Annals of Nuclear Energy 112 (2018) 486–506

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Improving prompt temperature feedback by stimulating Doppler broadening in heterogeneous composite nuclear fuel forms

Christopher G. Morrison, Wei Ji *

Department of Mechanical, Aerospace, and Nuclear Engineering, Rensselaer Polytechnic Institute, 110 8th St, Troy, NY 12180, USA

A R T I C L E I N F O

Article history:
Received 27 June 2017
Received in revised form 16 October 2017
Accepted 19 October 2017

Keywords:
Composite fuels
Reactivity insertion accidents
Multi-physics computations
Doppler feedback
Prompt temperature feedback
Monte Carlo neutron transport

A B S T R A C T

Nuclear fuels with similar aggregate material composition, but with different millimeter and micrometer spatial configurations of the component materials can have very different safety and performance characteristics. This research focuses on modeling and attempting to engineer heterogeneous combinations of nuclear fuels to improve negative prompt temperature feedback in response to reactivity insertion accidents.

Improvements in negative prompt temperature feedback are proposed by developing a tailored thermal resistance in the nuclear fuel. In the event of a large reactivity insertion, the thermal resistance allows for a faster negative Doppler feedback by temporarily trapping heat in material zones with strong absorption resonances.

A multi-physics simulation framework was created that could model large reactivity insertions. The framework was then used to model a comparison of a heterogeneous fuel with a tailored thermal resistance and a homogeneous fuel without the tailored thermal resistance. The results from the analysis confirmed the fundamental premise of prompt temperature feedback and provide insights into the neutron spectrum dynamics throughout the transient process.

1. Introduction

Reactivity insertion accidents can have catastrophic consequences (Salge, 2005; McLaughlin et al., 2000; Hodges and Sanders, 2014). When designing a reactor system, a negative prompt temperature feedback is required to mitigate the threat of a reactivity insertion accident. Reactors often utilize thermal expansion (Seidel et al., 1983), thermal neutron Maxwell–Boltzmann temperature shifting (Fouquet et al., 2003; Kontogeorgakos, 2015) and Doppler feedback to provide negative temperature feedback. Doppler feedback is attractive because it is a negative feedback present in any reactor with U-238, Th-232, or other resonance absorbers. Doppler feedback is a strong feedback able to counteract reactivity insertions of many dollars as shown later in this document. In addition, Doppler feedback is prompt as long as the resonance absorbers are atomically adjacent to the heat producing fissile material. This type of feedback is prompt compared to other kinds of feedback that require heat to transport out of the fissile fuel region such as in the case of thermal expansion feedback and Maxwell–Boltzmann neutron temperature shifting in the moderator.

While Doppler feedback is prompt, the material properties and geometry of the fuel form play a strong role in the temperature feedback response during a transient. Material properties will determine heat transfer and thermal inertia which will in turn affect the temperature that the Doppler absorbers are experiencing during a reactivity insertion scenario. This opens the possibility of attempting to improve prompt temperature feedback by engineering the fuel form to achieve certain heat transfer characteristics which are beneficial for promoting Doppler feedback.

A composite matrix fuel is an ideal fuel form for exploring the concept of improving prompt temperature feedback. A composite matrix fuel is composed of a fissile fuel kernel surrounded by a non-fissile matrix as shown in Fig. 1. Composite fuels often have a coating or multiple coatings to help with thermal–mechanical, safety, neutronic, or other considerations.

Inside of the composite fuel, the fissile fuel kernel and the matrix material are thermally isolated from each other as they are separate geometric regions. The thermal isolation can be further increased by adding coatings to the fissile fuel kernels. The concept behind improving prompt temperature feedback is based upon engineering the thermal resistance between the kernel and matrix. Composite matrix fuels can be designed to operate like a

* Corresponding author.
E-mail address: jiw2@rpi.edu (W. Ji).

https://doi.org/10.1016/j.anucene.2017.10.041
0306-4549/

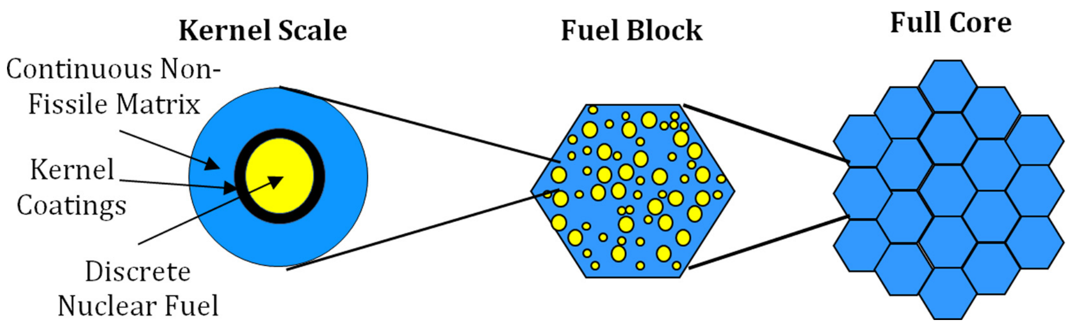

Fig. 1. Composite Matrix Fuel Overview.

metallic fuel during nominal power steady state operation letting heat move freely; but perform like a ceramic under off-nominal power transient situations keeping heat trapped in the fuel kernel. Keeping heat trapped in the fuel kernel stimulates stronger prompt temperature feedback by raising the temperature of the kernel and encouraging Doppler feedback. Fig. 2 illustrates the improved temperature feedback concept during the course of a reactivity insertion accident.

The transient begins with a large reactivity insertion. Over the course of milliseconds, the fuel kernel begins to heat. The heat is temporarily trapped within the fuel kernel for several hundred milliseconds. During that time there is a strong Doppler feedback as the temperature increases in the fuel kernel. The prompt feedback reduces the power peaking that would occur otherwise. After seconds have passed, the heat trapped in the kernel transfers into the matrix material.

There are heat transport parameters and nuclear parameters that define the behavior of a composite matrix nuclear system to a reactivity insertion accident. Fig. 3 below depicts the heat transport parameters.

In the figure, the subscript k refers to the kernel, c to the coating, and m to the matrix. The ρ represents the density and c_p the specific heat. By engineering the materials different thermal resistance can be created which in turn affect the prompt temperature feedback of the composite matrix fuel.

In addition to the thermal properties, the nuclear properties of the kernel, coating, and matrix materials are key for providing temperature feedback. Selecting kernel materials with strong

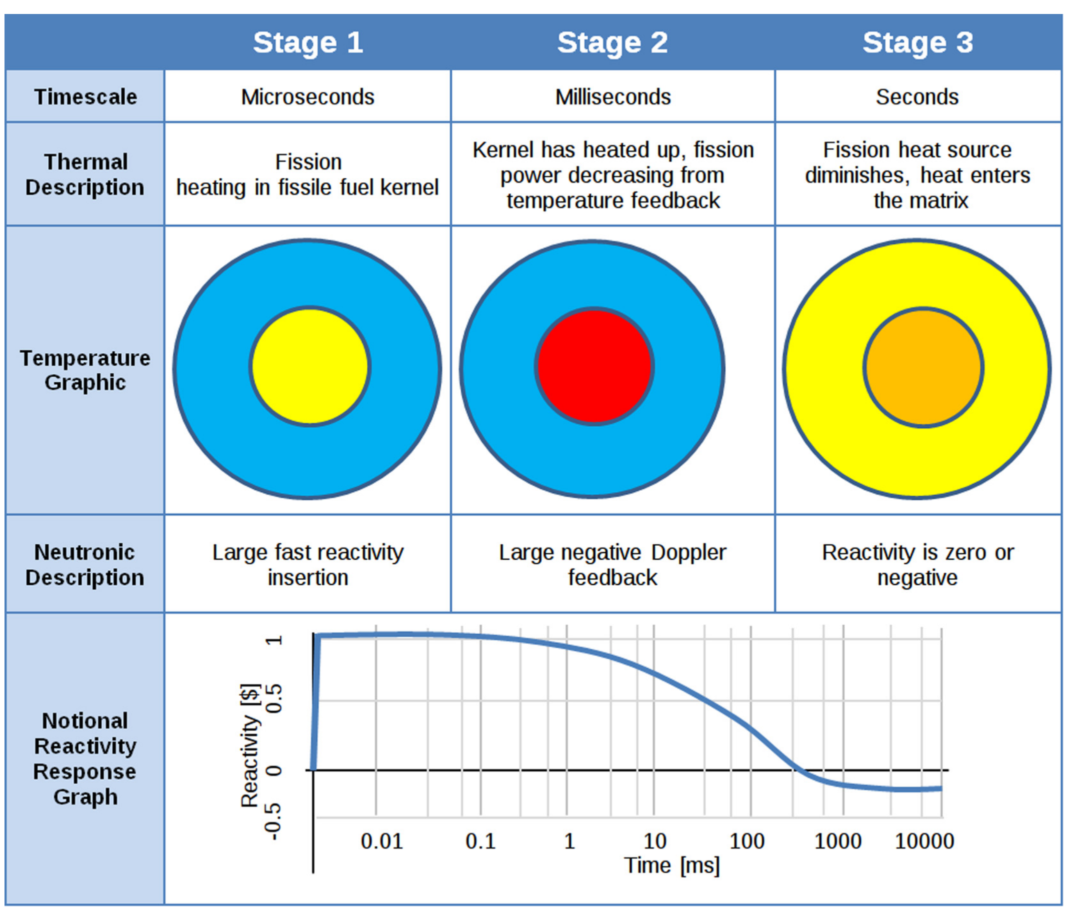

Fig. 2. Notional transient response for a composite matrix fuel with a high thermal conductivity matrix and a low thermal conductivity fuel kernel.