

## Parametric Neutronics Design of a Small and Long-Life HTR

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**Abstract** – Small and long-life high temperature gas-cooled Reactors (HTRs) are interesting because they can safely produce electricity or heat for remote areas or industrial users in developed and/or developing countries. Small HTRs have the advantages of transportability, modular construction, and flexible site selection. This paper presents the neutronic analysis of the U-Battery<sup>®</sup>, which is a small, long-life and block-type HTR based on currently mature HTR technologies. The 3.5 meter diameter of the reactor pressure vessel (RPV) is one of the design restrictions in order to secure its transportability. The lifetime of the U-Battery<sup>®</sup> is chosen to be 5 to 10 years in order to reduce its operating and maintenance costs. Key design parameters and possible core layouts of the U-Battery<sup>®</sup> were parametrically investigated using the TRITON 6 module in SCALE 5.1. The design parameters analyzed include fuel enrichment, the packing fraction of the TRISO particles, the radii of the fuel compacts and kernels, and the thicknesses of the top and bottom reflectors. The external side reflector, located outside the RPV of the U-Battery<sup>®</sup>, is proposed to improve neutron economy because the U-Battery<sup>®</sup> adopts a thin internal side reflector located inside the RPV. Possible layouts of the U-Battery<sup>®</sup> cover cylindrical cores and annular cores. Since the energy conversion system of the U-Battery<sup>®</sup> is supposed to be based on a Rankine cycle, the effect of steam or water on the reactivity was also investigated because water ingress is a design-basis accident for HTRs. The analysis shows that the design of the U-Battery<sup>®</sup> is feasible and flexible from neutronics point of view. The core layouts of 37\*4 (4 layers of 37 blocks), 30\*4 and 19\*4 are promising designs of the U-Battery<sup>®</sup>. Further thermal-hydraulic evaluations to these promising layouts are ongoing.

### I. 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 [1]. 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 [2-4].

Compared to large-size nuclear reactors, SMRs have some inherent advantages. They can be

fabricated in modularity 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 levels. For example, some small reactors, which adopt passively cooling methods during normal operation or accident, have been proposed based on different reactor technologies, such as light water

reactors (LWRs) [5], high temperature gas-cooled reactors (HTRs) and liquid-metal cooled reactors (LMRs) [6].

The inherent safety of modular HTRs has been validated directly by experiments over the last 30 years [7-9]. However, few studies have currently focused on small and long-life HTRs. So, this paper proposes a small, inherently safe and long-life HTR, called the U-Battery<sup>®</sup>, which can 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.

The second part of this paper presents the basic parameters of the U-Battery<sup>®</sup> in detail. The third part explains the models of the U-Battery<sup>®</sup> and analysis method. The fourth part parametrically investigates some key design parameters of the U-Battery<sup>®</sup>, including its fuel enrichment, the packing fraction of the TRISO particles, the thicknesses of the side, top and bottom reflectors, and the radii of the fuel compacts and fuel kernels. Moreover, the fifth part analyzes nine core layouts, including seven cylindrical cores and two annular cores in order to obtain a suitable core configuration. The sixth part studies the effect of water/steam density on the reactivity of the U-Battery<sup>®</sup> since water ingress is a design-basis accident for HTRs.

## II. DESCRIPTION OF THE U-BATTERY<sup>®</sup>

The U-Battery<sup>®</sup> is a small, inherently safe and transportable HTR with a long core life, 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 parameters of the U-Battery<sup>®</sup> are listed in Table 1.

Table 1 Basic parameters of the U-Battery<sup>®</sup>

Parameter	Value
Reactor type	Block-type HTR
Thermal power	20 MW
Core lifetime	5-10 years
Coolant	CO <sub>2</sub> , Helium
Diameter of RPV	< 3.5 m
Fuel type	UO <sub>2</sub> , TRISO coated fuel
Fuel enrichment	< 20 wt% U-235
Energy conversion system	Rankine steam cycle

Since the main idea behind the U-Battery<sup>®</sup> is inherent safety, modularity and near-term utilization, the U-Battery<sup>®</sup> has been developed based on currently mature block-type HTR technologies, so it inherits the inherent safety that has been validated by experiments. The reactor core of the U-Battery<sup>®</sup> consists of hexagonal graphite fuel and reflector elements, plenum elements and reactivity control

components, all located inside a reactor pressure vessel (RPV). The active core is comprised of a certain number of hexagonal fuel columns, side reflectors, top reflectors and bottom reflectors, as shown in Fig. 1(a). In the axial direction of the columns, which is also the axial direction of the active core, each 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<sup>®</sup> uses the fuel blocks developed by General Atomic for the GT-MHR project [10]. The block width cross flats is 36 cm and the height is 80 cm. Each fuel block includes 210 fuel channels, 108 coolant channels and 6 FBP channels. The diameters of the fuel channels, coolant channels and FBP channels are 1.27 cm, 1.88 cm and 1.27 cm, respectively. In each fuel channel, there are 14-15 fuel compacts of TRISO particles with low-enriched uranium (LEU) fuel kernels.

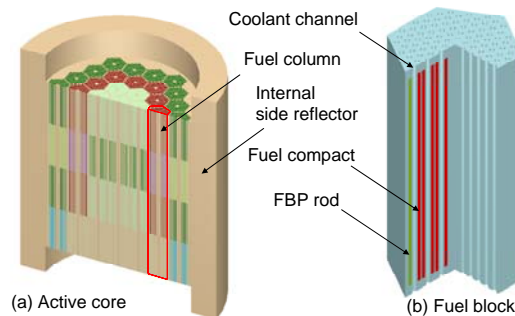


Fig. 1 3D schematic diagram of an active core and a fuel block; the top and bottom reflectors have been removed in the active core, and the fuel handling hole has also been removed in the fuel block.

Since the numbers of the fuel columns and fuel blocks are key parameters of the reactor active core, the notation of C\*B is used to represent the core layout of the U-Battery<sup>®</sup>, where C is the number of the fuel columns in the active core and B is the number of the fuel blocks in each fuel column. For example, the layout of the active core shown in Fig. 1(a) is 37\*4, which means that the reactor active core is comprised of 37 fuel columns and each column 4 fuel blocks in the height direction of the block (the axial direction of the active core).

A thermal power of 20 MW<sub>th</sub> opens up the possibility of using the U-Battery<sup>®</sup> for small industrial process heat applications, as well as for small electricity application. The U-Battery<sup>®</sup> with such thermal power can fill a niche of the market currently not open to nuclear energy. Fuel enrichment higher than 20 wt% U-235 is not feasible since 20 wt% U-235 is the maximum value for commercial applications with LEU. 10 wt% U-

235 or lower enrichment would be desirable from a practical point of view. The U-Battery<sup>®</sup> accepts carbon dioxide or helium as the coolant because these two coolants have been used for graphite-moderated reactors over 40 years. The diameter of the U-Battery<sup>®</sup>'s RPV is requested to be less than or equal to 3.5 meters so that the U-Battery<sup>®</sup> can be transported as a whole by rail, truck, or barge, etc. The power conversion system of the U-Battery<sup>®</sup> uses a Rankine steam cycle since the U-Battery<sup>®</sup> aims to be commercialized soon and the steam cycle is the most mature technology in the nuclear industry.

### III. MODEL OF THE U-BATTERY<sup>®</sup> AND CALCULATION METHOD

A 3D model of the U-Battery<sup>®</sup>, including an assembly of fuel blocks, internal and external side reflectors, top and bottom reflectors, as shown in Fig. 1(a), was built in SCALE 5.1 (Standardized Computer Analyses for Licensing Evaluation) [11] in order to obtain the neutronic performance of the U-Battery<sup>®</sup>. SCALE 5.1 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, etc. SCALE5.1 is a modular code system and is mainly comprised of functional modules and control modules. In the calculations of the U-Battery<sup>®</sup>, Two function modules (BONAMI and CENTRM) were used to process the resonance cross section of the materials and cells used in the U-Battery<sup>®</sup>. The KENO-VI module, a 3D Monte Carlo criticality safety code, was used to calculate the effective multiplication factor of the U-Battery<sup>®</sup>. The ORIGEN-S module was used to perform point depletion calculations and obtain isotopic concentrations in the U-Battery<sup>®</sup>. The TRITON6 module was used to serve as the controller of module sequencing, data transfer, and input/output control for multiple analysis sequences. The whole calculation controlled by TRITON6 can be summarized in the following steps:

- 1) Preparing resonance shielded and homogeneous cross sections for given unit cells. In the calculations of the U-Battery<sup>®</sup>, the smallest unit used is a homogenized fuel compact without explicit TRISO particles. Resonance cross sections of this unit are generated by the BONAMI and CENTRM modules in this step. Since the heterogeneity of the TRISO particles in the fuel compact is ignored when the cross sections of the unit cells are generated in this step, the results of all calculations in this paper are conservative from neutronics point of view because the heterogeneous effect of the TRISO particles can increase the effective multiplication factor of fuel blocks by 2-3%. The double

heterogeneity of the TRISO particles will be included in the future analysis.

- 2) Providing the cross sections generated in step 1 to the 3D Monte Carlo module KENO VI to perform criticality calculations and to obtain the effective multiplication factor and the flux profile of the U-Battery<sup>®</sup>. 3D KENO-VI models were built for the U-Battery<sup>®</sup> with the proper hexagonal block structure, as shown in Fig. 1(a).

- 3) Sending the flux profiles to ORIGEN-S module that performs depletion calculations of the U-Battery<sup>®</sup>. A 10-year lifetime is specified for the U-Battery<sup>®</sup>.

- 4) Feeding the new material compositions after each ORIGEN burnup step back to step 1 and repeating the whole process until completing all burnup.

### IV. KEY DESIGN PARAMETER ANALYSIS

Fuel enrichment, the packing fraction of the TRISO particles, the thicknesses of the top, bottom and side reflectors are key design parameters of the U-Battery<sup>®</sup>, which are analyzed parametrically in this section. Although changing the sizes of fuel compacts and fuel kernels is only optional to the design of the U-Battery<sup>®</sup>, they are still investigated in this section because these two factors greatly influence the 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 modeled explicitly. And the fuel handling holes in the center of the fuel blocks and the gaps between the fuel blocks are all ignored. These simplifications are proposed to save CPU time.

#### IV.A. Fuel enrichment

In the design of nuclear reactors, fuel enrichment is one of the most effective parameters that can be chosen freely in order to achieve a critical reactor and specific fuel lifetime. Figure 2 presents the effective multiplication factor,  $k_{eff}$ , of the U-Battery<sup>®</sup> with Layout 37\*4 as a function of the fuel enrichment and burnup. In this core layout, each fuel column is comprised of 4 fuel blocks, and the packing fraction of the TRISO particles is 0.3. Higher fuel enrichment achieves larger  $k_{eff}$  and longer lifetime because it means higher thermal and fast neutron utilization and more U-235 loaded into the U-Battery<sup>®</sup>. The lifetime of the U-Battery<sup>®</sup> reaches 10 effective full power years (EFPYs) when the fuel enrichment is 12 wt% U-235 for Layout 37\*4. The vertical distance between lines in Fig. 2 decreases as the fuel enrichment increases, which means that increasing the  $k_{eff}$  by higher fuel enrichment becomes less and less effective. The

reactivity of the U-Battery<sup>®</sup> increases by 0.021  $\Delta k/k$  when the fuel enrichment varies from 8 wt% U-235 to 10 wt% U-235 at beginning-of-life (BOL); however, the reactivity only increases by less than 0.005  $\Delta k/k$  per 1 wt% fuel enrichment when the fuel enrichment is larger than 14 wt% U-235.

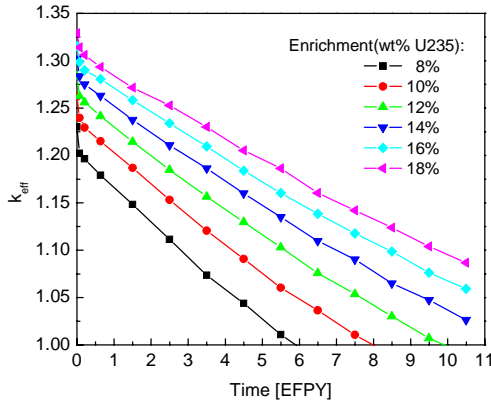


Fig. 2  $k_{eff}$  as a function of the fuel enrichment and burnup for Layout 37\*4

Reactivity change with fuel burnup (reactivity swing) should be maintained as low as possible in order to avoid moving control rods frequently to compensate for the reactivity loss as the fuel is used. 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 different packing fractions of the TRISO particles, as shown in Fig. 3. This means that higher fuel enrichment can suppress the reactivity swing, so less compensation is needed during the operation of the U-Battery<sup>®</sup>.

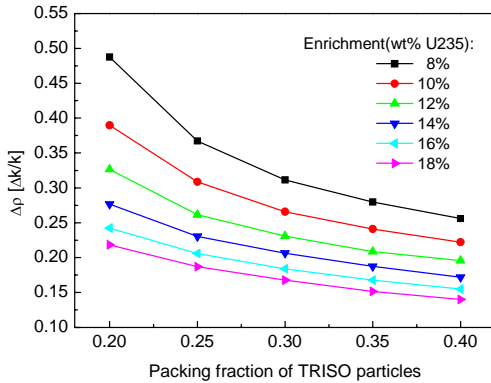


Fig. 3 Reactivity swing  $\Delta\rho(=\rho_{BOL}-\rho_{EOL})$  as a function of the packing fraction of the TRISO particles and fuel enrichment for Layout 37\*4

#### IV.B. Packing fraction of the TRISO particles

Compared to the fuel enrichment, the packing fraction of the TRISO particles in the compact is a more complex factor, which influences the neutronic

performance of the U-Battery<sup>®</sup>, especially the  $k_{eff}$  and the reactivity swing differently.

The  $k_{eff}$  of Layout 37\*4 is plotted as a function of the packing fraction of the TRISO particles in the compacts and burnup in Fig. 4. The active core is comprised of 148(=37\*4) fuel blocks and the fuel enrichment is 12 wt%. The higher the packing fraction of the TRISO particles is in the compacts, the longer the lifetime of the U-Battery<sup>®</sup> will be. 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. The  $k_{eff}$  decreases with the increase of the packing fraction of TRISO particles at BOL and increases at EOL.

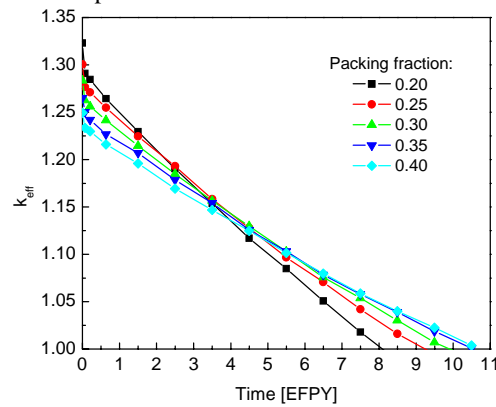


Fig. 4  $k_{eff}$  as a function of the TRISO particles' packing fraction and burnup for Layout 37\*4

Figure 5 shows the relationship between the  $k_{eff}$  and the packing fraction of the TRISO particles more directly than Fig. 4. At BOL, the higher packing fraction leads to a smaller  $k_{eff}$  because more heavy metal is loaded into the reactor core and neutron is severely under moderated on this condition. This condition changes with the fuel burnup. The  $k_{eff}$  is almost independent to the packing fraction of the TRISO particles at 3.5 years. After that, higher packing fraction means larger  $k_{eff}$ .

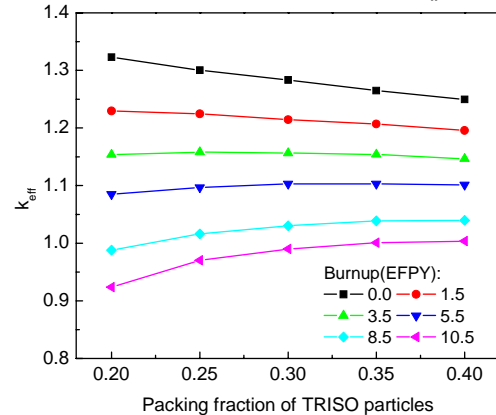


Fig.5  $k_{eff}$  as a function of the packing fraction of the TRISO particles for Layout 37\*4

The analysis showed that there is an optimum packing fraction of the TRISO particles in the compacts for a specific core layout, fuel enrichment and lifetime of the U-Battery®.

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 active core.

#### IV.C. Top and bottom reflectors

Adopting top and bottom reflectors can increase the neutron economy of the U-Battery® based on nuclear reactor theory, whose effect is investigated in this section. In all the calculations in the paper, the thickness of the top reflectors is the same as the bottom reflectors, and both are 50 cm in the other sections. The thickness of top reflectors is still the same as the bottom reflectors in this section; however they varied from 10 cm to 100 cm. The reactivity change  $\Delta\rho$  of Layout 37\*3 with the thicknesses of the top and bottom reflectors is plotted in Fig. 6. The  $\Delta\rho$  is defined as  $\Delta\rho = \rho - \rho_{10}$ , where  $\rho$  is the reactivity of the reactor with top and bottom reflectors at certain thickness; and  $\rho_{10}$  is the reactivity of the reactor with 10 cm top and bottom reflectors.

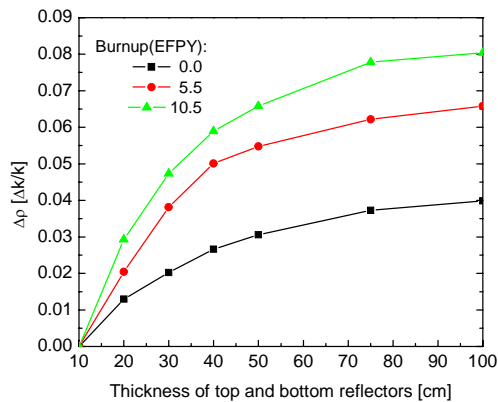


Fig. 6  $\Delta\rho(=\rho-\rho_{10})$  as a function of thicknesses of top and bottom reflectors for Layout 37\*3

As shown in Fig. 6, the  $\Delta\rho$  increases quickly for the thickness up to 75 cm, but slows down afterwards. For 100 cm top and bottom reflectors, the reactivity increases by 0.04  $\Delta k/k$  at BOL; however, it increases by 0.066  $\Delta k/k$  and 0.08  $\Delta k/k$  after 5.5 effective full power years (EFPYs) and 10.5 EFPYs, respectively. This means that the merit of the top and bottom reflectors increases with fuel burnup. 100 cm top and bottom reflectors are recommended for the U-Battery® based on these calculations.

#### IV.D. External side reflectors

The U-Battery® possibly adopts very thin internal side reflectors (e.g., 10 cm), located inside the RPV, in order to keep the RPV's diameter below 3.5 m. Since the diffusion length of neutrons in graphite is about 70 cm, a permanent, external side reflector (ESR) is proposed outside the RPV. According to the calculations in Sec. II.C, a 100 cm reflector is enough from the neutron economy point of view, so the thickness of the ESR was assumed as 100 cm in the calculations in this section.

The effect of the ESR on the neutronic performance of the U-Battery® was investigated based on two core layouts: Layout 37\*3 and Layout 61\*3. In the first active core layout, the thickness of the internal side reflector, located inside the RPV, is 45 cm; while in the second case it is 10 cm. The  $k_{eff}$  of these two core layouts loaded fuel with different fuel enrichments is plotted as a function of the fuel burnup in Figures 7 and 8, respectively. The ESRs obviously increases the  $k_{eff}$  of the reactor, which means that the ESR is an effective way to improve the neutron economy of the U-Battery®. The reactivity of Layout 37\*3 increases by 0.02-0.035  $\Delta k/k$ . The reactivity of Layout 61\*3 increases by 0.04-0.07  $\Delta k/k$ . The reactivity of the latter increases twice as much as the former because the thickness of the internal side reflector of the latter is only 10 cm and a large fraction of neutrons leak out of the core.

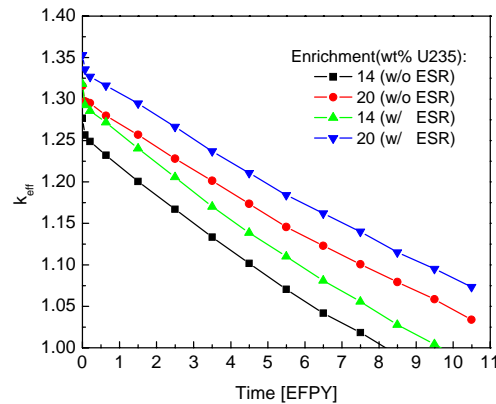


Fig. 7  $k_{eff}$  as a function of burnup and fuel enrichment for Layout 37\*3

Adding the external, permanent side reflectors is recommended from the neutronics point of view. However, the application of the ESR must be evaluated by thermal-hydraulic analysis because it may block heat transfer by radiation between the RPV and the reactor cavity cooling system (RCCS). This system is commonly used by modern HTRs in order to cool the RPV during normal operation and remove the decay heat at accident conditions.

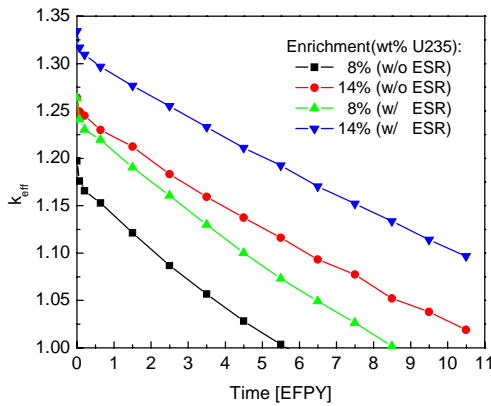


Fig. 8  $k_{eff}$  as a function of burnup and fuel enrichment for Layout 61\*3

#### IV.E. Other optional design parameters

As mentioned in Sec. II, the U-Battery<sup>®</sup> is designed based on currently mature HTR technologies, such as TRISO coated fuel particles and reference fuel blocks validated by past HTR projects in order to reduce its research and development cost. So, in the previous analysis, some design parameters, including the radii of the fuel compacts and the fuel kernels in the TRISO particles, are fixed to the reference values adopted by past HTR projects. The radius of the fuel compacts is 0.6225 cm, and the radius of the fuel kernels in the TRISO particles is 0.025 cm. However, these two parameters are investigated in this section because they greatly influence neutron moderation performance in fuel blocks.

The effects of the radii of the fuel compacts and fuel kernels were investigated based on a fuel block rather than a whole active core to reduce calculation times since they are the same for the U-Battery<sup>®</sup>. The fuel enrichment is 12 wt% U-235 and the packing fraction of the TRISO particles is 0.3 in the all calculations in Sections IV.E.1 and IV.E.2. A 3D prismatic fuel block was modeled in SCALE 5.1 with reflective boundary condition.

##### IV.E.1 Radius of kernels in the TRISO particles

Figure 9 illustrates the infinite multiplication factor,  $k_{inf}$ , of a fuel block as a function of the kernel radius and burnup. The radius of the fuel compact in the fuel block is 0.6225 cm. At BOL, the larger the kernel radius is, the smaller the  $k_{inf}$  is. This is because the larger the fuel kernel radius is, the more the uranium will be loaded and the less graphite there is in the fuel compacts, which leads to less sufficient neutron moderation. The situation of insufficient moderation changes slowly with the fuel burnup in the fuel block. At EOL, the  $k_{inf}$  increases

with the kernel size first and reaches the maximum value at 0.2 mm, then decreases slowly.

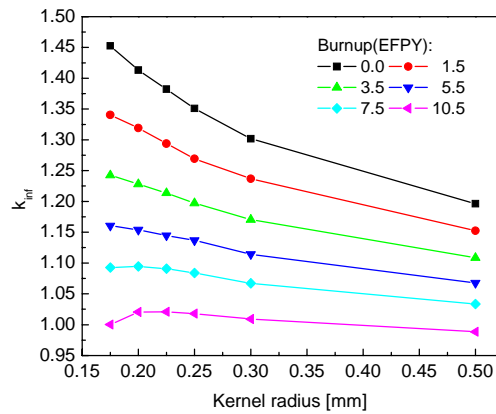


Fig. 9  $k_{inf}$  as a function of kernel radius and burnup for a fuel block with fuel compacts in 0.6225 cm radius

The second important effect of the 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 kernel with radius of 0.175 mm, the  $k_{inf}$  starts at the largest value among all 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, at 10.5 EFPYs, it drops by 0.31  $\Delta k/k$  quickly because the mass of the uranium in the fuel block is smallest, which leads to larger reactivity swing than others. So, large-radius kernel is preferred for the U-Battery<sup>®</sup> from reactivity control point of view. Since the TRISO particles are not modeled explicitly, the influence of the kernel radius on the reactivity only includes the mass of the uranium. The explicit effect of the TRISO particles will be included in the future.

##### IV.E.2 Radius of the fuel compact

Figure 10 illustrates the infinite multiplication factor,  $k_{inf}$ , of a fuel block as a function of the radius of the fuel compacts and burnup. The radius of the kernels in the fuel block is 0.25 mm. There are two similar effects of the fuel compacts' radius on the  $k_{inf}$  of the fuel block as the fuel kernel radius increases. At BOL, the larger radius of the fuel compacts is, the smaller  $k_{inf}$  is. This mode also changes with the fuel burnup as the kernel radius. At EOL, the  $k_{inf}$  first increases quickly and then decreases slowly with the increase of the radius of the fuel compacts. Increasing the radius of the fuel compacts means that the ratio of moderator (graphite) to the fuel (uranium) is reduced, which leads to be less sufficient neutron moderation. This situation is changed by the fuel burnup.

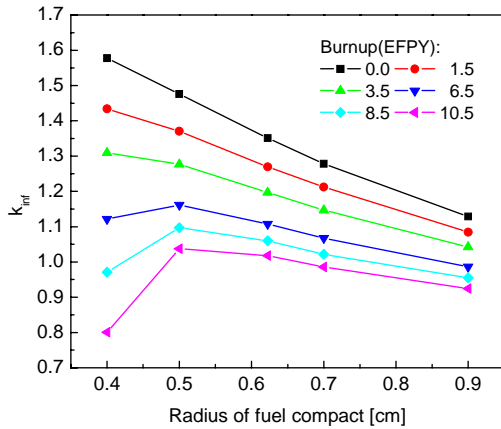


Fig. 10  $k_{inf}$  as a function of radius of fuel compacts and burnup for a fuel block with kernels in 0.25 mm radius

Since the sizes of the fuel compacts and kernels change the ratio of the fuel to the moderator in the fuel block and the infinite multiplication factor at the same time, combining these two factors together is a good way to obtain the optimum values for a specific layout of the reactor core of the U-Battery<sup>®</sup> with specific packing fraction and fuel enrichment. Figures 11, 12 and 13 show the  $k_{inf}$  of the fuel block as a function of the radii of kernels and fuel compacts at BOL, 5.5 EFPYs and EOL, respectively. Figure 11, does not explain the optimum kernel radius or fuel compact, but it suggests that increasing radii of the kernels and fuel compacts can reduce initial  $k_{inf}$  of the fuel block and the reactivity swing during fuel burnup. In addition, the effect of the radius of the fuel compacts is clearer than that of the radius of the kernels.

Some interesting results can be derived from Figures 12 and 13. Firstly, the  $k_{inf}$  of the fuel block with slimmer fuel compacts is more strongly dependent on the kernel radius. For example, the  $k_{inf}$  of the fuel compacts with 0.4 cm radius changes dramatically with the kernel radius and burnup. Secondly, there exists an optimum kernel radius for each fuel compact. For example, the fuel compact with 0.6225 cm radius achieves the maximum  $k_{inf}$  when the kernel radius is 0.225 mm at a burnup of 10 EFPYs in Fig. 13. Thirdly, the optimum kernel radius is also dependent on the fuel burnup. For example, the fuel compact with 0.5 cm radius achieves the maximum  $k_{inf}$  values when the kernel radii are 0.225 mm and 0.3 mm after 5.5 EFPYs and 10.5 EFPYs, respectively.

## V. CORE LAYOUT

Besides those parameters in Sec. IV, one can arrange the basic element (e.g. fuel and graphite blocks) to achieve a desirable and critical reactor

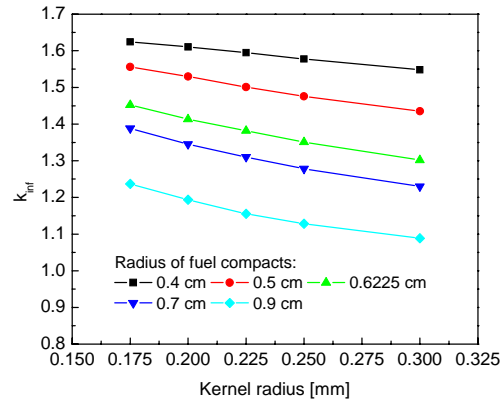


Fig. 11  $k_{inf}$  as a function of radii of fuel compacts and kernels at BOL

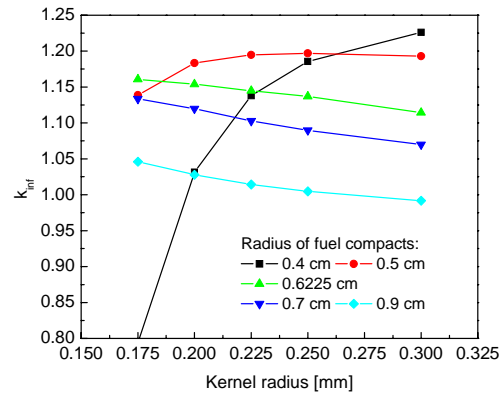


Fig. 12  $k_{inf}$  as a function of radii of fuel compacts and kernels at 5.5 EFPYs

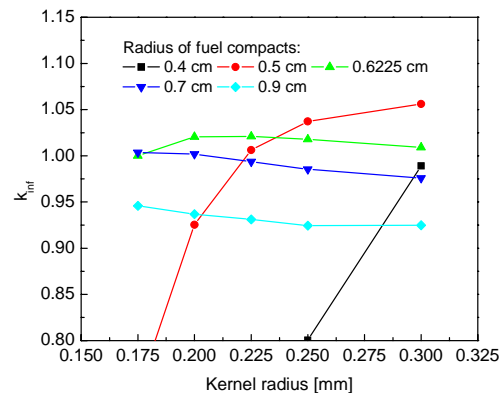


Fig. 13  $k_{inf}$  as a function of radii of fuel compacts and kernels at EOL

core. Seven reactor active cores were built in SCALE5.1, including five cylindrical reactor cores and two annular ones, as shown in Table 2. In the third column of Table 2, the first number is the total number of the fuel blocks in the active core and the second represents the active core layout of the U-Battery<sup>®</sup>. As mentioned in Sec. II, the notation of 19\*3 means that the active core of the U-Battery<sup>®</sup> is comprised of 19 fuel columns and each column 3

fuel blocks in the axial direction of the active core. Case 3 is the reference core layout of the U-Battery<sup>®</sup> for convenience. Other layouts are imagined as its modified versions. Case 1 is the core layout with the minimum number of fuel blocks, which is comprised of 19 fuel columns and each column 3 of fuel blocks.

Table 2 Core layouts of U-Battery<sup>®</sup>

Case	Core type	Number of fuel blocks/ Core layout
1	Cylindrical	57/19*3
2		76/19*4
3		111/37*3
4		148/37*4
5		183/61*3
6	Annular	90/30*3
7		120/30*4

For the cylindrical cores, the prismatic fuel columns are placed side by side inside the RPV of the U-Battery<sup>®</sup>. Figure 1(a) shows a typical layout of the cylindrical active core with 37 fuel columns and the internal side reflectors. In the annular core layout, the central fuel columns of the cylindrical cores are replaced by the same number of graphite columns. As shown in Fig. 14, this annular reactor core is comprised of 7 graphite columns (blue and light blue columns) in the center and 30 fuel columns surrounding the central graphite columns, which is a modified version of Case 4.

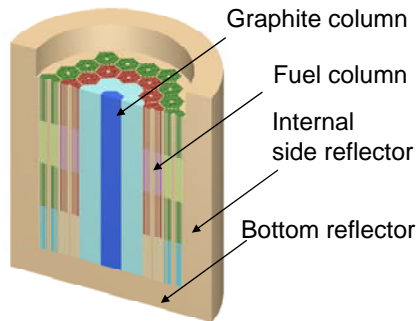


Fig. 14 A typical annular core layout (Case 7) with internal side and bottom reflectors

The fuel composition of the nine core layouts needed to achieve a specific lifetime is listed in Table 3. This table includes seven layouts listed in Table 2, a layout of Case 3 with 100 cm ESR (Case 8) and a layout of Case 5 with 100 cm ESR (Case 9). The third column of Table 3 presents the required fuel composition of the U-Battery<sup>®</sup> with 5-EFPY lifetime, and the fourth with 10-EFPY lifetime.

For the reference core layout, Case 3, the U-Battery<sup>®</sup> can achieve 10-EFPY lifetime using the LEU. The enrichment of the required fuel is 16.7 wt% U-235 and the packing fraction of the TRISO

particles is 0.3. Case 5 is built by adding 24 fuel columns around the reference reactor core, and the enrichment of the required fuel can reduce by 3 wt% U-235 compared to the reference core layout. This means that adding a fuel block reduces the fuel enrichment by 0.042 wt% U-235. Case 4 is built by adding 37 fuel blocks in the axial direction of the reference reactor core, and the enrichment of the required fuel reduces by 4.6 wt% U-235 (0.124 wt% U-235 per each fuel block).

Table 3 Fuel composition of 9 core layouts

Case	Core layout	5 years <sup>1</sup>	10 years <sup>1</sup>
1	19*3	6.4 years <sup>2</sup> /6.9 years <sup>3</sup>	
2	19*4	9.1 years <sup>2</sup> /9.85 years <sup>3</sup>	
3	37*3 (Reference layout)	9.55/0.3	16.7/0.3
4	37*4	6.9/0.3	12.1/0.3
5	61*3	7.59/0.3	13.7/0.3
6	30*3	9.8/0.3	17.3/0.3
7	30*4	7.6/0.3	12.9/0.3
8	37*3 w/ ESR	8.2/0.3	15.8/0.3
9	61*3 w/ ESR	5.5/0.3	9.0/0.3

Note:

1. Enrichment/Packing fraction (PF) of the TRISO particles.
2. Enrichment = 20% U-235 and PF = 0.3.
3. Enrichment = 20% U-235 and PF = 0.35 (Acceptable maximum PF)

Removing fuel blocks may be another good way to build new reactors, as well as adding ones. Four core layouts are based on reducing fuel blocks (Case 1, Case 2, Case 6 and Case 7). 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 active cores, which leads to annular core layouts. Removing the fuel blocks does not lead to a large increase of fuel enrichment. The fuel enrichment of Case 6 increases by 0.6 wt% U-235 compared to the reference layout. Compared to Case 4, Case 7 reduces 28 fuel blocks; however, the required fuel enrichment only increases by 0.8 wt% U-235. Although Case 7 uses 9 more fuel blocks than the reference layout, it reduces the fuel enrichment by 3.8 wt% U-235, which means that adding a fuel block can reduce the fuel enrichment by 0.42 wt% U-235. Compared to Cases 4 and 5, this value is quite large. These complex comparisons show that the concept of an annular core, such as Case 7, is a good choice for the U-Battery<sup>®</sup>.

As analyzed in Sec. II.D, an external side reflector can improve the neutron economy of the U-Battery<sup>®</sup>, so Cases 8 and 9 can use the fuel with the LEU to achieve 10-EFPY lifetime. For Case 8, a 100

cm ESR reduces the fuel enrichment by 1 wt% U-235. For Case 9, a 100 cm ESR even reduces the fuel enrichment by 4.7 wt% U-235 because Case 9 only uses a 10 cm internal side reflector inside the RPV.

For Cases 1 and 2, the U-Battery<sup>®</sup> does not achieve 10-EFPY lifetime even though the fuel enrichment is 20 wt% U-235, which is the acceptably maximum value recommended to modern commercial reactors with LEU. If the fuel enrichment is 20 wt% 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<sup>®</sup> increases to 6.9 EFPYs if the packing fraction is 0.35, which is the maximum value accepted in current TRISO technology. However, for Case 2, the U-Battery<sup>®</sup> achieves 9.1-EFPY and 9.8-EFPY lifetime if the packing fractions of the TRISO particles are 0.3 and 0.35, respectively. Although Case 2 can not reach 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<sup>®</sup> easier to transport.

## VI. WATER INGRESS

Since the U-Battery<sup>®</sup> adopts a power conversion system based on a Rankine cycle, the risk of water/steam ingress into the reactor core exists during its operation. Because the water/steam ingress is a design-basis accident for modern HTRs with steam cycles, the effect of the water/steam in the U-Battery<sup>®</sup> on the reactivity was investigated in order to make this risk known. The reactivity induced by the water/steam is plotted as a function of its density in the coolant channel of fuel blocks in Fig. 15 for Layout 37\*4, i.e., Case 4 in Table 2. As shown in Fig. 15, the water/steam in the reactor induces positive reactivity over the whole lifetime of the U-Battery<sup>®</sup>. For the water/steam density up to 0.001 g/cm<sup>3</sup>, a small positive reactivity ( $\Delta\rho < 0.002 \Delta k/k$ ) is induced. However, when the water/steam density in the reactor core is larger than 0.001 g/cm<sup>3</sup>, the reactivity induced begins to increase significantly and reaches a maximum value at a water density of 0.4 g/cm<sup>3</sup> for Layout 37\*4 at BOL, then drops off rapidly as the water/steam density increases because of the neutron absorption of water. The induced reactivity changes in the same pattern at different fuel burnups, but with different maximum values in different water/steam densities.

The possible maximum reactivity induced for Layout 37\*4, which is determined by the water/steam density, is illustrated in Fig. 16 at the different burnups of the U-Battery<sup>®</sup>. As shown in Fig. 16, the maximum reactivity induced by the water/steam increases with the fuel burnup and reaches the maximum value of 0.148  $\Delta k/k$  after 6.5

EFPYs, then drops quickly with the fuel burnup until EOL.

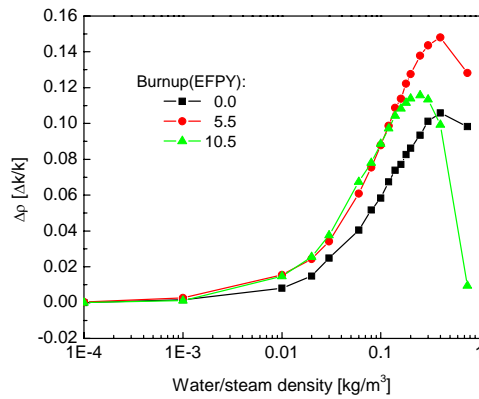


Fig. 15 Induced reactivity by water/steam as a function of the water/steam density and burnup for Layout 37\*4

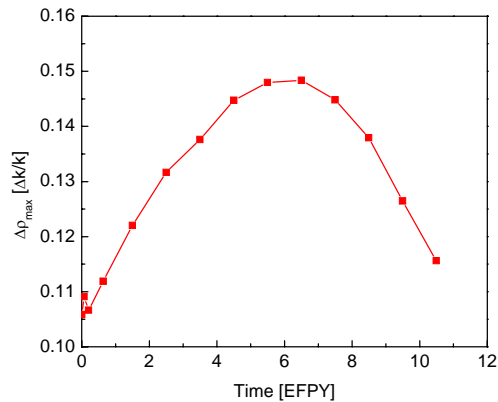


Fig. 16 Maximum reactivity induced by the water/steam as a function of burnup for Layout 37\*4

Figures 15 and 16 mean that the potential risk of the positive reactivity induced by water/steam does exist over the whole lifetime of the U-Battery<sup>®</sup>. Moreover, the induced positive reactivity is rather large because the neutron moderation is insufficient in the reactor core of Layout 37\*4. The maximum value should be considered as the design basis of the U-Battery<sup>®</sup> because this value involves safety of the reactor.

## VII. CONCLUSIONS

The U-Battery<sup>®</sup> is a small and long-life high temperature gas-cooled reactor, which is based on currently mature block-type HTR technologies and can be used soon. The neutronic performance of the U-Battery<sup>®</sup> was parametrically investigated in this paper by use of the TRITON6 module in SCALE5.1, including the effects of six important design parameters: fuel enrichment, the packing fraction of the TRISO particles, the thickness of the top and

bottom reflectors, the external side reflectors (ESRs) and radii of the fuel compacts and kernels.

Increasing fuel enrichment can easily increase the lifetime and the effective multiplication factor of the U-Battery<sup>®</sup>. Increasing the packing fraction of the TRISO particles can also increase the lifetime of the U-Battery<sup>®</sup>; however, the effective multiplication factor decreases with the increase of the packing fraction at BOL and increases with its increase at EOL. The higher the fuel enrichment and the packing fraction of the TRISO particles are, the less the reactivity swing with fuel burnup will be. The infinite multiplication factor of a fuel block comprised of fuel compacts with smaller radius is more strongly dependent on the kernel radius, and there is an optimum kernel radius for each fuel compact. This optimum kernel radius is also dependent on the fuel burnup. The external side reflector would be an option to improve neutron economy, especially for the core layout with thin internal side reflectors since the diameter of the RPV is limited to 3.5 m. 100 cm ESR can reduce the fuel enrichment by 0.9 wt% and 4.7 wt% U-235 for the core Layout 37\*3 and Layout 61\*3, respectively.

Nine possible core layouts analyzed include seven cylindrical cores (Layouts 37\*3, 37\*3 with ESR, 37\*4, 61\*3, 61\*3 with ESR, 19\*3 and 19\*4), and two annular cores (Layouts 30\*3 and 30\*4). Layout 37\*3 is the reference core arrangement of the U-Battery<sup>®</sup> and requires that the fuel enrichment is 16.7 wt% U-235 and the packing fraction of the TRISO particles is 0.3 for 10-EFPY lifetime. Layout 37\*4 can reduce the fuel enrichment by 4.6 wt% U-235 to achieve the same lifetime. Layout 61\*3 can reduce the fuel enrichment by 3 wt% U-235 for 10-EFPY lifetime. Annular cores are promising layouts, especially Layout 30\*4, which reduces the fuel enrichment by 3.8 wt% U-235 only by adding 9 fuel blocks and 28 graphite blocks, compared to Layout 37\*3. Although Layout 19\*4 only achieves 9-EFPY lifetime even though the enrichment is 20 wt% U-235 and the packing fraction of TRISO particles is 0.3, it still is a promising design because it not only adopts the minimum fuel blocks, but also leaves more space for other components inside the RPV of the U-Battery<sup>®</sup>.

The effect of water/steam density, arranging from 0.0001 g/cm<sup>3</sup> to 0.75 g/cm<sup>3</sup>, on the reactivity was analyzed since water/steam ingress is a design-basis accident for HTRs. The results show that water/steam induces positive reactivity over the whole lifetime of the U-Battery<sup>®</sup>, and the reactivity induced is strongly dependent on the density of water/steam and fuel burnup. For the water density up to 0.001 g/cm<sup>3</sup>, the induced positive reactivity is less than 0.002  $\Delta k/k$  for Layout 37\*4; however, it increases rapidly to 0.11-0.16  $\Delta k/k$  with the increase of water/steam density at different fuel burnups.

The parametric analysis shows that design and layouts of the U-Battery<sup>®</sup> are feasible and flexible from the neutronic point of view. More neutronic analysis of promising designs (e.g., Layouts 37\*4, 30\*4 and 19\*4) will be implemented, such as the double heterogeneity of the TRISO particles, and reactivity coefficients of the fuels, moderators and reflectors, and so on. These promising designs will be evaluated by thermal-hydraulic analysis too.

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