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REVIEW PAPER

Small/medium nuclear reactors for potential desalination applications : Mini review

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Abstract−Small/medium nuclear reactors (SMRs) are a promising alternative for powering large scale desalination plants. The modern generations of these systems manifest cost effectiveness and built-in safety features. The compatibility with geological and topological challenges is an added advantage. Moreover, funding opportunities and packages could be easily arranged for small/medium nuclear reactors (SMR). This mini review article provides the latest technical features of SMR nuclear plants with emphasis on pressurized light water reactors (PWR), boiling water reactors (BWR), heavy water reactors (HWR), gas cooled reactors (GCR), and liquid metal fast breeder reactors (LMFBR). Preliminary cost indicators for typical units were investigated as a part of joint effort to develop a cost database for these types of reactors. Security and safety features of small/medium reactors are identified and reviewed. This paper identifies and briefly discusses the various types of small/medium nuclear reactors to provide a preliminary evaluation and consideration of using this type of reactor in potential seawater desalination applications.

Keywords: Desalination, Small/Medium Nuclear Reactors, Technical Features

INTRODUCTION

The International Atomic Energy Agency (IAEA) has been developing smaller reactors, defining the type of reactor by a "small" reactor for electrical output less than 300 MWe and a "medium" reactor for an output capacity up to 700 MWe. The two terms can be combined into a common term of "small/medium-sized reactor" (SMR), represnt a reactor with electrical output less than 700 MWe [1]. Small/medium reactors provide easy grid match capacity for developing countries as well as represent a reliable option for remote areas requiring a localized small power center. They have small footprint due to reduced components compared to large reactors, and they are favorable for limited electrical grids [2-4]. Typical categories of SMRs are suitable for application in the regions suffering from desertification problem; typically these regions have little or no electric power distribution system. Thus, installing small reactors with smaller distribution systems is expected to have economic and infrastructure benefits [2].

SMR nuclear power plants could provide a specific mix of energy needs in remote locations with no or limited electrical grid [5]. For developing countries, SMR reactors can play an important role in accelerating development, urbanization and population relocation and relevant domestic applications [6]. However, the specific capital cost ($/KWe) of a nuclear reactor may decrease with size, due to the reduction of site-specific costs in investment activities (e.g., siting activities, or civil works) [7].

Innovative concepts for SMRs are in development in the USA, Russia, Argentina, Brazil, Canada, China, France, India, Japan, Republic of Korea, South Africa, and some emerging economies. Generally, modern SMR reactors used for power generation are expected to have greater simplicity of design, reliability, economy of mass production, and reduced costs [8].

Seawater desalination by nuclear energy is now being discussed at the IAEA, in response to the request from member countries [9, 10]. Recently, several small and medium reactors have been proposed by IAEA as an energy source for seawater desalination [2, 10-12]. The purpose of this paper is to present the technical and economic features determining the feasibility of SMR's for desalination. A literature review was undertaken on the technical, economic, social and some environmental features of SMRs. This paper is divided into three sections. The first section summarizes the technical features and design specifications as reported in publications. The second part provides safety features, and the third part gives economic indications of such reactors.

TECHNICAL FEATURES OF SMRS

At the fundamental level SMRs are not different from large reactors, but need to be considered separately due to the significant innovation in design and target markets. There are five major groups of small modular reactor designs which are actively being developed. The first group of SMRs is based on the design concepts of proven and widely utilized light water reactors, consisting of pressurized water reactor PWR; the second is the boiling water reactor BWR; the third group comprises the heavy water reactors HWR; the fourth group consists of gas-cooled SMRs, and the fifth group is the fast breeder reactor (FBR), liquid metal lead or sodium cooled FBR (LMFBR) which is considered the most common of this group [12].

1. Pressurized Light Water Reactors (PWR)

These reactors are two circuit, indirect energy conversion cycle

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Table 1. Basic characteristics of SMR: PWR

Reactor design	MWth/MWe	Cycle type	Primary coolant	Primary pressure MPa	Core inlet/output temperature °C	Fuel type	Ref.
CAREM-25	100/27	Indirect Rankine	Light water	12.25	284/326	UO2	21
SMART	330/100	Indirect Rankine	Light water	15	296/323	UO2	22,23
IRIS	1000/335	Indirect Rankine	Light water	15.5	292/330	UO2	24
IMR	1000/350	Indirect Rankine	BoilingLight water	15.5	330/345	UO2	9
ABV	2*38/2*8.5	Indirect Rankine	Light water	15.7	248/327	UO2 in inert matrix	25,26
VBER-300	917/325	Indirect Rankine	Light water	16.3	292/328	UO2	27
mPower	400/125	Indirect Rankine	Light water	13.1	297/321	UO2	28
NuScale	160/48	Indirect Rankine	Light water	10.7	248/289	UO2	29
NHR-200	200/65	Heat Production	Water	2.5	140/210	UO2	9

plants. The primary coolant is pressurized light water. Nuclear heat generated in the reactor core is transferred to the secondary power circuit through steam generators. A conventional PWR uses a pressure vessel to contain the nuclear fuel, control rods, moderator, and coolant. The majority of current reactors belong to that group, and are generally considered the safest and most reliable technology currently in large scale application [13-16]. Table 1 illustrates the basic characteristics of the small/medium PWRs available and/or under development.

2. Boiling Water Reactors (BWR)

BWR is similar to PWR, but with no steam generator. A boiling water reactor is cooled and moderated by light water, but at a lower pressure, allowing the water to boil inside the pressure vessel to produce the steam that runs the turbines. Saturated steam condensation cycle (Rankine cycle) is used for energy conversion. Unlike a PWR, there is no primary and secondary loop. BWRs have a thermal neutron reactor design, the newest of which are the Advanced Boiling Water Reactor and the Economic Simplified Boiling Water Reactor. BWRs are second to PWR in global application, accounting for about 21% of all currently operating reactors [14,16]. A typical reactor of this type is the VK-300 with a thermal/electrical capacity of 750 MWth/250 MWe. The core inlet is boiling water at pressure of 6.86 MPa. The used fuel is UO2.

3. Heavy Water Reactor (HWR)

Heavy water reactors (HWRs) represent about 10.5% of currently operating power reactors. These reactors are heavy-water-cooled and moderated pressurized-water reactors. Instead of using a single large pressure vessel as in a PWR, the fuel is contained in hundreds of pressure tubes. These reactors are thermal neutron designs, fueled with natural uranium, and can be refueled while at full power. They are very efficient in uranium usage since they allow for precise flux control in the core [13].

4. Gas Cooled Reactor (GCR)

Gas-cooled reactors are among the first nuclear plants commercially deployed and may be significant to energy security in the coming decades. They are cooled using a gas, and the heat extracted by the gas during the process of cooling the reactor is used either indirectly to generate steam or directly as the working fluid of the gas turbine. The moderator used in these types of reactors is graphite, offering the advantages of being stable under conditions of high radiation and temperatures [17,18].

They can have a high thermal efficiency compared with PWRs due to higher operating temperatures. There are a number of operating reactors of this design, mostly in the United Kingdom. Older designs (e.g., Magnox stations) are mostly shut down and will be replaced in the near future [17,18].

4-1. Advanced Gas Cooled Reactor (AGR)

This is a thermal neutron reactor design. All AGR power stations are configured with two reactors in a single building, with thermal power output of 1,500 MWt driving a 660 MWe turbine-alternator set. Decommissioning costs can be high due to large volume of reactor core [13,14].

4-2. High Temperature Gas Cooled Reactor (HTGR)

New high-temperature gas-cooled reactors are capable of delivering high temperature (1,000 °C), as the fuel for these reactors is in the form of TRISO (tri-structural-isotropic); the amount of used fuel is greater than that used for the same capacity in a light water reactor. The moderator is graphite; thorium-based fuels such as highly-enriched or low-enriched uranium with Th are used. They are sufficiently small to allow factory fabrication, and will usually be installed below ground level [17]. Examples of this type are GT-MHR, HTTR, HTR-10, HTR-PM, EM2, PBMR (including AVR, THTR-300 and MPBR) and GTHTR-300 [19]. Helium is used as a coolant. Heat recovery cycle is mainly based on indirect Rankine and Brayton cycles. Table 2 depicts the basic characteristics of HTGRs.

5. Liquid Metal Fast Breeder Reactor (LMFBR)

The reactor produces more fuel than it consumes as it is cooled by liquid metal which does not require much high pressure containment, as liquid metal does not need to be kept at high pressure, even at very high temperatures. This type of reactor is a “breed” fuel type, as it produces fissionable fuel during operation because of neutron capture. These reactors can function much like a PWR in terms of efficiency [18,20]. Table 3 illustrates the basic characteristics of LMFBR reactors.

NUCLEAR DESALINATION

Salty water can be desalinated via different techniques that can be classified into two main categories: thermal and membrane processes. The thermal processes mainly include multistage flash evaporation, multiple effect distillation, and vapor compression. The membrane processes comprise reverse osmosis (RO), electro-dialysis

Table 2. Basic characteristics of advanced SMR: HTGR (helium cooled)

Reactor design	MWth/MWe	Cycle type	Primary pressure MPa	Core inlet/output temperature °C	Fuel type	Ref.
HTR-PM	250/105	Indirect Rankine steam turbine	7	250/750	TRISO based pebble, UO2	34,35
PBMR	400/165	Direct gas turbine Brayton	9	488/900	TRISO based pebble, UO2	36
GTHTR-300	600/274	Direct gas turbine Brayton	7	587/850	TRISO based pin in block, UO2	9
GT-MHR	600/287	Direct gas turbine Brayton	7.07	497/850	TRISO based pin in block, UO2	17,37
HTTR	30/17	Brayton	4	396/950	Low enriched UO2	38,39
HTR-10	10/4.5	Brayton	4.3	250/700	UO2 multipass	40
EM2	500/240	Brayton	N/A	N/A/850	Used nuc. fuel	41
Antares	600/250	Direct steam	7	N/A/850	Triso SiC coated, UO2	42
Adams Engine	250/100	Brayton	2.07	N/A/800	Triso	42

Table 3. Basic characteristics of advanced SMR: LMFBR

Reactor design	MWth/MWe	Cycle type	Primary coolant	Primary pressure MPa	Core inlet/output temperature °C	Fuel type	Ref.
4S	30/10	Intermediate heat transport system, Indirect Rankine	Sodium	0.3	310/355	U-10Zr/17	20
SVBR-100	280/102.5	Indirect Rankine on saturated steam	Lead-Bismuth	0.001	320/482	UO2	9
PASCAR	100/37	Indirect Rankine on saturated steam	Lead-Bismuth	0.1	320/420	U-TRUZr/TRU	43
Hyperion	70/25	Indirect Rankine on saturated steam	Lead-Bismuth	N/A	395/545	UN	44

(ED), and nanofiltration (NF). RO desalination technology has gone through remarkable development and is considered as the fastest growing desalination technique. According to rapid increase in worldwide demand of potable water, and the fast development in membrane processes, RO plants have greatly increased in number and capacity. On the other hand, the desalting process is considered an energy extensive process [45-47].

In addition, energy is the largest single variable cost for a desalination plant, varying from one-third to more than one-half the cost of produced water [48]. Reverse osmosis consumes up to 6 kWh/m^3 of electricity (depending on both process and its original salt content), while thermal desalination consumes from 4-16 kWh/m^3 [49]. Electrical energy accounts for 44% of the typical water costs of an RO plant, with the remainder from other operation and maintenance expenses and fixed charges [48]. As a result of coupling renewable energy source and desalination system, the feasibility of integrating nuclear power and desalination process has been proven through years of experience, showing a promising option. Table 4 illustrates examples of applied desalination plants; it summarizes past experience as well as current developments and plans for nuclear-

Table 4. Examples of applied desalination plants [50,58]

Reactor type	Desalination plant capacity m^3/d	Location	Status
LMFR	80,000	Kazakhstan (Aktau)	In service till 1999
PWRs	1,000-2,000	Japan (Ohi, Takahama, Ikata, Genkai) 8 Units	In service with experience of over 125 reactor-years.
	40,000	Rep. of Korea	Under design
	12,000	Argentina	Under design
PHWR	6,300	India (Kalpakkam)	Under commissioning
	4,800	Pakistan (KANUPP)	Under design
	1,600	Pakistan	Under commissioning
NHR	80,000-120,000	China (4 projects)	Under design

powered desalination based on different nuclear reactor types. Most of the technologies in Table 4 are land-based, but the table also includes a Russian initiative for barge-mounted floating desalination plants. Floating desalination plants could be especially attractive for responding to temporary demands for potable water [50,51].

Table 4 presents examples of some applied nuclear desalination plants based on different reactor types. The Kazakhstan desalination plant of capacity 80,000 m^3/d MED utilizing LMFR power plant is an example of a high capacity system. PWR has been utilized for powering all capacity ranges. China developed desalination powered with NHR-PWR reactors for capacities of 80,000-120,000 m^3/d, mostly SWRO desalination. Pakistan is commissioning a 1,600 m^3/d MED nuclear desalination plant. There are eight units of nuclear desalination in Japan all in service with desalinating capacity (1,000-2,000 m^3/d/unit) incorporating BWR reactors [50-52].

SAFETY ASPECTS

Safety is the most important criterion in the selection process of a nuclear reactor. According to IAEA, all reactors must meet a minimum safety level, as the safer reactor designs are more likely to win government and public support [12-14]. All systems have improved safety through international operating experience as well as increasing the time required to take emergency actions. In most advanced designs, no operator action is needed for at least 24 hours [12]. The experience gained from nuclear reactor accidents reflects the design of small/medium reactors. Most current PWRs and BWRs are designed with numerous active safety systems and a few passive safety systems. Korea was the first to present the passive safety concept for PWRs reactors; two concepts have been proposed, designed to transfer the heat from the containment to the tank outside the containment through internal or external condensers [53,54].

Smart engineering designs for SMRs, such as the integral primary system reactor configuration, offer the same or better safety performance rather than gigawatt reactors. Reactors with passive safety features are quite attractive and competitive for locations where a stable power grid is unavailable. The safety improvements help in developing a roadmap for small commercial reactors in China, and enhance the efforts for safety and economic competitiveness [6,55]. International consideration for SMRs has been highlighted recently due to enhanced plant safety which offers protection of capital investment.

Increased safety features are instrumental in eliminating most of the accident initiators (large pipes in primary circuit), improving decay heat removal and passive heat removal from the reactor vessel, in-factory fabrications, site selection flexibility, smaller plant footprint and increased seismic safety [12,15].

FINANCIAL INDICATORS AND COST ANALYSIS

Reported SMRs levelized unit cost by authors and vendors tend to compete with large reactors, as well as the lower cost compared to the corresponding cost of generating electricity for arid or isolated areas. There are many factors affecting the cost of SMR reactors, according to reported experience: construction duration, design simplification, factory fabrication and economy of modular plant [7,35,51]. Table 5 presents the levelized capital overnight cost as updated for 2013 current cost for selected SMRs. It is has been noticed that SMRs have a competing cost with high thermal/low electrical capacity reactor, which is considered a notable advantage for countries willing to develop their own nuclear program.

As shown in Table 5, NHR-200 possesses the lowest overnight

Table 5. Overnight capital cost of selected SMRs

Reactor design	Reactor type	MWth/MWe	Coolant	Levelized OC cost USD/kWe (2013)	Ref.
ABV	PWR	38/8.5	Water	10334	25,26
CAREM-25	PWR	100/27	Water	4088	56,59
KLT-40S	PWR	150/35	Water	4202-4770	61
NHR-200	PWR	200/-	Water	919	51,62
SMART	PWR	330/100	Water	1947	23,59
CAREM-125	PWR	375/125	Water	2158	59
CAREM-300	PWR	900/300	Water	1363	59
VBER-300	PWR	917/325	Water	3180 barge-3975 land	59,27
QP-300	PWR	1000/325	Water	3145	63
IRIS	PWR	1000/335	Water	1363-1590	59
CNNP-600	PWR	1936/644	Water	1510	64
VK-300	BWR	750/250	Water	1249	59
CCR	BWR	1268/423	Water	4804	65
PHWR-220	HWR	862/220	Water	1590-1817	60,66
AHWR	HWR	920/300	Water	1476	33,59
CANDU-6	HWR	2064/715	Water	4088	63,31
HTR-PM	HTGR	250/105	Gas	1703	34,59
PBMR	HTGR	400/165	Gas	1931	59
GT-MHR	HTGR	600/287	Gas	1363	59
GTHTR-300	HTGR	600/274	Gas	2953	59
SVBR-100	LMFBR	280/101.5	Lead-Bismuth	1033.4	51

cost, but this kind is dedicated only for heat production. It can be deduced from the table that among the water cooled reactors, IRIS and Carem-300 have the lowest overnight cost in the PWR group, VK-300 has the lowest overnight cost in the BWR group, and the AHWR has the lowest in the HWR group. Among the gas cooled reactors, GT-MHR has the lowest, and SVBR the lowest among the LMFBR reactors [7,56,58].

Regardless of the fact that some SMRs specific investment costs are high, the production cycle of the total investment is relatively faster. Updated desalinated water unit cost using nuclear power desalination system shows a relatively competing option with other alternatives [58]. The cost of nuclear desalination varies in accordance with the type of coupling used. The cost in coupling a nuclear reactor to MED is 32% to 45% lower than the corresponding cost by the conventional system, while for coupling RO desalination with a nuclear reactor the cost is reduced to 28-35% than a conventional system [57]. The most proposed reactors for desalination are the Korean concept SMART and the Indian AHWR and PHWR reactors due to their lower cost and safety features [50,51,58].

CONCLUSIONS

In view of the pre-mentioned characteristics, there is an increasing interest in SMRs reactors. Several companies and investors have been supporting commercialization of SMRs. The advantages of SMRs, such as small footprint, short construction time, modularity, and flexibility in plant configuration, are attractive for implementation. SMRs have a significant potential to expand for peaceful applications.

Analysis of recent publications leads to the conclusion that the SMRs are suitable for small electrical grids and remote locations. They offer required energy for a variety of industrial sectors, such as desalination, process steam, heat and energy. The available cost data indicate the competitiveness of small/medium reactors. Reactors lower than 100MWe are being implemented in remote areas where no electricity is available in spite of their higher specific cost.

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NOMENCLATURE

GT-MHR : gas turbine modular helium reactor
GWe : gigawatt electrical
IAEA : international atomic energy agency
HTR : high temperature reactor
LFTR : liquid fluoride thorium reactor
LWR : light water reactor
MSR : molten salt reactor
MWe : megawatt electrical
PBMR : pebble bed modular reactor
PWR : pressurized water reactor
SMR : small modular reactor
BWR : boiling water reactor
RPV : reactor pressure vessel
HTGR : high temperature gas reactor
LWR : light water reactor

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