Issues in Modeling Metallic Fuel Systems with HT9 Clad, invited

R. Latta, J. Vollmer, M.J. Hackett, and G. Povirk
TerraPower LLC
11235 SE 6th St., Suite A-200
Bellevue, WA 98004
gpovirk@terrapower.com

INTRODUCTION

The objective of the presentation is to describe the issues associated with modeling metallic fast reactor fuel from both from a theoretical as well as experimental perspective. The presentation is organized into three parts: (1) a review of available swelling data on HT9 (Fe-12Cr-1Mo-VW) clad fuel elements that were tested in the Experimental Breeder Reactor-II (EBR-II) and comparisons of observed fuel element swelling with model predictions; (2) issues associated with modeling the thermo-mechanical behavior of fuel pins with metallic fuel; and (3) a review of data associated with element degradation caused by the diffusion of lanthanide fission products into the clad and the development of semi-empirical models used to predict this behavior. In all cases, the goal of the effort has been to develop a variety of models that are consistent with available data and that can extrapolate, with reasonable confidence, changes in behavior associated with different fuel element attributes or irradiation conditions.

DESCRIPTION OF THE ACTUAL WORK

The in-reactor behavior of fuel elements with a fuel smear density of about 75 percent and with low-swelling HT9 clad can be summarized as follows: (1) the fuel, which initially was fully-dense, becomes porous through the nucleation of fission gas bubbles and by a tearing mechanism that is associated with anisotropic growth of individual grains in the metallic fuel; (2) at a burnup of 1-2 atom percent, the porous fuel contacts the cladding; (3) up to a burnup of 8-10 atom percent, swelling of the fuel element remains minimal, which necessarily implies that the porosity in the fuel is being reduced by the accumulation of solid fission products; (4) past 10 atom percent burnup, the element begins to swell as fission gas pressure increases to the point where the clad begins to deform via irradiation creep.[1]

Thermo-Mechanical Models Of Fuel Element Behavior

Accounting for the behavior of the fuel itself is obviously a key part of any fuel performance model. Models that describe the mechanical response of fuel are complicated by the fact that the fuel becomes porous as fission gas bubbles are nucleated, solid fission products continually add solid volume to the fuel as well as altering fuel composition, eventually a fraction of the porosity links together and becomes connected to the plenum, and fuel constituents become redistributed over time. Understanding the detailed behavior of any of these phenomena from a completely fundamental perspective is not only difficult, but may result in a model of such complexity that the very basic behaviors of the fuel element are obscured. In addition, more fundamental models often have a great number of undetermined coefficients; given the paucity of performance data on HT9 clad metallic fuel elements and the approximate nature of many post-irradiation measurements, there is not likely to be data in sufficient quantities and quality to unambiguously determine all of the coefficients in a complex model.

RESULTS

A model for fuel deformation can be thought of as being developed in seven steps: (1) expressions for fission gas behavior and the accumulation of fission products; (2) observations and modeling of fission gas release; (3) expressions that describe the creep behavior of internally pressurized porous solids under the action of external loads; (4) a model for fuel with closed porosity; (5) a model for fuel with open porosity; (6) a model that estimates the combined effect of fuel with closed and open porosity; and (7) modeling the transport of thermal energy from the fuel to the coolant. The intent was to incorporate the basic physics of fuel deformation into a model that has a minimum number of undetermined coefficients.

The other principal challenge in developing models for fuel element deformation is to specify a set of relations that describe the behavior of the clad itself. HT9 steel has been supplanted by other more advanced steel alloys for use in fossil-fuel power plants. It remains of great interest for sodium-cooled fast reactors, however, because of the relatively extensive irradiation performance database from EBR-II and the Fast Flux Test Facility (FFTF), and because of its resistance to irradiation-induced swelling. Developing a model requires assembling and collating data on a variety of deformation mechanisms for HT9 and fitting that data with a physically consistent mathematical model.

Modeling Fuel Element Degradation From Lanthanide Fission Products

Fuel Clad Chemical Interaction (FCCI) in metallic fuel systems refers to chemical reaction between the fuel and clad components due to multi-component interdiffusion. Specifically, diffusion couple and irradiation experiments both demonstrate migration of clad components (Fe and Ni) into the fuel, while fission products (primarily the lanthanides like cerium, neodymium, and praseodymium) diffuse outward into the clad. FCCI leads to two primary concerns: reduction of clad mechanical properties from formation of brittle intermetallic compounds, and formation of relatively low melting eutectic compositions within the fuel and clad interface. These concerns ultimately help set performance limits for the fuel system, with the peak inner clad temperature being influenced by the low melting point (725°C) of the uranium-iron eutectic that forms at 33 at% Fe.

Although sodium-bonded metal fuel pins have been irradiated to peak burnups up to 20 at% with manageable amounts of FCCI, these irradiations typically were performed over the course of two to four years. Diffusion processes like FCCI are governed by three primary variables: concentration of the reactive species, temperature, and time at temperature. A general formula used to estimate the depth of a reaction zone for diffusion-limited processes is

$$x(t,T) = (D_0 \cdot e^{-\frac{Q}{RT}} \cdot t)^n \quad (1)$$

In this equation $x(t,T)$ is the thickness of the reaction zone, t is time, T is temperature, D_0 is the diffusion coefficient pre-exponential, Q the activation energy for diffusion, R the ideal gas constant, n is the time exponential factor (typically between 0.25 and 1), and C is a constant. This diffusion model neglects the concentration effect because it assumes a constant source term of the diffusing species (*i.e.*, the lanthanide fission products). This assumption is based on the knowledge that the lanthanide fission products tend to rapidly concentrate as secondary phases in open spaces near the perimeter of the fuel/clad interface.[2] Subsequent efforts will probe the reasonableness of this assumption, and potentially incorporate the effects of local fission product concentration.

Summary

Fuel performance modeling is difficult because of a multitude of complex behaviors, including the mechanical response of materials under irradiation, the large temperature gradients that exist within a fuel element, the accumulation and transport of solid and gaseous fission products, and the diffusion of fission products into the clad. Given the complexity of the phenomena involved, developing performance modeling tools for engineering use from a completely fundamental perspective is not possible at the current time. The approach here is to adopt fundamentally-based sub-models whenever possible, but to also use simple empirically-based sub-models when required. The overriding concern is to develop models that have both predictive capability but are also reasonably simple so that key trends in behavior can be identified and understood.

REFERENCES

[1] G.L. HOFMAN and L.C. WALTERS, "Metallic Fast Reactor Fuels, Material Science and Technology, A Comprehensive Treatment, in Nuclear Materials **10A**, 1 (1994)

[2] Y.S. KIM, G.L. HOFMAN, and A.M. YACOUT, "Migration of Minor Actinides and Lanthanides in Fast Reactor Fuel", *Journal of Nuclear Materials*, **392**, 164 (2009)