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Inert matrix fuel neutronic, thermal-hydraulic, and transient behavior in a light water reactor

W.J. Carmack [a,*], M. Todosow [b], M.K. Meyer [a], K.O. Pasamehmetoglu [a]

[a] Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-3860, USA
[b] Brookhaven National Laboratory, Brookhaven, NY, USA

Abstract

Currently, commercial power reactors in the United States operate on a once-through or open cycle, with the spent nuclear fuel eventually destined for long-term storage in a geologic repository. Since the fissile and transuranic (TRU) elements in the spent nuclear fuel present a proliferation risk, limit the repository capacity, and are the major contributors to the long-term toxicity and dose from the repository, methods and systems are needed to reduce the amount of TRU that will eventually require long-term storage. An option to achieve a reduction in the amount, and modify the isotopic composition of TRU requiring geological disposal is 'burning' the TRU in commercial light water reactors (LWRs) and/or fast reactors. Fuel forms under consideration for TRU destruction in light water reactors (LWRs) include mixed-oxide (MOX), advanced mixed-oxide, and inert matrix fuels. Fertile-free inert matrix fuel (IMF) has been proposed for use in many forms and studied by several researchers. IMF offers several advantages relative to MOX, principally it provides a means for reducing the TRU in the fuel cycle by burning the fissile isotopes and transmuting the minor actinides while producing no new TRU elements from fertile isotopes. This paper will present and discuss the results of a four-bundle, neutronic, thermal-hydraulic, and transient analyses of proposed inert matrix materials in comparison with the results of similar analyses for reference UOX fuel bundles. The results of this work are to be used for screening purposes to identify the general feasibility of utilizing specific inert matrix fuel compositions in existing and future light water reactors. Compositions identified as feasible using the results of these analyses still require further detailed neutronic, thermal-hydraulic, and transient analysis study coupled with rigorous experimental testing and qualification.

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1. Introduction

The Advanced Fuel Cycle Initiative Light Water Reactor transmutation fuel development program plans to test both mixed-oxide (MOX) and inert matrix fuel (IMF) in an irradiation test, designated LWR-2, in the Advanced Test Reactor, located at

* Corresponding author. Tel.: +1 208 526 6360; fax: +1 208 526 2930.
E-mail addresses: jon.carmack@inl.gov, wjc@inel.gov (W.J. Carmack).

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the Idaho National Laboratory. The goal of the AFCI LWR transmutation program is to develop a fuel composition that fulfills four general criteria:

1. The fuel must produce the same power as a standard uranium oxide (UOX) fuel in a light water reactor.
2. The fuel composition must target destruction of actinide species (Pu, Am, and Np) and emphasize proliferation resistant forms.
3. The fuel must perform these functions without greatly increasing the fissile material loading (which affects fuel cycle cost) in the overall nuclear fuel cycle, and should be within the existing safety envelope of commercial LWRs.
4. The fuel composition must allow for extraction and processing to recover the heavy metal for possible further destruction (via recycling into LWRs or fast reactors) or treatment for ultimate burial in a geologic repository.

To provide for flexibility in the incorporation of plutonium/actinide bearing fuels in pressurized and boiling water reactors, a variety of MOX and IMF compositions are being proposed for inclusion in the planned AFCI irradiation experiment, LWR-2. A variety of compositions are needed to determine the feasibility and performance of fuels containing significant amounts of TRU, and allow for flexibility in loading strategies for fuel management. This paper will explore the general neutronic and thermal-hydraulic performance of transmutation fuels based on the fertile-free matrix material magnesia–zirconia ($MgO–ZrO_2$). For comparison the neutronic and thermal-hydraulic performance characteristics of uranium dioxide (UOX), yttria-stabilized zirconia (YSZ) and SiC fuels are presented.

A variety of inert matrix materials compositions have been proposed and studied for use in high burnup actinide fuel systems, Degueldre and Yamashita [1]. Chang and Ryskamp [2] proposed inert matrix fuel pins inter-dispersed in standard LWR UO_2 fuel bundles to achieve burnup and destruction of Pu material without negatively impacting operational characteristics of LWR operation. Herring et al. [3] proposed a ThO_2 based transmutation fuel for LWR systems to eliminate the ^{238}U matrix from the reactor system entirely. Eaton et al. [4] proposed a full inert matrix of ZrO_2 stabilized with CaO and loaded with TRU. Much work has been performed in the yttria-stabilized zirconia (YSZ) matrix system for application to once-through and out (OTTO) fuel cycles, Schram et al. [5], Ledergerber et al. [6]. Irradiation and property test programs performed on the YSZ matrix have indicated excellent stability and performance both as a fuel system and as a final waste form meeting repository waste disposal criteria. In a once through fuel application Hellwig et al. [7] irradiated a YSZ matrix. The study compositions attained 440 kWd cm^{-3} burnup with no measurable fission gas release. The composition densified to 100% TD and pellet center-line temperature was found to be approximately 300–400 K higher than a comparable MOX fuel center-line temperature.

To implement an inert matrix fuel composition in the US commercial LWR fleet, the matrix composition must be insoluble in water, and should have a thermal conductivity higher than that found in the cubic ZrO_2. Preliminary property tests and fabrication trials by Medvedev [8,9] at the Idaho National Laboratory have indicated that the performance of a dual phase $MgO–ZrO_2$ matrix may be able to meet the requirements of the AFCI LWR fuel program. The AFCI LWR fuel development program intends to fabricate and test a variety of fuel $MgO–ZrO_2$ compositions in an irradiation campaign in the Advanced Test Reactor located at the Idaho National Laboratory in late-2006. The test will contain both IMF compositions and MOX fuel compositions for comparison. Some of the tested compositions will also include americium and neptunium to investigate the effect of minor actinides on the fuel matrices.

Fuel compositions actually employed in LWR transmutation fuels will be significantly affected by what TRU streams can be easily extracted in the separations process. The 'conventional' streams are Pu (which might not be allowed from proliferation concerns), Np + Pu (which is considered to have enhanced proliferation resistance; this fuel will result in some Am being present from the decay of ^{241}Pu after separation through fabrication and prior to reactor insertion), and Np + Pu + Am. Current plans do not envision the inclusion of curium. Table 1 presents a summary of the currently planned fuel compositions in the LWR-2 test series.

The $MgO–ZrO_2$ dual phase ceramic provides a combination of the properties of MgO and of ZrO_2 that may be able to fulfill the goals of the US LWR transmutation fuel program. When combined in the dual phase ceramic, the high thermal conductivity of MgO tends to overcome the poor thermal conductivity of ZrO_2, Medvedev [9]. The addition of MgO to ZrO_2 in significant quantity