Nuclear Engineering and Design 249 (2012) 287–296

Contents lists available at SciVerse ScienceDirect

Nuclear Engineering and Design

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

Self-sufficient nuclear fuel technology development and applications

Kyu-Tae Kim*

Dongguk University, College of Energy & Environment, 707 Seokjang-Dong, Gyeongju, Gyeongbuk 780-714, Republic of Korea

ARTICLE INFO

Article history:
Received 30 January 2012
Received in revised form 21 April 2012
Accepted 24 April 2012

ABSTRACT

A cutting-edge nuclear fuel technology in Korea has been acquired through four stepwise nuclear fuel technology development phases starting from the 1970s that may include a fuel import phase, a turnkey fuel technology transfer phase, a fuel technology joint-development phase and a self-sufficient fuel technology development phase. The self-sufficient fuel technology development procedures have been applied for developing four kinds of advanced PWR fuels such as PLUS7, 16ACE7, 17ACE7 and HIPER, an advanced cladding material of HANA and various fuel performance analysis computer codes. The PLUS7, 16ACE7 and 17ACE7 fuels have already been implemented on a batch scale in the PWRs operating in Korea. Based on the forty years' operation experience of the PWRs in Korea and various fuel verification/validation test databases acquired from the advanced fuel developments, main fuel failure causes observed in the PWRs seem to be grid-to-rod fretting wear, debris-induced wear and accelerated Zry-4 cladding corrosion. Outstanding countermeasures against such main fuel failures are proposed to accomplish an ultimate goal of zero fuel defects for the aforementioned advanced fuels.

1. Introduction

International cooperation for advanced nuclear reactor and fuel technology developments has been steadily increasing. Some world-leading nuclear vendors succeeded in intensified international collaborations with several developing countries. Those world-leading nuclear vendors have a capability of transferring advanced nuclear reactor and fuel technologies to new comers to a world nuclear industry circle. Through the nuclear reactor and fuel technology transfer programs supported by a world-leading nuclear vendor, Korea has succeed in acquiring competitive, advanced nuclear reactor and fuel technologies (Kim, 2011a). During the last four decades, 17 Pressurized Water Reactors (PWRs) and four Pressurized Heavy Water Reactors (PHWRs) have been successfully constructed and operating in Korea, and the nuclear fuel technology has been developed to a self-sufficient level. This has led Korea to recently award the nuclear power plant contracts from the United Arab Emirates. From now on, therefore, Korea may provide its self-sufficient nuclear fuel technologies to new comers planning to acquire advanced nuclear fuel technologies.

Nuclear fuel cycle costs account for 25–49% of the total power generation cost (Gueldner and Burtak, 1999). Although the cost of nuclear fuel fabrication only amounts to around 10% of the fuel costs, the key to cost savings and efficiency enhancements in the entire nuclear fuel cycle lies in advancement of nuclear fuel technology (Kim et al., 2008a,b). The nuclear fuel technology can be applied to three main areas such as fuel assembly and its components development, fuel materials development and fuel performance analysis computer code development. Basically, the nuclear fuel technology has to be verified through a full spectrum of out-of-pile tests and research reactor irradiation tests, and it has to be validated through a full spectrum of in-reactor irradiation tests. In order to establish a verified and validated fuel technology, therefore, one has to develop fuel materials, fuel assembly/components designs, fuel manufacturing facilities, verification/validation test equipment and facilities, and fuel performance analysis computer codes containing fuel performance models (Kim, 2011a). It should be noted that it may take more than 20 years to acquire the aforementioned proven fuel technology along with a full-spectrum infra-structure needed for fuel design, manufacturing, verification and validation tests.

Korea has developed a self-sufficient fuel technology through four stepwise phases; a fuel import phase, a fuel technology localization phase, a fuel technology joint-development phase and a self-sufficient fuel technology development phase (Kim, 2011a). Since the first PWR plant in Korea constructed in 1978, Korea had imported all PWR fuels for all PWRs operating in Korea up to 1989 (1st phase). However, the fuel technology localization phase started in 1986 when Korea Atomic Energy Research Institute (KAERI)

Abbreviations: PWR, Pressurized Water Reactor; PHWR, Pressurized Heavy Water Reactor; KNF, KEPCO Nuclear Fuel; KAERI, Korea Atomic Energy Research Institute; WEC, Westinghouse Electric Company; CHF, critical heat flux; FA, fuel assembly; LTA, Lead Test Assembly; LOCA, Loss of Coolant Accident; RIA, Reactivity Initiated Accident.

* Tel.: +82 10 8805 1447; fax: +82 54 770 2282.
E-mail address: ktkim@dongguk.ac.kr

0029-5493/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nucengdes.2012.04.023

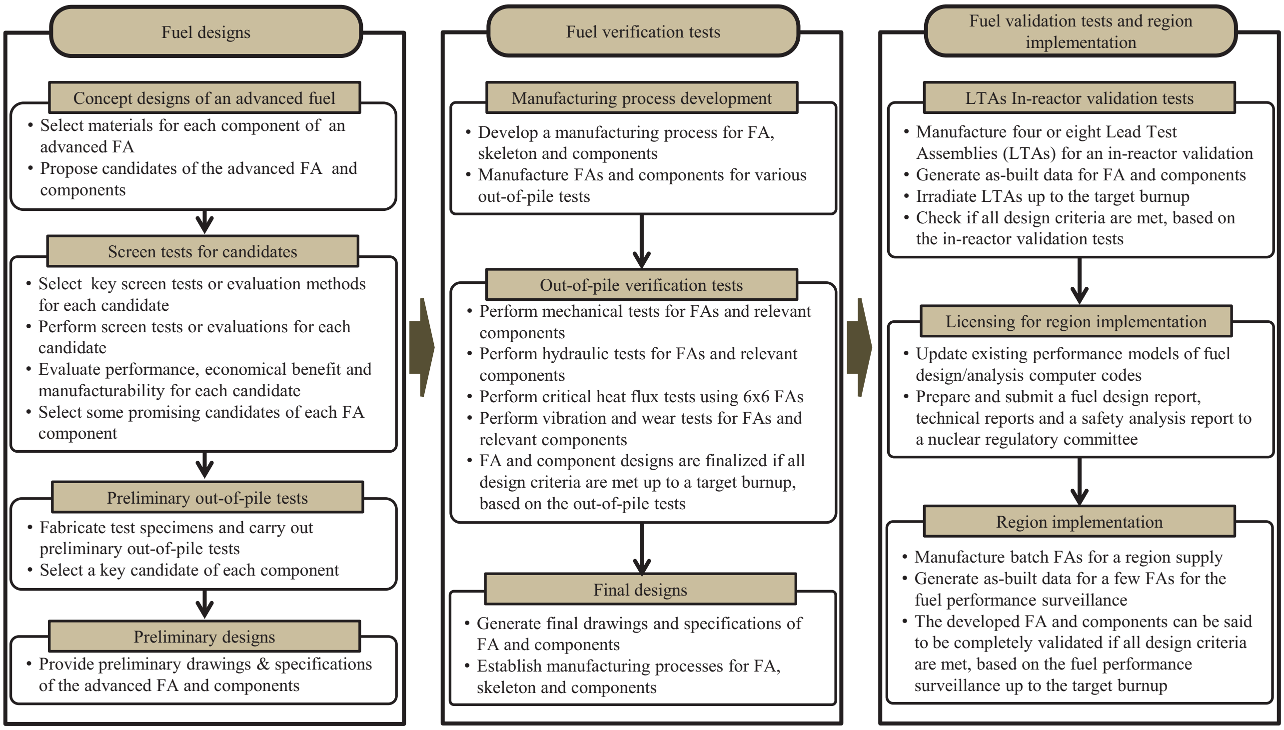

Fig. 1. A development procedure for an advanced fuel assembly.

and Korea Nuclear Fuel (KNF) took part in a joint development of PWR fuels with Siemens-KWU (2nd phase). Through this second phase, Korea localized a fuel design technology including design codes as well as a fuel manufacturing technology. Subsequently KNF started two joint R&D programs with Westinghouse Electric Company (WEC) from the year 1999 to develop advanced nuclear fuels such as PLUS7, 16 × 16ACE7 and 17 × 17ACE7 (3rd phase). Through this third phase, Korea acquired a fuel development technology including fuel verification and validation technology. Based on this fuel development technology, Korea started to develop the HIPER fuel to acquire a self-sufficient fuel technology from the year 2005 and then has completed the HIPER fuel design and out-of-pile verification tests by the end of 2010 (4th phase).

This paper will mainly describe three kinds of nuclear fuel technology development procedures that cover nuclear fuel assembly (FA) and components development, fuel materials development and fuel performance analysis computer codes development. The fuel technology development procedures will describe test items and purposes of out-of-pile verification with test FA and its components, research reactor verification with test specimens and fuel rods and in-reactor validation with pathfinder rods, lead test assemblies (LTAs) and batch assemblies. In addition, main fuel failure causes observed in the PWRs are provided and relevant countermeasures against such main fuel failures are proposed, based on the forty years' operation experience of the PWRs and the accumulated advanced fuel verification and validation test databases.

2. Nuclear fuel technology development procedures

In order to develop nuclear fuel assembly and components, nuclear fuel materials and nuclear fuel performance analysis computer codes, three kinds of the nuclear fuel technologies are to be established beforehand, which include nuclear fuel technology development procedures, manpower for fuel technology development and infrastructures such as out-of-pile test equipment and facilities, poolside examination equipment, hot-cell test facilities and nuclear fuel and materials manufacturing facilities. In this study, nuclear fuel technology development procedures acquired through the aforementioned stepwise fuel technology development phases are described. The development procedures can be applied for developing advanced nuclear fuel assembly and its components, nuclear fuel materials, and nuclear fuel performance analysis computer codes.

2.1. Nuclear fuel assembly and components

As shown in Fig. 1, an advanced nuclear fuel development procedure may be divided into such three phases as a nuclear fuel design phase, a nuclear fuel verification phase, and a nuclear fuel validation tests and region implementation phase. First of all, the fuel design phase is composed of concept designs, screen tests, preliminary out-of-pile tests and preliminary designs. Basically, prior to the concept designs, where-to-use and how-to-use for the advanced nuclear fuel to be developed are to be decided. In addition, voices of customers are to be collected and design target values of the advanced nuclear fuel are to be determined. The concept designs are to propose candidates of FA and its components configurations. Each candidate performance is to be evaluated through screening tests or relevant evaluation methods. The screening tests usually cover mechanical, hydraulic and corrosion tests with small-scale test specimens. Then, a concept and issues meeting is held to select some promising candidates, based on the screening test results or evaluation results. Usually nominal dimensions of promising candidates are generated and then small-scale fuel components are manufactured to perform the preliminary out-of-pile tests. Based on the preliminary tests, a key candidate of each component is to be selected. With the acquired databases through the full-scale fuel components and small-scale FA manufacturing processes, a relevant tolerance analysis is performed to add tolerances to the nominal dimensions of the FA and fuel components. Then,