GENIUSv2 Recipe Approximation Methodology for Mixed-Oxide Fuel

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INTRODUCTION

The Simulation Institute for Nuclear Enterprise Modeling and Analysis (SINEMA) developed the GENIUS (Global Evaluation of Nuclear Infrastructure Utilization Scenarios) project as the umbrella nuclear fuel cycle simulation package[1]. GENIUSv2 is the next iteration and is an object-oriented C++ program using Python pre- and post-processing wrappers.

As a package, GENIUSv2 supports dynamic modeling of regional and institutional interactions of nuclear fuel cycle facilities, using a discrete material/discrete facility paradigm. The engineering calculations and analysis needed for each different facility and process are handled by separate modules within GENIUSv2.

Results from the GENIUSv2 separations module are presented that detail the robust approximation methodology for creating mixed-oxide (MOX) fuel recipes from available separated material.

POST-SEPARATIONS ACTINIDE STREAM MATCHING

Challenges in Matching Arbitrary Actinide Streams with MOX Fuel Recipes

In a MOX fuel cycle the separations facility maintains an inventory of unseparated spent fuel for manufacturing new fuel with a particular target isotopic recipe. Prior to actually separating material, the separations facility determines which spent fuel streams will be used by modeling their separated constituents as barrels of various actinides. It is assumed that neither chemical nor isotopic separations processes can be further applied at the barrel level (although it is possible to change the parameters of the separation process itself in an attempt to optimize the overall system performance). Figure 1 illustrates the challenge of achieving a particular isotopic composition from barrels of available material, none of which have exactly that composition. A methodology has been developed for selecting a fraction of each barrel to approximate the desired fuel recipe based on the neutronics performance of the achieved recipe when no exact match is possible for the target fuel recipe.

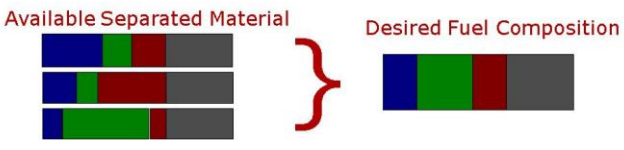

Fig. 1. Matching spent fuel from three waste streams into one MOX fuel recipe. Note: The different sections represent various isotopes within the respective barrels.

Performance Requirements for Non-Ideal MOX Fuel Recipes

The primary goal of the matching algorithm is to match the target isotopic recipe exactly. In cases when such a match is not possible, the algorithm must find the best approximation with respect to other performance requirements of the achieved recipe. Assuming that the best possible attempt at isotopic matching is not achieved, the next performance requirement is based on the neutronics/criticality behavior of the achieved recipe. Finally, it is also desirable that the total fuel mass be preserved, although the other performance constraints should naturally limit discrepancies in the total mass. In this work, the neutronics performance goal is implemented by attempting to match the k-eigenvalue of the fuel, approximated by a 1-group neutron reproduction factor. While this offers a similar gross neutronics performance at the time of insertion in the reactor core, it does not match performance in either the reactivity coefficients (safety) of the core or the burnup (lifetime) of the core.

GENIUSV2 RECIPE OPTIMIZATION

The MOX fuel recipe approximation problem (RAP) is based around the linear program (LP) optimization described in Eq. 1.

$$\begin{aligned} \min_{x,y} \quad & \vec{c}^{\,T}\vec{y} \\ \text{subject to} \quad & y = \left|M\vec{x} - \vec{r}\right| \\ & 0 \le x_b \le 1, \forall b \\ & \left|\vec{w}^{\,T}\vec{x} - w_r\right| \le \varepsilon_w \\ & \left|\vec{m}^{\,T}\vec{x} - m_r\right| \le \varepsilon_m \end{aligned} \tag{1}$$

In Eq. 1, $\vec{x}$ is a vector representing the fraction of each barrel, b, used in the approximation. Matrix M is the mass of each isotope in each barrel such that $\vec{y}$ is a vector of the discrepancies for each isotope between the approximation and the desired recipe, $\vec{r}$. In the objective

function, these discrepancies are weighted by the vector, $\vec{c}$, defined as the reciprocal of the mass of each isotope in the target MOX fuel recipe (or the total recipe mass if that isotope does not exist in the target recipe). This is necessary to ensure that minor constituents (*e.g.* ^{235}U) are matched with the same importance as major ones (*e.g.* ^{238}U). Vector $\vec{w}$ describes the neutronics performance of each barrel, allowing a constraint that limits the overall neutronics performance to be within ε_w of the target recipe's performance, w_r. Vector $\vec{m}$ is the total mass of each barrel, allowing a constraint that limits the overall mass of the approximation to be within ε_m of the target recipe's total mass, m_r.

The neutronics weighting parameter for a barrel is currently defined in Eq. 2 as

$$w_b \equiv \eta_b = \frac{\sum_{i \in b} \left(\nu N \sigma_f\right)_i}{\sum_{i \in b} \left(N \sigma_a\right)_i}, \qquad (2)$$

the ratio of the total neutron reproduction to the total neutron absorption.

GENIUSV2 MOX FUEL SCENARIO RESULTS

A simple MOX recycle scenario was simulated with a fleet of 12 UOX-fueled PWRs and a fleet of 3 Pu+Np MOX-fueled PWRs to test the LP. Figure 2 shows how well the neutronics and mass constraints were achieved under different constrain tolerance for each of the more than 800 MOX fuel orders placed in the 100 year simulation. The neutronics performance is routinely less than the target performance, and is nearly independent of the tolerance. The total mass is also less than the target value and unaffected by the variation in the neutronics performance tolerance. The recipes fluctuate over time due to changes in the composition of materials available at the time of each order. A future scenario will determine the separations plant unseparated fuel inventory requirements to achieve desired MOX fuel recipes for a certain number of MOX reactors.

CONCLUSIONS

The LP formulation offers a promising paradigm for the recipe approximation problem, but an improved neutronics weighting parameter must be developed. The current weighting parameter treats the total neutron multiplication of the new fuel recipe as an extrinsic property, growing as each new barrel is added. A more correct formulation will redefine this constraint as a function of the extrinsic properties of total neutron production and total neutron absorption, rather than their ratio. Future work will also focus on moving the constraints into the objective function, with different weights to represent the importance of each. In general, this LP formulation of the RAP allows other users/developers to propose and implement alternative sets of constraints and objective functions.

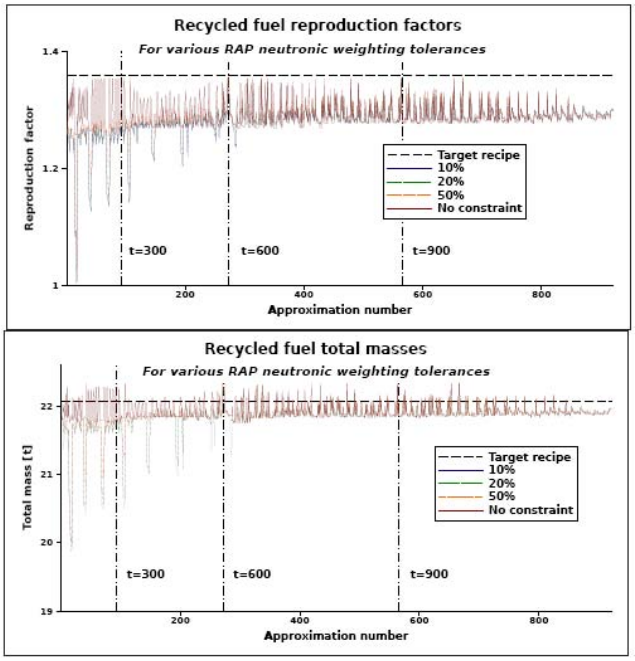

Fig. 2. Effects of neutronics constraint on neutronics and total mass performance of achieved recipes.

ACKNOWLEDGMENTS

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