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Abstract. The present paper summarizes some recent efforts related to uranium nitride composite fuel concepts, where the uranium nitride is "shielded" from water by one or more secondary phases. This work shows selected results from the analysis of advanced cladding for UN-based composite fuels with various secondary phases, including U_3Si_5, U_3Si_2, UB_2, and UB_4. These fuels are analyzed with various cladding, including Zircaloy, Stainless Steel, and several commercial alloys (Kanthal AF and APMT). Selected three-dimensional burn-up dependent equilibrium core analysis results with thermal feedback are compared for UO_2 and several UN-based composite fuels with UB_2 and UB_4. In this case, the UB_2 or UB_4 content as a tertiary phase has been optimized to match the performance of an Integral Fuel Burnable Absorber (IFBA).

1. Introduction

In the aftermath of Fukushima, the DOE-NE Advanced Fuels Campaign has supported development of advanced nuclear fuel and cladding options with potentially improved accident performance. Analytical evaluation of these fuel and cladding options is vitally important, because it identifies whether the options have at least equivalent performance as the present UO_2-Zr fuel system under nominal conditions.

An assessment of the viability and potential attractiveness of advanced nuclear fuels must include consideration of how proposed concepts will impact the nominal reactor performance and safety characteristics. This assessment includes reactor physics analyses to evaluate the impact on performance parameters (e.g., cycle length/burn-up) and safety-related characteristics (e.g., reactivity and control coefficients, kinetics parameters). BNL has developed and demonstrated a methodology to perform screening of performance and safety of candidate fuel concepts based on assembly and full-core equilibrium cycle three-dimensional reactor analyses [1 – 3]. With the post-Fukushima focus on fuels with enhanced accident tolerance for implementation in commercial light-water reactors the methodology has been refined and expanded to allow a more complete analysis of performance under a wide spectrum of potential transients and accidents, up to, but not including, Beyond Design Basis Accidents.

This paper summarizes screening efforts for uranium nitride composite fuel concepts, where the uranium nitride is "shielded" from water by one or more secondary phases. All nitride composite analyses in this paper assume 100% enrichment in ^{15}N. The use of natural nitrogen (which presents a significant reactivity penalty due to ^{14}N) has also been studied but is not presented here. This work shows selected results from the analysis of advanced cladding for UN-U_3Si_5 fuel, a fuel concept proposed by Los Alamos National Laboratory. Similar evaluations of advanced cladding have been performed at Oak Ridge National Laboratory, but focused on UO_2 fuel where the neutron energy spectrum is softer and the heavy metal loading is lower [4].

Selected equilibrium core analysis results with thermal feedback are compared for UO_2, UN-U_3Si_2, and UN-U_3Si_2-UB_4 fuels. In this case, the UB_4 content as a tertiary phase has been optimized to match the performance of an Integral Fuel Burnable Absorber (IFBA). This is highly relevant due to a recent Westinghouse patent in this area [5].

2. Analysis of SS304 Cladding with UN-U_3Si_5 Fuel

We evaluated the potential for stainless steel 304 (SS 304) cladding as a possible pairing with UN-U_3Si_5 fuel. We performed lattice-level neutronic analysis for a 17 x 17 PWR assembly with 4.9% enriched ^{235}U using the SCALE package [6] to assess the impact of these advanced cladding materials on reactivity, safety coefficients, and cycle length/burn-up. In this set of calculations, the UN phase constitutes 80% of the fuel volume, the U_3Si_5 phase 10% of the fuel volume, and the porosity is 10%. Changes in the volume percent or porosity of the individual phases will impact the specific result values. However, the qualitative physics-based conclusions remain valid. SS 304 has attractive properties relative to Zr alloy cladding, including potentially reduced oxidation rates in high temperature steam. SS 304 also has more than a decade of operational experience in LWRs, and experienced very low failure rates, especially in PWRs [7]. Five assembly level cases were compared as a function of burn-up (the fission gas gap was maintained at the same thickness for all cases):

- UO_2 with Zr alloy cladding
  - Fuel pellet outer radius (OR) = 0.4096 cm, clad thickness = 0.0572 cm
- UN – U_3Si_5 with Zr alloy cladding
  - Fuel pellet OR = 0.4096 cm, clad thickness = 0.0572 cm
- UN – U_3Si_5 with SS304-based cladding
  - Fuel OR = 0.4096 cm, clad thickness = 0.0572 cm
  - Fuel OR = 0.4096 cm, clad thickness = 0.0419 cm
  - Fuel OR = 0.4249 cm, clad thickness = 0.0419 cm

The three-batch cycle length and discharge burn-up is shown in Table 1. The infinite multiplication factor as a function of burn-up is shown in Figure 1. The initial reactivity penalty and parasitic neutron absorption in SS 304 is very high, approximately ~10,000 pcm (percent millirho) at BOL. These calculations assume a three-batch fuel management scheme with no burnable absorber loading or soluble boron and 3% neutron leakage. The ^{235}U enrichment of the fuel is 4.9% in all cases. The key result from the analysis is that the higher fissile content in UN-U_3Si_5 with 0.0419 cm thick clad compensates for the poisoning impact of the clad and matches the cycle length of the reference UO_2-Zr system. However, the discharge burn-up, and therefore the resource utilization, is reduced. The soluble boron coefficient is shown in Figure 2. The soluble boron coefficient illustrates the dual impact of spectral hardening due primarily to the increased heavy metal density of the UN-U_3Si_5 fuel and secondarily to the increased neutron absorption in the clad. Reducing the cladding thickness compensates somewhat for this impact, but increasing the radius of the fuel pellet significantly reduces soluble boron worth. This implies the need for enriched boron in the coolant.

TABLE 1. Three-Batch Cycle Length for SS 304 Cladding and UN-U_3Si_5 Fuel in Various Form Factors

Fuel - Clad	UO_2 - Zr (0.4096cm - 0.0572 cm)	UN - U_3Si_5 - Zr (0.4096 cm - 0.0572 cm)	UN - U_3Si_5 - SS304 (0.4096 cm - 0.0572 cm)	UN - U_3Si_5 - SS304 (0.4096 cm - 0.0419 cm)*	UN - U_3Si_5 - SS304 (0.4249 cm - 0.0419 cm)
Discharge burn-up (GWd/t)	61.6	60.9	45.7	50.8	45.8
Cycle length (EFPD)	533	656	492	547	571

* Note that this is the only calculation in this paper where the cladding outer diameter is modified resulting in a higher moderator-to-fuel ratio and similar performance to the case with a larger fuel pellet.

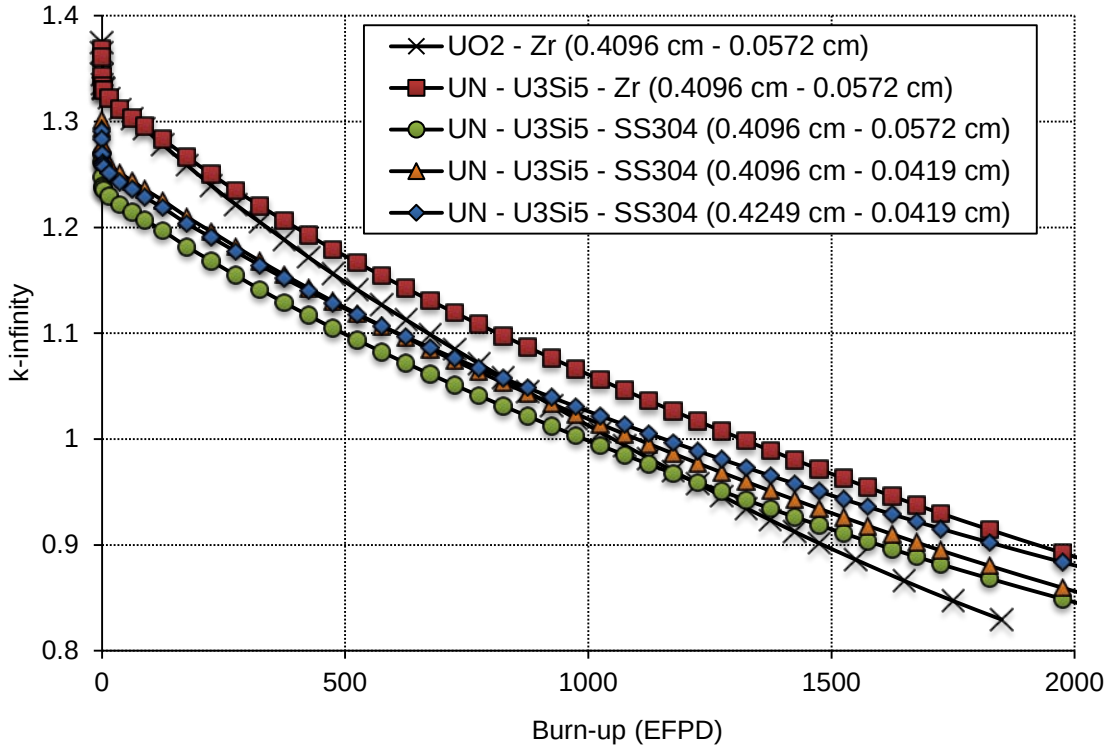

FIG. 1. Infinite Multiplication Factor as a Function of Burn-Up for SS 304 Cladding and UN-U_3Si_5 Fuel in Various Form Factors.

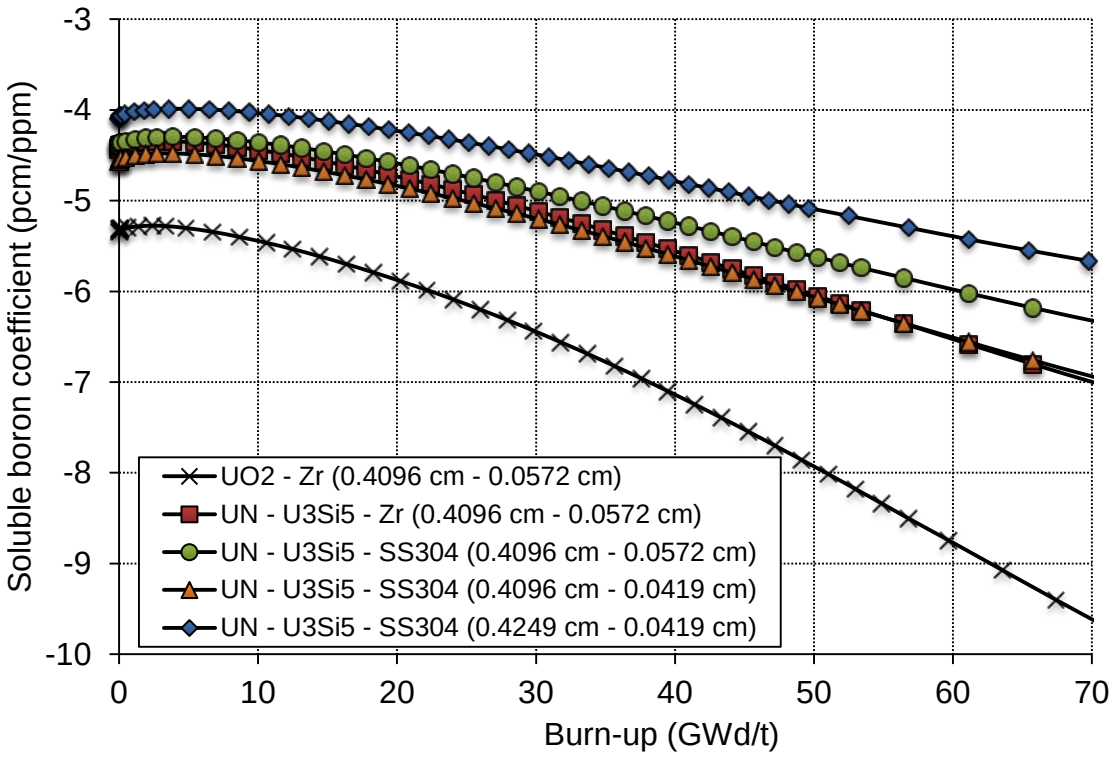

FIG. 2. Soluble Boron Coefficient as a Function of Burn-Up for SS 304 Cladding and UN-U_3Si_5 Fuel in Various Form Factors.

3. Analysis of Advanced Iron-Based Cladding Materials with UN-U_3Si_5 Fuel

Several advanced iron-based claddings are under consideration due to increased oxidation resistance versus zirconium-based cladding. We analyzed several stainless steels with significant operational history in reactors, 304 and 316. In addition, we considered two commercial alloys, Kanthal AF (referred to as FeCrAl) and Kanthal APMT (referred to as APMT). The cladding thickness for the predominantly iron-based cladding materials is 0.0419 cm versus 0.0572 cm for zirconium-based cladding. The fuel pellet thickness is increased due to this change in cladding thickness. The reduced cladding thickness is relevant given significant operational experience with iron-based cladding, such as SS304. Our analyses show that there is a large reactivity penalty due to these advanced claddings, as shown in Figure 3 plotted versus burn-up in GWd/t.

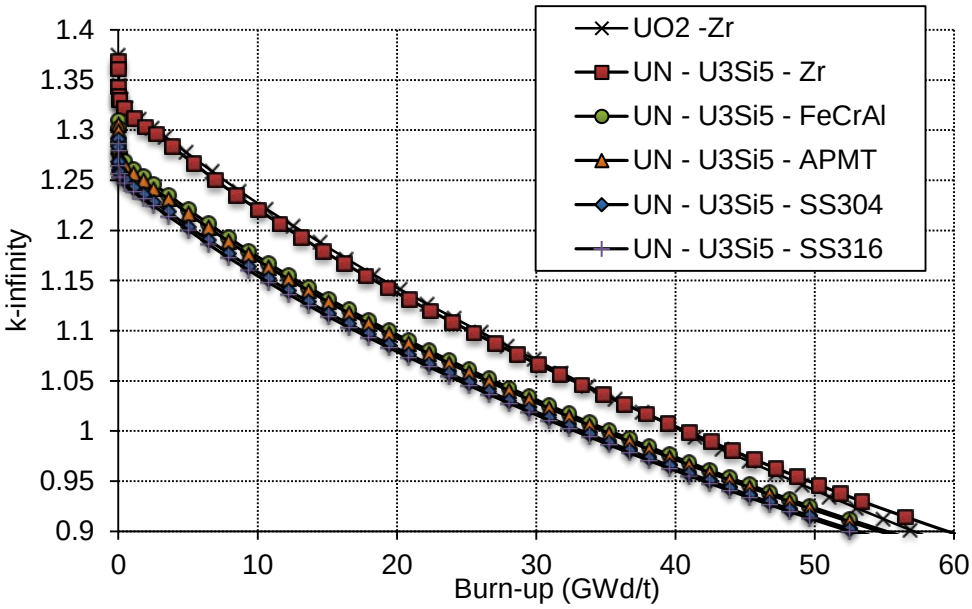

FIG. 3. Multiplication Factor vs. Burn-Up (GWd/t) for UN-U_3Si_5 Fuel and Cladding Combinations.

However, in terms of three-batch cycle length of nitride-composite fuels this reactivity penalty is compensated via the higher heavy metal loading and increased fuel pellet thickness, as shown in Table 2.

Table 2. Three- and four-batch cycle length and discharge burn-up for various advanced fuel/cladding options at 4.9%-enriched ^{235}U (nominal UO_2-Zr values are bolded).

Fuel	UO_2 - Zr	UN - U_3Si_5 - Zr	UN - U_3Si_5 - FeCrAl	UN - U_3Si_5 - APMT	UN - U_3Si_5 - SS304	UN - U_3Si_5 - SS316
Three-batch						
Batch burn-up (GWd/t)	**20.5**	20.3	17.4	17.2	16.4	16.2
Discharge burn-up (GWd/t)	**61.6**	60.9	52.2	51.5	49.2	48.5
Cycle length (EFPD)	**533**	656	604	597	570	562
Four-batch						
Batch burn-up (GWd/t)	16.4	16.1	13.7	13.5	12.9	12.7
Discharge burn-up (GWd/t)	65.7	64.3	54.7	54.0	51.5	50.8
Cycle length (EFPD)	426	519	475	469	448	442

4. Equilibrium Core Analysis for UN-U_3Si_2

We performed equilibrium core analysis of a variety of nitride composite fuel options, using a similar methodology as that described in Reference 1. This summary highlights a new proposed composite (UN-U_3Si_2-UB_4) with a tertiary component (UB_4) that has been tuned to match the performance of an assembly with 112 IFBA coated fuel rods. This type of configuration is relevant to a recent Westinghouse patent [5]. Three cases were compared in 17 x 17 assembly dimensions and an

AP1000-like core: a nominal UO_2-Zr case with 112 IFBA coated rods, a UN/U_3Si_2-Zr case with 112 IFBA coated rods, a UN/U_3Si_2/UB_4-Zr case with 5 concentric depletion zones ("rings") per fuel pin. In the UN-U_3Si_2-UB_4 case the same mass of natural boron from the 112 IFBA coatings is conserved, but is dispersed throughout all 264 of the fuel pins in the assembly as UB_4. The PARCS regulatory-grade core simulator was utilized in a full three-dimensional model of the reactor core including thermal-hydraulic/fuel temperature reactivity feedback [8]. Equilibrium cycle fuel shuffling was performed with the fresh assemblies located near the periphery of the core and the once- and twice-burned assemblies located throughout the central core region. This is a relatively high-leakage loading scheme that is necessitated due to the simplified burnable absorber loading and desire to maintain reasonable power peaking. The radial assembly peaking factors as a function of burn-up in EFPD are shown in Figure 4.

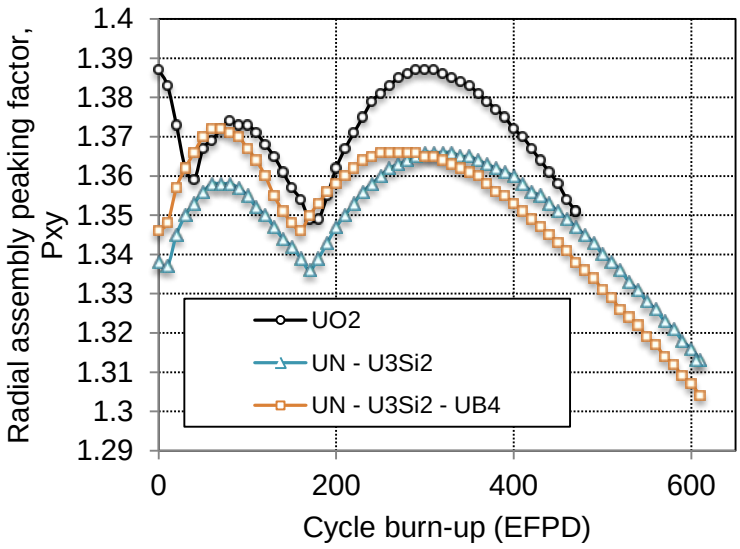

FIG. 4. Radial Assembly Power Peaking as a Function of Burn-Up (EFPD).

Radial power peaking in the core and End of equilibrium Cycle (EOC) is shown in Figure 5 for UO_2-Zr and UN/U_3Si_2/UB_4. Corresponding assembly-average fuel temperatures (assuming a gap conductance of 5,000 W/m-K) are shown in Figure 6. This analysis shows that this advanced composite fuel, even with burnable absorber integrated into the pin as a tertiary phase, can match the core performance of a nominal UO_2-Zr fuel. In addition, the fuel temperatures will be much lower due to the enhanced thermal conductivity of the fuel.

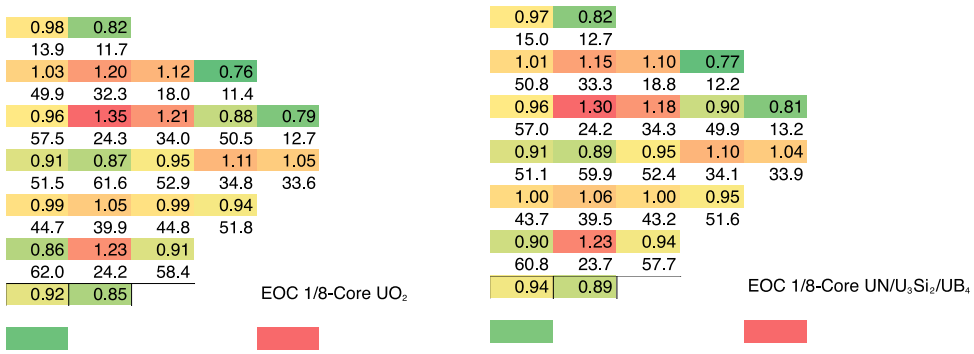

FIG 5. Radial assembly power peaking at EOC for an AP1000-like reactor core.

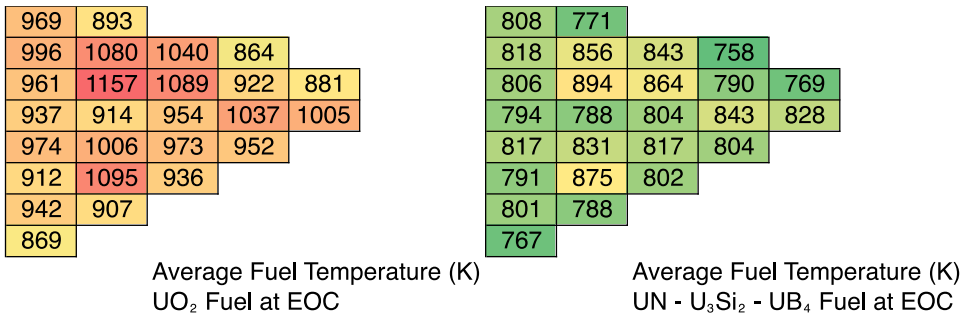

FIG 6. Assembly average fuel temperatures for an AP1000-like equilibrium reactor core at EOC.

5. Conclusions

Assuming a constant enrichment, the higher density of UN-based fuels can compensate for the parasitic absorption in Fe-based cladding in terms of cycle length in EFPD relative to the UO_2-Zr system. However, there will still be a marginal penalty in discharge burn-up in GWd/t.

The reactivity control capability of a UB_4 admixture in a UN composite fuel can closely match an IFBA coating burnable poison configuration. Admixture of UB_4 as reactivity control offers potentially enhanced flexibility for many advanced PWR fuels, and a UB_2 or UB_4 phase could even reduce the peak rod gas pressure in UO_2-based fuel pins (compared with IFBA-coating) by distributing the boron throughout an increased number of fuel rods. These results are obtained with natural boron, eliminating the need for enriched boron which is typically used in IFBAs.

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