Fuel Performance Analysis of EnCore® Fuel

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ABSTRACT

The Westinghouse EnCore Accident Tolerant Fuel (ATF) program is developing various accident tolerant materials, such as U_3Si_2, UN, ADOPT™ Fuel Pellets, SiC, and coatings on zirconium based cladding. In this work, we focus on the fuel performance of the ATF fuel rod during normal operation and transient conditions.

With limited performance data available for these new ATF materials, new approaches to fuel performance and design analysis are required. This paper describes the integrated Westinghouse approach for development of advanced ATF fuel performance models using the Westinghouse Performance Analysis and Design (PAD) code supplemented by the results of multi-scale modeling of materials properties and higher fidelity analyses with the BISON code. The EnCore ATF performance improvements over traditional UO_2 fuel with Zr-based cladding are demonstrated with application of PAD and BISON codes to fuel design with U_3Si_2 fuel pellets and Chromium-coated cladding, with a focus on the typical fuel rod design limits as specified in the US NRC Standard Review Plan (SRP), Section 4.2.

1. Introduction

Following the March 2011 events at Fukushima, the development of Accident Tolerant Fuel (ATF) for light water reactor (LWR) commercial fuel applications has become a high priority for the nuclear industry. The Westinghouse EnCore ATF program is developing various accident tolerant materials, such as U_3Si_2, UN, SiC, and coatings on zirconium-based cladding. Application of the Westinghouse ADOPT fuel pellet with large grain size and higher fuel density, used widely in Boiling Water Reactors (BWRs), to near term ATF operation, is also being considered. Lead Test Assemblies (LTAs) are currently planned with Lead Test Rods (LTRs) containing combination of uranium silicide fuel pellets, ADOPT fuel pellets and/or coated Zircaloy fuel rod cladding.

While much attention has been focused on the improvement of coping time and design margin for accident conditions, fuel performance of the ATF fuel rod during normal operation and transient conditions must also be evaluated to assure the integrity of the rod during all operating conditions. This study focuses on assessment of the performance of the rod design with coated Zircaloy cladding and U_3Si_2 fuel pellets. Coated cladding significantly improves the corrosion

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and hydrogen pickup performance. U_3Si_2 fuel development is driven by its higher uranium density and anticipated improvement in thermal conductivity relative to that of uranium dioxide (UO_2).

2. ATF Fuel Performance Model/Code Development

The primary tool used for fuel rod design (FRD) and fuel performance analyses in Westinghouse is the PAD code. The PAD code has recently been updated to version PAD5 and approved by the NRC[1]. PAD5 incorporates all relevant fuel performance phenomena, including fuel thermal conductivity degradation with burnup (TCD) and enhanced fission gas bubble swelling at high burnup, as an integrated set of interrelated performance models[2][3]. The fuel performance database used in the development of the PAD5 code covered a broad range of both commercial irradiation data and test rod data obtained at conditions beyond the range of typical commercial fuel operation. Using appropriate input describing fuel rod operating conditions, PAD calculates key fuel performance parameters such as cladding stress, strain, oxidation and hydriding, fuel temperature and volume changes, and rod internal pressure.

For new fuels to be licensed and customers to have confidence in the behavior of the new materials, Westinghouse must adapt, build and revitalize PAD to accommodate these advances in technology. Surveys of the available literature on U_3Si_2, and on U-Si compounds in general, revealed that very little is known with respect to their thermo-physical and thermodynamic properties. This shortage of data challenges development and especially analysis of U_3Si_2-fueled cores under normal operation, but especially under potential off-normal conditions when more specific knowledge of the thermodynamic stability and reaction kinetics of the fuel is required. Empirical data from in-reactor testing and post-irradiation exams (PIEs) should be combined with modeling data and results to provide a mechanistic and more robust methodology to predict the behavior of these accident tolerant fuel systems in light water reactor conditions.

In the technical literature, the vast majority of the known properties for U_3Si_2 are for unirradiated conditions[4][5][6]. There are very limited data on the irradiation-induced phenomena such as swelling and fission gas release (FGR)[6][7]. The material models are under constant modification as new experimental data become available and additional lower length scale work is completed. With correlations from literature and help from atomistic/multiscale modeling, PAD, updated for ATF, incorporates extensive updates in fuel performance and material property models for U_3Si_2 fuel material: density, fuel thermal conductivity, thermal expansion, melting temperature, Young's modulus, Poisson's ratio, densification and swelling, and relocation. For coated cladding, a reduced corrosion rate is modeled in the code, while all other mechanical properties are assumed to be the same as the base Zircaloy material.

With the addition of material properties and performance models for accident tolerant fuel, the PAD code is being developed to be the primary design tool for ATF in Westinghouse. PAD now captures the first order effects of the material changes. Using appropriate input describing fuel rod operating conditions, PAD can calculate key fuel performance parameters for EnCore fuel rods, such as cladding stress, strain, oxidation and hydriding, fuel temperature and volume changes, and rod internal pressure.

While the updated PAD code is expected to be the primary design tool for ATF, the higher fidelity BISON finite element based fuel performance code developed by Idaho National Laboratory (INL)[8], based on the Multiphysics Object-Oriented Simulation Environment

(MOOSE) framework[9] and coupled to the mesoscale fuel performance code MARMOT[10], will be used to provide confirmation of the expected performance of the new fuel and cladding materials. The MOOSE finite element based framework for the solution of non-linear differential equations is adapted in BISON to model fuel rod performance. BISON can model a variety of mesh geometries (e.g., 1.5D, 2D R-Z, and 3D). High definition material property and fuel performance models for a multiple fuel and cladding materials, based on first principals to the extent possible, are built into BISON, and the modular architecture supports the addition of new models as needed.

Basic material property and performance models for U_3Si_2 are already incorporated into BISON, and improved models are under development. The industry need for advanced fuel and cladding is driving efforts to add and/or update models for ATF materials. For fuel materials such as U_3Si_2, when data is limited, multiscale modeling is being done to define basic material behaviors on an atomistic scale. Using intermediate scale modeling, these fundamental atomistic scale models are translated into engineering scale models for incorporation into BISON (Figure 1). Complex models such as fission gas transport and release, gas bubble formation and gas bubble swelling can be derived on this basis and then extended to incorporate the effects of time and burnup. With the completion of these models, BISON will be capable of predicting ATF performance over the full range of planned operation and extending the understanding of expected behaviors beyond the range of available measured data.

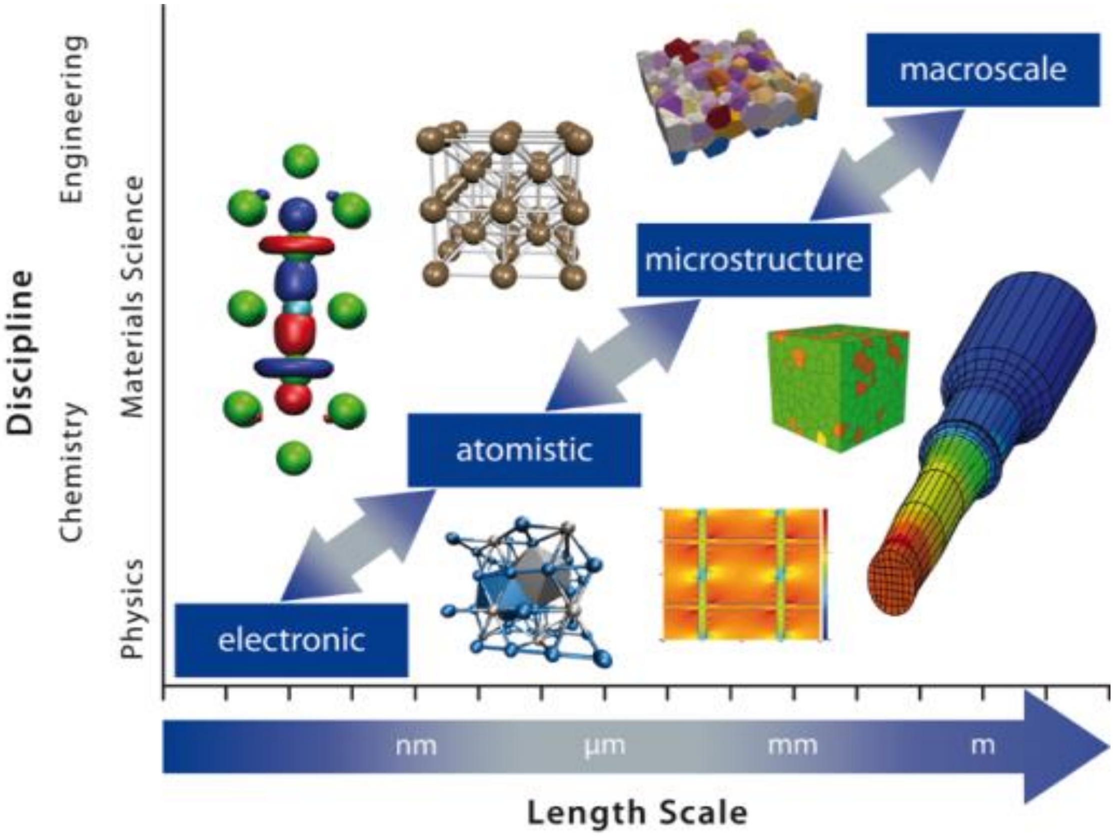

Figure 1. Multiscale Mechanistic Modeling Process

The application of BISON to ATF design is part of the Westinghouse BISON ATF Test Stand effort performed in conjunction with the US Department of Energy Consortium for Advanced Simulation of LWRs (CASL) and Nuclear Energy Advanced Modeling and Simulation (NEAMS) Programs.

3. Fuel Performance Assessment

The primary function of a fuel rod is to generate and transfer heat to the reactor coolant. In the process of generating this heat via fissioning, both radioactive and stable fission products are produced in the fuel. A second critical function of the fuel rod is to contain these fission products within the rod so that the reactor coolant does not become contaminated. To meet this goal, the structural integrity of the fuel rod must be maintained (i.e., fuel damage or penetration of fuel rod clad is to be precluded). The integrity of the fuel rods during normal operation and AOO (Anticipated Operational Occurrence) is ensured by designing the fuel rods so that specific design criteria are satisfied.

The performance analyses address the fuel rod design related aspects of the fuel system design as discussed in the US NRC Standard Review Plan (SRP), Section 4.2[11]. The performance improvements over traditional UO_2 fuel with Zr-based cladding are demonstrated with application of the PAD code to EnCore fuel design with U_3Si_2 fuel pellet and coated cladding. Key fuel performance parameters such as fuel temperature and cladding stress/strain are compared between EnCore fuel and current Westinghouse fuel in typical PWR operating conditions. Among these parameters, only fuel temperature and clad deformation (indicator for pellet cladding mechanical interaction, PCMI) results are presented. BISON results are also shown for fuel centerline temperature. For all comparisons between U_3Si_2 and UO_2 fuel, the fuel rod design parameters are based on the Westinghouse 17x17 Optimized Fuel Assembly (OFA) fuel design.

3.1. Thermal Results

The calculation of temperatures in a fuel rod is one of the primary goals of fuel element modeling. The main input data for these models are: thermal conductivity (filler gas, cladding and fuel), density (cladding and fuel), swelling rate (fuel), surface roughness and hardness (fuel and cladding), melting point (fuel and cladding), and relocation (fuel cracking and movement). The accuracy of these calculations strongly influences temperature-dependent physical phenomena such as fission gas swelling and release, thermal expansion, etc.

A comparison of the unirradiated thermal conductivity of U_3Si_2 and UO_2 as a function of temperature is shown in Figure 2. The figure indicates that for fresh fuel the thermal conductivity of U_3Si_2 is much larger than that of UO_2. Compared to UO_2, fuel temperatures will be much lower in U_3Si_2 due to a higher thermal conductivity. It should be noted that only the unirradiated thermal conductivities are plotted. Although the degradation of thermal conductivity in U_3Si_2 fuel is expected to be lower than in UO_2 fuel due to the electronic transport dominated mechanism in U_3Si_2, it cannot be quantified at this time due to the lack of measured data and/or lower scale modeling results.

Figure 3 shows the fuel temperature profile within the pellet for U_3Si_2 and UO_2 fuel. The temperature profile in the EnCore U_3Si_2 fuel is much flatter than in UO_2 fuel. This will result in less thermal stress in the U_3Si_2 fuel and hence less fuel cracking and reduced fuel relocation. The proposed U_3Si_2 is more ductile and less prone to cracking due to thermal gradients.

Figure 4 shows fuel centerline temperature as a function of power for U_3Si_2 and UO_2 fuel along with their melting temperature. U_3Si_2 fuel has a much higher Power-to-Melt (PTM) limit with respect to UO_2 because the high thermal conductivity in U_3Si_2 outweighs the lower melting temperature.

For the relatively limiting power history shown in Figure 5, a power ramp was added to the power history to simulate an AOO event. The fuel centerline temperatures are compared in Figure 6. Overall, U_3Si_2 has much lower fuel temperature than UO_2 fuel. In particular, during the ramp, the reduced temperature increase in U_3Si_2 fuel is beneficial for the mechanical performance (stress and strain) due to reduced fuel thermal expansion and less pellet cladding mechanical interaction.

BISON analyses were performed for the same fuel rod for both UO_2 and U_3Si_2 to evaluate the difference in fuel centerline temperature. Figure 7 shows BISON predicted maximum fuel centerline temperature as a function of rod average power for both UO_2 and U_3Si_2. The trends are very similar to that shown in Figure 4 for PAD.

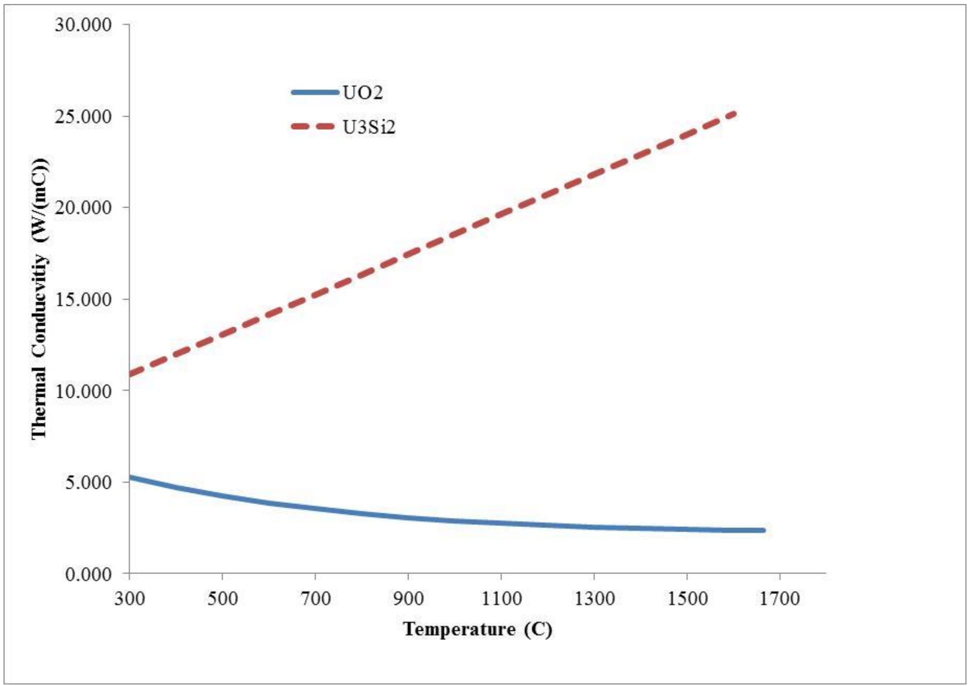

Figure 2. Comparison of the Unirradiated Thermal Conductivity of U_3Si_2 and UO_2 Fuel as a Function of Temperature

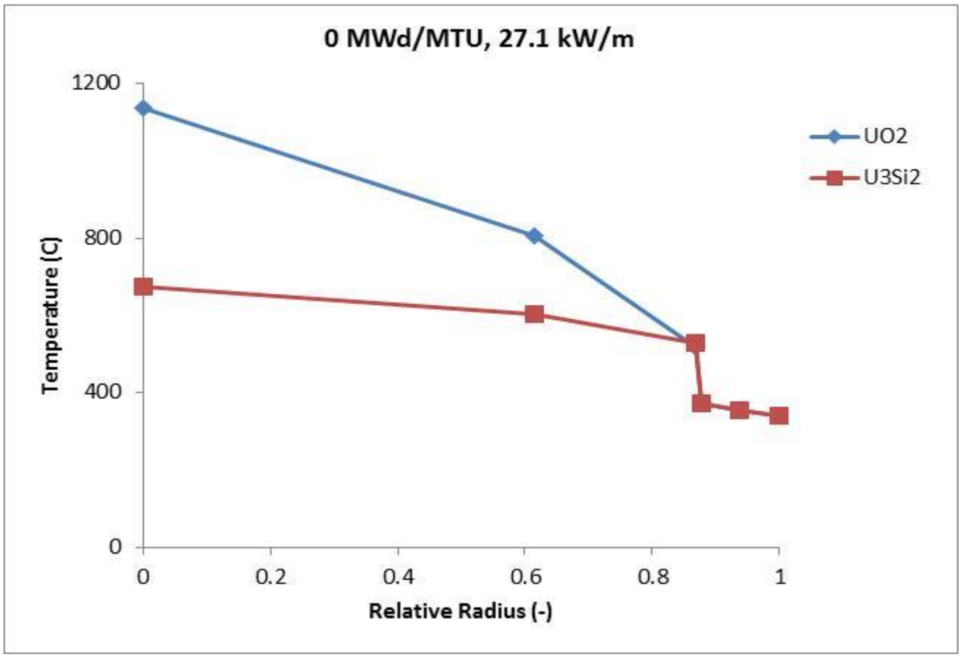

Figure 3. Comparison of the Fuel Temperature Radial Distribution of Fuel Temperature in U_3Si_2 and UO_2 fuel

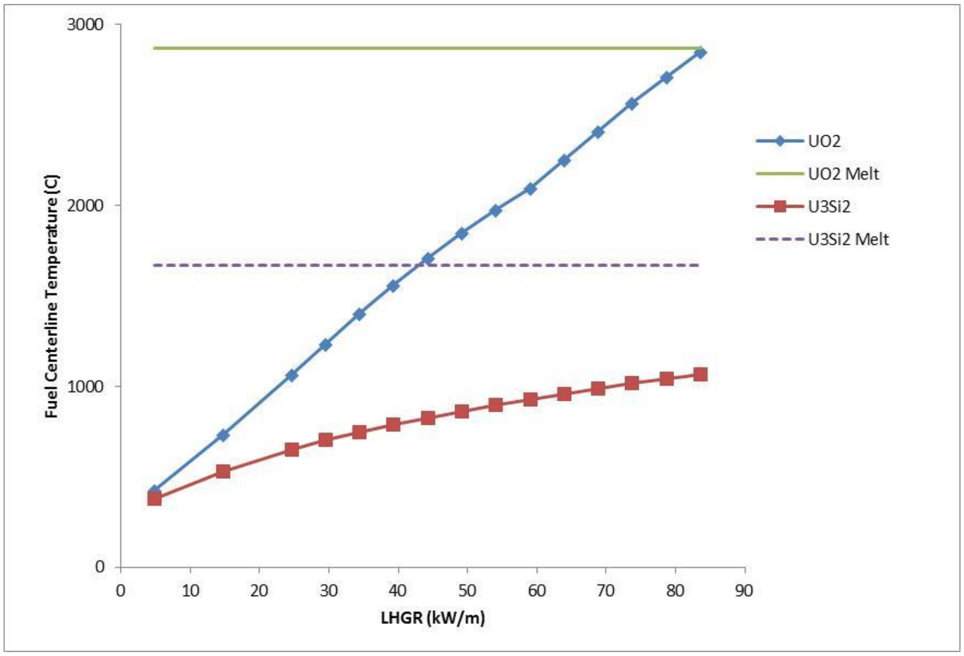

Figure 4. Comparison of the Fuel Centerline Temperature as a Function of Linear Heat Generation Rate (LHGR) for U_3Si_2 and UO_2 Fuel

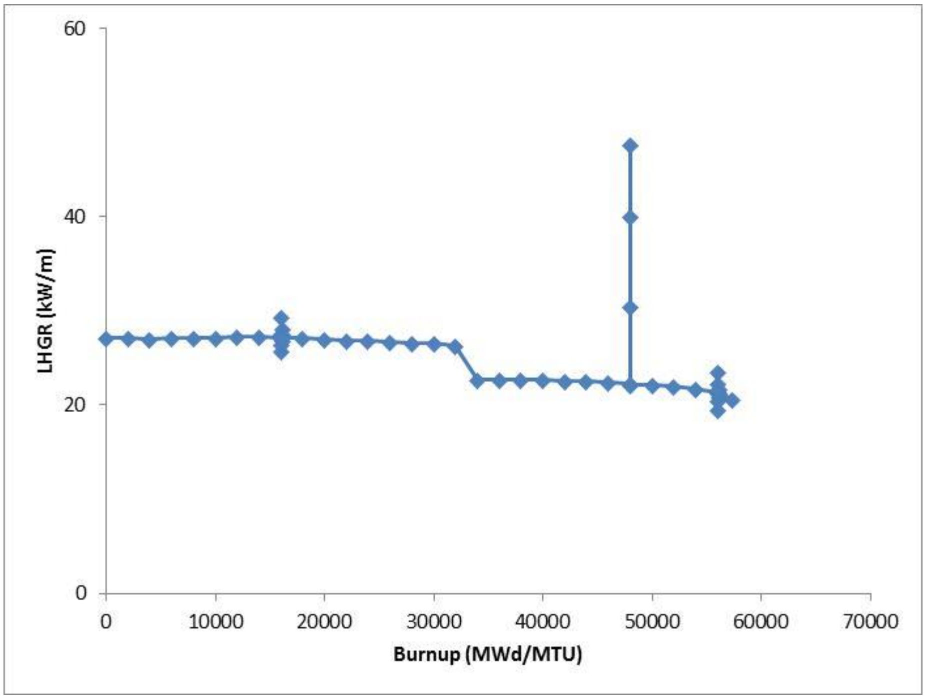

Figure 5. Sample Power History with AOO

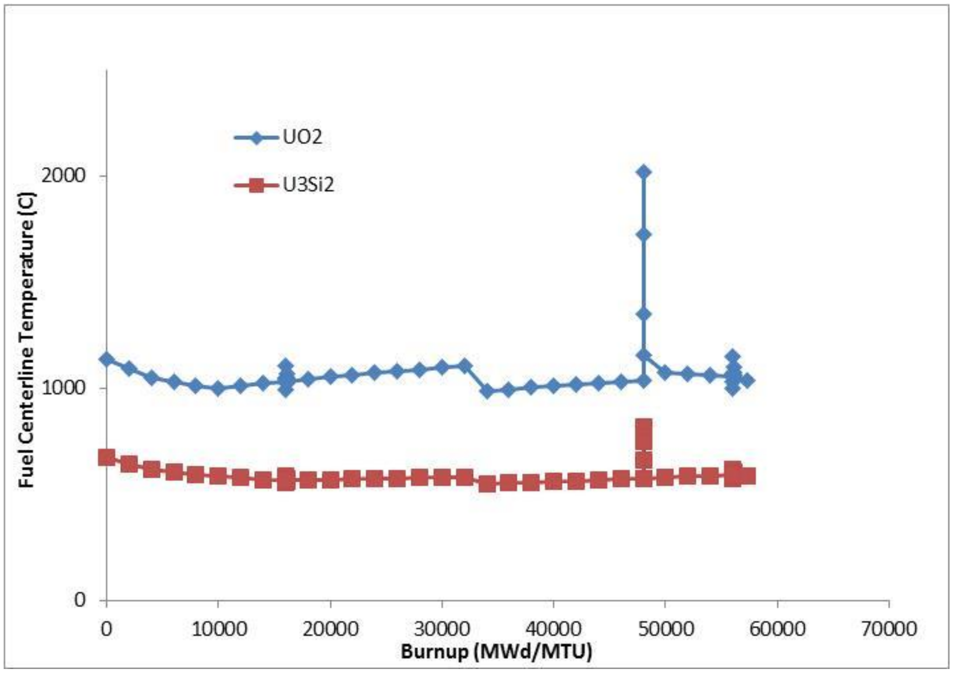

Figure 6. Comparison of the Fuel Temperature as a Function of Burnup for U_3Si_2 and UO_2 Fuel

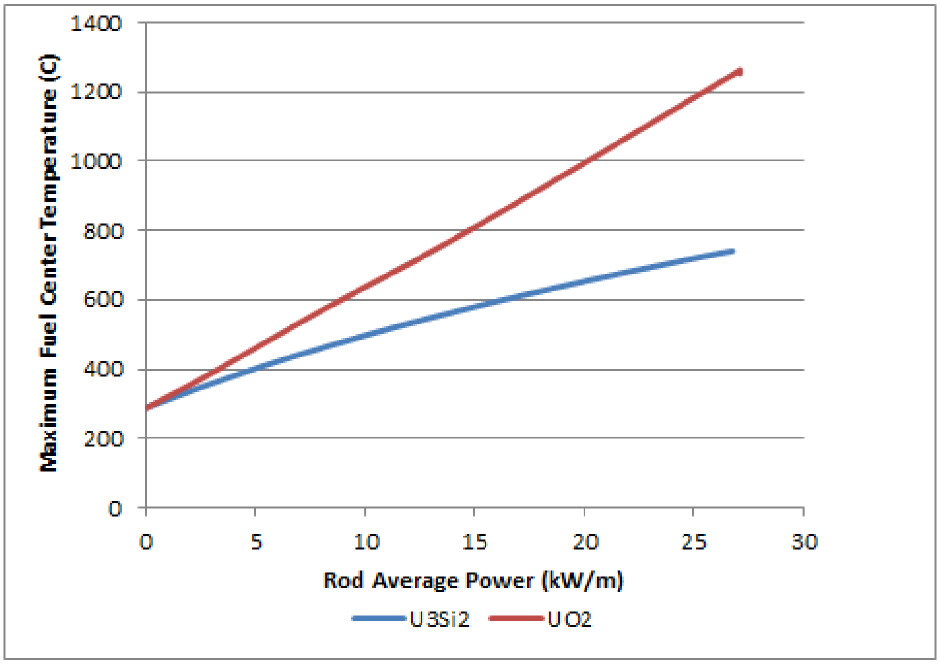

Figure 7. BISON Maximum Fuel Temperature versus Rod Average Power

3.2. Mechanical Results

The mechanical analysis consists of the calculation of stresses, strains and the corresponding deformations. The mechanical analysis is used to understand how the various changes in mechanical and physical properties affect the integrity of the fuel rod. The main models for mechanical analysis are the following: thermal expansion (clad and fuel), fuel densification and swelling, elastic-plastic properties such as Young's modulus and shear modulus (fuel and cladding), Poison's ratio (fuel and cladding), yield strength (cladding), and fission gas swelling and release. The fission gas swelling and release behavior from U_3Si_2 fuel are not yet well known. Atomistic modeling indicates that the fission gas diffusion coefficient is much higher for U_3Si_2 than for UO_2. However, the lower temperature in U_3Si_2 fuel will mitigate fuel gaseous swelling and fission gas release.

With the same power history shown in Figure 5, the cladding outer diameter result is shown in Figure 8. The decreasing diameter at low burnup is mainly from clad creep down. The spike in the diameter corresponds to the AOO event. The deformation of the cladding from the U_3Si_2 pellets during the ramp is much smaller than from UO_2 pellets due to lower fuel temperature rise (as shown in and discussed for Figure 6).

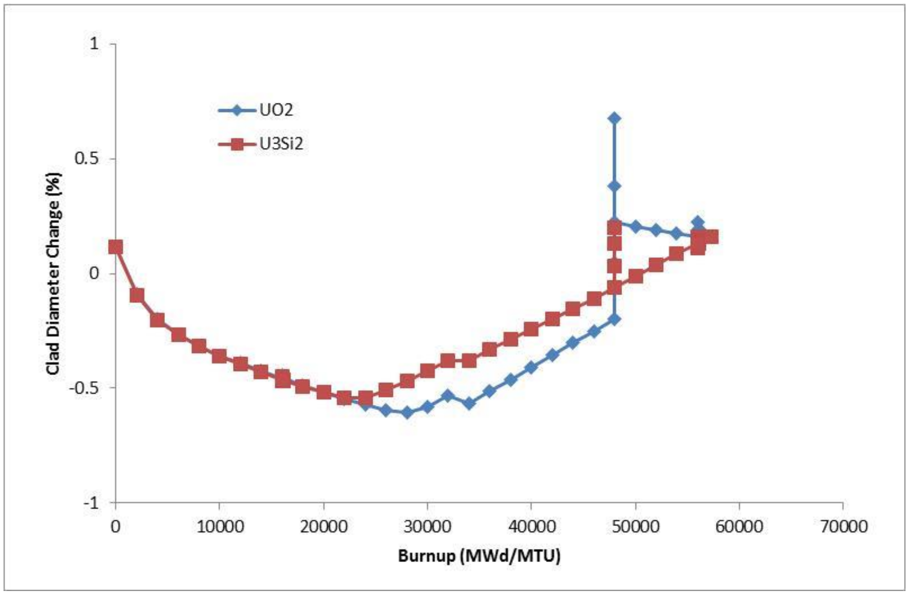

Figure 8. Comparison of Cladding Outer Diameter Change during Normal Operation and AOO

3.3. Design Criteria Assessment

The performance analyses address the fuel rod design related aspects of the fuel system design as discussed in the US NRC SRP, Section 4.2. Current FRD design criteria and licensed application methodology remain valid. There may be additional design criteria due to new ATF material, but no new failure mode has been uncovered from on-going tests. Table 1 summarizes the assessment of current design criteria based on the comparison study in Sections 3.1 and 3.2. EnCore fuel has improved design margin for the majority of the design criteria. It is noted that lower fuel temperature and rod internal pressure from normal operation are also used to initialize Loss of Coolant Accident (LOCA) and Non-LOCA safety analyses, which can therefore see improved margin as well.

Table 1. Assessment of Selected Design Criteria

FRD Criteria	Margin	Assessment
Clad Stress	Increase	Less PCMI due to low fuel temperature and pellet expansion
Clad Strain	Increase	Less PCMI
Rod Internal Pressure	Increase	Less FGR
Clad Fatigue	Increase	Less PCMI
Clad Oxidation	Increase	Coating significantly reduce the corrosion
Clad Hydrogen Pickup	Increase	Less hydrogen pickup with reduced corrosion
Fuel Rod Axial Growth	Same	No change in fuel rod growth expected

FRD Criteria	Margin	Assessment
Clad Creep Collapse	Same	No change in clad creep property
Clad Free Standing	Same	No significant change in mechanical strength
Fuel Temperature (Power-to-Melt)	Increase	High thermal conductivity outweighs lower melt temperature
Pellet/Clad interaction (PCI)	Increase	Chemical interaction should be reduced due to less stress and gas release

4. Conclusions

Westinghouse has an integrated approach for development of advanced ATF fuel performance models using the PAD code supplemented by the results of multi-scale modeling of materials properties and higher fidelity analyses with the BISON code. With the addition of materials properties and performance models for accident tolerant fuel, the PAD code is being developed as the primary design tool for ATF fuel rod design in Westinghouse. The performance improvements over traditional UO_2 fuel with Zr-based cladding are demonstrated with application of PAD and BISON codes to the EnCore fuel design with U_3Si_2 fuel pellets and Chromium-coated cladding. The improved performance of the EnCore fuel will translate into safer, more flexible and efficient plant operation.

5. References

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