General Atomics) [28] and ANTARES (Areva) [27].

with magnetic bearings. No commercial experience exists with vertically-oriented turbo-generators or helium/water and helium/helium heat exchangers, so they will need to be tested.

2.3. Liquid metal-cooled reactors

2.3.1. Lead alloy as a coolant in small reactors

Several countries have been developing small Lead/Pb–Bi reactors, including Russia, U.S, Germany, Sweden, Italy, Japan and S. Korea. Among the newer Russian designs is the 75–100 MWe Lead–Bismuth Fast Reactor (SVBR) which draws heavily on Russian submarine reactor experience [22]. This is an integral design, with the steam generators sitting in the same 400–480 °C Pb–Bi pool as the reactor core. It is designed to be able to use a wide variety of fuels: The reference model uses uranium oxide enriched to 16.5%, but MOX, uranium nitride, and uranium-plutonium fuels are also considered [12]. The unit would be factory-made and shipped as module, then installed in a tank of water which gives passive heat removal and shielding. A power station with 16 such modules is expected to supply electricity at lower cost than any other new Russian technology as well as achieving inherent safety and high proliferation resistance. SVBR units could also be built on a floating dock, making unit replacement by sea very easy when the units have surpassed their lifetime. Building on docks also allows the reactors to provide energy to areas where access by land is limited or too rugged to build on [22]. In mid-2008 Rosatom and Russkiye Mashiny put together a joint venture to build a civilian SVBR-100 reactor. The plan is to complete the design development by 2017 and put on line a 100 MWe pilot facility by 2020, with total investment by Russkiye Mashiny of RUB 16 billion ($585 million) [9]. During the developing of this prototype, certain problems were solved in order to master the lead–bismuth cooled reactors. Some of these milestones were: achieving corrosion resistance of structural materials, controlling the mass transfer processes, and assuring radiation safety during operation (polonium 210). This reactor could be the first one cooled by heavy metal to generate electricity.

Since mid-1990s, various research projects were initiated to identify highly proliferation-resistant reactor concepts that will have simplified designs and user-friendly operations. One gave birth to STAR (Secure, Transportable, Autonomous Reactor). Several STAR concepts were developed, including STAR-LW, STAR-LM, ENHS, and the most recently, SSTAR (which was selected as the U.S. concept for the Generation IV LFR category of advanced reactors) [13]. The ENHS (Encapsulated Nuclear Heat Source) reactor is in a pre-conceptual design phase. Presented in Fig. 4, it is a liquid metal-cooled reactor that can use either lead (Pb) or a lead–bismuth (Pb–Bi) alloy as coolant. The lead-based coolants are chemically inert with air and water, have higher boiling temperatures, and better heat transfer characteristics for natural circulation [13]. The fuel is loaded into the module in the factory and it can operate on full power for 15 years without refueling and fuel re-shuffling. The ENHS fuel is a metallic alloy of uranium and zirconium (U–Zr, enriched to 13%) or optionally uranium, plutonium or TRU, and zirconium (U–Pu–Zr; U–TRU–Zr), and exhibits good stability under irradiation. The core is surrounded by six groups of segmented tungsten reflectors [8]. The total weight of an ENHS module when fueled and when loaded with coolant to the upper core level is estimated to be 300 tons, which could pose a shipping challenge, especially to remote areas. The module height is dictated by the requirement of natural circulation. The advantages of this design are: sealed core no on-site refueling, transportability (entire core and reactor vessel remain as a unit), long-life core 30 year core life is a target, autonomous controls minimum operator intervention is required, local and remote observability, minimum industrial infrastructure required at host location, and very small operational (and security) footprint [13]. The Small STAR (SSTAR) is a small natural circulation fast reactor of 20 MWe/45 MWt, that can be scaled up to 180 MWe/400 MWt. SSTAR shares many of advanced of the ENHS reactor, including use of lead as coolant, and a long-life sealed core in a small, modular system. The SSTAR fuel consists of transuranic nitride, enriched in N-15, with five radial zones with enrichment of 1.5/3.5/17.2/19.0 and 20.7%. Core lifetime is 30 years with average burnup of 81 and the peak burnup of 131 MWd/kgHM. The coolant circulation is by natural convention, with core inlet temperature of 420 °C and the core outlet temperature of 567 °C. The core height is 0.976 m, and the core diameter is 1.22 m. For the power conversion, a supercritical CO_2 Brayton cycle is used. Overall, the STAR concept (ENHS and SSTAR) has a robust design, excellent safety potential, and proliferation resistance as well as good economical performance.

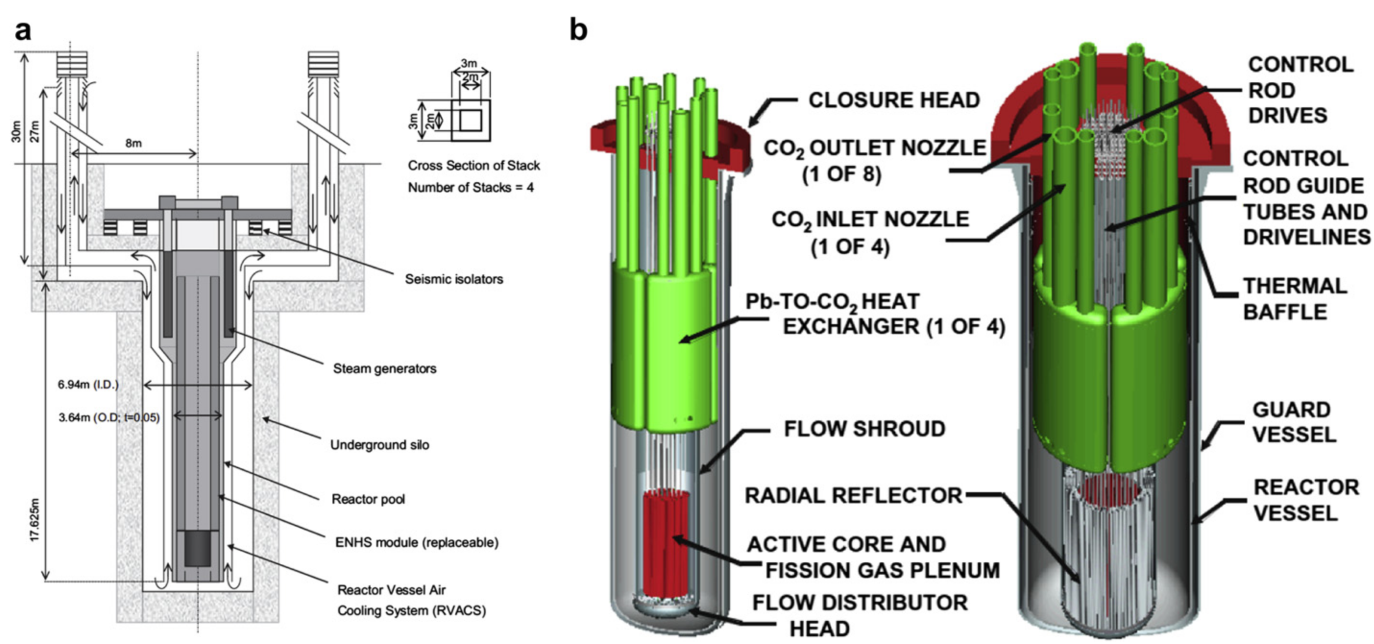

Fig. 4. Vertical cross sections of ENHS [24] and SSTAR [25].

2.3.2. Sodium as a coolant in small reactors

The 4S (Super-Safe, Small and Simple) reactor by Toshiba is a fast reactor design fueled with enriched uranium or plutonium and cooled by sodium. The fuel is metallic uranium-zirconium (169 pins 10 mm diameter) enriched to less than 20% or U–Pu–Zr alloy with 24% Pu for the 10 MWe (30 MWt) version or 11.5% Pu for the 50 MWe (135 MWt) version [9]. Refueling in these two cases will be 30 and 10 years, respectively. Steady power output over the core lifetime is achieved by moving a single reflector (safety element) upwards around the core at about 1 mm per week (see Fig. 5). After 14 years, a neutron absorber at the center of the core is removed and the reflector repeats its slow movement up the core for 16 more years. Also, by moving the reflectors the reactivity in the core is controlled. Severe accidents are eliminated by design: all the primary coolant is inside the reactor vessel, reactor coolant is at almost atmospheric pressure, and reactor vessel is inside a silo so core cannot be uncovered. Design performance is limited by the requirement to have a long-life core that has a negative void coefficient of reactivity.

In 2010, Advanced Reactor Concepts (ARC), LLC launched ARC-100, a 100 MWe sodium-cooled, fast-neutron-spectrum reactor that uses a novel U/Zr metal alloy fuel, with a refueling interval of 20 years (with average burnup of 80.6 MWd/tonne) and no on-site fuel storage [16]. The reactor system is comprised of a small uranium-fueled nuclear core submerged in a tank of ambient pressure liquid sodium. The liquid sodium is passed through the core where it is heated to 950 °F (510 °C), then passed through a heat exchanger where it heats sodium in an intermediate loop, which in turn heats a working fluid for energy conversion turbines. The working fluid can be water or carbon dioxide. The ARC-100 reactor is based on factory fabrication of shippable modules for fast deployment. The ARC-100 reactor also features a long-life core, a proliferation-resistant fuel cycle, seismically-isolated pool plant layout, small volume containment, compact footprint, passive decay heat removal, passive safety response for various incidents, ambient pressure in primary and secondary system (no LOCA hazard), possibility of co-generation and non-electric applications, and a full range of load-follow applications.

Another metal-cooled design is the TerraPower-designed Traveling Wave Reactor (TWR). Although at 500 MWe, the TP-1 model sits at the border between conventional reactors and SMRs, it has most of the benefits SMRs typically exhibit. It employs metallic U–Zr fuel with HT-9 cladding, has both a primary and secondary liquid sodium coolant loops to minimize water–sodium reactions with radioactive primary sodium, integral pumps and heat exchangers, and a passive Reactor Vessel Auxiliary Cooling System (RVACS) to cool the core in emergency situations. The TWR also aims to have a long fuel residence time (43 years for the 1150 MWe TPRP model), and high burnup (>14.5% FIMA). This is done by developing a wave of fissile material that slowly propagates through the core. An initial seed of fissile material is loaded with fertile material surrounding it. As time progresses, fissile material is built up in the fertile region, the initial seed is depleted, and the main power peak moves into the fertile region. When the reactivity becomes too low, the seed is discharged, the fertile region is advanced to the interior, and fresh fertile material is placed on the outside. The advantages of this scheme are passive safety, high uranium utilization due to high burnup, and high proliferation resistance due to long fuel residence time and no material being separated or enriched. The TWR's main obstacle is developing and testing materials to withstand the 500 dpa requirement imposed by the long fuel residence time [19].

2.3.3. Other concepts based on liquid salt coolant

The PB-AHTR (Pebble Bed - Advanced High Temperature Reactor) presented in Fig. 6 is a design using coated particle fuel already described in PBMR, which is cooled by liquid fluoride salt $^{7}Li_2BeF_4$. Liquid fluoride salts have high power density (which means that low pressure can be utilized compared to helium cooled reactors), high efficiency, low chemical reactivity, but among disadvantages it has high freezing temperature (495 °C) and special health safety is required for handling beryllium. A similar design called SmAHTR ("Sm" is for "small") [17] is being developed where the reactor would be cooled with $LiF\text{-}BeF_2$ liquid salt and will use coated TRISO UCO particles in 19 string fuel assemblies. Initial concept operating temperature is 700 °C, with a possibility of further evolution to close to 1000 °C. The SmAHTR employs prismatic core block concept with removable TRISO compact fuel elements, enrichment of 19.75%, low primary system pressure (atmospheric), indirect Brayton cycle power conversion, passive decay heat removal, and refueling interval of 2.5 years. Since non-traditional coolant is to be used, much research is expected to be needed in material technology and thermal hydraulics.

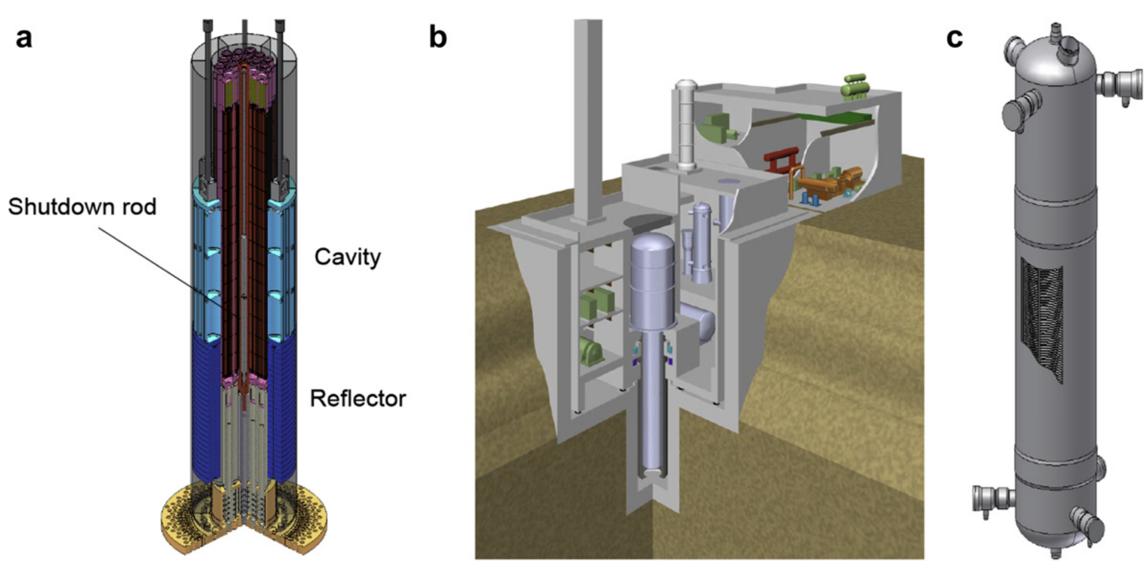

Fig. 5. Reflector controlled core for 4S reactor and steam generator [26].

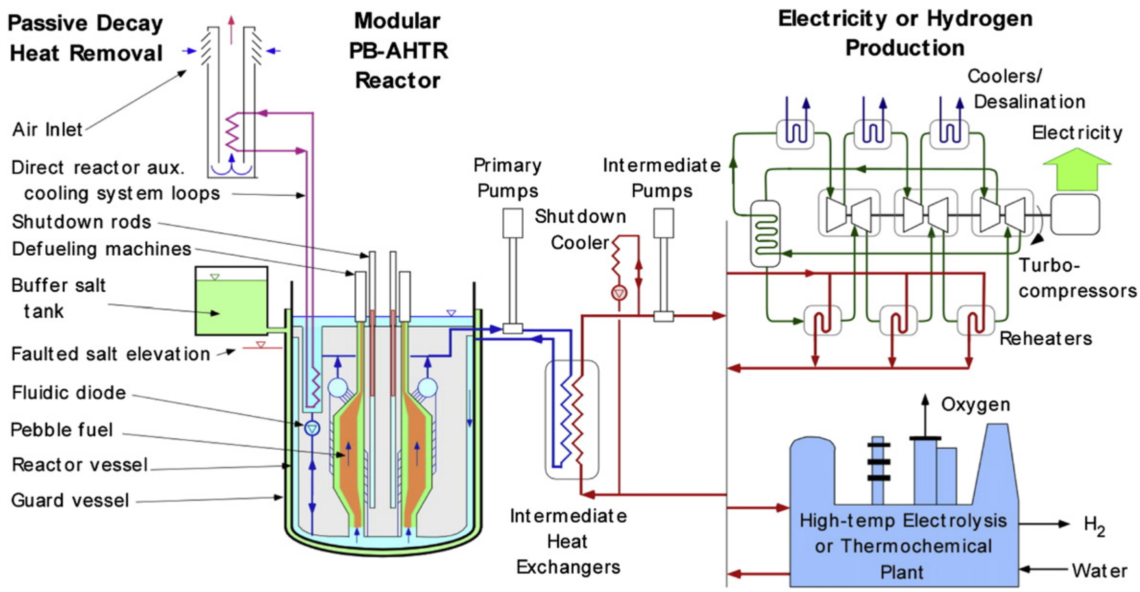

Fig. 6. PB-AHTR power plant design [15].

3. Economic aspects of small nuclear reactors

In order to evaluate the attractiveness of an investment in nuclear power plant, one should take into account the economic side of the investment. First are financial yield parameters: e.g., net present value [$], IRR [%] (internal rate of return), LUEC (economic evaluation production cost) [$/MWh], upfront investment [$], etc. Some secondary, but important, issues to be evaluated are the associated risk and cash flows, capital cost [$/MWe], construction time [years], etc. The so-called economy of scale tends to disfavor SMR as compared to larger reactors. We find that highly expensive fixed units of capital are common in nearly every mass manufacturing production process. A good example, apart from nuclear engineering, is investment in robotic technology for producing motor vehicles or assembling audio-visual equipment.

Specialization of the workforce: Within larger firms the production process can be split into separate tasks to boost productivity. The container principle. This is linked to the cubic law where doubling the height and width of a reactor or its building leads to a more than proportionate increase in the cubic capacity, hence its power. Learning by doing: There is growing evidence that industries learn-by-doing! The average costs of production decline in real terms as a result of production experience as businesses cut waste and find the most productive means of producing output on a bigger scale. Evidence across a wide range of industries into so-called progress ratios, or experience curves or learning curve effects, indicate that unit manufacturing costs typically fall by between 70% and 90% with each doubling of cumulative output. Businesses that expand their scale can achieve significant learning economies of scale.

In work of Politecnico di Milano SMR Economics Evaluation the code INCAS ver. 1.0 was used for evaluating the generation cost and key financial and economic parameters for small modular reactors in comparison with other sources of energy and NPP of bigger scale [14]. The conclusions of this study include the following: the economy of scale law could be overcome by other SMR features (e.g. modularization, lower capital risk) leading SMRs to competitiveness; the cash flow profile for SMRs is smoother and upfront investment is lower so the SMR projects can be more attractive for investors; regarding net present value and IRR, 4 SMRs are comparable with 1 LWR but n LWRs may have better performance than 4n SMRs. For indication, estimated SMR costs are as follows [10]: SMART - Construction cost $5000/kWe, O&M cost 6.1 cent$/kWh (which is lower than hydro power). NuScale Power - construction cost $4000/kWe for 40 month construction schedule, fuel cost $5.5/MWh. PB-AHTR has lower energy costs than Advanced Light Water Reactors since primary loop components are more compact and building volume per MWe is 50% smaller than ALWR. The 10 MWe variant of the 4S plant is projected to be very competitive with diesel in many remote locations, and the 50 MWe variant cost of electricity is slightly higher than large LWRs [9].

In a colloquium presentation given at the University of California, Berkeley Geoffry Rothwell, examined the economics of a generic light water SMR reactors. The figures presented came from a study currently in progress with the University of Chicago and show the projected levelized cost of of constructing a power plant in real 2011 dollars with real interest rates. These SMRs are estimated to cost about $8000/kWe for first-of-a-kind plants, which is based on a single installation 600 MWe worth of units. Nth -of-a-kind plants, which is assumed to be 19.2 GWe of installed SMR capacity, are estimated to cost $5000/kWe. The study suggests that if a 25 GWe fleet of SMRs were deployed over 40 years in the United States, it would have a positive impact on the economy (i.e. provide profit) if the first-of-a-kind costs are subsidized by the government [23].

IRIS is expected to have a capital cost and production cost comparable with larger plants. But any small unit such as this will potentially have a funding profile and flexibility otherwise impossible with larger plants. As one module is finished and starts producing electricity, it will generate positive cash flow for the next module to be built. Westinghouse estimates that 1000 MWe delivered by three IRIS units built at three year intervals financed at 10% for ten years require a maximum negative cash flow less than $700 million (compared with about three times that for a single 1000 MWe unit). For large plants with long lead times, financing costs can become more than 40% of the total capital cost of the plant [20]. This is less of a problem in areas where utilities are governmentally reimbursed based on owned capital, but for the growing deregulated energy market, SMRs shorter lead times make financial cost much more attractive to investor. For developed countries, small modular units also offer the opportunity to be built as necessary, and for developing countries it may be the only option since their electric grids cannot take 1000 + MWe single units [9].

4. Concluding remarks

This paper reviewed several SMR designs for early deployment, as well as some advanced generation IV designs. We expect that SMRs based on proven LWR technology will be easier to license and found more acceptable by general public. Other reviewed concepts could also become competitive and further research and development could allow these SMRs to become part of the energy mix in the future. The ideal SMR concept must satisfy requirements of sustainability, passive safety, proliferation resistance, simplicity of construction and operation, and affordability. SMRs could be broadly used by smaller utilities, by smaller countries with financial or infrastructural constrains, in isolated regions or for distributed power needs, and for various other non-electrical application (process heat, desalination, oil recovery for tar sends and oil shale, district heating). SMRs offer increased safety by eliminating most of accident initiators (for example, large pipes in primary circuit), by improving decay heat removal and including more efficient passive heat removal from reactor vessel, more in-factory fabrications, transportability and site selection flexibility, smaller plant footprint and use of seismic isolators for increased seismic safety, as well as reduced investment risk. Still, there are technical and institutional challenges to be addressed with further R&D: testing and validation of technological innovations in components, systems and engineering (especially testing and fabrication of fuel), fear of first-of-kind reactor designs, economy of scale, perceived risk factors for nuclear power plants, and regulatory and licensing issues. Other issues to be addressed are the cost of reactor decommissioning and spent nuclear fuel management.

In conclusion, the new small reactors have no insurmountable technical and regulatory issues to hinder their development and deployment, and the projected range of the cost of electricity from SMRs could be comparable or smaller with that of current large LWR.

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