Research article

Application target image of a small modular fluoride salt-cooled high temperature reactor based on the analysis of energy demand and environmental conditions in western China

Yanwen Guo¹, Ye Daia, Jinhong Zhanga, Dianqiang Jianga, Yao Fua,*

¹ Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai, 201800, China
² School of Nuclear Science and Technology, Xi’an Jiaotong University, Xi’an, 710049, China

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ABSTRACT

To meet the energy demand in remote areas of western China, a small modular fluoride-salt-cooled high-temperature reactor will be deployed there. The design of this reactor needs an application target image, including the power, lifetime, size, weight, and environmental restrictions. This paper analyzes the energy demand in northwest China to find the possible application scenarios and regions of this reactor. Then according to typical application scenarios, the power requirements of the reactor and the environment and transportation (size and weight) restrictions that need to be adapted can be obtained. The application target image of this reactor would be: a) the single unit capacity of 50MWe; b) the lifetime of at least 60 years; c) the length of less than 15.5 m, the diameter of less than 3.88 m, and weight of less than 60 tons; d) the adaptability to the severe climate and environment in the west, such as cold winter, deep-frozen soil layer, strong wind, arid environment, and complex terrain; e) the site selection to avoid geological disasters, such as landslides, collapses, torrents, mudslides, and ground fissures.

1. Introduction

To overcome the inherent safety issues and design issues of the second-generation nuclear power plants, Oak Ridge National Laboratory (ORNL), Sandia National Laboratories (SNL), and the University of California, Berkeley (UCB) developed the concept of the fluoride-salt-cooled high-temperature reactor (FHR). FHR has three core advantages: 1) FHR uses fluoride salt for cooling, which is derived from the high-temperature molten salt cooling technology of molten salt reactors (MSR); (2) FHR uses coated particle fuel, which is derived from the high-temperature burnup technology of high-temperature gas-cooled reactors (HTGR); (3) FHR uses passive decay heat removal system, which is derived from the passive safety technology of liquid metal fast reactors (LMFR).

Due to the inherent safety and economy of FHR, many studies have been performed. The typical designs of FHR so far are shown in Table 1. In 2007, the integral design progress of PB-AHTR was released. The fuel of PB-AHTR is TRISO coated particle fuel, and the coolant is low-pressure liquid salt. The high-temperature parts are made of alloy 800H coated with Hastelloy N. Its advantage is that when a good heat-electricity conversion efficiency is achieved, it has a higher energy density than a helium-cooled high-temperature reactor and reduces the investment cost of a nuclear power plant [6]. Later in the RELAPS-3D simulation of PB-AHTR, UCB found that the initial selection of power density was low, which was 10.2 MW/m³. Therefore, UCB is expected to develop a modular PB-AHTR with a power density of 20–30 MW/m³ [3]. In 2010, the design progress of SmAHTR was released. SmAHTR is based on the work of AHTR between 2002 and 2006. SmAHTR can provide safe, economical, and reliable electricity and high-temperature process heat. SmAHTR is easy to be transported and can be used in remote areas because its reactor vessel can be transported with standard commercial flatbed trailers [2]. Further, the derivative version SmAHTR-CTC was released in 2016, which used Carbonate thermochemical cycle (CTC) for efficient hydrogen production. The core inlet and outlet temperatures of the new version are 670 °C and 700 °C, respectively. The expected capacity factor is greater than 90% and the design lifetime is 60 years. The design of Mk1 PB-FHR was completed in 2014. Mk1 PB-FHR can provide more flexible and valuable services with high-temperature heat output. An improved GE 7FB gas turbine is used to generate power with the air Brayton cycle. Only using nuclear energy, the generation power is 100 MWe. During the peak of electricity consumption, combined with heat storage or natural gas co-firing, the generation power can be increased to 242 MWe [7, 8].

* Corresponding author.
E-mail address: fuyao@sinap.ac.cn (Y. Fu).

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At present, the development of FHR is still in the stage of a concept proposal, basic theory study, and experiment research [9, 10, 11]. In recent years, there has been continuous progress in radiation experiments, corrosion experiments, tritium control, thermal hydraulics, and neutron analysis. The development trends of FHR are as follows:

- Extend the lifetime and maintenance period. The design lifetime of the reactor should be 60 years, and the maintenance period should be no shorter than 10 years.
- Improve safety. To improve intrinsic safety, the reactor needs to be operated at low pressure. In addition, it should have a passive decay heat removal system and a more reliable physical barrier.
- Utilize the high-temperature heat. The reactor can be combined with a high-temperature and high-efficiency power generation system. The reactor can be also combined with molten salt energy storage to realize the hybrid utilization of energy, such as heating, seawater desalination, high-temperature hydrogen production, and so on.
- Modular design. The components of the reactor should be modularly designed and constructed, to maximize factory manufacturing instead of on-site processing. The size of the components should comply with the transportation conditions of most railways and roads. Multi-reactor expansion should be possible.
- Inherit existing technology. The relevant existing technologies should be applied in the new design as much as possible, including the related industrial equipment and design and construction experience of MSR.
- Improve environment adaptability. In the future, the site selection of SMR should be more flexible. The reactor needs to be adapted to a variety of areas, such as mining areas, mountainous areas, islands, etc.

However, the development of FHR also faces many challenges [12]:

- Equipment materials need to be able to withstand the corrosiveness of fluoride salts because fluoride ions in molten salts can react with most alloying elements.
- Although there are many options for high-efficiency power generation systems such as the helium Brayton cycle and supercritical carbon dioxide cycle, the coupling technology between the power generation cycle and the FHR system needs further research and verification.
- As the molten salt flows through the outside of the reactor, these pipes need to be insulated and heated to avoid the solidification of the fluoride salt. The heating process needs to be controlled to avoid local overheating.
- Tritium can cause corrosion and radiation damage to metal piping, which in turn affects the mechanical properties and service life of equipment materials. Therefore, the control of tritium is a key issue in the development of FHR.
- FLiBe is the primary coolant for FHR, which contains beryllium. Beryllium is a carcinogen, so workers must be protected accordingly.
- The melting point of FLiBe salt is 460 °C. The refueling operation of FHR needs to be carried out above 460 °C to avoid the solidification of the salt. This is a challenge for the core refueling system design.

In 2013, China proposed the concept of the “The Belt and Road Initiative”, which aims to strengthen the economic cooperation of Eurasian countries. In Figure 1, the red line depicts the land-based part of the new silk road, the “Silk Road Economic Belt”, while the blue line depicts the marine-based part of the new silk road, the “Maritime Silk Road of the 21st Century”. The “Silk Road Economic Belt” is a new economic development area formed based on the ancient “Silk Road” concept, including five northwestern provinces as well as four southwestern provinces in China. Due to their vast area and abundant resources, these areas have huge potential for economic development. Economic development relies on the supply of energy. However, the climate and traffic conditions of these areas make the energy supply difficult. There are abundant renewable energy resources along China’s western part of the ‘Silk Road Economic Belt’. Renewable energy, especially wind and solar energy, is unstable and intermittent due to the influence of weather conditions. Nuclear energy can be used as a supplement to a low-carbon energy system because of its stability and reliability. The purpose of this paper is to obtain a target image of applying small modular FHR in remote areas in western China through a comprehensive analysis of natural resources, energy demand, and environmental conditions.

The study is structured as follows. First, energy demand in remote areas of the west is analyzed in Section 2. Based on the energy demand, the typical application scenarios and regions are selected in Section 3. The environmental conditions of these regions are analyzed in Section 4. The application target image of applying small modular FHR in remote areas in western China is formed in Section 5. Finally, this paper will be concluded in Section 6.

2. Energy demand

Figure 2 shows the regions of northwest China. Gansu, Qinghai, Ningxia, and Xinjiang, the typical northwestern provinces, are chosen as exemplar regions in this section to analyze the energy demand from the perspectives of the research area overview, energy resources, energy production and consumption.

2.1. Overview of the research area

Table 2 shows the basic information of typical northwestern provinces. The annual average temperature in China is 8–18 °C. The annual average temperature in northwest China is lower than the national annual average temperature. Hence, the climate in this area is relatively cold. The annual average rainfall in China is 628 mm. The northwestern region has less rainfall, and the climate is relatively dry or even arid. Gansu, Qinghai, and Xinjiang have large elevation spans, including plateaus, mountains, and basins, so the topography of some areas is complex. At the end of 2019, the urbanization rate of China’s permanent population reached 60.6%. The urbanization rates in Gansu, Qinghai, and Xinjiang are all low. People scattered in rural and mountainous areas may face difficulties in energy supply. The population of ethnic minorities in the northwest is relatively large. The population of ethnic minorities in Qinghai, Ningxia, and Xinjiang is more than 1/3. Their unique concept of settlements and environment may affect the development and utilization of energy. In 2019, China’s primary, secondary, and tertiary industries accounted for 7.1%, 39%, and 53.9% of GDP, respectively. The primary industry (agriculture) in the northwest has a relatively high
To optimize the industrial structure and promote economic development in the northwest, more energy and resources need to be invested in the secondary (industry) and tertiary industries (service sector).

### 2.2. Energy resources

Table 3 shows the main energy resources of the typical northwestern provinces in 2016. Table 4 shows the proportions of fossil energy nationwide. China is a country with much coal, a little oil, and a little gas. Although the coal proportions of these four provinces are not high, the reserves are still abundant. Gansu and Xinjiang are rich in oil resources, while oil resources in Qinghai and Ningxia are relatively scarce. In terms of natural gas reserves, only Xinjiang has relatively abundant resources. Without carbon emission restrictions, northwestern provinces can rely on their fossil energy resources to achieve economic growth. However, in the context of a low-carbon economy, China is pursuing energy structure optimization to control the growth of total energy consumption, especially the growth of high-carbon energy from coal and petroleum [13]. Hence, Xinjiang can rely on its natural gas resources to solve energy supply problems, but Gansu, Qinghai, and Ningxia all need to work hard to develop non-fossil energy.
Table 2. Basic information of typical northwestern provinces.

|                      | Gansu          | Qinghai        | Ningxia        | Xinjiang       |
|----------------------|----------------|----------------|----------------|----------------|
| Annual average temp. | 0.15 °C        | 5.1–9.0 °C     | 5.3–9.9 °C     | 4.13 °C        |
| Altitude             | 1500–3000 m    | 3000–5000m     | 1100–1200m     | -155-8611m     |
| Annual rainfall      | 300 mm         | 400 mm         | 400 mm         | 150 mm         |
| Sunshine duration    | 1975–3000 h    | 2336–3341 h    | 3000 h         | 2500–3500 h    |
| Climate              | Temperate     | Plateau        | Temperate      | Temperate      |
| Topography           | Mountain      | Plateau-Tibet  | Plateau-Tibet  | Plateau-Tibet  |
| Area                 | 425,800 km²   | 722,300 km²    | 66,400 km²     | 1,660,000 km²  |
| Major minorities (%) | Hui (4.7%),    | Tibetan (22.5%),| Hui (33.9%),   | Uighur (45.2%),|
|                     | Dongxiang (1.8%),| Tu (3.9%),      | Mongolian (1.8%)| Kazakh (6.7%), |
|                     | Tibet (1.8%)  | Salar (1.8%)   |                | Hui (4.5%)     |
| Permanent residents  | 26,474,300    | 6,078,200      | 6,946,600      | 25,232,200     |
| Natural pop. growth rate | 6.21%  | 7.58%          | 8.03%          | 3.69%          |
| Urbanization rate    | 48.49%         | 55.52%         | 59.86%         | 51.87%         |
| GDP (2019)           | 871.83 billion ¥ | 296.595 billion ¥ | 370.518 billion ¥ | 1,359,711 billion ¥ |
| GDP per capita       | 32995 ¥        | 48981 ¥        | 54094 ¥        | 54280 ¥        |
| Primary, secondary, and tertiary industries (%) | 12.05%, 32.83%, 55.12% | 10.2%, 39.1%, 50.7% | 7.6%, 44.5%, 47.9% | 13.1%, 35.3%, 51.6% |

Table 3. Main energy resources of the typical northwestern provinces [14, 15, 16]

|                      | Gansu          | Qinghai        | Ningxia        | Xinjiang       |
|----------------------|----------------|----------------|----------------|----------------|
| Oil reserves (10⁶ tons) | 28261.7        | 8252.3         | 2432.4         | 59576.3        |
| Natural gas reserves (10⁶ m³) | 318.03        | 1354.44        | 274.44         | 10251.78       |
| Coal reserves (10⁸ tons) | 27.32          | 12.39          | 37.45          | 162.31         |
| Annual effective utilization hours of wind power(h) | 1787           | 1743           | 1811           | 2147           |
| Annual effective utilization hours of photovoltaic(h) | 1614           | 1695           | 1597           | 1611           |

2.3. Energy production and consumption

Figures 3, 4, and 6 show the energy production and consumption in the typical northwestern provinces in 2016. Except for Qinghai, other provinces can almost achieve self-sufficiency of coke (see Figure 3). The consumption of crude oil and natural gas in Gansu and Ningxia relies on input, and the factors of self-sufficiency are below 3% (see Figures 4 and 5). The four provinces can achieve self-sufficiency in power generation. Moreover, there is a certain margin that can be used to transmit power from west to east with the Ultra High Voltage (UHV) project (see Figure 6). Therefore, the energy supply gap in the underdeveloped regions of the northwest may lie in the non-electric applications of crude oil and natural gas.

The utilization ways of crude oil and natural gas in Gansu Province are analyzed here, to know whether there are alternative sources to meet the energy demand. Figure 7 shows the industry proportions in the oil and natural gas consumption in Gansu [17]. The top 3 in oil consumption are "industry", "transportation, storage and postal industry", and "living consumption", which account for 82% in total. The top 3 in natural gas consumption are "industry", "other industries", and "living consumption", which account for 78% in total. Several utilization ways of oil and natural gas cannot be replaced by other energy sources, such as chemical products, transportation fuel, household fuel, and so on. In industry, mining, high-temperature processes, and heat supply can be replaced by other energy sources. In the residents’ daily life, heating can be provided by other energy sources.

2.4. Energy demand in northwest China

Based on the previous discussion, the energy demand in northwest China is as follows:

- As the northwestern region is relatively arid, energy supply devices should not rely on water resources.
- The construction of energy supply devices needs to adapt to the cold environment and even snowy weather in winter in northwest China. Therefore, the on-site construction period is required to be short.
- The energy demands of scattered populations in rural and mountainous areas should be met. Because of the complex terrain there, the parts of the energy supply device should be as few as possible and suitable for transportation.
Due to the large population of ethnic minorities in remote areas in the west, the way of energy development and utilization should conform to the ethnic minority’s environmental protection concept of ‘sacred mountains and holy waters’ [18].

To promote the economic development of the western region and undertake the transfer of industries from the east, more energy needs to be invested in the secondary industry [19]. Therefore, the energy supply device should be able to meet some industrial energy demands.
Low-carbon energy should be provided to help achieve the national strategic goals of carbon peaking in 2030 and carbon neutrality in 2060 [20].

The western region is rich in renewable energy. Due to the unstable characteristics of solar and wind energy, it is required that energy supply devices should be able to integrate energy storage to help the local consumption of renewable energy.

Some non-electric applications of oil and natural gas should be replaced by other energy sources, such as mining, high-temperature processing, and heat supply.

3. Typical application scenarios and regions

3.1. Low-carbon power generation

The process of nuclear power generation is like that of thermal power generation. The heat for thermal power generation comes from the burning of fossil fuels in the boiler, while the heat for nuclear power generation comes from nuclear fission reactions [21]. Nuclear power has no direct CO₂ emissions during the production process. Thus, it is an important emission reduction measure for the power sector. Nuclear power is of high quality and cost-competitive, but there are problems with nuclear safety. Traditional large nuclear power plants also have other shortcomings, such as long construction periods, high investment, and no peak regulation function [22]. Due to the characteristics of FHR, such as inherent safety, modular design, and the feature that can be combined with molten salt energy storage, it can overcome the shortcomings above and be used for low-carbon power generation in remote western regions.

There are energy shortages and low-quality phenomena in remote areas in western China. An energy consumption survey in the desert area of the Hexi Corridor shows that 72.5% of farmers still use biomass energy, that is, using firewood and straw for heating and cooking [23]. The use of firewood has an impact on the fragile local ecosystem and pollutes the air. FHR can provide sufficient low-carbon electricity for this type of area, which is not only beneficial to the local ecological environment but...
also solves the problem of difficulty in setting up grids in areas with harsh weather and complex terrain.

Gansu is used as an example to analyze the electricity demand in rural areas. Figure 8 shows the rural population of each city in Gansu Province. According to the domestic electricity consumption per capita of 350 kWh/a in Gansu [17], the average power of rural domestic electricity consumption is also shown in Figure 8. If FHR is used to supply electricity to the rural population in various cities in Gansu Province, its power generation range should be 1-78MWe.

### 3.2. Mineral mining

Coal mines can be divided into open-pit coal mines and underground coal mines. Because the coal seam of an open-pit coal mine is close to the surface, the coal mine can be directly excavated by stripping the surface soil layer. The coal seam of underground coal mines is far from the surface, so it is necessary to dig underground tunnels to dig the coal mines. Most coal mines in China are underground mines. Figure 9 shows the energy consumption processes in underground coal mining. Energy

![Figure 8. Rural population and average power of rural domestic electricity consumption of each city in Gansu Province.](image)

![Figure 9. Energy consumption processes in underground coal mining [24].](image)
consumption is mainly concentrated in the mining, ventilation, and washing processes. According to the main purpose of each process, the energy consumption in coal mining areas is mainly electricity and heat. Therefore, when the mining area is remote, FHR can co-generate heat and power to meet the energy demand.

The annual production of some coal mining areas in Gansu Province is shown in Figure 10. The energy consumption per ton of coal in Gansu is 7.28 kg of standard coal. If each kilogram of standard coal is equal to 5 kWh [24], the average power consumption in each mining area is shown in Figure 10 as well. The power range of FHR used for coal mining should be 11–83 MWe.

3.3 Molten salt energy storage

Molten salt energy storage is often applied in tower CSP stations. The tower CSP station consists of three parts: a solar concentrating system composed of heliostat and heat absorber on the top of the tower, heat storage and exchange system composed of cold/hot salt tanks, cold/hot salt pumps and steam generators, and a power generation system composed of a steam turbine generator set and its auxiliary equipment [25]. The tower CSP station collects solar energy with the heliostats, then the heat is transferred to the heat sink of the central tower. Multiples of concentrated light can reach 500–1000, which makes the efficiency of the power generation high. The tower CSP station needs energy storage to meet the load at night. The heat absorption during the day ought to be greater than the heat release for power generation, hence the excess heat can be stored in the hot salt tank for power generation during the night [26].

The molten salt energy storage of the tower CSP station can not only be used for power generation during the night but also can make the CSP station become a peak-shaving power station, which can meet the local electricity demand combined with the non-dispatchable photovoltaic and wind power generation. However, when the power grid is large, or it is continuously rainy and windless, the heat storage from the concentrated solar energy may not be sufficient to meet the demand for peak shaving. Therefore, in the exploration trend of multi-energy coupling, it is considered that nuclear energy can be added to the local hybrid energy system. Part of the nuclear heat is used to supplement the molten salt energy storage of CSP stations, and the remaining nuclear heat is used for power generation. Table 5 shows some tower-type CSP stations in western China. If FHR is used for the molten salt energy storage of a hybrid energy system, it needs to completely replace CSP for grid peak shaving in bad weather. Therefore, considering that its installed capacity should be the same as that of a CSP station, that is, the design power range of FHR ought to be 50–100 MWe.

3.4 High-temperature hydrogen production

As a kind of clean energy, hydrogen has a wide range of applications (see Table 6). The outlet temperature of FHR exceeds 700 °C. The heat provided can be used in the high-temperature hydrogen production process. FHR is suitable for high-temperature electrolysis hydrogen production, where the heat-hydrogen conversion efficiency can reach more than 44% [28]. Compared with room temperature electrolysis hydrogen production, the advantages of high-temperature electrolysis are that it can reduce electricity demand, reduce the polarization loss and ohmic resistance of the electrolytic cell, and accelerate the electrode reaction. High-temperature electrolysis is the reverse operation of solid oxide fuel cells (SOFC). The flat-plate solid oxide electrolysis cells (SOEC) are currently mostly used. During water vapor electrolysis, a reduction

![Figure 10. Annual production and average power consumption of some coal mining areas.](image)

| Table 5. Some tower-type CSP stations in western China [27]. |
|-------------|-----------------|-----------------|-----------------|
| Project name                                      | Location          | Installed Capacity (MWe) | Heat storage time(h) | Status          |
| Beijing Shouhang Dunhuang Tower CSP Demonstration Project | Dunhuang, Gansu    | 100                       | 11                  | In operation    |
| Qinghai Supcon Delingha Tower CSP Project         | Haixi, Qinghai    | 50                        | 6                   | In operation    |
| China Power Construction Republic Tower CSP Project | Hainan, Qinghai    | 50                        | 6                   | In operation    |
| Luneng Haixi Golmud Tower CSP Project              | Haixi, Qinghai    | 50                        | 12                  | In operation    |
| China Power Engineering Hami Tower CSP Project     | Hami, Xinjiang    | 50                        | 13                  | In construction |
| Beijing Shouhang Yumen Molten Salt Tower CSP Project | Yumen, Gansu      | 100                       | 10                  | Construction preparation |

| Table 6. Hydrogen applications [33]. |
| Application type | Application scenario                       |
|------------------|-------------------------------------------|
| Fuel             | Space shuttle, rocket, city bus          |
| Industry         | Electronics industry, metallurgical industry, food industry, oil refining industry, etc. |
| Observation and testing | Meteorological observation, gas chromatography |
| Fuel cell        | electric car                            |
reaction occurs at the cathode to obtain hydrogen. Then the generated oxygen ions move to the anode and release electrons to generate oxygen. The high-temperature electrolysis hydrogen production reaction can be summarized as cathode \(2e^- + H_2O \rightarrow H_2 + O_2^-\), anode \(O_2^- \rightarrow \frac{1}{2}O_2 + 2e^-\). The total reaction is \(H_2O \rightarrow H_2 + \frac{1}{2}O_2\) [29].

In China’s “14th Five-Year Plan” and the draft outline of 2035 long-term goals, it is required to deploy future industries in frontier fields such as hydrogen energy and energy storage. For example, Ningxia province strives to build 1–2 hydrogen refueling stations with a minimum daily hydrogen refueling capacity of 500 kg by 2025, and form an industry cluster of hydrogen energy [30]. In April 2021, the “National Comprehensive Demonstration Project for Hydrogen Production by Solar Energy Electrolysis” at the Ningdong Energy and Chemical Base in Ningxia was officially put into production. The production capacity of this project reached 20,000 Nm\(^3\) per hour [31]. Assuming that FHR is used for high-temperature electrolysis hydrogen production, as the energy consumption of hydrogen production is 3.7 kWhe/Nm\(^3\) [32], the FHR installed capacity is required to be 74 MWe to achieve the same production capacity of this project.

4. Environmental conditions

This section analyzes the environmental conditions of typical application areas. Four application areas are chosen from the typical application scenarios: Pingliang (Gansu) for low-carbon power generation, Qingyang (Gansu) for mineral mining, Haixi (Qinghai) for molten salt energy storage, and Yinchuan (Ningxia) for high-temperature hydrogen production.

4.1. Climate conditions analysis

Figure 11 shows the temperature in the typical application regions. The winter in the western region is cold, which will form a frozen soil layer and affect ground operations. For example, in Yinchuan, the annual minimum temperature is \(-30.6 \degree C\), which makes the depth of frozen soil in winter reach 1 m. The average annual maximum temperature of these areas is 33.7 \degree C. The annual average temperature is between 0 and 10 \degree C in these areas.

Figure 12 shows the sunshine duration in typical application areas. Yinchuan has the longest annual sunshine duration, which is 2906 h. Pingliang has the shortest annual sunshine duration, which is 2262 h. Regarding the typical construction cities in China, the sunshine duration in Beijing is about 2400 h, and that in Shanghai is 1886 h. Thus, the sunshine duration in the typical application areas of FHR will not affect the construction.

Figure 13 shows the wind speed in the typical application regions. The annual average wind speed in China is 1.9 m/s. The annual average wind speed in each typical region is higher than the national average. For
example, the annual average wind speed in Haixi reaches 4 m/s. To be more precise, the annual average wind speed in Haixi is affected by the topography, which in the basin is generally 3–4 m/s, and which on the mountain is above 4 m/s. Moreover, the annual maximum wind speed in each typical region is higher than 17 m/s, which is strong wind above level 8. It occurs 9 times a year on average in Pingliang. Therefore, the construction of FHR projects needs to consider the influence of local wind speed.

Figure 14 shows the precipitation in the typical application regions. The precipitation in each typical application region is below the national average of 628 mm. Pingliang has the highest precipitation, which is 511 mm. The precipitation of Yinchuan is only 200 mm. The western area in China is generally arid and semi-arid. Due to the lack of water resources, the construction of FHR needs to adapt to the arid environment.

4.2 Geographical conditions analysis

Table 7 shows the geographical conditions of typical application regions. Haixi and Yinchuan are at risk of earthquakes. For safety reasons, it is not suitable to build a reactor there. In other areas, there are common risks of landslides, collapses, torrents, and mudslides. Thus, FHR should pay special attention to avoiding locations with these risks when selecting sites. Each typical application region has both highways and railways. It is not difficult to transport the reactor vessel to the cities. However, to reach a specific construction site, the vehicle may need to

| Typical application regions | Pingliang | Qingyang | Haixi | Yinchuan |
|-----------------------------|-----------|----------|-------|----------|
| Topography                  | Hilly area| Gully area, hilly area | Ring-shaped distribution of mountains, hills, gobi, plains, lakes, and marshes | Floodplain |
| Transportation              | Highway, railway | Highway, railway, airport | Highway, railway, airport | Highway, railway, airport |
| River                       | A big river | Multiple small rivers | Multiple small rivers | A big river |
| Geological disaster         | Landslides, mountain torrents, gully debris flows | Floods, landslides, mudslides | Earthquake | Earthquake |
| Population density          | 187.8/km² | 82.3/km² | 1.7/km² | 246.5/km² |
pass through complex terrain. Therefore, the modular design, especially the size and weight, should take the transportation requirements into account to avoid transportation accidents. The river resources in each typical application region are related to local drinking and domestic water, so they cannot be used for a reactor to avoid safety accidents. Compared with the eastern coastal cities in China, the typical application areas in the west have a lower population density. Thus, it is relatively easy to find suitable locations for the FHR layout.

5. Application target image

5.1. Power and lifetime

The installed capacity demand of FHR’s typical application scenarios in Section 3 is summarized in Table 8. The power range of typical application scenarios is 1–100 MWe. The single-reactor capacity of FHR can be set to 50 MWe, and higher power demand can be achieved with multi-reactor expansion. The multi-reactor expansion of the small modular reactor can not only meet a variety of power demands but also reduce the cost of electricity [34]. To ensure the economy of FHR, it is necessary to have a competitive design lifetime. When nuclear power plants in the United States are put into operation, the Nuclear Regulatory Commission (NRC) issues a 40-year operating license for them. However, as of 2015, 74 of the 100 nuclear reactors in service in the United States have obtained new licenses for 20 years, and the operating life of these reactors would be extended to 60 years [35].

The design life of a nuclear power plant is currently determined by two non-replaceable components, namely the reactor pressure vessel and the containment vessel. To make the reactor pressure vessel design meet the requirements of relevant laws and regulations, various influencing factors will be considered conservatively. Therefore, when the nuclear power plant reaches the design lifetime, the pressure vessel can still be used for a period. In 2020, a total of 6 units worldwide have been approved for life extension, including 3 Spanish units, 2 U.S. units, and 1 Russian unit [36]. In the future, there will be more pressurized water reactors that were put into operation in the last century facing life expansion. China’s Qinshan nuclear power station and Daya Bay nuclear power station are also facing life expansion. Therefore, to be economically competitive in the future, the design lifetime of FHR should be at least 60 years.

To support the FHR’s life up to 60 years, the choice of materials for the non-replaceable reactor vessel is critical. The material of the FHR reactor vessel should have the characteristics of being able to withstand high-temperature static tension, thermal stress fatigue, and creep-fatigue [12]. Alloys 800H or HT, Hastelloy N, and Haynes 242 have been considered as reactor vessel materials for AHT due to their sufficient corrosion resistance to molten fluoride salts and sufficient strength to high temperatures [1]. Hastelloy N is further used in the reactor vessel of SmAHTR [2]. PB-AHTR uses alloy 800H as the material of the reactor vessel, and the part in contact with the molten salt is covered with Hastelloy N [3]. 316 Stainless Steel is used for the reactor vessel material of Mk1 PB-FHR, while 304 Stainless Steel and Alloy N are considered as alternative materials [4]. Currently, China can produce alloy GH3535, which has similar properties to Hastelloy N [12]. Since AHTR [37], SmAHTR [38], and Mk1 PB-FHR [4] are designed to last for 60 years, the designers assumed that these metallic materials could last up to 60 years. However, as a relatively new type of reactor, FHR needs further experimental verification for the life of the reactor vessel.

5.2. Size and weight

Since the reactor needs to be transported by trains and trailers, it needs to meet size and weight requirements. Generally, goods transported by train must be within the limits of rolling stock. The rolling stock boundary is the maximum width and height of different parts of the rolling stock and the minimum distance between the bottom and the track surface. It is the largest cross-section of rolling stock. The boundary of rolling stock and the boundary of bridges and tunnels restrict each other, that is, when rolling stock is loaded with goods, even if it shakes or deviates, it will not contact the bridges, tunnels, and other equipment on the line. The China Railway Transport Bureau stipulates the limits of rolling stock [39]. If the reactor vessel should not exceed the boundary of the rolling stock, the diameter of the vessel should be less than 3.4 m.

Train cargo sometimes exceeds the boundary of rolling stock, which can be divided into first-level over-limit, second-level over-limit, and super over-limit. Over-limit cargo will increase transportation costs [39]. If it is considered that the reactor vessel cannot exceed the second-level over-limit, the diameter of the reactor vessel should be less than 3.88 m. Moreover, train transportation generally needs to meet the requirements that the length is less than 15.5 m, and the load is less than 60 tons.

The weight limit for trucks with 6 axles and above is 49 tons. Because the self-weight of tractors and semi-trailers is 15 tons, the trailer can carry about 34 tons. The semi-trailer is 13.75 m in length, 2.55 m in width, and 4 m in height [40]. Therefore, if the road transportation of the reactor vessel is considered as ordinary transportation, the length of the reactor vessel should be less than 13.75 m, the diameter should be less than 2.55 m, and the weight should be less than 34 tons. Since FHR is a high-value cargo, special transportation can also be considered for road transportation of the reactor vessel. In this case, there is no need to consider the size and weight restrictions, but the removal of the toll station will increase a lot of transportation costs. The widest lane of the toll gate is 4.5 m.

The size and weight restrictions above are summarized in Table 9. If the reactor vessel is transported with ordinary transportation, the length should be less than 13.75 m, the diameter should be less than 2.55 m, and the weight should be less than 34 tons. However, if the reactor vessel is transported with special transportation, the length should be less than 15.5 m, the diameter should be less than 3.88 m, and the weight should be less than 60 tons.

To verify the rationality of the size and weight restrictions, some current SMRs were investigated (see Table 10). These SMRs have a height range of 5.4–30 m, a diameter range of 2–8.5 m, and a weight range of 42–1250 tons. There is no clear relationship between the size-weight parameters and the power-type parameters. Hence the above-mentioned FHR size and weight restrictions considering transportation are rational.

5.3. Environmental restrictions

The environmental conditions of the typical application regions in Section 4 are summarized as follows:

| Table 9. Size and weight restrictions considering transportation. |
|---------------------------------------------------------------|
| **Railway transport (ordinary)** | **Railway transport (special)** | **Road transport (ordinary)** | **Road transport (special)** |
| length | ≤15.5m | ≤15.5m | ≤13.75m | / |
| diameter | ≤3.4m | ≤3.88m | ≤2.55m | ≤4.5m |
| weight | ≤60t | ≤60t | ≤34t | / |
The weather in winter is cold, and the frozen soil layer is deep. The annual average wind speed is high, and there are strong winds above 8 levels. The environment is generally arid. There are risks of landslides, collapses, torrents, mudslides, and ground fissures. The terrain is complex.

To adapt to the above environment restrictions, FHR needs to be inherently safe and should have no demand for an off-site emergency. FHR needs to be modularized to shorten the construction period on site. The structure of FHR ought to be compact and sturdy, and the size and weight should be suitable for train and trailer transportation. FHR needs to adapt to anhydrous conditions. Moreover, the site selection should avoid areas with a high incidence of natural disasters.

In addition to the environmental constraints of the reactor itself, the important components of FHR power plants, such as the direct reactor auxiliary cooling system (DRACS) and the energy conversion system, are also subject to environmental constraints. DRACS is used to remove decay heat from the reactor core during normal shutdowns or emergencies. DRACS uses an air cooling tower, thus its coolant should have a low melting point to prevent salt from freezing inside the circuit [2], especially in winter. The arid environment requires that the power generation system does not use water as the working fluid. Compact systems and smaller equipment are also important for transport and assembly. Supercritical carbon dioxide (SCO2) Brayton cycle has a compact system due to its high energy density and is a potential choice for the FHR power generation system [12].

6. Conclusion

To form the target image of a small modular FHR in remote areas of western China, an energy demand analysis of the research area was firstly performed in this paper. Then the specific power demand and the environmental conditions were analyzed for typical application scenarios and regions. Finally, the target image was formed including the power, lifetime, size, weight, and environmental requirements. This paper finds that the small modular FHR matches the energy demand of remote areas in western China. It can provide clean power and high-temperature process heat for typical application scenarios such as low-carbon power generation, mineral mining, molten salt energy storage, and high-temperature hydrogen production. The single unit capacity can be set to 50 MWe, and higher power demand can be achieved through multi-reactor expansion. If FHR can be transported with special transportation due to the high value, the reactor vessel needs to be less than 15.5 m in length, less than 3.88 meters in diameter, and less than 60
tons in weight. The design lifetime should be at least 60 years. In addition, FHR also needs to adapt to the climate and geographical conditions of the remote areas in western China.

Declarations

Author contribution statement

Yanwen Guo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Ye Dai: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.
Jinhong Zhang: Contributed reagents, materials, analysis tools or data.
Dianqiang Jiang: Performed the experiments.
Yao Fu: Conceived and designed the experiments.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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