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PRIMARY STUDY ON THE PROSPECT OF SMALL MODULAR REACTOR

Huailin LI[1], Qingyan ZHU[1] and Haihong XIA[1]
[1] State Nuclear Power Research Institute, China
lihuailin@snptc.com.cn, zhuqingyan@snptc.com.cn, xiahaihong@snptc.com.cn

Abstract

Compared with large scale nuclear power reactor, SMR has the feature of smaller power, shorter construction period, longer operating cycle between refueling, lower cost on location selection, and so on. Thus, SMR is suitable for today's developing countries, which often have insufficient infrastructure and small electricity grids. In industrialized countries, the electricity market deregulation is calling for a flexibility of power generation and applications that smaller reactors may offer. In this paper, the prospect of SMR is discussed from technology development status, constraints, economic, etc.

1. Introduction

IAEA defines the reactors with a nominal output of less than 300MWe as the SMR (small modular reactor). According to the US DOE, the SMR has adopted the "factory fabrication, rail/road transportation, and multi-modular construction" method, which is an advanced technique besides, the SMR has many advantages such as shorter construction time, longer refueling cycle, and low cost of site selection. Due to the small capacity, the SMR will have fairly small impact on the power grid, and can be used in remote areas and developing countries, which often have insufficient infrastructure and limited funds for larger reactor investment. There are also new applications for SMR, such as district heating, electricity supply for remote markets, coal liquefaction, seawater desalination, hydrogen production, and many others. Because of its flexibility, variety of uses, and lower investment risk, the SMR has attracted extensive attention worldwide.

There are 56 different designs of innovative SMR[1,2] under development funded by national or international programs in American, Japan, France, Russia, China, and so on. By different technical routes, SMR can be classified into, water-cooled, gas-cooled, liquid metal cooled and others (Table 1, Table 2, Table 3).

Table 1.The main water-cooled concepts and designs

Name	Capacity	Type	Developer
KLT-40S	35 MWe	PWR	OKBM, Russia
VK-300	300 MWe	BWR	Atomenergoproekt, Russia
CAREM	27-100 MWe	PWR	CNEA & INVAP, Argentina
IRIS	100-335 MWe	PWR	Westinghouse-led, international
Westinghouse SMR	200 MWe	PWR	Westinghouse, USA
mPower	150-180 MWe	PWR	Babcock & Wilcox + Bechtel, USA
SMR-160	160 MWe	PWR	Holtec, USA
SMART	100 MWe	PWR	KAERI, South Korea
NuScale	45 MWe	PWR	NuScale Power + Fluor, USA
ACP100	100 MWe	PWR	CNNC & Guodian, China

Table 2.The main gas-cooled concepts and designs

Name	Capacity	Type	Developer
HTR-PM	250 MWt	Gas-cooled	INET&Huaneng，China
PBMR	110MWe	Gas-cooled	ESCOM, South Africa
EM^2	240MWe	Helium cooled	GA, USA

Table 3.The main liquid metal cooled concepts and designs

Name	Capacity	Type	Developer
STAR	180MWe	LFR	ANL
SVBR	75～100MWe	LBFR	Russia
4S	10MWe，50MWe	SFR	Japan
PRISM	311MWe	SFR	GE
TWR	400～500MWe	SFR	TerraPower

2. Characteristics[3]

After the Fukushima accident, the world put more emphasis on reactor safety. The SMRs with inherent or passive safety features were proposed to solve the problem of passive decay heat removal, financial problem caused by the present large reactors, and the need for cogeneration.

2.1 Investment

Due to the module design and factory manufacture, the construction time of SMRs is considerably reduced, which will also reduce the uncertainty of the finance and can potentially improve the net present value. For the same capacity, the biggest negative cash flow of four SMRs is half of the large reactor’s (Fig1).

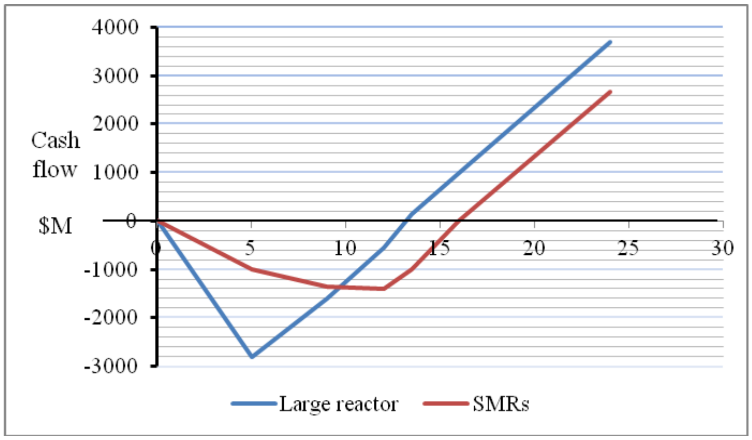

Fig.1 Comparision of the overnight cost of PWR and SMR

Although the SMRs do not have the advantage in economies of scale, they are more flexible to match the economic and financial requirements. When markets conditions (i.e. the electricity, the investment capital of reactors) are considerably uncertain, SMRs can be built one after another or in parallel. An additional effect of temporal and spatial flexibility of development is related to lower costs of capital and self-financing, which means that the cash inflows from early deployed units by the sale of electricity can be employed to finance the later units. M. Ricotti’s study showed this distinctive feature (Fig.2).

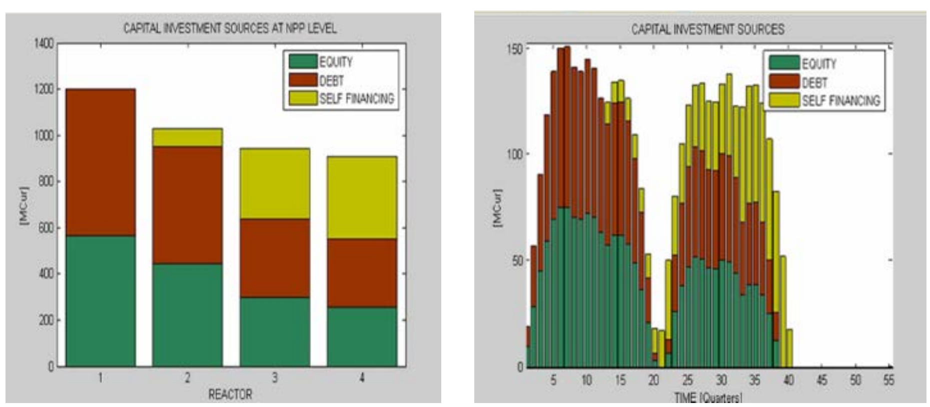

Fig.2 Investment sources of SMRs

2.2 Site selection

Due to their lower capacity, the SMRs can be easier to be adjusted to the small or less well-developed grids. Moreover, the inherent and modular designs allow the SMRs to adapt to a reduced space, where large reactors are confined to be built.

2.3 Safety

Along with the down-scaling of reactor designs, the heat and radioactivity are tremendously reduced. Besides the inherent safety properties, the passive safety system and modular design lead to relying more on reactor self-control to reduce manual operation and less equipment and structures that require maintenance.

2.4 Social benefit

Oxford's study (2008) used Input-Output analysis to define the relationship between different kinds of impacts through the use of multipliers. During the construction phase, the total employment (including direct on-site and off-site, indirect employment, and induced employment) of SMRs is 11% higher than that of large reactors, which means the SMRs will provide more job opportunities and the welfare to the country, which is also an important objective of the national investor. According to Thomas (2009), the SMRs will suffer less challenge in finding qualified people to support the constructions because of the flexibility of deployment.

3. Economic analyses[4]

Generally speaking, the main factors associated with the capital investment of a series of reactors are capacity, learning effect, units on the same site, as well as modular construction and simplicity of design. This paper will indirectly evaluate the economy of the SMRs by comparing these factors of 4 SMRs with a large reactor

3.1 Economy of scale factor

The capacity of the reactor is the most obvious factor that can bring economies of scale. The specific capital cost will fall with the increasing of the capacity in some extent (Fig.3). Under this circumstance, the calculated specific cost of the total 4 SMRs(with the capacity of 335MWe each) is 1.78 times more than that of an large reactor(with the capacity of 1300～1400MWe).

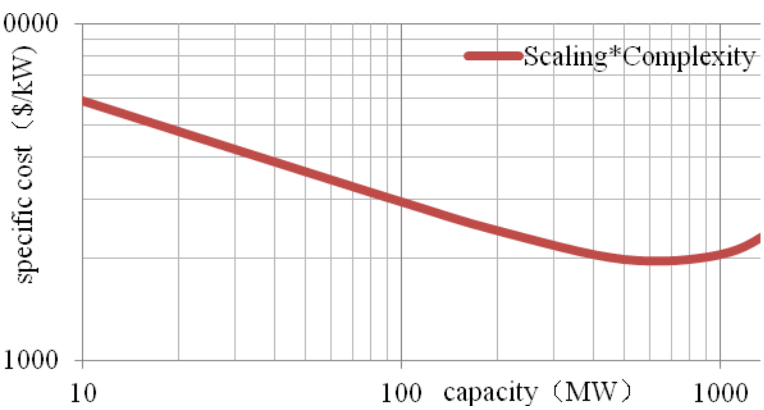

Fig.3 Economy of scale

3.2 Learning effect

Learning effect reflects in reducing production cost, management cost, investigation/research cost by standardization production, evolutionary in process and, mass production. According to previous studies, we extrapolate the average total investment of 4 SMRs is 8～10% lower than that of an large reactor with the same capacity only taking the learning effect into account (Fig.4).

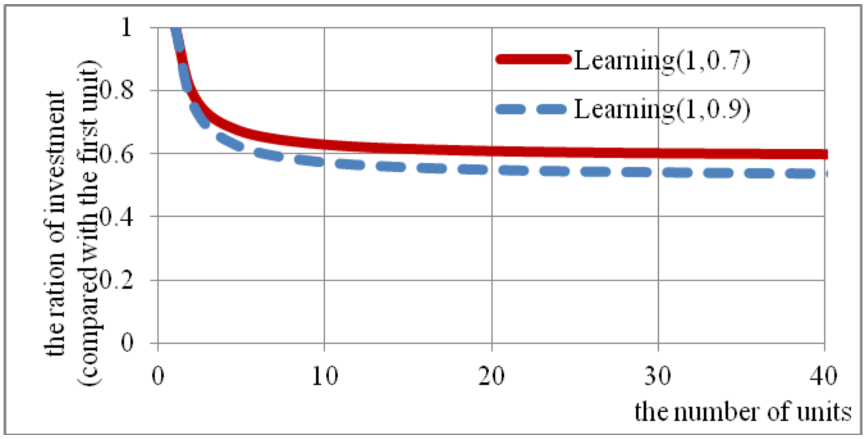

Fig.4 Learning effect

3.3 Co-sitting

Co-sitting factor means multiple units being built on the same site, which will save cost due to the sharing infrastructure and information and full employment of human resources. Given the assumption that cost of a standalone unit is 1, the total indirect cost for then unit can be calculated by the following formula (M.D. Carelli, 2010):

$$C_{ind} = 1 + (n - 1) \times (1 - AS)$$

C_{ind},-the total indirect cost for n plants on a single site, AS -the asymptotic saving for indirect cost, equal to 0.42, n- the number of the reactor on the same site.

$$\text{Co-sitting factor} = A \times AS + B \times BS,$$

A-the ratio of the indirect costs to the total cost, B- the ratio of the direct costs to the total cost, BS –the saving for direct cost, equal to 5% for two units

Therefore, the total saving is equal to 14.21% in this case.

3.4 Modular construction and simplified design

Modular construction allows shorter construction time. Normally, it will take five years to build a large reactor, while it only takes three years for an SMR. The shorter construction time leads to cost reduction by 6%. Even more than that, the eliminations of large primary piping, vessel head, and bottom penetration, the high pressure injection emergency core cooling system, the integration with the reactor pressure vessel of the main primary component, and so on, will simplify the systems and meanwhile reduce the cost.

A reasonable saving due to modularization and simplification for a 335MWe reactor estimated by ORNL is about 13%. M.D. Carelli (2010) used an account-by-account analysis to evaluate the IRIS reactor, and found the saving is about 17%[5]. Based on the practical investigation and combination of the upper opinions, 16% is used here as the saving cost for modularization and simplification.

Table 4.The quantification of four factors in SMRs and large reactor

The investment of an large reactor equal to 1		
Factors	Individual effect	Cumulative effect
Economy of scale	↑ 78%	1.78
Learning	↓ 8-10%	1.6
Co-sitting	↓14.21%	1.37
Modular construction and simplified design	↓ 16%	1.153

4. Potential and prospect of market in China

SMRs are particularly well-suited for the remote areas, electricity or heat supply for island, and can be exported to less developed country with small grid.

4.1 Electricity supply

In China, by regulations, the capacity of a single unit should not exceed 10% of the total provincial grid capacity in order to ensure the grid safety and stability. For some small grid, the SMRs are the best alternative. According to an earlier domestic study, it takes 50～60 million dollars(not including the energy loss, operation and maintenance cost, and other fees) to build a 200KV single-circuit transmission line that is 200 kilometers from the main grid. Because the SMRs with small capacity require less spinning reserves than that of large reactors, they can better ensure the safety of power network dispatching, even in the case of 100% load rejection, the negative influence to the grid is still limited.

4.2 Desalination

After extensive researches, IAEA proposed that integrated nuclear desalination system will be an attractive and realistic alternative source of potable water. There are two main desalination processes, multiple effect distillation (MED, requiring electricity and heat) and reverse osmosis (RO, requiring electricity). No matter which process will be chosen, using nuclear energy is the most economical option compared with other alternatives[6]. According to our technical and economical analysis, given the assumption that the investment of an SMR with capacity of 300MWe is 500～700 million dollars and the improved hot-film coupling is used, the cost of desalination will be reduced to $0.645/metric ton, which is 19% lower than the cost of fresh water. Moreover, the concentrated salt solution separated from the waste can be sold to salt chemical industry to bring more profits.

Integrated nuclear desalination system can not only supply domestic water but also moisturize the air, then destroy the haze-forming condition and manage the environmental factor to improve the climatic conditions.

4.3 Replacement for thermal power plants

It's proposed that replacing small thermal power plants with SMRs in an ordered, progressive way is a strategic choice for safe energy supply, energy structure improvement, and environment protection. According to our energy program, if small thermal power plants with the total capacity of 20000MWe would be shut down from 2010 to 2014, the remaining capacity of small thermal power will still be 16900MWe. If SMRs are designed to replace all closed small thermal power plants, the SMRs will have a huge market with big potential and bright prospect.

In central China, due to the emphasis on the conservation of energy and reduction of pollutant emissions, large and medium-sized thermal is limited to replace small thermal power plant. Besides, the shortage of natural gas and petroleum makes other fossil power impossible to be largely used, and the wind, solar energies are also limited geographically. In central China, the SMR is a realistic and necessary option. While in northeast, there is an urgent need of clean energy to substitute for condensing small thermal reactors, which cause high energy consumption and heavy contaminate. Due to regional restriction and requirement for high safety standard and site condition, large reactors are difficult to fulfill all requests. In this case, SMRs will be ideal heat source for cogeneration in northeast.

5. Conclusions

The advanced integrated SMRs are under conceptual design, so it's hard to make a precise evaluation of the economics of SMRs. This paper firstly introduces the basic characteristics of SMRs, and then completes a preliminary economic assessment for SMRs. The potential users of SMRs are wide, which are from remote areas with small grid and industrial sites in off-grid locations to developing countries, plants for applications in seawater desalination, hydrogen production, and so on.

SMRs and large reactors are both competitive and complementary. The investment of SMRs is 15% higher than that of large reactor, but less than that is predicted with the economics of scale in this paper. However, this weakness can be compensated by variety market applications, low initial capital cost, and lower financial risk.

Overall, this paper gives a brief technical and economic evaluation of the development of the SMRs. and. Further study will be carried out in future to disclose more details.

6. References

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