ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/266880277

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

**Article** · October 2010

CITATIONS
5

READS
1,106

2 authors:

Ming Ding
Harbin Engineering University

Jan Leen Kloosterman
Delft University of Technology

117 PUBLICATIONS 799 CITATIONS

SEE PROFILE

175 PUBLICATIONS 2,218 CITATIONS

SEE PROFILE

**Some of the authors of this publication are also working on these related projects:**

Project Master Thesis: Design of a Freeze Plug for the Molten Salt Fast Reactor(MSFR) View project

Project Design and evaluation on a small and long-life HTR (U-Battery) View project

All content following this page was uploaded by Ming Ding on 30 January 2015.

The user has requested enhancement of the downloaded file.

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

Ming Ding, Jan Leen Kloosterman[1]
*Delft University of Technology*
*Mekelweg, 15, 2629 JB, Delft, The Netherlands*
*phone: +31-15-2784041, m.ding@tudelft.nl*

[1] *Delft University of Technology*
*Mekelweg, 15, 2629 JB, Delft, The Netherlands*
*phone: +31-15-2781191, j.l.kloosterman@tudelft.nl*

**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®, 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® 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® 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, and the thicknesses of the top and bottom reflectors. The external side reflector, located outside the RPV of the U-Battery®, is proposed to improve neutron economy because the U-Battery® adopts a thin internal side reflector located inside the RPV. Nine possible layouts of the U-Battery® covers 7 cylindrical cores and 2 annular cores. The analysis shows that the design of the U-Battery® is feasible and flexible from neutronics point of view. The core layouts of 37*4(4 layers of 37 fuel blocks), 30*4 and 19*4 are promising designs of the U-Battery®. Moreover, the U-Battery® has the negative temperature coefficient of reactivity during its whole lifetime. However, the water ingress risk is obvious from the neutronic point of view because the induced positive reactivity by water or steam in the gas coolant varies in the range from 0 to 0.15 Δk/k.*

## 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®, 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® in detail. The third part explains the models of the U-Battery® and analysis method. The fourth part parametrically investigates some key design parameters of the U-Battery®, including its fuel enrichment, the packing fraction of the TRISO particles, and the thicknesses of the side, top and bottom reflectors. 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 two key neutronic characteristics of the U-Battery®, including the effect of water/steam density and temperature on the reactivity.

## II. DESCRIPTION OF THE U-BATTERY®

The U-Battery® 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® are listed in Table 1.

Table 1 Basic parameters of the U-Battery®

| Parameter | Value |
|---|---|
| Reactor type | Block-type HTR |
| Thermal power | 20 MW |
| Core lifetime | 5-10 years |
| Coolant | $CO_2$, Helium |
| Diameter of RPV | < 3.5 m |
| Fuel type | $UO_2$, TRISO coated fuel |
| Fuel enrichment | < 20 wt% U-235 |
| Energy conversion system | Rankine steam cycle |

Since the main idea behind the U-Battery® is inherent safety, modularity and near-term utilization, the U-Battery® 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® 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® 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.

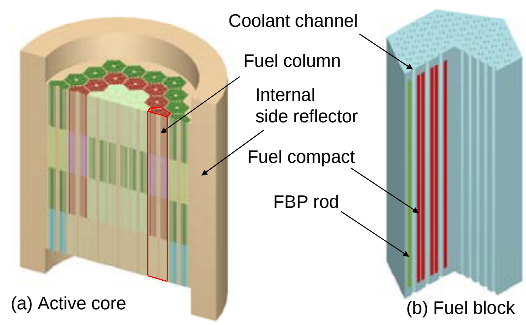


Fig. 1 3D schematic diagram of an active core and a fuel block; the top and bottom reflectors have been removed in the active core, and the fuel handling hole has also been removed in the fuel block.

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®, 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 $MW_{th}$ 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 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® 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®'s RPV is requested to be less than or equal to 3.5 meters so that the U-Battery® can be transported as a whole by rail, truck, or barge, etc. The power conversion system of the U-Battery® uses a Rankine steam cycle since the U-Battery® aims to be commercialized soon and the steam cycle is the most mature technology in the nuclear industry.

## III. MODEL OF THE U-BATTERY® AND CALCULATION METHOD

A 3D model of the U-Battery®, 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®. 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®, Two function modules (BONAMI and CENTRM) were used to process the resonance cross section of the materials and cells used in the U-Battery®. The KENO-VI module, a 3D Monte Carlo criticality safety code, was used to calculate the effective multiplication factor of the U-Battery®. The ORIGEN-S module was used to perform point depletion calculations and obtain isotopic concentrations in the U-Battery®. 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®, 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 4-5%. 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®. 3D KENO-VI models were built for the U-Battery® 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®. A 10-year lifetime is specified for the U-Battery®.

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®, which are analyzed parametrically in this section. The external side reflector is also proposed and investigated in this section in order to improve the neutron economy because the U-Battery® may adopt a very thin internal side reflector.

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® 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®. The lifetime of the U-Battery® 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® 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.

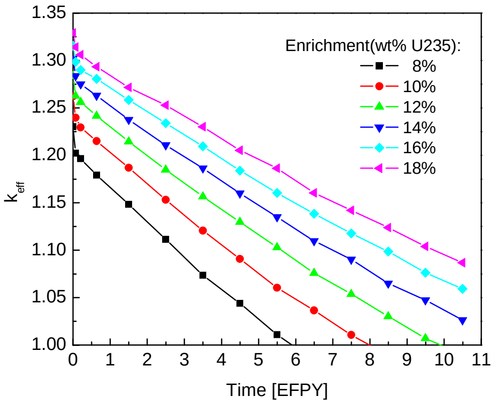


Fig. 2 $k_{eff}$ as a function of the fuel enrichment and burnup for Layout 37*4

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®.

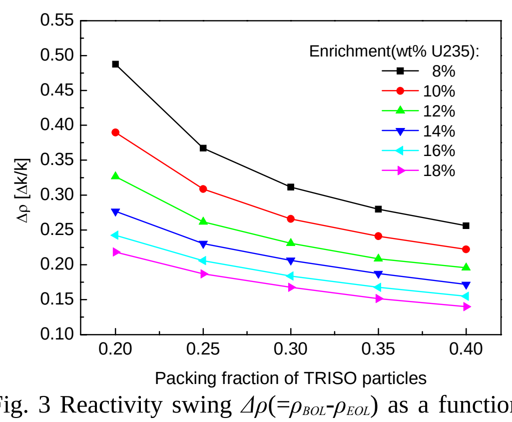


Fig. 3 Reactivity swing $\Delta\rho(=\rho_{BOL}-\rho_{EOL})$ as a function of the packing fraction of the TRISO particles and fuel enrichment for Layout 37*4

*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®, 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® 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.

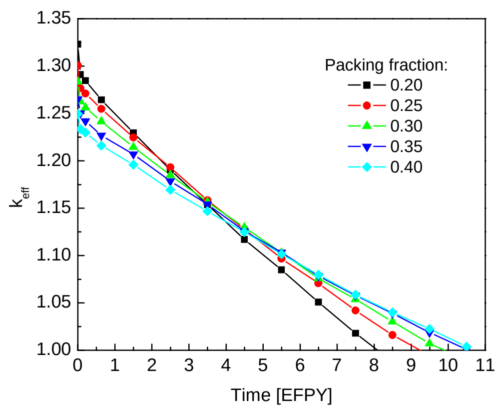


Fig. 4 $k_{eff}$ as a function of the TRISO particles' packing fraction and burnup for Layout 37*4

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 $k_{eff}$.

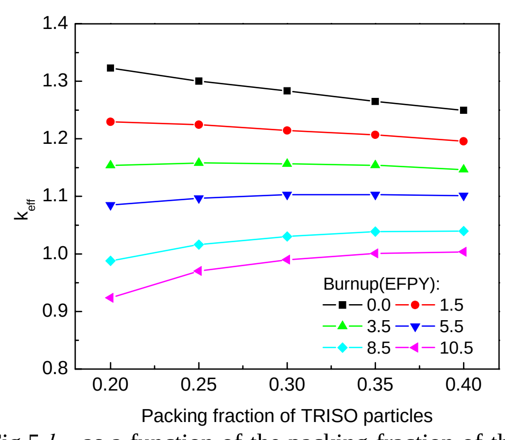


Fig.5 $k_{eff}$ as a function of the packing fraction of the TRISO particles for Layout 37*4

The analysis shows 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.

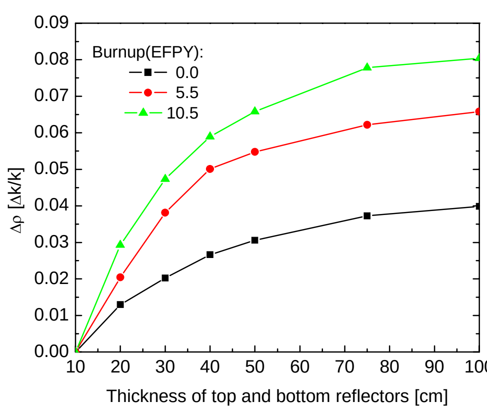


Fig. 6 $\Delta\rho(=\rho-\rho_{10})$ as a function of thicknesses of top and bottom reflectors for Layout 37*3

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.

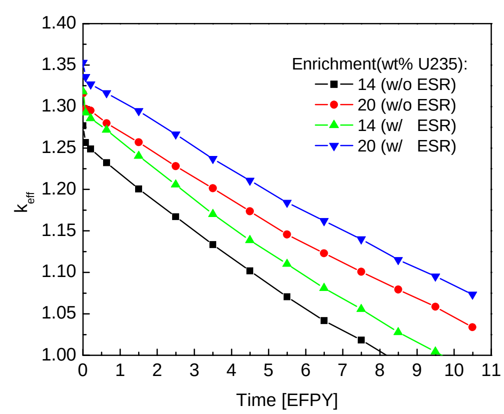


Fig. 7 $k_{eff}$ as a function of burnup and fuel enrichment for Layout 37*3

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.

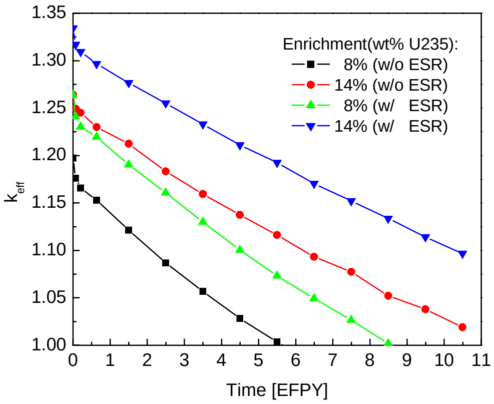


Fig. 8 $k_{eff}$ as a function of burnup and fuel enrichment for Layout 61*3

## 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 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®. As mentioned in Sec. II, the notation of 19*3 means that the active core of the U-Battery® 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® 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®

| 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®. 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.

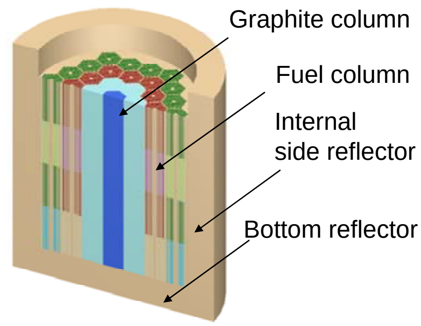


Fig. 14 A typical annular core layout (Case 7) with internal side and bottom reflectors

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® with 5-EFPY lifetime, and the fourth with 10-EFPY lifetime.

For the reference core layout, Case 3, the U-Battery® 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).

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®.

Table 3 Fuel composition of 9 core layouts

| Case | Core layout | 5 years[1] | 10 years[1] |
|---|---|---|---|
| 1 | 19*3 | 6.4 years[2]/6.9 years[3] | |
| 2 | 19*4 | 9.1 years[2]/9.85 years[3] | |
| 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 wt% U-235 and PF = 0.3.
3. Enrichment = 20 wt% U-235 and PF = 0.35

As analyzed in Sec. II.D, an external side reflector can improve the neutron economy of the U-Battery®, 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® 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® 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® 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® easier to transport.

## VI. TWO IMPORTANT NEUTRONIC CHARACTERISTICS of U-BATTERY®

Reactivity temperature coefficient is one of the most important neutronic parameters for any reactors, so it is investigated in this section. For water-cooled reactors, coolant density coefficient of reactivity is another important one. Because gas coolants, especially helium and $CO_2$, commonly are transparent to neutrons, the coolant density coefficient is not important for gas-cooled reactors. However, for graphite-moderated U-Battery, the water/steam in the coolant obviously affects the reactivity of the reactor. Thus, the water or steam density in the coolant is also investigated in this section.

### *VI.A. Reactivity temperature coefficient*

One of very important characteristics of HTRs is that they have large negative temperature coefficients of reactivity, which partly ensures the inherent safety of the HTRs. The U-Battery naturally has this characteristic. Table 4 presents the average temperature coefficient of reactivity of Layout 30*4, a typical layout, from 800 K to 2000 K. In Table 4, the fuel means the fuel compacts in the fuel blocks because the homogeneous model is used in the calculations; the moderator means the graphite structure of the fuel blocks excluding the fuel compact; and the reflector means the internal side graphite reflector and central graphite reflector for Layout 30*4. As shown in Table 4, Layout 30*4 keeps the negative temperature coefficient of reactivity in the whole lifetime. Secondly, all of the fuel, moderator and reflector have the negative temperature coefficient of reactivity. Finally, the fuel has the largest value among the three coefficients. Other layouts of the U-Battery have the same order of negative temperature coefficient of reactivity as Layout 30*4.

Table 4 Average temperature coefficient of reactivity of Layout 30*4 arranging from 800 K to 2000 K

| Time [EFPYs] | Fuel [pcm/K] | Moderator [pcm/K] | Reflector [pcm/K] | Total [pcm/K] |
|---|---|---|---|---|
| 0.0 | -3.6 | -1.4 | -0.6 | -5.6 |
| 5.0 | -4.7 | -3.2 | -0.2 | -8.1 |
| 10.0 | -4.4 | -3.1 | -0.2 | -7.7 |

### *VI.B. Water ingress risk*

Since the U-Battery® may 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 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® 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*3, 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®. For the water/steam density up to 0.001 g/cm$^3$, 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$^3$, the reactivity induced begins to increase significantly and reaches a maximum value (0.1 $\Delta k/k$) at a water density of 0.4 g/cm$^3$ for Layout 37*3 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 burnup, but with different maximum values in different water/steam densities, for example, 0.15 $\Delta k/k$ and 0.11 $\Delta k/k$ for 5.5 EFPYs and 10.5 EFPYs.

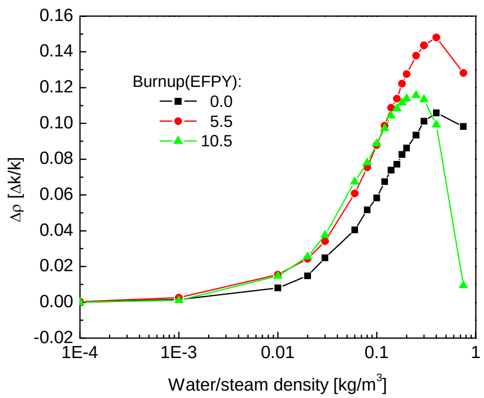


Fig. 15 Induced reactivity by water/steam as a function of the water/steam density and burnup for Layout 37*3

Figure 15 means that the potential risk of the positive reactivity induced by water/steam does exist over the whole lifetime of the U-Battery®. Moreover, the induced positive reactivity is rather large because the neutron moderation is insufficient in the reactor core of Layout 37*3. The maximum value should be considered as the design basis of the U-Battery® because this value involves safety of the reactor.

## VII. CONCLUSTIONS

The U-Battery® 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® was parametrically investigated in this paper by use of the TRITON6 module in SCALE5.1, including the effects of four important design parameters: fuel enrichment, the packing fraction of the TRISO particles, the thickness of the top and bottom reflectors, and the external side reflectors (ESRs).

Increasing fuel enrichment can easily increase the lifetime and the effective multiplication factor of the U-Battery®. Increasing the packing fraction of the TRISO particles can also increase the lifetime of the U-Battery®; 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 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® 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®.

The parametric analysis shows that design and layouts of the U-Battery® are feasible and flexile 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.

The U-Battery® has the negative temperature coefficient of reactivity during its whole lifetime, which partly ensures its inherent safety. However, the water ingress risk is obvious from the neutronic point of view because the induced positive reactivity by water or steam varies in the range from 0 to 0.15 $\Delta k/k$.

REFERENCES

[1] V. Kuznetsov. 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, 2008, 50, 242-250

[2] N. Ueda, I. Kinoshit, and A. Minato, etal. Sodium Cooled Small Fast Long-Life Reactor 4S. Progress in Nuclear Energy, 47:222-230, 2005.

[3] International Atomic Energy Agency. Innovative Small and Medium Sized Reactors: Design Features, Safety Approaches and R&D Trends. IAEA-TECDOC-1451, 2005.

[4] International Atomic Energy Agency. Status of Small Reactor Designs Without On-Site Refueling. IAEA-TECDOC-1536, 2007.

[5] S. M. Modro, J. E. Fisher, K.D. Weaver, etal. Multi-Application Small Light Water Reactor Final Report Idaho National Engineering and Environmental Laboratory, 2003.

[6] J. Sienicki, A. Moisseytsev, W. Yang, etal. Status Report on the Small Secure Transportable Autonomous Reactor (SSTAR)/Lead-Cooled Fast Reactor (LFR) and Supporting Research and Development. Argonne National Laboratory, 2008.

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

[8] S. Nakagawa, K. Takamatsu and Y. Tachibana, etal. Safety demonstration tests using high temperature engineering test reactor. Nuclear Engineering and Design, 233:301-308, 2004.

[9] H. Gottaut and K. Krüger. Results of Experiments at the AVR Reactor. Nuclear Engineering and Design, 1990, 121, 143-153.

[10] General Atomics. Gas Turbine-Modular Helium Reactor (T-MHR) Conceptual Design Description Report. Revision1, Report 910720, San Diego, CA, 1996.

[11] SCALE: A Modular Code System for Performing Standardized computer Analyses for Licensing Evaluations, RNL/TM-2005/39, Version 5, Vols. I-III, Oak Ridge National Laboratory, Oak Ridge, TN, April 2005. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-725.

View publication stats