TRANSITION CYCLE ANALYSIS FOR OPTIMUM ATF IMPLEMENTATION IN CURRENT PWRs

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ABSTRACT

Fuel designs using advanced, accident tolerant fuel materials can improve fuel efficiency and extend fuel management capability in addition to improving safety margins for LWRs. The concepts proposed by Westinghouse include Cr-coated cladding, which enhance corrosion resistance, and can improve accident tolerance, and higher density higher thermal conductivity U_3Si_2 fuel, which improves reactor performance and reduces fuel cost. Because of the increased density, the use of U_3Si_2 also extends the energy output and cycle length capability for PWR fuel assemblies while remaining below the 5 w/o enrichment limit for commercial fuel. The Westinghouse ATF can thus either decrease the fuel cycle cost of 18-month cycles by reducing the number of feed assemblies and increasing fuel utilization, or it can make 24 month cycles economical for today's uprated, high power density PWRs. This paper focuses on the implementation of the Westinghouse ATF into current PWRs operating on UO_2 fuel and 18-month cycles transitioning to either 18-month or 24-month cycles with ATF. Economic analysis shows that the Westinghouse ATF has very favorable economics not only at the ATF equilibrium cycle but also during the transition cycles from UO_2 to ATF, especially when transitioning to a 24-month cycle operational regime, which thus represents the recommended path forward for implementation.

KEYWORDS: Accident Tolerant Fuel, Transition Cycles, Fuel Management

1. Introduction

Cladding improvements to reduce high temperature corrosion and fuel pellet improvements to increase thermal conductivity are under active investigation to further improve LWR safety while reducing fuel costs. Cr-coated Zr-based cladding has been identified as a potential cladding material that is less susceptible to high temperature corrosion and hydrogen pick up than the standard Zircaloy cladding, with only a small neutronic penalty deriving from the application of the coating. Fuel pellet materials such as U_3Si_2 show improved thermal conductivity compared to UO_2 and will operate at lower temperatures. In addition to improving safety, use of these materials can also increase fuel efficiency and reduce fuel cycle costs, primarily as a result of the higher uranium density associated with these pellet materials which ultimately allows better fuel usage, e.g. the number of feed assemblies per reload can be reduced compared to traditional UO_2 schemes. In addition, the higher uranium density can extend the core operating capability compared to current fuels, while maintaining the current 5 w/o ^{235}U enrichment limit for commercial fuel, yet enabling economically competitive fuel management schemes for the longer cycles. Past studies have discussed the ATF fuel cycle economics improvements for representative equilibrium cycle conditions [1-3]. This study focuses on a realistic analysis of actual ATF implementation scenarios in PWRs, including the transition cycles from UO_2 to ATF and the associated fuel cost economics.

In particular, the introduction of ATF in a current 18-month cycle high-power density PWR to accomplish a transition from UO_2 to ATF either maintaining the currently predominant 18-month cycle operational regime, or extending it to 24-month will be analyzed. Implementing the Westinghouse ATF to achieve a more cost effective 18-month cycle will deliver fuel cost savings thanks to the resulting fewer fresh assemblies per reload and improved fuel utilization that it entails. Implementing the Westinghouse ATF in conjunction with a transition to 24-month cycle will yield economic benefits thanks to the resulting reduced number of outages and related savings, which offset the slightly higher fuel costs than at the 18-month cycle. In addition, it will be shown that the impact of the transition cycles when ATF is implemented in conjunction with a transition to 24-month cycle is significantly reduced than when ATF is implemented maintaining the 18-month cycle operational regime.

This paper is based on 3D core analysis with viable fuel management schemes modeled using the Westinghouse PARAGON2/ANC PWR core analysis package [4,5]. A 4 loop, 193 assembly core at a 3,587 MWt power rating was assumed as representative for the analysis. 502 and 680 Effective Full Power Days (EFPDs) of operation characterizing respectively the 18 and 24-month cycle have been assumed.

2. ATF Pellet Design Options

Table 1 summarizes pellet outer diameter, moderator-to-fuel ratio, expressed as atoms of hydrogen to atoms of uranium ('H/U'), the kg of uranium per fuel assembly and the percent delta in kg of uranium per assembly with respect to the UO_2 17x17 Robust Fuel Assembly design, the predominant fuel option for Westinghouse 4-loop PWR fuel offering. It can be seen that replacing UO_2 with U_3Si_2, as shown in the U_3Si_2 RFA design option in Table 1, increases the uranium content of the assembly by 17%. This large uranium increase is obviously desirable to enable more efficient fuel management schemes, but the resulting decrease in H/U, from ~4.0 in UO_2 RFA to ~3.3 in U_3Si_2 RFA, excessively penalizes neutron moderation and thereby utilization of the initial fissile content of the fuel. An increase in hydrogen content of the lattice, e.g. by reducing the pellet diameter, is thus appropriate to counterbalance the higher uranium density and restore adequate neutron moderation. For this reason, two alternative ATF designs have been considered: the first is a U_3Si_2 Optimized Fuel Assembly design (OFA), based on the pellet size of the corresponding UO_2 OFA design, which results in a ~3.7 H/U and ~7% higher uranium content than UO_2 RFA. This design has the benefit of relying on the already proven OFA design, aside for the change in fuel pellet material. The second alternative ATF design features a ~0.3-in pellet diameter, so that same H/U of the UO_2 RFA design is obtained, yet enabling a ~4% increase in uranium content compared to UO_2 RFA.

Fuel Matrix	**Pellet Outside Diameter (in)**	**Moderation Ratio (H/U)**	**KgU/Fuel Assembly**	**%ΔKgU/Fuel Assembly**
UO_2 RFA	0.3225	4.02	464	Reference
U_3Si_2 0.3-in	0.3032	4.02	482	+4%
U_3Si_2 'OFA'	0.3088	3.70	498	+7%
U_3Si_2 'RFA'	0.3225	3.30	543	+17%

Table 1 Fuel pellet options: impact on moderation ratio and uranium content

The lattice k-infinity plotted versus fuel burnup for the three ATF design options explored is shown in Fig. 1. It can be seen that due to the better neutron thermalization the two designs with higher H/U have higher reactivity at any given burnup until burnups of ~ 50 GWd/tU. At that point the trend is reversed due to the higher plutonium breeding from the harder spectrum in the U_3Si_2 RFA design. Given that the core reactivity is dominated by fresh and once-burned fuel, the higher reactivity in the low burnup range is expected to be the dominant effect, and from this standpoint the ATF designs with higher H/U are preferable. Note however that the specific power (W/gU) of the U_3Si_2 RFA design is lower than the other designs, which implies that the k-infinity at a given cycle energy (EFPDs) for the U_3Si_2 RFA design may not necessarily be lower than the two other designs, especially in the high EFPD range, which suggests consideration of U_3Si_2 RFA at least as an option for 24-month ATF implementation. In order to obtain a more realistic assessment of the behavior and fuel cost potential of the various options, core analysis of U_3Si_2 RFA and OFA will be carried out in the next section. Given the proximity in reactivity of U_3Si_2 OFA and 0.3-in, and the existing familiarity with OFA, it is decided to drop the 0.3-in pellet design option from the list of potential ATF design candidates for the follow on core analysis.

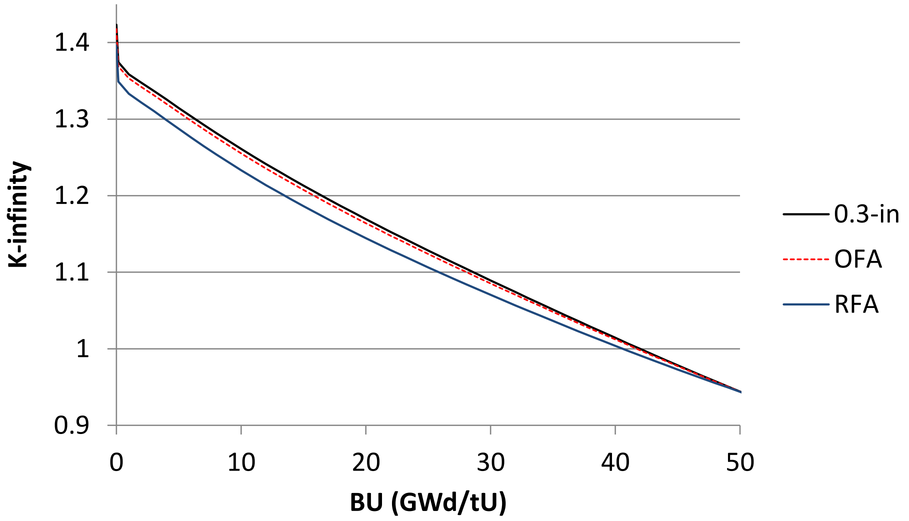
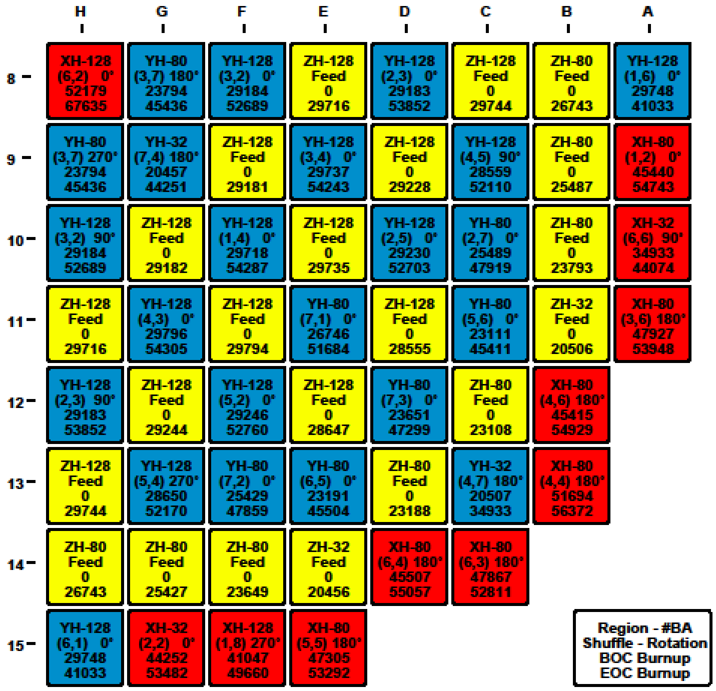


Figure 1 k-infinity for a 4.2% ^{235}U enriched 17x17 U_3Si_2 fuel lattice of various pellet sizes (~0.3-in, OFA and RFA pellet)

3. Reference 18-month UO_2 Core Design

As starting point for the transition, a reference 18 month cycle equilibrium core model has been generated which is representative of the current state-of-the-art fuel management for 4-loop PWRs. The corresponding energy requirement assumed is equivalent to 502 Effective Full Power Days (EFPD), which translates into 18 calendar months between refueling with an assumed 30 day outage and 97% capacity factor. Westinghouse 17x17 RFA fuel with a rod diameter of 0.374 inch and pellet diameter of 0.3225 in was modeled. The core design loads 76 feed assemblies out of 193 total each cycle, with 8 inch 2.60 w/o ^{235}U annular axial blankets on the top and bottom of the fuel rod. The Westinghouse ZrB_2 Integral Fuel Burnable Absorbers (IFBA) [6] is utilized on selected fuel rods in the 128 inch central fuel stack, featuring ^{235}U enriched at 4.75 w/o. The very low leakage core loading pattern of this 18-month cycle is shown in Figure 2 and is consistent with Ref. 3. The fuel cost calculated from the uranium provision of this 18-month UO_2 RFA reloading scheme, with the following economic assumptions, will be used as terms of comparison for the downstream analysis to evaluate potential cost benefits resulting from ATF implementation.



	H	G	F	E	D	C	B	A
8	XH-128 (6,2) 0° 52179 67635	YH-80 (3,7) 180° 23794 45436	YH-128 (3,2) 0° 29184 52689	ZH-128 Feed 0 29716	YH-128 (2,3) 0° 29183 53852	ZH-128 Feed 0 29744	ZH-80 Feed 0 26743	YH-128 (1,6) 0° 29748 41033
9	YH-80 (3,7) 270° 23794 45436	YH-32 (7,4) 180° 20457 44251	ZH-128 Feed 0 29181	YH-128 (3,4) 0° 29737 54243	ZH-128 Feed 0 29228	YH-128 (4,5) 90° 28559 52110	ZH-80 Feed 0 25487	XH-80 (1,2) 0° 45440 54743
10	YH-128 (3,2) 90° 29184 52689	ZH-128 Feed 0 29182	YH-128 (1,4) 0° 29718 54287	ZH-128 Feed 0 29735	YH-128 (2,5) 0° 29230 52703	YH-80 (2,7) 0° 25489 47919	ZH-80 Feed 0 23793	XH-32 (6,6) 90° 34933 44074
11	ZH-128 Feed 0 29716	YH-128 (4,3) 0° 29796 54305	ZH-128 Feed 0 29794	YH-80 (7,1) 0° 26746 51684	ZH-128 Feed 0 28555	YH-80 (5,6) 0° 23111 45411	ZH-32 Feed 0 20506	XH-80 (3,6) 180° 47927 53948
12	YH-128 (2,3) 90° 29183 53852	ZH-128 Feed 0 29244	YH-128 (5,2) 0° 29246 52760	ZH-128 Feed 0 28647	YH-80 (7,3) 0° 23651 47299	ZH-80 Feed 0 23108	XH-80 (4,6) 180° 45415 54929	
13	ZH-128 Feed 0 29744	YH-128 (5,4) 270° 28650 52170	YH-80 (7,2) 0° 25429 47859	YH-80 (6,5) 0° 23191 45504	ZH-80 Feed 0 23188	YH-32 (4,7) 180° 20507 34933	XH-80 (4,4) 180° 51694 56372	
14	ZH-80 Feed 0 26743	ZH-80 Feed 0 25427	ZH-80 Feed 0 23649	ZH-32 Feed 0 20456	XH-80 (6,4) 180° 45507 55057	XH-80 (6,3) 180° 47867 52811		
15	YH-128 (6,1) 0° 29748 41033	XH-32 (2,2) 0° 44252 53482	XH-128 (1,8) 270° 41047 49660	XH-80 (5,5) 180° 47305 53292				

Region - #BA
Shuffle - Rotation
BOC Burnup
EOC Burnup

Figure 2 18-mo cycle UO_2 RFA core loading pattern

Item	Value
U_3O_8 Price ($/lb)	$40 (Baseline); $80 (High); $20 (Low)
Conversion Price ($/kgUn)	$10 (Baseline); $15 (High); $5 (Low)
Separating Working Unit Price ($/SWU)	$80 (Baseline); $120 (High); $40 (Low)
Fabrication Price ($/kgU)	$275
Pre-Operational Interest (%/Yr)	6.0%
Spent Fuel Cooling Time (Months)	120
Spent Fuel Disposal Charge ($/MWhre)	$1
Spent Fuel Dry Storage Charge ($/Asm)	$50,000
Inflation Rate	2.0%
Return on Fuel Investment (%/Yr)	8.0%
Outage Cost (M$/Outage) – includes costs for replacement energy, personnel and outage planning	45 M$ (Baseline); $30 (Low); $60 (High)

Table 2 Economic Assumptions for Fuel Cost Calculations

4. Economic Assumptions for Fuel Cost Calculations

Table 2 shows the main economic assumptions which are used to assess fuel costs together with the fuel provision characterizing each reload option. Note that the key assumptions bearing most of the weight on the fuel cost calculation are the U_3O_8 and SWU prices and, when comparing 18- to 24-month economic performance, the outage costs. For these figures, a set of baseline prices has been assumed and, unless otherwise specified, employed for the economic evaluation. The sensitivity of the economic evaluation on these key figures will be shown in the last section of this paper.

5. 18-month UO_2 to ATF transition

As previously discussed, the ATF fuel design options assessed for the transitions are based on RFA and OFA U_3Si_2 fuel pellets. Same pellet-to-cladding gap and cladding thickness as the current UO_2 fuel has been assumed. The burnable absorber employed is a novel integral absorber under development at Westinghouse, featuring boron in the form of UB_2 admixed in the fuel pellet. When UB_2 is employed, it is applied to all the pins of an assembly. Similar to IFBA the ^{10}B in UB_2 burns out completely over a depletion cycle leaving no residual isotopes leading to a reactivity penalty. The relatively high density of UB_2 and the small concentration employed ensure that there is virtually no displacement of uranium from the fuel pellet as a result of UB_2 incorporation. By blending the UB_2 with the U_3Si_2, significant manufacturing savings can be obtained compared to the current ZrB_2 application methods. In addition, un-enriched boron can be used since the use of UB_2 does not decrease the ^{235}U concentration due to the higher UB_2 density as compared to U_3Si_2.

The progression in number of fuel assemblies of the various types during the transition cycles from UO_2 to ATF is shown in Table 3. In particular, the number of fuel assemblies per fuel type (e.g. UO_2 or U_3Si_2) and burnup condition (e.g. fresh, once-burned, twice-burned and thrice-burned) is shown. Numbers in parenthesis in the table refer to U_3Si_2 OFA while numbers not in parenthesis refer to U_3Si_2 RFA. The maximum ^{235}U enrichment in the fresh ATF assemblies is ~4.95% for both U_3Si_2 RFA and OFA designs.

It can be seen that 68 ATF fresh assemblies are implemented in transition cycle #1 for both U_3Si_2 RFA and OFA. This choice is related to the desire to not exceed the licensed peak pin burnup limit of 62 GWd/tU in more than 9 fuel assemblies, in an attempt to write off the number of assemblies exceeding such limit as Lead Test Assemblies [8], at least in the "legacy" UO_2 fuel. Subsequent cycles for the U_3Si_2 RFA design require 60 fresh ATF assemblies for transition cycle #2 and 56 ATF fresh assemblies for transition cycle # 3 and following cycles, versus 64 fresh ATF assemblies for transition cycle #2 and an alternation of 61 and 60 fresh ATF assemblies for the following cycles for the U_3Si_2 OFA design. It can be observed that convergence to equilibrium in the number of assemblies of the various types is achieved for transition cycle #4 (OFA) and #5 (RFA), corresponding to 6 and 7.5 years of operation respectively.

Transition Cycle #	UO_2	UO_2	UO_2	U_3Si_2	U_3Si_2	U_3Si_2	U_3Si_2
	Once-burned	Twice-burned	Thrice-burned	Fresh	Once-burned	Twice-burned	Thrice-burned
Tr. 1 RFA Tr. 1 OFA	76 (76)	41 (41)	0 (0)	68 (68)	0 (0)	0 (0)	0 (0)
Tr. 2 RFA Tr. 2 OFA	0 (0)	65 (61)	0 (0)	60 (64)	68 (68)	0 (0)	0 (0)
Tr. 3 RFA Tr. 3 OFA	0 (0)	0 (0)	9 (0)	56 (61)	60 (64)	68 (68)	0 (0)
Tr. 4 RFA Tr. 4 OFA	0 (0)	0 (0)	0 (0)	56 (60)	56 (61)	60 (72)	21 (0)
Tr. 5 RFA Tr. 5 OFA	0 (0)	0 (0)	0 (0)	56 (61)	56 (60)	56 (72)	25 (0)

Table 3 Number of core Fuel Assemblies of UO_2 and U_3Si_2 for U_3Si_2 RFA (not in parenthesis) and OFA (in parenthesis) for the transition cycles

As expected, there is a significant decrease in the number of fresh fuel assemblies from the reference UO_2 core to the equilibrium core of both ATF design options, e.g. 20 fewer fresh assemblies per reload for U_3Si_2 RFA and 15/16 for U_3Si_2 OFA. This improves neutron economy, by implementing very low leakage fuel management schemes, improves fuel utilization, by increasing the discharged fuel average residence time, and reduces fuel disposal costs.

Year of the transition from UO_2 to ATF	Delta $/kgU of ATF vs. UO_2	
	U_3Si_2 RFA	U_3Si_2 OFA
1	$135	$(101)
2	$96	$(35)
3	$60	$24
4	$(97)	$(91)
5	$(59)	$(100)
6	$(25)	$(107)
7	$(33)	$(47)
8	$(45)	$(69)
9	$(56)	$(89)
Average	**$(3)**	**$(68)**

Table 4 Delta fuel cost (as $/kgU, NPV) of ATF vs. UO_2 during the transition cycles from UO_2 to ATF (18-month cycle)

The resulting effect on fuel economics is shown in Table 4, displaying the net present value (NPV) of the ATF delta fuel cost from the reference UO_2 core, expressed in terms of delta $/kgU, and using a simplified fuel cash flow, lumped on a yearly basis. It can be seen that the average NPV of the fuel cost savings from switching from UO_2 to ATF is ~70 $/kgU for U_3Si_2 OFA (corresponding to ~1.4 M$/year) and ~3 $/kgU for U_3Si_2 RFA. It should be pointed out that these savings do not include any potential cost adder that may need to be incorporated as a result of manufacturing ATF vs. standard UO_2/Zircaloy fuel.

While there is significant margin in the potential savings for implementing U_3Si_2 with OFA design, the savings are virtually zero for U_3Si_2 with RFA design. This difference in fuel cycle economics is mostly attributed to the behavior in the first transition cycle, where the ATF average burnup at the end of cycle is still quite low and there is significantly lower reactivity in U_3Si_2 RFA compared to U_3Si_2 OFA given the lower neutron moderation of the U_3Si_2 RFA design. As a consequence, the fuel costs of U_3Si_2 RFA vs. OFA for the first transition cycle are much higher. Notably, the fuel cost savings vs. UO_2 are ~ 70$/kgU for U_3Si_2 RFA at the equilibrium cycle (vs. 3 $/kgU NPV on average for the transition cycles) and ~ 120 $/kgU for U_3Si_2 OFA at the equilibrium cycle (vs. 70 $/kgU NPV on average for the transition cycles). This clearly shows the importance of accounting for the transition cycles for a more informed economic evaluation of ATF implementation.

Investigation of the core physics parameters of the ATF core at 18-mo cycle shows a beneficial reduction in the power defect, due to the lower fuel operating temperature compared to UO_2, which benefits the shut-down margin. The moderator temperature coefficient is more negative than for UO_2 as a result of the harder spectrum and higher fuel burnup. As a result of adopting fuel management schemes with fewer fresh assemblies in the ATF reloads, the degrees of freedom in the core design space diminish and the peaking factors tend to increase. While the general increase in peaking factors resulting from ATF implementation in 18-month cycles should be manageable from a safety analysis standpoint, the acceptability in terms of the resulting, potentially higher, CIPS risk that would result from the higher peaks needs to be determined.

6. 18-month UO_2 to 24-month ATF transition

Similarly to the 18-month ATF transition, the ATF fuel design options assessed for the 24-month transition are based on RFA and OFA U_3Si_2 fuel pellets, incorporating UB_2 as burnable absorber to provide the required reactivity hold-down over the cycle. The energy requirement assumed is equivalent to 680 EFPD, which translates into 24 calendar months between refueling with an assumed 30 day outage and 97% capacity factor.

The core make-up of the various fuel types during the transition cores is summarized in Table 5. The U_3Si_2 RFA core features 96 fresh assemblies for the first transition cycle and 88 for the subsequent cores. The U_3Si_2 OFA core feature 96 fresh assemblies for all reloads. The maximum ^{235}U enrichment in the fresh ATF assemblies is ~4.95% for both U_3Si_2 RFA and OFA designs.

The higher loading of fresh ATF assemblies for the 24-month transition vs. the 18-month transition, ~ 30 more ATF assemblies per reload, enables a much quicker convergence to equilibrium core fuel management scheme, thereby minimizing the impact of the transition cores, associated challenges and potential financial burden. The larger number of fresh assemblies characterizing 24-month vs. 18-month ATF cycles is also beneficial from a core peaking factor management standpoint. Further, the lower fuel discharge burnup mitigates the duty on the cladding and related challenges in meeting the licensed peak pin rod burnup.

Transition Cycle #	UO_2	UO_2	UO_2	U_3Si_2	U_3Si_2	U_3Si_2	U_3Si_2
	Once-burned	Twice-burned	Thrice-burned	Fresh	Once-burned	Twice-burned	Thrice-burned
Tr. 1 RFA Tr. 1 OFA	76 (76)	21 (21)	0 (0)	96 (96)	0 (0)	0 (0)	0 (0)
Tr. 2 RFA Tr. 2 OFA	0 (0)	9 (1)	0 (0)	88 (96)	96 (96)	0 (0)	0 (0)
Tr. 3 RFA Tr. 3 OFA	0 (0)	0 (0)	0 (0)	88 (96)	88 (96)	17 (1)	0 (0)

Table 5 Number of core Fuel Assemblies of UO_2 and U_3Si_2 for U_3Si_2 RFA (above, not in parenthesis) and OFA (below, in parenthesis) for the transition cycles

Year of the transition from UO_2 to ATF	Delta \$/kgU of ATF vs. UO_2	
	U_3Si_2 RFA	U_3Si_2 OFA
1	\$291	\$88
2	\$274	\$83
3	\$(1,236)	\$(1,464)
4	\$1,555	\$1,586
5	\$(1,165)	\$(1,318)
6	\$112	\$77
Average	**\$(28)**	**\$(158)**

Table 6 Delta fuel cost (as \$/kgU, NPV) of ATF vs. UO_2 during the transition cycles from UO_2 to ATF (18-month cycle)

While 24-month cycles are typically economically penalizing due to the higher fuel costs, from the lower fuel utilization, than for 18-month cycles, the higher uranium content of U_3Si_2 helps offsetting part of the fuel cost gap from the 18-month cycle and making best use of the reduced outage costs at the 24-month cycle. The resulting effect on fuel economics is shown in Table 6, displaying the net present value (NPV) of the ATF delta fuel cost from the reference 18-month UO_2 core, expressed in terms of delta \$/kgU, and using a simplified fuel cash flow, lumped on a yearly basis. It can be seen that the average NPV of the fuel cost savings from switching from UO_2 to ATF while extending the cycle length from 18 to 24-month cycles is ~160 \$/kgU for U_3Si_2 OFA and ~ 30 \$/kgU for U_3Si_2 RFA. The potential savings offered by adopting U_3Si_2 OFA are very significant, and much larger than those from U_3Si_2 RFA thanks to the substantially better economic performance of U_3Si_2 OFA, especially during the first transition cycle, for similar reasons than those previously discussed for the 18-month ATF transition. Table 6 shows also that notwithstanding the improvements in fuel management from the higher uranium content, the fuel cost for U_3Si_2 OFA at the 24-month cycle is still ~ 80\$/kgU higher than that of UO_2 at the 18-month cycle, indicating a lower fuel utilization, but the savings offered by the reduced number of outages (under the assumed 45 M\$/outage) more than offset the higher fuel costs, making adoption of the Westinghouse ATF in conjunction with a transition to 24-month cycle of operation the currently recommended path forward for the implementation.

The importance of accounting for the transition cycles for a more informed economic evaluation of ATF implementation is confirmed by comparing the 24-month ATF fuel cost savings at the equilibrium cycle vs. the transition cycles: ~ 80$/kgU for U_3Si_2 RFA at equilibrium vs. 28 $/kgU NPV on average for the transition cycles, and ~ 200 $/kgU for U_3Si_2 OFA at equilibrium cycle vs. 160 $/kgU NPV on average for the transition cycles, noting that this fuel cost differential is smaller than for the 18-month cycle ATF implementation due to the longer transition period of the latter.

Investigation of the core physics parameters of the ATF core at 24-month cycle shows a similar beneficial reduction in power defect with related shut-down margin benefits relative to UO_2 cores than that that previously discussed for the 18-month ATF cycle. A reduction in power peaks due to the more favorable reloading scheme that can be obtained for 24-month reloads vs. 18-month reloads is also observed.

7. Fuel Cost Sensitivity to Uranium Price and Outage Costs

The fuel cost sensitivity to the uranium price assumptions for both 18- and 24-month cycle ATF transitions is shown in Table 7. While the potential ATF fuel cost savings increase with the uranium price at the 18-month cycle, the opposite is true at the 24-month cycle. The reason is that at the 18-month cycle the ATF savings derive from the improved fuel utilization vs. UO_2, e.g. by allowing implementation of more efficient fuel management schemes. Thus, the fuel cost savings for 18-month cycle ATF implementation are directly correlated to uranium prices. On the other hand, at the 24-month cycle, the ATF economic benefits derive from the outage savings outweighing the higher fuel costs at the 24- vs. 18-month cycle. Since fuel costs, and thus fuel cost differential for 24- vs. 18-month cycles, decrease as the uranium price decrease, while the outage cost remains flat, savings are inversely related to uranium price for 24-month ATF implementation. The above considerations and the low current, and projected, uranium price, constitute another point in favor of implementation of ATF in conjunction with cycle length extension to 24-month cycle.

	Delta $/kgU of U_3Si_2 OFA vs. UO_2	
Uranium Price Scenario	18-mo ATF implementation	24-mo ATF implementation
High	(92) $/kgU	(82) $/kgU
Baseline	(68) $/kgU	(158) $/kgU
Low	(55) $/kgU	(205) $/kgU

Table 7 Delta fuel cost (as $/kgU, average NPV over the transition cycles) of ATF vs. UO_2 for various uranium price scenarios

Table 8 shows the sensitivity of the ATF savings on outage costs, for 24-month cycle implementation, and using baseline uranium price assumptions. Notably, the potential ATF savings are still significant, ~75 $/kgU, even assuming low, 30 M$/outage, outage cots. This strengthens confidence that the Westinghouse ATF is an economically favorable solution to extend cycle length to 24-month cycle, in addition to the safety benefits that it delivers from the enhanced accident resistance.

Outage Cost	Delta \$/kgU of U_3Si_2 OFA vs. UO_2 24-mo ATF implementation
30 M\$	(75) \$/kgU
45 M\$	(158) \$/kgU
60 M\$	(241) \$/kgU

Table 8 Delta fuel cost of ATF vs. UO_2 (as \$/kgU, average NPV over the transition cycles from 18-mo UO_2 to 24-mo ATF) for various outage costs

8. Conclusions

Westinghouse is developing accident tolerant fuel materials Cr-coated cladding and U_3Si_2 fuel that improve PWR fuel efficiency and extend fuel management capability, in addition to improving safety margins. As shown in this paper, because of the increased density, the use of these materials extends the energy output and cycle length capability while remaining below the 5 w/o ^{235}U enrichment limit for commercial fuel, and can make 24-month cycle operation economical for today's uprated, high power density PWRs.

The comprehensive evaluation performed for this paper is based on detailed core analysis, including modeling the transition from the current UO_2 18-month operating cycle to ATF at either 18- or 24-month operating cycles. A comparison of the economics of 24-month cycles with ATF fuel relative to the current 18-month cycle with UO_2 fuel shows significant economic benefits by switching to ATF in conjunction with a transition to a 24-month cycle for all outage costs and uranium price scenarios considered, and including the transition cycles. The economic benefits from 24-month ATF implementation appear to be substantially larger than for 18-month ATF implementation, for the prevalent uranium price and outage cost scenarios considered. This, together with more beneficial power peaks, lower impact of the transition cycles and reduced dependence on uranium price assumptions, make adoption of the Westinghouse ATF in conjunction with a transition to 24-month cycle of operation the recommended path forward for the implementation.

From the fuel design standpoint, U_3Si_2 with OFA fuel dimensions is the preferred option, offering substantial economic benefits compared to U_3Si_2 with RFA fuel dimensions, which due to the suboptimal neutron moderation ratio offers markedly inferior economic performance especially during the first transition cycle, as a result of the low fuel burnup and resulting reactivity deficit to U_3Si_2 OFA fuel.

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