EIGHTEEN- VERSUS TWELVE-MONTH IN-CORE FUEL CYCLE: ALPS ECONOMICS SEARCH CAPABILITY

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ABSTRACT

One of the most important issues facing a nuclear electric power supplier is its economic competitiveness with other sources of electrical power and even other suppliers in a deregulated environment. The economic viability of any in-core fuel management scheme depends on factors related to the regulated vs. deregulated electric power environment, as well as technical and licensing issues related to the optimization problem at hand. Given the prior regulated environment and long outage times, longer fuel cycles up to 24 months made for better economics. The current trend of deregulation with objectives for faster return on investment and cheaper replacement power costs, coupled with the trend toward short outages, changes the direction towards shorter cycle lengths to obtain better economics. This paper shows an example of one such study, which contrasts a 12-month equilibrium cycle versus an 18-month equilibrium cycle. Until the changes in the market stabilize, there will be an on-going need for these studies. This paper also demonstrates a subsequent, new, flexible economics capability for the Westinghouse Advanced Loading Pattern Search code, ALPS, which can be used to meet user-defined operational and safety, as well as economics objectives during the search process for future studies of this nature. This capability was accomplished using the Westinghouse-developed ***tulip***™ scripting language that allows the integration of external procedures into the search process of the ALPS program. The simplicity and flexibility of a ***tulip***™ script allows for the customization of the economics evaluation per each supplier's criteria.

1. INTRODUCTION

Economic performance is highly dependent on many factors among which generation costs exemplified by fuel, outage, maintenance and operations costs and spent fuel issues like on-site storage, high level waste (HLW) removal uncertainty, and change from electric output to volume charging basis. The most economical length for a cycle is primarily driven by the balancing the impact of the fuel cycle costs versus the replacement power and outage costs on a yearly average. In the past the long outage lengths, outage scheduling, and high replacement power costs drove the industry towards longer cycles, approaching 24 months. This trend is re-enforced by other issues such as limited spent fuel pool capacity and disposal costs. Longer cycles result in higher utilization of the fuel and fewer assemblies, but higher fuel cycle costs. In a regulated industry many of these costs could be passed on to the customers in the rate base.

The longer cycle has been recently challenged by some utilities in an attempt to improve their nuclear power plants' (NPPs) economic performance in an extremely competitive, changing market environment. The current trend to significantly reduce the outage lengths, coupled with the availability of cheaper replacement power and competition with cheaper power producers due to deregulation, has made a return to shorter 18-, and even 12-, month cycles more attractive.

In this paper, we report on two economics studies using the Westinghouse Advanced Loading Pattern Search code, ALPS, to compare an eighteen- versus twelve-month in-core fuel cycle. The first study will give an example of the type of process required to determine the optimum cycle length. The second study will show how the economics criteria can be incorporated as an integral factor in the search process of ALPS in the future, using the new ***tulip*****™** scripting-writing capability.

In the first example, a 2-loop Westinghouse core is used to contrast the economic performance of the two cycle lengths throughout the expected plant lifetime of twenty years without the aid of including economics objective in the search process. ALPS is used to generate candidate LPs that are later used to generate the equivalent equilibrium solution. The economic performance of each equilibrium solution is then assessed and ranked with respect to the rest of the other LP candidates. Since ALPS does not have the capability to generate an equilibrium solution nor does it include the economics parameters in the LP search process of this study, any economic study performed by ALPS until now is an iterative process which depends highly on the nuclear designer's skills and experience.

Including the economic objectives into the LP search process has been accomplished via the ALPS powerful capability of script-writing which allows the integration of external procedures of the user's own design[1-4]. This capability gives the user added flexibility to describe unusual constraints and objective functions. The development of the ***tulip*****™** language at Westinghouse has made possible the customization of a utilities economic evaluation process into the search process. In the second example given in this paper, a 4-loop Westinghouse core is used where a simple economics figure of merit (EFM) is defined and included into the search process as an objective function via a ***tulip*****™** script. The search process proceeds to find LPs that satisfy the economics objective function, while simultaneously balancing it against other design constraints and objectives per the user input importance-weighting functions. LPs found exhibit a clear trend of favoring better EFM right out of the search process. This is in contrast of what is usually done by iteratively trying to find LPs that meet constraints and objective functions, some of which can influence the economic outcome, and then **hope** that in doing so the economics objectives are also met. No direct economics criterion is applied to the search.

2. DISCUSSION

Factors that affect the comparative economic study of a NPP can be divided into two major categories; those that are related to the regulated-versus-deregulated market environment and those that are inherent to the optimization problem at hand. Concerning the environmental factors there are several major differences between a regulated and a deregulated electric utility industry that should be taken into consideration. As the nuclear electric utility industry moves from a regulated environment to a deregulated one, the goal will be to increase the return on revenue (ROR). The cost of replacement power and the cost and length of time for outages should also decrease. The costs of unit fuel, dominated by uranium ore, separative work unit (SWU) and fuel fabrication costs, will be under pressure to decrease. In special circumstances, such as those in the United States of America (USA), the spent fuel disposal costs might change dramatically depending on the government resolution of the HLW issue which is now pending, making the capacity of on-site retention of fuel a key constraint for some suppliers. Left unresolved and dependent on the costs of on-site storage, some NPPs will need to keep the number of feed assemblies to a minimum, potentially increasing the overall fuel costs, as enrichments must be increased. The pricing of these factors, when coupled with the traditional cycle-specific in-core parameters determine the criteria for an “optimum” solution.

Factors inherent to the optimization problem traditionally affecting the fuel cycle costs are present regardless of the electric power market environment. However, their values and, consequently, their final impact on the fuel cycle costs depend on the environment. Inherent factors include the amount of ore, SWU, and component fabrication, the plant capacity factor, and the length of refueling outages. One of the inherent key factors in any economic evaluation is the utilization of the fuel, determined by the in-core residence time (RT) or, in other words, its fuel discharge burnup. Increasing fuel discharge burnup tends to (1) reduce the number of feed assemblies and, thus, fabrication and disposal costs, (2) increase, exponentially, enrichment charges, and (3) increase interest charges. Increased discharge burnup also pushes the fuel closer to fuel performance limits, where reliability issues can negatively impact the final realized costs. The risk is that these losses can over-shadow any savings obtained by pushing the fuel performance limits. Balancing all these factors to find the most economical LP while meeting all safety and operational objectives is a very difficult optimization problem and are best handled if they can be included in the search process.

For any economic study to yield any meaningful results, not only should both environmental and inherent factors be taken into consideration, but also the study should cover a relatively long period of time that is comparable to what is remaining in the plant’s expected lifetime. The following represents an equilibrium cycle case study, which has been chosen as an example of the methodology used for an economic study of the optimum cycle length. At the time of this study, the assumed outage lengths were around 45 days and the replacement costs were somewhat higher than today. The magnitude of the changes in these parameters would not change the conclusion, which shows the 18-month to be more profitable than the 12-month. However, the changing market environment requires a continuing evaluation of this type of study until the market environment becomes more predictable. The subsequent demonstration of the ***tulip*™**

capability to include an economics evaluation and constraint or objective function into ALPS provides a means to incorporate and balance the importance of the economics into the LP search phase for future studies.

3. NUMERICAL RESULTS

3.1 EQUILIBRIUM CASE

Case (1) of this study is a representative of a 2-loop Westinghouse core operating a 12-month cycle, or 329 effective full power days (EFPD), which utilizes the heavy Westinghouse standard (STD) 14x14 bundle design with enriched solid axial blankets. The feed batch size for the cycle energy output is 28 fresh assemblies with an average enrichment of 3.931 w/o U^{235} assuming a nominal initial loading of 404.93KgU per assembly. The burnable absorber requirements are met using 160 ZrB_2 integrated fuel burnable absorber (IFBA) rods assuming a B^{10} coating density of 1.77 mg/in (1X) over the central 120 inches of the fuel stack.

Case (2) is the same as Case (1) but operating at an 18-month cycle, or 510 EFPD. The feed batch size for this cycle energy output is 40 fresh assemblies with an average enrichment of 4.553w/o U^{235} assuming a nominal initial loading of 404.93KgU per assembly. The burnable absorber requirements are met using 1984 IFBA rods assuming a B^{10} coating density of 3.54 mg/in (2X) over the central 120 inches of the fuel stack. Table 1 summarizes the design parameters and the uranium requirements for both cases. Table 2 summarizes the prices for the different uranium requirements used in the study.

Using the data in Tables 1 and 2, the total cycle costs are $16,354,462 and $27,613,657 for the 12- and 18-month cycles respectively. An EFM is defined to be the total fuel cycle cost per the total cycle's thermal energy output defined as MWD. For Case (1) EFM equals 30.12$/MWD and for Case (2) EFM equals 32.81$/MWD. But for this specific example the refueling and maintenance outage lasts 43 and 45 days for the two cases respectively and costs approximately the same for both cases namely; $20,000,000. This makes the total cycle length for the two cases 372 and 555 days. If the remaining life-time of the plant is 20 years, then the number of full cycles available during that time are 19.62 and 13.15 cycles for the two cases. If the rest of operation and maintenance (O&M) costs are assumed to be the same for both cases and is 0.07$/$KW_e$hr then the O&M costs will be $291,836,160 and $452,390,400 per total cycle length respectively. Finally, during the refueling outages the plant has an obligation to its customers to still supply them with electricity that will be bought for a reduced price of $0.09/$Kw_e$hr. This amounts to a total of $49,040,640 and $51,321,600 respectively for replacement power costs per total cycle length. For the sake of simplicity, if it is assumed that the money is borrowed just before the cycle start-up and it takes 20 years to pay the principal plus a fixed 6% annual interest, then the total amount paid for each case is $313,757,098,300 and $307,341,238,300 respectively. However, if electricity is sold for a fixed price of 0.12/KW_ehr, then Case (1) will generate $500,290,560 and Case (2) will generate $775,526,400 of operating revenues per total cycle length. If operating revenues are allowed to accumulate interest for a period of 20 years, Case (1) will generate $416,110,037,000 while Case (2) will generate $432,323,874,500 over the lifetime of the plant.

The lifetime net profit for the 12-month cycle, then, equals $102,352,938,700 and that for the 18-month cycle equals $124,982,636,200.

Though simplistic in nature, the above example of a Westinghouse 2-loop NPP shows that an 18-month cycle is economically more attractive than a 12-month cycle. This is consistent with what has been widely known in the nuclear power industry. However, it is very important to note the following:

1. this conclusion is highly dependent on the assumptions made a priori, and
2. LPs found are checked for their EFM after the search has been concluded not while in progress. This implies that searching for LPs with good EFM in ALPS is an iterative process that highly depends on the designer's skills and experience.

3.2 ***tulip***$^{\mathbf{TM}}$ CASE

The following represents two LP search cases that include the EFM as an objective function in the search process. Both cases are transition cycles from a 20-month cycle, which was the lowest of a three-cycle equilibrium with a high cycle length of 24 months. Case (3) is a representative of a 4-loop 3338MW_{th} Westinghouse core operating a 12-month cycle, or 329 effective full power days (EFPD), which utilizes the Westinghouse optimized fuel assembly (OFA) 17x17 bundle design with fully enriched annular axial blankets. The feed batch size for the cycle energy output is a split of 24 fresh assemblies with an enrichment of 3.8 w/o U^{235} and 32 assemblies with an enrichment of 4.2w/o U^{235}, assuming a nominal initial loading of 416.93KgU per assembly. The burnable absorber requirements are met using 4352 ZrB_2 integrated fuel burnable absorber (IFBA) rods assuming a B^{10} coating density of 2.25 mg/in (1.5X) over the central 132 inches of the fuel stack.

Case (4) is the same as Case (3) but operating at an 18-month cycle, or 510 EFPD. The feed batch size for this cycle energy output is a split of 36 fresh assemblies with an enrichment of 4.4 w/o U^{235} and 44 assemblies with an enrichment of 4.8 w/o U^{235} assuming a nominal initial loading of 416.93KgU per assembly. The burnable absorber requirements are met using 8448 IFBA rods assuming a B^{10} coating density of 2.25 mg/in (1.5X) over the central 132 inches of the fuel stack. Table 3 summarizes the objective functions along with the issues that they represent which are included the search process for Cases (3) and (4).

Many of the objectives in Table 3 offer conflicting requirements on the LP that must be balanced during the search process. The minimum leakage (6), the minimum EFM (7), and the minimum vessel weld fluence (8) objectives tend to reduce powers at the core periphery, while the maximum center assembly pin burnup (2), maximum peak pin power (3), and maximum detector response (9) objectives tend to increase peripheral powers. The limits/objectives input to ALPS must be chosen and defined carefully to allow the LP search to balance all of these objectives and obtain desired margins.

Out of all of the objectives listed in Table 3, the minimum EFM, the minimum vessel weld fluence, and the maximum detector response need to be mathematically defined in external procedures that are integrated within ALPS own LP search process. This is accomplished through writing a

***tulip*™** script in a simplified C-like syntax that is then compiled and linked at run time to ALPS main program.

The pressure vessel's weld fluence can be expressed as follows:

$$PVF_{tot} \equiv \sum_{t}^{T} \Delta BU(t) \sum_{i}^{I} \sum_{j}^{J} PVR(i,j) \times POWER(i,j,t) \tag{1}$$

where PVF_{tot} is the total vessel weld fluence at the end of the cycle, *DBU(t)* is the burnup increment from last to current burnup step, *t*, *PVR(i,j)* is the position-dependent vessel response matrix, *POWER(i,j,t)* is position-dependent power distribution at any burnup step, *t*, *T* is cycle length, *I*, and, *J* are core boundary locations.

Similarly, the excore detector's response can be expressed as follows,

$$EXC(t) \equiv \sum_{i}^{I} \sum_{j}^{J} EXR(i,j) \times POWER(i,j,t) \tag{2}$$

where *EXC(t)* is the excore detector response at any time, *t*, and *EXR(i,j)* is the position-dependent detector response matrix.

Finally, the EFM is expressed as the total fuel batch cost in dollars per total cycle output in terms of MWD. The fuel batch cost, however, can be broken down to five major components namely; yellow cake costs, conversion costs, SWU costs, fuel fabrication costs, and IFBA costs. For feed enrichment, *e*, the feed to product ratio can be expressed as follows:

$$\frac{F}{P} \equiv \frac{e - e_t}{e_f - e_t} \tag{3}$$

where e_t is the tails enrichment, 0.2%, and e_f is the ore enrichment, 0.711%. Also, SWU per KgU can be expressed as:

$$\frac{E}{P} \equiv \left[V(e) - V(e_t)\right] - \frac{F}{P}\left[V(e_f) - V(e_t)\right] \tag{4}$$

where *V(e)* is the separation potential for enrichment, *e*, which can be expressed as:

$$V(e) \equiv \left[(2e - 100)\ln\frac{e}{e - 100}\right] \div 100 \tag{5}$$

Using Equations (3-5) the total fuel batch cost can be expressed as follows:

$$DOLLARS_{tot} = FuelRods_{tot} \times Fab\_price + IFBARods_{tot} \times IFBA\_price + \left\{ \frac{F}{P} \left[2.613 \times Yellowcake\_price + Conversion\_price \right] + \frac{E}{P} \times SWU\_price \right\} \times KgU_{tot} \quad (6)$$

Consequently, EFM is defined as follows:

$$EFM = \frac{DOLLARS_{tot}}{MW_{th} \times EFPD} \quad (7)$$

Table 4 shows the compliance with respect to the objective functions of the best LP for test Cases (3) and (4) namely, the 12– and 18–month cycles. The table also shows the user-defined importance weight for each of the objective functions. As it is clear from the table, both cases met or exceeded the most important objectives namely; minimizing peak pin power (3), minimizing the EFM (7), minimizing the peak pin burnup for the center assembly (1), and minimizing the peak pin burnup for the whole core (2). However, margins obtained for different objectives in the 12–month cycle case are understandably larger than those obtained in the 18–month cycle case. This is because the previous cycle which serves as the starting point for fuel assembly inventory selection for both cases is a 20–month cycle. Hence, the excess energy available for the 12-month cycle is larger than that available for the 18-month cycle as shown in Table (4). This allows for more freedom for fuel selection and placement in the current cycle and consequently more margin in various objectives. For example, to meet the target cycle length, minimize the EFM, and minimize the peak pin burnup for both the center assembly and the whole core for the 18-month cycle case, a low leakage pattern was found. That LP minimized the leakage from the core and consequently minimized the pressure vessel weld fluence. However, in doing so, the detector response objective was not met because of lower number of neutrons reaching the detector locations. In the 12-month cycle case, however, the excess energy existing in the core from the relatively longer previous cycle helped meet the same objectives as in the 18-month cycle case. This was done with a much lower number of feed assemblies, a more favorable EFM, and lower peak pin burnups for both center assembly and the whole core.

Finally, it should be noted that Cases (1) and (2), equilibrium cases, discussed above have the following major differences when compared to Cases (3) and (4), ***tulip*****™** cases:

1. Cases (1) and (2) are equilibrium cases versus Cases (3) and (4) which are transitions cycles. Equilibrium cycles are usually used for long-term economic studies whereas transition cycles are used for short-term economic studies.
2. LPs found in equilibrium cases are checked for their EFM after the search has been concluded not while in progress. This implies that searching for LPs with good EFM in ALPS is an iterative process that highly depends on the designer's skills and experience. ***tulip*****™** cases, on the other hand, have EFM objective defined for ALPS LP search a priori. This implies EFM objective has a higher chance of being met without the need for time-consuming iterations.
3. Conclusions reached for equilibrium cases are based on economic study that spans the expected plant lifetime of twenty years. The study takes into account the fuel costs, outage

and refueling costs, replacement power costs, and O&M costs. Conclusions reached for ***tulip*™** cases only consider fuel costs for current transition cycle.

Despite the differences listed above equilibrium cases yielded EFM results comparable to that of the ***tulip*™** cases. For Case (1) EFM is calculated to be 30.12$/MWD and for Case (2) EFM is calculated to be 32.81$/MWD. This implies that the inclusion of economic objectives into ALPS search process has managed to replace in part what used to be an iterative and time-consuming process of generating LPs with good economic performance indicators.

CONCLUSIONS

ALPS has been demonstrated to successfully find LPs that meet economics objectives as well as user-defined operational and safety objectives. This has been made possible by the development of ***tulip*™** language that allows the integration of external procedures into the search process of the main ALPS program. In Cases 3 and 4 above, an EFM has been defined and included via a ***tulip*™** script into the fuel management optimization problem of a 4-loop Westinghouse core operating at an eighteen- and twelve-month cycle. Although LPs found by ALPS in these cases are not in equilibrium, they exhibit a clear trend of meeting and, in some cases, exceeding the EFM objective function defined for ALPS search process a priori. This capability will aid greatly in future equilibrium studies, such as those found in Cases 1 and 2, as well as cycle specific design. Since each utility and/or NPP may have a different definition or criteria for an EFM, the flexibility inherent with ***tulip*™** scripts provides a simple means to customize the goals and include in the search.

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Table 1. Design Parameters and Uranium Requirements for the Two Study Cases

Design Parameter	Case 1	Case2
Power MWth	1650	1650
EFPD	329	510
Fuel Type	STD	STD
Pellet Outer Diameter	0.3659	0.3659
Clad Outer Diameter	0.4220	0.4220
Clad Inner Diameter	0.3734	0.3734
# Feed - Region 1	16	16
Average U^{235} w/o	3.88	4.40
# Feed - Region 2	12	24
Average U^{235} w/o	4.28	4.95
Loading KgU	404.93	404.93
# IFBA Rods	160	1984
IFBA Loading (mg/in)	1.77	3.54
Blanket U^{235} w/o	2.60	2.60
Discharge Burnup MWD/MTU	47874	51950
Lead Rod Burnup	58000	65000
Uranium Loading KgU	11338	16197
Ore Requirement lb U_3O_8	261727	437959
SWU Requirement	58429	102785
Conversion Requirement $KgU_{natural}$	100152	167588

Table 2. Prices of Uranium Requirements

Ore Price ($/$KgU_{nat}$)	30
SWU Price ($/KgU-SWU)	90
Conversion Price ($/$KgU_{natural}$)	5
Fabrication Price ($/$KgU_{enriched}$)	240
IFBA Price ($/Rod)	125 for 1X and 250 for 2X

Table 3. Issues and Corresponding Objective Functions/Constraints Modeled in Test Problem

Objective Function/Constraint	**Issue**
1. Minimize center assembly pin burnup (< 62 GWD/MTU)	Required for licensing compliance
2. Minimize twice-burned fuel pin burnup (< 60 GWD/MTU)	Required for licensing compliance
3. Minimize $F_{\Delta H}$ (< 1.505)	Technical Specification compliance and margin for operation flexibility
4. Maximize assembly power; power (< 1.385) for all core assemblies	Technical Specification compliance and margin for operation flexibility
5. Maximize control rod worth; $power_{avg}$ (> 1.2) for D-bank assemblies	Provide adequate control worth late in the cycle to reduce amount of boration/dilution and water processing needed for power changes
6. Minimize power in peripheral assemblies $power_{avg}$ (< 0.57)	Low fuel cycle costs - meeting cycle length with lower feed enrichment or fewer feed assemblies
7. Minimize batch fuel cost; (EFM < 34.4 $/MWD)	Low fuel cycle costs - meeting cycle length with lower feed enrichment or fewer feed assemblies
8. Minimize a cumulative power adjoint-derived response for vessel weld below benchmarked limit (< 0.4)	Low vessel weld fluence - evaluated at end-of-cycle
9. Maximize a power adjoint-derived response for excore detector above a benchmarked limit (> 0.37)	Sufficient excore detector response throughout cycle

Table 4. Best LP for Twelve - and Eighteen - Month Cycle

Objective Function (weight)	Target	Case (3) 12-Month	Case (4) 18-Month
1. Center Assembly (60)	<62GWD/MTU*	54.807	58.454
2. High Burnup (60)	<60GWD/MTU*	56.324	58.824
3. Max $F_{\Delta H}$ (200)	<1.505**	1.505	1.509
4. Max P_{HOT}(25)	<1.385 (pow.)	1.393	1.403
5. D-Bank Worth(15)	>1.10 (avg. pow.)	1.261	1.179
6. FCC (20)	<0.57 (avg. pow.)	0.533	0.538
7. EFM (80)	<34.4 $/MWD	31.830	33.903
8. Vessel Weld Fluence(20)	<0.40 (adj. pow.)	0.418	0.381
9. Detector Response(10)	>0.375 (adj. pow.)	0.400	0.365
Excess Energy	0 days	~ 5.4	~ 2.2

* Limit is 62GWD/MTU

** Limit is 1.527

Note: 1) Reminder that "Targets" do not have definite limits, but must be checked with more accurate design modeling.

2) These results are directly from the search process in ALPS; Minor LP refinements could improve these results.