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PWR core design with Metal Matrix Micro-encapsulated (M3) fuel

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ABSTRACT

Metal Matrix Micro-encapsulated (M3) fuel consists of TRISO coated fuel particles directly dispersed in a matrix of zirconium metal to form a solid rod. In this integral fuel concept the cladding tube and the failure mechanisms associated with it have been eliminated; therefore, M3 fuel, compared to existing fuel designs, is expected to provide greatly improved operational performance. The main challenge to the deployment of M3 fuels is the low heavy metal load. This needs to be compensated with high density fuel (uranium nitride), larger rods and mainly higher enrichment. This study found that M3 fuel requires about 15.5% enriched UN TRISO particles to match the cycle length of standard fuel when loaded in a PWR. In order to achieve comparable reactivity feedbacks, in particular moderator temperature, the pitch to rod diameter ratio should be reduced to 1.20 compared to the typical 1.326. As M3 fuel provides a better path for heat transfer from the fuel, such smaller pitch is expected to be feasible, but further evaluations especially to examine thermal-hydraulic aspects are required. Analyses of possible load patterns for burnable poisons showed that M3 fuel maintains similar cycle length to that of standard fuel and pin power peaks are also comparable. Nevertheless, further optimization will be required to limit assembly power peaks.

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1. Introduction

Metal Matrix Micro-encapsulated (M3) fuel consists of TRISO (tristructural isotropic) coated fuel particles directly dispersed in a matrix of zirconium metal to form a solid rod (Fig. 1). In this integral fuel concept the cladding tube and the failure mechanisms associated with it have been eliminated; therefore, pellet clad interactions (PCI), thin tube failure due to oxidation and hydriding, and tube pressurization and burst are absent. Grid-to-rod wear, instead, is mitigated by the high stiffness of the integral rod design, and no irradiation growth is expected due to absence of texture in the metal matrix (Terrani et al., 2012a, 2012b). For these reasons M3 fuel, compared to existing fuel designs, is expected to provide greatly improved operational performance. Multiple barriers to fission product release (ceramic coating layers in the coated fuel particle and the metal matrix) and the high thermal conductivity of the zirconium alloy metal matrix contribute to the enhanced fuel behavior. Even under design basis accident scenarios fuel performance will be superior to the conventional oxide fuel since PCI and

rod burst have been eliminated. Nevertheless, a crucial aspect to the viability of M3 fuel in light water reactors is the reduced heavy metal (HM) load compared to standard fuel design. Although, partially compensated by the use of large kernels and high density fuels like uranium nitride, the heavy metal load in M3 rods is no more than 40% of the load in standard rods. The scope of this study is to evaluate the core design requirements to operate a pressurized water reactor (PWR) with M3 fuel in order to obtain operational performance (cycle length, reactivity coefficients, and power peaking factors) comparable to that of standard fuel. This manuscript is organized as follows: Section 2 describes the state of the art of M3 fuels, Section 3 describes models and methodologies employed in this study, Section 4 provides comparative performance results for M3 and standard fuel, and Section 5 summarizes the main findings.

2. Metal matrix and micro-encapsulated fuel

Fuel performance under normal operating conditions largely impacts cost of electricity from nuclear energy. Fuel failure mechanisms in light water reactors (LWRs) are dominated by rod-to-grid fretting and more in general are associated with the degradation process of the cladding tube (Fig. 2). This explains why attempts to

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Fig. 1. Conventional pellet-clad (a) and M3 (b) fuel rod.

enhance fuel performance are mainly directed to improve cladding. The M3 fuel concept takes a new approach. It eliminates the cladding and replace the standard “pellets in tube” rod design with an integral full length rod. As a result: (1) pellet-clad interaction does not occur; (2) far larger margins are available to accommodate oxidation and wear compared to thin tubes; (3) vibration and fretting wear are reduced by the stiffness of the integral rod. The discontinuous nature of fissile material encapsulated in coated particles provides additional assistance. For instance if a M3 fuel rod is snapped into multiple pieces, only the limited number of fuel particles at the failure cross section are susceptible to release fission products. This is in contrast to the conventional oxide fuel where the presence of a small opening in the cladding provides the pathway for release of the entire inventory of fission products from the fuel rod. Under design-basis reactivity initiated accident (RIA) and loss of coolant accident (LOCA), M3 is still expected to perform

better than standard fuel since the principal failure mechanisms under such conditions, i.e. PCI in RIA, and ballooning and burst in LOCA, do not occur.

M3 fuel fabrication was successfully demonstrated at the Oak Ridge National Laboratory (ORNL) by hot pressing, hot isostatic pressing, and extrusion techniques. Rod-lets containing surrogate coated particles (with kernels made of zirconia instead of fuel) were irradiated in ORNL's High Flux Isotope Reactor up to 2×10^{25} n/m² fast fluence ($E > 1$ MeV) with no sign of deformation or damage (Terrani et al., 2012b). While conventional metal fuels (e.g. U-Zr and U-Mo) are typically expected to experience large swelling under irradiation due to the high degree of damage from fission fragments and introduction of fission gas into the lattice, this is not the case for M3 fuels. The fissile portion of the fuel is contained within the coated particle where enough room is available to accommodate fission gases and kernel swelling. The zirconium metal matrix will not be exposed to fission products and its swelling is known to be very limited when exposed solely to neutrons. Irradiation growth, instead, occurs if anisotropies are present in the crystal structure or in the grain orientation, but the fabrication techniques used for M3 fuel, in contrast with tube fabrication techniques, do not introduce any anisotropy and the observed irradiation growth is very limited.

TRISO fuel particles have been largely developed for high temperature gas reactor applications (High Temperature Gas, 2010). They consist of a spherical fuel kernel encapsulated in multiple spherical shells. The kernel is surrounded by a porous carbon layer (buffer) that provides free volume to retain gaseous fission products escaped from the kernel and absorb the kinetic energies from recoiled fission fragments. The buffer is encapsulated in three layers that have the ultimate function to retain fission products: an inner high density pyrolytic carbon layer (IPyC), a silicon carbide layer (SiC), and an outer pyro-carbon layer (OPyC). The fission products retention capability of TRISO particles has been demonstrated up to high temperature and high burnups (High Temperature Gas, 2010). M3 fuel would enable to use this technology in LWRs. BISO particles features only two layers around the fuel kernel, buffer and SiC, and could also be employed in M3 fuels. Traditionally, high temperature reactors envision the use of TRISO particles with uranium dioxide or uranium oxy-carbide fuel kernel. Due to the reduced heavy metal load, TRISO-based fuels for LWRs will require higher density fuel and efforts are ongoing to develop uranium nitride fuel kernels (Besmann et al., 2012).

Although M3 fuel is expected to provide superior performance under normal operating conditions and in design-basis accident scenarios, under beyond-design-basis accident conditions it could face a main challenge. In these scenarios fuel rods are exposed to high temperature steam (>1200 °C) for prolonged periods and in such conditions zirconium undergoes a rapid oxidation reaction with steam. Since this reaction is exothermic, heat is deposited in the fuel at a high rate (faster than the decay heat) challenging the fuel integrity. Furthermore, the steam-zirconium reaction generates hydrogen as by-product that could exacerbate accident consequences. A thin steam resistant layer (e.g., alumina forming alloy steel), integrated into the solid rod during fabrication by co-extrusion or hot isostatic-pressing, offers the potential to provide additional fuel protection from steam interaction, blanketing under a range of boiling regimes and under severe accident conditions up to high temperatures well beyond what is currently possible in the conventional fuel.

3. Models and methodology

An extensive analysis was carried to determine fuel design requirements, mainly from a neutronics perspective, in order to deploy M3 fuel in current or future PWRs. In particular this analysis

Fig. 2. Trends and mechanisms of LWR fuel failure in the United States (Edsinger).

Table 1
Properties of standard and M3 fuel.

Property	Standard fuel	M3 fuel
Material	UO ₂	UN
Density, g/cm ³	10.47	14.33
Enrichment, %	4.5	≤19.5
Pellet diameter, cm	0.82	—
Gap thickness, cm	0.017	—
Rod outer diameter, cm	0.95	0.90–1.20
Pitch-to-diameter ratio	1.326	1.05–1.40
Heavy metal load, g/rod	2075	524–931
Fissile load, g/rod	93	40–182

Table 2
Design properties of the reference PWR (Westinghouse, 2011).

Property	Value
Total power, MW	3400
Assemblies	157
Core average coolant temperature, °C	303
Pressure, bar	155
Core average coolant density, kg/m ³	719
Active length, m	4.27

evaluated M3 fuel assembly designs under the constraint that assembly dimensions (side-to-side distance and height) and fuel pins 17×17 lattice would remain the same as in conventional PWR assemblies. Performance metrics like cycle length, burnup, reactivity coefficients, etc., were determined using a single assembly model based on the AP1000 17×17 assembly design (Westinghouse, 2011). This assembly contains 264 fuel rods, 24 guide thimbles, and 1 instrumentation thimble. For comparison purposes, both standard and M3 fuels were analyzed. Standard fuel was assumed made of 4.5% enriched uranium oxide. Fuel kernels in M3 fuel, instead, were filled with uranium nitride (UN) that features higher density and partially compensate for the reduced heavy metal load (Table 1). Kernel diameter (750 μm), and thickness of buffer (70 μm), inner pyrolytic carbon (35 μm), SiC (35 μm), and outer pyrolytic carbon (35 μm), as well as TRISO packing (45%), were assumed constant. Uranium enrichment in UN was varied between 7.5% and 19.5%. The rod pitch was kept constant and equal to that in the reference design, whereas the fuel rod diameter was assumed variable.

The assembly model used reflective boundary conditions on its four sides to generate a lattice that is radially infinite, but finite in length—the model was completed with axial reflectors at the two extremities made of a mix of water and steel (50%–50% volume

mix, 100 cm height). Core parameters are summarized in Table 2. Cycle length and attainable burnup were determined from the depletion results of a single assembly averaging reactivity with the assumption of a constant power rate through the fuel lifetime (Fratoni and Greenspan, 2009). The core average reactivity at end of cycle included a positive margin large enough to account for 3% radial neutron leakage so to compensate for the radially infinite model. All results illustrated in this manuscript assume control rods completely withdrawn and do not include the steam resistant steel layer for M3 fuel, unless otherwise specified.

The assembly was reproduced using the Serpent code version 1.1.17 (Leppanen, 2012). TRISO particles were individually modeled, including all coatings, and placed in the rods according to a simple cubic lattice. Material volumes were accurately, rather than theoretically, calculated using Serpent in order to account for cut-off particles. Cross sections from the ENDF/B-VII.0 library at the following temperatures were applied: 900 K for fuel kernels and 1100 K for standard fuel pellets, 600 K for clad and coolant. Thermal scattering cross sections were applied to water and carbon in the TRISO coatings. Depletion calculations employed Chebyshev Rational Approximation Method (CRAM) and a high resolution flux spectrum based on the unified energy-grid structure to calculate one group cross sections. Number of cycles and number of histories per cycle were chosen so to maintain a standard deviation below 30 pcm for the multiplication factor.

4. Neutronics results

A preliminary evaluation of the neutronic properties of M3 fuel was performed at beginning of life. The neutron balance was evaluated in a fuel rod of same outer diameter (0.95 cm), and same rod pitch (1.26 cm), as in the reference design. Two levels were considered for M3 fuel enrichment: (1) the same level assumed for conventional fuel, 4.5%; (2) the level that matches fissile load per fuel rod of the reference conventional fuel, 16%. Table 3 shows that the low enrichment case, besides the low HM load, is also penalized by neutron absorption in the zirconium matrix. The higher enrichment case suffers the same penalties, but they are compensated by the enhanced neutron utilization in the fuel. M3 was assumed to use natural nitrogen, but nitrogen-14 (99.632% natural abundance) presents a relatively high (n,p) cross section (1.769 b at 0.0253 eV). For the matching enrichment case about 4.6% of the neutrons absorbed in the fuel are lost to nitrogen. This loss drops to 1.9% for the matching enrichment case. Further details on the effects of natural nitrogen versus enriched nitrogen-15 are discussed in Section 4.1.

Table 3
Comparison of neutronics properties of M3 and standard fuel at beginning of life.

Property	Standard fuel	M3 fuel matching enrichment	M3 fuel matching fissile
Enrichment, %	4.5	4.5	16.0
H-to-HM atom ratio	4.0	14.3	14.3
H-to-fissile atom ratio	88	314	88
k_{∞}	1.40345 ± 0.00008	1.30081 ± 0.00007	1.58776 ± 0.00006
Fuel capture-to-fission ratio	0.67	0.60	0.44
Neutron absorption, %			
Fuel	95.43	85.26	93.62
Buffer	—	0.01	0.01
IPyC	—	0.01	0.01
SiC	—	0.29	0.12
OPyC	—	0.02	0.01
Matrix	—	3.09	1.79
Clad	0.91	0.15 ^a	0.09 ^a
Water	3.66	11.17	4.36

^a Absorption in thimbles.

Fig. 3. Comparison of neutron spectrum in M3 and conventional fuel at beginning of life.

Fig. 3 compares neutron spectrum in conventional and M3 fuel. Matching the fissile load generates similar spectrum even if the moderator-to-fuel ratio is considerably larger in M3 fuel.

4.1. Cycle length and burnup

M3 fuel is expected to carry numerous improvements to fuel performance, but a very important requirement to enable deployment in current and future PWRs is to match or exceed the cycle length of conventional fuel. A parametric analysis determined attainable cycle length as function of fuel enrichment and fuel rod outer diameter. This analysis was carried under the assumption that the fuel enrichment could exceed the current commercial limit of 5%, but could not exceed the low enrichment limit of 20%. It was also required that M3 fuel would maintain the current 17×17 assembly geometry. **Fig. 4** and **Fig. 5** illustrate the results of the parametric analysis for cycle length and burnup. Uranium enrichment was varied between 7.5% and 19.5%, and the pitch-to-diameter ratio (P/D) from 1.05 to 1.40. This range was covered

Fig. 4. Cycle length (EFPD) for M3 fuel in PWRs as a function of pitch-to-diameter ratio and enrichment.

Fig. 5. Attainable burnup (GWd/tHM) for M3 fuel in PWRs as a function of pitch-to-diameter ratio and enrichment.

varying the fuel rod outer diameter while keeping the pitch constant. The reference PWR conventional fuel features 452 EFPD (effective full power days) cycle length and a total 52.1 GWd/tHM burnup at discharge. In order to achieve the same cycle length M3 fuel requires about 15.5% initial enrichment with P/D less than or equal to 1.20. With a P/D equal to the reference design (1.326) the maximum cycle length, corresponding to the maximum enrichment allowed in this study (19.5%), is slightly shorter at 439 EFPD. If a 100 μm -thick steam-resistant layer (i.e., FeCrAl) is added to M3 fuel, the cycle length is shortened by about 15 EFPD and an additional 0.5% enrichment increase is necessary to maintain the same cycle length. Such enrichment requirements correspond to an increase between threefold and fourfold compared to conventional fuel. On the other hand M3 fuel operates at higher specific power—110–140 W/gHM vs. 38.5 W/gHM—and achieves burnup between 150 and 180 GWd/tHM. As a result a 3400 MWth PWR operating at 90% capacity factor would require about 7–9 tHM per year if loaded with M3 fuel, instead of about 26 tHM/yr required for standard fuel. **Fig. 6** shows SWU (separative work units) as a function of P/D and

Fig. 6. Separative work for M3 fuel as a function of pitch-to-diameter ratio and enrichment, normalized to separative work for standard fuel (132 g-SWU/MWd). Calculations assumed 0.25% ^{235}U concentration in the tails and 0.711% in natural uranium.

Table 4
Comparison of discharged fuel composition (kg/GWd).

Nuclide	Standard fuel	M3 fuel P/D 1.20 enrichment 15.5%	M3 fuel P/D 1.326 enrichment 19.5%
^{235}U	0.157	0.109	0.077
^{236}U	0.117	0.1582	0.158
^{238}U	17.623	5.272	4.119
^{237}Np	0.014	0.016	0.014
^{239}Pu	0.115	0.040	0.024
^{240}Pu	0.056	0.022	0.016
^{241}Pu	0.034	0.016	0.010
^{241}Am	0.001	0.000	0.000
Total HM	18.150	5.656	4.443
Total fissile	0.306	0.164	0.110
Fission products	1.032	1.033	1.034

enrichment normalized to SWU for standard fuel (132 g-SWU/MWd). Designs with M3 fuel that match cycle length, require 60% or more SWU. M3 fuel also requires at least 20% more fissile (about 1.04 kg vs. 0.86 kg per thermal GWd) as breeding of ^{239}Pu and ^{241}Pu from ^{238}U is less effective. At the end of life, indeed, fissile (^{235}U , ^{239}Pu , and ^{241}Pu) content is half or less than in standard fuel (Table 4). A benefit of the higher enrichment, instead, is a reduction in the mass of transuranics to be disposed of.

4.2. Burnable poisons

Typically in PWR the reactivity excess is compensated adding burnable poisons to the fuel and soluble poisons to the coolant (Secker and Brown, 2010). Multiple schemes are possible and currently an extensive evaluation of poison options is undergoing. This Section presents results for selected cases. The chosen reference model features 104 rods coated with IFBA (Integral Fuel Burnable Absorber), 50 μm thick, made of ZrB_2 (1688 kg/m^3) and natural boron, corresponding to 0.77 $\text{mg}/\text{cm}^{10}\text{B}$ load. The M3 fuel assembly employs boron nitride (BN, 1.9 g/cm^3) as burnable poison. This is uniformly mixed (1.7% volume fraction) to the fuel in all kernels, with two levels of boron-10 enrichment: 50% contained in 104 rods (those corresponding to the IFBA rods in the standard fuel assembly) and 19.9% (natural) in all other rods (Fig. 7). The

Fig. 7. Layout of the high ^{10}B content rods in the M3 fuel assembly replicating IFBA rods layout in standard fuel assemblies.

Fig. 8. Comparison of infinite multiplication factor as a function of depletion time in standard and M3 fuel (15% enrichment, P/D 1.20) with and without burnable poison.

corresponding ^{10}B load varies, respectively, from 0.6 to 1.1 mg/cm and from 0.2 to 0.4 mg/cm , depending on the rod diameter. Fig. 8 shows that similar cycle length can be obtained with the burnable poison distributions considered, but M3 fuel experience higher reactivity peaks that could imply larger power peaks across the core and need to be further investigated in a full core model.

Figs. 9 and 10 show the power distribution within the assembly at beginning of life (BOL) and end of life (EOL) for standard fuel and the M3 fuel assembly design as above. The maximum pin power peaking factor is similar (about 1.07) and in both cases occurs at the EOL.

4.3. Reactivity coefficients

Reactivity coefficients were calculated for numerous M3 fuel assembly designs at two levels of enrichment (15% and 19.5%), as well as standard fuel. Fuel temperature coefficient (FTC) was calculated increasing the fuel kernel temperature by 100 K. Moderator temperature coefficient (MTC) was calculated increasing the coolant temperature by 10 K and reducing the coolant density accordingly (from 719 kg/m^3 to 696 kg/m^3). Coolant void coefficients were calculated for both small void (SVC) and large void (LVC) reducing the coolant density by 5% and 90%, respectively, while keeping the nominal coolant temperature. Tables 5 and 6 show that reactivity coefficients at beginning of life (BOL) and end of life (EOL) for M3 fuel are negative and comparable to those of conventional fuel when P/D $\approx$ 1.30 or less. Although it might appear surprising that coolant-related feedbacks remain negative considered the much larger moderator-to-heavy metal atom ratio in M3 fuel compared to conventional fuel, the actual driver of those feedbacks is the moderator-to-fissile atom ratio, and this is similar in both fuel designs.

The results illustrated above did not account for soluble poison dispersed in the coolant as at this stage accurate let-down curves have not been established. Nevertheless, the sensitivity of the reactivity coefficients to boron concentration in the coolant was evaluated. Figs. 11 and 12 show coolant small and large void reactivity coefficients as a function of boron concentration and in core residence time. The large rods design (P/D 1.20) maintains negative coefficients, whereas the small void coefficient turns positive towards end of life for the standard rod size design (P/D 1.326). This might be of concern and needs to be addressed in a full core model.

Fig. 9. Pin-by-pin power distribution (pin to pin average power ratio) in a standard fuel assembly.

Fig. 10. Pin-by-pin power distribution (pin to pin average power ratio) in a M3 fuel assembly.

Table 5

Fuel and coolant temperature reactivity coefficients for standard fuel and M3 fuel at beginning and end of life.

Fuel	P/D	FTC, pcm/K		MTC, pcm/K	
		BOL	EOL	BOL	EOL
Standard	1.326	-1.74 ± 0.04	-3.49 ± 0.13	-31 ± 1	-76 ± 1
M3 15% enrich.	1.050	-2.40 ± 0.13	-4.56 ± 0.46	-37 ± 1	-101 ± 5
	1.100	-1.37 ± 0.11	-4.50 ± 0.47	-30 ± 1	-100 ± 5
	1.200	-1.66 ± 0.09	-3.16 ± 0.50	-23 ± 1	-66 ± 5
	1.300	-1.35 ± 0.08	-2.99 ± 0.51	-17 ± 1	-45 ± 5
	1.400	-1.33 ± 0.07	-2.36 ± 0.48	-8 ± 1	-8 ± 5
M3 19.5% enrich.	1.050	-1.71 ± 0.04	-4.15 ± 0.15	-32 ± 1	-94 ± 2
	1.100	-1.83 ± 0.03	-3.93 ± 0.16	-30 ± 1	-96 ± 2
	1.200	-1.49 ± 0.03	-3.34 ± 0.18	-24 ± 1	-72 ± 2
	1.300	-1.06 ± 0.02	-3.07 ± 0.16	-18 ± 1	-46 ± 2
	1.326	-1.11 ± 0.02	-2.57 ± 0.17	-15 ± 1	-34 ± 2
	1.400	-0.98 ± 0.02	-2.44 ± 0.18	-11 ± 1	-13 ± 2

Table 6

Small and large coolant void reactivity coefficients for standard fuel and M3 fuel at beginning and end of life.

Fuel	P/D	SVC, pcm/void%		LVC, pcm/void%	
		BOL	EOL	BOL	EOL
Standard	1.326	-97 ± 1	-244 ± 3	-477 ± 1	-961 ± 1
M3 15% enrich.	1.050	-109 ± 3	-301 ± 9	-300 ± 1	-721 ± 1
	1.100	-94 ± 2	-274 ± 9	-317 ± 1	-1067 ± 1
	1.200	-67 ± 2	-205 ± 10	-312 ± 1	-1349 ± 1
	1.300	-43 ± 2	-129 ± 10	-300 ± 1	-1325 ± 1
	1.400	-32 ± 2	-28 ± 10	-280 ± 1	-1123 ± 1
M3 19.5% enrich.	1.050	-105 ± 1	-295 ± 3	-220 ± 1	-614 ± 1
	1.100	-98 ± 1	-295 ± 3	-245 ± 1	-977 ± 1
	1.200	-75 ± 1	-240 ± 4	-253 ± 1	-1340 ± 1
	1.300	-55 ± 1	-140 ± 3	-256 ± 1	-1389 ± 1
	1.326	-49 ± 1	-119 ± 3	-251 ± 1	-1355 ± 1
	1.400	-37 ± 1	-42 ± 4	-248 ± 1	-1226 ± 1

Fig. 11. Coolant small void reactivity coefficient as a function of boron concentration in the coolant for selected M3 fuel assembly designs.

Fig. 12. Coolant large void reactivity coefficient as a function of boron concentration in the coolant for selected M3 fuel assembly designs.

A change in the physical conditions of the matrix in M3 fuel could also potentially cause a reactivity feedback. These effects were evaluated considering two separate changes: (1) increase of the matrix temperature only; (2) increase of the matrix temperature and consequent volumetric expansion. Increasing the temperature of the matrix has no significant effect on reactivity (-0.04 pcm/K). For the volumetric expansion it was assumed that rods are axially constrained and only expand radially. The linear thermal expansion coefficient was estimated to be $6.80 \mu\text{m/m}^\circ\text{C}$ at 600 K (Whitmarsh, 1982). The feedback of the volumetric expansion combines the effect of reduced M/F and that of increased axial leakage, but due to the single assembly model, it does not account for radial leakage. The reactivity change was found to be relatively constant through the fuel life and equal to about -0.15 pcm/K.

4.4. Design options for reducing enrichment

Within the constraints of maintaining the current assembly geometry, some design solutions could be implemented to further reduce the uranium enrichment for M3 fuel. In particular two options could be considered: (1) enriched nitrogen, and (2) long fuel rods. Fig. 13 shows the gain in cycle length when 100% ^{15}N is used for

Fig. 13. Difference in cycle length between enriched and natural nitrogen fuel as a function of uranium enrichment and P/D.

Fig. 14. Cycle length for long M3 assemblies as a function of uranium enrichment and P/D.

the fuel kernel, instead of natural nitrogen. The cycle length increases by 10 and 20 EFPD for standard and reduced P/D, respectively. The increment is slightly less for higher enrichment.

In M3 fuel fission products are retained by the coatings of the TRISO particles and the integral rod concept eliminates the need for a clad and together with it of a gas plenum. In current analysis it was assumed that the core active length remains as in the reference design. Nevertheless, gas plenum regions are not needed in this case and the active length of each pin could be extended within this region. In the AP100 upper and lower plena extend for a total of about 29 cm (Westinghouse, 2011). Conservatively it was assumed that the active length of M3 fuel rods could be extended by 25.4 cm. This implies a 6% increase in the heavy metal load. Fig. 14 shows that the cycle length can be extended up to about 33 EFPD using long rods. The benefit increases slightly reducing the P/D and increase considerably increasing enrichment.

Comparing these results with the parametric analysis illustrated in Section 4.1 Fig. 4, it is estimated that combining enriched nitrogen and longer rods, the fuel enrichment could be reduced by about 1–2%.

5. Conclusions

M3 fuel consists of TRISO particles dispersed in a zirconium metal matrix to form a full length integral fuel rod. Such design eliminates the clad and all its failure mechanisms; therefore, it is expected to offer greatly improved performance in nominal and design basis accident conditions when compared to standard pellet-clad fuel. Because of the nature of TRISO particles, the volume available for fuel is only a fraction (~14%) of the rod volume. In order to sustain acceptable fuel cycles, the fissile density in the core

must be boosted with high density fuel (uranium nitride), large fuel rods, and mainly high fuel enrichment. It was found that M3 fuel requires at least 15.5% enriched UN TRISO particles to match the cycle length of standard fuel when loaded in a PWR. The threefold increase in enrichment is partially compensated by high specific power and high burnup. As a result M3 fuel requires about 60% more SWU than standard fuel, and about 20% more fissile. Although M3 fuel is likely to be more costly than standard fuel, the advantages deriving from an enhanced reliability in nominal and design basis accident conditions may, at least partially, offset the higher costs. Furthermore, in order to achieve comparable reactivity feedbacks, in particular moderator temperature, the pitch-to-rod diameter ratio should be reduced to 1.20 compared to the typical 1.326. As M3 fuel provides a better path for heat transfer from the fuel, such smaller pitch is expected to be feasible, but further evaluations especially to examine thermal hydraulic aspects are required. Analyses of possible load patterns for burnable poisons showed that M3 fuel maintain similar cycle length to that of standard fuel and pin power peaks are also comparable, but further optimization is required to limit assembly reactivity peaks. Reactivity feedbacks remain acceptable when accounting for soluble poisons only for assembly designs with larger rods (P/D 1.20 or less). The results obtained in this study do not consider a steam-resistant protective layer on the outer surface of the fuel rod. It is estimated that a 100- μ m layer of alumina-forming steel reduces the cycle length by about 15 EFPD, thus it would require an additional increase in enrichment of about 0.5%. A detailed evaluation of the impact of the steam-resistant layer will be necessary once the requirements for thickness and composition have been established. To further assess the viability of M3 fuel, future work will also consider detailed full core models for addressing assembly power peaks and soluble poison requirements, and heat transfer and thermal hydraulic models for evaluating the feasibility of large M3 fuel rods.

References

- Besmann, T.M., Shin, D., Lindemer, T.B., 2012. Uranium nitride as LWR TRISO fuel: thermodynamic modeling of U-C-N. *J. Nucl. Mater.* 427 (1–3), 162–168.
- Edsinger, Kurt, 2010. EPRI and the zero fuel failures program. *Nucl. News* 53 (13).
- Fratoni, M., Greenspan, E., 2009. Neutronic design of hydride fueled BWRs. *Nucl. Eng. Des.* 239, 1531–1543.
- High Temperature Gas Cooled Reactor Fuels and Materials, Tech. Rep. IAEA-TECDOC-1645, International Atomic Energy Agency, Vienna (2010).
- Leppanen, J., 2012. PSG2/Serpent - a Continuous-energy Monte Carlo Reactor Physics Burnup Calculation Code. Tech. rep., VTT Technical Research Centre of Finland.
- Secker, J.R., Brown, Jeffery A., Nov. 2010. Westinghouse PWR Burnable Absorber Evolution and Usage.
- Terrani, K.A., Snead, L.L., Gehin, J.C., 2012. Microencapsulated fuel technology for commercial light water and advanced reactor application. *J. Nucl. Mater.* 427 (1–3), 209–224.
- Terrani, K.A., Kiggans, J.O., Snead, L.L., 2012. Fabrication and preliminary evaluation of metal matrix microencapsulated fuels. *J. Nucl. Mater.* 427 (1–3), 79–86.
- Westinghouse AP1000 Design Control Document Rev. 19, Westinghouse Electric Company LLC, 2011, Ch. 4. Reactor.
- Whitmarsh, C.L., Jul. 1982. Review of Zircaloy-2 and Zircaloy-4 Properties Relevant to n.s. Savannah Reactor Design. Tech. Rep. ORNL-3281.