Nuclear Engineering and Design 340 (2018) 9–16

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

A miniature integrated nuclear reactor design with gravity independent autonomous circulation

Qin Zhou[a], Yan Xia[b,c,*], Guoqing Liu[b,c], Xiaoping Ouyang[d]

[a] Institute of Nuclear and New Energy Technology of Tsinghua University, the Key Laboratory of Advanced Reactor Engineering and Safety, Ministry of Education, Beijing 100084, China
[b] Beijing Institute of Spacecraft Environment Engineering, Beijing 100094, China
[c] Science and Technology on Reliability and Environmental Engineering Laboratory, Beijing 100094, China
[d] State Key Laboratory of Intense Pulsed Radiation Simulation and Effect, and Radiation Detection Research Center, Northwest Institute of Nuclear Technology, Xi'an 710024, China

ARTICLE INFO

Keywords:
Autonomous circulation
Integrated nuclear reactor
Stirling cycle
Independence on gravity
Inherent safety

ABSTRACT

A miniature integrated nuclear reactor design with gravity independent autonomous circulation (ACMIR) was newly proposed. The reactor core, energy transfer system of Stirling and linear electric motors are integrated in the reactor pressure vessel to achieve high power density and autonomous circulation capability. The coolant circulation is autonomously driven by gas expansion at heat end and compression at cool end thus is independent on gravity. Twelve sets of rotary drum controller and reflector are used to regulate reactivity outside the reactor pressure vessel. The physics and thermodynamic properties, as well as the safety performances are analyzed. According to these analysis, inherent safety characteristics are obtained, and the reactor is capable to shut down and remove residual heat passively without any external intervention, in accident conditions such as loss of external power supply, overtemperature/overpressure of the reactor, impact when rocket launching or landing, stagnation of the displacer or piston, et al. The integration, less pipes design, gravity independent autonomous circulation features make it a good candidate for space flight propulsion, the Moon and Mars base power supply, the deep-sea or other tilt and swing situation applications.

1. Introduction

As a kind of clean energy which provides large scale stable electric power, nuclear energy is one of the most important means to alleviate the contradiction between energy needs and environment. The key issues to the application of nuclear energy is its safety. With the development of nuclear technology, most of Generation III and Generation IV nuclear power systems have inherently safe characteristics, as with key assurance techniques such as full power or partial power natural circulation, passive residual heat removal system, et al. (Abram and Ion, 2008; Rowinski et al., 2015).

Man is exploring the universe deeper while the solar power gets less available and adequate, especially for missions beyond Mars (Oman, 2003; Summerer and Stephenson, 2011; Woo and Lee, 2014; Nuclear Reactors to Power Space Exploration, 2017). Even for Moon surface bases' usage; solar power faces the shortage problem as one moon night lasts for a half earth month. ESA and NASA have been conducting researches on nuclear power sources (NPS) in space for several years (Oman, 2003; Summerer and Stephenson, 2011; Woo and Lee, 2014; Nuclear Reactors to Power Space Exploration, 2017; Bennett, 2008; Cassady, 2008). Thus, space usage friendly nuclear electric power of scores or hundreds of kilo watt is a critical requirement.

Space NPS includes radioisotope power sources (RPSs) and space nuclear fission reactors. RPSs convert decay heat of radioisotopes into electricity. They are relatively small and satisfy mainly under 1 kilo watts supply need. Nuclear fission reactors are relatively large, and are more economic for space power demands of Moon/Mars bases and deep solar system explorer propulsion (Oman, 2003; Nuclear Reactors to Power Space Exploration, 2017).

Space nuclear fission reactors are principally similar to terrestrial reactors, but have to make structurally and functionally space adaptive modifications in all parts like reactor cores, cooling and heat transfer system, control system, energy conversion system, and heat rejection system. Even though, as shown in Fig. 1-1, typical terrestrial pressure water reactor nuclear power plant and space nuclear fission reactor power system are still the same in taking two functional units coupling

* Corresponding author at: Beijing Institute of Spacecraft Environment Engineering, Beijing 100094, China.
E-mail address: xiayan_cast@163.com (Y. Xia).

https://doi.org/10.1016/j.nucengdes.2018.09.013
Received 5 July 2018; Received in revised form 3 September 2018; Accepted 14 September 2018
0029-5493/

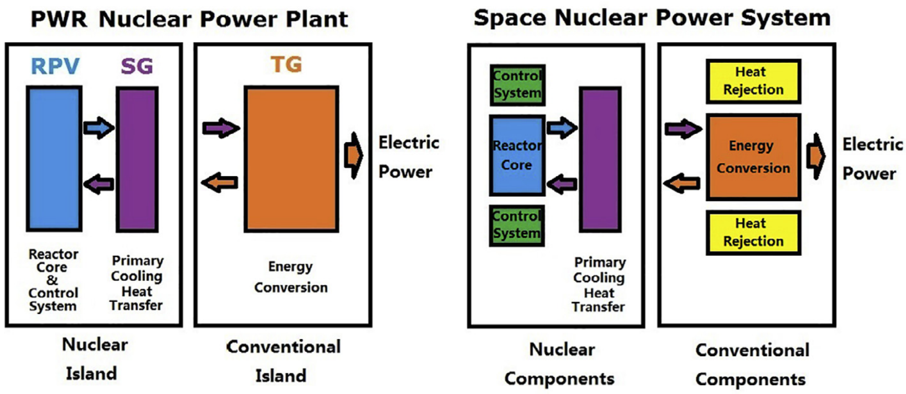

Fig. 1. -1. Typical pressure water reactor nuclear power plant and space nuclear fission reactor power system (RPV: Reactor Pressure Vessel, SG: Steam Generator, TG: Turbo-Generator).

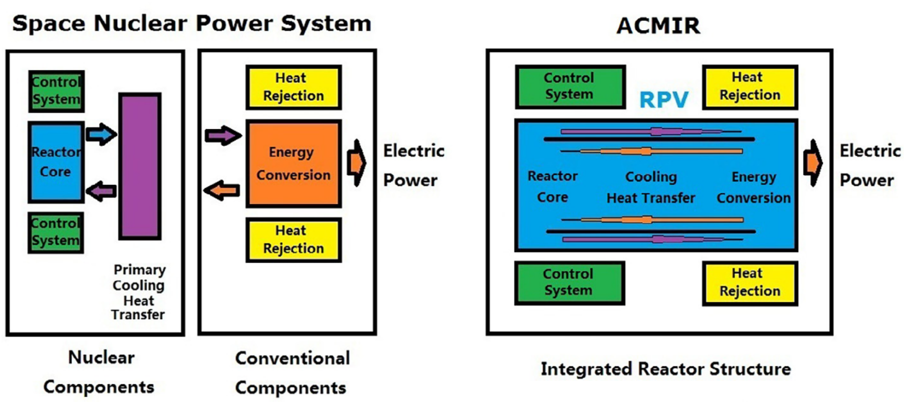

Fig. 1. -2. Typical space nuclear power system and autonomous circulation micro integrated nuclear reactor (ACMIR) in this article.

structure, miniature integrated reactors are barely designed and discussed.

The cooling choices of space reactor mainly include liquid metal cooling, gas cooling, liquid metal heat pipe, et al. Liquid metal heat pipes have high security performance via avoiding single point failure, but technique for transferring hundreds of kilo watt or larger power from a small reactor core via heat pipes is immature (Summerer and Stephenson, 2011; Woo and Lee, 2014). Liquid metal cooling and gas cooling have no large differences to those of terrestrial reactors, and thus have higher technological maturity. But terrestrial coolant natural circulation is generally driven by gravity and coolant density difference, which is no longer valid in space environment Thus, pumps or draught fans have to be used in space reactors for driving gas or metal coolant, and bring risk of core melting caused by pump or draught fans failure and loss of cooling capability (Poston, 2001; Powell et al., 2003; El-Genk and Tournier, 2004; Na and Upadhyaya, 2006; Na, 2006; Na and Upadhyaya, 2006; Na and Upadhyaya, 2006; King and El-Genk, 2006; Maise et al., 2006, 2006.; Na and Upadhyaya, 2007; King and El-Genk, 2007, 2007.; King and El-Genk, 2007; Schriener and El-Genk, 2008; Poston, 2008; King and El-Genk, 2009; Craft and King, 2009).

The energy conversion choices of space reactor mainly include thermocouple, thermion, Stirling cycle, and close Brayton cycle, et al. Thermocouple conversion methods are most widely used at present for its composing none moving components. However, thermocouples have poor radiation resistance and low energy conversion efficiency mostly under 10%, – extremely high hot end temperature beyond 1200 K is necessary to promote beyond 10% conversion efficiency but brings challenges to high-temperature tolerant materials and structures. Thus, ESA and NASA have been vigorously promoting other energy conversion methods as Stirling cycle and close Brayton cycle. Compared to thermocouples, they have much higher energy conversion efficiency, but also have larger and more complex mechanical structures, more moving components, especially for close Brayton cycle (Summerer and Stephenson, 2011; Woo and Lee, 2014).

This article presents a work on mainly space use dedicated miniature integrated nuclear reactor design with gravity independent autonomous circulation (ACMIR for short) and its preliminary reactor physics and thermal hydraulic analysis. The design achieves inherently safety and realizes space autonomous circulation independent on gravity. It also reduces mass and avoided complex and frail mechanical structures of energy conversion units. It provides higher energy conversion efficiency at relatively lower hot end temperature. It contains less pipes and is more likely to survive impact during launching.

The main idea for achieving both key features of gravity independent coolant autonomous circulation and simplified energy conversion system is to integrate the reactor core and energy conversion system together in the reactor pressure vessel (RPV), i.e., integrate two function units into one, as shown in Fig. 1-2.

The design is a dynamic reactor with ingenious and novel reactor structures. The reactor core continually heats the gas coolant making it expand and push moving parts to move. Moving parts does work to electric machinery, let coolant cool and compress contributing extra moving forces. The coolant is autonomously driven by gas expansion at heat end and compression at cool end thus is independent on gravity. The coolant in RPV takes two roles, on the one hand is reactor core cooling and transferring heat to energy conversion system, on the other hand is working medium of conversion system and doing work to electric machinery.