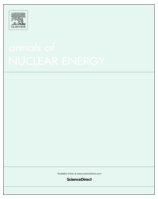
Annals of Nuclear Energy 103 (2017) 306–314

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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



Design of emergency shutdown system for the Tehran Research Reactor; Part I: Neutronics investigation

M. Safarinia [a], F. Faghihi [a,c,*], S.M. Mirvakili [b], A. Fakhraei [a]

[a] *Department of Nuclear Engineering, School of Mechanical Engineering, Shiraz University, 71936-16536 Shiraz, Iran*
[b] *Reactor Research School, Nuclear Science and Technology Research Institute (NSTRI), AEOI, Tehran 14399-51113, Iran*
[c] *Radiation Research Center, Shiraz University, Shiraz 71936-16536, Iran*

ARTICLE INFO

Article history:
Received 1 January 2017
Accepted 19 January 2017

Keywords:
Heavy water
Secondary shutdown system
Neutronics
Tehran Research Reactor

ABSTRACT

In this paper, a neutronics design of the secondary (i.e., emergency) shutdown system for the Tehran Research Reactor (TRR) is carried out based on a heavy water tank design. The heavy water tank in a cylindrical shape is around the core, and calculations for the optimized radius and height of the tank are performed. The performance of the heavy water tank calculations are carried out based on two types of fuel loading, which are called the "*first and equilibrium cores*" of the TRR. For both cases, neutronics and standard safety analysis are taken into account, benchmarked, and described herein. Heavy water discharging flow rate is also studied in the current research, and the results are compared with the IAEA criteria. Moreover, thermal flux in the radioisotope channel with and without the heavy water tank (as the reflector) are studied herein. Specifically, a core with and without the heavy water tank for the cases of 5 × 6, 5 × 5, 5 × 4, and 4 × 4 fuel assemblies are investigated (for two types of fuel loading—first and equilibrium cores). Based on our optimization, the 5 × 5 fuel assembly, which is called "B configuration," has better performance and efficiency than that of the other described layouts.

1. Introduction

A fast and effective emergency shutdown system is one of the most important elements of nuclear reactors. This is an essential requirement for the secondary shutdown system as well. The design and analysis of such a system are vital in the reactor safety assessment. The primary shutdown system consists of control rod banks that fall within the core when the scram's signal is ordered. Including a secondary (i.e., emergency) shutdown system embodies the defense-in-depth philosophy, which is expected to significantly improve the safety margin.

Secondary systems can be designed based on different types. The secondary shutdown system must be able to meet (and enhance) the safety criteria of a reactor. At the same time, it should have negligible impact on the core performance, e.g., amount of excess reactivity, neutron flux level, flux cycle length, etc.

In recent years, a heavy water tank has been a favored option as the secondary shutdown system of a typical research reactor. Most developed and/or developing countries have used the so-called emergency types and/or have constructed them to achieve improved safety (as well as other benefits), which are described in the current research.

For instance, 60 MW Advanced China research reactor (Chen et al., 2012; Tian et al., 2007), which came into operation in 2010, includes two independent shutdown systems with the secondary shutdown system being the heavy water tank. The reactor would be sub-critical by discharging the heavy water from the tank into the core. Moreover, 20 MW OPAL reactor (Kim, 2006; Villarino and Doval, 2011), an Australian reactor, contains two independent shutdown systems that use a heavy water tank as the secondary shutdown system. The CRCN /RPM-1 reactor (Barroso et al., 1998), an open pool-type reactor of 20 MW thermal power, is another example.

Heavy water tanks achieve sub-criticality by discharging the heavy water from the tank into the draining tank away from the core. Because, the heavy water has lower absorption across section as well as larger thermal diffusion length than the light water coolant, so the heavy water removal achieves sub-criticality (El-Wakil, 1971).

The Tehran Research Reactor (TRR) is a 5 MW pool-type with the order of flux of 10^{13} n/cm^2-s. It is designed to produce radioisotopes for medical and industrial purposes (Ghasempour et al., 2014; Lashkari et al., 2012). The current research attempts to achieve two goals: 1), to design an independent, secondary

---

[*] Corresponding author at: Department of Nuclear Engineering, School of Mechanical Engineering, Shiraz University, 71936-16536 Shiraz, Iran.

E-mail address: faghihif@shirazu.ac.ir (F. Faghihi).

http://dx.doi.org/10.1016/j.anucene.2017.01.029
0306-4549/

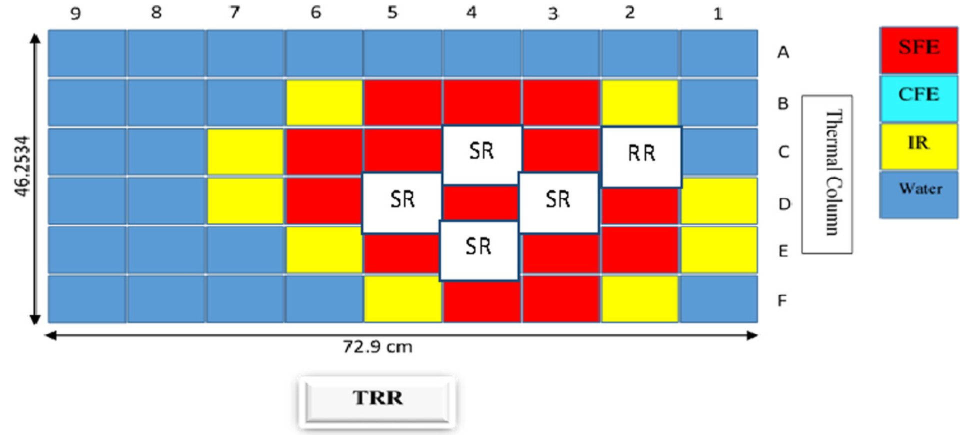


Fig. 1. Configuration of the first-core of TRR includes SFE: Standard Fuel Element; CFE: Control Fuel Element; IR-BOX: Irradiation Box; SR: Shim Safety Rod; and RR: Regulating Rod.

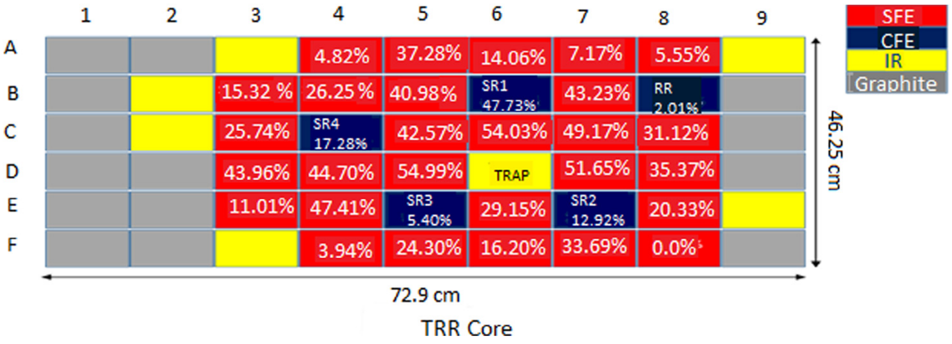


Fig. 2. Configuration of the TRR equilibrium-core with the average fuel burn-up of each fuel assembly.

(emergency) shutdown system; 2) to design an area so that irradiation facilities can be placed inside the tank to make more (and more efficient) space for irradiation. In the following sections, the TRR core is first modeled based on two types of fuel loading. Then the heavy water tank modeling is studied as the secondary shutdown system. The main goals of the assumed and modeled emergency shutdown system are as follows:

- to achieve a safe secondary shutdown system, that is independent from the primary shutdown system;
- to increase the neutron flux in the TRR core;
- to produce more radioisotopes with the higher neutron flux;
- to increase the fuel cycle length with larger excess reactivity;
- to reduce the core size for easier control;
- to reduce fuel loading and better fuel utilization; and
- to have more options in the future, e.g., more space in the heavy water tank can be used for radioisotope production.

A heavy water tank has been studied for the secondary shutdown system to achieve these goals.

2. Codes and methods

All neutronics calculations were performed using MCNPX2.6, which is a general-purpose Monte Carlo code coupled with neutron and gamma rays developed by the Los Alamos National Laboratory (LANL) Pelowitz, 2008. This code has cross-sections as a function of continuous energy and thermal scattering kernels for various materials used. The ENDF/B-VI cross section library is used in the present study (MacFarland, 1994).

For all neutronic calculations, with and without the heavy water tank, two general cases are considered. The first case is called the *"first-core,"* which contains the maximum excess reactivity. The second case is called the *"equilibrium core."* Calculations for both cases are performed herein.

2.1. TRR current core description

The *first* and *equilibrium cores* of TRR are simulated with cores containing 14 and 28 Standard Fuel Elements (SFE), respectively.

Table 1
TRR core specification (Atomic Energy Organization of Iran, 2006).

Meat material/Enrichment	U_3O_8-AL/20%
Number of fuel plates in SFE/CFE	19/14
Maximum grid plate capacity	6 × 9 Fuel Element
Meat thickness	0.07 cm
Cladding thickness	0.04 cm
Water channel thickness	0.27 cm
Meat width	6.00 cm
Total plate width	6.70 cm
Meat length	61.50 cm
Inner distance between side wall	6.70 cm
FE dimension	8.1 × 7.7 × 61.5 cm
Average thermal flux in the core ($n/cm^2.s$)	3.1 E+13
Fuel plate cladding and side wall material	AL6061
Absorber type	Fork
Absorber material for shim safety rods	Ag-In-Cd
Absorber material for fine regulating rod	AISI-316/L stainless steel
Uranium per fuel plate	15.26 g
Maximum inlet design temperature	37.8 °C
Maximum outlet design temperature	46 °C