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ABSTRACT

The nuclear fuel cycle is a very complex system that includes considerable dynamic complexity as well as detail complexity. In the nuclear power realm, there are experts and considerable research and development in nuclear fuel development, separations technology, reactor physics and waste management. What is lacking is an overall understanding of the entire nuclear fuel cycle and how the deployment of new fuel cycle technologies affects the overall performance of the fuel cycle. The Advanced Fuel Cycle Initiative's systems analysis group is developing a dynamic simulation model, VISION, to capture the relationships, timing and delays in and among the fuel cycle components to help develop an understanding of how the overall fuel cycle works and can transition as technologies are changed. This paper is an overview of the philosophy and development strategy behind VISION. The paper includes some descriptions of the model and some examples of how to use VISION.

1. INTRODUCTION

The Advanced Fuel Cycle Initiative's system analysis group is developing a dynamic simulation model as part of their systems analysis of future nuclear energy in the United States[1]. The Verifiable Fuel Cycle Simulation (VISION) model is being used to analyze and compare various nuclear power technology deployment scenarios. The scenarios include varying growth rates, reactor types, nuclear fuel and system delays. Analyzing the results leads to better understanding of the feedback between the various components of the nuclear fuel cycle that includes uranium resources, reactor number and mix, nuclear fuel type and waste management. VISION links the various fuel cycle components into a single model for analysis and includes both mass flows and economics as a function of time.

This model is intended to assist in evaluating "what if" scenarios and in comparing fuel, reactor, and fuel processing alternatives at a systems level for U.S. nuclear power. The model is not intended as a tool for process flow and design modeling of specific facilities nor for tracking individual units of fuel or other material through the system. The model is intended to examine the interactions among the components of the U.S. nuclear fuel system as a function of time varying system parameters; this model represents a dynamic rather than steady-state approximation of the nuclear fuel system.

2. VISION MODEL

VISION tracts the flow of material through the entire nuclear fuel cycle. The material flows start at mining and proceeds through conversion, enrichment, fuel fabrication, fuel in and out of the reactor and then used fuel management, either recycling, storage, or final waste disposition. Each of the stages in the fuel cycle includes material tracking at the isotopic level, appropriate delays and associated waste streams. VISION is able to track radioactive decay in any module where the material resides for a minimum of a year.

VISION also tracks the life cycle of the strategic facilities that are essential in the fuel cycle such as, reactors, fuel fabrication, separations, spent fuel storage and conditioning and repository facilities. The life cycle begins by ordering, licensing, construction and then various stages of on-line periods and finally decommission and disposition. The model allows the user to adjust the times for various parts of the lifecycle such as licensing time, construction time and active lifetime.

VISION calculates a wide range of metrics that describe candidate fuel cycle options, addressing waste management, proliferation resistance, uranium utilization, and economics. For example, waste metrics include the mass of unprocessed spent fuel, mass in storage, final waste mass and volume, long-term radiotoxicity, and long-term heat commitment to a geologic repository. Calculation of such metrics requires tracking the flow of 81 isotopes and chemical elements.[2]

Figure 1 is a schematic of a nuclear fuel cycle, which is organized into a series of modules that include all of the major facilities and processes involved in the fuel cycle, starting with uranium mining and ending with waste management and disposal. The arrows in the diagram indicate the mass flow of the material. Not shown, but included in each module, are the information and decision algorithms that form the logic for the mass flow in VISION. The mass flows are combined with cost and waste packaging data to provide insight into economics and transportation issues of the fuel cycle.

3. SYSTEM DYNAMICS

System dynamics is a computer-based method for studying dynamic, problematic behavior of complex systems. The method emerged in the 1960s from the work of Jay Forrester at the Sloan School of Management at Massachusetts Institute of Technology. A detailed description of the system dynamics approach was first given in "Principles of

Systems".[3] The methodology is used in many fields including global environmental analysis of world system,[4,5] global and regional sustainable development issues[6], environmental management,[7] water resources planning and management[8] and environmental and ecological modeling.[9] System dynamics models are implemented with icon-based stock-and-flow software programs such as Stella©, Vensim© and Powersim Studio©. VISION uses the commercial system dynamics tool, PowerSim Studio.[10]

System dynamics models are valued for the clarity of their "stock-and-flow" structure, the inclusion of nonlinear and delayed relationships, the ease of numerical simulation and the potential for highly interactive operation from "user-friendly" interfaces.

The key aspect of system dynamics is the use of feedback principles in the analysis of complex systems. A system dynamics computer model consists of interacting feedback loops forming the complex structure and mathematical equations defining the relationships between the variables in a complex system. The model is built around the concept of stocks and flows developed through a system dynamics methodology.[11] Variables are identified as stock, flow, or converter variables, where stocks represent accumulations, flows represent rate of change in accumulations, and converters represent all miscellaneous calculations and decision rules.

System dynamics models are descriptive in nature. Each element in the model must correspond to actual entities in the real world. The decision rules in models must conform to actual practice. System dynamics models are useful for evaluating options, designing policies, and informing decisions. Policies, as represented in the equations of a system dynamics model, are the rules by which decisions are made. The policies state what decision should result from any possible combination of current conditions. The recommended policy states how to make a stream of decisions moment by moment through time. The model allows policies and conditions to be varied, allowing the user to evaluate options, test policies and better understand the interconnections within a system and the potential impact of policies on a system over time.

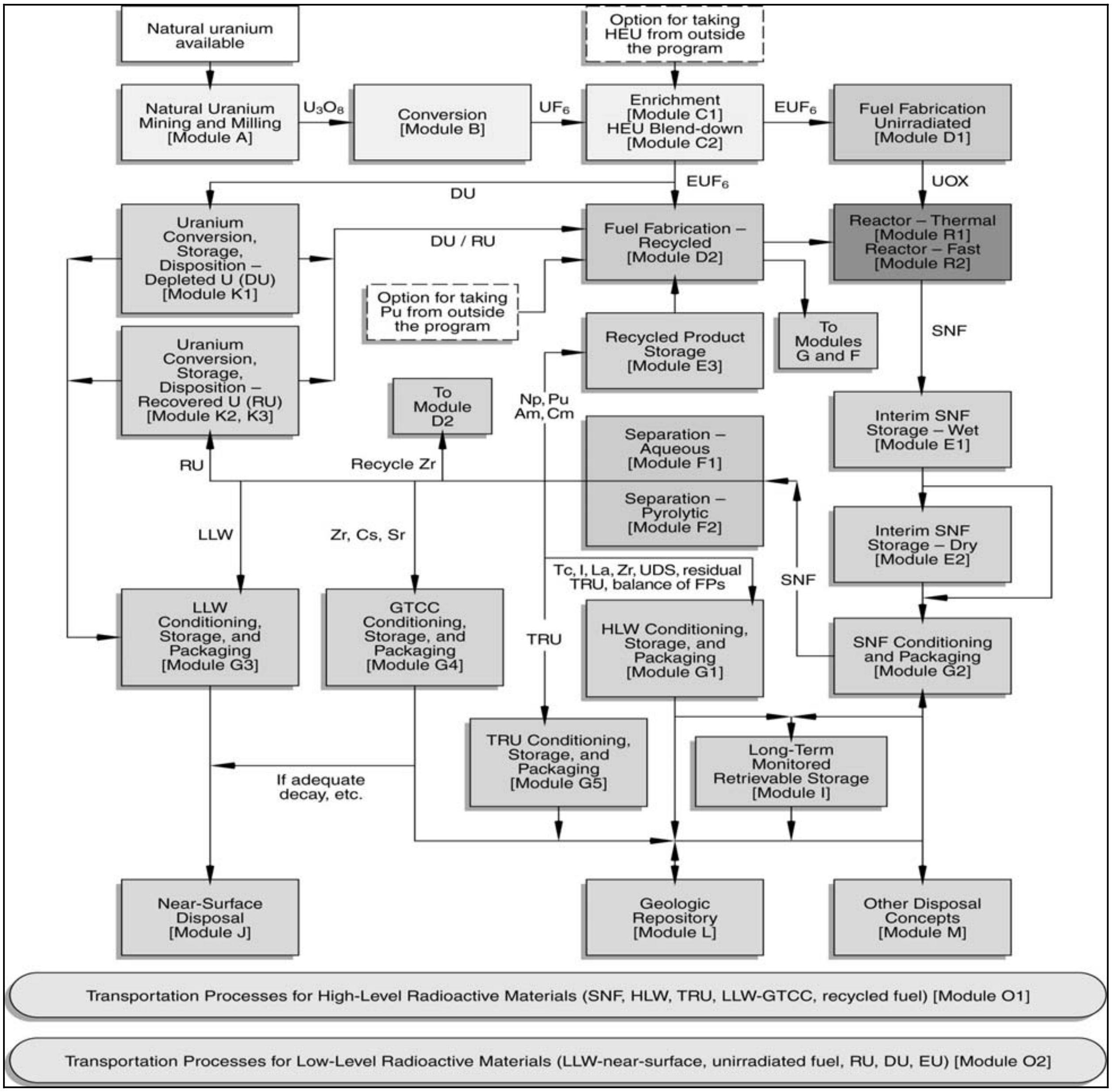

Fig. 1 Schematic of VISION modules representing the nuclear fuel cycle processes and facilities.

4. VISION FUNCTIONALITY

4.1Overview

VISION is designed to run on a desktop personal computer with run times less than 5 minutes. The program can be distributed for free and run through a free model player that can be obtained through the Powersim website.[10] Users can run scenarios by selecting pre-defined base cases or by modifying the options that make up a scenario.

Results are displayed in a variety of charts and graphs that are part of the interface or the user can open up the Excel charts that include many more tables and charts.
The VISION model takes a projected energy growth rate and nuclear power market share over the next century and builds reactors in order to meet this demand, along with the necessary support facilities. Options are included in the model that will allow the user to recycle used nuclear fuel with many different separation technologies, use several different reactor and fuel types, and have several different waste management options. The results of the model will help policy makers and industry leaders know and understand the infrastructure requirements, material flows, and comparative metrics for any combination of advanced fuel cycle scenarios.

The subsections below describe key algorithms and approaches that comprise VISION's functionality. The first several subsections address the issue of when new facilities are ordered. VISION now has a complex look-ahead ordering algorithm for new facilities. The user can instead force the model to build facilities by inputting the capacity for each type of facility. The discussion on facility ordering entails subsections on facilities themselves as an introduction, supplies needed for the facility, and outputs from each facility. After ordering facilities, the section turns to energy growth rate, and then the physics issues of which isotopes are tracked in VISION and how VISION uses reactor physics data.

4.2. Tracked Isotopes

VISION tracks mass at an isotopic level, which is valuable from several aspects. First, the model is able to calculate some important metrics, such as, decay heat, toxicity and proliferation resistance. Second, it allows the model to use specific isotopes, such as Plutonium, for flow control in separations and fuel fabrication based on availability of Pu239, Pu240 and Pu241 from separated spent fuel. Lastly, it allows the estimate of isotopic decay.

Table 1 below lists the 81 isotopes that VISION currently tracks the main fuel flow model. For the four radionuclide actinide decay chains (4N, 4N+1, 4N+2, 4N+3), it will track all isotopes with half-life greater than 0.5 years, with the exception of 5 isotopes whose inventory appears never to be significant. For fission products, VISION calculates isotopes found to dominate each possible waste stream, CsSr (Group 1A/2A), halogens, inert gases, transition metals, Zr, Tc, lanthanides, H-3, and C-14. In each case, both key radioactive isotopes and stable mass must be tracked because for the key elements, it is needed to calculate the mass of the key fission product divided by the total mass of that element. For example, to assess the "CsSr" waste option, VISION tracks Sr90 (with Y90 decay energy), Cs134, Cs135, Cs137 (with Ba137m decay energy), stable Rb, other Sr mass, other Cs mass, and stable Ba.

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Table 1: Tracked Isotopes and Chemical Elements.

Actinides and Decay Chain		Fission Products	
He4 (stable)		H3	
Pb206		C14	Other gases
Pb207		C-other	
Pb208	Transition metals	Kr81	
Pb210		Kr85	Inert gases (Group 0)
Bi209		Inert gas other (Kr, Xe)	
Ra226	Group 2A	Rb	
Ra228		Sr90 w/Y90 decay	Group 1A/2A
Ac227		Sr-other	
Th228		Zr93 w/Nb93m decay	
Th229	Actinides	Zr95 w/Nb95m decay	Zirconium
Th230		Zr-other	
Th232		Tc99	Technetium
Pa231		Tc-other	
U232		Ru106 w/Rh106 decay	Transition metals that constrain glass waste forms
U233		Pd107	
U234	Uranium	Mo-Ru-Rh-Pd-other	
U235		Se79	
U236		Cd113m	
U238		Sn126 w/Sb126m/Sb126	Other transition metals
Np237	Neptunium	Sb125 w/Te125m decay	
Pu238		TM-other (Co-Se, Nb, Ag-Te)	
Pu239		I129	Halogens (Group 7)
Pu240	Plutonium	Halogen-other (Br, I)	
Pu241		Cs134	
Pu242		Cs135	
Pu244		Cs137 w/Ba137m decay	Group 1A/2A
Am241		Cs-other	
Am242m	Americium	Ba	
Am243		Ce144 w/Pr144m/Pr144 decay	
Cm242		Pm147	
Cm243		Sm146	
Cm244		Sm147	
Cm245	Curium	Sm151	Lanthanides (plus Y)
Cm246		Eu154	
Cm247		Eu155	
Cm248		Ho166m	
Cm250		LA-other plus Yttrium	
Bk249	Berkelium		
Cf249			
Cf250	Californium		
Cf251			
Cf252			

Only isotopes with halflife greater than 0.5 year are candidates for being tracked in fuel cycle simulations. A half year is two VISION time steps. Not tracking such short-lived isotopes does not significantly impact mass and radiotoxicity assessments. (Spot checks of gamma and heat indicate the same thing.) Short-lived progeny of other isotopes, however, must be considered. Their heat and decay energy emission must be included when their parent isotopes decay. For example, Y90 decay energy must be included with decay of Sr90.

For actinide and decay chain isotopes, we started with all isotopes with halflife greater than 0.5 year. . The behavior of actinide and decay chain isotopes is so complex that we essentially have to include all isotopes with halflife greater than 0.5 years. However, we do discard five of the candidate isotopes (Np235, Np236, Pu236, Cf248, and Es254) because their yield is so low. In subsequent calculations of radiotoxicity, heat, etc, the decay input of those isotopes less than 0.5 years must be accounted for as being in equilibrium with longer-lived parents.

Compared to actinide and decay chain isotopes, the complexity of behavior is less and the number of candidate isotopes is greater for fission products. We started with the set of fission product isotopes previously studied in AFCI system studies and added isotopes (and blocks of "stable" elements) such that the mass and radiotoxicity of each of the candidate waste streams (inert gases, lanthanides, CsSr, transition metal, Tc, halogens) calculated from the reduced set of isotopes and elements was within a few percent of calculations using all the isotopes for UOX at 51 MWth-day/kg-iHM burnup. The current version of the code evaluates the heat loads, radiotoxicity, proliferation metrics and other parameters at key location in the fuel cycle (repository, dry storage, etc.). For separation and recycle of used thermal fuel, the youngest (shortest time out of the reactor) and then least cycled fuel has priority for the available capacity. The repository capacity can be varied with time, and includes permanent and retrievable capacities, and the rate material can be sent to the repository can also be varied with time. In contrast to separations, the oldest (longest time out of the reactor) and then most cycled fuel has priority for the repository.

4.3. Neutronics Parameters

A key feature of the VISION model is that direct neutronics calculations are not performed within model, which makes it much simpler and more user friendly compared to other fuel cycle system codes that include this type of calculations such as COSI and NFCSIM codes.[12,13] The neutronics calculations are made external to the model and parameters from those calculations are used as fixed parameters within the model. The important parameters are the composition of fresh and spent fuel that corresponds to a certain type of reactor/fuel, and the initial reactor core loading and the loading per a batch of fuel. More than one composition vector (recipe) can be provided for the same fuel, e.g., in case of recycling in FR, a non-equilibrium (startup) composition is needed for early cycled fuel and an equilibrium (recycle) composition is needed for fuel cycled greater than or equal to 5 times. Table 2 below shows an example of a typical set of those fuel compositions. Users can input whatever input/output fuel recipes they wish. The two types of LWR fuels shown in the table are typical medium- and high-burnup PWR fuel. The medium burnup fuel has an initial enrichment of 3.2% U-235 and a discharge burnup of 33,000 MW-day/tonne-HM. The high burnup fuel has an initial enrichment of 4.3% U-235 and a discharge burnup of 51,000 MWth-day/tonne-iHM. The compositions shown in the table are based on transmutation calculations performed elsewhere.[14] Other current sources of data include Hoffman, Asgari, Ferrer.[15,16,17] The user can alternatively input their own input and output isotopic recipes.

Table 2. Example Fresh Fuel and Spent Fuel Compositions. Note: the table only lists a few of the isotopes that are actually tracked in VISION.

	UOX-33	UOX-50	MOX		FR Startup		FR Recycle	
Wt, %	Spent Fuel		Fresh Fuel	Spent Fuel	Fresh Fuel	Spent Fuel	Fresh Fuel	Spent Fuel
Pu	0.893	1.163	12.450	9.713	47.130	34.700	53.890	40.920
Am	0.037	0.064	0.000	0.737	6.823	5.645	10.550	8.948
Np	0.034	0.062	0.660	0.099	2.138	1.256	1.430	0.860
Cm	0.002	0.008	0.000	0.099	0.733	0.943	3.491	3.049
Pu-238	0.012	0.031	0.328	0.604	2.946	2.988	4.224	3.414
Pu-239	0.513	0.615	6.608	4.101	19.860	12.420	14.860	9.438
Pu-240	0.226	0.292	3.126	2.840	13.960	12.310	21.020	17.450
Pu-241	0.096	0.138	1.471	1.469	5.584	2.455	4.466	2.574
Am-241	0.029	0.044	0.000	0.213	4.777	3.615	4.316	3.363
Sr-90	0.048	0.070	0.000	0.036	0.000	0.118	0.000	0.113
Cs-137	0.107	0.162	0.000	0.163	0.000	0.631	0.000	0.632
FP	3.409	5.258	0.000	5.179	0.000	18.690	0.591	19.250

The fast reactor compositions shown in the table are based on the following calculations. Transmutation in low conversion ratio fast reactor is based on a compact fast burner reactor design that can achieve low conversion ratios.[16] This design is the basis for all transmutation options that used TRU from UOX, MOX or IMF spent fuel into a burner fast reactor in the VISION calculations.

4.4. Isotopic Decay

Isotopic decay can be applied to any storage area where fuel is allowed to stay more than one year. This includes key areas (wet interim storage, dry interim storage, managed retrievable storage, and repository storage. Three options are currently available: run the model with decay everywhere, run the model with decay in the wet interim storage only, or run the model with no decay.

Isotopic decay of fresh fuel and spent fuel can have dramatic effects on performance, heat loads, handling requirements and toxicity. VISION seeks to include various features and metrics related to a variety of isotopes, in an effort to better evaluate the evolution of the fuel cycle dynamics. Some of those isotopes are short lived and their quantities are significant to radiotoxicity and dose calculations, which can be important, for example, to waste packaging and reprocessing facilities. Thus, taking into account the decay of those isotopes is an important feature of VISION. In addition, the VISION system model allows for the simulation of spent fuel of different cooling times; this requires tracking of the decay of the transuranic isotopes.

The general equation representing decay from $^{224}\mathrm{Ra}$ to $^{220}\mathrm{Rn}$ is shown below.

$$\frac{d}{dt}N_{Rn-220} = N_{Ra-224}\lambda_{Ra-224} - N_{Rn-220}\lambda_{Rn-220} \tag{1}$$

Where λ is represented by $\lambda = \frac{\ln(2)}{T_{\frac{1}{2}}}$ and N is the mass of the specific isotope.

Fig. 3 below shows the basic model structure used to emulate isotopic decay within VISION. Used fuel flows into a storage facility. Each year the material resides in storage it loops around the decay loop and the decay algorithm is applied and the material. At the end of its storage time the material moves out of storage and into the next fuel cycle component.

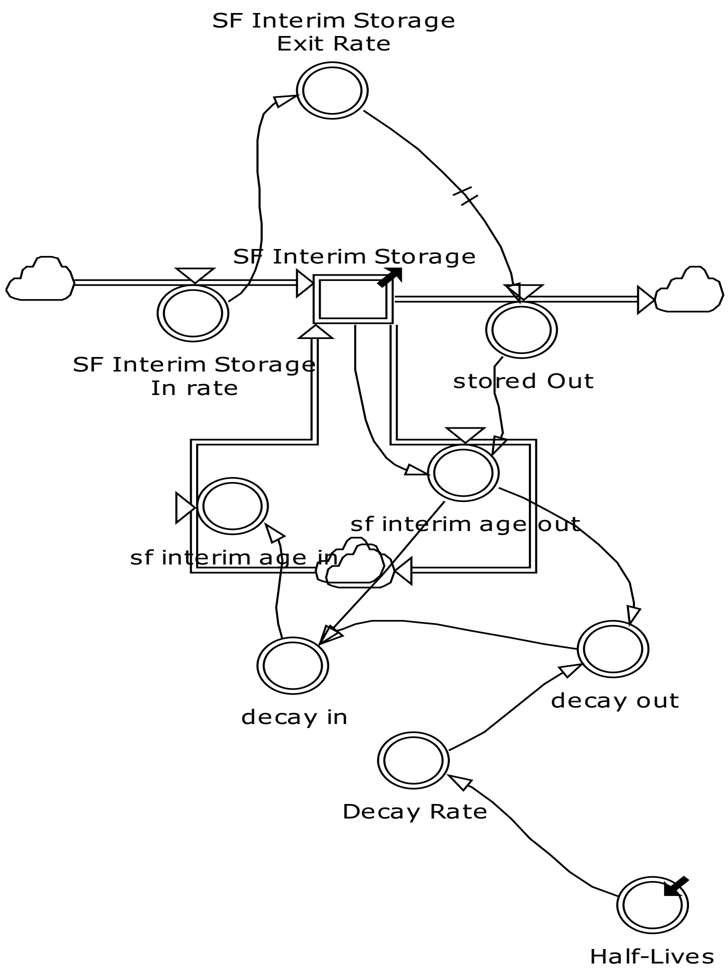

Fig. 3 Complete condensed decay flow as it appears within the model.

One consequence of including isotopic decay is that the isotopic composition of the feedstocks available for making fuel continually changes with time. Isotopic composition also varies as fuel burnup, the number of times material is recycled, and transitions from one fuel cycle option to another. The composition vectors (recipes) currently used in VISION assumes a known and fixed feedstock composition. To fully utilize the feedstock material, the composition vectors will have to shift with time. Other system codes have approached this need to dynamically change the composition vectors several ways. The NFCSIM code contains its criticality engine, which is combined with the depletion calculations that are performed using the ORIGEN2 code.[18] The COSI code uses the equivalency method combined with the CESAR depletion code.[19] For the fuel based on Pu, the Pu content is calculated by taking into account the plutonium composition, and using dedicated formula expressed in fissile isotopes or equivalent Pu-239. In the case of fast spectrum reactors, COSI uses the reactivity coefficient equivalent to Pu-239 for all important isotopes of U and Pu. In the case of thermal reactors, the code uses the results of large sets of LWR deterministic calculations to interpolate the cross sections needed for the CESAR code calculations and to estimate the equivalent enrichment. As mentioned before both codes perform a certain level of detailed neutronics calculations, which will be avoided in the VISION model. In order to avoid the detailed calculations, VISION aims at estimating the new fresh and spent fuel composition vectors using interpolation within tabulated values, correlations of recipes as a function of key input parameter (e.g. UOX burnup) or using a perturbation method to cover the possible range of operations of certain type of fuel. This work is currently underway and the methodology will be based on a large number of deterministic calculations for different types of fuel and reactor.

In dynamic simulations of fuel cycles, the isotopic composition of material that is available in a given time step “never” exactly matches the fixed static calculation one obtains from a transmutation analysis calculation. For example, the average age of separated material available to make fuel might be 11.5 years whereas the closest calculation for a recipe might be for 10 years. Therefore, for several years, we have been building a set of tools that would allow adjustments of fuel input and output fuel recipes in models such as VISION. There are three types of tools:

- Increase the number of recipes available so that the deviation between available material composition and requested fuel composition is minimized.

- Correlations that interpolate the input and output recipes based on specific identified input materials. VISION presently has two such correlations. The first provides the LWR UOX input and output compositions as a function of burnup between 33,000 and 100,000 MWth-day/kg-IHM.[20] When using this correlation, the user identifies in each year the assumed average LWR UOX burnup of the reactor fleet. The second correlation provides the fast reactor input and output compositions as a function of the fast reactor transuranic conversion ratio between 0.00 and 1.00. This ratio is defined as the production of transuranic material divided by the total destruction of transuranic material. It is similar but different than the classic fissile breeding ratio because it is more appropriate as a waste management metric; and fast reactors do obtain net neutrons from essentially all transuranic isotopes. As with LWR UOX burnup, when using the fast reactor TRU conversion ratio correlation, the user indicates each year the average fleet conversion ratio. Correlations of input/output recipes for UOX as a function of burnup and for FR fuel as a function of FR TRU conversion ratio.[20]

- A perturbation approach using 1-group cross sections for fission and neutron capture.[21] In a real system using recycled material, the composition will vary near a target composition as the source material's burnup, aging time, etc. vary. So, this method, still under development, involves starting with a target composition (obtained above) and then varying the composition based on 1-group cross sections. As the reactivity worth of the available recycled transuranic material varies versus the target composition, the equations provide an increase or decrease in the ratio of TRU/uranium in input fuel and the adjusted composition input recipe then matches the isotopic mix of input material. The output recipe is correspondingly adjusted using 1-group cross sections for the appropriate irradiation time and the original target composition.[21]

5. SIMULATION

The real power of simulation models lies in learning insights into total system behavior as time, key parameters, and different scenarios (e.g. growth rate, reactor type) are considered. This is more valuable (and more credible) than attempting to make design and management decisions on the basis of single-parameter point estimates, or even on sensitivity analyses using models that assume that the system is static. System dynamic models allow designers and stakeholders to explore long-term behavior and performance, especially in the context of dynamic processes and changing scenarios. When comparing different management/design scenarios did the system perform better or worse over the long term?

System dynamic models serve many of the same purposes as flight simulators. Indeed, the reason the user input is described as a "cockpit" is that such a model allows the designer/stakeholder to simulate management of the system over time. System dynamic models serve many of the same purposes as flight simulators. After repeated simulations, a student pilot gains deeper understanding of how the aircraft systems will respond to various perturbations (none of which will exactly match a real flight) – without the expense and risk of gaining such experience solely in real flights. Instead of simulating an aircraft flight, VISION simulates the nuclear fuel cycle system with as many of its dynamic characteristics as possible. This allows decision makers and developers to learn how the fuel cycle system may respond to time and various perturbations – without having to wait decades to obtain data or risk a system disconnect if a poor management strategy is used. VISION also allows users to test a range of conditions for parameters such as energy growth rate and licensing time which are not controlled by developers of nuclear energy but affect its implementation so that robust and flexible strategies can be identified to address uncertainties.

6. APPLICATION

VISION is capable of exploring a range of strategies for an advanced fuel cycle system. In this context, a strategy is a general approach to fuel management that encompasses a range of options with similar basic characteristics. A strategy identifies which materials are recycled (if any), the type of nuclear power plant, the type of spent fuel processing technology, and which materials go to geologic disposal. For the purpose of discussion, four strategies are considered in this paper:

- The current U.S. strategy is **once-through** - all the components of spent fuel are kept together and eventually sent to a geologic repository.

- The second strategy is **limited recycle**, recycling transuranic elements once. Remaining transuranic elements and long-lived fission products would go to geologic disposal. Uranium in spent fuel, depleted uranium, and short-lived fission products would be disposed as low-level waste. This strategy uses existing types of nuclear power plants, which are all thermal reactors.

- The third strategy is **continuous recycle**, recycling transuranic elements from spent fuel repeatedly until destroyed. Continuous recycle is more technically challenging than limited recycle and therefore more research, development, and deployments would be required. Uranium in spent fuel can be recycled or disposed. Essentially no transuranic elements would go to geologic disposal. Long-lived fission products would either go to geologic disposal or some could be transmuted in power plants. Short-lived fission products would be disposed as low-level waste. This strategy would use a combination of thermal reactors and burner fast reactors.

- The fourth strategy is **sustained recycle**, which differs from transitional recycle primarily by enabling the recycle of depleted uranium to significantly extend fuel resources. This strategy would primarily use breeder fast reactors.

Fig. 4 below presents the four strategies in a diagram that outlines the path for each strategy. These four strategies are among the pre-defined cases loaded into VISION. Below are some results that demonstrate the outcomes and comparison capabilities that are available through VISION.

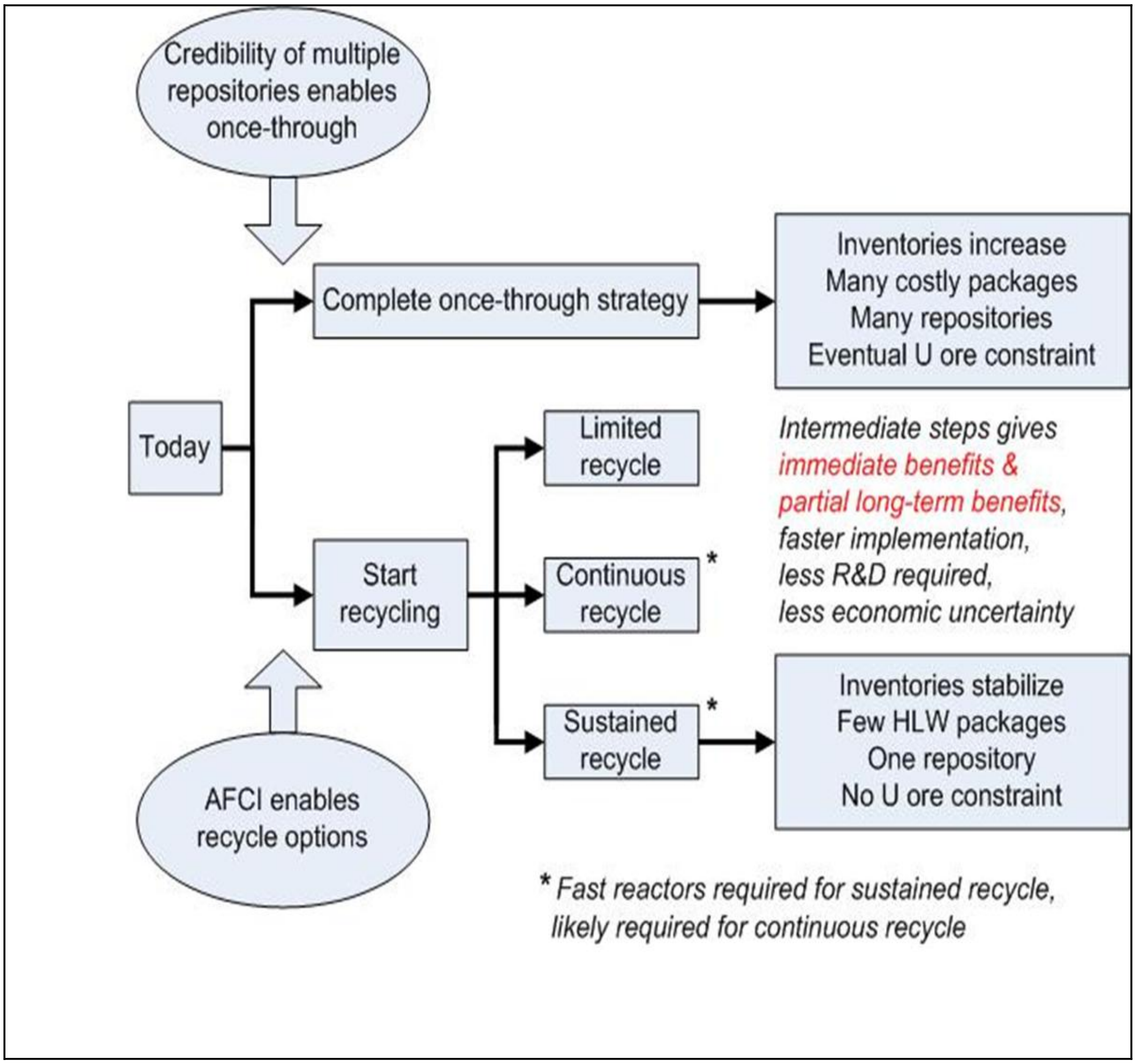

Fig. 4 This diagram depicts the four basic strategies for nuclear growth in the US.

The basic assumptions used for the four strategies are shown in Table 3 below.

Table 3 Basic assumptions used for 4 strategies.

Strategy	Reactor Type	Fuel Type	Fuel Separation	Material Sent to Repository
Once through	thermal reactors	UOX	No	Spent fuel
Limited recycle	thermal reactors	UOX & MOX	Yes	HLW
Continuous recycle	thermal reactors & burner fast reactors	UOX & fast reactor	Yes	HLW
Sustained recycle	Breeder Fast Reactor	UOX & fast reactor	Yes	HLW

In the case below we started the scenarios in 2000 with 103 reactors already on line. The growth rate was set at 1.8% for each of the cases. The output in Fig.. 5 below shows the total mass in the system for each of the four cases. The total mass includes all mined material, material in reactors, wet storage, dry storage, separations and final repository. The once through case has generates the most mass in the system since no material is recycled. Fast breeder reactors generate the least amount of material since once the reactors are fully fueled they require no more mined material.

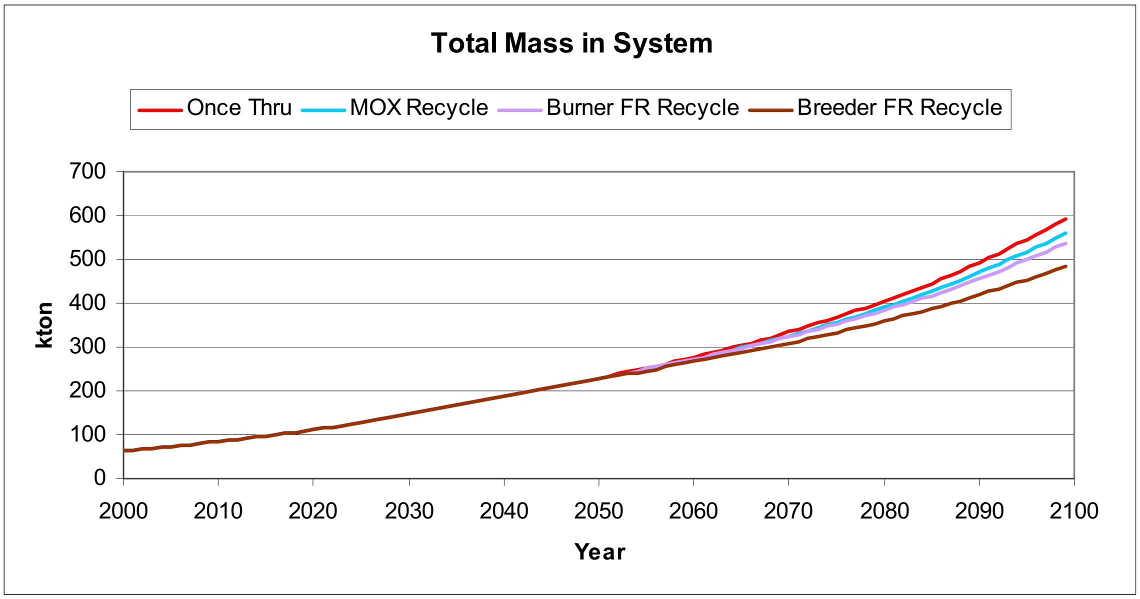

Fig. 5 This chart displays a comparison of total mass in the system of the four base cases of once-through, MOX recycle, Burner Fast Reactor and Breeder Fast Reactor.

Fig 5 is just one example of the type of output that is generated from running scenarios with VISION. In addition to charts, VISION also generates a large number of data tables. The tables are also output to Excel files where the user can generate new charts and figures from the results.

7. SPREADSHEET CONNECTIVITY

Powersim has a variety of tools for adjusting input parameters and visualizing results but VISION required more control for both input and output because of the complexity of the model. Fortunately, Powersim Studio has a powerful connection capability with Microsoft Excel. VISION extensively uses connections to Excel to exchange both input as well as output data.

For input, the predefined cases are defined in a set of tabs in Excel. The user selects the scenario to run from the user interface in VISION and then the data is loaded from Excel spreadsheets. There are over 50 predefined scenarios for the user to select from that cover the myriad of options for nuclear reactor deployment. The user can select any of these pre-defined scenarios or there are some place holders set aside that allow the user can define their own scenarios.

Because of the number of metrics that VISION calculates each time period, it was necessary to export the data to Excel in order to be able to display the output in a useable fashion. Over 200 time-dependent output parameters are exported to Excel after each run. By exporting output data to Excel much more elaborate charts and graphs can be used to compare the output results from several different scenarios. The results in Excel are divided up into select categories such as reactor data, separations data, and waste calculation. VISION is set up to allow the user to run up to 5 different scenarios in a comparative mode. The results from the 5 scenarios will be displayed in comparative charts and tables in Excel for easy comparisons. In addition, all the raw results are output to Excel for additional analyses if necessary.

8. LIMITATIONS

There are three major limitations of this study. First, thermal reactors (TR) are always represented by Light Water Reactors (LWR) and both convertor fast reactors (CFR) and breeder fast reactors (BFR) are always represented by Sodium Fast Reactors (SFR). (We are aware many colleagues use the phrase “burner fast reactor;” however, this report uses “consumer” so the acronym (CFR) differs from BFR and minimizes the chance of misinterpretation of “burn” in the chemical reaction sense.) Processing of thermal reactor fuel is performed at centralized plants using UREX+ technology. Processing of fast reactor fuel is performed at power plants using pyrochemical technology. To first order, we do not believe the conclusions in this report would differ substantially for other thermal or fast reactor options based on the AFCI evaluation of Generation IV transmutation impacts.[22] We have not considered ultra-high burnup with the Very High Temperature Reactor (VHTR) concept.

The second assumption is that all options studied are technically feasible and available at the time indicated in various deployment scenarios (typically 2025), which implies the necessary underlying research, development, and demonstration have been completed. Thus, in this report, there is no analysis on the basis of technological maturity or readiness to deploy. Similarly, there is no analysis on the basis of R&D costs.

The third is that detailed fuel cycle data are only available for a finite subset of specific recycle cases. Although great care has been taken to assure the fuel cycle performance for each case has been analyzed in a consistent manner, not all promising options have been considered. In future work, the scenario evaluations will be utilized to define additional cases for detailed analyses; and new fuel cycle transmutation data on specific options will be incorporated into the dynamic model, as available.

9. CURRENT MODEL AND FUTURE DEVELOPMENT

VISION currently supports multiple reactors (up to 10). The fuel recipes specify the initial fuel isotopic composition going into a reactor and the fuel compositions at the time the fuel is removed from the reactors. The model tracks radioactively decay for all materials in the model when mass remains in a location for 1 or more years. Reactors and all support facilities (fuel fabrication, separations, and storage facilities) have a specified life time and are then retired. Retired facilities are replaced with new facilities so that there is no drop in support. Support facilities are ordered based on future projection requirements for their services so that they start when needed.

Used fuel separations strategies are defined by the user and includes detailed specifications of isotope separation and waste stream design. Separations strategies can be modified for any fuel type throughout the simulation time period. A large number of performance metrics are tracked throughout the entire simulation time period. The metrics include reactor as well as fuel tracking calculations. All metrics are exported to Excel for post-simulation analyses. Up to 5 simulations can be run in a comparative set of analyses. These comparative sets are plotted in comparative graphs in Excel for easy comparisons of the simulation scenarios.

Future development will include the development of a graphical user interface that will help guide the user through the myriad of options and scenarios that VISION can simulate. Additionally, adding in regions into the model will allow VISION to start to simulate user/supplier states such as those being proposed by Global Nuclear Energy Partnerships (GNEP).

10. SUMMARY

For high-stakes strategy analysis, a system dynamics model, as a result of upfront scientific work, is easier to understand, more reliable in its predictions, and ultimately far more useful than discussion and debate propped up by traditional data analysis techniques such as histograms, Pareto charts and spreadsheets. System Dynamics is an analytical approach that examines complex systems through the study of the underlying system structure. By understanding a system's underlying structure, predictions can be made relative to how the system will react to change.

One consequence of the modeling effort has been the active involvement of universities in the development of the model and its components. Initially summer interns were used to help verify the model and develop some small components. This effort then blossomed into full collaboration efforts between the INL and several universities which resulted in graduate students developing more complex components as part of the graduate studies. The end results more detailed VISION model components in addition to 3 master's degrees and 2 PhD degrees based on work with the VISION code. Also, there are several universities that are using VISON for their fuel cycle classes. VISION is a dynamic systems model that tests nuclear energy deployment scenarios. This model is under continuous development and future revisions will include more reactor and fuel types, more detailed economic analyses, tracking of transportation of new fresh and spent fuel, and allowing for regional fuel cycle facilities. The model is actively used and is supporting AFCI Systems Analysis.

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ACRONYMS

Am	Americium
Cm	Curium
DOE	Department of Energy
FBR	Fast burner or breeder reactor
HLW	High level waste
IMF	Inert matrix fuel, i.e., uranium free fuel
LLW	Low level waste
LTH	Long-Term Heat, a metric describing the heat committed to waste disposal from time of repository closure to ~1500 years
LTR	Long-Term Radiotoxicity, a metric describing the radiotoxicity of isotopes at a specific time after repository emplacement, taken to be 1000 years in this report
LWR	Light Water Reactor
LWRmf	Light Water Reactor capable of using multiple fuels
MOX	Mixed Oxide fuel, a mixture of uranium oxide and one or more transuranic element oxides, e.g. MOX-Pu or MOX-TRU
MWth-day /kg-iHM	Megawatt thermal day per kilogram heavy metal, a unit of burnup, i.e., energy per mass of fuel. Equivalent to GWth-day/tonne-iHM
Np	Neptunium
Pu	Plutonium
RU	Recovered uranium, uranium separated as a product from used nuclear fuel
S	Supply rate
SNF	Spent Nuclear Fuel, also called used fuel
Th	Thorium
TR	Thermal Reactor
TRU	Transuranic elements (Neptunium, plutonium and higher on periodic table) or Transuranic waste
U	Uranium
UOX	Uranium Oxide fuel
UREX	Uranium Extraction
U.S.	United States
VISION	**V**er**i**fiable Fuel Cycle **Si**mulati**on**, a dynamic simulation of the nuclear fuel cycle

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