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Vision – Verifiable Fuel Cycle Simulation of Nuclear Fuel Cycle Dynamics

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**VISION – VERIFIABLE FUEL CYCLE SIMULATION
OF NUCLEAR FUEL CYCLE DYNAMICS**

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ABSTRACT

The U.S. DOE Advanced Fuel Cycle Initiative's (AFCI) fundamental objective is to provide technology options that – if implemented – would enable long-term growth of nuclear power while improving sustainability and energy security. The AFCI organization structure consists of four areas; Systems Analysis, Fuels, Separations and Transmutations. The Systems Analysis Working Group is tasked with bridging the program technical areas and providing the models, tools, and analyses required to assess the feasibility of design and deployment options and inform key decision makers. An integral part of the Systems Analysis tool set is the development of a system level model that can be used to examine the implications of the different mixes of reactors, implications of fuel reprocessing, impact of deployment technologies, as well as potential “exit” or “off ramp” approaches to phase out technologies, waste management issues and long-term repository needs.

The Verifiable Fuel Cycle Simulation Model (VISION) is a computer-based simulation model that allows performing dynamic simulations of fuel cycles to quantify infrastructure requirements and identify key trade-offs between alternatives. It is based on the current AFCI system analysis tool “DYMOND-US” functionalities in addition to economics, isotopic decay, and other new functionalities. VISION is intended to serve as a broad systems analysis and study tool applicable to work conducted as part of the AFCI and Generation IV reactor development studies.

INTRODUCTION

The nuclear fuel cycle represents a dynamic system, with both mass-flow and continuing structural changes (construction and retirement of facilities), which are constrained in one or more ways. Mass-flow is always constrained by the need of fuel, driven by the number and type of reactors built and the availability of fuel (enriched uranium and/or transuranic [TRU] elements). Generally, the number of reactors built is itself determined by nuclear energy growth,

which can be an input parameter, or a parameter that is dynamically calculated using energy-economic models where the cost of nuclear energy itself feeds back into nuclear growth. Simulation of such dynamic system represents a challenge to the AFCI program as decision are to be made regarding the choices of advanced nuclear energy systems to be deployed in the U.S.

The AFCI program has four major objectives, [1] as follows:

1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.
2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.
3. Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting factor for nuclear power.
4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.

Each of the above objectives has two or three explicit goals,[1] which can be measured by various metrics such as long-term heat to the geologic repository. The integrated fuel cycle simulation tool that is proposed here, VISION, is anticipated to calculate essentially all of the quantitative metrics. The first phase of this system model, VISION mod-1, includes relatively few feedback, control, or optimization loops that control the fuel cycle operation and evolution. In later versions of VISION, those advanced features will be added per program needs.

The following sections describe the AFCI system code DYMOND-US, [2] which will be implemented in the VISION system model with new additional features. In addition, the paper describes the different VISION modules and its specifications with a focus on the major new capabilities, the range of potential applications of the model, and current plans for its development.

DYMOND-US MODEL

VISION is the successor to DYMOND-US, the Dynamic Model of Nuclear Development. DYMOND was originally developed for the Generation IV Fuel Cycle Cross Cut group [3,4]. In addition, the DYMOND-US version of the model has been the main system dynamics model in use by the AFCI program to perform future deployment scenarios of advanced AFCI nuclear energy systems [5-8]. It is built using the commercial system dynamics software iThink/Stella [9], providing a detailed system dynamics model for the total nuclear energy enterprise with different fuel cycle technologies. The model tracks the mass flow of nuclear materials within the fuel cycle and includes different types of delays and feedbacks associated with the construction of nuclear facilities and the decisions to build such facilities. It can be run with either world-wide or domestic parameters, e.g., 430 or 103 initial reactors. The latest version of the model can analyze any fuel cycle scenario if the user provides reactor fuel input and output composition vectors (recipes). The options currently available include light water reactor/uranium oxide (at burnups of 33, 50, and 100 GWD/t), light water reactor/mixed oxide fuel (recycling NpPu-1pass, NpPuAm-multiple passes), light water reactor/inert matrix fuel (recycling NpPu-1pass or NpPuAmCm-1pass), low-conversion sodium fast reactor (following either LWR/UOX, LWR/MOX, or LWR/IMF), high-conversion sodium fast reactor (following LWR/IMF or LWR/UOX), and once-through very high temperature thermal reactor (VHTR). The model provides several time-dependent outputs including masses of select elements and isotopes, long-term heat intervals, and long-term dose. For recycle fuels, the model's major flow control is the availability of elemental Pu to make recycle fuels.

VISION SYSTEM MODEL

VISION is planned as the system dynamic and integration model for the Advanced Fuel Cycle Initiative (AFCI) system analysis, a multi-laboratory collaboration (INL, ANL, SNL, and DOE). Similar to the DYMOND-US system, it models the flow of mass throughout all parts of the nuclear reactor fuel cycle, and dynamically simulates the fuel cycle's mass flow. In addition, it calculates metrics for comparison against AFCI program objectives, as the fuel cycle evolves from the status quo into and through various postulated changes in fuel cycle approach, e.g., recycling in thermal reactors, synergistic mixtures of thermal and fast reactors, and pure fast reactor fleets. It then calculates various metrics that describe the characteristics and ramifications of those mass flows, grouped by the AFCI program objectives – waste management, proliferation resistance, energy recovery, safety, and economics. The values of various metrics can feedback into how the system operates and changes. As mass attempts to flow through the system there are various controllers or constraints. There are also various operators that alter the mass flow, such as transformation of mass (transmutation in reactors, isotope decay) and partition of mass (fabrication, separation).

VISION is intended to be the AFCI system analysis simulation of the entire fuel cycle to assist in evaluating and improving major fuel cycle options against all four AFCI programmatic objectives – waste management, proliferation resistance, energy recovery, and systematic fuel management (economics, safety, at-reactor storage). It is ***NOT*** intended to actually manage the fuel cycle. For example, there is no intent to track each fuel assembly from each reactor, as might be required for actual fuel management system.

All functionality in the DYMOND model will be kept in VISION. VISION will be built in accordance with a set of pre-specified requirements and a software management plan. The software platform for VISION was selected in accordance with a software evaluation activity where the PowerSim software [10] is selected. The mass flow and non-economic metrics in VISION will be built primarily on the draft report on Simulation, Evaluation, and Trade-off Studies.[11,12] The economic costing information and approach in VISION will be built on the Cost Basis Report.[13]. The following sub-sections describe the different VISION modules focusing on the important features of this new system model that include isotopic decay, economic capabilities, and other important features.

Modules

VISION design is based on a modular structure. This subsection describes the modules and its functions. One-letter modules, A through R, describe mass flow. Two-letter modules denote metrics, control, and integration, e.g., WM calculates waste management metrics and ED calculates required number of reactors based on energy demand. Figure 1 shows this structure and the mass flow between the different modules.

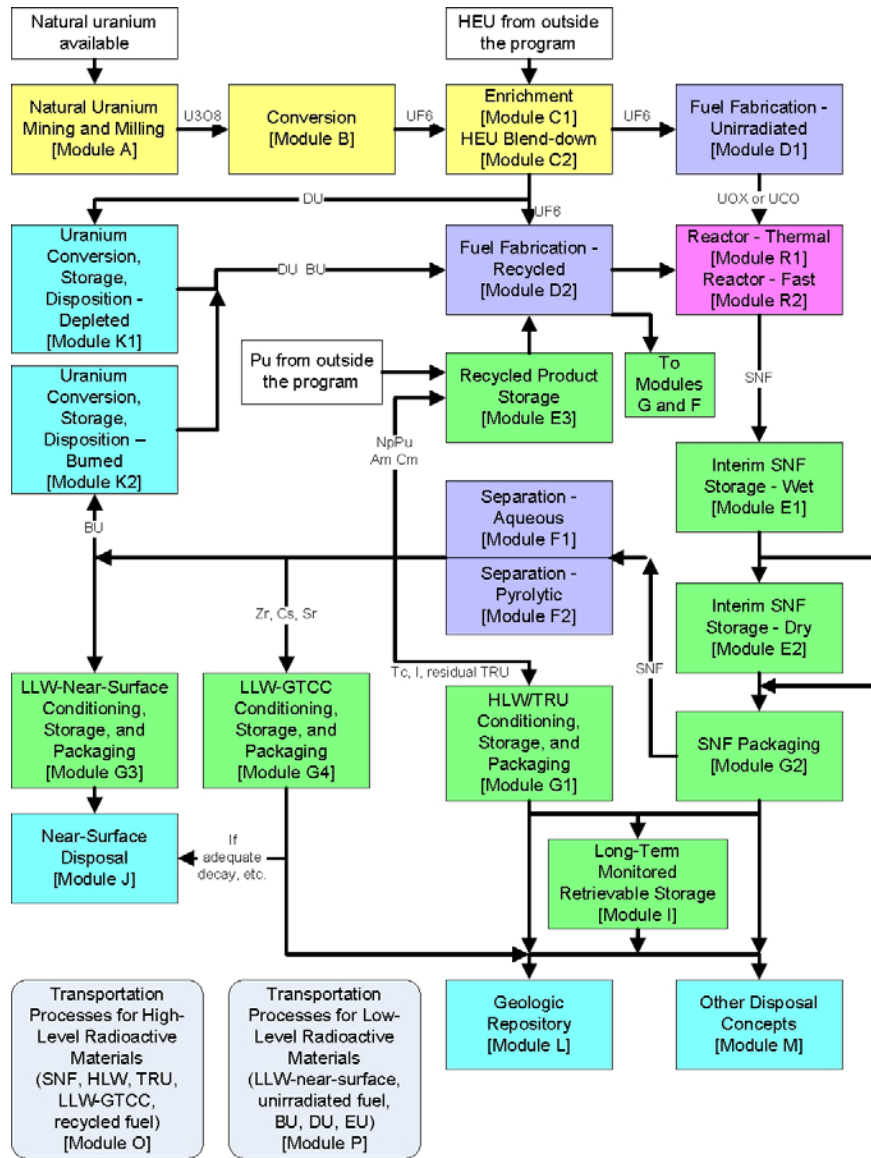


Fig. 1 VISION Flow Model Modules
 (Not shown: energy demand (ED), and metrics for waste management (WM), proliferation resistance (PR), energy recovery (ER), and safety and environment (SE))

As mentioned before the likely software for development of this systems model is Powersim software. This software allows for a modular structure where each module is placed in a separate model page (tabbed page similar to Microsoft excel). As with DYMOND-US, mass flow will take place directly from one module to the other. For every variable appearing in more than one module, “Ghosts” will be used to show the repetition of a “stock” in more than one module. The current design intention is to create a copy of each variable that is shared between any one page (module) and one or more other modules, and use it to transfer the data between modules. This will allow for development of the different modules by different developers, which is consistent with the multi-lab collaborative nature of this work. The fixed system data are planned to be

input into the code through an excel spreadsheet allowing for flexibility in data inclusion into the code (e.g., the spent fuel isotopic vectors, in addition to restricting access to any sensitive data (such as separation facility data) that can be used in the calculations.

Neutronics Parameters

A key feature of the VISION system is that direct neutronics calculations are not performed within model which makes it much simpler and user friendly compared to other fuel cycle system codes that include this type of calculations such as COSI [14] and NFCSIM [15] codes. Similar to the DYMOND-US model, 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 in addition to the equilibrium (recycle) composition. Table I. shows an example of a typical set of those compositions.

Table I. Example Fresh Fuel and Spent Fuel Compositions

Wt. %	UOX-33	UOX-50	MOX		FR Startup		FR Recycle	
	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 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. The high burnup fuel has an initial enrichment of 4.2% U-235 and a discharge burnup of 50,000 MW-day/tonne. The compositions shown in the table are based on depletion calculations that were performed using the ORIGEN2 [16] computer code. Those ORIGEN2 calculations [17] used the one-group cross sections that were provided with the code. Also available but not shown in the table are calculations for ultra-high burnup UOX fuel with 100,000 MW-day/tonne that were performed with ORIGEN2 using one-group cross sections [18] that are based on WIMS8 [19] cell calculations [18] instead of using the cross sections provided with ORIGEN2 (which did not provide reasonable results). WIMS8 calculations used 172-group, JEF2.2-based cross section library which has been previously determined to provide accurate modeling of the important Pu-239, Pu-240, and Pu-241 resonances.

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.[20] 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 DYMOND calculations. The other type of fast reactor used in this study, that is the breeder fast reactor, has a different design from the converter fast reactor.[21] The ANL suite of fast reactor analysis codes was used to evaluate reactor operating parameters of either fast reactor designs.

Specifically, the MC2-2, REBUS-3, and DIF3D codes were used. [22, 23, 24] For each fuel composition, the MC2-2 code is used to obtain regional group constants based on ENDF-V data by performing a critical buckling search (fundamental mode calculation). REBUS-3 is a fuel cycle analysis code for fast reactors which couples the DIF3D multigroup neutron flux code system to a multigroup depletion code. In those designs the enrichment search option of the REBUS-3 code is used to compute equilibrium cycle compositions for each reactor design. The REBUS-3 code takes the user defined TRU feed (recycled transuranics from UOX, MOX, or IMF), the base feed (depleted uranium), the reactor operating cycle, and the fuel loading scheme and determines the necessary fuel enrichment and equilibrium discharge compositions (spent fuel composition) to assure criticality at the end of cycle (EOC). To get the detailed composition for key isotopes at discharge or a number of years after discharge, ORIGEN2 depletion calculations are performed using a one-group cross-section set that is provided by the detailed REBUS-3/DIF3D calculations. Thus, for each TRU isotopic vector from UOX, MOX, or IMF, the detailed MC2-2 and REBUS-3/DIF3D calculations, followed by the ORIGEN2 depletion calculations are performed to provide the spent fuel vector for both startup and equilibrium cores of the fast reactors.

Notice that the spent fuel compositions provided in this table correspond to compositions at 5 years of cooling after discharge. This timing corresponds to the typical cooling time before the reprocessing of spent fuel for recycling in thermal or fast reactors. This is an approximation since in reality spent fuel of longer or shorter periods of cooling times might be reprocessed, which will change the fresh fuel composition vector. This change in fresh composition vector will lead to changes in the spent fuel composition vectors and the corresponding core loading and batch size. This deviation from the assumptions made (5 years of cooling) will require new neutronics calculations. The aim of the VISION system compared to the predecessor DYMOND system is to automatically handle those possible deviations in the fresh fuel compositions and the resulting deviations in the spent fuel compositions without doing a new set of neutronics calculations as will be discussed in the next sub-section.

Finally, notice that only a limited set of isotopic data were initially of interest to the DYMOND code although the neutronics calculations can provide fractions for many more isotopes. This limited set of isotopes covered its needs to calculate the long term integrated decay heat and the short term decay heat which are of interest to the repository capacity calculations. However, the VISION system will include many more isotopes as the system will not be limited to only estimating metrics related to repository capacity, but also other metrics such as radiotoxicity and dose.

Isotopic Decay Modeling

The VISION system 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 will be an important feature of the new systems model. In addition, the VISION system model will allow for the simulation of spent fuel of different cooling times, and possibly a mix of spent fuel of different cooling times. This will also require the tracking of the isotopic decay of the transuranic isotopes.

The inclusion of the isotopic decay into the VISION system dynamic model is currently under investigation, and it will be straightforward to include it in the new model. However, the

consequences of including isotopic decay, especially as related to the composition vectors (recipes), will need more work. The main consequence is that those vectors will be dynamic vectors that are changing with time, and possibly changing with each batch of fuel in certain cases. Other system codes have different approaches to handle this need to dynamically change the composition vectors. The NFCSIM code contains its criticality engine, which is combined with the depletion calculations that are performed using the ORIGEN2 code. The COSI code uses the equivalency method combined with the CESAR [25] depletion code. 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, the code aims at estimating the new fresh and spent fuel composition vectors using interpolation within tabulated values 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.

Other issues that are related to isotope decay are associated with the models characteristic time periods as follows:

- The main mass flow during the fuel cycle active management time period, which is taken to be 2000 to 2100, and sometimes to 2300.
- Short-term heat load while in storage, e.g., the division between wet/dry storage, or when material is cool enough to emplace in the repository. The time frame is therefore 1-100 years after material comes out of a reactor or separation plant.
- Hypothetical long-term dose (LTD) from material emplaced in the repository, which is potentially relevant from ~1,000 to 1,000,000 years after emplacement. In practice, the time of 10,000 years after emplacement is determinant for whether emplaced waste meets the 10,000-year dose criterion as estimated dose increases with time through 10,000 years. The time frame of 200,000-500,000 years after emplacement appears decisive regarding whether emplaced waste meets the new proposed post-10,000 year dose criterion.
- Long-term heat (LTH) load to the repository, which has a time frame of when ventilation stops (minimum of 50 years after Yucca Mountain opens) to ~1500 years.
- Long-term radiotoxicity (LTR) from material emplaced in the repository. The explicit AFCI objective is a reduction of a factor 100 relative to once-through; the underlying motivation for this objective is to lower the LTR below that of uranium ore within 1,000 years after emplacement in a repository. Thus, the time period of ~1,000 years is the key determinant for this metric.

The above time periods can be re-cast as questions to be answered by the VISION model as follows:

- When can SNF in wet storage be moved to dry, or transported elsewhere?
- How much SNF/HLW can be emplaced in a geologic repository from the standpoint of wall heat load/temperatures at the time of emplacement? How much additional capacity can be gained if emplacement is delayed or high-heat isotopes removed?
- When can/should repository ventilation be turned off, i.e., repository closed?

- How much SNF/HLW can be emplaced in a geologic repository from the standpoint of heat load/temperatures at ~1500 years after emplacement? How much additional capacity can be gained if ventilation is extended or high-heat isotopes removed?

Tracked Isotopes

VISION will track 56 isotopes in the main fuel flow model. For the four radionuclide 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 6 isotopes whose inventory appears never to be significant. For fission products, VISION calculates H-3, C-14, Sr-90, Tc-99, I-129, Cs-137. Also to be tracked are Cs-134 and Cs-135 because for the key elements of Sr, Tc, I, and Cs, it is needed to calculate the mass of the key fission product divided by the total mass of that element. This is approximated by including an “other” isotope for each of these four elements, approximated as being stable (time independent). The “other” isotope for these elements is defined as the amount of all non-tracked isotopes at t=1 year after discharge. So, for example, Cs-total = time dependent (Cs-134, Cs-134, Cs-137) + time independent (Cs-other). There is also a time-dependent “fission product other” that will have such special characteristics as heat per unit time.

Economics Modeling

The modules in VISION are aligned as closely as possible with the AFCI Cost Basis Report (CBR), where the most recent CBR was issued in 8/2005.[13] VISION starts with the module structure shown in Figure 1. There are modest differences between the 2005-CBR and VISION, as follows:

- Explicit mention of the three possible inputs to the system: natural uranium, HEU, weapons-grade Pu.
- Add new module for burned uranium (BU) “K2” so that BU is either stored with recycled product storage “E3”, which would be expensive, or stored with depleted uranium “K1”. The costs of BU and DU storage may be the same, but for flow purposes, they must be kept separate. BU is used in multi-pass MOX concepts. Both BU and DU can be used in fast reactors.
- Explicitly show that SNF in wet storage could be packaged for transportation, without the intermediate step of dry storage.
- Explicitly show that waste from fuel fabrication “D2” flows to the “G” modules, out of spec fuel from fabrication flows to separation plants “F1”/“F2”.
- Divide the waste conditioning, storage, and packaging modules to correspond to the five types of waste under U.S. Nuclear Regulatory Commission (NRC) and Environmental Protection Agency (EPA) rules.
 - HLW and TRU waste, destined for geologic repositories “G1”
 - Unprocessed SNF, destined for geologic repositories “G2”
 - LLW that qualifies for near-surface burial, i.e., waste meeting the isotope concentration limits in 10CFR61 [26] – waste Classes A, B, C in “G3”
 - LLW that does not qualify for near-surface burial, i.e., waste meeting the disposal dose objectives in 10CFR61 but does not meet the isotope concentration limits derived for near-surface disposal. This is known as Greater than Class C (GTCC) waste. If a suitable intermediate disposal concept is developed, LLW-GTCC can go there. Otherwise, LLW-GTCC must also go to geologic repositories, “G4”

Other Models

There are other models that are to be implemented in the VISION system such as proliferation resistance metric and transportation modules. Module PR calculates proliferation resistance metrics. Table II. lists the official AFCI program objectives for proliferation resistance. Table III lists the metrics to be calculated by module PR.

Table II. Proliferation Resistance Objectives [1]

Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.
In the short-term, develop fuel cycle technologies that enhance the use of intrinsic proliferation barriers.
In the short-term, demonstrate the capability to eliminate more than 99.5 percent of transuranic weapons-usable materials from waste streams destined for direct disposal by destroying these materials through recycling.
In the long-term, stabilize the inventory of weapons-usable material in storage by consuming it for sustained energy production.

Table III. Proliferation Resistance Metrics Calculated in Module PR

AFCI Objective/Metric	Purpose	Weakness	Suggested Future Work
Pu-239 in system Pu in system	Common simplified metrics for quantity of weapons usable material	Ignores all other weapon-usable isotopes, weights all Pu isotopes the same.	Replace with Pu-239 equivalent metric.
Pu-239 fraction of total Pu in system	Indicator of quality of weapons-usable material, relevant to short-term goal of enhancing intrinsic proliferation barriers	Poor indicator of "quality", but simple to calculate.	Better "quality" metric needed. Dose calculations for representative fuels and geometries needed.
Unshielded dose rate (duplicate of objective 4 metric)	Indicator of handling resistance, relevant to short-term goal of enhancing intrinsic proliferation barriers	Scaled from past calculation, not a new calculation. See section 3.3.	
Pu-239-equivalents in repository TRU mass in repository (duplicate of objective 1 metric)	Short-term objective to eliminate 99.5% of TRU weapons-usable material from repository	Pu-239 equivalent is the more technically valid measure of "weapons-usable" inventory, see section 3.3. "TRU mass" weights all TRU isotopes the same.	The metric "TRU mass" should be replaced with Pu-239 equivalent metric.
Pu-239-equivalents in system TRU mass in system (duplicate of objective 1 metric)	Long-term objective to stabilize weapons-usable inventory		

The other modules of interest are the transportation modules P and O. Those modules deal with the transportation of both low level and high level waste to storage facilities and fresh fuel and spent fuel transportation. The initial design basis for this model considers the division of the U.S. into 9 regions that correspond to the census regions, where each region will have its one initial reactor park, and its own growth projects. The center of each region will connect to the locations of the reprocessing and fabrication plants in addition to the locations of repositories.

POTENTIAL APPLICATIONS

The proposed VISION model would be used for the following:

- Evaluating the range of options against the range of objectives
- Examining the implications of different mixes of reactors, impact of deployment of different technologies, as well as potential “exit” or “off ramp” approaches to phase out technologies if the need arises.
- Examining timing issues of reactor deployment, reprocessing against waste generation and repository needs.
- Evaluating the capability of various reactor systems to handle transmutation, including extended burn-up of plutonium in Light Water Reactors (LWRs) and gas-cooled reactors, potential for destroying minor actinides in LWRs, and consumption of transuranics in fast reactors and accelerator driven systems.
- Assessing the benefits of advanced fuel cycles to reduce the need for additional geological waste repositories and more efficiently use the first repository.
- Performing dynamic simulations of fuel cycles to quantify infrastructure requirements and identify key trade-offs between alternatives.
- Evaluating creative solutions to make the nuclear fuel cycle cost competitive.
- Evaluating repository performance for characteristics such as volume, mass, and heat load; comparing various fuel cycles, reactor facility requirements, life cycle costs, and repository savings.

CURRENT PLAN FOR VISION MODEL

In FY06, the Verifiable Fuel Cycle Simulation (VISION) model will incorporate the DYMOND-US model and add (1) isotopic flow control and decay, (2) additional recipes from transmutation analyses such as VHTR with recycling, (3) simplified models for fuel separation and fabrication, (4) cost parameters, (5) a uranium resources model, and (6) increased flexibility in transitions and combinations of individual fuel cycle technologies. This will require a shift to another software platform. Isotopic flow control and decay will improve the quality of simulations, capturing effects associated with ever-varying isotopic composition of fuel entering the fuel separation plant and decay during long storage. Simplified models for fuel separation will compare options on a more consistent basis, e.g., a UOX recycle plant is dominated by uranium mass flow, IMF recycle plant by plutonium mass flow, and MOX intermediate. The simplified model for fuel fabrication will allow comparison of options that combine americium recycle (reducing long-term heat) while minimizing how much of fuel fabrication must be remote vs. glove box vs. hands on (reducing economic penalties).

SUMMARY

This work is part of a multi-national laboratory collaboration among Argonne National Laboratory, Idaho National Laboratory, Sandia National Laboratory and United States

Department of Energy. The paper summarizes the basics of the VISION system dynamics model, its functionalities and developments, and potential applications.

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