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Small long-life transportable high temperature gas-cooled reactors (HTRs) are interesting because they can safely provide electricity or heat in remote areas or to industrial users in developed or developing countries. This paper presents the neutronic design of the U-Battery, which is a 5 MWth block-type HTR with a fuel lifetime of 5–10 years. Assuming a reactor pressure vessel diameter of less than 3.7 m, some possible reactor core configurations of the 5 MWth U-Battery have been investigated using the TRITON module in SCALE 6. The neutronic analysis shows that Layout $12\$\times 2B, ascatteringcorecontaining2layersof12fuelblockseachwith20\times 3and6\times\$4$ with a 25-cm thick BeO side reflector achieve a fuel lifetime of 7 and 10 EFPYs, respectively. The comparison of the different core configurations shows that, keeping the number of fuel blocks in the reactor core constant, the annular and scattering core configurations have longer fuel lifetimes and lower fuel cost than the cylindrical ones. Moreover, for the 5 MWth U-Battery, reducing the fuel inventory in the reactor core by decreasing the diameter of fuel kernels and packing fraction of TRISO particles is more effective to lower the fuel cost than decreasing the 235U enrichment.

Full Text

Preamble

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Feasibility Neutronic Design for the Reactor Core Configurations of a 5 MWth Transportable Block-Type HTR

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Abstract

Small long-life transportable high temperature gas-cooled reactors (HTRs) are interesting because they can safely provide electricity or heat in remote areas or to industrial users in developed or developing countries. This paper presents the neutronic design of the U-Battery, which is a 5 MWth block-type HTR with a fuel lifetime of 5–10 years. Assuming a reactor pressure vessel diameter of less than 3.7 m, some possible reactor core configurations of the 5 MWth U-Battery have been investigated using the TRITON module in SCALE 6. The neutronic analysis shows that Layout 12$×$2B, a scattering core containing 2 layers of 12 fuel blocks each with 20% enriched ^{235}U, reaches a fuel lifetime of 10 effective full power years (EFPYs). When the diameter of the reactor pressure vessel is reduced to 1.8 m, a fuel lifetime of 4 EFPYs will be achieved for the 5 MWth U-Battery with a 25-cm thick graphite side reflector. Layouts 6$×3*and*6×$4 with a 25-cm thick BeO side reflector achieve a fuel lifetime of 7 and 10 EFPYs, respectively.

The comparison of the different core configurations shows that, keeping the number of fuel blocks in the reactor core constant, the annular and scattering core configurations have longer fuel lifetimes and lower fuel cost than the cylindrical ones. Moreover, for the 5 MWth U-Battery, reducing the fuel inventory in the reactor core by decreasing the diameter of fuel kernels and packing fraction of TRISO particles is more effective to lower the fuel cost than decreasing the ^{235}U enrichment.

Key words

Feasibility design, Reactor core configurations, Transportable reactors, Small modular reactors, Block-type HTRs

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 rely heavily on the infrastructure of reactor sites, this has motivated development of small modular nuclear reactors (SMRs) based on different reactor technologies[2–4], especially for developing countries and remote areas off main grids.

The SMRs can be fabricated in modularity and transported to sites by rail, barge, truck, etc. After a long operation (e.g., 5–10 years), the SMRs can be brought back to factories for refueling or directly replaced by new ones. Moreover, 5–10 SMRs at a site may become a nuclear power plant (NPP) with a comparable power level to large NPPs.

Over the last 30 years, the inherent safety of small modular HTRs (high temperature gas-cooled reactors) has been validated directly by experiments[5–7]. Our previous paper[8] presents the neutronic designs of a 20 MWth long-life block-type HTR, called the U-Battery, which can be commercialized in the near future. For the 20 MWth U-Battery, the reference reactor core configuration adopts 148 (=37$\times$4) fuel blocks developed for the GT-MHR project[9], a 29-cm-thick graphite side reflector, and 50-cm-thick top and bottom graphite reflectors. Although the outer diameter of the reactor pressure vessel (RPV) of the U-Battery is limited to 3.7 m based on the maximum size of road transport, the weight of the whole reactor core of the 20 MWth U-Battery is quite large, decreasing the flexibility for road transport of the U-Battery. In order to strengthen the transportability of the U-Battery, two designs for a 5 MWth U-Battery are proposed in this paper. The first design described in Section 2 uses an RPV with 3.7-m diameter in order to make full use of neutron economy, while the second described in Section 3 uses an RPV with 1.8-m diameter to minimize the reactor core of the U-Battery.

Reactor Core Design with 3.7-m RPV Diameter

This section describes a U-Battery reactor core with thermal power of 5 MWth. Because the thermal-hydraulic design of the 20 MWth U-Battery leads to a volume-averaged reactor core temperature of 727°C, and temperatures of 227°C at the top, 727°C at the bottom, and 527°C at the side reflectors[10,11], the nuclear design of the 5 MWth reactor core adopts these temperatures as reference temperatures for the material mixtures. All calculations are implemented by the TRITON module in SCALE 6[12].

At the 3.7-m outer diameter of the RPV, Fig. 1 shows the eight reactor core configurations of the 5 MWth U-Battery. Layout 37$\times 1 hasaverysmallheightofthereactorcoreandthusRPV, whic$
$Batteryhavebetterneutronicperformancebecauseofalargermassratioofgraphitetouraniumandthusbetterneu$
fuel blocks are shown in Fig. 1 (IV), (V) and (VI), respectively.

The neutronic calculations for the eight reactor core configurations are shown in Table 1 . The second column shows the names of reactor core configurations. The third and fourth columns are the effective multiplication factors at beginning of life (BOL) and end of life (EOL), respectively. If the effective multiplication factor of a certain configuration is less than unity, the data in the bracket is the possible maximum fuel lifetime for the specific configuration; otherwise this data is given after operation time of 10 years. The fifth column shows the uranium total mass in the reactor core, and the sixth column shows the fuel cost. All eight reactor core configurations use 20% enriched ^{235}U.

Case 2 consists of 38 fuel blocks and reaches a fuel lifetime of 10 effective full power years (EFPYs), with resulting keff at EOL of 1.028. Case 3 consists of 36 fuel blocks, and the keff is 1.045 at EOL. Although the number of fuel blocks of Layout 18$\times 2 islessthanthatofLayout 19\times 2, thekeffoftheformerislargerthanthelatterbecauseofbetterneutr$
$EFPYfuellifetime, andthemaximumpossiblefuellifetimeis 7.0 EFPYs, becauseofthe 29-$

$cm-thinsidereflectorandalargeneutronleakage.Ifthenumberoffuelblocksreducesto24(12\times 2),Cases5and6ju$
$EFPYfuellifetime,whileCase4fails.Thismeansthatthereactorcoreconfigurationisofimportance,eventhou$
$EFPYfuellifetimebecausethenumberoffuelblocksistoosmall.TheneededuraniummassofLayout12\times 2Bdecr$

Since the effective multiplication factors of both Layouts 19$\times 2and18\times$2 are larger than unity at 10 EFPYs, there are three ways to improve the economic performance of the two configurations. The first is to extend the fuel lifetime of the U-Battery until the keff of the reactor is unity. The second is to lower the ^{235}U enrichment while keeping the fuel kernel size (Rk) and the packing fraction (PF) of the TRISO particles constant. Cases 1 and 4 in Table 2 are the results of this approach. It shows that the enrichment of ^{235}U reduces by 2% for Layout 19$\times 2, andby3.2\times$2, thus their fuel cost reduces by 9% and 15.4%, respectively.

The third way of increasing the economic performance of Layouts 19$\times 2and18\times$2 is to decrease the inventory of uranium in the reactor core by changing the geometric parameters of the TRISO particles, i.e., fuel kernel radius and PF, while keeping the enrichment of the ^{235}U constant. Cases 2 and 3 as well as Cases 5 and 6 in Table 2 are the results for Layouts 19$\times 2and18\times 2, respectively.ComparisonofCase2withCase3showsthatreducingthefuelkernelradiusRkandP$
reducing the fuel kernel radius is better than reducing the PF of TRISO particles, but their difference is rather small.

Reactor Core Design with 1.8-m RPV Diameter

In order to further decrease the reactor weight for better transportability of the U-Battery, reducing the diameter of RPV is effective because this can effectively reduce the reactor core weight. The inner diameter of RPV is fixed to 1.8 m, because it is the same as the inner diameter of flasks for the transportation of PWR or BWR spent fuel assemblies, and the transportation experience of the flasks over the world can be utilized for the transportation of the U-Battery. For the RPV with the 1.8-m inner diameter, the 6 fuel columns are the possible maximum number in the reactor core, and the number of fuel blocks in the axial direction and the material of the side reflector are two key design parameters as shown in Fig. 2 [Figure 2: see original paper]. If the height of the reactor core is limited to about 4 m, the 4 fuel blocks in the axial direction of the reactor core are the maximum value.

In terms of 1.8-m RPV inner diameter, the results of the nuclear design are shown in Tables 3 and 4 for the U-Battery with graphite and BeO side reflectors, respectively. The second column shows the reactor core configuration of the U-Battery. The third and fourth columns are the parameters of the side reflector, i.e., material and maximum thickness. The fifth column shows the maximum fuel lifetime for each reactor core configuration, and the sixth column shows the total reactor mass, including the fuel blocks, central, top, bottom and side reflectors, barrel (assumed 5 cm) and RPV (assumed 10 cm). Because the reactor core is very small and the side reflector is very thin, the barrel and RPV were modeled for all cases in this section to include their reflection effect.

3.1 Graphite Side Reflector

Group A in Table 3 contains three basic cases for the 5 MWth U-Battery in terms of 1.8-m RPV inner diameter. The number of fuel blocks for Case A.1 is 12; for A.2, 18; and for A.3, 24. The material of the side reflector is nuclear graphite, whose possible maximum thickness is 25 cm if the thickness of the barrel is 5 cm and gas gap between barrel and RPV is 5 cm. As shown in Table 3, the maximum possible fuel lifetime of Layouts 6$×2, 6×3*and*6×$4 are 0.4, 2.0 and 3.0 EFPYs, respectively. Case A.1 in Table 2 has the same number of fuel blocks as Case 8 in Table 1, but the difference in the effective multiplication factors is very large. Assuming Case 8 in Table 1 has a sufficiently thick side reflector, Case A.1 in Table 2 has very poor neutronic performance because a large fraction of neutrons leaks from the reactor core through the RPV.

Since the small reactor core faces large neutron leakage, external side reflector (ESR) located outside the RPV is considered to reflect neutrons which leak from the reactor core. Group B in Table 3 shows the neutronic effects of the ESR. Comparing pairwise group B with group A, the neutronic effects of the 50-cm-thick ESR can be neglected. This means that the RPV and barrel reflect the neutrons back to the reactor core. So it is recommended to model the barrel and RPV for the neutronic analysis of the U-Battery with a thin side reflector.

Group C shows the results of two configurations for a 1 MWth U-Battery. If the thermal power of the U-Battery decreases to 1 MWth, the maximum fuel lifetimes of Layouts 6$×3*and*6×$4 are 10 and 18 EFPYs, respectively. Comparing Cases C.1 and C.2 with A.2 and A.3, an approximately linear relationship between thermal power and fuel lifetime is clear. If so, the maximum thermal power of the U-Battery is about 4 MWth if the fuel lifetime is fixed to 5 EFPYs.

In terms of the results of groups A, B and C, it is impossible to achieve a design of the 5 MWth U-Battery with a fuel lifetime of 5 EFPYs and 1.8-m diameter when the side reflector is 25-cm-thick graphite. Case 8 in Table 1 shows that a reactor core with 12 fuel blocks is able to achieve 4 EFPYs if there is a sufficiently thick side reflector, even though the model does not include the neutron reflection effect of the barrel and RPV. In other words, all reactor configurations in Table 3 have very poor neutron economy because of very thin side reflectors. Since the ESR is not effective to reflect the leaked neutrons out of the RPV because of the double blockage of the barrel and RPV, the only way to increase the neutron economy of the U-Battery with 1.8 meter RPV in diameter is to improve the neutronic performance of the side reflector.

3.2 Beryllium Oxide Side Reflector

Beryllium is a good moderator material from neutronic point of view, which has a larger moderating power and higher density than graphite. Compared with metallic beryllium, beryllium oxide (BeO) with higher melting temperature and density is used for the U-Battery with 1.8-m RPV in diameter. Three groups of reactor core configurations are investigated (Table 4).

The first group (group D) is the limit design of the reactor core, because all the space between the reactor core and barrel is filled with BeO, and a high density of BeO, 3.0 g/cm^3, is used. Cases D.1 and D.2 achieve 8 and 10.5 EFPY fuel lifetime, respectively.

The second group, i.e., group E, shows the influence of the thickness of BeO side reflector. Comparing Cases E.2 and E.3 shows that the 20-cm-thick BeO side reflector is enough for the side reflector of the U-Battery from neutronic point of view, even though the BeO density decreases from 3.0 g/cm^3 to 2.8 g/cm^3. From thermal-hydraulic point of view, it is really helpful to have a 5-cm annular space between the side reflector and barrel. This means that there is a small space to accommodate the side thermal insulation in order to protect the barrel and RPV.

Group F shows the results of two reactor core configurations of the U-Battery with 10 MW thermal powers for the same-size RPV. Comparing Cases F.1 and F.2 with Cases E.3 and E.4, respectively, the fuel lifetime of the reactor core is still linear to the thermal power for the two cases of group F. From economic point of view, the 10 MWth U-Battery with a 5-EFPY fuel lifetime is more economic than the 5 MWth U-Battery with a 10-EFPY fuel lifetime.

Conclusion

The reactor core configurations of a transportable 5 MWth HTR with 5–10 effective full power years (EFPYs), called U-Battery, have been investigated by the TRITON module in SCALE 6. In order to emphasize its transportability, the diameter of RPV is limited to 3.7 m and 1.8 m.

For the 3.7-m RPV diameter, the reactor core with 24 fuel blocks loaded with 20% enriched ^{235}U reaches a fuel lifetime of 10 EFPYs for the 5 MWth U-Battery. Comparisons of the different reactor core configurations with 24 fuel blocks show that Layout 12$×2B, ascatteringcore, achievesthelowestfuelcost.Moreover, reducingthefuelinve by 11%.

When decreasing the RPV diameter from 3.7 m to 1.8 m, it is possible to achieve a fuel lifetime of 4 EFPYs for the 5 MWth U-Battery with a graphite side reflector. If nuclear graphite is replaced by BeO, Layouts 6$×3and6×$4 with the 25-cm-thick BeO side reflector achieve 7 EFPYs and 10 EFPYs, respectively, for the 5 MWth U-Battery. The 20-cm-thick BeO side reflector is sufficiently thick from neutronic point of view. Moreover, it provides more space for the side thermal insulation to protect the barrel and RPV.

Future work will focus on the design of the reactivity control system of Layouts 6$×3and6×$4 with 20-cm-thick BeO side reflector, and on the coupled neutronic/thermal-hydraulic evaluation of the different designs.

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