ARTICLE IN PRESS

Annals of Nuclear Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Neutronics and thermal hydraulics analysis of a low-enriched uranium cermet fuel core for a Mars surface power reactor

Kevin J. Schillo [a,*], Akansha Kumar [b], Kurt E. Harris [c], Yayu M. Hew [d], Steven D. Howe [e]

[a] Department of Mechanical & Aerospace Engineering, University of Alabama in Huntsville, Huntsville, AL 35899, United States
[b] Center for Space Nuclear Research, Idaho National Laboratory, Idaho Falls, ID 83401, United States
[c] Department of Mechanical & Aerospace Engineering, Utah State University, Logan, UT 84322, United States
[d] Department of Aeronautics and Astronautics Engineering, Stanford University, Stanford, CA 94305, United States
[e] Talos Power LLC, Idaho Falls, ID 83402, United States

ARTICLE INFO

Article history:
Received 31 March 2016
Received in revised form 13 May 2016
Accepted 16 May 2016
Available online xxxx

Keywords:
Supercritical
Neutronics
Thermal hydraulics
CO_2
Mars

ABSTRACT

A fission reactor utilizing low-enriched uranium cermet fuel and supercritical carbon dioxide as coolant was designed to provide electrical power for a manned Mars base. The reactor was designed to generate 1.67 MWth for a fifteen year operational lifetime, with an electric output of 333 kWe. The core has alternating rows of fuel elements and a breeder blanket, with nineteen coolant channels in the fuel element and a single coolant channel in the breeder blanket. The design uses 15% isotopic enriched U-235 based cermet fuel, and uranium dioxide fuelled blankets. S-CO_2 is used as a coolant, which converts the heat generated by the reactor to electricity using a closed Brayton cycle. Cermet fuel is used in the form of hexagonal shaped elements with 19 coolant channels and a zirconium hydride neutron moderator. The reactor uses B_4C based control drums for control and safety. ZrC is used as thermal insulator, and ensures that the ZrH moderator does not reach an unacceptably high temperature. The coolant channels have a cladding of tungsten to prevent the release of fission gas from the fuel into the coolant. Beryllium reflectors are used to moderate and reflect neutrons back into the active core. The active core has a bull's eye configuration, in which there are alternate fuel and blanket circular rows. Nuclear reactor modeling, neutronics, and depletion analysis were done using MCNP6. The neutronics analysis found the maximum peaking factor that would occur in the core. This was used to determine the greatest amount of thermal power that the core's fuel elements and breeder blanket would experience. This provided the basis for the thermal hydraulics, which sought to determine the maximum inlet and outlet temperatures of the S-CO_2 that could be obtained while also keeping all of the reactor materials within an acceptable temperature range. Maximizing these temperatures would provide the highest performance for a power conversion system. Finding the coolant conditions that kept this section of the core below the maximum permissible temperature would ensure that the rest of the core would also remain within an acceptable temperature limit. Simulations were conducted at the different power levels the fuel element and breeder blanket would generate throughout the reactor's fifteen-year lifecycle. The thermal hydraulics which was done using COMSOL Multiphysics. This research presents a very viable reactor design that uses materials currently tested on other types of reactors.

1. Introduction

In 2009, NASA identified a surface nuclear power reactor as a mission enabling technology for manned Mars expeditions by supplying the power needed for in-situ resource utilization (ISRU). Such a power system offers continuous power as well as lower mass and volume than an equivalent solar power system (Drake, 2009).

The reactor designed uses a low-enriched uranium (LEU) cermet fuel developed at the Center for Space Nuclear Research (CSNR) O'Brien et al., 2012. A Brayton cycle was selected for the power conversion system due to its simplicity, low mass and historic use in spacecraft systems (Mason, 2001). Supercritical carbon dioxide (S-CO_2) was selected as the reactor coolant due to the abundance of carbon dioxide in the Martian atmosphere. ISRU equipment that will also be needed for the Mars base will be

* Corresponding author.
E-mail address: kjs0011@uah.edu (K.J. Schillo).

http://dx.doi.org/10.1016/j.anucene.2016.05.035
0306-4549/

Nomenclature

CSNR	Center for Space Nuclear Research	UO_2	uranium dioxide
ISRU	in-situ resource utilization	W	tungsten
LEU	low enriched uranium	ZrC	zirconium carbide
S-CO_2	supercritical carbon dioxide	ZrH	zirconium hydride

capable of extracting the CO_2 from the atmosphere and bring it to supercritical conditions. This capability to produce reactor coolant on Mars is crucial for the long-term survival and prosperity of a colony (Figs. 1 and 7).

This paper is part of a larger study into the design of a fission power reactor intended to provide a total of 1 MWe for a manned Mars base for fifteen years. The study analyzed the neutronics and thermal hydraulics of the core, as well as the power distribution and power conversion systems. The focus of this paper is the neutronics an thermal hydraulics analysis of the core.

MCNP6 was used for the nuclear reactor modeling, neutronics, shielding, and depletion analyses. COMSOL Multiphysics is used to simulate the most extreme thermal power that would be subjected to a fuel element and breeder channel in the reactor core that has been designed. Maximum values for the inlet and outlet temperatures of the S-CO_2 for both the fuel element and breeder channel were obtained while also ensuring that the materials in the core did not exceed their own maximum permissible temperatures.

The thermal power generated by the fuel element and breeder channel varies as a function of time, and numerous simulations were conducted at different phases of the reactor's operational lifetime. The maximum values for the S-CO_2 inlet and outlet temperatures were obtained at these different thermal power levels. This provides an overview of how the flow conditions of the S-CO_2 must be carefully managed as the reactor operates.

2. Reactor core design

The design of the power conversion system found that the system mass would be optimized by using three separate nuclear reactors, with each generating 333 kWe. The mass of the power conversion system would also be minimized by operating at 20% efficiency. This necessitated that each of the three reactor cores generated 1.67 MWth.

The reactor core has a bullseye configuration, in which there are alternating layers of fuel and breeder blanket hexagonal configurations. The cermet fuel used in the core is comprised of tungsten and uranium-thorium dioxide, with the uranium having an enrichment of 15%. The W-(U-Th)O_2 cermet offers good thermal conductivity, a high melting point, resistance to creep deformations at high temperatures, and good radiation self-shielding. The fuel element has nineteen coolant channels Tungsten cladding is used in the coolant channels of the fuel element in order to prevent the dissipation of gas from the cermet fuel into the coolant. Zirconium hydride (ZrH) was selected as the neutron moderator for both the fuel element and the breeder blanket. Zirconium carbide (ZrC) is used as thermal insulator, and ensures that the ZrH moderator does not become as hot as the rest of the fuel element materials.

The breeder blanket consists of natural uranium dioxide with a single coolant channel and is surrounded by additional ZrH. Fig. 2 illustrates this.

B_4C control drums are used in the core for control and safety. Beryllium reflectors are used to moderate and reflect neutrons back into the active core. Fig. 3 provides a radial overview of the core design:

The specifications of the core are provided in the following table (see Table 1).

For this study, the reactor must provide continuous 1.67 MWth for fifteen years of operation. It is therefore vital that the reactor remains critical for this entire duration of time. The reactor's k_{eff} for this fifteen years of operation is shown in Fig. 4.

From this figure, it can clearly be seen that the reactor will remain critical throughout the entire fifteen year lifecycle.

Throughout the reactor's operational lifetime, the U-235 in the fuel elements is gradually depleted as it undergoes fission reactions, causing the fuel elements to generate less power over an extended period of time. While this is happening, the U-238 in the breeder blanket is converted to Pu-239 from neutron capture. This causes the breeder blanket to generate more power as the reactor operates over time. Fig. 5 shows the change in the power fraction generated by the fuel element and the breeder blanket throughout fifteen years of the reactor's operation:

At the beginning of the reactor's operation, the fuel element generates 83% of the thermal power and the breeder blanket generates 17%. After fifteen years, the fuel element will generate 76% and the breeder blanket will generate 24%.

The main limiting factor for the reactor was the use of ZrH. While ZrH is a very effective neutron moderator, it can only be permitted to reach a maximum temperature of 923 K before it

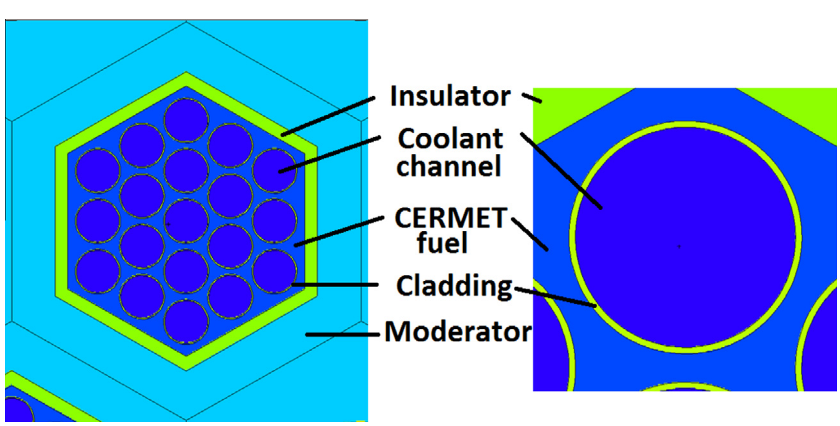

Fig. 1. Cermet fuel element.

Please cite this article in press as: Schillo, K.J., et al. Neutronics and thermal hydraulics analysis of a low-enriched uranium cermet fuel core for a Mars surface power reactor. Ann. Nucl. Energy (2016), http://dx.doi.org/10.1016/j.anucene.2016.05.035