A LCOE Estimation on HALEU Fuels for Small Modular Reactors

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INTRODUCTION

Many Small Modular Reactors (SMR) and micro-reactors are actively being pursued by various entities worldwide for a variety of applications, ranging from civilian applications to specialized military purposes [1]. The economic market requirements for these reactors are not yet well defined, but one common trend observed among them is that most conceptual designs are considering the use of high assay low-enriched uranium (HALEU) fuel for potential near deployment. HALEU is defined as any uranium fuel that is enriched above 5% but lower than 20%, which is above the NRC enrichment limit of 5%. The potential commonality of HALEU utilization provides an opportunity for a broadly applicable economic cost study.

Since the application of HALEU fuels is primarily considered for potential economic benefits, it is necessary to understand how effective HALEU fuel may be in improving the economic efficiency of a nuclear power plant. The key economic benefits of using higher enriched fuel include increasing revenue from a higher capacity factor and reducing overall refueling costs. Higher enriched fuel has the potential to prolong a reactor's fuel cycle by increasing its maximum achievable fuel burnup with marginal effects on capital costs (one-time costs required for plant operation) and operation and maintenance (O&M) costs. These longer durations of power generation reduce the refueling frequency resulting in improved reactor economy depending on the cost of fuel enrichment.

Although the overall price of fuel is expected to decrease due to higher burnup, the specific cost of higher enriched fuel is expected to increase. Since there is currently no existing HALEU supply chain, early batches may be cost-prohibitive for individual plants without long term cost control factors. Additionally, the higher burnup inferred from increased enrichment suggests higher fuel fabrication costs as the fuel must be designed to mitigate additional mechanical stress and embrittlement [2]. Moreover, enriching fuel to HALEU levels affects transportation costs; higher radiation and proliferation risks require increased standards for transportation and packaging regulations. From the reactor aspect, extending the cycle time with negligible changes in outage time from prolonged decay heat, the reactor pressure vessel (RPV) is exposed to more neutrons over a shorter cycle length, causing a reduction in operational lifetime.

In order to assess the economic viability of increasing a reactor's fuel enrichment, a model for estimating plant levelized cost of electricity (LCOE) was developed. NuScale's 160 MWt SMR concept was chosen as a case study example to demonstrate the potential economic benefits of increasing fuel enrichment for the following reasons: (1) It is far along in the NRC licensing process and can realistically begin operation within 10 years. (2) It is based on standard PWR designs, of which, the economics have been thoroughly studied. (3) It uses uranium oxide fuel, which has well-known fabrication costs.

LCOE MODEL

The LCOE for a nuclear power plant is the price of electricity generated by a plant where revenues would equal costs, indicating a return on the capital invested equal to the discount rate, often expressed in units of \$/MWh. This definition accounts for all lifetime costs of the project. Therefore LCOE is a measure of the total cost of a power plant over the total energy produced for a cycle length and may be calculated as

$$\mathrm{LCOE} = \frac{C_{\mathrm{cc}} + C_{\mathrm{O\&M}} + C_U}{P \cdot \eta \cdot T_{cycle}}, \tag{1}$$

where C_{cc}, $C_{\mathrm{O\&M}}$, and C_U represent the cycle averaged capital, O&M and fuel costs respectively, and η is power plant capacity factor and T_{cycle} is the total fuel cycle length in days. A reactor cannot easily increase its LCOE by extending cycle time by reducing power production because the resulting increase in cycle time would be offset by lower revenue from reduced power output. For this study, all reactor options are assumed to be operating at the same full-power except when refueling, where the power output is zero. The reactor cycle length and capacity factor are only influenced by varying potential fuel burnup resulting from changes in fuel enrichment. As can be seen from Eq. (1), the LCOE can be broken into three terms where the last term is the levelized cost of fuel (LCOF). Thus it is possible to simplify Eq. (1) to estimate the HALEU LCOE without the knowledge of capital and O&M costs as.

$$(\mathrm{LCOE})_E = \left[(\mathrm{LCOE})_O - (\mathrm{LCOF})_O\right]\frac{\eta_O}{\eta_E} + (\mathrm{LCOF})_E, \tag{2}$$

where $\left(\text{LCOE}\right)_O$ is the LCOE at standard enrichment, $\left(\text{LCOF}\right)_O$ is the LCOF at standard enrichment, η_O is the capacity factor at standard enrichment, while $\left(\text{LCOE}\right)_E$, $\left(\text{LCOF}\right)_E$, and η_E represent the LCOE, LCOF, and capacity factor at updated enrichments. Eq. (2) provides a ballpark LCOE estimation model and can be used to evaluate the overall effectiveness of fuel enrichments at various cycle lengths. The parameters needed to solve Eq. (2) include reported prices involved in fuel production and reactor design parameters [3-5].

The LCOE can be estimated for product enrichments from 5-20 w/o and tails enrichments from 0.2-0.3 w/o for various fuel cycle lengths based on the reported plant LCOE. It is worth mentioning that the economic model employed here is primarily based on the changes in fuel costs and capacity factors. The changes in other costs (capital, O&M, decommissioning, transport, etc.) were assumed to be negligible under this model.

The total fuel cost per cycle, C_U, can be considered a summation of four costs: mining and milling, conversion, enrichment, and fuel fabrication. These four specific costs can each be multiplied by the material mass needed to produce one batch of fresh fuel (~1/3rd of the core) to find their respective total costs per cycle. The economic effect on overall fuel costs from enriching fuel to HALEU levels is best interpreted by levelized cost of fuel (LCOF) model

$$\text{LCOF} = \frac{C_U}{P \cdot \eta \cdot T_{cycle}}, \tag{3}$$

where P represents the electric power generated by the plant. It can be seen in Eq. (3) that by increasing fuel enrichment, the LCOF will be affected by the resulting change in fuel costs and increases in capacity factor and cycle time, the product of which represents a plant's effective full-power days (EFPD).

The mining and milling cost consist of the extraction of natural uranium ore from the Earth and the process of converting it into pure U_3O_8. This price is typically reported in dollars per kilogram of U_3O_8. The process of conversion involves chemical processes that convert solid U_3O_8 to a gaseous UF_6 to prepare uranium for enrichment. The price of conversion is typically reported in dollars per kilogram of uranium. In addition, the price of enrichment is priced in units of dollars per separative work unit (SWU). Separative work is a measure of the amount of energy needed to enrich the uranium and is calculated using Eq. (5) as follows

$$\begin{aligned}\text{SW} &= M_W\left(2x_w - 1\right)\ln\left(\frac{x_w}{1-x_w}\right)\\ &+M_P\left(2x_P - 1\right)\ln\left(\frac{x_P}{1-x_P}\right) - M_F\left(2x_F - 1\right)\ln\left(\frac{x_F}{1-x_F}\right)\end{aligned}. \tag{4}$$

where x_P, x_w, and x_F are the respective product, waste and feed enrichments; M_P, M_F, and M_W are the respective product, feed, and waste masses. For easier evaluation, the product mass can be assumed to be one kilogram. In this case, the feed-to-product and waste-to-product ratios become the feed and product masses, so M_F and M_W equals M_F / M_P and M_W / M_P, which can be considered as functions of enrichment [3]. By substituting these ratios in Eq. (5) a formula for finding the separative work in SWUs can be derived as a function of enrichments . By substituting these ratios in Eq. (5) a formula for finding the separative work in SWUs can be derived as a function of enrichments. The cost of enriching one kilogram of product, C_{UE}, can thus be calculated by relating the separative work of enrichment to the price in dollars per SWU (C_{SWU}) as

$$C_{UE} = C_{SWU}\left[\begin{array}{l}\left(\frac{x_P - x_F}{x_F - x_W}\right)\left(2x_w - 1\right)\ln\left(\frac{x_w}{1-x_w}\right)\\ +\left(2x_P - 1\right)\ln\left(\frac{x_P}{1-x_P}\right)\\ -\left(\frac{x_P - x_W}{x_F - x_W}\right)\left(2x_F - 1\right)\ln\left(\frac{x_F}{1-x_F}\right)\end{array}\right]. \tag{5}$$

As can be seen from Eq.(6), it is not necessary to know the feed or waste masses to find the necessary separative work to enrich uranium fuel to a certain level. For this model, it is assumed that a reliable HALEU supply chain has been established. Additionally, the total mining, milling, and conversion costs must be considered into the enrichment feed factor to determine the mass of U_3O_8 and natural uranium needed to produce one kilogram of product.

Fuel fabrication cost is the cost of converting enriched uranium from its gaseous form, UF_6, to its final fuel form. In the case of NuScale, like that of most PWRs, the fuel is in the form of ceramic UO_2 fuel pellets. Fabrication prices range from \$200-\$400 per kilogram of uranium and are higher for fuels designed to withstand higher burnup [3].

RESULTS

If an increase in total fuel cost overpowers the impact of extending cycle length, then a reactor cannot justify increasing its enrichment. The total fuel cost for NuScale's 160 MWt SMR design was estimated to range from 12.8 to 13.6 million USD (U.S. dollars). The minimum total fuel cost for HALEU fuels, 15.2 million USD, corresponds to the lowest product and tails enrichments at 5 w/o and 0.2 w/o respectively. Likewise, the maximum total fuel cost, 62.7 million USD, corresponds with the highest product and tails enrichments at 20 w/o and 0.3 w/o.

The average LCOE estimated for NuScale's SMR is approximately 86 \$/MWh [6]. The increase in total fuel costs due to higher enrichment may only be considered economically viable if the resulting LCOE is no more than the original design and available competing power generation technologies. Fig. 1 illustrates this concept by displaying the estimated LCOE for HALEU level enrichments of cycle lengths of 2.5, 3, 3.5, and 4 years assuming a fixed tails enrichment of 0.2 w/o. *Eq.* (2), which is used to calculate the curves shown in Fig. 1, provides an economic assessment and does not account for potential practical restrictions of NuScale's SMR design. The red line labeled with 'NuScale LCOE (Standard Enrichment)' refers to the estimated LCOE for NuScale's current SMR design.

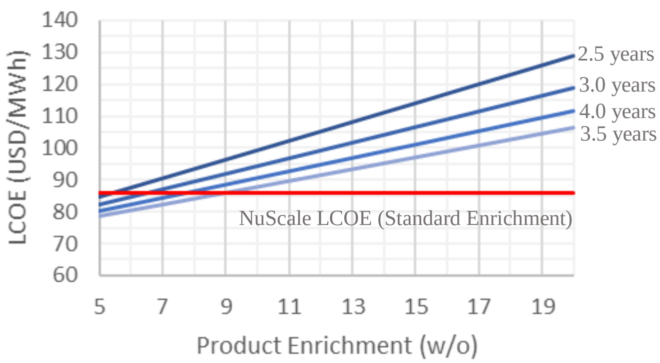

Figure 1. LCOE of target enrichments and cycle lengths.

Fig. 1 indicates that a four-year cycle at 5 w/o enrichment can achieve the lowest LCOE. However, a four-year cycle is unachievable at that enrichment without reducing power or significantly altering core design. If the optimized enrichment required to extend the cycle life of NuScale's SMR falls to the right of the intersection between the red line and the target cycle length's LCOE curve, it would not be economically beneficial to extend the cycle length. The upper limit of economically viable enrichments is 5.4, 6.6, 7.8, and 9.0 w/o for cycle lengths of 2.5, 3, 3.5, and 4 years respectively. Extrapolating this trend implies the maximum HALEU enrichment of 20 w/o could operate economically for a maximum cycle of approximately 8.6 years.

By employing Studsvik LWR reactor analysis code suites, a revised core loading for NuScale's 160 MWt SMR can be optimized for a 48-month fuel cycle with HALEU fuels. The revised design employed the NuScale's equilibrium 3-batch out-in loading scheme, in which the core's center assembly is replaced every cycle [4]. The average fresh fuel loading enrichment of the 48-month core design was found to be around 8.34 w/o U-235.

The HALEU SMR design mentioned above is estimated to operate at an LCOE of 84.8 $/MWh, or 1.23 $/MWh less than that of NuScale's 24-month design. By assuming a linear reactivity model [7], a relationship for enrichment and cycle length was established. Fig. 2 illustrates this relationship. The optimal core loading enrichments for 30, 36, and 42-month cycles were found to be 5.21, 6.26, and 7.30 w/o while their corresponding LCOEs were 85.5, 85.2, and 84.9 $/MWh respectively.

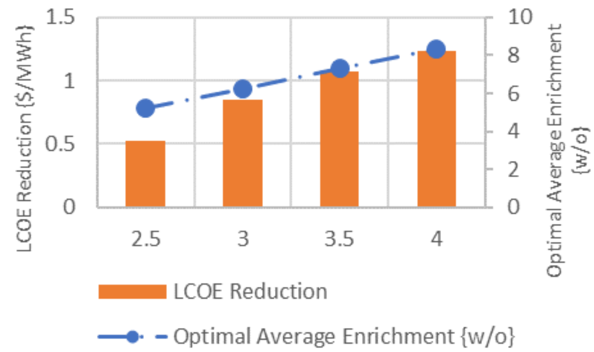

Figure 2. Optimized enrichments and LCOE reduction for SMR with extended cycle length.

CONCLUSIONS

With a power output of 45 MWe, the yearly savings for one 48-month cycle reactor using HALEU fuel is estimated to be $482,000. The total savings of NuScale's 12 module plant is expected to be roughly $5,790,000. Increasing the fuel enrichment to extend cycle length to 48 months may greatly increase the economic efficiency of an SMR. While many implications such as lack of current HALEU manufacturing infrastructure and increased fuel transport costs may diminish the benefits of HALEU fuels, it is still a very promising step in furthering the economic advantages of nuclear power.

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