Nuclear Engineering and Technology 50 (2018) 738–744

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Development of an evaluation method for nuclear fuel debris–filtering performance

Joon-Kyoo Park [a, **], Seong-Ki Lee [a], Jae-Hoon Kim [b, *]

[a] Nuclear Fuel Technology Dept., R&D Center, KEPCO Nuclear Fuel, 242, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon 34057, South Korea
[b] School of Mechanical Engineering, Chungnam National University, 99 Daehak-ro, Yuseong-gu, Daejeon 34134, South Korea

A R T I C L E I N F O

Article history:
Received 11 December 2017
Received in revised form
2 March 2018
Accepted 7 March 2018
Available online 28 March 2018

Keywords:
Comprehensive Debris-Filtering Efficiency
Debris-Filtering Performance
Debris-Filtering Test
Debris-Induced Failure
Nuclear Fuel
Weighted Mean

A B S T R A C T

Fuel failure due to debris is a major cause of failure in pressurized water reactors. Fuel vendors have developed various filtering devices to reduce debris-induced failure and have evaluated filtering performance with their own test facilities and methods. Because of the different test facilities and methods, it is difficult to compare filtering performances objectively. This study presents an improved filtering test and an efficiency calculation method to fairly compare fuel-filtering efficiency regardless of the vendor's filtering features. To enhance the reliability of our evaluation, we established requirements for the test method and had a facility constructed according to the requirements. This article describes the debris specimens, the amount of debris, and the replicates for the proposed test method. A calculation method of comprehensive debris-filtering efficiency using a weighted mean is proposed. The test method was verified by repeated tests, and the tests were carried out using the PLUS7 and 17ACE7 test fuels to calculate the comprehensive debris-filtering efficiencies. The evaluation results revealed that the filtering performance of PLUS7 is better than that of 17ACE7. The proposed method can be used on any kind of debris-filtering devices and is appropriate for use as a standard.

1. Introduction

It is critical to secure the integrity of nuclear fuel in nuclear power plant operation. Nuclear utilities and nuclear fuel vendors are making great efforts to improve the reliability of nuclear fuel because fuel failure affects not only public acceptance of nuclear power but also the financial feasibility of power plant operation. The fuel failure rate has been significantly reduced by these efforts, but failures from various causes continue to be reported. In Korea, fuel failure due to debris is one of the most severe causes of failure [1]. In the world, failure from debris is identified as the highest cause of fuel failure, followed by grid-to-rod fretting wear [2]. Debris is generated during plant construction or maintenance operations. Fuel-damaging debris consists mostly of metal of various shapes and sizes. Pieces of metallic debris can enter from the bottom of the fuel with the reactor coolant and may be trapped between fuel rods and the spacer grid that supports the rods. Debris-induced failure is generated by wear if the trapped debris vibrates for a long time. To mitigate this failure, fuel-filtering devices must be developed, along with reliable evaluation methods.

Fuel vendors have developed various debris-filtering devices to enhance the filtering performance; for performance evaluation, these vendors calculate the filtering efficiency with their own test facilities. Moreover, fuel vendors use not only their own debris specimens but also different methods along with their test facilities for the evaluation of the newly developed filtering devices [3–7]. To improve the test method and to yield statistically valid results, Park et al. proposed a debris-filtering test methodology [8]; however, their method did not deal with the comprehensive filtering efficiency considering the various shapes of debris for comparison. Therefore, it is necessary to introduce a new filtering performance evaluation method that includes a reliable test method and an efficiency calculation method based on filtering test results.

In this article, to elevate the reliability of test results, we propose an improved filtering test method for nuclear fuel; we confirm the validity of the test method through replicates with representative debris specimens. Using a weighted mean to compare filtering performances, we introduce the concept of comprehensive debris-filtering efficiency. In addition, the performances of PLUS7 and

* Corresponding author.
** Corresponding author.
E-mail addresses: jkpark@knfc.co.kr (J.-K. Park), skilee@knfc.co.kr (S.-K. Lee), kimjhoon@cnu.ac.kr (J.-H. Kim).

https://doi.org/10.1016/j.net.2018.03.011

17ACE7, commercial nuclear fuels in Korea [9], are compared using the proposed evaluation method.

2. Requirements for evaluation method

Debris-filtering devices and reactor-operating conditions differ depending on the type of nuclear fuel and the power plant. However, to objectively evaluate the filtering performance, the requirements for the test conditions, the type of debris specimens, the amount of debris, and the calculation method of the filtering efficiency need to be established.

First, the test flow rate and the geometry of the test structures need to be similar to reactor conditions. If this requirement is not met, the hydraulic force acting on the debris will be different from the real conditions and affect the test results.

Second, the debris specimen should represent the various kinds of debris generated in the reactor core and be visible to the naked eye. Because the debris found in the reactor core is very diverse in size and type, it is necessary to propose standardized debris specimens that represent most debris to obtain more credible test results.

Third, the number of debris specimens in a test and the number of replicates by debris type should be appropriately determined to obtain statistically meaningful test results. Practically, large amounts of debris are rarely found in nuclear fuel. Only one or two debris particles are occasionally found in the filtering devices. Therefore, the number of debris specimens in each test should be acceptably determined to minimize the interference between the debris objects. If a large amount of specimen is used to cause interference, the debris is intensively trapped and accumulates in the filtering devices, so that a fair evaluation cannot be performed. The total number of replicates should be sufficient for dependable results. In other words, the optimum number of debris objects in each test should be injected without interference, and enough replicates should be performed to meet the required confidence level.

Finally, based on test results, the debris-filtering efficiency should be expressed as a value that can determine the level of the filtering performance. In addition, for a fair comparison, the efficiency score should indicate comprehensive performance considering various types of debris.

3. Materials and methods

3.1. Test configuration

According to the first requirement for the evaluation method, the debris-filtering test facility should be constructed to simulate reactor conditions. The piping and configuration of the test facility used in this study are depicted in Fig. 1. This test facility consists of a test housing, strainers, a water tank, a pump, a debris injection hole, and valves. The debris-filtering test can be classified into two types according to the fuel used: full array fuel [6,8] and partial fuel [3,7]. To make the test as realistic as possible, we used a test fuel assembly with full array rods. To allow visual identification of the amount and location of filtered debris in the fuel during the test, the test housing was made of transparent plates. It accommodated one set of test fuel, which contained the filtering devices. In addition, a transparent lower core structure was installed at the bottom of the test fuel to allow easy identification of the filtered debris and simulate the core structure in which the fuel is placed. Strainers on the pipe were set up to collect debris that is lost during the test or debris that passed through the fuel and also to prevent the debris from entering the pump. The debris injection hole was equipped with a bypass pipe and valves so that the debris specimens could flow into the test loop under the required flow rate conditions. For comparison of filtering performances, the 17ACE7 and PLUS7 nuclear fuel assemblies, which are supplied commercially in Korea, were selected as the test fuel assemblies. As shown in Fig. 1, the test fuel assemblies were fabricated with debris-filtering devices consisting of a bottom nozzle and a protective grid, in which most of the debris was filtered.

3.2. Debris specimen

For the second requirement of the evaluation method, to obtain objective results, the type and size of the debris specimen need to be standardized, and the specimen should represent the debris found in the field. Therefore, the debris specimens were classified into three types: wire, plate, and ball. All the debris specimens used in the test were separated into 51 groups according to their type and size. These groups consisted of 20 groups of wire, 27 groups of plate, and 4 groups of ball. The wire is typical fuel-damaging debris which originates from metallic wire wheels and brushes that are used in plant maintenance operations. Plate debris was selected to simulate sheet metal objects that could be generated from nuclear fuel or reactor components. Ball debris was selected to evaluate the performance according to the maximum pass-through size of the filtering devices. To achieve meaningful test results for the performance, we determined the size of the specimens that could pass through the lower core structure and flow holes of the bottom nozzle. The specimen surfaces were painted red to improve the visibility. The ranges of size and shape of each specimen group are shown in Table 1.

3.3. Number of debris in each test

For the third requirement of the evaluation method, the number of debris objects that can be injected at the same time without any interference between debris specimens is determined. The maximum limiting number of debris objects can be determined using the concept of the mean free path [8]. By applying debris objects instead of particles in the mean free path, the distance traveled between the collisions of debris objects can be calculated. Based on this, it is possible to calculate the number of debris objects that can move independently without collision within the volume of interest. Considering the number of debris objects contained in the unit volume, the mean free path of the debris, λ, can be expressed as

$$\lambda = \frac{1}{\pi l^2 n_v} \quad (1)$$

where l denotes the representative length of the debris and n_v is the number of debris objects in the unit volume [10]. The maximum number of debris objects per unit volume without collision can be derived [10] as Eq. (2) by applying the relative velocity and collision angle, θ, of two moving debris objects to Eq. (1).

$$n_v = \frac{1}{\pi l^2 \lambda \sqrt{2 - 2cos\theta}} \quad (2)$$

Consequently, the maximum limiting number of debris objects without interference can be calculated by multiplying the volume of interest by Eq. (2). As shown in Fig. 2, the region of interest without collision corresponds to the volume from the inlet of the lower core structure to the bottom of the debris-filtering devices. A collision occurs when the debris objects cross each other. Thus, debris objects moving along the pipe may collide if there is a change in the flow direction. The holes of the lower core structure have a chamfer at the inlet, which affects the flow direction and may cause collisions between debris objects. Therefore, the