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A VISION OF ADVANCED NUCLEAR SYSTEM COST UNCERTAINTY

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ABSTRACT

VISION (VerifIable fuel cycle SImulatiON) is the Advanced Fuel Cycle Initiative's nuclear fuel cycle systems code designed to simulate the U.S. commercial reactor fleet. The code is a dynamic stock and flow model that tracks key material mass flows at the elemental and isotopic levels through the entire nuclear fuel cycle. VISION.ECON is a sub-model of VISION that was developed to estimate the costs of electricity. The sub-model uses the mass flows generated by VISION for each of the fuel cycle functions and calculates costs based on the Department of Energy Advanced Fuel Cycle Cost Basis report.

This paper provides an evaluation of the cost uncertainty effects attributable to fuel cycle system parameters and scheduling variations. A scenario utilizing a single light-water reactor (LWR) using uranium oxide fuel is examined to ascertain the effects of simple parameter changes. The four variable parameters are burnup, thermal efficiency, capacity factor, and reactor construction time. The effect variables are the total cost of electricity (TCOE) and the fuel cycle costs (FCC). Strategies for future analysis are also discussed. Future work consists of extending the analysis to more complex scenarios, including LWRs using mixed oxide fuel and fast recycling reactors using transuranic fuel.

KEY WORDS

nuclear fuel cycle, uncertainty analysis, economics

INTRODUCTION

Nuclear power is experiencing a renaissance as utility companies try to keep up with increasing power demand and pressure to reduce greenhouse gas emissions. There are a multitude of paths forward as the U.S. moves to a more sustainable nuclear fuel cycle. Important choices in reactor type, fuel type, fuel fabrication, reprocessing, and waste management will all have significant impacts on the future of nuclear power. Underlying all these choices is the pressure to be economically viable. The Verifiable Fuel Cycle Simulation (VISION) model is a tool that can help compare the multitude of strategies to determine the favorable paths forward [1]. VISION.ECON extends the modeling capability of VISION by including dynamic economic analyses of the cost of future nuclear power. This paper describes the sensitivity of the economic measures of VISION to variations in nuclear designs, facility operations, and fuel cycle system parameters. These economic sensitivities are pertinent in nuclear deployment decisions.

VISION MODEL

VISION is a dynamic model of the U.S. commercial nuclear fuel cycle developed at Idaho National Laboratory (INL). The objective of VISION is to serve as a broad systems analysis and study tool applicable to the Advanced Fuel Cycle Initiative (AFCI) and Generation IV reactor development studies. The model simulates the fuel cycle from cradle to grave, from mining of raw materials, to disposition of waste after electricity generation. VISION provides the capability to study the entire fuel cycle in detail for system level economics and tradeoff studies, key isotopic mass flows, and facility needs. The model's flexibility allows selection of fuel type, reactor type, reactor mix, separation technologies, support facilities, and timing issues. VISION is designed to run on a desktop computer in 5 minutes or less. The current VISION model focuses on the U.S. reactor fleet, with the potential for expansion to international reactors and fuel cycles in the future.

The document, *Software Requirements Specification Verifiable Fuel Cycle Simulation (VISION) Model* was developed to define the objective, scope, and key assumptions of VISION [2]. In addition, expectations and requirements were developed for model variables (flow model, cost model), analysis of estimates or measures, general model architecture elements, hardware/software, constraints, and use cases. Software quality is ensured through design requirements (e.g., code transparency), quality documentation (e.g., user manuals), and performance testing (e.g., independent verification and review). The model uses nonproprietary, off-the-shelf commercial software; has an open architecture; is readily usable by fuel cycle practitioners and technical experts; and supports communication of analysis and results to less technical audiences. The graphical user interface provides an intuitive understanding of the model functionality and the capability to trace through the causes of system behavior to identify the key variables driving the behavior within the system. The VISION User Guide provides general user information, base case definitions, and default values [3]. The VISION model is constructed using Powersim Studio, a commercial system dynamics tool [4].

A schematic of the components in the VISION model is shown in Figure 1. The model is organized into a series of modules that include all of the major functions and processes involved in the fuel cycle, starting with uranium mining and ending with waste management. The arrows in the diagram indicate the mass flow of the fuel; VISION provides an isotopic mass balance of fuel and calculation of fuel by-products, such as cladding. Not shown, but included in each module are the information, decision rules, and algorithms that control the flows among the modules that form the logic for the mass flow in VISION. In the economic sub-model of VISION, the mass flows are combined with unit costs to provide insight into the economics of the fuel cycle.

Powersim Studio provides the functionality to allow economics to be included as a separate sub-model based on the flows in the core of the model. As a sub-model, new versions are easily plugged into the VISION model. In addition, development of the economics sub-model can occur independently of the VISION model.

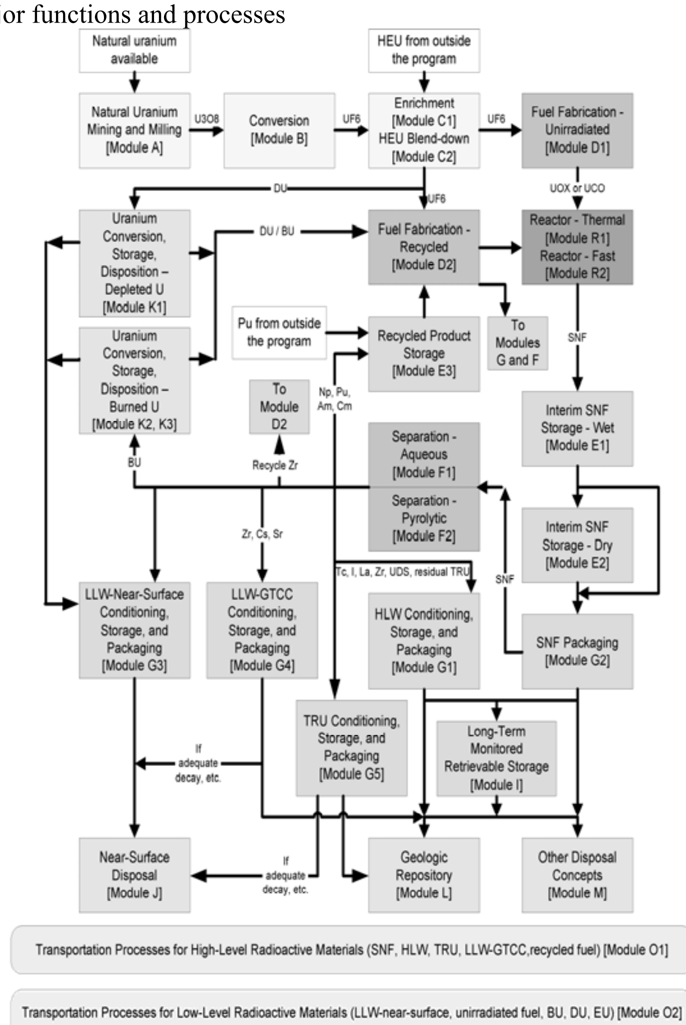

FIGURE 1. SCHEMATIC OF VISION MODULES REPRESENTING THE NUCLEAR FUEL CYCLE PROCESSES AND FACILITIES AND SHOWING MASS FLOW.

The VISION.ECON sub-model uses the mass flows generated by VISION for each of the modules and calculates the annual cost based on cost distributions (low, nominal, high) provided by the Advanced Fuel Cycle Cost Basis report [5]. Costs are calculated for each cost module, and the modules are aggregated into total fuel cycle costs, including the front-end and back-end costs. The fuel cycle front-end costs encompass uranium mining, conversion, enrichment, depleted uranium disposition, and fabrication. The fuel cycle back-end costs include used fuel conditioning and disposal in the repository. The total cost of electricity consists of the reactor capital costs, reactor annual operations and maintenance (O&M) costs, as well as the total fuel cycle costs.

SENSITIVITY ANALYSIS

The Powersim platform on which VISION is built contains a tool for sensitivity analysis, which is denoted as the "Risk Assessment" analysis capability [4]. This risk analysis feature allows users to vary parameters and measure the effect on selected variables. The risk analysis has four variable types: assumptions, decisions, objectives, and effects. Assumptions are parameters set by the user and are sampled from a user-selected distribution, which includes normal, triangular, and uniform distributions. Decisions are parameters, which the user changes to a static value that differs from the nominal value in the model. Objectives are computed variables that are a target for optimization and are not utilized in this analysis. The effects are variables that are analyzed due to changes in the assumption and decision variables. Multiple assumption, decision, and effects variables can be chosen for a risk analysis run.

The risk assessment feature clones the entire model so that changes made will not affect the main model. Simulation settings must be defined specifically for the risk analysis. The user must also define the sampling method from the choices of Latin Hypercube or Monte Carlo. The Latin Hypercube is the recommended sampling method. It partitions the data space according to its probability distribution and then randomly samples each partitioned data set. The Monte Carlo method randomly samples the entire data space. The drawback to the Monte Carlo method is longer run times due to more samples being needed to ensure that the entire data space is sampled for accurate results.

Other settings for the risk assessment include the run count, seed type and number, and the history of effects. The run count specifies the number of simulation runs for the analysis and decides how many samples to create. The seed type is a variation between random and fixed. The random option creates a random seed number from a generator for each run and the fixed option is user input so that the user may repeat results. The risk analysis samples the assumption variable using the user-defined distribution and method. The modeling algorithm analyzes the effect variable for each given sample and returns the results in percentile values selected by the user. The user may also select high or low values, average, and the standard deviation of the samples.

The effect variables used throughout this study are the two main economic measures of VISION.ECON: the TCOE and the FCC. The TCOE is calculated as the total electricity costs divided by total electricity produced (in units of kilowatt-hours). The FCC is calculated as the total fuel cycle costs divided by total electricity produced. The TCOE includes reactor costs, whereas the FCC does not include reactor costs. The units of the TCOE and FCC are mills/kWh. The sensitivity analysis considers numerous assumption variables such as burnup, reactor power, and capacity factor.

ONCE THROUGH SCENARIO

The scenario examined is a once-through fuel cycle with a single light-water reactor (LWR) using uranium oxide fuel (UOX). Parameters for this scenario are listed in Table 1. The authors acknowledge that this scenario is not truly representative of the existing U.S. commercial reactor fleet. This scenario is designed simplistically to analyze system parameters that significantly affect costs. For this scenario, the model to set to begin on January 1, 2000, and continues for 100 years with a time step of 3 months. Figure 2 diagrams the specific fuel cycle processes for Base Case 1.

TABLE 1. ONCE THROUGH SCENARIO PARAMETERS.

Mining Time	1 yr
Conversion Time	0.25 yr
Enrichment Time	1 yr
Fabrication Time	1 yr
Estimated Conventional Resources	12000 kt U
Tails Enrichment	0.25%
Number of Batches	5
Cycle Length	1 yr
Reactor Power	1.3 GWe
Capacity Factor	0.9
Thermal Efficiency	0.34
Wet Storage Time	5 yrs
Dry Storage Time	5 yrs
Interest Rate	10%
Scenario Start Date	1/1/2000
Scenario End Date	1/1/2100
Timestep	0.25 yr

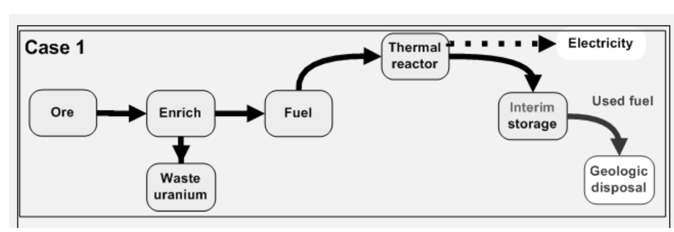

FIGURE 2. FUEL CYCLE DIAGRAM FOR BASE CASE 1 SCENARIO.

The front end of the fuel cycle consists of mining, conversion, enrichment, and fuel fabrication. Uranium mining is contingent upon world supply markets and demand from the reactor. Conversion, enrichment, and fuel fabrication are limited by the amount of material from the previous step and process time. In this scenario, fuel fabrication facilities are assumed to be commercial entities possessing excess capacity, and are not expected to be a limiting factor. The reactor lifetime of the LWR is set to span the simulation lifetime, meaning no additional reactors are constructed or will begin operating. At the simulation start point, the LWR is constructed and operated with reserve fuel. There are five batches of fuel in the reactor with a batch cycle length of 1 year.

The back end of the fuel cycle in this scenario consists of spent nuclear fuel repository disposal costs. Subsequent more complex scenarios will also feature reprocessing in the back end of the fuel cycle. Fuel cycle batches are removed from the reactor and sent to wet storage for a period of 5 years. The spent fuel is then sent to dry storage for the remainder of the simulation. Wet and dry storage is located at the reactor site and is included in reactor costs. Materials in product storage are altered by decay during their tenure by VISION.

When examining this scenario, a run of the VISION code is analyzed to examine the largest contributing factors to the main economic measures, TCOE, and FCC. Figure 3 shows components that constitute the total fuel cycle cost annually at the scenarios' equilibrium. The fuel cycle cost each year defines the FCC when divided by electricity production. The approximate percentage of the component that comprise the fuel cycle cost each year is 19% for ore mining, 3% for ore conversion, 25% for enrichment, 9% for fuel fabrication, 3% for depleted uranium disposition (DUD), 4% for conditioning, and 38% for repository disposal. [5]. The unit costs used in this analysis are based on nominal near term (next 10–15 years) cost expectations, and represent an average cost over a wide range of costs that have considered recent increases in uranium ore, enrichment services, and power plant construction costs. Figure 4 shows components that constitute the total cost annually at the scenarios' equilibrium. TCOE is defined as the total cost each year divided by the electricity produced. The approximate percentage of each component that comprises the total cost each year is 9% for the front end, up to 6% for the back end, 62% for reactor capital costs, and 23% for reactor operations costs.

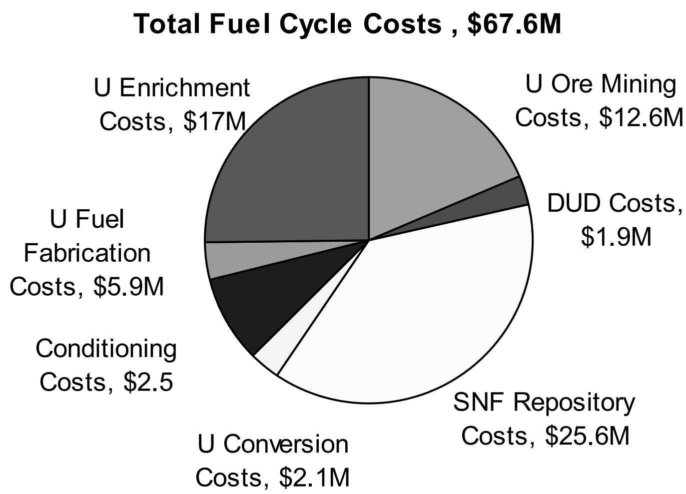

FIGURE 3. TOTAL FUEL CYCLE COSTS ANNUALLY BY COMPONENT AT EQUILIBRIUM FOR ONCE THROUGH SCENARIO.

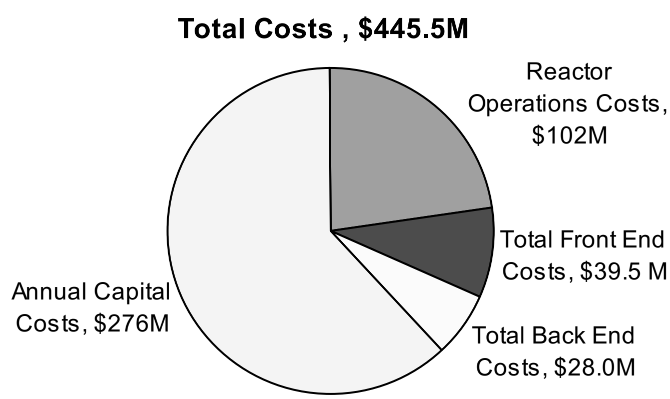

FIGURE 4. TOTAL COST ANNUALLY BY COMPONENT AT EQUILIBRIUM FOR ONCE THROUGH SCENARIO.

Assumption variables are chosen based on component contribution to costs and electricity production. The largest contributing component to total fuel cycle costs is repository disposal costs followed by uranium enrichment costs. The user-input system variable that greatly influences these costs is burnup. Higher burnups will require higher initial enrichment, but less mass of uranium. However, higher burnups lead to greater electricity production, which offsets the enrichment cost increase when analyzing fuel cycle costs (FCC). Due to these interesting tradeoffs, burnup was chosen as an assumption variable. Thermal efficiency was chosen as an assumption variable because it is a user-defined variable that is directly input. Thermal efficiency also has implications in the two largest components to total fuel cycle costs.

The largest contributor to total costs each year is the reactor annual capital costs. Reactor capital costs are based on reactor size, overnight capital costs, and the interest during construction (IDC). The reactor capital costs are annualized by amortizing the costs over the economic lifetime of the reactor using a capital recovery factor. An assumption variable that influences the reactor capital is the interest costs. Varying the interest rate would influence the total reactor capital cost. However, this sensitivity analysis is interested in the effects due to system parameters, not economic parameters; therefore, reactor construction time was chosen as a variable because it determines the amount of time that the interest is charged. The reactor capacity factor was also chosen as an assumption variable due to its direct affect on the amount of electricity annually produced.

Reactor annual capital costs are directly dependent on the reactor size, and it would seem that reactor size would be a choice as an assumption variable. However, reactor size is also directly involved with the calculation of electricity produced yearly. The main economic measures TCOE and FCC are ratios of costs-to-electricity production. A change in costs due to reactor size would scale proportionately with changes in electricity production causing no change in the economic measures. For this reason, reactor size was not chosen as an assumption variable.

Other system parameters directly input by the user were candidates as assumption variables, but had inherent problems. All modeling times for the various fuel cycle process steps (i.e., mining time, conversion time, etc.) and facility construction times were analyzed. The simplicity of the scenario made the system parameters irrelevant as assumption variables. Mining time was found to be irrelevant due to the fact that the scenario is to begin with ready fuel for reactor operation, which negates delays in mining. System parameters, not directly input, were also considered. It was found that system parameters that were not directly input were defined by variables that are directly input from the user. Reactor power is an example of one such system parameter. Reactor power is defined as the product of reactor size and a capacity factor representing availability. Capacity factor and reactor size are both user input variables. Therefore, reactor power was not chosen as an assumption variable to avoid redundancy and aid simplicity of analysis. Lastly, some system parameters were eliminated as assumption variable choices because of their embedded definitions. Fuel enrichment is defined in VISION based on fuel recipes, which are user input parameters. Fuel recipes, represented in an isotopic array, would need to be modified in order to model enrichment changes. Further research on the embedded definitions will be undertaken, but are not included in this analysis.

Using capacity factor, reactor construction time, burnup, and thermal efficiency as assumption variables and TCOE and FCC as effect variables the risk analysis produces results as illustrated in the tornado diagrams in Figures 5 and 6. Each assumption variable was sampled while the other variables were set to their nominal values. Therefore, each bar of the tornado diagram denotes a different risk analysis. The risk analysis gives the value of 43.41 mills/kWh for the TCOE and 6.59 mills/kWh for FCC with nominal values set for every assumption variable. In Figure 5, the capacity factor is shown to be uniformly sampled between 0.80 and 0.95 with a nominal value of 0.90. Reactor construction time is uniformly sampled from 4 to 6 years with a nominal value of 5 years. Burnup is uniformly sampled from 50 to 80 GWth*d/MT with a nominal value of 51 GWth*d/MT. Thermal efficiency is uniformly sampled from 0.30 to 0.35 with a nominal value of 0.34.

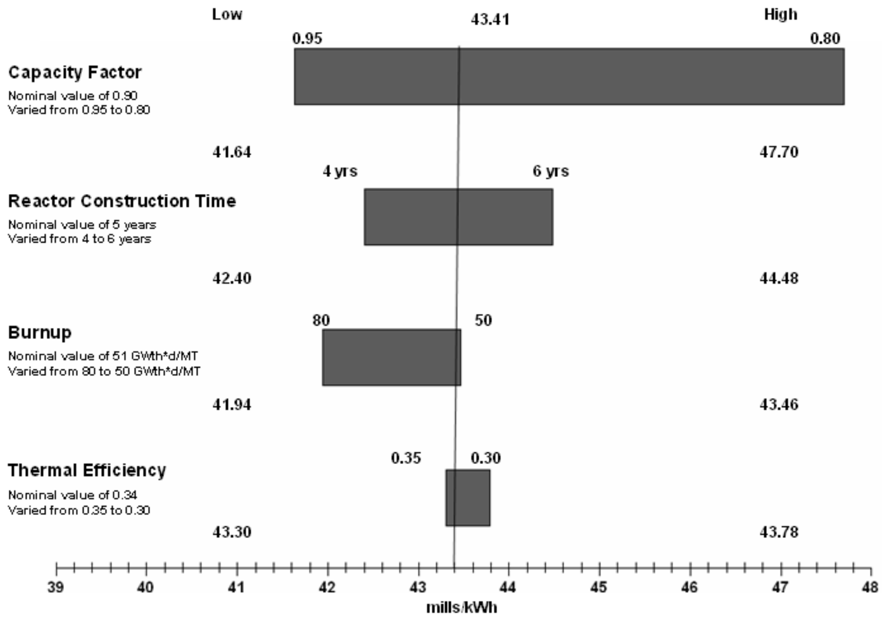

FIGURE 5. TORNADO DIAGRAM SHOWING LOW AND HIGH VALUES OF TCOE WITH VARIATIONS IN CAPACITY FACTOR, REACTOR CONSTRUCTION TIME, BURNUP, AND THERMAL EFFICIENCY.

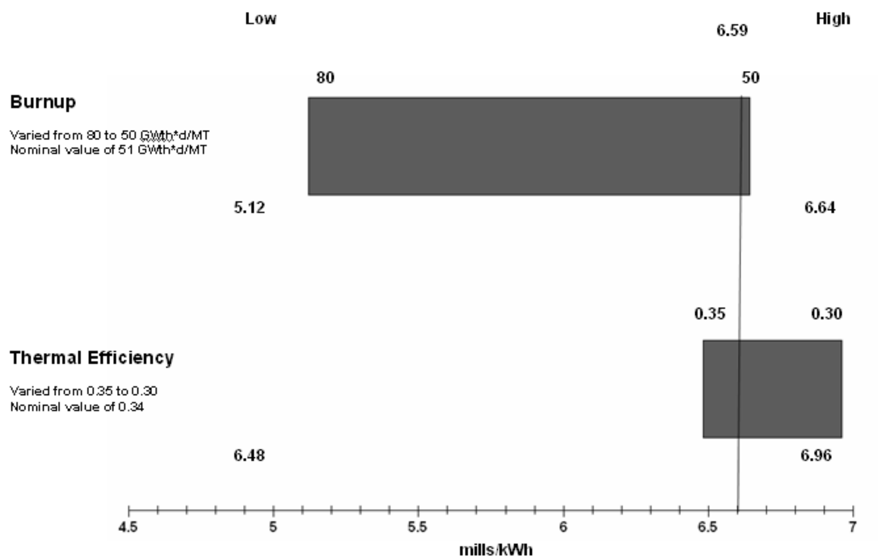

FIGURE 6. TORNADO DIAGRAM SHOWING LOW AND HIGH VALUES OF FCC WITH VARIATIONS IN BURNUP AND THERMAL EFFICIENCY.

As shown in Figure 5, an increase in TCOE results from reductions in the reactor capacity factor and thermal efficiency, and from lower fuel burnup. Longer construction times also cause an increase in the TCOE. In Figure 6, increases in FCC can result from lower reactor burnup and lower thermal efficiency. Changes in the reactor capacity factor and construction time have no affect on the FCC.

The VISION model coding and output were analyzed to understand the system implications from these results. Analysis of the results begins with single runs of the main VISION model using the high and low values of the assumption variables to discern their affects on TCOE and FCC.

Burnup is a user input variable given in GWth*d/MT. VISION uses burnup to calculate the fuel consumption rate, which is defined as the thermal power divided by the burnup. The fuel consumption rate dictates how much fuel is ordered, the front-end process rates, such as mining rate and conversion rate, and the back-end storage rates. Changes in burnup do not influence the electricity produced. Lower burnup rates require more mass at a lower enrichment to meet the specified power demand. As shown in Table 2, the lower burnup value increases the fuel cycle costs due to the increase in fuel mass flows in the front and back end of the fuel cycle. A decrease in burnup increases front-end costs by increasing the demand for uranium ore mining, conversion, fabrication, and depleted uranium disposition. However, fuel enrichment requirements (energy needed to produce fissile LWR fuel) for low burn up fuels are less on a per unit basis than for high burn up fuels. Back-end costs increase due to more reactor total fuel mass for disposition. Reactor costs do not vary with change in burnup. Table 2 illustrates the differences in cost due to varying burnup.

TABLE 2. TCOE AND FCC WITH DEFINING COMPONENTS AT HIGH AND LOW RANGES OF BURNUP.

Burnup Value	50 GWth*d/MT	80 GWth*d/MT	Units
Electricity Produced Yearly	1.03E+10	1.03E+10	kWh
Total Front End	4.03E+07	2.52E+07	$
U Ore Mining	1.29E+07	8.05E+06	$
U Ore Conversion	2.15E+06	1.34E+06	$
U Enrichment	1.74E+07	1.08E+07	$
Fuel Fabrication	6.03E+06	3.77E+06	$
DUD	1.90E+06	1.18E+06	$
Total Back End	2.81E+07	2.72E+07	$
Repository Costs	2.56E+07	2.56E+07	$
Conditioning	2.50E+06	1.56E+06	$
Reactor Costs	3.78E+08	3.78E+08	$
Fuel Cycle Costs	6.67	5.11	mills/kWh
Total Cost of Electricity	43.50	41.93	mills/kWh

Thermal Efficiency is a user input variable. VISION uses thermal efficiency to determine how much thermal energy generated is converted to electric energy in the reactor. Increasing thermal efficiency decreases front and back-end costs. The increase in thermal efficiency decreases the amount of source material needed in the front-end processes and mass of material needing to be disposed. Reactor costs and electricity production are not influenced by thermal efficiency and are constant. Table 3 illustrates the effect of thermal efficiency on TCOE and FCC.

TABLE 3. TCOE AND FCC WITH DEFINING COMPONENTS AT HIGH AND LOW RANGES OF THERMAL EFFICIENCY.

Thermal Efficiency Value	0.3	0.35	Units
Electricity Produced Yearly	1.03E+10	1.03E+10	kWh
Total Front End	4.48E+07	3.84E+07	$
U Ore Mining	1.43E+07	1.23E+07	$
U Ore Conversion	2.39E+06	2.04E+06	$
U Enrichment	1.93E+07	1.65E+07	$
Fuel Fabrication	6.70E+06	5.74E+06	$
DUD	2.11E+06	1.81E+06	$
Total Back End	2.84E+07	2.80E+07	$
Repository Disposal	2.56E+07	2.56E+07	$
Conditioning	2.78E+06	2.38E+06	$
Reactor Costs	3.78E+08	3.78E+08	$
Fuel Cycle Costs	7.14	6.48	mills/kWh
Total Cost of Electricity	43.96	43.30	mills/kWh

Capacity factor is a user input variable, which defines the availability of the reactor. Reactor power is then defined as a product of capacity factor and reactor size. An increase in capacity factor corresponds to an increase in front and back-end costs, as well as increased annual electricity production. Total fuel cycle cost increases are offset by the increase in electricity production leaving the FCC unchanged with varying capacity factor. This is not the case with TCOE due to reactor costs. Reactor costs have a strong dependence on reactor size. Reactor size does not vary with the capacity factor. Therefore, reactor costs have only a slight change with the change in capacity factor. TCOE is the ratio of total annual costs, reactor and fuel cycle, to annual electricity production. Therefore, with a higher capacity factor, the total costs are outpaced by the increase in electricity, hence lowering the TCOE. Table 4 illustrates the changes in TCOE and FCC with variations in capacity factor.

TABLE 4. TCOE AND FCC WITH DEFINING COMPONENTS AT HIGH AND LOW RANGES OF CAPACITY FACTORS.

Capacity Factor Value	0.8	0.95	Units
Electricity Produced Yearly	9.12E+09	1.08E+10	kWh
Total Front End	3.51E+07	4.17E+07	$
U Ore Mining	1.12E+07	1.33E+07	$
U Ore Conversion	1.87E+06	2.22E+06	$
U Enrichment	1.51E+07	1.80E+07	$
Fuel Fabrication	5.25E+06	6.24E+06	$
DUD	1.65E+06	1.96E+06	$
Total Back End	2.50E+07	2.97E+07	$
Repository Disposal	2.28E+07	2.71E+07	$
Conditioning	2.18E+06	2.59E+06	$
Reactor Costs	3.76E+08	3.79E+08	$
Fuel Cycle Costs	6.59	6.59	mills/kWh
Total Cost of Electricity	47.79	41.57	mills/kWh

Construction time is used to evaluate the accrued interest during construction (IDC). The interest is amortized over the reactor lifetime and contributes to annual capital cost. A change in reactor construction time does not affect any fuel cycle or reactor operations cost. It does have a significant impact on the reactor annual capital costs, which comprise three-fourths of the total cost of electricity. This leads to a significant increase in TCOE. Table 5 illustrates the changes in the TCOE with variation in reactor construction time.

TABLE 5. TCOE AND FCC WITH DEFINING COMPONENTS AT HIGH AND LOW RANGES OF REACTOR CONSTRUCTION TIME.

Construction Time Value	4 yrs	6 yrs	Units
Electricity Produced Yearly	1.03E+10	1.03E+10	kWh
Total Front End	3.95E+07	3.95E+07	$
U Ore Mining	1.26E+07	1.26E+07	$
U Ore Conversion	2.10E+06	2.10E+06	$
U Enrichment	1.70E+07	1.70E+07	$
Fuel Fabrication	5.91E+06	5.91E+06	$
DUD	1.86E+06	1.86E+06	$
Total Back End	2.81E+07	2.81E+07	$
Repository Disposal	2.56E+07	2.56E+07	$
Conditioning	2.45E+06	2.45E+06	$
Reactor Costs	3.67E+08	3.89E+08	$
Reactor Operations	1.02E+08	1.02E+08	$
Annual Capital	2.65E+08	2.87E+08	$
Fuel Cycle Costs	6.59	6.59	mills/kWh
Total Cost of Electricity	42.37	44.50	mills/kWh

FUTURE WORK

The once-through scenario is a starting point for sensitivity analysis of VISION. Future work includes extending the analysis to at least two scenarios with increasing levels of complexity. The first scenario is a one-tier fuel cycle that begins with the build of new LWRs, and then fast recycling reactors are later deployed to recycle the used LWR fuel. The second scenario is a two-tier fuel cycle that also includes LWRs and fast recycling reactors. The implicit difference is that the two-tier fuel cycle also features mixed oxide fuel recycling in LWRs prior to recycling of transuranic fuel in fast reactors operating with low conversion ratios.

An analysis of the tiered fuel cycle scenarios will begin with the assumption variables selected for the once through scenario. The introduction of fast reactors into the scenario will include fast reactor assumption variables, such as fast reactor construction time, reactor power, and capacity factor. The introduction of recycling in these latter scenarios will allow selection of assumption variables, such as conversion ratio and separation efficiencies. These more complex system studies include variations in queuing times between processes. Analyses will progress from the simplistic once-through scenario, testing appropriate variables and adding complexity as modeling confidence and user knowledge grows.

CONCLUSION

The VISION program is a tool for analyzing an analogue of the U.S. commercial reactor fleet. VISION tracks key material mass flows at the elemental and isotopic levels through the nuclear fuel cycle. VISION.ECON then uses the mass flow to estimate costs. This sensitivity analysis provides insight into what influence system parameters have on both FCC and the TCOE main economic measures. Assumption variables used in this analysis are capacity factor, reactor construction time, burnup, and thermal efficiency. A decrease in thermal efficiency and burnup corresponds to an increase in FCC. A decrease in capacity factor, burnup, and thermal efficiency leads to an increase in TCOE. Also, an increase in reactor construction time leads to an increase in TCOE. The sensitivity analysis shows that the optimal economic outcome is obtained from a system with increased capacity factor, burnup, and thermal efficiency coupled with a minimized reactor construction time. Future work is planned to extend the sensitivity analysis to more complex scenarios.

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