Annals of Nuclear Energy 116 (2018) 388–394

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Simulation and test of Fuel Handling System for Accelerator Driven Subcritical Reactor

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ARTICLE INFO

Article history:
Received 7 November 2017
Received in revised form 28 February 2018
Accepted 4 March 2018

Keywords:
Accelerator Driven Subcritical Reactor
Fuel handling
Numerical simulate
Prototype
Test

ABSTRACT

For the fuel handling in Accelerator Driven Subcritical Reactor (ADSR), some key issues should be considered, such as the accelerator proton beam tube blocking, the liquid metal corrosion and the radiation. As a critical part of the reactor, the innovation design of the double rotating plugs and split-type center column scheme of the Fuel Handling System in the vessel was proposed according to the features of ADSR. A location computation model for the computer simulation was established based on the system. Through the comparative analysis between the numerical simulation results, the proposed structure is optimized and the operating range of the system can completely cover the refueling operation range of the core. Then, a principle prototype in air condition has been developed and tested. The simulated automatic refueling that covering all assemblies was realized on the prototype.

1. Introduction

The Accelerator Driven Subcritical Reactor (ADSR), which consists of a proton accelerator, a subcritical reactor and a heavy metal spallation target, has exhibited great superiority in achieving long-lived radioactive nuclear wastes transmutation and is being developed by many countries (Hassanzadeh and Feghhi, 2014; IAEA-TECDOC-985, 1997; OECD/NEA, 2002). High-energy protons generated by the accelerator impinge on the target to produce spallation neutrons, and they can interact with the nuclear fuel in the reactor to realize the transmutation (Wu et al., 2016a). For having many unique thermal-physical and chemical attributes in the nuclear application, Pb-Bi eutectic (LBE) is selected as the spallation target material and the liquid lead or lead-alloy cooled (lead-based) reactor was proposed as a preferred option for ADS (Abderrahim et al., 2012; Saito et al., 2006; Wu et al., 2014). The Institute of Nuclear Energy Safety Technology (INEST) of Chinese Academy of Sciences has conducted research and development (R&D) on the ADS. The China LEAd-based Research Reactor (CLEAR-I) with 10MWth has been designed for the research of ADSR (Zeng et al., 2015). A uniform proton beam with radius of 50 mm is selected to perform the spallation process and the deposited energy as heat in spallation region is about 1.2 MW when the proton beam with 250 MeV power and 5 mA intensity penetrates the beam window (He et al., 2016).

The teleoperation technology is wildly used in fuel handling in the reactor because nuclear radiation is lethal to human health. It is the indispensable tool and the lifeline of the nuclear industry (Chen, 1994). Safety is considered the top priority in the nuclear energy development, in particular after the Chernobyl nuclear accident in 1986 and the Fukushima nuclear accident in 2011 (Wu et al., 2016b). In the field of energy, the nuclear energy plays a more and more important role for that it can meet the great demand of the energy for human beings. Nuclear radiation is fatal to human health, so developing the nuclear remote robot is the key to resolve the above conflict that the people can't directly operate the facilities in the nuclear power plants (Yang et al., 2008). The refueling is carried out once a few years in most of the nuclear power stations. For instance, the refueling cycle is two years for the most pressurized water reactor (PWR). The teleoperation Fuel Handling System (FHS) plays an important role in reactor refueling, transportation, storage, and other processes. At present, the PWR adopts mature refueling technology that operates outside the reactor vessel. The refueling pattern with rotating plugs to locate in the reactor vessel has been used in liquid-metal fast reactor, such as BN-800 (Saraev et al., 2010), PFBR (Sankar et al., 2012), CEFR (Wang et al., 2008), XADS (Cinotti et al., 2003) etc. In CLEAR-I, the FHS also uses rotating plugs and is required to replace and transport the fuel assemblies inside the reactor vessel. This form of in-vessel refueling is more common in the design of the liquid

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https://doi.org/10.1016/j.anucene.2018.03.004
0306-4549/

metal cooled reactor in the world, especially in the lead-based ADSR, for instance, MYRRHA (Abderrahim et al., 2001) and ADS-ALMR (Ebrahimkhani et al., 2016). Nevertheless, most of them are still in the conceptual design stage for refueling, with no engineering implementation and verification.

ADSR has an inherent characteristic that the accelerator proton beam tube runs through the pile cap into the core. And the proton beam tube cannot be removed when the refueling is being carried out in the closed state of the reactor cap. Meanwhile, the peripheral rotating plugs system also cannot move and the control rod driven mechanism (CRDM) runs through the rotating plug. All these cause the inner structure of reactor complex and the space limited for fuel handling. The transfer machine is difficult to reach all the assemblies using the traditional refueling structure with rotating plugs. Therefore, the FHS and the accelerator proton beam tube must be well coupled and the FHS can achieve all the points and realizes the refueling function in the ADSR. In addition, the key components are required to be immersed in high temperature and heavy corrosive liquid of lead-bismuth alloy (Wu et al., 2013). These fundamentally decide the complexity and particularity of the FHS.

This paper presents the development of a nuclear automatic machine for the remote refueling in the reactor and a double rotating plugs and split-type center column structural scheme of the FHS to solve the refueling problem. Operational objectives and constraint conditions are analyzed to identify the requirements for a suitable Fuel Handling System. In order to further optimize the structure and verify its function, numerical simulation method is used to establish a computation model. The proposed structure is described and optimized through the comparative analysis between the results. Then, a principle prototype in scale of 1:2.5 under normal temperature condition has been developed and the experimental tests were made. The function of the FHS has been realized on the prototype and it builds a firm foundation for the engineering design and construction of the FHS.

2. Requirements for fuel handling

Nowadays, the teleoperation technology is wildly used in fuel handling outside the vessel, especially in PWR. For CLEAR-I, much more problems need to be solved. The FHS is required to complete fuel assembly loading and unloading operations task in high-temperature and liquid metal environment, without need to open the primary container (Zeng et al., 2015). The composite motion of the plugs achieves the positioning and addressing functions of the transfer machine.

In order to design a suitable FHS for CLEAR-I, the analysis of the action object is required in the engineering design (Pahl et al., 2007). The design requirements will be clear through the object analysis. The gripper and arm configurations of the FHS depend on the properties of the object to be grasped, such as orientation, position, shape and size, as well as depend on the upcoming manipulation task (ElKhoury and Sahbani, 2010; Johansson, 1996; Touvet et al., 2012). The core of CLEAR-I includes assemblies of fuel, reflection, shielding, control rod and spallation target (Wu et al., 2016a), shown in Fig. 1. The total number of the assemblies which are required to be installed and replaced by the FHS is 192. They consist of 63 fuel assemblies, 78 reflector assemblies, 48 shielding assemblies, and 3 control rod assemblies. And all the assemblies have the same external hexagonal structure (Wu et al., 2016a). The spallation target is located at the center of the reactor core and it is attached to the end of the accelerator proton beam tube. The spallation target occupies the position of 7 FAs. The target channel surrounded by assemblies which is nearly cylinder and the target channel diameter is set at 260 mm (He et al., 2016). In the channel, the beam tube with a hemi-spherical window is adopted for the target. The preliminary structure design parameters of the Fuel Assembly (FA) and other components are listed in Table 1.

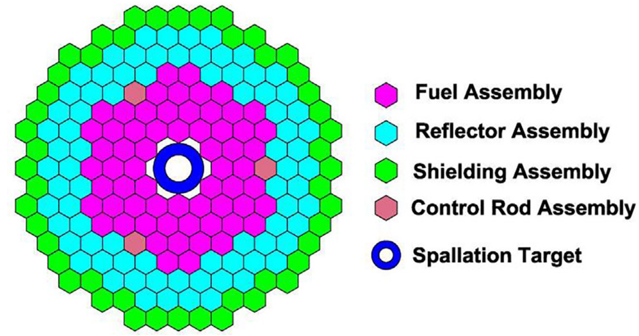

Fig. 1. Core layout of ADSR.

The outside dimension of FA (Wu et al., 2016a) is shown in Fig. 2. The external structure of FA mainly consists of operating head, casing and socle moving from the top to the bottom. The fuel was wrapped inside the casing. Considering the characteristics of lead-based reactor, ballast was chosen as the fixation method for ADSR FA. An integrated system of the ballast and fuel element ensures correct positioning of the FAs in normal and the refueling operations (Han et al., 2015).

Operating head with the same external hexagonal structure is the key component of FA, which is required to be connected to the gripper of the FHS. There are three grabbing slots uniformly distributed around the side of the operating head.

Table 1
Main related design parameters for FHS.

Items	Values
External form of FA	Regular hexagon
FA diameter (mm)	117.2
FA gap (mm)	3.5
Number of grabbing slots of FA	3
Core diameter (mm)	1052.2
Reflector diameter (mm)	1507.5
Shielding diameter (mm)	1740.8
Control rod diameter (mm)	235
Spallation target diameter (mm)	260
Total number of assemblies	192

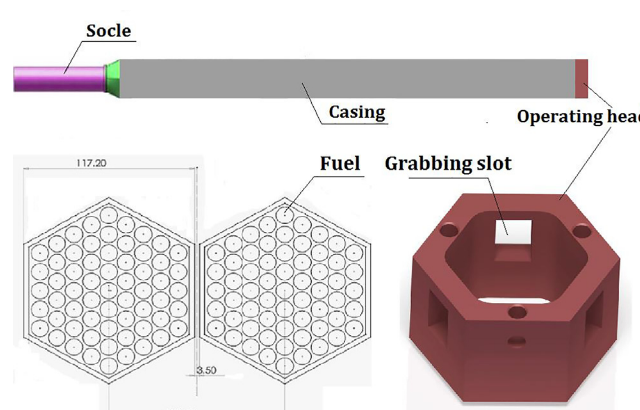

Fig. 2. Outline dimension of fuel assembly.