GLOBAL EVALUATION OF NUCLEAR INFRASTRUCTURE UTILIZATION SCENARIOS (GENIUS)

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A new and unique fuel cycle systems code has been developed. Need for this analysis tool was established via methodical development of technical functions and requirements followed by an evaluation of existing fuel cycle codes. As demonstrated by analysis of GNEP-type scenarios, the GENIUS code discretely tracks nuclear material from beginning to end of the fuel cycle and among any number of independent regions. Users can define scenarios starting with any/all existing reactors and fuel cycle facilities or with an ideal futuristic arrangement. Development and preliminary application of GENIUS capabilities in uncertainty analysis/propagation and multi-parameter optimization have also been accomplished.

I. INTRODUCTION

The Global Evaluation of Nuclear Infrastructure Utilization Scenarios (GENIUS) computer code is being developed to model and simulate global nuclear fuel cycles. Code development is part of the SINEMA (Simulation Institute for Nuclear Energy Modeling and Analysis) Laboratory Directed Research and Development (LDRD) project at the Idaho National Laboratory (INL).

Modeled nuclear fuel cycle scenarios span multiple geographical regions, taking into account the variety of nuclear energy policies around the globe and incorporating technologies both available today and those projected to be available in the future. Other nuclear fuel cycle codes have been developed. These codes exist at various levels of maturity ranging from those under construction to those abandoned and unfunded. GENIUS differs from these other codes in both the intended scope and level of fidelity at which a hypothetical nuclear fuel cycle can be modeled[1].

The increased scope and fidelity is provided by three primary features of the code: (1) the flexibility to characterize individual reactors and fuel cycle facilities, (2) the option to include any number of independent regions in a simulation and (3) the ability to track discrete quantities of nuclear fuel and materials throughout a scenario.

II. GENIUS

II.A. Features

In modeling a given fuel cycle scenario with GENIUS, nuclear reactors and fuel cycle facilities are individually defined at a level of detail necessary to simulate material movement and facility lifecycles. For example, a user can input reactor characteristics such as lifetime, power rating, cycle length and batch number. Parameters such as actual core geometry go beyond the level of detail modeled in a code such as GENIUS. The freedom to characterize any number of fuel cycle facilities and reactors means that the actual infrastructure of a given nation may be modeled and then multiple evolutions of that nation's fuel cycle can be explored.

The capability to define individual reactors and fuel cycle facilities is not in itself unique to GENIUS. However, the flexibility to define those objects in multiple regions is unique. With few exceptions in the current global nuclear industry, there are no strictly national nuclear fuel cycles. In the course of a typical fuel procurement operation, reactor operators order materials and services from entities in one or more other countries. By allowing a user to define as many regions as necessary for a simulation, GENIUS provides a basic framework for simulating a global fuel cycle as it truly exists, not just as a handful of generic regions defined by a generic strategy.

The capability to define and characterize both the technology and policy of a multitude of different regions also supports the modeling of international initiatives for nuclear cooperation like those found in the Department of Energy's (DOE) Global Nuclear Energy Partnership (GNEP) program[2].

Discrete material tracking in GENIUS takes place on the scale of a fuel batch for light water (LWR) and gas-cooled thermal reactors and fast reactors (FR) and at the monthly discharge mass for pressurized heavy water reactors (PHWR). Eventually the scale may be taken down to the fuel assembly level for all types of reactors. Even though fuel assemblies within a batch are assumed to have identical compositions, tracking at the individual assembly level will allow subsets of assemblies from different batches to be commingled, e.g. blended to make fresh fuel for fast reactors. Throughout a simulation, tracking of fuel batch characteristics includes the name of the reactor that ordered the fuel, the fuel mass and the requested isotopic recipe. As a fuel batch order passes through a facility, the location, arrival time, and shipping time are recorded. The tracked life of a fuel batch ends if it enters reprocessing and is separated into multiple new forms. Fuel fabricated with separated material is assigned a new identity for tracking purposes.

The discrete material tracking feature in GENIUS increases model fidelity and provides data sets useful for various analyses. In reality, nuclear fuels and materials are shipped in discrete quantities. If material movement is modeled as mass flow it becomes difficult to distinguish one shipment from another as they move through similar facilities with different characteristics and costs. Safety and proliferation risks can be better assessed when a given packet of material is individually characterized by chemical and isotopic composition, location, physical form and a variety of other characteristics.

Discrete tracking of used fuel can also facilitate optimization of feedstock for fabrication of hot fuel going to fast reactors. In this model and others, new and used fuel “recipes” are referenced, rather than dynamically computing discharged fuel composition as a function of the isotopic content of fresh fuel placed into a reactor. However, exactly matching a desired fast reactor fuel recipe with the composition of light water reactor (LWR) spent fuel is unrealistic. There is significant variation in the composition of spent fuel from the various reactors that may be deployed in a simulation. Those used fuel recipes will vary depending on initial composition, burn up and decay time. If assemblies are discretely tracked, algorithms can be developed to choose which assemblies to reprocess at a given time to most closely match a desired fresh fuel load for a fast reactor. In practice, processing spent fuel to create new fast reactor fuel likely would occur on a campaign basis. Because all types of fuel treatment involve significant quantities of in-process material at any given time, tailoring new fuel composition by choosing particular assemblies would require a start from practically zero in-process material. Otherwise, there likely would be little effect on the overall composition of the resulting new fuel. The remaining issue will be how much variation in the recipe is acceptable, which in turn will depend on the design of the fast reactor in question.

II.B. Application

As a proof of this modeling/coding concept, the GENIUS –1 code has been developed at Idaho State University (ISU) and Idaho National Laboratory (INL). Two GNEP-type scenarios have been modeled to demonstrate the analysis capabilities. Scenario One is a base case, of sorts, with the objective to estimate the fuel cycle capacity necessary to provide fuel to existing potential reactor or client states (non-fuel cycle states) over a 100 year time period. This case assumes that one generalized fuel cycle region leases fresh fuel to 24 different reactor states and then accepts back used fuel for processing and use in fast burner reactors. It was conservatively assumed that the fuel cycle region consists of the enrichment and reprocessing capacities of the five nuclear weapons states (as defined by the Nuclear Non-proliferation Treaty) and Japan. Each reactor state begins the scenario with the actual fleet of reactors that currently exist. New reactors are deployed in response to nuclear energy demand growth curves unique to each state or region[3]. The code output includes masses of fuel and other process materials provided by the fuel cycle region.

Uranium ore resources were assumed to be unlimited and were not identified with a specific region for the simulation. Naturally occurring uranium is assumed to have a ^{235}U content of 0.711%. Enrichment facilities operate with a tails ratio of 0.3%.

It is assumed that light water reactors and advanced gas reactors share the same isotopic fuel input and output recipes. The fuel for this group of reactors has an enrichment of 4.3% and a maximum discharge burn-up of 51,000 MWd/MT. The reactors are refueled every 18 months. The same fuel composition is used for all existing and new reactors. This assumption is obviously not valid for all current reactors and does not take into account the trend of increasing burn-up over time for future reactors. This limitation reflects the absence of variable recipes in the current model and will be easy to remedy in future versions.

All of the heavy water reactors simulated in the model operate on natural uranium fuel with a maximum burn-up of 7,500 MWd/MT. This does not take into account the possibility of widespread use of slightly enriched uranium in heavy water reactors in the future. The reason for this is again the lack of input and output isotopic recipes in the current model. The PHWRs in the model are assumed to be refueled online.

In states that use light water and heavy water reactors, both reactor types are deployed based on the initial relative power generation from each reactor type. For example, if a country's current reactor fleet consists of 20% heavy water reactors and 80% light water reactors in terms of electrical generation, the same generation mix is maintained throughout the simulation.

Figs. 1 through 4 indicate the simulated bulk fuel cycle needs per year of the potential client states determined by the code for Scenario One. These needs are compared to total existing fuel cycle capacity for the relevant front-end stages of the fuel cycle.

Each potential supplier state begins the simulation with all existing fuel cycle facilities. Those facilities are decommissioned in accordance with assumed lifetimes. All new fuel cycle facilities are constructed in the generalized fuel cycle supplier region.

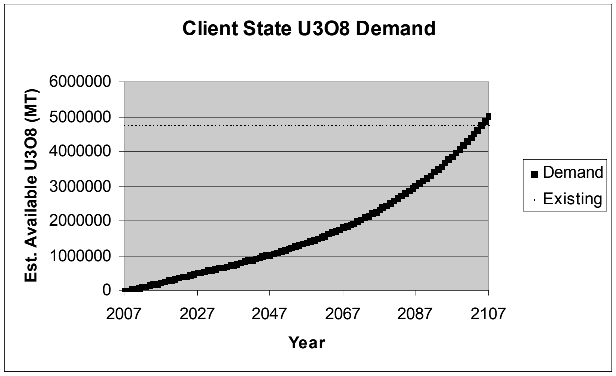

Fig. 1. Projected cumulative client state U_3O_8 demand compared to estimated and reasonably assured uranium resources and inferred resources.

According to the projection in Fig. 1, the supplier states in the scenario will consume all of the current reasonably assured and inferred uranium resources by the end of the scenario[4].

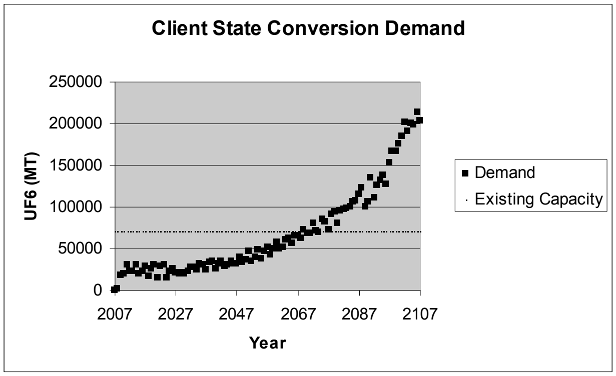

Fig. 2. Projected differential client conversion demand compared to existing current global conversion capacity.

Fig. 2 shows that the projected conversion capacity needed to supply the client states would exceed existing capacity at about 2070 and would have to be nearly tripled by 2107.

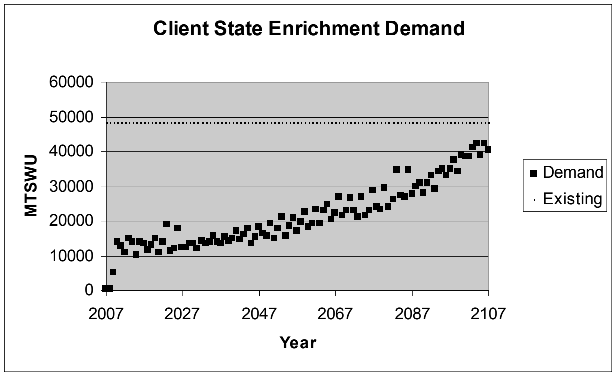

Fig. 3. Projected differential client enrichment demand compared to existing current global enrichment capacity.

Fig. 3 indicates that projected client state enrichment demand does not exceed current global supply capacity at any point during the scenario. It was assumed that PHWRs continue to operate on natural uranium fuel.

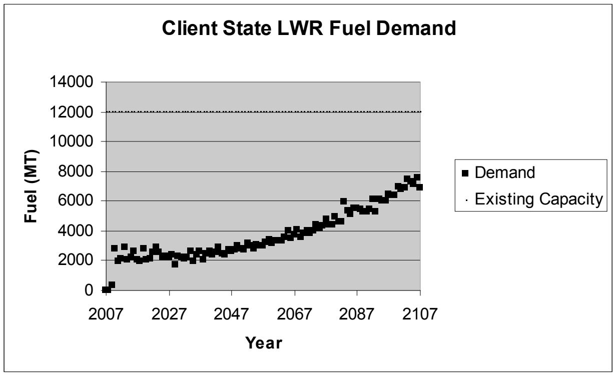

Fig. 4. Projected differential client state LWR fuel fabrication demand compared to existing current global LWR fabrication capacity.

As with enrichment demand, Fig. 4 shows that the projected client state demand for LWR fuel fabrication does not exceed the current global LWR fuel fabrication capacity at any point during the simulation. The current LWR fuel fabrication capacity is roughly double that required for the existing global (client and fuel cycle states) LWR generation capacity given the burn-up assumptions used in the scenario. However, when including supplier states in the scenario, the existing capacity is exceeded by need at about half way through the 100-year time period. (See discussion of Scenario Two.)

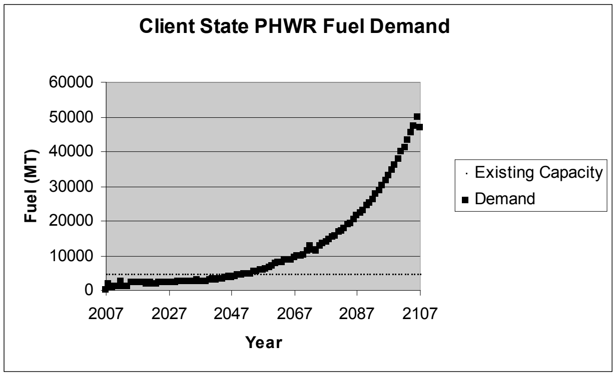

Fig. 5. Projected differential client state PHWR fuel fabrication demand compared to existing current global PHWR fabrication capacity.

Fig. 5 indicates that the projected client state demand for PHWR fuel fabrication will exceed current supply capacity by about 2040 and will be more than nine times current capacity by the end of the scenario. The demand for PHWR fuel mass grows at a greater relative rate than the LWR fuel mass largely due to India's primary use of PHWRs. India has the second highest demand growth rate in the scenario. The highest growth rate belongs to China. When including in the scenario the LWR demand for China, the necessary fuel mass for this one country eclipses all of the others combined. However, China is considered a supplier state for this discussion and thus is not included in the plots for the reactor states.

For the back end of the fuel cycle in Scenario One, supplier states would require LWR fuel reprocessing capacity roughly equivalent to the LWR fuel fabrication demand shown in Fig. 4 (reaching approximately 7500 MT in 2100.) Deployment of reprocessing capacity would lag behind fuel fabrication capacity by approximately the total fuel irradiation time plus post irradiation cooling time. Total current existing reprocessing capacity is about 5,600 MT/year. It is assumed that PHWR fuel is not reprocessed in this scenario.

The goal of Scenario Two is to estimate the necessary excess fuel cycle capacity that may be required to support a virtual fuel bank[5]. A virtual fuel bank is defined here as the maintenance of excess fuel cycle capacity in the global marketplace that can be used to address supply shortages. In a GNEP style fuel leasing agreement, a virtual fuel bank would help assure supply to reactor states should any one fuel cycle state discontinue service.

Scenario Two builds on Scenario One by dividing the general fuel cycle region into several independent regions. Each reactor state region accepts fuel services from one of the fuel cycle regions according to current regional interaction data. Similar to Scenario One, it was assumed that the fuel supplier states were the five nuclear weapons states (China, France, Russian Federation, United Kingdom and the U.S.) and Japan. It is conceivable that other countries also could become fuel cycle suppliers.

In Scenario Two, aqueous reprocessing facilities are deployed to process spent LWR fuel. Fast reactors are deployed in the fuel supplier regions in order to burn transuranics separated from irradiated LWR fuel. Both a hot fuel fabrication facility and pyroprocessing facility are assumed to be co-located with each fast burner reactor.

The LWR fuel demand shown in Fig. 6 for Scenario Two can also be used as a proxy for enrichment demand. The number of SWUs required per metric ton of LWR fuel can easily be back calculated if the product enrichment and tails assay are known.

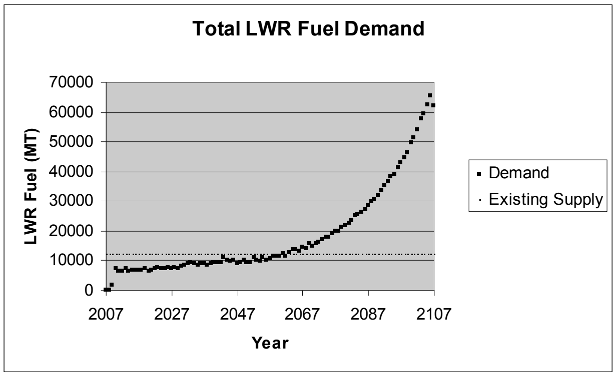

Fig. 6. Projected global differential LWR fuel fabrication demand compared to existing current global capacity.

Fig. 6 shows that global (reactor and fuel cycle states) LWR fuel fabrication demand will exceed current capacity around 2060. The data points near zero at the beginning of the scenario are a result of the batch fueling nature of the model.

In a GNEP world, supplying certain states with reactor fuel may require a significant amount of capacity at every front-end step of the fuel cycle. For the purpose of illustration, three countries were chosen to represent high, medium, and low service requirement cases. Fig. 7 shows that, under the stated model assumptions, countries such as Brazil and Bulgaria may not require a significant percentage of global fuel cycle capacity. However, countries with potential generation capacities similar to the Republic of Korea could present a major load on global fuel cycle demand. The percentages in the plot are relative to total global demand. They decrease over time because the demand of other countries grows faster.

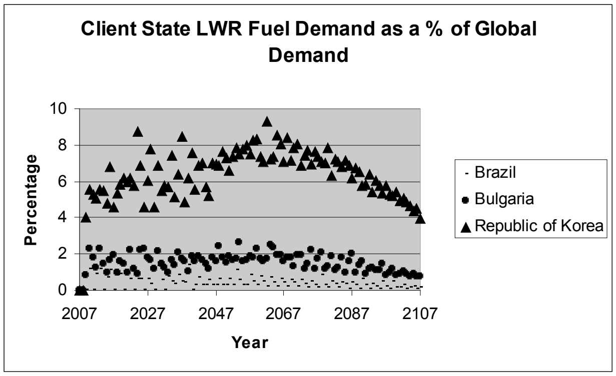

Fig. 7. Percent of global LWR fuel fabrication required to supply Brazil, Bulgaria and the Republic of Korea.

Reprocessing service demand for Scenario Two is shown in Fig. 8.

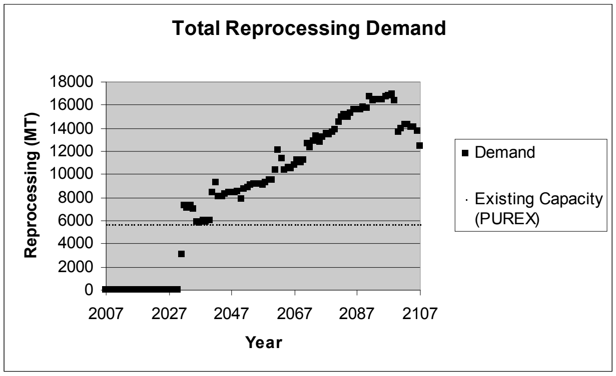

Fig. 8. Total reprocessing demand for Scenario Two compared to existing global capacity.

In Scenario Two, 1000 MT/year aqueous reprocessing plants are deployed in the fuel supplier states to reprocess both the fuel supplier state's fuel and its partner client states' fuel. The first reprocessing facilities are brought online in 2030 in all of the fuel supplier states. At that point only fuel from the supplier states is reprocessed. In 2040 all potential client states are associated with fuel supplier states and the supplier states begin to implement fuel-leasing agreements, including the reprocessing of the client states fuel. New aqueous reprocessing facilities are deployed to meet demand and also to maintain as high a capacity factor as possible.

In this scenario, legacy used nuclear fuel is not considered. However, a stock of used fuel does accumulate in all regions prior to the incorporation of reprocessing. During the simulation, the used fuel backlog is slowly processed and is no longer present by about 2095. The effect is the decreased reprocessing need that can be seen at that time in Fig. 8. Incorporating the reprocessing of legacy fuel into the scenario would alter both the timing and extent of deployment of both reprocessing facilities and fast reactors.

Enticing countries to sign up to a GNEP style fuel leasing agreement will require an assurance of fuel supply. A supply disruption between a supplier and a client could occur for a variety of reasons. If such a disruption occurs for reasons other than those of non-proliferation, the remaining supplier countries need to maintain excess fuel cycle capacity. Maintaining such a capacity to service countries such as the Republic of Korea could require sustained funding in the billions of dollars. As a point for comparison, the International Atomic Energy Agency's 2007 budget is roughly 382 million dollars[6].

II.C. Evolution

II.C.1. GENIUS-2

As the code evolves, new features and capabilities are being incorporated. GENIUS-2 (G2), being developed by the University of Wisconsin-Madison and the INL, has an object-oriented architecture to facilitate straightforward extensibility and the adoption of advanced algorithms for managing material flows. G2 is designed fundamentally around the modeling of individual (discrete) **facilities**. The ability to track discrete **material** is a natural consequence of tracking discrete facilities. All facilities will be owned by **institutions** that will operate in a **region** to satisfy the **demand** of that region. A **manager** will model relationships among facilities/institutions/regions to support the transfer of discrete quantities of material in the fuel cycle. The quantum of discrete material being implemented for initial development is a **batch** of fuel assemblies. At any point in time, a facility will have a log of the material currently in its control, and each unit of material will retain a log of its entire history: which facilities it resided in and for how long. The simulation will proceed on regular time steps managed by a simulation **timer**, probably with monthly resolution in the initial development.

The object-oriented concept of inheritance is being used to develop specific facility types from a common basis. The common basis will allow, where logical, a common representation of facility parameters including both financial and operational parameters. For example, at the first level of specificity, facilities will be differentiated among reactors, fuel fabrication, separations, enrichment, storage, etc. At the next level, reactors may be differentiated among LWRs, PHWRs, FRs, etc, and storage might be differentiated as wet storage, dry storage, interim storage, geologic disposal, etc. Each facility will be "listening" to the simulation timer and taking action depending on the current time. Those actions will include changing the state of the facility (eg. for reactors: licensing, construction, operation, refueling, shutdown, decommissioning) and making requests to the manager to fulfill material transfer needs.

Regions will have independent demand curves and be subject to constraints on the type of facilities that can be constructed within their boundaries. Those constraints will represent generic international agreements on fuel cycle development and interactions. In initial development, regions will be assumed to adhere to those constraints, but future development will allow us to model either overt or covert abrogation of their agreed upon relationships.

The notion of an institution is introduced to allow variations in the characteristics of private corporations, government-funded corporations, national governments and their agencies, and regional/global international agencies. Two specific characteristics that may differ between institutions are their financial parameters (e.g. government vs private industry) and in their relationships across regions (e.g. IAEA fuel bank). Each institution will have a set of financial parameters (e.g. cost of capital/internal rate of return, tax rate), which, when combined with the facility parameters will allow the economic performance of each facility to be determined. Initial financial parameter sets and financial models will be based on simple levelized cost of electricity formulae, but allow for alternative arrangements as development proceeds.

Methods will be developed for the manager to accumulate requests from facilities at the beginning of a time step, negotiate those requests to satisfy various constraints, and issue orders to the facilities to distribute materials and alter their operational states as necessary. It is expected that the bulk of the complexity of G2 as it develops will be housed in the methods/algorithms being pursued by the manager. There may be opportunities in the future to transition to a pure agent-based framework that would perhaps reduce the need for an explicit manager.

The generic (parent) material class will include data members for the description of the isotopic content of a quantum of material as well as its full historical log of facilities. A material's history will only survive for as long as its chemical form is maintained. That is, any change in chemical form is assumed to introduce a fungeability of material that invalidates the notion that said material exists as a discrete quantum. It is expected that to the extent necessary, post-processing of material histories can identify weak connections between the input and output quanta of material in a chemical process. For example, by correlating the time at which spent fuel arrives at a separations facility with the time at which separated material leaves that facility can imply a weak relationship between those materials.

With discrete modeling of facilities and relationships between regions, G2 has the potential to help answer a number of lingering questions about the GNEP framework. For instance, what kind of financial incentives, if any, will be necessary to induce client states to participate in fuel leasing or purchasing agreements rather than encouraging their own institutions to develop fuel cycle facilities? Similarly, what financial consequences would arise from the kinds of supply shortcomings (or for that matter, the supply excesses) that GENIUS-1 predicts? Implementing a cashflow-balancing paradigm[7] or perhaps some other agent-based financial modeling techniques from the literature[8], will give GENIUS-2 the ability to probe these questions.

II.C.2. Numerical Methods Development

Additional analysis capabilities include optimization and uncertainty propagation. The capability to propagate the various sources of uncertainties, e.g. input data including cross-sections, manufacturing, exposure history, etc., through the different fuel cycle codes to the back-end fuel cycle metrics, e.g. heat load, and radio-toxicity, will provide more informed basis for decision makers to assess various fuel cycle scenarios. Moreover, identifying key sources contributing to calculated metrics uncertainties will provide directions for future R&D investments required to reduce the effect of identified uncertainties.

We have recently focused on the quantification of spent fuel isotopic number densities uncertainties due to input data uncertainties, mainly in cross-section values. Isotopic uncertainties can then be used to calculate heat load and radio-toxicity uncertainties as functions of time since reactor discharge. Evaluating isotopic uncertainties is a non-trivial task due to the complexity of fuel cycle codes and the large volume of cross-sections available in the Evaluated Nuclear Data Files (ENDF).

For GENIUS application, a non-intrusive method denoted as the Efficient Subspace Method[9] (ESM) is employed to complete the uncertainty analysis. ESM propagates input data uncertainties via the perturbation of input data and the processing of output data for existing computer models. This approach is well suited for applications where the number of metrics and number of input data are too large to render other uncertainty propagation methods practical, while also requiring minimum effort to implement via I/O processing[10]. To be successful as currently implemented, linear responses of outputs to inputs over the range of input uncertainties must exist.

Decay heat and radio-toxicity uncertainties have been quantified for several fuel cycle scenarios, including advanced recycle reactors under equilibrium cycling conditions[11]. Figs. 9 and 10 plot the decay heat and radioactivity (left scale), respectively, and their estimated uncertainty (right scale), for once through and recycled fast reactor fuels. Note that the once through uncertainties are due to cross-sections uncertainties only, whereas recycled fuel uncertainties are due to both cross-sections and recycled fuel isotopics uncertainties. The recycle model is based on a UREX process with only uranium and transuranic (TRU) streams. For the numerical experiment presented, 80% of the TRU came from recycled fast reactor fuel and 20% from spent LWR fuel. These results demonstrate that a major part of the repository performance metrics uncertainties originate due to uncertainties in the isotopics concentrations of the recycled fuel, thus emphasizing the role of processing/partitioning on the heat loads and radio-toxicity to be discharged permanently in the waste repository.

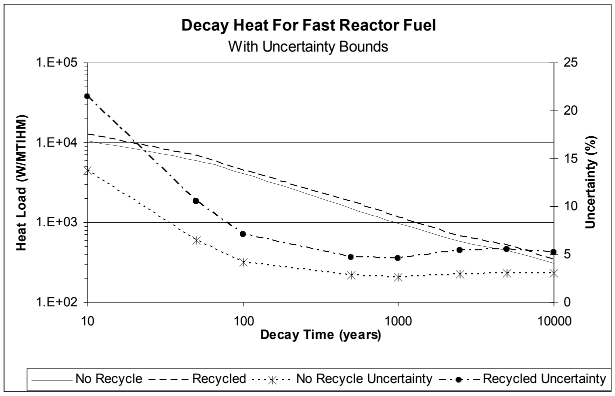

Fig. 9. Decay heat and uncertainty for once-through and recycled fast reactor fuel.

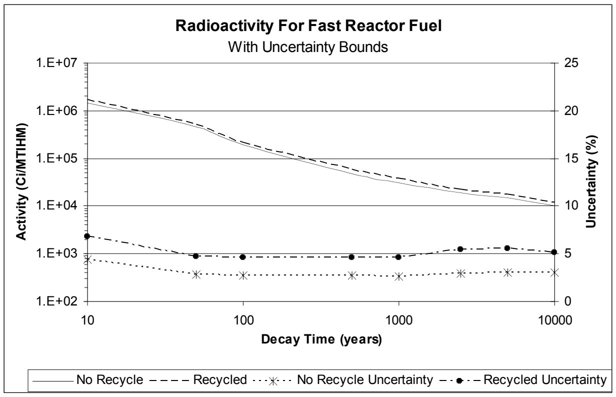

Fig. 10. Radioactivity and uncertainty for once through and recycled fast reactor fuel.

Given the complexity of closed fuel cycles within the constraints of GNEP implementation, mathematical optimization will be utilized to determine the family of near optimum facility deployment strategies across multi-objective tradeoff surfaces[12].

Stochastic optimization methods are well suited to the potentially large and discontinuous space of variables over which one may wish to search for an optimum solution. Those characteristics that describe an optimum solution are expressed quantitatively as Objective- or Cost-Functions (e.g. minimum levelized-cost-of-electricity, or maximum amount of electricity generated for a given unit of repository capacity). The extrema of these functions and the tradeoffs between them are then sought by evaluating a series of deployment scenarios that differ in the choices of input variables (the so-called Decision Variables).

The design and physical implementation of the fuel cycle optimization program, like the G2 code, draws heavily on Object-Oriented programming concepts. Those features that are of interest in optimization, and are common across multiple fuel cycle deployment codes, are encapsulated into a set of base-classes. Optimization algorithms are then created to work from outside of the simulation based on these common properties. Therefore few, if any, changes must be made to the optimization framework or the user interface components when switching from one fuel cycle simulation code to another. This has added benefit of allowing the concurrent development of the optimization capability with the fuel cycle simulation.

Initial tests are underway using a Simulated-Annealing (SA) optimization algorithm on the VISION fuel cycle analysis code[13]. These tests are aimed both at analyzing the fuel cycle simulation itself, in order to refine the choices of objectives and decision variables, and at analyzing the underlying data structures and program organization. Finally, these tests give an opportunity to further clarify the user interface and make user interactions more straightforward and intuitive. The SA algorithm was chosen for this initial work because it is both powerful, yet computationally straightforward. The next step forward will involve the implementation of a Genetic-Algorithm (GA) optimization driver to provide reduced runtimes and increased search-space coverage through a combination of intrinsic scalability and more highly refined search parameters.

III. CONCLUSIONS

Preliminary development of a unique fuel cycle systems code has been accomplished through a joint national laboratory and university effort. The object oriented GENIUS code discretely tracks nuclear material through fuel cycle scenarios to facilitate analysis including proliferation risk assessment and the effects of supply disruption. In addition to material flow, scenarios can be analyzed from an economic perspective. Fuel cycles can be completely defined by the user or GENIUS will be used to optimize a future fuel cycle based on multiple parameters. Because all existing reactor and fuel cycle facilities are available as a starting point for scenario definition, more realistic analyses are possible.

The GENIUS code will become increasingly useful as the uncertainty analysis and propagation capabilities are more fully incorporated. Planned future developments also include more detailed, agent based modeling of facility interactions. The user interface will include a world map, complete with all existing reactors/facilities and transportation routes. Users will define regions and perform drag-and-drop deployment of facilities on the map.

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