# Extensions to the CYCLUS Ecosystem in Support of Market-Driven Transition Capability
## LLNL-PROC-656426

Kathryn D. Huff[1], Massimiliano Fratoni[1], Harris R. Greenberg[2]
[1]*Department of Nuclear Engineering, University of California, 2150 Shattuck Ave., Suite 230, Berkeley, CA 94709*
*huff@berkeley.edu, maxfratoni@berkeley.edu*
[2] *Lawrence Livermore National Laboratory, 7000 East Ave., L-223, Livermore, CA 94550*
*greenberg6@llnl.gov*

## INTRODUCTION

The CYCLUS Fuel Cycle Simulator [1] is a framework for assessment of nuclear fuel cycle options. While CYCLUS has previously been capable of system transitions from the current fuel cycle strategy to a future option, those transitions have never previously been driven by market forces in the simulation. This summary describes a set of libraries [2] that have been contibuted to the CYCLUS framework to enable a market-driven transition analysis.

This simulation framework is incomplete without a suite of dynamically loadable libraries representing the process physics of the nuclear fuel cycle (i.e. mining, fuel fabrication, chemical processing, transmutation, reprocessing, etc.). Within Cycamore [3], the additional modules repository within the CYCLUS ecosystem, provides some basic libraries to represent these processes. However, extension of CYCLUS with new capabilities is community-driven, relying on contributions by user-developers. The libraries contributed in this work are examples of such contributions.

### Motivation

The attractiveness of a new technology can be assessed to first order by evaluating equilibrium fuel cycle scenarios. Equilibrium scenarios are those at steady state, in which technologies are deployed statically. However, transition dynamics leading up to that equilibrium state also contribute to the viability of deploying such a technology [4].

For this reason, fuel cycle scenario analysis is often concerned with the transition from one nuclear fuel cycle technology or strategy to another. Such analyses are termed “transition scenarios.” Transition scenarios seek to model the real world dynamics of such a technology shift, in part to inform Research Development and Design (RD&D) decision-making.

Transition scenarios are often modeled from a technology availability perspective, deploying new technologies based on their readiness. The capability represented by this work, a transition driven by market forces (i.e., material availability) is more realistic. In that case, technology readiness may be applied only as a constraint.

### Background

Previous fuel cycle simulators have achieved market-driven deployment capability using look-ahead algorithms for facility deployment [5, 6]. These simulators typically conduct guess-and-check simulation attempts, restarting or crashing if their algorithm failed to generate a coherent simulation.

The development version of the CYCLUS simulator has long been capable of technology driven scenarios [7] that relied on explicit demand or deployment profiles defined by the user. This capability shared the disadvantages of the guess-and-check methods of other simulators, since the user-defined deployment profiles may lead to incongruous scenarios (i.e., insufficient material or processing availability and unexpected idle facilities).

By harnessing the CYCLUS dynamic resource exchange paradigm and emphasizing generality, the Agents contributed in this work are capable of dynamically checking material availability in the simulation and responding accordingly. These contributions thereby enable market-driven transition scenarios for a range of future use cases in the CYCLUS ecosystem.

### Method

Extensions to the CYCLUS framework are necessary because the available institution, region, and facility archetypes packaged with the Cycamore repository are not sufficient to model the specific goals of all simulation descriptions. In this case, Facility Agents were contributed to support reprocessing and fuel fabrication specifications in the transition scenario definition of interest and an Institution Agent was contributed to support market-driven building and decommissioning of transitioning technologies.

This is a canonical example of a user-developer’s workflow for capability extension in CYCLUS. That is, each scenario specification of interest in fuel cycle analysis is usually sufficiently pathological that modifications must almost always be made in any simulation framework. This effort demonstrates how the modularity built into the CYCLUS framework allows extension without modification of the core logic.

| Facility Type | Agent | Key Parameters |
|---|---|---|
| Mine | SourceFacility | Capacity |
| Enrichment | EnrichmentFacility | feed enrchment%<br>tails enrichment%<br>Process time |
| LWRFuelFab | StreamBlender | Process time<br>Fissile Source |
| SFRFuelFab | StreamBlender | Process time<br>Fissile Sources<br>Fertile Sources |
| LWR | BatchReactor | Installed Capacity<br>Capacity Factor<br>Batches per core<br>Cycle length<br>Fresh Fuel Comp.<br>Spent Fuel Comp. |
| SFR | BatchReactor | Installed Capacity<br>Capacity Factor<br>Batches per core<br>Cycle length<br>Fresh Fuel Comp.<br>Spent Fuel Comp. |
| LWRWetStorage | CommodConverter | Process time |
| SFRWetStorage | CommodConverter | Process time |
| LWRSeparation | SeparationMatrix | Capacity<br>Process Time<br>Efficiency Matrix |
| SFRSeparation | SeparationMatrix | Capacity<br>Process Time<br>Efficiency Matrix |
| HLW Repository | SinkFacility | Capacity |

TABLE 1: Facilities and their implementations with key parameters.

## SIMULATION DESCRIPTION

### Scenario Definition

The simplified transition scenario modeled was from the current once-through Light Water Reactor (LWR) fuel cycle, to a fleet of Sodium-Cooled Fast Reactors (SFRs) with 100% recycle of spent fuel. The simulation starts in January 2014 and lasts until transition to 100% SFRs is complete. The nuclear installed capacity is constant (100GWe). The transition is driven by the criteria that when sufficient separated material is present, an LWR (1000MWe) should be decommissioned and replaced with three ($333.\bar{3}$) SFRs.

All facility implementations for the simulation are described in Table 1.

*Material Flow*

A summary of the material flows in the simulation can be found in Figure 1 and Table 2.

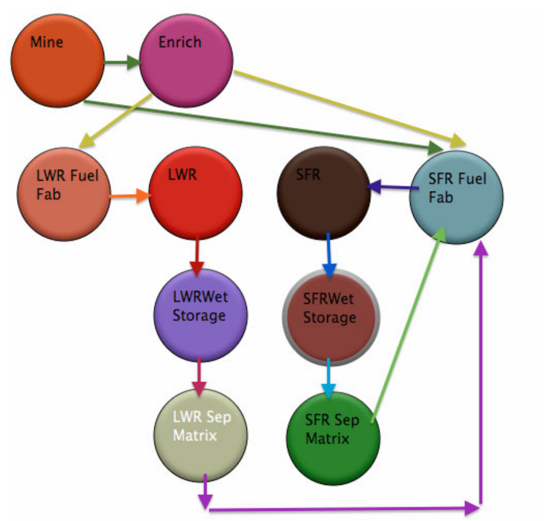


Fig. 1: The basic material flow paths for this simulation. This image was generated by Cycic, the input controller for CYCLUS [8]. Note that the Sink facility which collects waste commodities is not depicted above.

| Commodity | Offered By | Requested By |
|---|---|---|
| Natural U | Mine | Enrichment |
| LEU | Enrichment | LWRFuelFab |
| Depleted U | Enrichment | SFRFuelFab |
| fresh LWR fuel | LWRFuelFab | LWR |
| fresh SFR fuel | SFRFuelFab | SFR |
| LWR UNF | LWR | LWRWetStorage |
| SFR UNF | SFR | SFRWetStorage |
| cool LWR UNF | LWRWetStorage | LWRSeparation |
| cool SFR UNF | SFRWetStorage | SFRSeparation |
| separated LWR U | LWRSeparation | SFRFuelFab |
| separated LWR TRU | LWRSeparation | SFRFuelFab |
| separated SFR U | SFRSeparation | SFRFuelFab |
| separated SFR TRU | SFRSeparation | SFRFuelFab |

TABLE 2: Commodity flow in the transition simulation

*Desired Outputs*

The desired outputs of this simulation include deployment metrics (i.e., the year during which the transition becomes complete). Additionally, installed capacity profiles should demonstrate that generating shortages do not occur. Key metrics also include material metrics such as separated surplus PU or TRU profiles, LWR used fuel reprocessing rate (t/yr), SFR used fuel reprocessing rate (t/yr), LWR used fuel mass in storage (t), and SFR used fuel mass in storage (t).

*Deployment Regions and Institutions*

In order to facilitate a deployment profile for the LWR to SFR transition, an existing Cycamore model was used. The GrowthRegion model maintains a power generation profile specified by the user. It does this by deploying or decommissioning reactors when necessary to maintain the specified growth profile.

In this case, a constant 100GWe "growth" is maintained in the simulation. This region encapsulates all of the facilities in this simulation. When sufficient material is available to support a new set of three SFRs, an LWR is decommissioned. When power generating capacity is lost due to an LWR (1000MWe) decommissioning, the GrowthRegion deploys sufficient SFR capacity (three 333.3MWe SFRs) to replace it.

## CAPABILITY EXTENSIONS

A number of exsiting capabilities were used to acheive this simulation. One is the GrowthRegion, which can maintain a power profile according to a demand curve. Another is the BatchReactor, which generically represents multi-batch reactor models with fresh and spent fuel material compositions defined by the user. The Source Facility and Sink Facility produce and consume material, respectively. Accordingly, they represent the Mine and HLW Repository in this simulation. The details can be seen in Table 1 and Figure 1. Other capabilities had to be contributed, however. This section describes those capabilities.

### Commodity Converter Facility

One versatile facility model contributed by this work is the CommodityConverter, a simple representation of timed commodity transformation. After receiving a resource (e.g., a material), this facility waits for a user-defined time period. Once that time period has passed, the resource is offered to the resource exchange system as a new commodity type. With this behavior, the Commodity Converter facility is ideal for representing storage. In that case, this model requests a commodity such as spent fuel, then waits for a cooling period before offering the same Material Resource as a cooled spent fuel Commodity.

| Parameter | Units | Default | Range |
|---|---|---|---|
| Input Commodity | string | "" | any string |
| Output Commodity | string | "" | any string |
| Delay Time | months | 0 | $0-\infty$ |
| Storage Capacity | kg | $\infty$ | $0-\infty$ |

TABLE 3: Input parameters for the Commodity Converter Facility Agent

Note that Commodity and Material are distinct concepts in the CYCLUS framework. A Material is a subtype of Resource. All Resources have a Commodity type. A single Material composition in CYCLUS can therefore be a "fuel" or"waste" Commodity or any arbitrary string registered within the simulation, irrespective of the isotopic composition.

### Stream Blender Facility : Fuel Fabrication

The process of fuel fabrication from separated materials streams can most concisely be described as blending into a recipe. To most generically represent this process, the Stream Blender Facility has been added to the CYCLUS ecosystem. This new Facility Agent handles the combination of various commodity streams in appropriate proportions to achieve a goal recipe.

| Parameter | Units | Default | Range |
|---|---|---|---|
| Input Commodities | set of strings | "" | |
| Output Commodities | set of strings | "" | |
| Waste Commodity | string | "waste" | |
| Production Capacity | kg/month | $\infty$ | $0-\infty$ |
| Process Time | months | 0 | $0-\infty$ |
| Source Preferences | - | - | - |
| Goal Recipe | mass vector | - | - |

TABLE 4: Input parameters for the Stream Blender Facility Agent

### Matrix-Based Separation Facility Model

By describing the separations process as a simple matrix of efficiencies, a material stream transformation can be conducted. The specific process chemistry for the separation at hand is treated as elemental, as representative of a non-laser separations process. The efficiencies must be defined to transform an incoming composition vector, $I$, with $N$ constituent amounts, $I_n$ to an outgoing set of $M$ streams, $E_m$. The efficiency matrix, $\eta$, is therefore an $N\times M$ matrix of efficiencies. The matrix of separation efficiencies has a default value: the identity matrix of size $N\times N$. In this context, the identity matrix represents complete and perfect elemental separation without losses.

$$\begin{bmatrix} \eta_{11} & . & . & . & . & . & \eta_{1M} \\ \eta_{21} & . & . & . & . & . & \eta_{2M} \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ \eta_{N1} & . & . & . & . & . & \eta_{NM} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ . \\ . \\ . \\ I_N \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \\ . \\ . \\ . \\ E_M \end{bmatrix} \quad (1)$$

For realistic separations, the user is expected to provide an efficiency matrix representing the separations technology of interest to them. By requesting the feedstock from the appropriate markets, the facility acquires an unseparated feedstock stream. Based on the input parameters in Table 5, the separations process proceeds within the time steps and other constraints of the simulation.

| Parameter | Units | Default | Range |
|---|---|---|---|
| In-Commodity | string | “” | any string |
| Out-Commodities | map | $N:N$ | any map |
| Waste Commodity | string | “waste” | any string |
| $\eta$ Matrix | % yield | Identity | positive matrix |

TABLE 5: Input parameters for the Matrix-Based Separation Facility Model

Thereafter, separated streams as well as a stream of losses are offered the appropriate markets for consumption by other facilities. In the transition scenario at hand, the StreamBlender fuel fabrication facility purchases the streams it desires in order to produce SFR fuel.

### Market Driven Institution

A new Institution Agent has been based on an already existing institution model in Cycamore and added a market-driven deployment capability to faithfully model this scenario. That is, by relying on inheritance from a mix-in class already available within the CYCLUS toolkit, an institution can deploy and decommission facilities based on any decision criteria. By also relying on the dynamic resource exchange interface, it is possible to base that decision criteria on the availability of resources being offered by other facility agents in the simulation.

In this case, a specific quantity of separated transuranic material must exist before an LWR can be decommissioned (to be replaced with three SFRs). That decision criteria, combined with the capability of decommissioning facilities, gives the Market Driven Institution.

## RESULTS AND ANALYSIS

To extend the capabilities of the CYCLUS ecosystem to include market-driven building and decommissioning, physics agnostic separations, simple storage, and source-preferential fuel fabrication, the following Agents were developed:

- SeparationsMatrix Facility, physics agnostic separations, (https://github.com/katyhuff/separationmatrix)
- CommodConverter Facility, timed-release storage, (https://github.com/katyhuff/commodconverter)
- StreamBlender Facility, source-preferential fuel fabrication, (https://github.com/katyhuff/streamblender)
- MktDrivenInst, a market-driven institution, (https://github.com/katyhuff/mktdriveninst)

## ACKNOWLEDGEMENTS

This work relied heavily on work by the Cyclus development team. Most notably, Paul P.H. Wilson, Matthew J. Gidden, Robert W. Carlsen, and Anthony M. Scopatz.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Additionally, this material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number(s) DE-NA0000979.

## REFERENCES

1. R. W. CARLSEN, M. GIDDEN, K. HUFF, A. C. OPOTOWSKY, O. RAKHIMOV, A. M. SCOPATZ, Z. WELCH, and P. WILSON, “Cyclus v1.0.0,” (Jun. 2014).
2. K. HUFF, “Market Driven Transition Capability for Cyclus Simulations,” *Figshare* (Aug. 2014).
3. R. W. CARLSEN, M. GIDDEN, K. HUFF, A. C. OPOTOWSKY, O. RAKHIMOV, A. M. SCOPATZ, and P. WILSON, “Cycamore v1.0.0,” (Jun. 2014).
4. S. J. PIET, B. W. DIXON, J. J. JACOBSON, G. E. MATTHERN, and D. E. SHROPSHIRE, “Dynamic Simulations of Advanced Fuel Cycles,” *Nuclear Technology*, **173**, 3, 227–238 (Mar. 2011).
5. E. A. SCHNEIDER, C. G. BATHKE, and M. R. JAMES, “NFCSim: A Dynamic Fuel Burnup and Fuel Cycle Simulation Tool,” *Nuclear Technology*, **151**, 1, 35–50 (Jul. 2005).
6. J. J. JACOBSON, R. F. JEFFERS, G. E. MATTHERN, S. J. PIET, and W. D. HINTZE, “User Guide for VISION 3.4. 7 (Verifiable Fuel Cycle Simulation) Model,” Tech. rep., Idaho National Laboratory (INL) (2011).
7. M. GIDDEN, P. WILSON, K. HUFF, and R. CARLSEN, “Once-Through Benchmarks with C YCLUS, a Modular, Open-Source Fuel Cycle Simulator,” in “Proceedings of the 2012 ANS Winter Conference,” San Diego, CA (Nov. 2012).
8. R. FLANAGAN and E. A. SCHNEIDER, “Input Visualization for the Cyclus Nuclear Fuel Cycle Simulator: Cyclus Input Control,” in “Proceedings of GLOBAL 2013,” Salt Lake City, UT, United States (Oct. 2013).