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Neutronic feasibility design of a small long-life HTR

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ABSTRACT

Small high temperature gas-cooled reactors (HTRs) have the advantages of transportability, modular construction and flexible site selection. This paper presents the neutronic feasibility design of a 20 MWth U-Battery, which is a long-life block-type HTR. Key design parameters and possible reactor core configurations of the U-Battery were investigated by SCALE 5.1. The design parameters analyzed include fuel enrichment, the packing fraction of TRISO particles, the radii of fuel compacts and kernels, and the thicknesses of top and bottom reflectors. Possible reactor core configurations investigated include five cylindrical, two annular and four scatter reactor cores for the U-Battery. The neutronic design shows that the 20 MWth U-Battery with a 10-year lifetime is feasible using less than 20% enriched uranium, while the negative values of the temperature coefficients of reactivity partly ensure the inherent safety of the U-Battery. The higher the fuel enrichment and the packing fraction of TRISO particles are, the lower the reactivity swing during 10 years will be. There is an optimum radius of fuel kernels for each value of the fuel compact design parameter (i.e., radius) and a specific fuel lifetime. Moreover, the radius of fuel kernels has a small influence on the infinite multiplication factor of a typical fuel block in the range of 0.2–0.25 mm, when the radius of fuel compacts is 0.6225 cm and the lifetime of the fuel block is 10 years. The comparison of the cylindrical reactor cores with the non-cylindrical ones shows that neutron under-moderation is a basic neutronic characteristic of the reactor core of the U-Battery. Increasing neutron moderation by replacing fuel blocks with graphite blocks and dispersing the graphite blocks in the reactor core are two effective ways to increase the fuel burnup and lifetime of the U-Battery. Water or steam ingress may induce positive reactivity ranging from 0 to 0.16 $\Delta k/k$, which further demonstrates that the U-Battery is under-moderated.

1. Introduction

In the past fifty years, the size of nuclear reactors has grown from 60 MWe to more than 1600 MWe in order to make full use of economy of scale (Kuznetsov, 2008). However, because large-size nuclear reactors usually require high capital investment and heavily rely on the infrastructure of reactor sites, this has motivated designers to develop small and medium-size reactors (SMRs), especially for developing countries and remote areas off main grids (Ueda et al., 2005; IAEA, 2005, 2007; Ingersoll, 2009).

Compared to large-size nuclear reactors, SMRs have some inherent advantages. They can be manufactured in modules and transported to sites by rail, barge, truck, etc. After a long operation, these reactors can be brought back to factories for refueling or directly replaced by new ones, which would greatly reduce the dependence of nuclear reactors on infrastructure. Thus, SMRs' sites can be chosen more flexibly than large-size reactors'. More importantly, SMRs can be inherently or passively safe, because they commonly operate at low power density levels. For example, some small reactors, which adopt passive cooling methods during normal operation or accident, have been proposed based on different reactor technologies, such as light water reactors (LWRs) (Modro et al., 2003), high temperature gas-cooled reactors (HTRs) and liquid metal cooled reactors (LMRs) (Sienicki et al., 2007).

The inherent safety of modular HTRs has been validated directly by experiments over the last 30 years (Gottaut and Kruger, 1990; Hu et al., 2006; Nakagawa et al., 2004). However, only few studies have focused on small long-life HTRs. This paper presents the neutronic feasibility design of a 20 MWth U-Battery, which is long-life block-type HTR, and aims to be commercialized in the near future. The term U-Battery is used for this small HTR in order to emphasize its long-life core, transportability and inherent safety. Because the U-Battery is still at the early design stage, the main aims of the

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Table 1
Basic parameters of the U-Battery.

Parameter	Value
Reactor type	Block-type HTR
Thermal power	20 MW
Lifetime	5–10 effective full power years (EFPYs)
Coolant	Helium
Diameter of RPV	3.7 m
Fuel type	UO_2, TRISO coated fuel
Fuel enrichment	<20%
Energy conversion system	Rankine steam cycle
Energy utilisation	Electricity, process heat

design are the neutronic feasibility of the U-Battery under some new design requirements, like a 10-year or longer lifetime and a limited diameter of reactor pressure vessel, the neutronic influence of design parameters, and possible reactor core configurations.

The second section of this paper presents the basic design requirement of the U-Battery in detail. The third section explains the calculation method and model of the U-Battery, as well as a simple assessment of the model. The fourth section parametrically investigates several key design parameters of the U-Battery, including fuel enrichment, the packing fraction of TRISO particles, the thicknesses of top and bottom reflectors, and the radii of fuel compacts and fuel kernels. The fifth section analyzes eleven possible reactor core configurations, including five cylindrical, two annular and four scatter cores, in order to obtain a suitable core configuration for the U-Battery. The sixth section addresses the reactivity temperature coefficients of two reactor core configurations, and the effect of water/steam density on the reactivity of the U-Battery since the U-Battery may adopt the Rankine steam cycle as a power conversion system.

2. Description of the U-Battery

The U-Battery aims to be a small, inherently safe and transportable HTR with a long-life core, which is designed to provide electricity to residential sites that are not connected to national grids, or process heat for different industrial costumers. The basic design requirements the U-Battery are listed in Table 1.

Since the main ideas behind the U-Battery are inherent safety, modularity and near-term utilisation, the U-Battery has been developed based on currently mature block-type HTR technologies, and may inherit the inherent safety that has been validated by experiments. The reactor core is comprised of a certain number of hexagonal fuel columns with side, top and bottom reflectors, as shown in Fig. 1(a). In the axial direction of the fuel columns, which

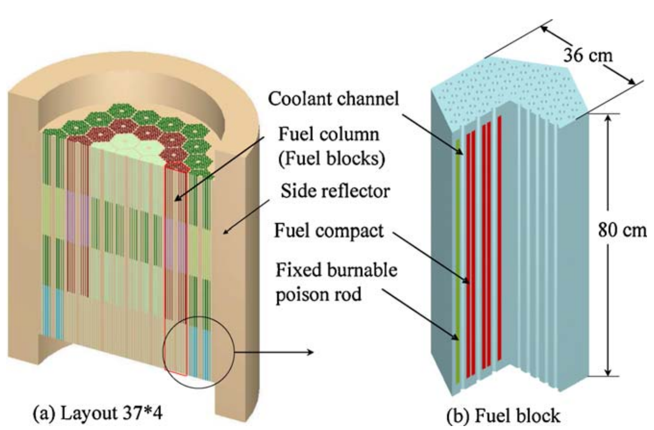

Fig. 1. The 3D schematic diagram of a reactor core and fuel block; for clarity the top and bottom reflectors have been removed in the reactor core, and the fuel handling hole has also been removed in the fuel block.

Table 2
Basic parameters of the fuel blocks of the U-Battery.

Parameter	Value
Block level	
Width across flats	36 cm
Height of blocks	80 cm
Number of fuel channels	216 (incl. 6 FBP channels)
Radius of fuel channels	0.635 cm
Number of coolant channels	102/6
Radius of coolant channels	0.794/0.635 cm
Number of fuel compacts per channels	15
Radius of fuel compacts	0.6225 cm
Height of fuel compacts	4.93 cm
TRISO particles	
Packing fraction of TRISO particles	0.3
Radius of fuel kernels	250 μm
Density of fuel kernels	10.5 g/cm^3
Thickness of buffer layer	100 μm
Density of buffer layer	1.0 g/cm^3
Thickness of IPyC layer	35 μm
Density of IPyC layer	1.9 g/cm^3
Thickness of SiC layer	35 μm
Density of SiC layer	3.2 g/cm^3
Thickness of OPyC layer	40 μm
Density of OPyC layer	1.97 g/cm^3

is also the axial direction of the core, each fuel column consists of several hexagonal graphite fuel blocks including blind holes for fuel compacts and fixed burnable poison (FBP) rods, and full length channels for coolant flow, as shown in Fig. 1(b). The U-Battery uses the fuel blocks developed by General Atomic for the GT-MHR project (GA, 1996). The block width cross flats is 36 cm and the height is 80 cm. Each fuel block includes 210 fuel channels, 108 coolant channels (including 6 small coolant channels with the same size as the fuel channels) and 6 FBP channels which are used as fuel channels for the U-Battery. The diameters of the fuel channels, coolant channels and FBP channels are 1.27 cm, 1.588 cm and 1.27 cm, respectively. In each fuel channel, there are 15 fuel compacts including TRISO particles with low-enriched uranium (LEU) fuel kernels. Basic geometric parameters of the fuel blocks of the U-Battery are shown in Table 2, which are used in all calculations of the U-Battery.

Since the number of fuel columns and fuel blocks are two key parameters of a reactor core configuration, the notation of Layout C*B is used to represent the reactor core configurations of the U-Battery, where C is the number of fuel columns in the reactor cores and B is the number of the fuel blocks in each fuel column. For example, the configuration of the reactor core shown in Fig. 1(a) is Layout 37*4, which means that the reactor core is comprised of thirty-seven fuel columns and each column consists of four fuel blocks in the height direction of the block (the axial direction of the core).

A thermal power of 20 MWth opens up the possibility of using the U-Battery for small industrial process heat applications, as well as for small electricity application. The U-Battery with such thermal power can fill a niche of the market currently not open to nuclear energy. Fuel enrichment higher than 20% U-235 is not feasible since 20% U-235 is the maximum value for commercial applications with LEU. 10% U-235 or lower enrichment would be desirable from a practical point of view. The U-Battery accepts helium as coolant because it has been used for graphite-moderated reactors over 40 years. The diameter of the U-Battery's RPV is requested to be less than or equal to 3.7 m so that the U-Battery can be transported as a whole by rail, truck, barge, etc. The power conversion system of the U-Battery may use a Rankine steam cycle since the U-Battery aims to be commercialized in the near future and the steam cycle is the most mature technology in the nuclear industry.

Table 3
The infinite multiplication factor of a typical fuel block of the U-Battery.[a]

Parameters	BOL (0 EFPY)			EOL (10 EFPY)		
Enrichment	6	12	20	6	12	20
k_{inf}^{Hom} [b]	1.2791	1.3521	1.3945	0.9082	1.0298	1.1335
k_{inf}^{Het} [c]	1.338	1.4073	1.4456	0.9371	1.0794	1.188
$(k_{inf}^{Hom} - k_{inf}^{Het})/k_{inf}^{Het}$	−0.044	−0.039	−0.035	−0.031	−0.046	−0.046

[a] Packing fraction of TRISO particles = 0.3; Radius of fuel kernels = 0.025 cm; radius of fuel compacts = 0.6225 cm; Temperature = 800 K.
[b] Volume-weighted homogenization.
[c] Explicit TRISO particle model.

3. Calculation method and model evaluation

3.1. Calculation method and code system

3D models of the U-Battery, including an assembly of fuel blocks with reflectors, as shown in Fig. 1(a), were built in SCALE 5.1 (Standardized Computer Analyses for Licensing Evaluation) (ORNL, 2005) in order to obtain the neutronic performance. The SCALE code system has been developed at Oak Ridge National Laboratory for nuclear applications such as problem-dependent resonance self-shielding of cross-section data, criticality safety, radiation and shielding. SCALE 5.1 is a modular code system and is mainly comprised of functional modules and control modules. In the calculations of the U-Battery, two function modules (BONAMI and CENTRM) were used to process the resonance self-shielding of the cross sections of the materials and cells used. KENO-VI, a 3D Monte Carlo criticality safety code, was used to calculate the effective multiplication factor of the U-Battery. ORIGEN-S was used to perform point depletion calculations and to obtain the isotopic concentrations in the U-Battery. TRITON 6 was used to serve as the controller of module sequencing, data transfer, and input/output control for multiple analysis sequences. The whole calculation procedure controlled by TRITON 6 can be summarized in the following steps:

(1) Preparing resonance self-shielded cross sections for the given unit cells by the BONAMI and CENTRM modules. In the calculations of the U-Battery, the smallest unit cell used is a volume-weighted homogenized (VWH) fuel compact surrounded by a small hexagonal graphite block. The block width cross flats is 0.94 cm, and the height is 80 cm.
(2) Providing the cross sections generated in step 1 to the 3D Monte Carlo based module KENO-VI to perform criticality calculations and to obtain the effective multiplication factor and the flux profile of the reactor core of the U-Battery. Different 3D reactor core configurations were built for the U-Battery with the proper hexagonal block structure, including the fuel compacts and coolant channels, as shown in Fig. 1(b). However, all 6 channels of fixed burnable poison were used as fuel channels in the U-Battery. Except for the calculations of the temperature coefficients of reactivity, the number of neutron generations was 350 and each generation used 1000 neutrons for all calculations of the U-Battery in KENO-VI. Moreover, the results of the first 20 generations are neglected. The uncertainty of the multiplication factors is in the range of ±0.0011 to ±0.0017. For the calculations of the temperature coefficients of reactivity, more neutron generations and more neutrons per generation were used, and the uncertainty of the multiplication factors reduces to ±0.00050.
(3) Transferring the flux profiles and absolute flux values to ORIGEN-S which performs the depletion calculations of the U-Battery. At the first 100 days, the time step in burnup calculations usually is 4.5 days because of the influence of the short-lived fission products. The time step increases to 36.5 days for the other burnup calculations. Moreover, besides those nuclides present in the mixtures defined by the input compositions, a specific parameter in TRITON 6 was used to include actinides and fission products, totally 232 nuclides, during the burnup calculations of the U-Battery.
(4) Feeding the new material compositions after each ORIGEN burnup step back to step 1 and repeating the whole process until completion of all burnup.

3.2. Double heterogeneous effect evaluation at block level

One important neutronic feature of the fuel blocks of the U-Battery is double spatial heterogeneity. The first level of the double heterogeneity is the distribution of the coated TRISO particles or grains inside the fuel compacts, and the second level is the lattice of fuel pins in the fuel blocks.

As mentioned in Section 3.1, one important simplification of the models of the U-Battery is included in all calculations in the following sections. The coated TRISO particles in fuel compacts have been homogenized based on a volume-weighted homogenization method. This simplification eliminates the first level of the double heterogeneity in the fuel blocks of the U-Battery. The main reason is that SCALE 5.1 is not capable of doing the burnup calculations of the fuel blocks with the explicit coated TRISO particles. However, the heterogeneous effect of the coated TRISO particles does increase the multiplication factor of fuel blocks because of the lumping of uranium. The double heterogeneity of fuel blocks with the explicit TRISO particles is evaluated by SCALE 6 based on a typical fuel block in this section, since it is an important simplification in all calculations in the other sections.

As shown in Table 3, two types of fuel blocks were modelled by SCALE 6, in order to demonstrate the neutronic influence of the heterogeneity of the coated TRISO particles in the fuel blocks of the U-Battery. One type is the fuel block with the volume-weighted homogenized fuel compacts, whose multiplication factor is k_{inf}^{Hom} in the third row of Table 3. The other one is the fuel block with the fuel compacts containing explicit coated TRISO fuel particles, whose multiplication factor is k_{inf}^{Het} in the forth row of the same table. The relative difference between k_{inf}^{Hom} and k_{inf}^{Het}, which means the reactivity effect of the double heterogeneity of the coated TRISO fuel particles, is presented in the last row of Table 3. Except for the method of dealing with the coated TRISO particles, these two types of fuel blocks have the same parameters. The packing fraction of the coated TRISO particles is 0.3; the radii of the kernels and fuel compacts are 0.25 mm and 0.6225 cm, respectively; the thermal power of the fuel block is 20 MW/(37*4 fuel blocks) = 0.135 MW. The results show that the k_{inf}^{Het} is 3–5% larger than the k_{inf}^{Hom} during 10 effective full power years (EFPYs) when the enrichment of the fuel varies from 6% U-235 to 20% U-235. This means that the heterogeneous effect of the explicit TRISO particles can increase the infinite multiplication factor of the fuel block by 3–5%.

In fact, the double heterogeneous effect of fuel blocks is mainly because of the increase of the resonance escape probability, p, as shown in Table 4, which shows the four factors (Duderstadt and Hamilton, 1976) of the typical fuel block with different-enrichment

Table 4
Four factors (Duderstadt and Hamilton, 1976) of a typical fuel block of the U-Battery.

Factors	Het		Hom	
	4	20	4	20
η	1.8329	2.0139	1.8326	2.0139
ϵ	1.1023	1.4889	1.1063	1.5114
f	0.9778	0.9946	0.9779	0.9947
p	0.6295	0.4730	0.5934	0.4468

fuel. The notation of Het represents the fuel block with the explicit TRISO particles, while Hom represents the fuel block with volume-weighted homogenized compacts. The input parameters of the fuel block in Table 4, such as temperature, the packing fraction of the coated TRISO particles, and so on, are the same as in Table 3. The volume-weighted homogeneous compacts have the same values of thermal neutron utilisation (f) and average number of fission neutrons produced per absorption of a thermal neutron (η) as the heterogeneous compacts, and have a slightly higher fast neutron fission factor (ϵ).

Although the 3–5% underestimation of the multiplication factors for the volume-weighted homogenization model in the following sections looks rather conservative in some degree, it is still acceptable for the current feasibility design of the U-Battery which mainly aims to determine the possible reactor core configurations. Moreover, the current analysis ignores the neutronic influence of other parameters, which would decrease the multiplication factors. For example, graphite always contains some impurities, especially boron, which leads to a loss of reactivity. Fixed burnable poison would be included into the fuel blocks in order to control the excess reactivity of the U-Battery, which would lead to a few percent decrease of the multiplication factors of the U-Battery. On the other hand, the analysis of the following sections aims to compare the different reactor core designs of the U-Battery and to obtain the general conclusions of the key design parameters. In this sense, the relative values of the multiplication factors are more important than the absolute ones. The underestimation of the multiplication factor will not change the main conclusions of the paper. A reactor core configuration with a larger k_{eff} calculated by the homogeneous model should also have a larger k_{eff} when the double heterogeneous model is used. In fact, in the feasibility design stage, it is much cheaper to do many neutronic calculations by the homogeneous model than the double heterogeneous one in order to search more reactor core configurations. However, the double heterogeneous effect of the fuel blocks should be included for the detailed design of the U-Battery.

4. Main design parameters analysis

Fuel enrichment, the packing fraction of TRISO particles, the thicknesses of top and bottom reflectors are main design parameters of the U-Battery, which are analyzed parametrically in this section. Although changing the size of fuel compacts and fuel kernels is only optional to the design of the U-Battery, they are also investigated because these two factors greatly influence neutron moderation performance.

In all the calculations, the material temperature is specified as 800 K. As mentioned in the previous section, the TRISO particles in the fuel compacts are not modelled explicitly. The fuel handling holes in the center of the fuel blocks and the gaps between the fuel blocks are all neglected. These simplifications are proposed to save CPU time in the current feasibility design stage.

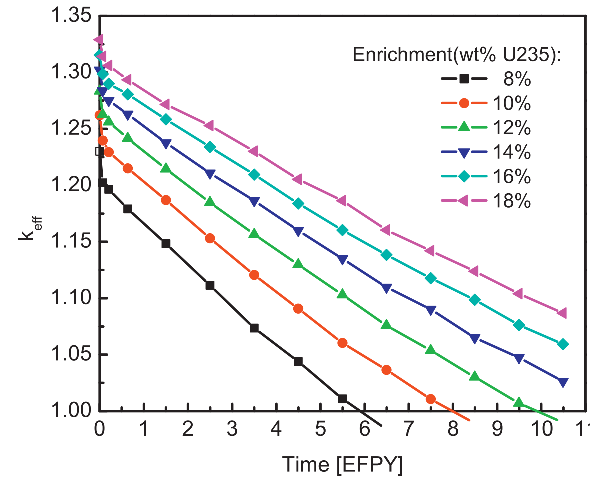

Fig. 2. k_{eff} as a function of the fuel enrichment and time for Layout 37*4.

4.1. Fuel enrichment

In the design of nuclear reactors, fuel enrichment is one of the most effective parameters to achieve a critical reactor and a specific fuel lifetime. Fig. 2 presents the effective multiplication factor, k_{eff}, of the U-Battery with Layout 37*4 as a function of time and with fuel enrichment as a parameter. In this reactor core configuration, there are 37 fuel columns in the reactor core and each fuel column is comprised of 4 fuel blocks in the axial direction of the reactor. The packing fraction of TRISO particles is 0.3. As shown in Fig. 2, a higher fuel enrichment achieves a larger k_{eff} and a longer lifetime. The lifetime of the U-Battery reaches 10 effective full power years (EFPYs), when the fuel enrichment is 12% U-235 for Layout 37*4. The vertical distance between the lines decreases, as the fuel enrichment increases, which means that increasing the k_{eff} by higher fuel enrichment becomes less and less effective. For example, the reactivity of the U-Battery increases by 0.021 Δk/k when the fuel enrichment varies from 8% U-235 to 10% U-235 at beginning-of-life (BOL); however, the reactivity only increases by less than 0.005 Δk/k per 1% fuel enrichment, when the fuel enrichment is larger than 14% U-235. Moreover, as shown in Fig. 2, the k_{eff} of Layout 37*4 is almost linear with time except for the drop at BOL because of the buildup of short-lived fission products like Xe-135 and Sm-149.

Time-dependent reactivity change, i.e., reactivity swing, should be maintained as low as possible in order to avoid moving control rods frequently to compensate for the reactivity loss as fuel is consumed. As shown in Fig. 3, the reactivity swing, defined as the reactivity difference between beginning-of-life and end-of-life (EOL), decreases with the increase of the fuel enrichment for Layout 37*4 with the different packing fractions of the TRISO particles, because a higher fuel enrichment means more U-235 loaded. Since the higher fuel enrichment can suppress the reactivity swing of the reactor, less compensation is needed during the operation of the U-Battery.

4.2. Packing fraction of TRISO particles

The packing fraction of TRISO particles has a different influence on the neutronic performance of the U-Battery, especially the k_{eff} and the reactivity swing.

The k_{eff} of Layout 37*4 is plotted in Fig. 4 as a function of the packing fraction of TRISO particles and with time as a parameter. The reactor core is comprised of 148(=37*4) fuel blocks and the fuel enrichment is 12% U-235. The higher the packing fraction of TRISO particles is, the longer the lifetime of the U-Battery will be.

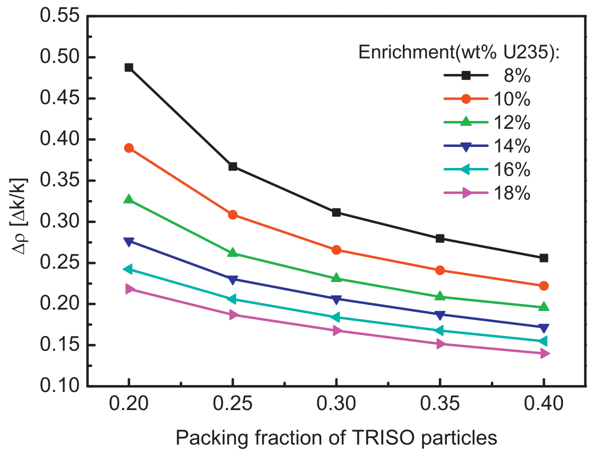

Fig. 3. Reactivity swing ($\Delta\rho = \rho_{BOL} - \rho_{EOL}$) as a function of the packing fraction of the TRISO particles and fuel enrichment for Layout 37*4.

This is because increasing the packing fraction means that more fuel or heavy metal is loaded into the reactor core. However, more fuel does not mean a larger effective multiplication factor. As the packing fraction of TRISO particles increases, the k_{eff} of Layout 37*4 at BOL decreases, and it increases at EOL. At BOL, a higher packing fraction leads to a smaller k_{eff} because more heavy metal is loaded into the reactor core, which is severely under-moderated. However, when the fission reaction starts in the reactor, the fertile U-238 is produced to fissile Pu-239 and Pu-241. Moreover, there are fission resonances in the range from 0.1 eV to 1 eV for Pu-239 and Pu-241. These two factors lead to a different effect of the packing fraction of TRISO particles from BOL. As shown in Fig. 4, the k_{eff} is almost independent to the packing fraction of the TRISO particles at 3.5 EFPYs. After that, a higher packing fraction leads to a larger k_{eff}. The analysis showed that there is an optimum packing fraction of TRISO particles in the fuel compacts for a specific reactor core configuration, fuel enrichment and lifetime of the U-Battery because of the trade-off between the generation and buildup of plutonium and neutron moderation in the reactor core.

Reactivity swing is also sensitive to the packing fraction of the TRISO particles, as shown in Fig. 3. Increasing the packing fraction of the TRISO particles reduces the reactivity swing for Layout 37*4 because more fuel is loaded into the reactor core.

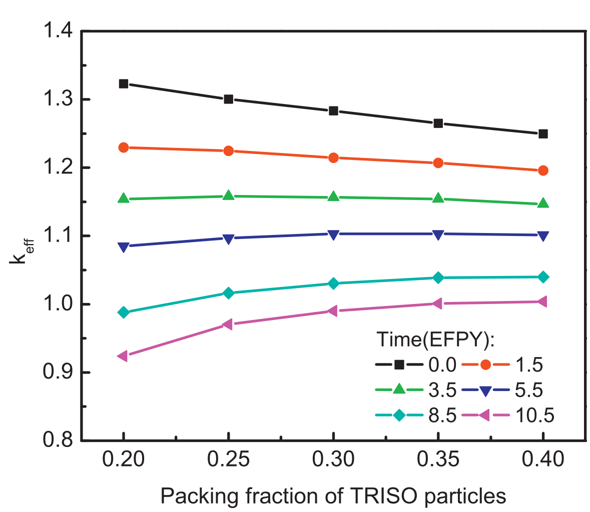

Fig. 4. k_{eff} as a function of the packing fraction of TRISO particles for Layout 37*4.

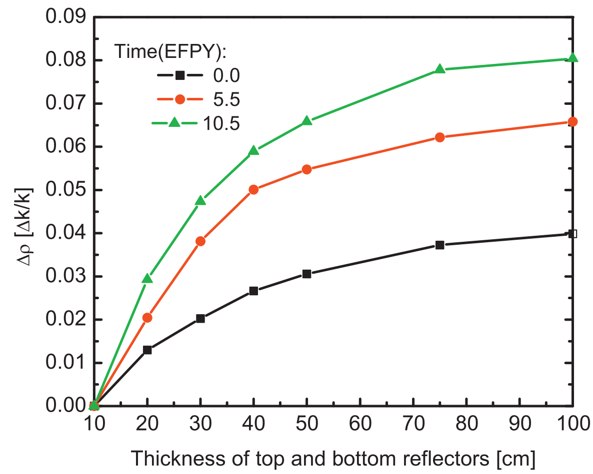

Fig. 5. $\Delta\rho(= \rho - \rho_{10})$ as a function of the thickness of the top and bottom reflectors for Layout 37*3.

4.3. Thicknesses of top and bottom reflectors

The reflectors reflect neutrons back to the reactor core of the U-Battery, which increases the neutron economy. Because the diameter of the reactor pressure vessel is limited to 3.7 m for the U-Battery, the thickness of the side reflector is limited to 30–60 cm and thus it is not necessary to investigate it. However, the thicknesses of the top and bottom reflectors need be investigated for the U-Battery in order to optimize their thicknesses. In order to simplify calculations, the thickness of the top reflector is assumed to be the same as the bottom reflector. This assumption is also applicable for the all calculations in the other sections.

The reactivity change $\Delta\rho$ of Layout 37*3 is plotted in Fig. 5 as a function of the thickness of the top and bottom reflectors and with time as a parameter. The thickness of the top and bottom reflectors varies from 10 cm to 100 cm. The $\Delta\rho$ is defined as $\Delta\rho = \rho - \rho_{10}$, where ρ is the reactivity of the reactor core with a certain-thickness top and bottom reflectors; and ρ_{10} is the reactivity of the reactor with 10-cm-thick top and bottom reflectors.

As shown in Fig. 5, the $\Delta\rho$ increases quickly when the thickness is less than 50 cm. For 100-cm-thick top and bottom reflectors, the reactivity increases by 0.04 Δk/k at BOL; however, it increases by 0.066 Δk/k and 0.08 Δk/k after 5.5 EFPYs and 10.5 EFPYs, respectively. Pu-239 or Pu-241, produced from U-238, has a larger average number of neutrons produced per neutron absorbed in fuel and a larger thermal neutron absorption cross section, so the neutron energy spectrum of the reactor core of Layout 37*3 gradually hardens. Since faster neutrons usually have a large leakage probability, the importance of top and bottom reflectors increases with time because of the generation and buildup of Pu-239 and Pu-241.

As shown in Fig. 5, the $\Delta\rho$ of Layout 37*3 increases slowly when the thickness of top and bottom reflectors is larger than 50 cm. Moreover, there is usually thermal insulation (e.g., carbon bricks) outside the reflectors, which could reflect a part of neutrons leaked from reflectors. In order to minimize the height of the U-Battery, 50-cm-thick top and bottom reflectors are recommended for the U-Battery and used in all the calculations in the other sections. Moreover, the thickness of the top reflector of the U-Battery is also assumed to be the same as the bottom reflector.

4.4. Other optional design parameters

As mentioned in Section 2, the U-Battery is designed based on currently mature HTR technologies, such as the validated geometric parameters of the coated TRISO fuel particles and fuel blocks by

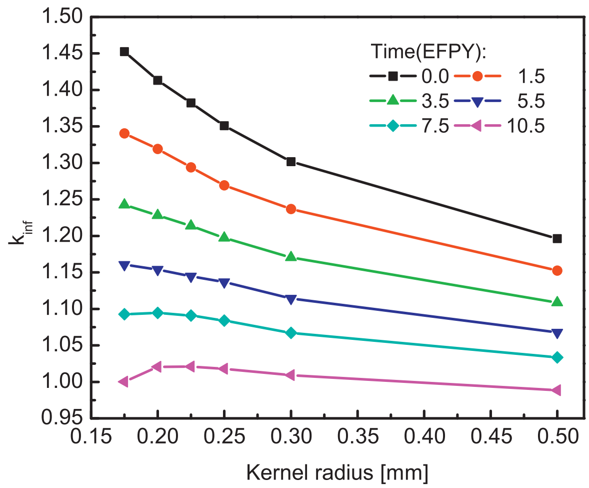

Fig. 6. k_{inf} as a function of the radius of fuel kernel and with time as a parameter for the typical fuel block with 0.6225 cm fuel compacts in radius.

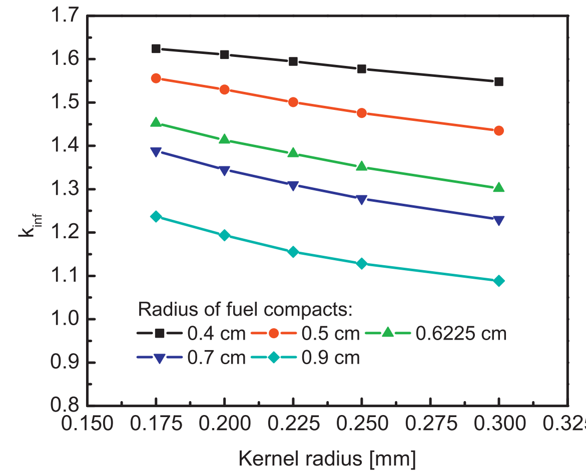

Fig. 7. k_{inf} of fuel block as a function of the radius of fuel kernels and with the radius of fuel compacts as a parameter at BOL.

past HTR projects, in order to reduce its research and development cost, as well as time. As a result, two design parameters, the radii of the fuel compacts and the fuel kernels, are fixed to the reference values adopted by past HTR projects in the previous analysis. That is, the radii of the fuel compacts and kernels are set to 0.6225 cm and 0.025 cm, respectively. However, because these two parameters greatly influence the neutron moderation performance of fuel blocks, they are investigated in this section in order to confirm whether changing them may lead to better designs of the U-Battery.

The effects of the radii of the fuel compacts and fuel kernels were investigated based on a typical fuel block rather than a whole core in order to save CPU time. Moreover, the fuel enrichment is 12% U-235; the packing fraction of the TRISO particles is 0.3; the thermal power of the fuel block is 0.135 MW. A 3D prismatic fuel block including explicit fuel compacts and coolant channels was modelled in SCALE 5.1 with reflective boundary condition.

4.4.1. Radius of fuel kernels

Fig. 6 illustrates the infinite multiplication factor, k_{inf}, of the typical fuel block as a function of the radius of fuel kernel and with time as a parameter. The radius of the fuel compacts in the fuel block is 0.6225 cm. At BOL, a larger kernel radius leads to a smaller k_{inf}, as the black (square-dot) line shown. The larger fuel kernel radius is, the more uranium will be loaded and the less graphite is in the fuel compacts, which leads to less neutron moderation. However, the fertile U-238 is produced into the fissile Pu-239 and Pu-241 with time. Moreover, Pu-239 and Pu-241 have fission resonances in the range of 0.1 eV to 1 eV. Along with the build up of Pu-239 and Pu-241, the larger fuel kernels means the more plutonium produced in the fuel block. Therefore, the k_{inf} at EOL increases with the kernel size first because of the produced Pu-239 and Pu-241 and reaches the maximum value at 0.2 mm, then decreases slowly because of the worsened neutron moderation.

The second important effect of the fuel kernel radius on the neutronic performance of the fuel block is that the larger the kernel radius is, the smaller the reactivity swing will be during the whole lifetime of the fuel block. For the fuel kernels with a radius of 0.175 mm, the k_{inf} starts at the largest value among all fuel kernels because the ratio of graphite to uranium in the fuel block is largest and the neutron moderation is better than those with larger radii. However, it quickly drops by 0.31 $\Delta k/k$ during 10.5 EFPYs because the mass of the uranium in the fuel block is smallest, which leads to a larger reactivity swing than others. So a large-radius fuel kernel is preferred for the U-Battery from reactivity control point of view. Since the TRISO particles are not modelled explicitly, the influence of the fuel kernel radius on the reactivity only includes that of the mass of the uranium, and excludes that of the geometry. More accurate analysis of the TRISO particle sizes will be included in the future.

4.4.2. Size optimization of fuel kernels and compacts

The fuel compacts also have a similar time-dependent effect on the k_{inf} of the fuel block as the fuel kernel radius. At BOL, the larger radius of the fuel compacts is, the smaller k_{inf} of the fuel block is, because of the worse neutron moderation. When there is enough Pu-239 and Pu-241 produced from U-238, the k_{inf} of the fuel block first increases quickly with the increase of the radius of the fuel compacts, and then decreases slowly because of the worsened neutron moderation.

Since the sizes of the fuel compacts and fuel kernels change the fuel-to-moderator ratio and inventory of plutonium in the fuel block and thus the infinite multiplication factor, combining these two factors together is a good way to obtain the optimum values for a specific configuration of the reactor core of the U-Battery with specific packing fraction and fuel enrichment. Figs. 7, 8 and 9 show the k_{inf} of the fuel block as a function of the radius of fuel kernels and with the radius of fuel compacts as a parameter at BOL, 5.5 EFPYs and 10.5 EFPYs, respectively. Fig. 7 does not show any optimum values of fuel kernels or fuel compacts, but it suggests that increasing the radii of fuel kernels and fuel compacts can reduce the initial k_{inf}

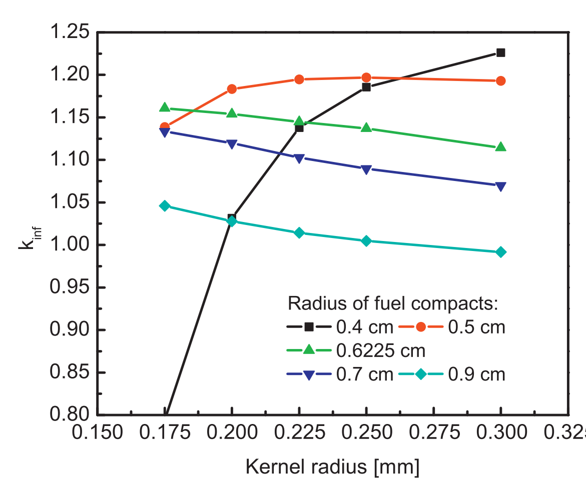

Fig. 8. k_{inf} of fuel block as a function of the radius of fuel kernels and with the radius of fuel compacts as a parameter at 5.5 EFPYs.

Table 5
Fuel compositions of seven reactor core configurations.

Case	Configuration	Number	Type	5 years[a]	10 years[a]
1	Layout 19*3	57	Cylindrical	6.4 years[b]/6.9 years[c]	
2	Layout 19*4	76		9.1 years[b]/9.85 years[c]	
3	Layout 37*3	111	Cylindrical	9.55/0.3	16.7/0.3
4	Layout 37*4	148		6.9/0.3	12.1/0.3
5	Layout 61*3	183		7.59/0.3	13.7/0.3
6	Layout 30*3	90	Annular	9.8/0.3	17.3/0.3
7	Layout 30*4	120		7.6/0.3	12.9/0.3

[a] Enrichment/packing fraction(PF) of the TRISO particles.
[b] Maximum lifetime when enrichment = 20% and PF = 0.3.
[c] Maximum lifetime when enrichment = 20% and PF = 0.35.

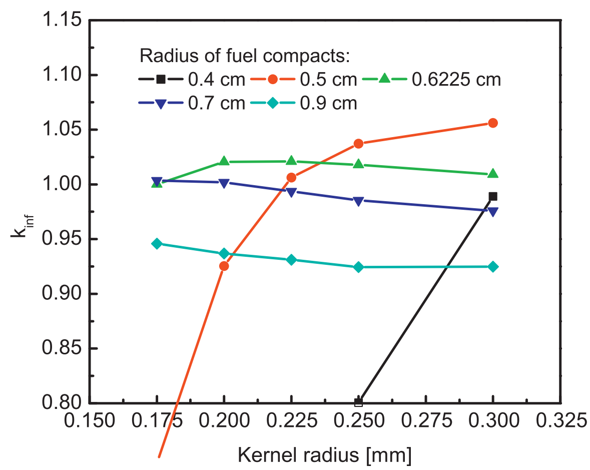

Fig. 9. k_{inf} of fuel block as a function of the radius of fuel kernels and with the radius of fuel compacts as a parameter at 10.5 EFPYs.

of the fuel block and thus the reactivity swing during 10.5 EFPYs. In addition, the effect of the radius of fuel compacts is more obvious than the radius of fuel kernels in the range investigated.

Some interesting results can be derived from Figs. 8 and 9. Firstly, the k_{inf} of the fuel block with slimmer fuel compacts is more strongly dependent on the radius of fuel kernels because of the lower mass of uranium in the fuel block. For example, the k_{inf} of the fuel block with 0.4 cm fuel compacts in radius changes drastically with the fuel kernel radius and time during 10.5 EFPYs. Secondly, there exists an optimum fuel kernel radius for each fuel compact. For example, the 0.6225 cm fuel compact in radius achieves the maximum k_{inf} when the radius of fuel kernel is 0.225 mm at 10 EFPYs in Fig. 9. Thirdly, the optimum kernel radius depends on time. For example, the 0.5-cm-radius fuel compacts achieve the maximum k_{inf}, when the kernel radii are 0.225 mm and 0.3 mm after 5.5 EFPYs and 10.5 EFPYs, respectively.

As shown in Fig. 9, for the fuel block with 0.6225 cm fuel compacts in radius, the radius of fuel kernels has the minimum influence on the k_{inf} of the fuel block. Moreover, the optimum radius of fuel kernels is in the range from 0.2 to 0.25 mm. Because of such characteristics of the fuel block, the neutronic design of the 20 MWth U-Battery with a lifetime of 10 EFPYs will use the reference parameters from the past HTR projects in the following sections, that is, 0.6225 cm fuel compacts and 0.25 cm fuel kernels in radius.

5. Reactor core configuration

Besides those geometric and composition parameters discussed in the previous sections, the configurations of the reactor core is a basic design parameter as well.

5.1. Comparisons of different reaction core configurations

Seven reactor cores were modelled by using SCALE 5.1, as shown in Table 5. The second and third columns of Table 5 show the name of configurations and the total number of fuel blocks in the reactor cores, respectively. For example, Layout 37*4 means that the reactor core of the U-Battery is comprised of 37 fuel columns and each column consists of 4 fuel blocks in the axial direction of the reactor core, which has 148 fuel blocks totally in the reactor core. Case 3 is currently considered the reference reactor core configuration of the U-Battery. Other configurations are considered as its modified versions. Case 1 is the reactor core configuration with the minimum number of fuel blocks, which is comprised of 19 fuel columns and 3 fuel blocks per fuel column.

The seven reactor core configurations may be divided into two groups. One group is the cylindrical reactor cores and the other is the annular ones. The cross sections of a typical cylindrical and

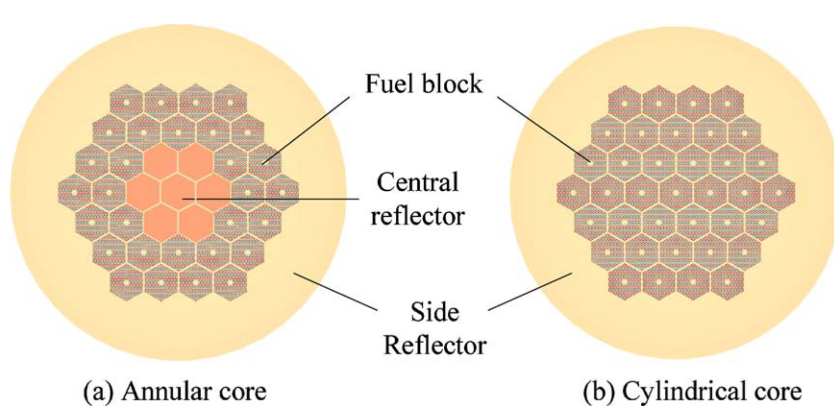

Fig. 10. Typical cylindrical (cases 3 and 4 in Table 5) and annular reactor core configurations (cases 6 and 7 in Table 5).

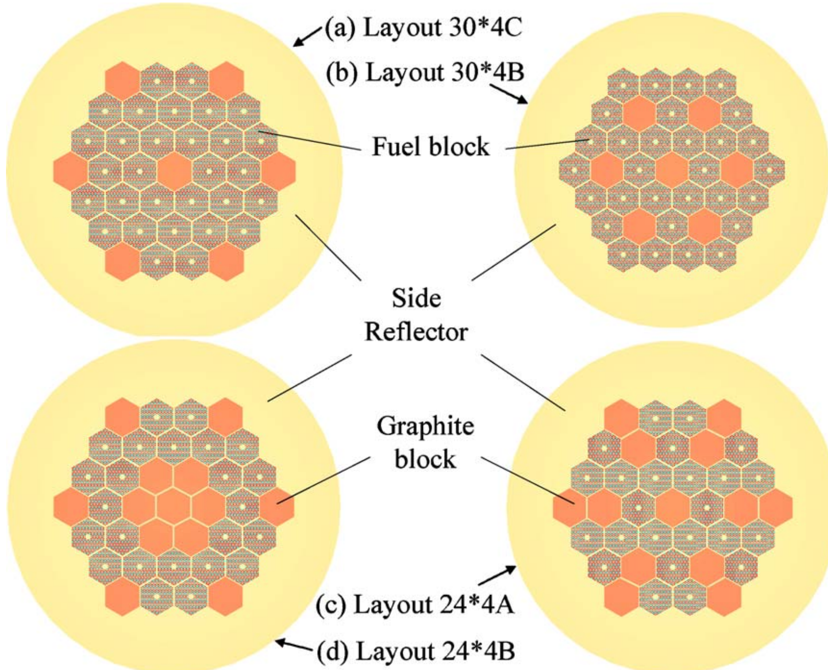

Fig. 11. Four non-cylindrical reactor core configurations.

annular reactor core configurations are shown in Fig. 10. Fig. 10(b) shows the configuration of the cylindrical reactor core with 37 fuel columns, i.e., cases 3 and 4 in Table 5. For the cylindrical reactor cores, the prismatic fuel columns are placed side by side inside the RPV of the U-Battery. In the annular reactor core configurations, the central fuel columns of the cylindrical reactor cores are replaced by the same number of graphite columns. As shown in Fig. 10(a), this annular reactor core is comprised of seven graphite columns in the center and 30 fuel columns surrounding the central graphite columns, i.e., cases 6 and 7 in Table 5.

The required fuel compositions of the seven reactor core configurations to achieve a specific lifetime are listed in Table 5. Except for the packing fraction of coated TRISO particles, other geometric parameters of the fuel block are identical. For example, the radii of fuel kernels and fuel compacts are 0.25 mm and 0.6225 cm, respectively. The fourth and fifth columns of Table 5 present the required fuel compositions of the configurations with 5-EFPY lifetime and 10-EFPY lifetime, respectively.

For the reference core configuration, i.e., case 3, the U-Battery can achieve 10-EFPY lifetime. The required enrichment of the fuel is 16.7% U-235 and the packing fraction of TRISO particles is 0.3. Case 5 is built by replacing a part of side reflector by 24 fuel columns (i.e., 72 fuel blocks totally) around the reference reactor core, and the required enrichment of the fuel can be reduced by 3% U-235 compared to the reference core configuration. This means that on average adding one fuel block reduces the fuel enrichment by 0.042% U-235. Case 4 is built by adding 37 fuel blocks in the axial direction of the reference reactor core. In this case, the required enrichment of the fuel reduces by 4.6% U-235 (0.124% U-235 per each fuel block on average). Adding the fuel blocks in the axial direction is more effective than adding them to the periphery of the reactor core, because the latter method uses thinner side reflector and leads to more neutron leakage from the reactor core.

Besides adding fuel blocks, removing ones is another option to build new reactors because the graphite moderated U-Battery is under-moderated. Four reactor core configurations in Table 5 are built using less fuel blocks (cases 1, 6 and 7) in terms of the reference configuration. For cases 6 and 7, 7 fuel columns (21 and 28 fuel blocks, respectively) are replaced by the same number of graphite columns in the center of the reactor cores, which leads to annular core configurations. Removing the fuel blocks does not lead to a large increase of the fuel enrichment for cases 6 and 7. The fuel enrichment of case 6 increases by 0.6% U-235 compared to the reference configuration. Case 7 has 120 fuel bocks, which is 28 less than case 4; however, the required fuel enrichment only increases by 0.8% U-235. Although case 7 uses 9 fuel blocks more than the reference layout, it reduces the fuel enrichment by 3.8% U-235, which means that adding a fuel block can reduce the fuel enrichment by 0.42% U-235. As mentioned in the previous paragraph, adding one fuel block for cases 4 and 5 reduces the fuel enrichment by 0.042% and 0.124%, respectively. Compared to cases 4 and 5, the value of 0.42% is 10 and 3.4 times higher, respectively. It attributes to a higher moderator-to-fuel ratio and fuel lumping effect. The higher moderator-to-fuel ratio leads to the better neutron moderation, and the fuel lumping contributes to higher resonance escape probability of neutrons. The complex comparisons show that the annular core design, like case 7, is a good choice for the U-Battery.

Cases 1 and 2 do not achieve 10-EFPY lifetime even though the fuel enrichment is 20% U-235, which is the acceptable maximum value for modern commercial reactors with LEU. If the fuel enrichment is 20% U-235 and the packing fraction of the TRISO particles is 0.3, case 1 only achieves 6.4-EFPY lifetime. The lifetime of the U-Battery will be 6.9 EFPYs if the packing fraction increases to 0.35. However, for case 2, the U-Battery achieves 9.1-EFPY and 9.8-EFPY lifetime, respectively, if the packing fractions of the TRISO particles are 0.3 and 0.35. Although case 2 does not reach the required 10-EFPY lifetime, it needs the minimum number of fuel blocks and has the minimum core volume and weight, which makes the U-Battery easier to transport.

5.2. Further analysis of scatter reactor core configurations

The configuration comparisons in Section 5.1 show that the required fuel enrichment of the annular Layout 30*4 is slightly higher than that of the cylindrical Layout 37*4, but it greatly reduces the number of fuel blocks from 37*4 to 30*4. There are three advan-

Table 6
k_{eff} of six reactor core configurations with kernel radius of 0.25 mm (enrichment = 20% U-235, packing fraction of TRISO particles = 0.3).

Time	Layout					
	37*4	30*4	30*4B	30*4C	24*4A	24*4B
0.0 EFPYs	1.2980	1.3397	1.3887	1.3242	1.3922	1.3504
5.0 EFPYs	1.1727	1.199	1.2495	1.1787	1.2289	1.1904
10.0 EFPYs	1.0788	1.0941	1.1494	1.0735	1.1049	1.0709
15.0 EFPYs	1.0034	1.0039	1.0508	0.9801	0.9803	0.9508
20.0 EFPYs	0.9304	0.9093	0.9513	0.8955	0.8427	0.8209

tages for Layout 30*4 over Layout 37*4. Firstly, the U-Battery with annular reactor core improves uranium utilisation by loading less fuel into the reactor core and thus a higher burnup of the fuel, which saves on the fuel cost of the U-Battery. Secondly, extra graphite blocks in the center of the reactor core provide larger heat capacity to accommodate the decay heat generated by fission products, especially during loss of forced-cooling accidents. Thirdly, control rods can be placed in these graphite blocks which replace the fuel blocks in the central regions, since the thickness of the side reflector is very small because of the limited diameter of the RPV.

More non-cylindrical or scatter core configurations with different number and distribution of graphite blocks in the reactor core are investigated in this section. Four different scatter core configurations are shown in Fig. 11. Layout 30*4B and Layout 30*4C have the same number of fuel blocks (120) and graphite blocks (28) in the reactor cores as Layout 30*4 as shown in Fig. 10(a). However, the distributions of these 28 graphite blocks are different from Layout 30*4. For Layout 30*4, all 28 graphite blocks are placed in the central regions of the reactor core, which leads to an annular reactor core configuration. The 28 graphite blocks are evenly dispersed in the fuel zone for Layout 30*4B, and are placed in the outermost and center zone for Layout 30*4C. Layouts 24*4A and 24*4B uses more graphite blocks (6 graphite blocks per layer) to replace the same number of fuel blocks than Layouts 30*4, 30*4B and 30*4C.

Tables 6 and 7 present the effective multiplication factor (k_{eff}) of Layouts 30*4, 30*4B, 30*4C, 24*4A and 24*4B with the 0.25 mm and 0.3 mm fuel kernels in radius, respectively. Note that, the fuel enrichment of the configurations in Tables 6 and 7 has been increased up to 20% U-235 in order to investigate the feasibility of a 20-EFPYs lifetime. The k_{eff} of Layout 37*4 is also shown in the two tables as a reference. For 0.25-mm-radius fuel kernel, all five non-cylindrical core configurations (one annular core and four scatter cores) have higher k_{eff} than Layout 37*4 at beginning of life (BOL), i.e., 0.0 EFPYs, and 5.0 EFPYs. At 10.0 EFPYs, Layouts 30*4, 30*4B and 24*4A still have higher k_{eff} than Layout 37*4, and Layouts 30*4C and 24*4B have only slightly lower k_{eff} than Layout 37*4. The larger moderator-to-fuel ratio contributes to the higher k_{eff} of the annular and scatter reactor core because of the under-moderated reactor core of the U-Battery.

The results of the five non-cylindrical reactor core configurations are still quite different, even though some of them have the same number of graphite and fuel blocks. In terms of the results in Table 6, the distribution of the graphite blocks apparently plays an important role for neutronic performance of the configurations.

Table 7
k_{eff} of six reactor core configurations with kernel radius of 0.3 mm (enrichment = 20% U-235, packing fraction of TRISO particles = 0.3).

Time	Layout					
	37*4	30*4	30*4B	30*4C	24*4A	24*4B
0.0 EFPYs	1.2706	1.3223	1.3712	1.3012	1.3753	1.3386
10.0 EFPYs	1.0875	1.1143	1.1643	1.0887	1.1365	1.0994
20.0 EFPYs	0.9555	0.9613	1.0072	0.9352	0.9407	0.9135

Table 8
Maximum lifetime/burnup of six reactor core configurations.

Configuration	Lifetime[EFPYs]/Burnup [GWd/MTU]	
	Kernel radius = 0.25 [mm]	Kernel radius = 0.3 [mm]
Layout 37*4	15.2 /86.6	16.3/73.4
Layout 30*4	15.2/107.3 (+23.8%)	17.4/96.8 (+31.8%)
Layout 30*4B	17.6/124.0 (+43.1%)	20.5/113.5 (+54.6%)
Layout 30*4C	14.0/98.8 (+14.0%)	15.6/86.3 (+17.5%)
Layout 24*4A	14.2/125.1 (+44.4%)	17.0/117.8 (+60.5%)
Layout 24*4B	13.0/114.2 (+31.9%)	15.3/106.2 (+44.6%)

Layout 30*4B has the maximum k_{eff} among all reactor core configurations with 28 graphite blocks in the reactor core from 0.0 EFPYs to 20.0 EFPYs because of the more uniform distribution of the graphite blocks in the reactor core. Compared with the distribution of Layout 30*4B, the distribution of the graphite blocks for Layout 30*4 is over-centralized and Layout 30*4C over-dispersed. More even dispersion contributes to a higher resonance escape probability.

All reactor core configurations in Table 6 do not achieve 20-EFPY lifetime, even though the fuel enrichment is 20% U-235. However, if the radius of fuel kernels in the coated TRISO particles increases to 0.3 mm, as used by the HTTR in Japan, Layout 30*4B achieves 20-EFPY lifetime, as shown in Table 7. The lifetime of the U-Battery is extended only by changing the arrangement of the fuel and graphite blocks, rather than increasing the number of the fuel blocks or reducing the thickness of the internal side reflector. Although the mass of the heavy metal loaded into the reactor core increases (about 2.3 kg per block) when the radius of fuel kernels increase from 0.25 mm to 0.3 mm, its influence is relative small for the total mass of the reactor core or the reactor system of the U-Battery. This means that the height and diameter of the reactor core for the U-Battery with 20-EFPY lifetime maintain as the U-Battery with 10-EFPY lifetime, which is rather positive for the transportability of the U-Battery, and the economy of the U-Battery.

Table 8 shows the maximum lifetimes with k_{eff} up to unity and fuel burnup of the five non-cylindrical reactor core configurations, as well as Layout 37*4 as a reference. As shown in Table 8, compared with the reference configuration, although the lifetime of some core configurations decreases slightly, like Layout 24*4B, the fuel burnup greatly increases for all non-cylindrical reactor core configurations, that is, the uranium utilisation improves obviously. For example, compared with the burnup of Layout 37*4, the burnup of Layouts 30*4, 30*4B, 24*4A and 24*4B increase by 23.8%, 43.1%, 44.4% and 31.9%, respectively, when the radius of fuel kernels is 0.25 mm. If the radius of fuel kernels increases to 0.3 mm, the fuel burnup increases even more. For example, the burnup of Layout 24*4A increases by 60.5% compared with Layout 37*4. The increase of fuel burnup mainly results from the smaller amount of fuel loaded, which improves the neutron moderation in the reactor core. On the other hand, the longer lifetime also contributes to the increase of the fuel burnup for some core configurations, like Layout 30*4B.

The comparison of cylindrical cores with non-cylindrical ones shows that the core design of the U-Battery is under-moderated, and thus increasing the neutron moderation in the core by replacing fuel blocks with graphite blocks is an effective way to extend lifetime and increase the fuel burnup of the U-Battery, or fuel utilisation.

6. Two key neutronic characteristics of U-Battery

For the U-Battery, there are two neutronic parameters important for its inherent safety. The first one is reactivity temperature coefficient, and the other one is reactivity change induced by water or steam in the coolant in the reactor core. These two safety-related

Table 9
Average reactivity temperature coefficient of U-Battery from 800 K to 1000 K.

Configuration	Time [EFPYs]	Fuel [pcm/K]	Moderator [pcm/K]	Reflector [pcm/K]
Layout 30*4	0.0	−3.8	−1.6	+0.5
	5.0	−5.4	−3.1	+0.1
	10.0	−5.3	−3.8	+0.8
Layout 37*4	0.0	−5.4	−2.9	+1.2
	5.0	−7.5	−3.4	+0.4
	10.0	−7.2	−4.1	+0.2

characteristics of the U-Battery are investigated in this section for two typical reactor core configurations, including cylindrical cores, Layout 37*4 or Layout 37*3, and an annular core, Layout 30*4.

6.1. Temperature coefficient of reactivity

One of the important principles of nuclear reactor design is that reactors should have negative reactivity temperature coefficient. Table 9 presents the average temperature coefficients of reactivity of Layout 37*4 (cylindrical core) and Layout 30*4 (annular core) from 800 to 1000 K. The term fuel means the fuel smeared compacts in the fuel blocks; the term moderator means the graphite structure of the fuel blocks excluding the fuel compact; and the term reflector means the graphite side reflector and central graphite reflector (if present). As shown in Table 9, both reactor core configurations have negative temperature coefficients of reactivity during the whole lifetime. The fuel and moderator have negative temperature coefficients of reactivity, while the reflector has a slightly positive reactivity temperature coefficient. The positive reactivity temperature coefficients attributes to the hardened energy spectrum at higher temperature. In fact, the positive reactivity temperature coefficient of the reflector of the U-Battery is smaller than other HTRs like HTR-10 because of a larger neutron leakage.

The positive reactivity temperature coefficient of the reflector does not lead to any safety problems for the U-Battery. Firstly, the reactivity temperature coefficients of the fuel and moderator are negative, and the absolute values of the negative coefficients of the fuel and moderator is far larger than that of the reflector. Secondly, the temperatures of the fuel and moderator will increase faster than that of the reflector. This means negative reactivity will be induced first by the fuel and moderator before positive reactivity may be induced by the reflector. Thirdly, the temperature change of the reflector will be less than those of the fuel and moderator because of the large heat capacity of the reactor core of the U-battery, which means that the positive reactivity possibly induced by the reflector can easily be offset by the negative reactivity induced by the fuel and moderator.

6.2. Neutronic risk of water ingress

Since the U-Battery will probably adopt a power conversion system based on a Rankine cycle, the risk of water/steam ingress into the reactor core exists during its operation. Because water/steam ingress is a design-basis accident for modern HTRs with steam cycles, the effect of water/steam in the U-Battery on the reactivity was investigated in order to gain insight into this risk known. The reactivity induced by the water/steam is plotted as a function of the water density in the coolant channel of fuel blocks in Fig. 12 for Layout 30*4, i.e., case 7 in Table 5. As shown in Fig. 12, the water/steam in the reactor induces positive reactivity during the whole lifetime of the U-Battery. For the water/steam density up to 0.001 g/cm^3, a small positive reactivity ($\Delta\rho$< 0.002 Δk/k) is induced. However, when the water/steam density is larger, the reactivity induced increases significantly and reaches a maximum

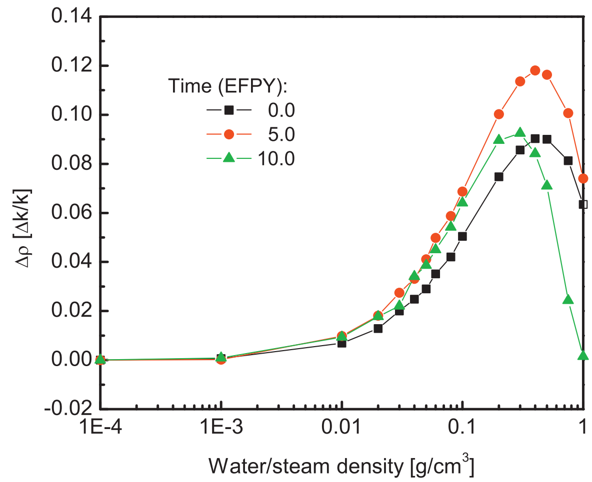

Fig. 12. Induced reactivity by water/steam as a function of the water/steam density and time for Layout 30*4.

value at a water density of 0.4 g/cm^3 for Layout 37*3 at BOL, then drops off rapidly because of the neutron absorption in the water. The induced reactivity changes with the same pattern at different fuel burnup times, but with different maximum values in different water/steam densities.

For Layout 37*3, the reactivity induced by water/steam is similar. However, the maximum possibly induced reactivity of Layout 30*4 is less than that of Layout 37*3 because the central graphite blocks provide better neutron moderation. Although the neutron moderation of Layout 30*4 is better than that of Layout 37*3, Layout 30*4 is still under-moderated. The maximum reactivity induced for Layout 37*3 and 30*4, which is determined by the water/steam density, is illustrated in Fig. 13 as a function of time. As shown in Fig. 13, the maximum induced reactivity for Layout 37*3 increases with the fuel burnup and reaches the maximum value of 0.148 Δk/k after 6.5 EFPYs, then drops quickly with the fuel burnup. For Layout 30*4, the maximum value and time are 0.119 Δk/k and 6.0 EFPYs, respectively.

Figs. 12 and 13 indicate that the potential risk of the positive reactivity induced by water/steam does exist for the whole lifetime of the U-Battery. Furthermore, the possibly induced positive reactivity is rather large because the neutron moderation is insufficient in the reactor core of Layout 37*3, as well as Layout 30*4. If a Rankine cycle is adopted by the U-Battery, the high risk of posi-

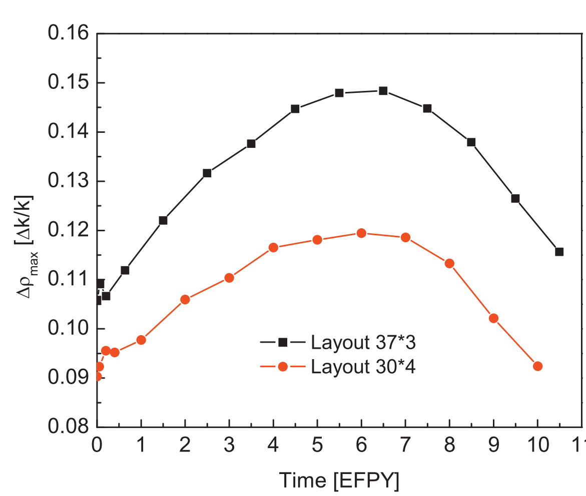

Fig. 13. Maximum reactivity induced by the water/steam as a function of the burnup for Layout 37*3 and Layout 30*4.

tive reactivity insertion should be considered in the design basis of the U-Battery. A coolant purification system should be designed to limit the maximum steam density in the reactor. Other gas cycles like SCO_2, N_2 or $He–N_2$ are recommended for the U-Battery in order to eliminate water ingress risk.

7. Conclusions

The neutronic feasibility of the 20 MWth U-Battery with a lifetime of 10 effective full power years (EFPYs) or longer has been investigated by using SCALE 5.1 based on validated HTR technologies. The neutronic calculations show that the design of the 20 MWth U-Battery with a 10-EFPY lifetime is feasible and still rather flexible using less than 20% enriched uranium, like Layout 37*4 and Layout 30*4. The U-Battery has negative temperature coefficients of reactivity during the whole 10-EFPY lifetime, which partly ensures its inherent safety.

The neutronic effects of six important design parameters have been investigated parametrically. (1) Increasing fuel enrichment can easily increase the lifetime and the effective multiplication factor of the U-Battery. (2) As the packing fraction of TRISO particles increases, the fuel lifetime of the U-Battery increases; however, the effective multiplication factor at beginning-of-life (BOL) decreases because of the lower neutron moderation. (3) The higher the fuel enrichment and the packing fraction of TRISO particles are, the lower the reactivity swing during 10 EFPYs will be. (4) There is an optimum fuel kernel radius for each fuel compact (i.e., radius) and a specific fuel lifetime. (5) The radius of fuel kernels has a small influence on the k_{inf} of a typical fuel block in the range of 0.2–0.25 mm, when the radius of fuel compacts is 0.6225 cm and the lifetime of the fuel block is 10 EFPYs.

Eleven possible reactor core configurations analyzed include five cylindrical reactor cores (Layouts 37*3, 37*4, 61*3, 19*3 and 19*4), two annular reactor cores (Layouts 30*3 and 30*4), and four scatter reactor cores (Layouts 30*4B, 30*4C, 34*4A and 24*4B). The comparison of the cylindrical reactor cores with the non-cylindrical ones shows that neutron under-moderation is a basic characteristic of the reactor core of the U-Battery, because a large amount of heavy metal is loaded into the reactor core for a 10-EFPY or longer lifetime. Thus, increasing the neutron moderation in the reactor core by replacing some fuel blocks with graphite blocks and dispersing the graphite blocks in the reactor core are two effective ways to extend the fuel lifetime and to increase the fuel burnup of the U-Battery. For the same reason, positive reactivity ranging from 0 to 0.16 $\Delta k/k$ is induced by water or steam with density up to 1.0 g/cm^3 if it enters the reactor core of the U-Battery. Some promising designs, like Layout 37*4, Layout 30*4 and Layout 30*4B, will be evaluated by thermal-hydraulic analysis in the near future.

References

Duderstadt, J.J., Hamilton, L.J., 1976. Nuclear Reactor Analysis. John Wiley & Sons.

GA, 1996. Gas turbine-modular helium reactor (GT-MHR) conceptual design description report. Tech. Rep. 910720, General Atomics, California, USA.

Gottaut, H., Kruger, K., 1990. Results of experiments at the AVR reactor. Nuclear Engineering and Design 121, 143–153.

Hu, S., Wang, R., Gao, Z., 2006. Transient tests on blower trip and rod removal at the HTR-10. Nuclear Engineering and Design 236, 677–680.

IAEA, 2005. Innovative small and medium sized reactors: design features, safety approaches and R&D trends. Tech. Rep. IAEA-TECDOC-1451, International Atomic Energy Agency, Vienna, Austria.

IAEA, 2007. Status of small reactor designs without on-site refuelling. Tech. Rep. IAEA-TECDOC-1536, International Atomic Energy Agency, Vienna, Austria.

Ingersoll, D.T., 2009. Deliberately small reactors and the second nuclear era. Progress in Nuclear Energy 51, 589–603.

Kuznetsov, V., 2008. Options for small and medium sized reactors (SMRs) to overcome loss of economies of scale and incorporate increased proliferation resistance and energy security. Progress in Nuclear Energy 50 (2-6), 242–250.

Modro, S.M., Fisher, J.E., Weaver, K.D., Reyes, J.N., Groome, J.T., Babka, P., Carlson, T.M., 2003. Multi-application small light water reactor final report. Tech. Rep. INEEL/EXT-04-01626, Idaho National Engineering and Environmental Laboratory, Idaho, USA.

Nakagawa, S., Takamatsu, K., Tachibana, Y., Sakaba, N., Iyoku, T., 2004. Safety demonstration tests using high temperature engineering test reactor. Nuclear Engineering and Design 233, 301–308.

ORNL, April 2005. SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations Version 5, vols. I–III. Oak Ridge National Laboratory, Oak Ridge, TN, Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-725.

Sienicki, J.J., Moisseytsev, A., Wade, D.C., Nikiforova1, A., 2007. Status of development of the small secure transportable autonomous reactor (SSTAR) for worldwide sustainable nuclear energy supply. In: Proceedings of International Congress on Advances in Nuclear Power Plants, Nice, France.

Ueda, N., Kinoshita, I., minato, A., Kasai, S., Yokoyama, T., Maruyama, S., 2005. Sodium cooled small fast long-life reactor 4S. Progress in Nuclear Energy 47, 222–230.