Identification of Fuel Cycle Simulator Functionalities for Analysis of Transition to a New Fuel Cycle

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ABSTRACT

Dynamic fuel cycle simulation tools are intended to model holistic transient nuclear fuel cycle scenarios. As with all simulation tools, fuel cycle simulators require verification through unit tests, benchmark cases, and integral tests. Model validation is a vital aspect, as well. Although comparative studies have been performed, there is no comprehensive unit test and benchmark library for fuel cycle simulator tools. The objective of this paper is to identify some of the “must test” functionalities of a fuel cycle simulator tool within the context of specific problems of interest to the Fuel Cycle Options Campaign within the U.S. Department of Energy’s Office of Nuclear Energy (DOE-NE). This paper identifies the features needed to cover the range of promising fuel cycle options identified in the DOE-NE Fuel Cycle Evaluation and Screening and categorizes these features to facilitate prioritization. Features are categorized as *essential functions*, *integrating features*, and *exemplary capabilities*. A library of unit tests applicable to each of the essential functions should be developed as future work. An international dialog on the functionalities and standard test methods for fuel cycle simulator tools is encouraged.

Key Words: Fuel cycle simulator, transition analysis, unit tests.

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1. INTRODUCTION

In 2011, the U.S. Department of Energy Office of Nuclear Energy (DOE-NE) chartered the nuclear fuel cycle Evaluation and Screening (E&S) study [1] to identify nuclear fuel cycle options that offer significant potential benefits versus the present once-through fuel cycle with light water reactors (LWRs). These benefits are related to performance in key areas like natural resource utilization and nuclear waste generation. Thousands of possible nuclear fuel cycles were identified and grouped based on fundamental physics characteristics, including feed material, the neutron energy spectrum of the reactor stage, and recycled materials. The E&S identified a promising fuel cycle at an equilibrium condition (steady state), but was not focused on issues associated with the transition from the present fuel cycle to a potential future fuel cycle.

Fuel cycle simulator tools can inform time-dependent nuclear fuel cycle scenarios and performance [2]. This includes a transition from the present well-understood once-through fuel cycle to a future fuel cycle that presents significant potential economic, resource utilization, and environmental benefits relative to the present fuel cycle in the United States. The goal is to develop a once-through fuel cycle with enrichment using thermal spectrum reactors. Significant effort has recently been devoted to the development of fuel cycle simulator tools and simulation frameworks. Examples of fuel cycle simulation tools used within the Fuel Cycle Options Campaign include CYCLUS [3, 4], DANESS [5], DYMOND [6], ORION [7], and VISION [8]. The development of these tools required testing and verification. In addition, the scenario models developed using these tools must be validated.

Previous benchmark and comparison studies between these and other fuel cycle codes were often conducted for complete fuel cycle scenarios involving entire fleets with different reactor types, specific energy demand profiles, various fuel cycle facilities, etc., and the level of agreement depended greatly on the specific scenarios modeled. Therefore, successful code verification for one specific scenario (e.g., transition from thermal spectrum reactors to fast spectrum reactors) does not imply that the same codes will agree for a different scenario with even small differences. Therefore, this paper proposes that these codes should be tested for their specific fundamental functionalities via a common library of “unit tests” rather than for specific scenarios in order to isolate the true sources of differences.

One general challenge that fuel cycle simulators face is the validation process; there may be ambiguities in the correct answer for problems and a lack of hard data for validation of models and verification of tools. Also, the problems these simulators tackle are complex, with many loosely and strongly coupled interactions between systems and material flows. These challenges were evident in two recent benchmark studies focused on complex integral scenarios [9,10]. Therefore, these unit tests must be clear in their specifications to avoid multiple interpretations from different participants.

There is a need to develop unit tests for fuel cycle simulator tool verification. In addition to the unit tests, there is interest in more realistic (but still simplified) transition scenario cases that test the comprehensive capabilities of the simulator. Both of these types of test cases are vital for verification of a fuel cycle simulator. Therefore, it is proposed to develop a library of unit test cases that would be useful for tool developers worldwide to use for testing functionalities and verification of possible

transition scenarios. This focus dovetails with the main purpose of most fuel cycle simulators: to study scenarios for transition from the existing fleet to a new fuel cycle system.

A key question in defining test cases for studying transition to a promising future fuel cycle is: *what are the problems we are trying to solve and what functionalities are necessary to solve them?* This question is part of the overall goal to identify fuel cycles with significant benefits to the current once-through fuel cycle in the United States. This goal requires study of methods to transition from the present situation to advanced cycles. This transition study identifies constraints on the rate at which transition to an advanced fuel cycle can be achieved.

Several fuel cycles are considered qualitatively herein, and particular features of interest/relevance for each cycle are identified. A three-tier hierarchy of features was considered:

- Basic features or essential functionalities are foundational elements of the simulation; they represent the basic building blocks.
- Integral features are necessary to bind the essential functionalities together and produce useful transition results.
- Finally, exemplary features enable a particular tool to study particular sensitivities, technology choices, etc., but they may not be essential or present in every tool.

Fuel cycles were selected for the scope of this paper with the goal of *identifying and documenting essential functionalities* for modeling those fuel cycles in a fuel cycle simulator (including those at

the front end, back end, and reactor/transmutation stages). The example fuel cycles in this document are from the comprehensive E&S study [1].

The objective of the E&S study was to evaluate nuclear fuel cycle options and identify those that offer significant potential benefits compared to the present once-through fuel cycle with light water reactors. These performance benefits are in key areas such as natural resource utilization and generation of nuclear waste. Thousands of options were considered in the study and were condensed into forty evaluation groups (EGs) with fundamental physics characteristics, such as material feed and neutron energy spectrum.

Three fuel cycles are considered in this paper: (1) once-through low-enriched enriched uranium (LEU) in thermal spectrum reactors (EG01), (2) continuous recycle of uranium and plutonium in fast spectrum reactors (EG23), and (3) continuous recycle of thorium and uranium (mostly ^{233}U) in fast reactors (EG28). Short descriptions and justifications for these fuel cycles are shown in Table 1. Each fuel cycle is a single-stage fuel cycle, i.e., one reactor type only. However, because the transition from one fuel cycle to another is inherently a multi-stage problem, the scope of this paper covers the behavior of multi-stage fuel cycles. Multiple facilities and fuel types are needed to model each of these transition problems. Transitions to multi-stage fuel cycles, such as continuous recycle of uranium and plutonium in fast reactors with uranium and plutonium also used in thermal reactors (EG29), share similar functionalities as EG23 but have added constraints and questions. One key question is: what strategy should be used in deploying the reactors in the different stages of the two-stage fuel cycle? This is an important question, but it was determined that this and similar

questions for two-stage fuel cycles are outside the scope of the present paper.

This paper identifies the features needed to model a transition scenario from the present fuel cycle to continuous recycle of U-Pu or Th-U3 in fast spectrum reactors. In this paper U3 is a uranium vector that contains ^{233}U as the primary fissile isotope, but also includes ^{234}U , ^{235}U , and other uranium isotopes. A transition scenario begins with a fleet of legacy LWR reactors which use low-enriched uranium (LEU) fuel. The new fuel cycle is then deployed using some source of fissile material. The transition scenarios relevant to this study are those in which the present once-through fuel cycle transitions over a period of time to an advanced future fuel cycle with significant potential benefits. This study represents an initial identification of basic features associated with transition to two specific fuel cycles. Other features may be associated with transition to other fuel cycles. This paper also includes an example of a possible unit test, a fixed rate of growth in nuclear energy demand.

Table 1. Example fuel cycles for identification of essential functionalities

Fuel cycle option	Description	Justification
EG01	Once-through thermal reactor with low-enriched uranium fuel	<ul style="list-style-type: none">• Status quo low-enriched uranium thermal reactors,• This case represents the initial condition in a potential transition to a sustainable nuclear fuel cycle.
EG23	Continuous recycle of uranium-plutonium in fast reactors	<ul style="list-style-type: none">• Recycling of U/Pu, in fast reactors,• This fuel cycle was identified as one of the most promising fuel cycles in the E&S [1].
EG28	Continuous recycle of thorium-uranium (mostly ^{233}U) in fast reactors	<ul style="list-style-type: none">• Th/U3 fuel, in fast reactors,• This fuel cycle was identified as a promising fuel cycle in the E&S [1]; uses thorium-based fuels.

2. GENERAL OVERVIEW OF FUEL CYCLE SIMULATOR FEATURES

Common functionalities were identified that spanned the transition to each of these sustainable fuel cycles (or a subset of the fuel cycles) in Table 1. Specific examples are highlighted below.

2.1. Material Compositions

The backbone of a fuel cycle simulation involves the flow of fuel materials through the system. Modeling of these fuel materials must include the primary fissile and fertile actinide isotopes (^{232}Th , ^{233}U , ^{235}U , ^{238}U , ^{239}Pu , ^{240}Pu , ^{241}Pu) to allow for modeling of fuel enrichment and depletion. The remaining fuel's initial heavy metal mass must also be modeled as a minimum as lumped masses of the remaining actinides and fission products so that a material balance can be maintained. Isotopic decay of materials in storage becomes a requirement as additional isotopes are modeled, or if the quantity or importance of ^{241}Pu is significant. Modeling of intermediate isotopes may also be required if their half-lives approach or exceed the modeling timestep (e.g. ^{233}Pa in the thorium cycle). Tracking

of fission products beyond a simple lumped sum is exemplary but often included so that waste properties or material storage/transportation/handling issues (radiotoxicity, decay heat, etc.) may be estimated. Modeling of compounding/alloying/binding materials in fuels and waste forms (e.g., oxygen in UO_2) and associated hardware/packaging are also exemplary and rarely included. The example material composition features identified in this paper are shown in Table 2.

Table 2. Example material composition features

Feature	Hierarchy
Modeling of fuel materials including primary fissile and fertile actinide isotopes (^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu)	Basic
The remaining fuel's initial heavy metal mass modeled as lumped masses of the remaining actinides and fission products to conserve mass	Basic
Isotopic decay of materials in storage (including ^{241}Pu)	Exemplary
Modeling of intermediate isotopes (e.g. ^{233}Pa in the thorium cycle)	Exemplary
Tracking of fission products beyond a simple lumped sum	Exemplary
Modeling of compounding/alloying/binding materials in fuels and waste forms (e.g., oxygen in UO_2)	Exemplary

2.2. Deployment of Fuel Cycle Facilities

Facility (e.g., reactor, front end, fabrication, separations, back-end) deployment is a necessary functionality to simulate transition to an advanced fuel cycle. These facilities may be *deployed and retired* according to an appropriate prescribed schedule and associated lifetime. Construction time delays are also relevant basic functionalities. Strategic deployment of appropriate facilities to meet nuclear demand is an integral functionality. Significant overlap is expected in this area because all fuel cycles require deployment and retirement of facilities. Proposed tests include modeling a single

reactor or fuel cycle facility through its lifetime to ensure proper accounting of construction lead time, operational functionality, capacity utilization, and retirement. The example material composition features identified in this paper are shown in Table 3.

Table 3. Example fuel cycle facility deployment features

Feature	Hierarchy
Facility (e.g., reactor, front end, fabrication, separations, back-end) deployment and retirement	Basic
Construction time delays	Basic
Strategic deployment of appropriate facilities to meet nuclear demand	Integral

2.3. Front-End Facility Models

Required models include a source (mining and milling or recycling) that may include both uranium and thorium feedstock. The specific details of mines and mills are seldom modeled and are not necessary except as an indication of the annual and total quantities available. However, conversion may be modeled (mainly for economics), and enrichment is typically modeled (required for mass flows). The timing and capacity of recycle facilities are also typically required.

Collectively, these facilities would be necessary for each fuel feed for a given fuel cycle. The fuel cycles fall broadly into two categories: (1) the first pass, which is unirradiated uranium fabrication, and (2) recycled fuel fabrication, which is a mix of unirradiated and previously irradiated recycled U/Pu or U/TRU or Th/U3 (with or without TRU) fabrication. This will include some delta time between mining/milling/conversion and fabrication or separations and fabrication (fabrication time). Losses in fabrication (0.2% in the E&S) must be accounted for, because losses to waste are an

important feature to track. Examples of proposed unit tests include (1) a test of fuel enrichment and burnup (correlated/recipe based), including front-end mining, enrichment, and fabrication facilities (uranium mined, depleted uranium generated, LEU fuel charged and discharged, spent fuel disposed), and (2) a test of the constrained availability of front-end facilities/raw material and verification that the availability of LWR fuel is affected. The example front-end fuel cycle features identified in this paper are shown in Table 4.

Table 4. Example front-end fuel cycle facility features

Feature	Hierarchy
Source facility (mining and milling or recycling) that may include both uranium and thorium feedstock	Basic
Details of mines and mills including the annual and total quantities available	Exemplary
Conversion and enrichment facilities	Basic
Timing and capacity of recycle facilities	Basic
Fuel fabrication (fresh and recycle fuel)	Basic
Time delays and losses in separations and fabrication	Basic

2.4 Separations and Material Recycling Facilities

These models will be necessary for tracking spent fuel in a recycle fuel cycle. Depending on the strategy for transition, additional separations facilities may be required for LWR spent fuel, U/Pu, U/TRU, and Th/U3 fuel. Behavior for separations facilities is a necessary functionality that will include a time interval between discharge and separations (cooling time) and the losses in separations (assumed to be 1.0% in the E&S).

Apart from the uranium enrichment process, there are very few ways to alter the isotopic vectors of any material stream. This limitation has several key impacts for any fuel cycle simulation model. The first impact is to material selection from the available spent fuel supply in order to match a given

recycled fuel specification. In other words, we are constrained to a given set of spent fuel compositions to match a specified fuel recipe intended for recycled fuel (i.e., the "winery problem"). Beyond the selection of recycled feed materials, variations in isotopic vectors going into a reactor will lead to corresponding variations in the spent fuel coming out. At the level of the fuel cycle simulation model, many of these complications are avoided through the use of simplifying assumptions, such as assuming the fungibility of isotopic vectors to meet a given fixed fuel recipe. Wherever possible, the impact of these simplifying assumptions should be assessed either through simple test cases or through comparisons with separate analyses. For example, the VISION fuel cycle simulator can enforce conservation of total Pu (or TRU, etc.) mass when creating fuel from recycled material; in doing so, it tracks the isotopic mass discrepancy created by this assumption. This discrepancy should be evaluated to ensure that it does not represent a significant error with respect to any of the fuel cycle metrics under consideration. The example separations and material recycling features identified in this paper are shown in Table 5.

Table 5. Example separations and material recycling features

Feature	Hierarchy
Separations facilities may be required for LWR spent fuel, U/Pu, U/TRU, and Th/U3 fuel	Basic
Time interval between discharge and separations (cooling time)	Basic
Losses in separations	Basic
Material selection from the available spent fuel supply ("winery problem")	Basic

2.5 Reactor Facilities

Reactor facilities feature fueling requirements. Reactor facilities burn fuel, a process which consists of charge and discharge of driver and blanket fuel with associated residence times. The fuel is

defined according to pre-generated isotopic from reactor physics calculations (“recipes”), or it is defined by calculations performed in real time based on physics models. Pre-generated isotopic compositions are considered to be an essential feature for the fuel cycles considered in this paper. However, the pre-generated recipes must account for high importance isotopes, such as ^{241}Pu , with a relatively short half-life. Real time calculations based on reactor physics models are considered to be exemplary for the example fuel cycles in this paper, but for some other scenarios (such as those with variable cooling time) this feature would be essential. Each reactor will have a prescribed lifetime, construction time, and decommissioning time. The initial charge for the first core and the discharge for the final core must reflect accurate heavy metal mass requirements. Proposed features to be tested include (1) reactor lifetime, construction, deployment, retirement, and associated mass flows, (2) a check that steady state separation stream values do lead to a steady state condition without material accumulation. The example reactor facility features identified in this paper are shown in Table 6.

Table 6. Example reactor facility features

Feature	Hierarchy
Reactor facilities fueling requirements , including number of batches, cycle length, and fuel charge per batch	Basic
Multiple fuel types in reactor facility (driver, blanket, etc.)	Basic
Pre-generated charge and discharge isotopic compositions	Basic
Real time calculations based on reactor physics models	Exemplary
Reactor facility lifetime, construction time, and decommissioning time	Basic
Initial charge for the first core and the discharge for the final core	Basic

2.6 Back-End Features

Back-end features include cooling of spent fuel that is to be disposed of or recycled. Some specifics on the back end (e.g., the disposal facility) will include conservation of disposed material

mass and consistency with charge masses and the generated power. Back-end features are necessary for tracking metrics for nuclear waste management. The example back-end fuel cycle facility features identified in this paper are shown in Table 7.

Table 7. Example back-end fuel cycle facility features

Feature	Hierarchy
Cooling of spent fuel that is to be disposed of or recycled	Basic
Conservation of disposed material mass and consistency with charge masses and the generated power	Basic

2.7 Starting the New Fuel Cycle

Startup is a difficult problem for some fuel cycles due to fissile material requirements because an initial source of fissile material is needed to start the reactors in the fuel cycle. Details on the features of a specific fuel cycle simulator tool are necessary to address multiple fuel cycle starting strategies. Startup of some fuel cycles may be more straightforward than others, but transition to all fuel cycles without enrichment at equilibrium will involve an external source of fissile material. One option is to assume fuel cycle startup using fissile material recovered from spent LWR fuel, but additional strategies exist, including using LEU to start a new fuel cycle. The capability to use more than one material for starting a new fuel cycle is an integral feature. However, many transition scenarios considered to date focus on plutonium start-up of fast reactors, and the codes used to perform that work may not be capable of modeling multiple fuel types for a reactor (primary and back-up fuel). The example fuel cycle startup features identified in this paper are shown in Table 8.

Table 8. Example fuel cycle startup features

Feature	Hierarchy
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External source of fissile material	Basic
Startup on recycled fuel from other facilities	Integral
Primary and back-up fuel types	Exemplary

2.8 Materials Queuing and Prioritization under Capacity Limitations

A specific transient scenario may feature phases in which materials are allowed to accumulate prior to being moved to their next point of utilization. For example, if Pu/U from LWR spent fuel is used to bootstrap the fuel cycle, this material will build up prior to the start of separations, and separated material may build up prior to being fabricated into finished fuel. Wherever material is allowed to accumulate or when there are multiple sources available, decisions must be made regarding the priority order in which the material will be used. The simplifying assumptions used in many fuel cycle simulators may render these issues inactive or untestable for most common scenarios. However, if radioactive decay or time-varying fuel compositions are to be modeled (exemplary features), then care must be taken to ensure that they are handled in a consistent manner between each model. (Note that this may be outside the present scope of unit or integral testing.) The example material prioritization features identified in this paper are shown in Table 9.

Table 9. Example material prioritization features

Feature	Hierarchy
Material accumulation	Basic
Material prioritization	Integral and/or Exemplary
Radioactive decay or time-varying fuel compositions	Exemplary

2.9 Energy Demand Algorithms

Information on the features related to energy demand are necessary to enable deployment (or

retirement) of reactors to meet a change in nuclear energy demand. These features allow for technology penetration allocation and checking for material availability and backup reactor technology. In addition, the algorithm must enable ordering and deployment of multiple reactor technologies at the same time. This is a key feature for integral tests and modeling of actual transition scenarios as opposed to unit tests. Proposed tests include (1) checking that the reactor ordering algorithm is able to cover the assigned energy demand when no material constraints are identified and (2) checking that backup technology is deployed when material constraints are encountered. The example energy demand algorithm features identified in this paper are shown in Table 10.

Table 10. Example energy demand algorithm features

Feature	Hierarchy
Technology allocation accounting for availability	Integral
Ordering and deployment of multiple reactor technologies	Integral

3. EXAMPLE FEATURES OF SPECIFIC NUCLEAR FUEL CYCLES

This section of the paper explores identified features specific to a particular fuel cycle. In some cases, possible unit tests or integral tests are proposed to address these features.

3.1 Once-Through Thermal Reactor with LEU Fuel (EG01)

The EG01 scenario, which serves as the reference fuel cycle in the E&S, is representative of the present U.S. once-through fuel cycle. However, it is notable that the present U.S. fuel cycle does not have a permanent repository. LEU oxide fuel is irradiated in existing commercial pressurized water reactors (PWRs) to approximately the current LWR average discharge burnup (~50 GWd/t).

Discharged fuel (DF) is cooled in onsite spent fuel storage and sent to a geologic disposal (see material flow diagram in Fig. 1). The major focus of this paper is on identification of features to simulate the potential transition from EG01 to another fuel cycle.

Fig. 1. EG01 [1] fuel cycle material flow.

Potential functionalities were identified for the modeling of a once-through fuel cycle with LEU in LWRs. One essential feature is the tracking of radioactive decay and related properties (activity, radiotoxicity, and decay heat). These properties will directly impact fuel cycle performance metrics related to nuclear waste management.

Another key issue relates to the reactor mix in the present U.S. nuclear fuel cycle. About two-thirds of the current LWR fleet is made up of PWRs, and the remaining third is boiling water reactors (BWRs). Distinguishing the reactor types is an essential functionality for simulation tools. In

addition, instead of modeling a single reactor specification and set of assumptions, the simulator could include the functionality to model a realistic set of different combinations of reactor burnups, enrichments, refueling times, and licensed operational lifetimes.

3.2 Continuous Recycle of U/Pu in Fast Reactors (EG23)

There are several existing approaches exist for transition from the LWR system to a system with breakeven U/Pu fueled sodium fast reactors (SFRs). In this context breakeven means that the fissile inventory ratio is unity, after accounting for losses and isotopic change due to transmutation and isotopic decay in cooling. Options include using LWR spent fuel (legacy or accumulated after a set time) or LEU fuel. At the specified time, the LWR spent fuel is recycled, with uranium and plutonium being used as fuel for a fleet of breakeven sodium fast reactors that replace the retiring LWR fleet. New LWRs may be built as needed to replace legacy reactors retiring prior to the availability of the new SFR reactors or if the recycled material should be insufficient to meet the overall power demands. The EG23 fuel cycle is shown in Fig. 2.

Note: Low-Level Waste (LLW) will be produced in performing various fuel cycle functions.

Legend:

NU = Natural Uranium

RU = Recovered Uranium

MA = Minor Actinide

DF = Discharged Fuel

FP = Fission Products

Pu/RU = Co-separation of uranium and plutonium

SFR = Sodium-cooled fast reactor

△ = Nuclear Waste Disposal Technologies

○ = Nuclear Material Storage Technologies

→ = Nuclear Material Transport Technologies

Fig. 2. EG23 [1] fuel cycle material flow.

To ensure that each fuel cycle simulator is functioning as intended and to provide a basis for comparisons within the code, a few key features of each simulator should be closely evaluated, some of which are described below. These features will apply to many scenarios besides the one described here.

The EG23 fuel cycle uses recycled material at equilibrium. To transition from the equilibrium EG01 fuel cycle to the EG23 fuel cycle requires an approach for starting the fuel cycle. There are at least two strategies for starting the fuel cycle: (1) using LWR spent fuel or (2) using LEU fuel directly in the SFR. Simple tests and the ability to switch charge vector are therefore relevant for this fuel cycle. The driver and blanket represent separate charge fuel streams and therefore will require separate front-end facilities.

3.3 Continuous Recycle of Th/U3 in Fast Reactors (EG28)

EG28 is a challenging transition problem because thorium fertile fuel is used and the primary fissile nuclide (^{233}U) does not exist in nature, nor is it a product of the present once-through LWR fuel cycle. The mass flow diagram for EG28 is shown in Fig. 3.

Fig. 3. EG28 [1] fuel cycle material flow.

Transition from the present once-through fuel cycle to EG28 presents unique considerations and constraints. EG28 will require an external source of fissile material to be deployed. This would likely be LEU driver fuel, U/Pu (or TRU) fuel from LWR spent fuel, or Th/Pu (or TRU) driver fuel with the Pu (or TRU) recovered from LWR spent fuel. The SFRs would initially be fueled by the external source of fissile material with pure Th blankets, and eventually enough U3 would build up to begin fueling reactors with their intended feed material.

This transition requires the functionality to shift from one fuel input to another for a single reactor type. In other words, the initial feed to an EG28 SFR would consist of an external source of fissile material, such as LEU driver fuel, as well as Th blanket fuel. The Th blanket fuel would be reprocessed, and the U3 vector (U isotopics resulting from the Th cycle) would be co-extracted with Th and stockpiled for eventual deployment as driver fuel for SFRs. When enough fuel is built up, the charge recipe for the driver fuel would shift to the intended driver fuel for the fuel cycle: Th/U3. Depending on the transition strategy (for example, if U/Pu driver fuel recycled from LWR spent fuel is used), multiple separations or fuel fabrication facilities may be required for a single reactor.

4. EXAMPLE UNIT TEST FOR GROWTH IN ENERGY DEMAND

An example unit test case is described for a growth scenario. In this scenario, reactors are deployed to meet a fixed growth rate in nuclear energy demand (in this case 1% per year beginning with a 100 GWe capacity). The functionalities tested by this example case are:

- reactor deployment according to a growing energy demand,
- steady state operation with an infinite source of fuel,
- material flow tracking in the reactor,
- accumulation of spent fuel in cooling storage and dry storage, and
- time delays associated with cooling storage.

Additional parameters of this example unit test are shown in Table 11. This example scenario was

solved in four fuel cycle simulator tools: CYCLUS, DYMOND, ORION, and VISION. The analytical solution was used to compare the different simulator tools. All of the tools exhibited results consistent with their respective architectures for deployment of facilities to meet demand, the definition of the test, and the interpretation of the test by a particular analyst. This example is intended to demonstrate one possible approach to testing a few basic features.

Table 11. Parameters for example unit test for 1% growth in nuclear energy demand

Duration	200 years [Begin year 0; end year 199]
Mining	There is no modeling of mining features in this unit test.
Fabrication	There is no modeling of fabrication features in this unit test.
Fuel	No specific fuel composition features are used in this test case. An infinite supply of generic reactor fuel is assumed.
Deployment	<p>A 100 GWe generic reactor capacity exists at the beginning of the simulation. The capacity factor is 0.9, so the electricity generated is 90 GWe per year. After deployment, the reactor operates at steady state throughout the duration of the simulation.</p> <p>Each year the energy demand grows by 1%, so 100 GWe capacity in year 0 becomes 101 GWe in year 1 (compounded annually), and so on. Reactors (1 GWe capacity) are deployed as needed to meet the energy demand.</p>
Retirement	There is no modeling of facility retirement features in this unit test.
Core loading and discharge	<p>The total initial core loading of a deployed reactor is 90 t of heavy metal. The annual core charge per reactor is 19.909 t/yr, and core discharge is 19.909 t/yr. Annual loading and discharge occur at the beginning of each year, from year 0 throughout the duration of the simulation.</p> <p>The generic reactors operate on 19.909 t/yr of an unlimited supply of heavy metal.</p>
Wet and dry storage	<p>The discharged fuel is cooled in wet storage for a total of 4 years. The first discharge enters wet storage at the beginning of year 1, and this continues throughout the duration of the simulation.</p> <p>After cooling, the fuel is moved to dry storage, where it accumulates throughout the duration of the simulation. The first batch of fuel is moved from wet storage to dry storage immediately at the beginning of year 5.</p>

Fig. 4. Example solutions to a unit test for 1% annual growth in demand for nuclear energy.

This paper is focused on identifying functionalities that may be relevant for unit tests given example transition problems to several example fuel cycles. This paper is not intended to define the unit tests themselves. The unit test shown in Table 11 is just an example. The objective of this paper is not to fully prescribe these tests or features, but rather to present the results of one expert elicitation focused on the identification of general observations about needed features and limited identification of potential specific functionalities to test.

5. SUMMARY AND FUTURE WORK

Example functionalities relevant to solving a particular type of transient problem for a fuel cycle simulator are identified. The transient problem in question is a scenario in which a once-through

nuclear fuel cycle with LEU in thermal reactors transitions to a sustainable advanced fuel cycle. Some example basic features and exemplary features are identified for two potential future fuel cycles.

This work defines the basic features of fuel cycle simulator tools. These functionalities support the development of unit test cases to perform verification of the proposed tools. Functionality outside the basic features' scope is also important, and added capabilities must be tested and verified by the developers of the particular tools.

Basic features must be subjected to verification via unit tests. The value of simplified, standardized, and open cases has been noted in the literature [11]. However, even the cases identified in Reference 9 have significant complexity and competing effects. Test cases with a simplified basis are needed to enable quality assurance while avoiding error cancellation. In addition, the analytical solutions to the test cases must be unambiguous. There is added value in having a set of strictly defined test cases for dynamic fuel cycle simulators.

These basic features are a platform to potentially develop an open library of unit tests. These unit test cases would serve as the building blocks for development of more sophisticated cases. The unit tests are focused on isolating particular features or modules and verifying that behavior is in accordance with the expected result given the architecture of a particular tool. Unit tests serve as the foundation of a holistic benchmarking effort, which would eventually include integral test cases of entire transition scenarios [12]. The effort in the present paper is complementary to previous efforts to develop essential requirements document for fuel cycle simulators and taking a comparative

inventory of these simulators [13].

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