Design of the Graphite Reflectors in Research Reactors

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1. Introduction

Graphite is often used as one of reflector materials for research reactors because of its low neutron absorption cross-section, good moderating properties, and relatively low and stable price. In addition, graphite has excellent properties at high temperatures, so it is widely used as a core material in high temperature reactors. However, its material characteristics such as strength, elastic modulus, thermal expansion coefficient, dimensional change, and thermal conductivity sensitively depend on neutron fluence, temperature, and its manufacturing process. In addition, the Wigner energy and the treatment of the graphite waste such as C-14 should also be considered. For the design of the graphite reflectors, it is therefore essential to understand the material characteristics of chosen graphite materials at given conditions. Especially, the dimensional changes and the thermal conductivity are very important factors to design the nuclear components using graphite as a nonstructural material.

Hence, in this study, the material characteristics of graphite are investigated via some experiments in literature. Improving design methods for graphite reflectors in research reactors are then suggested to minimize the problems, and the advantages and disadvantages of each method are also discussed.

2. Material Characteristics of Graphite

2.1 Dimensional Changes

Irradiation of graphite leads to considerable dimensional changes. Some cases such as JRR-4, OSTR, and IEA-R1 research reactors have shown that cracks occurred on the cladding of the graphite reflectors due to the irradiation growth of graphite. The basic processes of the dimensional changes are well described in the reference [1]. Some studies [1-5] on the dimensional changes of several anisotropic graphite materials have been performed and found that some anisotropic graphite grows in the direction perpendicular to the basal planes (along the c-axis) and contracts in the direction parallel to the basal planes (along the a-axis). In contrast, some anisotropic graphite materials contract in both directions at high temperatures (above 300^{o}C) [5]. In addition, as the neutron fluence increases, these materials start to rapidly expand after “turnaround” points. For isotropic and near-isotropic graphite materials, contraction in all direction is observed at high temperatures [3], and then expansion is observed after “turnaround” points, which is similar to anisotropic graphite materials at high temperatures. However, the dimensional changes of isotropic graphite at low temperatures are now well known, and very limited studies have been performed. The JRR-4 reports [6-8] are the only case available, so the characteristics of isotropic graphite at low temperatures are discussed based on the study.

The JRR-4 is a 3.5MW pool-type Japan Research Reactor built in 1965, and isotropic graphite, IG-110, is used as a reflector material. The dimensional changes of the IG-110 graphite material under the JRR-4 operation condition are shown in Fig. 1. For the given range of the fast neutron fluence (E > 0.18 MeV), irradiation growth was observed at low temperatures (below 200^{o}C), and the maximum irradiation growth ratio was 7.13×10^{-25} % m^{2}/n. It should be noted that the dimensional change and the fast neutron fluence in Fig. 1 indicate the averages of the 4 side value, and the dimensional change includes the effect of the retardation caused by the cladding. Hence, the inflection of the curve does not mean the rate of the irradiation growth of IG-110 decreases with increasing the neutron fluence, and moreover, it is not clear the region where the cladding effect is included. Based on the report [6-7], it is expected that the upper limit where the cladding effect is negligible is around 2% of dimensional change.

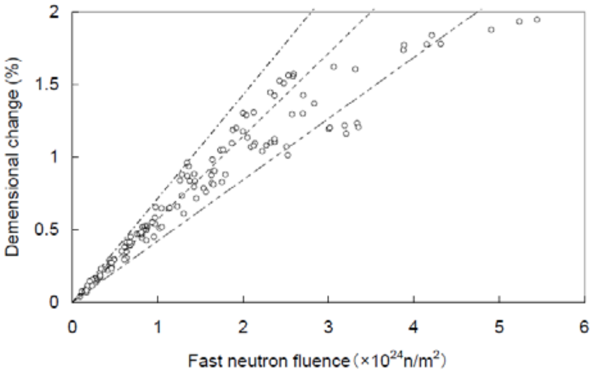

Fig. 1. Dimensional changes of the IG-110 graphite under the JRR-4 operation condition [8].

2.2 Thermal Conductivity

The thermal conductivity is another important factor to design the graphite reflectors. Several studies [5,9] have shown that the thermal conductivity of both anisotropic and isotropic graphite is drastically reduced by irradiation effect. Maruyama and Harayama [9] have used IG-110U as one of the graphite materials. The thermal conductivity of unirradiated graphite was 119 W/mK at room temperature, and after the irradiation of fast neutron fluence 1.92×10^{20} n/cm^2 (E > 1 MeV) at 200^{o}C, the value became just 2.6 W/mK which is just 2% of original value. As the thermal conductivity affects the graphite temperature, the irradiation growth and contraction are severely depend on the value.

3. Design of the Graphite Reflectors

An example of graphite reflectors are shown in Fig. 2. Bulk-type graphite reflectors with some irradiation holes are placed next to the core, and the maximum fast neutron flux (E > 0.18 MeV) in the region is about 1.4×10^{13} n/cm^{2}s. When the reactor is operated 200 days a year, the maximum fast neutron fluence per year is 2.5×10^{20} n/cm^{2}yr. When we assume that the average temperature in the graphite is below 200^{o}C, the expected maximum irradiation growth is about 1.8% per year based on the JRR-4 case. Hence, sufficient initial gaps between the cladding and the graphite block should be considered. As mentioned in Section 2, however, it is impossible to expect the dimensional changes after 2% in JRR-4 case. If the irradiation growth rate is assumed to be linear, the lifetime of the graphite reflectors would be very short, and the frequent replacement of graphite reflectors during the operation period is indispensible.

There are some alternative plans to solve the problem. One is increasing the temperature of graphite block over 300^{o}C, to make the blocks contracted. In the MURR graphite reflectors, ceramic thermal spacers are installed between the aluminum can and the graphite, which makes the temperature increased. This method, however, should solve some problems. First, we should consider the effect of the irradiation shrinkage. Second, to hold high temperatures in the reflectors, the thermal spacers (or gas) should be also used around holes for irradiation devices. This makes the volume of graphite reduced by about 80% and severely affects the core reactivity.

Another method may use graphite powder to relax the irradiation growth. Graphite blocks with low density are made by compressing graphite power, and the irradiation growth of graphite at low temperatures can be accommodated in the can. The problems of this method are: 1) it has low thermal conductivity compared to the original graphite; 2) the graphite block made from powder swells when the temperature is around 200^{o}C; 3) its low density does affect the core reactivity; 4) the irradiation growth data is still needed to predict the material behavior at the high neutron fluence.

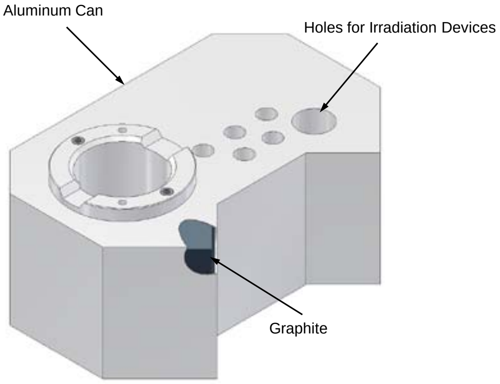

Fig. 2. A graphite reflector consists of graphite blocks and aluminum can. Some holes for irradiation devices are provided.

3. Conclusions

The material characteristics related to the dimensional changes and thermal conductivity are severely sensitive to temperature, neutron fluence, and material type. Especially, in high fast neutron flux region, the dimensional change is a very important factor to determine the lifetime. It is therefore very important to understand the material behavior of graphite under the given operation conditions. In addition, because the thermal conductivity of graphite and the gaps between the can and the graphite block are varied during the operation, it is necessary to thoroughly examine these problems during designing the graphite reflectors and to consider periodic replacement during the operation.

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