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Conceptual design study of the low power and LEU medical reactor for BNCT using in-tank fission converter to increase epithermal flux

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ABSTRACT

A preliminary design of LPMR with unique FC facility, for increasing epithermal flux, similar to a MNSR core is investigated. The U_3Si_2-Al fuel with enrichment of 18.75% is optimized as LEU fuel. Important neutronics parameters are calculated to investigate safety of the LPMR. The optimization of the FC and BSA are performed. Presence of 34 FC rods increase epithermal flux by 22.14%. The beam parameters are $\phi_{epi} = 1.01 \times 10^9 (n.cm^{-2}.s^{-1})$, $\varphi_{th}/\varphi_{epi} = 0.033$, $\dot{D}_{fn}/\varphi_{epi} = 1.83 \times 10^{-13} (Gy.cm^2/n)$ and $\dot{D}_\gamma/\varphi_{epi} = 1.47 \times 10^{-13} (Gy.cm^2/n)$ that can satisfy the IAEA requirements of a medical reactor.

1. Introduction

Boron neutron capture therapy (BNCT) is a kind of the most promising radiotherapy is applied for the treatment of deep-seated melanoma, malignant gliomas and liver tumors, which are very difficult to treat with surgical methods or other traditional therapies (Nano et al., 2004; Barth et al., 2005; Azahra et al., 2008; Terlizzi et al., 2009; Faghihi and Khalili, 2013; Kasesaz et al., 2014). The International Atomic Energy Agency (IAEA) has recommended standard beam parameters for BNCT including limits of the epithermal neutron flux (φ_{epi}), epithermal neutron flux to thermal neutron flux ratio ($\varphi_{epi}/\varphi_{th}$), fast neutron dose rate per epithermal neutron flux ($\dot{D}_{fn}/\varphi_{epi}$), gamma dose rate per epithermal neutron flux ($\dot{D}_\gamma/\varphi_{epi}$), epithermal neutron current to epithermal neutron flux (J^+_{epi}/φ_{epi}), and size of the beam aperture that all are given in Table 1 (IAEA-TECDOC-1223, 2001).

The design of hospital-based neutron source reactor with high safety for satisfying future BNCT development is suggested by IAEA (IAEA-TECDOC-1223, 2001; Yongmao, 2009). Low-powered research reactors such as Miniature Neutron Source Reactor (MNSR) due to high inherent safety, easy operation, and low construction cost are very desirable to locate in any hospital. The MNSR is one of the tank in pool type research reactors with nominal power equal to 30 kW and maximum thermal flux about 10^{12} $(n.cm^{-2}.s^{-1})$ in the all Internal Irradiation Sites (IISs) that uses light water as moderator and coolant, UAl_4-Al with less than 1 kg of uranium-235 as high-enriched uranium (HEU - more than 20% ^{235}U) fuel, and beryllium as reflector (Boafo et al., 2012; Faghihi and Mirvakili, 2009). Recently, China has specially designed and constructed an interesting In-hospital neutron irradiator (IHNI) for BNCT based on MNSR that uses UO_2 (12.5% ^{235}U) as low-enriched uranium (LEU - below 20% ^{235}U) fuel, light water as coolant and moderator, and Al and Al_2O_3 as fast neutron to epithermal neutron moderator (Ke et al., 2009). The epithermal neutron flux at the beam exit of IHNI is 0.4×10^9 $(n.cm^{-2}.s^{-1})$. The design calculation and optimization of an epithermal neutronic beam are done at the HEU Syrian MNSR by Shaaban and Albarhoum (2015). They obtained the epithermal neutron flux equal to 0.283×10^9 $(n.cm^{-2}.s^{-1})$ at the treatment position. Newly, Monshizadeh et al. (2015) studied performance of HEU Isfahan MNSR as a neutron source for BNCT using MCNP4C Monte Carlo code and obtained the epithermal neutron flux of 0.635×109 $(n.cm^{-2}.s^{-1})$ at the beam

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Nomenclature

MNSR	Miniature Neutron Source Reactor
BNCT	Boron Neutron Capture Therapy
BSA	Beam Shaping Assembly
EIS	External Irradiation Site
FC	Fission Converter
IAEA	International Atomic Energy Agency
IIS	Internal Irradiation Site
LEU	Low-Enriched Uranium
LPMR	Low Power Medical Reactor
NAA	Neutron Activation Analysis
SDM	Shut-Down Margin
SRF	Safety Reactivity Factor

exit. Previous works on MNSR type reactors did not achieve epithermal neutron flux of 1×10^9 ($n.cm^{-2}.s^{-1}$).

Fission converters (FCs) can be used for low-powered research reactors to improve epithermal beam quality and flux-to-power ratio near the treatment position. FCs are a number of fuel elements located in the beam line but away from the reactor core for absorption of thermal neutrons and generation of fast fission neutrons. When fast neutrons appropriately moderated and filtered, enhance epithermal neutrons at the patient position (Harling and Kiger, 1996; IAEA-TECDOC-1223, 2001). Rief et al. (1993) originally proposed a FC source to increase beam quality at small reactors. Liu and Brugger (1996) demonstrated that FC can enhance the intensity of an epithermal neutron beam at high-powered and low-powered research reactors. After extensive feasibility studies on the performance of the FC, the first FC-based facility was constructed at the MITR-II research reactor (Riley et al., 2003; Harling, 2009). MITR-II researchers illustrated performance characteristics of the FC coupled with operational versatility and provided suitable facility that can satisfy the clinical needs of BNCT (Harling, 2009).

Research and test reactors generally are being operated worldwide with HEU dispersion fuel elements consisting of UAl_x or U_3O_8-Al. (Nazaré, 1984). According to the international Reduced Enrichment for Research and Test Reactors programs, the new research reactors should be designed with LEU fuel. The LEU fuels have further strengthened the inherent safety in reactor power accident due to the widening effect of prompt resonance absorption peak of ^{238}U (Hippel, 2004). High density silicide fuels are currently used in some reactors in the world as LEU fuel (Albarhoum, 2011). They have good advantages such as sufficiently high density, acceptable blister temperatures (higher than 5000 deg. C.) and the same nature of the actual fuel. These fuels under irradiation can be used up to high burn-ups (Hofman et al., 1983; Chae et al., 2004).

In this work, the preliminary neutronics design calculation of a low power medical reactor (LPMR) with unique FC facility based on MNSR for BNCT is done. The core is designed with U_3Si_2-Al as LEU Fuel. Furthermore, the optimization of the fuel elements enrichment, beam size, FC, fast neutrons to epithermal neutrons moderator, reflector surrounding collimator, thermal neutron and photon filters is carried out.

2. Materials and methods

MCNP4C code is used to design the LEU Core, the FC facility and the beam shaping assembly (BSA). Furthermore, the neutronic calculations are done at the initial coolant temperature of 15 °C and rated thermal power of 30 kW.

2.1. Description of LEU core and FC

The material properties of LPMR proposed LEU U_3Si_2-Al fuel is compared with MNSR HEU UAl_4-Al fuel in Table 2. The LPMR core consists of 350 fuel rods and 4 tie rods that are arranged on ten concentric circles (see Table 3and Fig. 1). The reactor is controlled

Table 2
The fuel material properties of MNSR HEU fuel and LPMR LEU fuel.

Fuel properties	UAl_4-Al	U_3Si_2-Al
Meat density (g/cm3)	3.403	6.97
Disp. phase density (g/cm3)	5.7	12.20
Wt.% U in Disp. Phase	64	92.69
U density in Disp. phase (g/cm3)	3.7	11.30
U density in meat (g/cm3)	0.946	5.09
Vol. fraction of Disp. phase (%)	23.44	45
Enrichment (%)	89.97	18.75
Wt.% Al content in the meat	72.37	21.29

Table 3
LPMR core lattice arrangement.

Circle Number	Rods Number	Circle diameter (mm)	Radial pitch (mm)
1	6	21.9	11.47
2	12	43.8	11.47
3	19	65.7	10.86
4	26	87.6	10.98
5	32	109.5	10.78
6	39	131.4	10.58
7	45	153.3	10.70
8	52	175.2	10.58
9	58	197.1	10.68
10	65	219	10.58

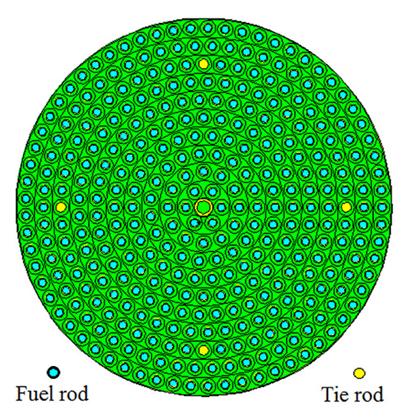

Fig. 1. Top view of LPMR core fuel lattices.

Table 1
IAEA limits for BNCT beam parameters (IAEA-TECDOC-1223, 2001).

$\varphi_{epi}(n.cm^{-2}.s^{-1})$	$\frac{\varphi_{epi}}{\varphi_{th}}$	$\frac{\dot{D}_{fn}}{\varphi_{epi}}(Gy.cm^2)$	$\frac{\dot{D}_{\gamma}}{\varphi_{epi}}(Gy.cm^2)$	$\frac{J^+_{epi}}{\varphi_{epi}}$	Aperture size (cm)
$\geq 10^9$	≥20	$\leq 2 \times 10^{-13}$	$\leq 2 \times 10^{-13}$	≥0.7	12–14