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Resident heating SMR technology development and project siting study

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ABSTRACT

In china, the coal is popularly used to supply heat for resident in the winter. Around 500 million tons of coal is needed for resident heating in one year in china. Resident Heating SMR (RHSMR) has been developed for heat supply to the resident to reduce the carbon release and mitigating air pollution in one area. To take advantage of local heat distribution system and market, RHSMR has a goal to be a safe and reliable heat resource with reasonable cost. As widely recognized, the swimming pool reactor has no possibility of reactor melting in any case when the pool integrity is maintained and the water is kept in the pool with natural air circulating during heating season. The RHSMR is evolved from the pool reactor and combines the module construction technology. The RHSMR has the scale and output complying with the demand of utility area. The main facilities are reactor building, fuel building, auxiliary building and conventional building. Each unit can be operated independently and the number of units will be designed according to the utility demand as unit module lay out. The module technology will reduce the construction work on site comparing with traditional construction technology One project siting has been investigated and the selected site has typical site features in northeast of China. For this selected site with 5 to 6 months of heating in the winter, the RHSMR will be able to supply cheaper heat than Natural Gas heating

BACKGROUND

Per the International Energy Agency, nearly 6% of all global heat production is supplied via district heating (IEA, 2019) with the majority of that in China, Russia, and the EU.
In china, the coal is popularly used to supply heat for resident in the winter. For one of provinces in northeast of China, the cities have district heating area from 10,000,000 m^2 to 300,000,000 m^2. The total heating area is about 650,000,000 m^2. If the heat was supplied by nuclear power, 20,800,000 Ton coal would be saved. Around 500 million tons of coal is needed for resident heating annually in china. The traditional coal supplying resident heat would be replaced by clean energy to help china achieve carbon peaking and carbon neutrality goals in future.
While the U.S. produces only a small fraction in the world, there are still about 2,500 district heating systems in the U.S. using about 200 BBtus/year (Steve Tredinnick, 2013). There is also a significant opportunity for use of nuclear in process heat applications. In the U.S. manufacturing sector alone, nearly 7,500 TBtu/year of production are needed for process heating, with only about 5% currently coming via electricity generation, the remaining from localized steam or carbon-based fuels (U.S. DOE, 2019)
Resident Heating SMR (RHSMR) has been developed for heat supply to the resident to reduce the carbon release and mitigating air pollution in one area. To take advantage of local heat distribution system and market, RHSMR has a goal to be a safe and reliable heat resource with affordable cost, which can be accepted by local government to replace the operating traditional coal thermal power plant. The operating heating parameters are required to be taken into account as design input. For future application, the operating thermal power plant could be taken as RHSMR site after the power plant is closed.

Development of RHSMR and main characteristics of RHSMR

As widely recognized, the swimming pool reactor has no possibility of reactor melting in any case when the pool integrity is maintained and the water is kept in the pool with natural air circulating during heating season. The RHSMR is evolved from the pool reactor and combines the module construction technology. The RHSMR has the scale and output complying with the demand of utility area.
The RHSMR has the main characteristics as follow: two-loop trifle-pressurized water reactor, specified thermal parameters for heat-supply, five radioactive barrier & four circuit, RPV and primary loop seated in the pool as intermediate heat sink, passive ESF systems. The standardized RHSMR has 200MW of thermal capacity. The reactor has been designed as small reactor with shorting fuel assembly which is widely used in PWR technology.
RHSMR has another feature for operation which is to design a thermocline system for supplying heat following the heat loading without changing reactor power. This system uses heat storing system as a balance tool.
The system scheme is as following figure:

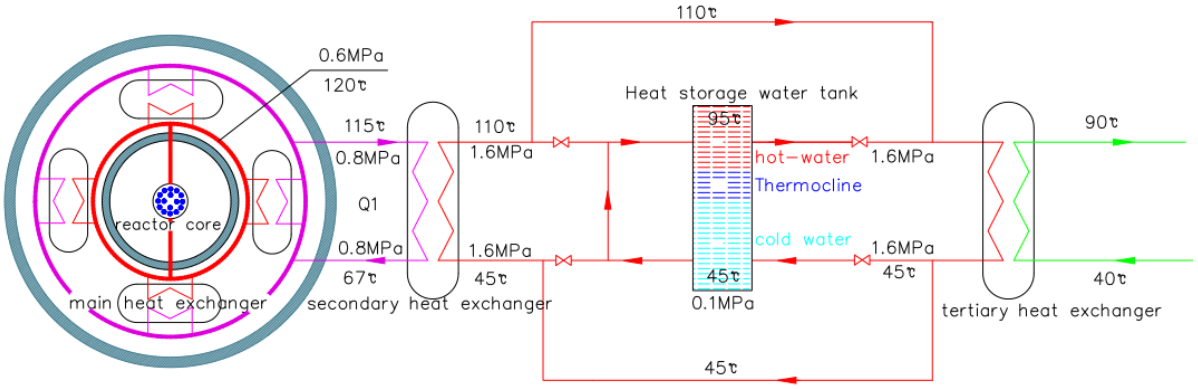

Figure 1 **System Scheme**

The second loop is designed with higher pressure than first loop to avoid leakage from first loop to third loop. RHSMR is designed to send heat to a city which has electric grid to support reliable electricity for operation. However, the loss of offsite electricity has been taken as a basic design case. For this case, one extra cooling system connecting the first loop will be operated to transfer heat of first loop to the water pool by natural circulation.

The main features of RHSMR are in the following table:

Table 1: The main features of RHSMR.

Main Parameters	Value	Main Parameters	Value
Thermal power（MWt）	200	Core inlet/outlet temp.（℃）	80/120
Heat capacity per unit（GJ）	3 million	Primary/secondary water load（t）	20/100
Heating area per unit（m^2）	5~7 million	Shield and cooling pool volume(m^3)	1000
Fuel No./Type	37/truncated fuel assembly	Operation/design secondary pressure（MPa）	0.8/1.6
Core Active length （m）	1.92	Secondary inlet/outlet temperature（℃）	67/115
Core equivalent diameter（m）	1.51	Heat network pressure（MPa）	0.6
Fuel load（t）	10	Heat network inlet/outlet temperature（℃）	110/50
Operation/design primary pressure (MPa)	0.6/1.6		

The typical layout of RHSMR

RHSMR has a typical layout including the main facilities which are reactor building, fuel building, auxiliary building and conventional building. Each unit can be operated independently and the number of units will be designed according to the utility demand as unit module lay out. The module technology will reduce the construction work on site comparing with the traditional construction technology.
The main plan and main section of reactor water pool is shown as follows:

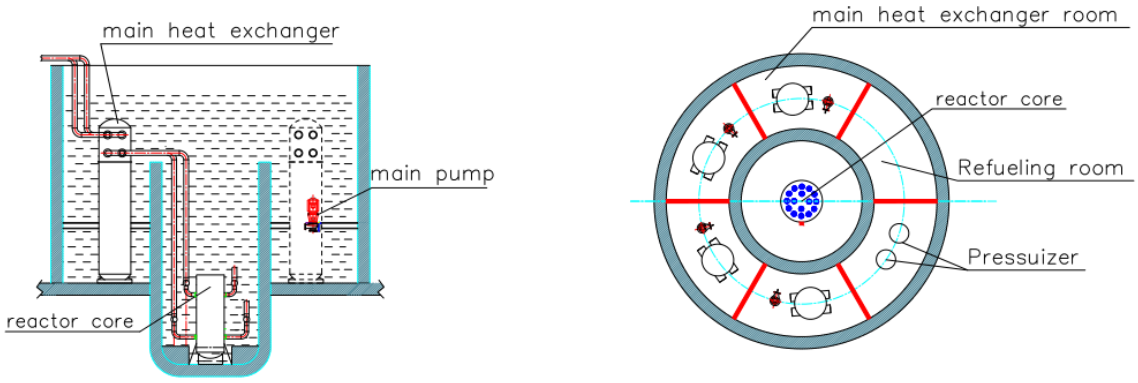

Figure 2 Main Plan and main Section of reactor water pool

The water pool containing the first loop is put in the reactor building. The reactor vessel, heat exchangers, pipes, pressurizer and main pumps are set in different water rooms which are connected. The function of water pool in the reactor building during accident is to keep the reactor in the water below boiling point to avoid the core melting. The volume of water pool is designed to absorb the total heat for required period from the start of shutdown of reactor. The additional cooling system is also designed to set in the water pool using the water in the thermocline system as long time cooling water resource in case of loss of all power electricity.
RHSMR can be near the city and replace the operating thermal power plant. To enhance the seismic capability, the water pool containing first loop is designed below the ground. The embedded water pool has the excellent seismic capacity. The upper part of the building is designed to use light structure with high strength to reduce the seismic effect and enhance the seismic capability
RHSMR supplying heat will mostly be operated in the cold area, in which less construction time and worst construction condition will be. The best way from updated engineering practice is to apply module technology in the design. The steel plate concrete structure modules are designed including reactor vessel pit module, heat exchanger room module, main pump room module, additional cooling system room module and pressuriser room module. The work on site will be controlled only passing two winters and the estimated schedule allows 18 months from the start work on site to starting supplying heat.

Siting criteria

The siting criteria complied with the related safety guideline issued by Chinese nuclear safety authority, at the same time the IAEA guideline and technical documentation were taken as reference. The local utility demand had been taken as input of preliminary feasibility study. The basic criteria of siting for SMR is to take high safety margin which can be expressed as much lower probability of severe accident and release of radioactive material. RHSMR is developed following general SMR safety principle and has more safety margin than general PWR SMR which is used to produce electricity.
The practice in other country has been taken into account. For example, to better address the possible future deployment of SMRs, the NRC has been proceeding with the development of new emergency preparedness requirements that adopt a consequence-oriented, risk-informed, performance-based, and technology-inclusive approach that could be implemented by SMR licensees and would continue to

provide reasonable assurance that adequate protective measures can and will be implemented to protect the health and safety of the public. This methodology has also recognized by Chinese industry.
"Defence in depth" from nuclear industry includes "Adequate site selection and the incorporation of good design and engineering features providing safety margins, diversity and redundancy". To apply this principle, IAEA guideline provides the following aspects in siting research:

a) The effects of external events occurring in the region of the particular site (these events could be of natural origin or human induced);
b) The characteristics of the site and its environment that could influence the transfer to persons and the environment of radioactive material that has been released;
c) The population density and population distribution and other characteristics of the external zone in so far as they may affect the possibility of implementing emergency measures and the need to evaluate the risks to individuals and the population."

Combining the requirements of Chinese nuclear safety administration and IAEA principle, the siting requirement for RHSMR was made. The RHSMR twin-unit layout is set to be able to supply heat for one district with residential area of 10,000,000 m^2.

a) The planned capacity and construction scale at each stage of RHSMR would be determined according to the short-term and long-term Heating Load as verified through investigation and planning of the local region with enough margin of capacity. The planned site should be as close as possible to the thermal load area. The maximum transmission distance of hot water piping network is 30 km which is for investment estimation.
b) The site would be 2km further away from agglomerations of more than 10,000 people, the radius of planned restricted area is one-kilometer from the center of the reactor. At this stage, the exclusion area covers the area with a 150-meter radius from the center of the reactor.
c) The site should be as far away from the active fault as possible. Neither a site with a distance less than 5km away from capable fault nor a site with safe-shutdown earthquake peak ground acceleration greater than 0.30g is selected.
d) Protected lands (national park, historic area, and wildlife refuges etc.) are excluded. Land located in proximity to hazardous facilities (airports, gas station etc.) is avoided.
e) The foundation of the plant site should be set at bedrock or stable soil layer which can meet the requirements of bearing capacity and deformation of the foundation of the nuclear reactor. There are no unfavorable geological phenomena affecting site and foundation stability, and no other factors possibly leading to foundation destabilization.
f) The site is not affected by river flooding and waterlogging.
g) The water source near the site is sufficient for the construction and operation of the plant.

The parameter of RHSMR standard design for siting see the following table,

Table 2: The siting parameter for RHSMR

No.	Item	Unit	Site	Notes
1	Lot area of project	h ㎡	3.00-3.50	
	1)main building area	h ㎡	1.50-2.00	
	2)office building area	h ㎡	0.30-0.40	
	3)auxiliary building area	h ㎡	1.0-1.5	
2	area per kW	㎡/kW	0.08-0.09	
3	area for construction	h ㎡	1.5	
4	Water consumption during operation of the heating season	2 units	50m ³/d （18250m ³/a）	Assurance rate 97%
5	Water consumption during the construction term	2 units	150m ³/h（1200000m ³/a）	Assurance rate 90%

No.	Item	Unit	Site	Notes
6	Equipment size		Heaviest piece weight:23t	Largest piece : 3900×3000×2800(mm)

One siting investigation and preliminary feasibility study

One project siting has been investigated and the project preliminary feasibility study had been done and reviewed independently. The selected site is in the northeast of China and has been selected as a demonstrated site for RHSMR. The selected site has typical site features in northeast of China.
The project was planned to replace the operating coal heating power plant with RHSMR. The planned city has the operating coal heating area of 15.97 million m^2. The maximum heating load is 859.2MWt, and the minimum heating load is 265.9MWt. The average heating load would be 527.8MWt. One biggest district in the city has district heating area of 14.69 million m^2, the left area includes other smaller area. The planned city is shown as following figure and one river is cross the city.

Figure 3. Plan of studied city.

The selected city has a distributed heating system supplying heat to local resident, and heat is from local traditional coal power plants which would be replaced by twin RHSMR from local government future plan.

Figure 4 location of candidate sites

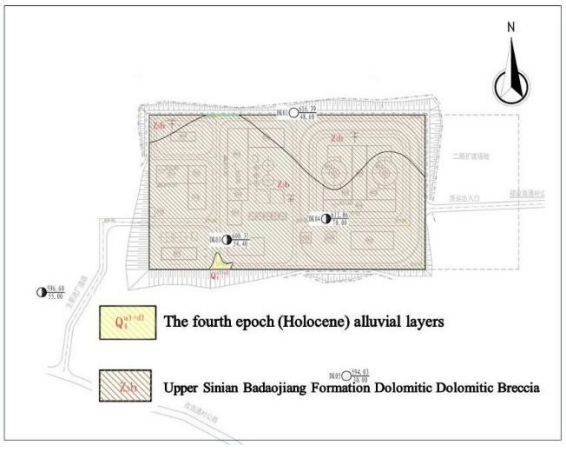

Figure 5 Soil condition of foundation

During site grading, two site candidates were selected which are noted by two green points in figure 4. Both of the sites are sitting at stable soil and one of which is show in the figure 5. Around both site,

there is no active fault. Slightly weathered dolomite is taken as supporting layer. One candidate site is planned as in figure 6 and its beautiful landscape can be seen in figure 7.

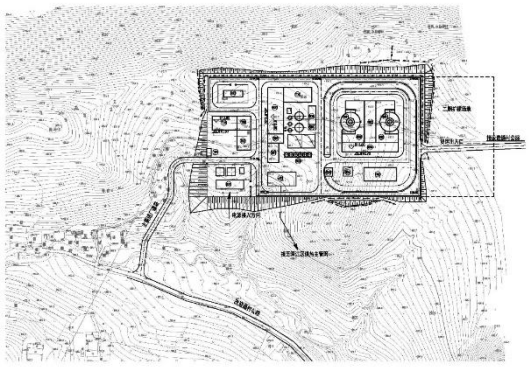

Figure 6

Figure 7

From preliminary earthquake safety analysis, the estimated seismic input is about 0.2g in horizontal direction at the free field. As a demonstrated project, two candidate sites are about 3km to 5km far from the downtown boundary which is not the requirement from emergency evacuation but the public acceptance for one demonstrated project.
The parameters comparison of two candidate sites can see following table:

Table 2: The siting parameter for two candidate sites

No.	Item	Unit	Site 1	Site 2	Notes
1	Lot area of project	h ㎡	3.07	3.45	
	1)main building area	h ㎡	1.44	1.93	
	2)office building area	h ㎡	0.28	0.37	
	3)auxiliary building area	h ㎡	1.34	1.15	
2	area per kW	㎡/kW	0.077	0.086	
3	area for construction	h ㎡	1.5	1.5	
4	Water consumption during operation of the heating season	2 units	50m³/d （18250m³/a）		Assurance rate 97%
5	Water consumption during the construction term	2 units	150m³/h（1200000m³/a）		Assurance rate 90%
6	Equipment size		Heaviest piece weight:23t Largest piece : 3900×3000×2800(mm)		

The designed operation allows RHSMR to be operated with half power and full power, which is needed for early period and the normal heating period. The estimated investment would be 1.9 billion RMB for twin RHSMR, which can be expressed as 4750 RMB per KWt. For this selected site with 5 to 6 months of heating in the winter, the RHSMR will be able to supply cheaper heat than Natural Gas heating.

CONCLUSION

RHSMR was developed to be focus on the resident heating during winter. The updated and evolved technology of reactor in water pool is used because of its safety of no reactor melting which is widely recognized in nuclear power industry.
One RHSMR would be in operation to supply resident heating for around 5,000,000 m^2, which saves amount of 160,000 Ton coal or 80,000,000 m^3 gas. One site was selected and evaluated as a demonstrated project complying with the siting standard and siting safety requirement. The siting preliminary feasibility study had been finished. The suggestion given to the local government is to start this demonstrated project of RHSMR as soon as possible, which will contribute to the carbon reduction in local area and be the best one of cleaning energy heating technology. From project economic analysis, the heat supplied at the selected site would be affordable by local resident which is cheaper that natural gas.
From the above project engineering practice, RHSMR will also be able to help other countries with the similar condition as the selected site because RHSMR meets the IAEA siting requirement. Although RHSMR is developed for resident heating, RHSMR could be developed to supply cold or desalinate seawater with an additional system.

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