Simulation of Spent Nuclear Fuel loading into a Final Waste Repository

Gwendolyn J. Chee, Kathryn D. Huff

University of Illinois at Urbana-Champaign, Department of Nuclear, Plasma, and Radiological Engineering, Urbana, IL 61801

Objectives

- Create a Cyclus Waste Conditioning Model that packages spent fuel bundles into packages which have user-defined properties.
- Create a Cyclus Medium-Fidelity Repository Model that gives accurate time and spatial dependent temperature values and loads the repository based on a user-selected loading strategy.

Motivation

Previous work in studying repository loading have used spent nuclear fuel (SNF) with an average burn up composition [4] to evaluate the heat load in the repository [2]. This work aims to use **U.S. historical SNF inventory data** [8] in various simulations to study how waste acceptance strategies impact repository loading. The Unified Database (UDB) contains assembly-specific data including initial enrichment, burnup, metric ton of heavy metal (MTHM), assembly type and discharge date [7]. Irradiation and decay calculations using SCALE [1] were performed on each spent fuel assembly based on the collected data to obtain mass, heat, activity and isotopic composition for each assembly [6].

This data is inputted into Cyclus using the UDB reactor agent []. Cyclus is capable of tracking discrete isotopes and their time-dependent decay. We can use these capabilities to more accurately study the dynamic loading of a waste repository.

Cyclus

Cyclus is an agent-based extensible framework for modeling flow of material through user-defined nuclear fuel cycles [3]. In Cyclus, each facility in the fuel cycle is modeled individually and they interact with one another as independent *agents*. The goal of this work is to develop a waste conditioning *facility agent* and a waste repository *facility agent* to provide Cyclus with the capabilities to run simulations to study how waste acceptance strategies impact repository loading.

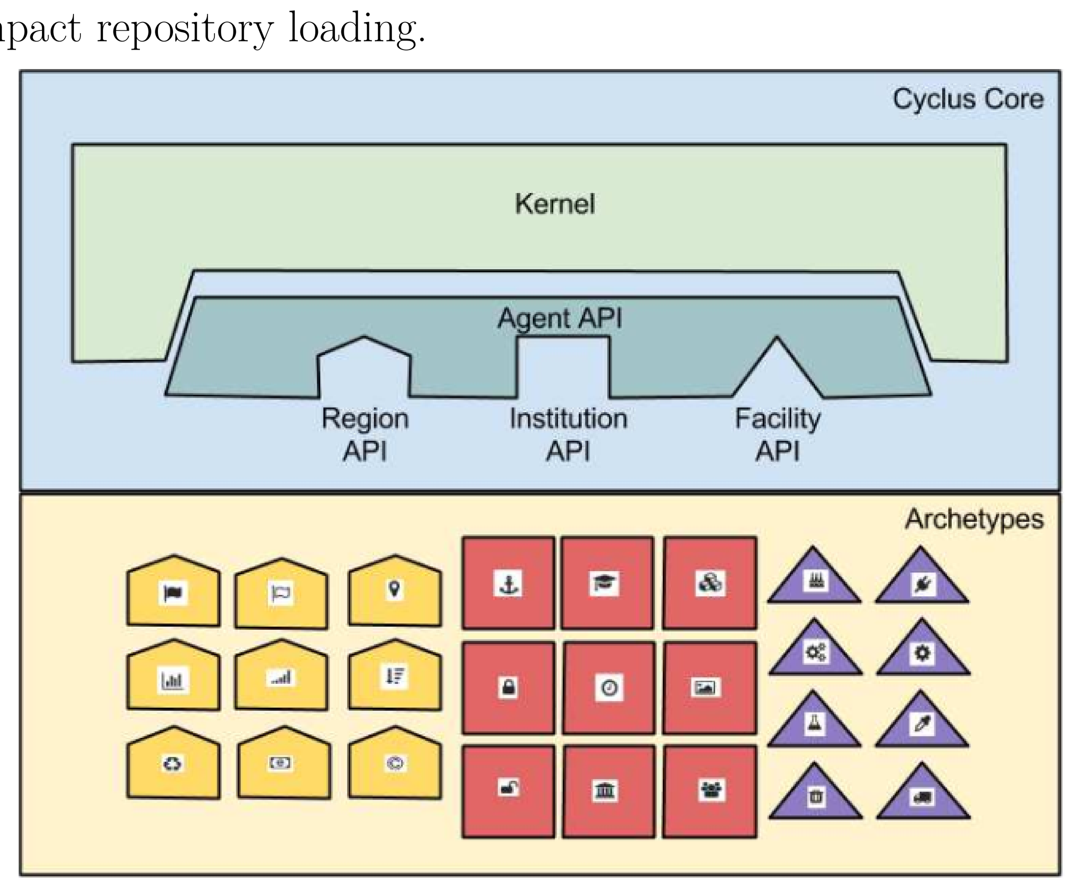

Figure: Cyclus API allows for modular build of simulations [3]

Waste Conditioning Model

The waste conditioning model accepts spent fuel bundles and puts them into a cylindrical waste package. The model allows the user to define multiple package material layers and the thermal conductivity and diffusivity of each layer.

In the waste conditioning model, the user can define the variables:

- Number of spent fuel bundles in each package
- Radius of each package material layer
- Thermal Conductivity of each package material layer
- Thermal Diffusivity of each package material layer
- Radius and height of package

Waste Repository Model

The waste repository model accepts waste packages and emplaces them into available positions within the waste repository based on a thermal criteria. If the thermal criteria is not met, the waste package will be placed into a buffer until it meets the thermal criteria. The thermal criteria is a defined temperature limit at the interface between waste package surface and the host geology, that is set based on the repository's host geology.

Table 1 shows the temperature limits, thermal conductivity and thermal diffusivity for the host geology included in this study.

Table: Temperature limit at interface between waste package surface and each host geology [9]

Rock Type	T_{limit} [°C]	k $[\frac{W}{mK}]$	α $[\frac{m^2}{s}]$
Granite	100	2.5	1.13
Clay	100	1.75	6.45
Salt	200	4.2	2.07

In the waste repository model, the user can define the variables:

- Distance between waste packages
- Distance between drifts
- Repository host geology
- Loading Strategy

Thermal Model

At each time step, the waste repository model recalculates the temperature at each location in the repository after the addition of new waste packages. If the addition of this new package results in its temperature being over the thermal limit, it will be placed back into the buffer. To accurately determine the temperature in the repository, a thermal model that relies on a transient 'outside' model and quasi-steady-state 'inside' model is used [9].

Transient Outside Model

The outside model assumes a homogenous medium with the Engineered Barrier System (EBS) replaced by the geologic medium. Figure 1 shows the conceptual layout of the central waste package and the adjacent point and line sources.

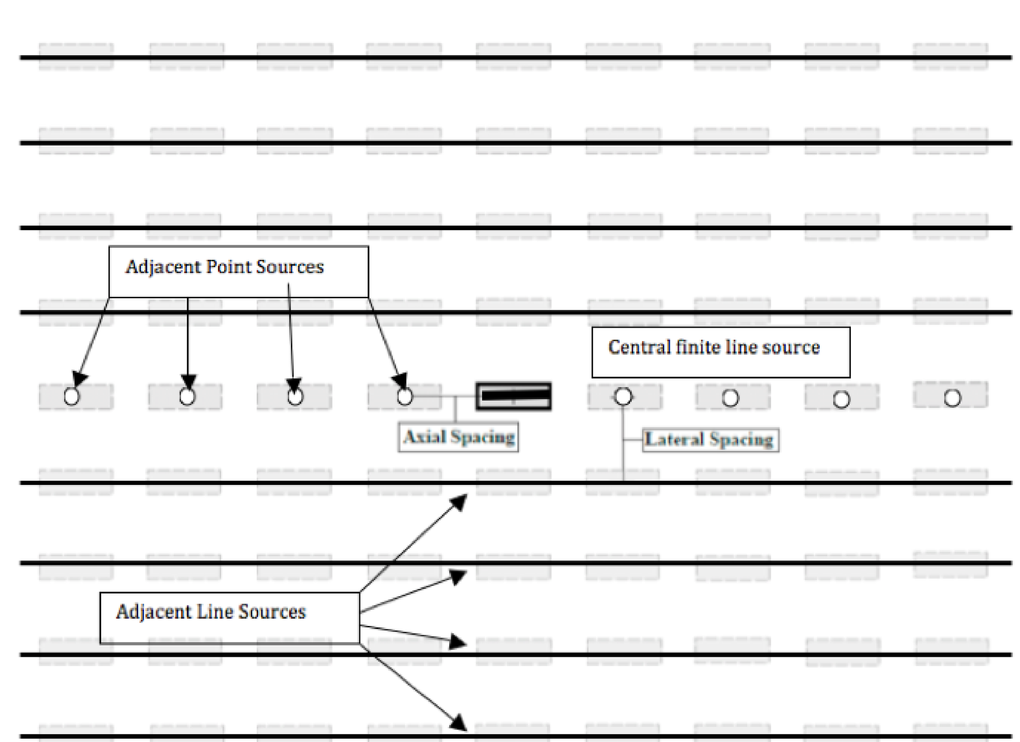

Figure: Outside Model: Conceptual layout of the central waste package, its adjacent point sources and adjacent line sources [9]

Temperature solutions for the central waste package, adjacent point and line sources are superimposed to calculate the temperature at specific points in the repository. The equations for calculating temperature of each contributing component are included below [9].

The central drift consists of one finite line source which represents the central waste package.

$$T_{line}(t,x,y,z) = \frac{1}{8\pi k}\int_0^t \frac{q_L(t')}{t-t'} e^{\frac{-(x^2+z^2)}{4\alpha(t-t')}} \left[erf\left[\frac{1}{2}\frac{y+L/2}{\sqrt{\alpha(t-t')}}\right] - erf\left[\frac{1}{2}\frac{y-L/2}{\sqrt{\alpha(t-t')}}\right]\right]dt'$$

The central drift also consists of point sources that represent neighboring waste packages in the central drift.

$$T_{point}(t,r) = \frac{1}{8k\sqrt{\alpha}\pi^{3/2}}\int_0^t \frac{q(t')}{(t-t')^{3/2}} e^{\frac{-r^2}{4\alpha(t-t')}}dt'$$

The neighboring drifts are represented by infinite line sources.

$$T_{\infty line}(t,x,z) = \frac{1}{4\pi k}\int_0^t \frac{q_L(t')}{t-t'} e^{\frac{-(x^2+z^2)}{4\alpha(t-t')}}dt'$$

Waste Repository Model

Quasi-steady-state 'inside' model

The inside model is considered to be at a quasi-steady-state condition since there is relatively low thermal mass of EBS compared to the infinite geologic medium [9]. The steady state calculation is performed at each time step with the heat source and interface temperature as boundary conditions. Figure 1 shows an example of an EBS layout.

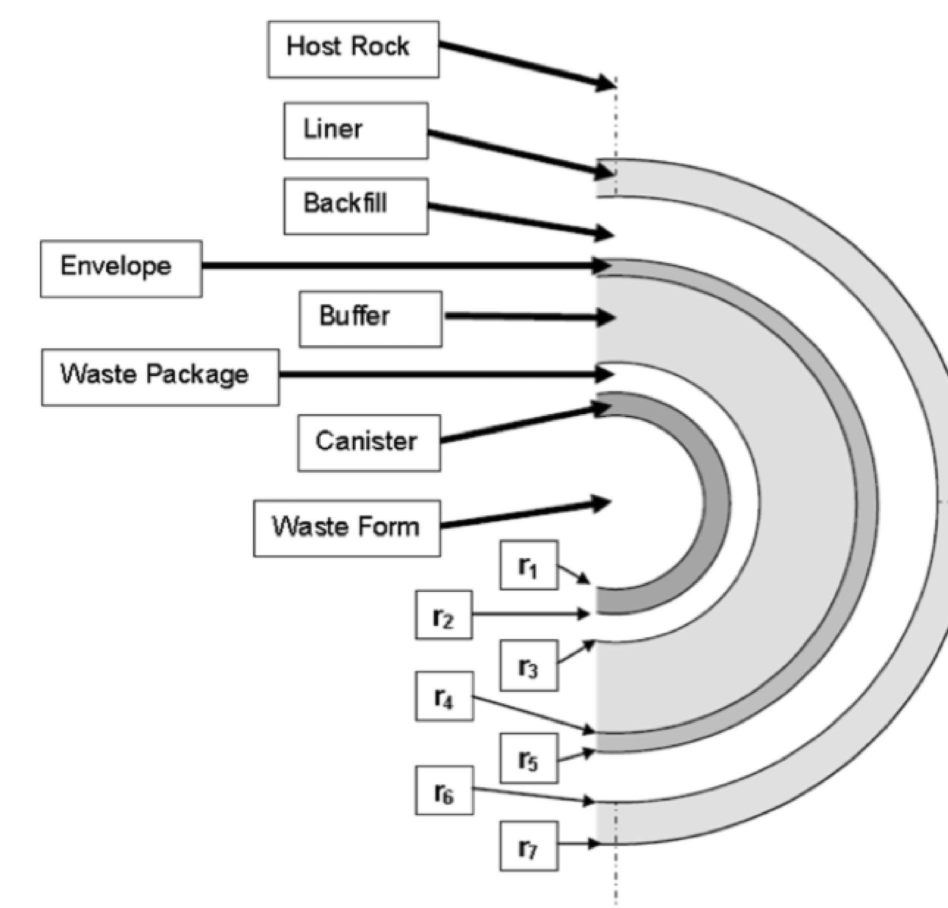

Figure: Layers in an Engineering Barrier System [9]

Loading Strategies

Loading strategies that will be studied:

- First-in-first-out
- Last-in-first-out
- Load SNF from shutdown sites first [5]

Acknowledgements

This research is being performed using funding received from the DOE Office of Nuclear Energy's NEUP (Project 16-10512) 'Demand-Driven Cycamore Archetypes'.

References

[1] S. M. Bowman. SCALE 6: Comprehensive Nuclear Safety Analysis Code System. *Nuclear Technology*, 174(2):126–148, May 2011.

[2] H. Greenberg, J. Blink, M. Fratoni, M. Sutton, and A. Ross. Application of Analytical Heat Transfer Models of Multi-layered Natural and Engineered Barriers in Potential High-Level Nuclear Waste Repositories. In *WM2012*, Phoenix, AZ, Mar. 2012. LLNL-CONF-511672.

[3] K. D. Huff, M. J. Gidden, R. W. Carlsen, R. R. Flanagan, M. B. McGarry, A. C. Opotowsky, E. A. Schneider, A. M. Scopatz, and P. P. H. Wilson. Fundamental concepts in the Cyclus nuclear fuel cycle simulation framework. *Advances in Engineering Software*, 94:46–59, Apr. 2016. arXiv: 1509.03604.

[4] B. Johnson, A. Newman, and J. King. Optimizing high-level nuclear waste disposal within a deep geologic repository. *Annals of Operations Research*, pages 1–23, June 2016.

[5] G. M. Petersen, S. E. Skutnik, J. Ostrowski, and R. A. Joseph. Determining Optimal Used Fuel Allocation Strategies. *Nuclear Technology*, 200(3):208–224, Dec. 2017.

[6] J. Peterson, C. Olson, J. St. Aubin, and B. Craig. Additional Capability Being Developed from UNF-ST&DARDS Unified Database: System Analysis and Fuel Cycle Option Analysis. *Nuclear Technology*, 199(3):320–329, Sept. 2017.

[7] J. Peterson and J. Scaglione. Fuel Cycle Applications with the Data Stored Within the Unified Database. page 5, 2015.

[8] J. Peterson, B. van den Akker, R. Cumberland, P. Miller, and K. Banerjee. UNF-ST&DARDS Unified Database and the Automatic Document Generator. *Nuclear Technology*, 199(3):310–319, 2017.

[9] M. Sutton, J. A. Blink, M. Fratoni, H. R. Greenberg, and A. D. Ross. Investigations on Repository Near-Field Thermal Modeling - Repository Science/Thermal Load Management & Design Concepts (M41uf033302). Technical Report LLNL-TR-491099, 1031294, July 2011.