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Application of hafnium hydride control rod to large sodium cooled fast breeder reactor

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HIGHLIGHTS

- Application of hafnium hydride control rod to large sodium cooled fast breeder reactor.
- This paper treats application of an innovative hafnium hydride control rod to a large sodium cooled fast breeder reactor.
- Hydrogen absorption triples the reactivity worth by neutron spectrum shift at H/Hf ratio of 1.3.
- Lifetime of the control rod quadruples because produced daughters of hafnium isotopes are absorbers.
- Nuclear and thermal hydraulic characteristics of the reactor are as good as or better than B-10 enriched boron carbide.

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ABSTRACT

This study treats the feasibility of long-lived hafnium hydride control rod in a large sodium-cooled fast breeder reactor by nuclear and thermal analyses. According to the nuclear calculations, it is found that hydrogen absorption of hafnium triples the reactivity by the neutron spectrum shift at the H/Hf ratio of 1.3, and a hafnium transmutation mechanism that produced daughters are absorbers quadruples the lifetime due to a low incineration rate of absorbing nuclides under irradiation. That is to say, the control rod can function well for a long time because an irradiation of 2400 EFPD reduces the reactivity by only 4%. The calculation also reveals that the hafnium hydride control rod can apply to the reactor in that nuclear and thermal characteristics become as good as or better than 80% B-10 enriched boron carbide. For example, the maximum linear heat rate becomes 3% lower. Owing to the better power distribution, the required flow rate decreases approximately by 1%. Consequently, it is concluded on desk analyses that the long lived hafnium hydride control rod is feasible in the large sodium-cooled fast breeder reactor.

1. Introduction

This study examines the properties of hafnium hydride and its application to a large sodium-cooled fast reactor in pursuit of the development of long-lived control rod using hafnium hydride. Extension of lifetime is a key matter in the development of control rod, although absorbers for control rod of sodium-cooled reactors are usually B-10 enriched boron carbide. The good points of the B-10 enriched boron carbide are a large absorption cross section, a good compatibility with sodium, a high thermal conductivity, and a high melting point. On the other hand, the enriched boron carbide will swell due to the accumulation of the helium and lithium produced by (n,α) reaction and irradiation damage (Risovany et al., 2011; Walter and Reynolds, 1981). The helium builds up also the pressure of gas plenum in the case of without ventilation. The reactivity worth is likely to reduce because the generated Li-7 has a low melting point (180.54 °C) and a small capture cross section. In order to avoid the absorber-cladding mechanical interaction due to the swelling of the boron carbide, several kinds of designing are available: expanding the gap between absorber and cladding, arranging

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shroud tube between both, and choosing sodium as a bond material with venting helium. Additionally the optimization of axial heterogeneous control rod can suppress the peak of swelling. The other issue is that the life duration is limited to 1 or 2 years due to the reactivity loss of B-10 incineration in the case of primary control rod.

In order to overcome the above problem, a development program of long-lived control rods for sodium-cooled fast breeder reactor started in 2006, taking advantage of the properties of hafnium hydride (Konashi et al., 2006a,b). The comprehensive research and development of 6 years investigated hafnium hydride control rod, including fabrication tests, property measurements, irradiation tests, designs (Konashi et al., 2010, 2011; Konashi and Yamawaki, 2010, 2012).

Fabricating hafnium hydride pellets by hydrogen absorption and coating the inner surface of cladding by aluminum oxide to reduce hydrogen permeation through cladding were experimentally succeeded (Konashi et al., 2008; Hirai et al., 2010), and test pieces were supplied to other kinds of researches (Konashi et al., 2013a,b; Suzuki et al., 2013). Sodium filling method was researched for sodium-bonded type control rod elements (Ariyoshi et al., 2010; Mizutani et al., 2013).

Physical and chemical properties of hafnium hydride were widely measured (Konashi et al., 2008; Ito et al., 2009, 2010; Suzuki et al., 2013). High-temperature stability was observed from out-of-piles experiments to confirm the integrity of the hafnium hydride elements at normal operation (Hirai et al., 2010) and to evaluate the safety of fire accidents at manufacturing and storage facilities (Konashi et al., 2013a). Hafnium hydride pellets were irradiated at Joyo (Konashi et al., 2008), and at BOR-60 (Konashi et al., 2013b).

In order to assess the nuclear characteristics of the hafnium hydride absorber experimentally, the reactivity of cells simulating the control rod by hafnium and polyethylene plates was measured in Fast Critical Assembly (FCA) of JAEA and calculated (Andoh et al., 2011). As for the application to sodium-cooled reactors, nuclear calculations found out the potential of long lifetime of the hafnium hydride control rod (Iwasaki and Konashi, 2009).

This paper makes a first attempt to examine the properties of hafnium hydride and evaluates the nuclear and thermal characteristics of the fast reactor with the hafnium hydride control rods at details by the design methodology. Furthermore the comparison with the B-10 enriched boron carbide rods. Conformity to requirements is assessed by design approach and issues to be investigated are discussed. Naturally any achievements of other papers are not duplicated except for explicit remarks. This article focuses on the nuclear design of the large sodium-cooled fast reactor with the hafnium hydride control rods, considering the safety design and achievements of this project.

In Section 2, general requirements of absorber are determined and hafnium hydride is assessed. In Section 3, the methodology, calculation conditions, and design requirements for reactor of this study are explained. Section 4 provides calculation results of nuclear and thermal characteristics of the reactor and control rods. Discussion treats mechanism of flat distributed heating source in the absorber and decreased power distortion by inserting the control rods in Section 5. Section 6 points to the technical issues of hafnium hydride for practical realization and future work before conclusions.

2. Requirements of absorber and assessment of hafnium hydride

The basic properties of hafnium hydride are assessed based on general requirements of absorber.

2.1. Requirements of absorber for sodium-cooled reactor

V. D. Risovany, A. V. Zakharov, E. P. Klochkov, and T. M Guseva set requirements of absorber in reactors (Risovany et al., 2011). That is, absorber material for control rods in sodium-cooled reactors should satisfy the following requirements.

Requirement C1

Absorber is required to absorb neutrons efficiently and have a low rate of neutron absorbing nuclides incineration under irradiation. That is, it has a large cross section of (n,α) reaction, or (n,γ) reaction and it is preferable that produced daughter nuclides are absorbers.

Requirement C2

Absorber is required to be robust in the circumstance of sodium-cooled reactor: an enough resistance to radiation damage; a low chemical activity in regard to surrounding materials and matter; a high corrosion resistance in the coolant; high heat, high thermal, and vibration resistance; and excellent mechanical and thermal-physical characteristics at operation temperature. For example, absorber must not melt, even if at any supposable accident and cladding must not break due to the neutron induced-swelling. Absorber should not chemically interact with coolant or cladding.

Naturally control rods shall be designed so that, in operational states and in accident conditions other than severe accidents, a geometry that allows for adequate cooling is maintained. Since this is “Requirement 44” of IAEA Specific Safety Requirements No. SSR-2/1 (IAEA, 2012) for fuels, it is mostly required for control rods. Moreover, due account shall be taken of wear out and of the effects of irradiation, such as burnup, changes in physical properties and production of gas in “Requirement 45” (IAEA, 2012).

Requirement C3

The other requirements to be considered are a low induced radioactivity, manufacturability, rich reserves of raw materials, and a low cost.

2.2. Assessment of hafnium hydride

Hafnium hydride is assessed to be an excellent neutron absorber, based on Requirements C1 to C3 as follows.

Hafnium hydride meets Requirement C1 because it has a large neutron capture cross section, and the daughters of neutron absorber. First, hafnium has a large capture cross section, which is smaller than B-10. Fig. 1 shows the capture cross sections of Hf-177, 178, 179 with B-10. Hafnium isotopes have half or quarter as large a capture cross section as B-10. However, hydrogen absorption of hafnium enhances it four or six times. The absorption cross sections of B-10, hafnium with hydrogen and without, europium, and gadolinium, the abundance of isotopes, and the nuclides produced by neutron absorption are shown in Table 1. The absorption cross sections are calculated from the data of JENDL-4.0 (Shibata et al., 2011) by weighting with neutron flux energy spectrum. Second, since hafnium has five stable isotopes, it is unlikely to lose neutron absorption ability owing to its transmutation mechanism. Fig. 2 shows the transmutation of hafnium isotopes; hafnium-176, 177, 178, 179, 180 are stable and their capture reactions produce higher isotopes of absorber. Therefore the reactivity of the control rod is hard to decrease during irradiation as shown in the preceding article (Iwasaki and Konashi, 2009).

Hafnium hydride meets also Requirement C2 because it is robust in the circumstance of fast reactors. The 3 years of irradiation experiment in BOR-60 demonstrated that the capsules of hafnium hydride absorber maintain integrity under conditions simulating operation environment (Konashi et al., 2013b). It was proved by