Cyclus, an agent-based fuel cycle simulator
Brief Overview

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Agent-based Framework

- Cyclus is agent-based, which means it's very modular
- User can develop / plug in facilities
  - User can 'design' their own fuel cycle
  - Highly customizable

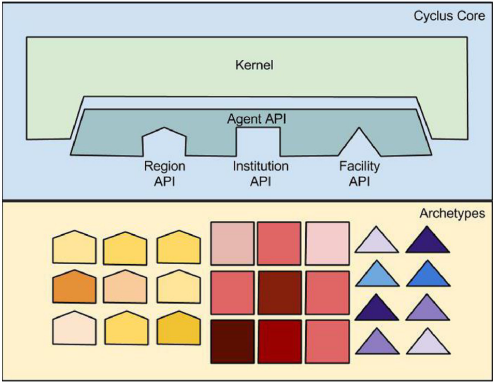
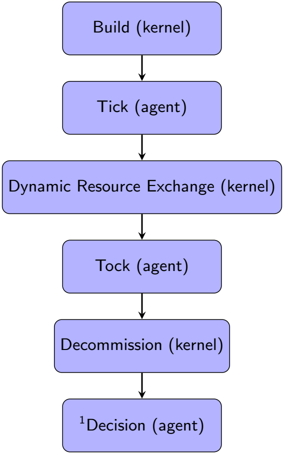


Figure 1: Modular Design of Cyclus

Timestep Execution

A simplified explanation: Each timestep:



[1] Decision phase is planned to be added in the next release.

General Info

- Written in: C++, Python
- Input file: xml, json, python
- Output file: .sqlite, .hdf5

Terminology

- **Archetypes**: A collection of logic and behavior which can be configured into a prototype which can then be instantiated in simulation as a agent. Archetypes are represented as C++ classes that inherit from the base cyclus::Agent class. (e.g. Reactor module, Sink module)
- **Prototypes**: Archetype + parameters (e.g. Reactor with input-defined `name, cycle time, assembly size, core size etc`)
- **Agents**: Every single 'entity' in play during simulation (Region, Institution, Facility)

Terminology

- **Region**: The group agent that is a collection of institutions (Can manage / control regions)
- **Institution**: Agent that manages facilities (Can deploy, decommission facilities)
- **Facility**: The agent that 'trades' and does calculations (Trades material and transmutes, separates)

Extensions - Archetypes

Since Cyclus is an extensible framework, anyone can develop a new archetype and plug-and-play. (Institution, region, facility otherwise.)

- Cycamore: Sink, Storage, Recipe Reactor, Fuelfab, Enrichment, Source, DeployInst, Mixer, Separations, GrowthRegion
- *D3ploy: Demand-driven deployment Institution (NEUP 16-10512)
- *CYBORG: Reactor depletion analysis tool using ORIGEN
- *CYCLASS: Fuelfab and Reactor depletion using neural network.
- *CYDER: A CYclus Disposal Environment and Repository object.
- *CORRM: Continuous On-line Reprocessing Reactor Module.
- *Pyre: Pyroprocessing module with non-proliferation metrics
- *Peddler: Simulate trucks and transport material between facilities.
- And more..

* Third party module in active development.

Extensions - Analysis / Drivers

There are other tools to help visualization / output data analysis of Cyclus.

- RICKSHAW: Automated stochastic driver for Cyclus
- Cymetric: Extracts important fuel cycle metrics
- Analysis: Collection of functions to extract metrics (e.g. natU usage, trade between two facilities, etc.)
- Cycmap: GIS visualization tool for Cyclus
- Cyclist: GUI for Cyclus (DEPRACATED)

Installation - Binary

Better, more thorough explanations are in `fuelcycle.org`

- Windows: N/A
- MacOS: `conda install -c conda-forge cyclus cycamore`
- Linux: `conda install cyclus cycamore`

Installation - Build from Source

All source files are open-source, and available on Github.
`github.com/cyclus/cyclus` and `github.com/cycamore/cycamore` has the source files, and guides

1. Clone repository (`git clone [url]`)
2. Install dependency (see github guide README)
3. `python install.py`

Installation - TroubleShooting

Look for your error message or make a new post in the following Cyclus communities:

1. Github Issue in `github.com/cyclus/cyclus`
2. Cyclus google user group
3. Email jbae11@illinois.edu (me)

Structure

1. `Control`: Simulation Definition
2. `Archetypes`: List of available archetypes
3. `Facility`: Facility prototypes - define parameters of archetypes
4. `Region`: Region agents
5. `Institution`: Institution agents (inside Region definition)
6. `Recipe`: recipe definitions

Control

```xml
<control>
  <duration>2280</duration>
  <startmonth>1</startmonth>
  <startyear>1970</startyear>
  <decay>manual</decay>
</control>
```

Archetypes

```xml
<archetypes>
  <spec>
    <lib>cycamore</lib>
    <name>Source</name>
  </spec>
  <spec>
    <lib>cycamore</lib>
    <name>Sink</name>
  </spec>
  <spec>
      <lib>cycamore</lib>
      <name>Reactor</name>
  </spec>
  <spec>
    <lib>agents</lib>
    <name>NullRegion</name>
  </spec>
  <spec>
    <lib>agents</lib>
    <name>NullInst</name>
  </spec>
  <spec>
    <lib>cycamore</lib>
    <name>DeployInst</name>
  </spec>
  <spec>
    <lib>cycamore</lib>
    <name>Separations</name>
  </spec>
</archetypes>
```

Facility - Cycamore::Separations

```xml
<!-- La Hague Model from Schneider & Marignac -->
<!-- Since 1976 -->
  <facility>
    <name>LA_HAGUE</name>
    <config>
      <Separations>
         <feed_commods>   <val>cooled_french_uox_waste</val> </feed_commods>
         <feed_commod_prefs> <val>20.0</val> </feed_commod_prefs>
         <feedbuf_size>91600</feedbuf_size>
         <!-- 1100 tons/year 91.6 tons/timestep -->
         <throughput>91600</throughput>
         <leftover_commod>lahague_raffinate</leftover_commod>
         <leftoverbuf_size>91600</leftoverbuf_size>
         <streams>
          <item>
            <commod>french_uox_Pu</commod>
            <info>
              <buf_size>91600</buf_size>
              <efficiencies>
                <item>
                  <comp>Pu</comp> <eff>.998</eff>
                </item>
                </efficiencies>
            </info>
          </item>
          <item>
            <commod>uox_U</commod>
            <info>
              <buf_size>91600</buf_size>
              <efficiencies>
                <item>
                  <comp>U</comp> <eff>.998</eff>
                </item>
                </efficiencies>
            </info>
          </item>
        </streams>
      </Separations>
    </config>
  </facility>
```

Facility - Cycamore::Reactor

```
<facility>
  <!-- France -->
  <!-- PWR -->
  <name>FLAMANVILLE-1</name>
  <config>
    <Reactor>
      <fuel_inrecipes>  <val>uox_fuel_recipe</val>       <val>mox_fuel_recipe</val>        </fuel_inrecipes>
      <fuel_outrecipes> <val>uox_used_fuel_recipe</val>  <val>mox_used_fuel_recipe</val>   </fuel_outrecipes>
      <fuel_incommods>  <val>uox</val>                   <val>mox</val>                    </fuel_incommods>
      <fuel_outcommods> <val>french_uox_waste</val>             <val>mox_waste</val>              </fuel_outcommods>
      <fuel_prefs>      <val>1.0</val>                   <val>3.0</val>                    </fuel_prefs>
      <cycle_time>18</cycle_time>
      <refuel_time>2</refuel_time>
      <assem_size>446</assem_size>
      <n_assem_core>257</n_assem_core>
      <n_assem_batch>86</n_assem_batch>
      <power_cap>1330</power_cap>
    </Reactor>
  </config>
 </facility>
```

Region

```xml
<region>
  <name>Poland</name>
  <config>
    <NullRegion/>
  </config>
  <institution>
    <name>Poland_government</name>
    <config>
      <DeployInst>

        <prototypes>
          <val>CHOCZEWO</val>
          <val>NONAME</val>
        </prototypes>

        <build_times>
          <val>708</val>
          <val>780</val>
        </build_times>

        <n_build>
          <val>1</val>
          <val>1</val>
        </n_build>

        <lifetimes>
          <val>720</val>
          <val>720</val>
        </lifetimes>

      </DeployInst>
    </config>
  </institution>
</region>
```

Recipe

```xml
<recipe>
  <name>natl_u_recipe</name>
  <basis>mass</basis>
  <nuclide>
    <id>U235</id>
    <comp>0.711</comp>
  </nuclide>
  <nuclide>
    <id>U238</id>
    <comp>99.289</comp>
  </nuclide>
</recipe>
```

Benefits

1. User can generate input file from database
    - Reactor Specifications
    - Facility deploy / decom times
    - Spent fuel recipe
2. Sensitivity study using external driver (e.g. RAVEN)
3. Simple automation / modification of input file

Output

Cyclus records all transactions between `Facilities` and other metrics unique to each archetype, such as:

- Cycamore::Reactor - Power generation per timestep
- Cycamore::Enrichment - SWU per timestep

Example Workflow

This workflow was used in the paper `Synergistic Spent Nuclear Fuel Dynamics Within the European Union` (in ANS 2017 Winter meeting, journal publication pending).

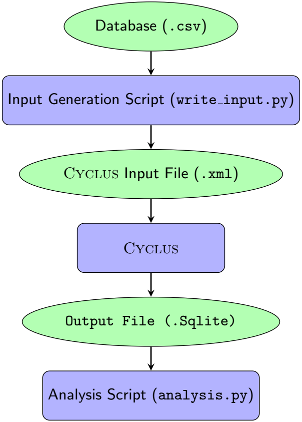


Figure 2: Green circles and blue boxes represent files and software processes,

CSV to Cyclus input file

1. Python script to parse through CSV file (reactor name, start / decom date, power output, etc)
2. Use Jinja template to construct input file (Python script fills curly brackets)

```
<facility>
   <!-- {{ country }} -->
   <!-- {{   type  }} -->
   <name>{{ reactor_name }}</name>
   <config>
     <Reactor>
       <fuel_inrecipes>  <val>uox_fuel_recipe</val>       </fuel_inrecipes>
       <fuel_outrecipes> <val>uox_used_fuel_recipe</val>  </fuel_outrecipes>
       <fuel_incommods>  <val>uox</val>                   </fuel_incommods>
       <fuel_outcommods> <val>uox_waste</val>             </fuel_outcommods>
       <fuel_prefs>      <val>1.0</val>                   </fuel_prefs>
       <cycle_time>18</cycle_time>
       <refuel_time>2</refuel_time>
       <assem_size>{{assem_size}}</assem_size>
       <n_assem_core>{{ n_assem_core}}</n_assem_core>
       <n_assem_batch>{{n_assem_batch}}</n_assem_batch>
       <power_cap>{{capacity}}</power_cap>
     </Reactor>
   </config>
 </facility>
```

Output analysis

- Python script to query and process output data
- Use Jupyter notebook to organize / visualize output

Output - regional analysis

- The user can separate analysis by regions
- Concept of children-parent: each `facility` has a parent `Institution`, and each `Institution` has a parent `Region`.

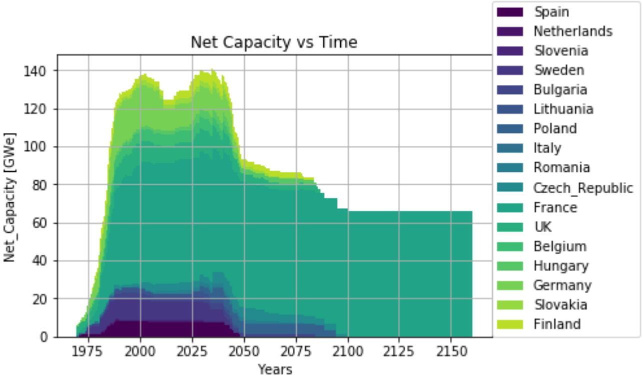


Figure 3: Power generation is separated by region.

Output - regional analysis

- The user can separate analysis by regions
- Concept of children-parent: each `facility` has a parent `Institution`, and each `Institution` has a parent `Region`.

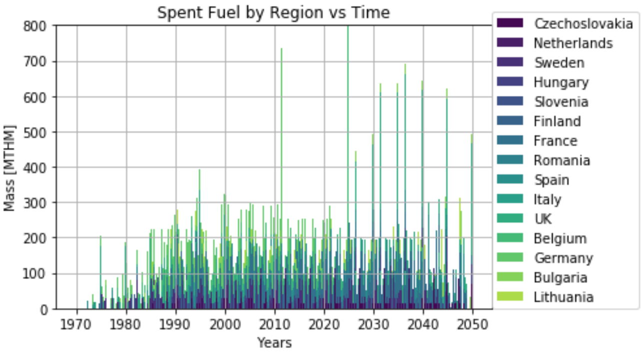


Figure 4: Waste output mass is separated by their origin region.

Output - Prototype analysis

- The user can separate analysis by prototype
- User can see how much `power` is from SFRs compared to PWRs.

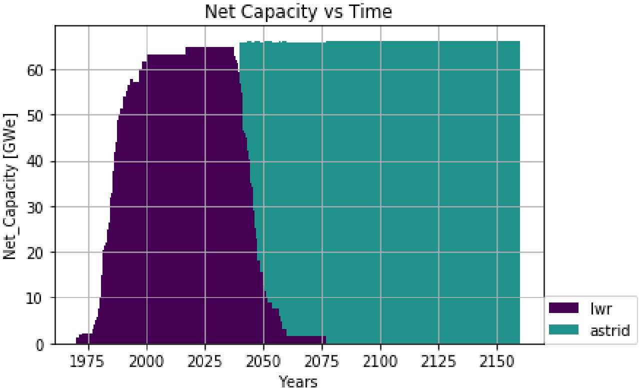


Figure 5: Power generation is separated by prototype (SFR, PWR).

Output - Prototype analysis

- The user can separate analysis by prototype
- User can see how much fuel is from which facility.

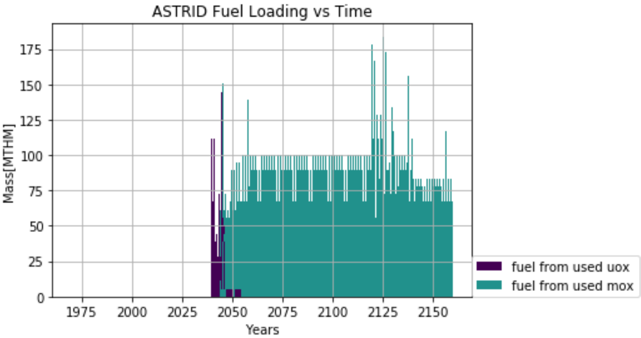


Figure 6: Fuel production is separated by production facility.

Sensitivity Study

Breeding ratio sensitivity study can be done by simply changing the SFR output fuel recipe in the input file.

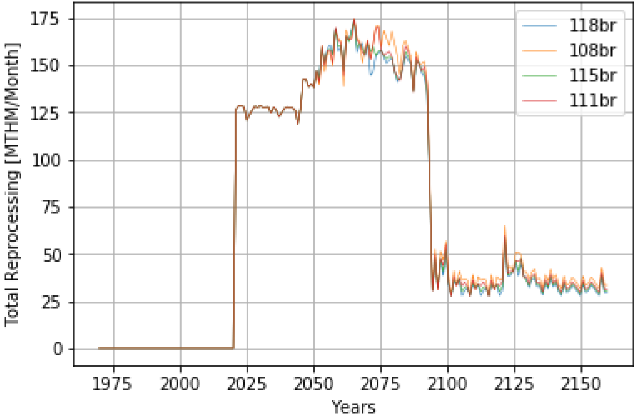
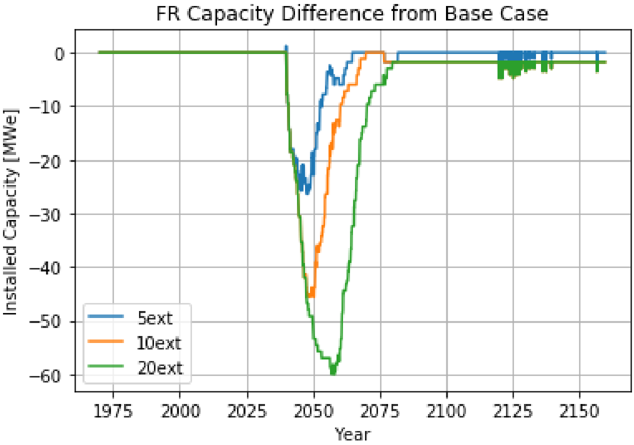


Figure 7: Breeding Ratio affect on total reprocessing.

Sensitivity Study

Lifetime extension sensitivity study can be done by adding the lifetime of the pwrs and adjusting SFR deployment accordingly.



Predicting the past - U.S

Work done by undergraduate researcher Gyutae Park at the University of Illinois - Urbana Champaign.

1. Import database to construct Cyclus simulation
2. ‘Predict the past’ - fuel usage, power generated
3. Demonstrate GIS capabilities of Cyclus

Example Workflow

Similar workflow has been used for this analysis study.

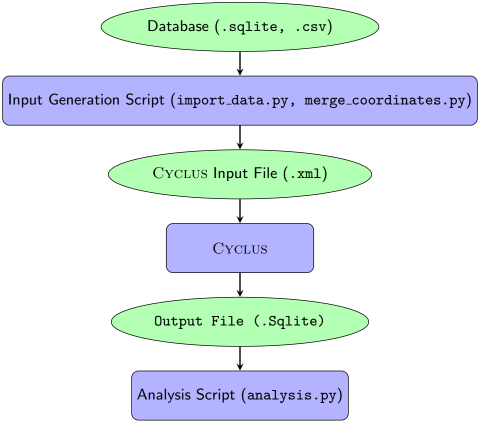


Figure 9: Green circles and blue boxes represent files and software processes, respectively, in the computational workflow.

Results - Fuel into reactors

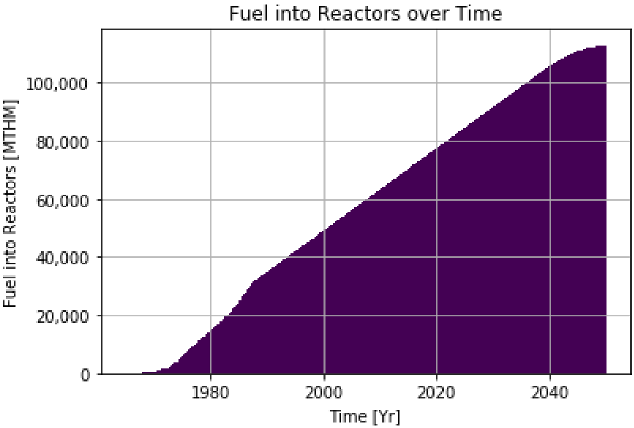


Figure 10: Cumulative fuel into U.S. reactors over time.

Results - Natural Uranium usage

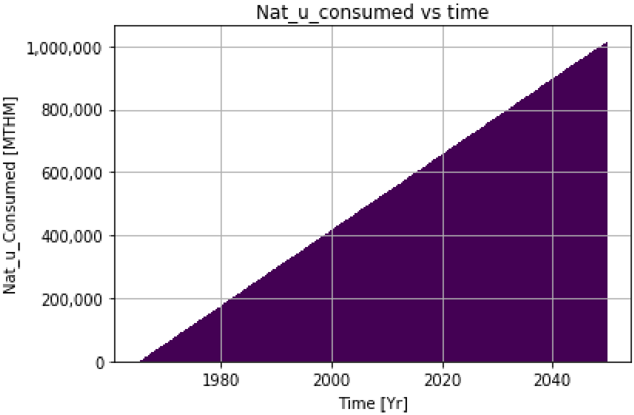


Figure 11: Cumulative natural uranium consumption in the U.S. over time.

Results - Power generated

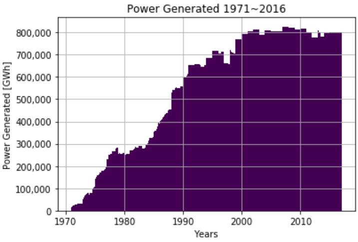


Figure 12: Nuclear Power generated simulated by Cyclus

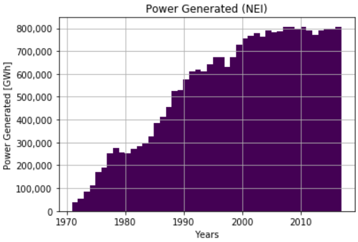


Figure 13: Nuclear power generation data from NEI [3]

[3] US Nuclear Generating Statistics. (n.d.). Retrieved from https://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Generating-Statistics

Results - GIS

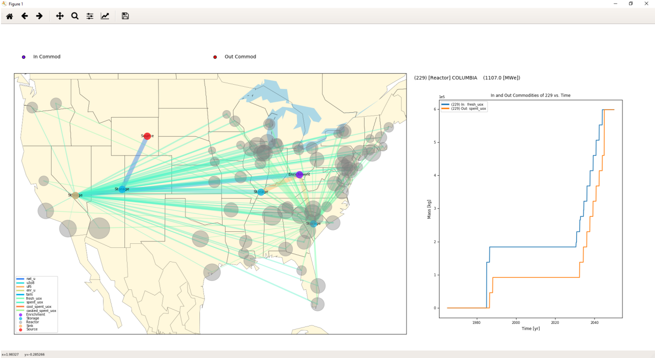


Figure 14: Interactive map of U.S. reactors and fuel cycle facilities. Lines show transactions between two facilities.

Standardized Verification of fuel cycle modeling

- 2016 paper on comparing ORION, VISION, DYMOND, MARKAL.
- Transition scenario from once-through to closed

Results - Deployed reactor capacities

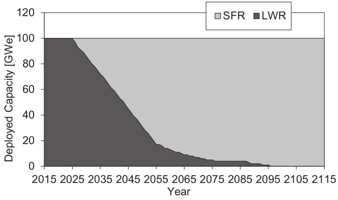


Fig. 4. Deployed reactor capacities at the end of each year.

Figure 15: Deployed reactor capacities from paper. [5]

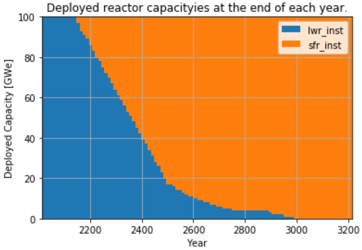


Figure 16: Deployed reactor capacities from CYCLUS.

[5] Feng, B., B. Dixon, E. Sunny, A. Cuadra, J. Jacobson, N. R. Brown, J. Powers, A. Worrall, S. Passerini, and R. Gregg. Standardized Verification of Fuel Cycle Modeling. Annals of Nuclear Energy 94 (August 2016): 300312. https://doi.org/10.1016/j.anucene.2016.03.002.

Results - LWRs retired and SFRs started up each year

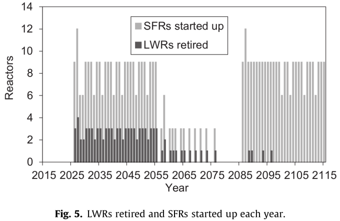


Figure 17: LWRs retired and SFRs started up each year from paper [7]

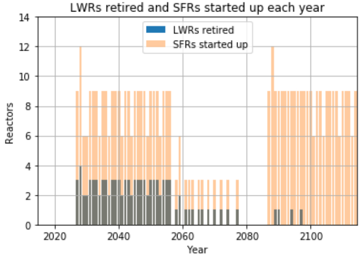


Figure 18: LWRs retired and SFRs started up each year from CYCLUS

[7] Feng, B., B. Dixon, E. Sunny, A. Cuadra, J. Jacobson, N. R. Brown, J. Powers, A. Worrall, S. Passerini, and R. Gregg. Standardized Verification of Fuel Cycle Modeling. Annals of Nuclear Energy 94 (August 2016): 300312. https://doi.org/10.1016/j.anucene.2016.03.002.

Results - Annual fresh fuel loading rates

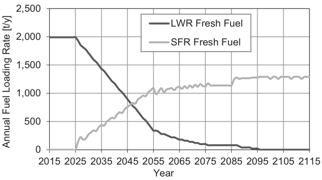


Figure 19: Annual fresh fuel loading rates from paper [9]

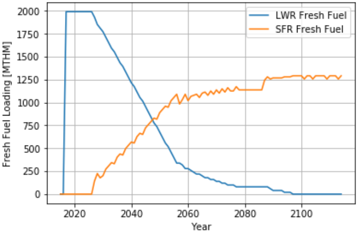


Figure 20: Annual fresh fuel loading rates from CYCLUS.

[9]Feng, B., B. Dixon, E. Sunny, A. Cuadra, J. Jacobson, N. R. Brown, J. Powers, A. Worrall, S. Passerini, and R. Gregg. Standardized Verification of Fuel Cycle Modeling. Annals of Nuclear Energy 94 (August 2016): 300312. https://doi.org/10.1016/j.anucene.2016.03.002.

Results - Inventory of discharged UNF in mandatory cooling storage

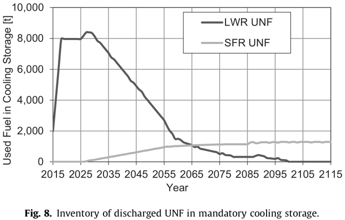


Figure 21: Inventory of discharged UNF in mandatory cooling storagefrom paper. [11]

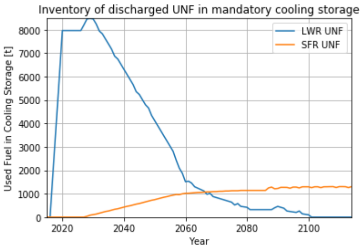


Figure 22: Inventory of discharged UNF in mandatory cooling storagefrom CYCLUS.

[11] Feng, B., B. Dixon, E. Sunny, A. Cuadra, J. Jacobson, N. R. Brown, J. Powers, A. Worrall, S. Passerini, and R. Gregg. Standardized Verification of Fuel Cycle Modeling. Annals of Nuclear Energy 94 (August 2016): 300312. https://doi.org/10.1016/j.anucene.2016.03.002.

Results - Inventory of discharged and cooled UNF waiting for reprocessing

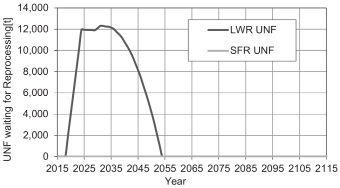


Fig. 9. Inventory of discharged and cooled UNF waiting for reprocessing.

Figure 23: Inventory of discharged and cooled UNF waiting for reprocessingfrom paper. [13]

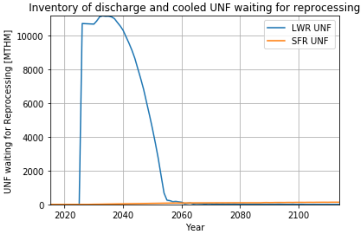


Figure 24: Inventory of discharged and cooled UNF waiting for reprocessingfrom CYCLUS.

[13] Feng, B., B. Dixon, E. Sunny, A. Cuadra, J. Jacobson, N. R. Brown, J. Powers, A. Worrall, S. Passerini, and R. Gregg. Standardized Verification of Fuel Cycle Modeling. Annals of Nuclear Energy 94 (August 2016): 300312. https://doi.org/10.1016/j.anucene.2016.03.002.

Results - Annual reprocessing rate

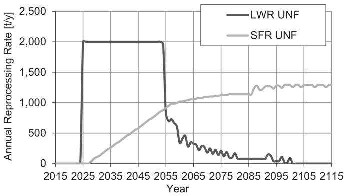


Figure 25: Annual reprocessing ratefrom paper. [15]

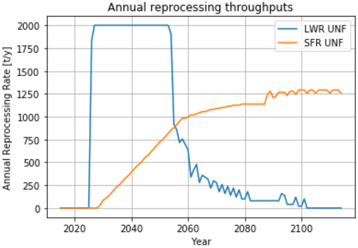


Figure 26: Annual reprocessing ratefrom CYCLUS.

[15] Feng, B., B. Dixon, E. Sunny, A. Cuadra, J. Jacobson, N. R. Brown, J. Powers, A. Worrall, S. Passerini, and R. Gregg. Standardized Verification of Fuel Cycle Modeling. Annals of Nuclear Energy 94 (August 2016): 300312. https://doi.org/10.1016/j.anucene.2016.03.002.

Results - Inventory of unused TRU recovered from UNF

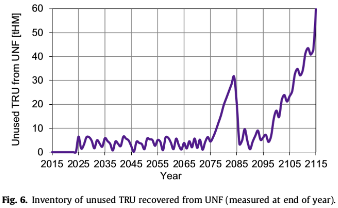


Figure 27: Inventory of unused TRU recovered from UNFfrom paper. [17]

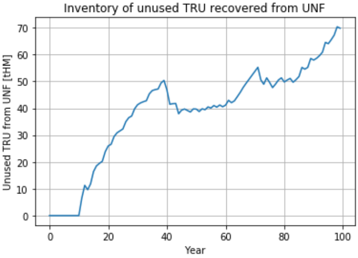


Figure 28: Inventory of unused TRU recovered from UNFfrom CYCLUS.

[17]Feng, B., B. Dixon, E. Sunny, A. Cuadra, J. Jacobson, N. R. Brown, J. Powers, A. Worrall, S. Passerini, and R. Gregg. Standardized Verification of Fuel Cycle Modeling. Annals of Nuclear Energy 94 (August 2016): 300312. https://doi.org/10.1016/j.anucene.2016.03.002.

Benchmark Conclusions

- Excellent agreement for most metrics
  1. Reactor deployment
  2. Fresh fuel loading
  3. Discharged UNF in cooling stage
  4. Discharged and cooled UNF waiting
  5. Annual reprocessing rate
- **Non-agreement for Inventory of unused TRU**

Possible sources of error

1. Fraction batches (CYCLUS has discrete batches)
2. timestep (CYCLUS default timestep is a month - user can change)
3. CYCLUS material buffers leading to analysis error
4. Error in analysis

Conclusion

Cyclus is a performant, expanding fuel cycle simulator that holds promise for future applications. It demonstrated its capability to:

- 'Predict the past'
- Model dynamic transition scenarios
- Perform sensitivity studies
- Visualize important, dynamic fuel cycle metrics

Future Work Ongoing

`Cycamore` is adequate for rough analyses, but more accurate modules or additional tools would increase analysis fidelity

- Dynamic archetype parameters (e.g. `refuel_time` changing in time or sampled from a distribution)
- In-module depletion (i.e. Using in-module SERPENT Reduced-order-model)
- Demand-driven deployment [18]

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Thank you.