

Coupled Reactor and Engine Nuclear Thermal Propulsion Modeling Methodology

Jacob Stonehill¹, Daria Nikitaeva¹, Corey Smith¹, Matthew Duchek²

¹Advanced Projects Huntsville, Analytical Mechanics Associates, Huntsville, AL, 35806

²Advanced Projects Denver, Analytical Mechanics Associates, Denver, CO, 80211

Primary Author Contact Information: jacob.c.stonehill@ama-inc.com

[Placeholder for Digital Object Identifier (DOI) to be added by ANS]

The design and development process of a Nuclear Thermal Propulsion (NTP) system requires extensive multiphysics modeling to couple the neutron physics and thermal feedback effects to determine the reactor's power shape. Propulsion system performance codes utilize this power shape to determine NTP key performance parameters. While the power shape is heavily dependent on the temperature profile and geometry of the reactor, many analyses either assume a constant power shape, or use neutronics analysis to determine a power shape for a specific reactor configuration. The development of a coupling interface for a propulsion system performance code and a Monte Carlo neutron transport code (OpenMC) allows for the reactor power shape to be calculated in a Picard iteration.

The interface utilizes a file share system to transfer geometry dimensions, temperatures, and material identifiers to OpenMC, which is used to perform a neutron transport simulation of a design like the government Testing Reference Design reactor. The interface is then able to post-process the results from OpenMC and use the same file share system to share a power shape and other important neutron transport parameters to the system performance code. Initial results show that neglecting the changes to power shape when comparing reactor configurations can yield inaccurate results. Furthermore, utilizing propellants other than hydrogen gas can cause significant changes to the power shape, and thus, the thermal performance of a specific reactor design. This methodology is being expanded to allow for multiple families of NTP reactors to be analyzed, including block moderator, particle bed, and NERVA-derived reactors.

I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) has released strategic goals for extending human presence to the Moon and Mars. The pursuit of expanding humanity's presence beyond earth and cislunar space requires the utilization of advanced propulsion methods due to the relatively long transit times and risks involved

with deep space travel. Nuclear Thermal Propulsion (NTP) emerges as a candidate propulsion system, promising double the specific impulse of conventional chemical rockets. However, successful design and development of such a system demands a comprehensive understanding of the thermal performance and the physics governing the nuclear reactions within the reactor core. These underlying multiphysics effects are also extremely dependent upon one another, thus a routine that iteratively converges on desired reactor performance metrics is imperative for proper system-level modeling.

This work introduces a novel methodology developed by Analytical Mechanics Associates that seamlessly connects a Simulink-based NTP system performance code¹⁻² with the open-source Monte Carlo neutron transport code, OpenMC³. The Simulink tool converges on all state points of the NTP engine from propellant tank exhaust to the exit nozzle exhaust through physics-based solvers of all internal components, including the reactor subsystem. Following initial convergence, the thermal hydraulic solver provides axial and radial temperature and density distributions of all in-core solid materials as well as the flowing propellant to OpenMC for higher fidelity neutronics analyses. Results of the neutronics analysis include static core-specific performance metrics, such as the neutron multiplication factor, and power distributions for each region of thermal importance that are readable for the next Simulink iteration. This process is repeated until desired engine convergence metrics are reached, typically the thrust, specific impulse, and reactor thermal power.

II. METHODOLOGY

II.A. NTP System Power Balance Model

The thermal hydraulic performance of the NTP system is determined by a power balance engine modeling suite coded in Simulink, known as the X-NTP model¹⁻². This code analyzes various engine cycles, including expander and bleed cycle configurations. Propellant state points (temperature, pressure, and mass flow rate) communicate the performance of the NTP system and allow for easy

connection of various components to form different engine cycles. Figure 1 shows a typical flow cycle for the governing Testing Reference Design (TRD).⁴

The X-NTP model is formed as a modular engine design suite with the capability to pick and choose the engine cycle, flow schedule, and components utilized. Figure 2 shows a general schematic of a component model. Each component block houses equations that govern the state points that are connected to it and the system performance parameters that it calculates.

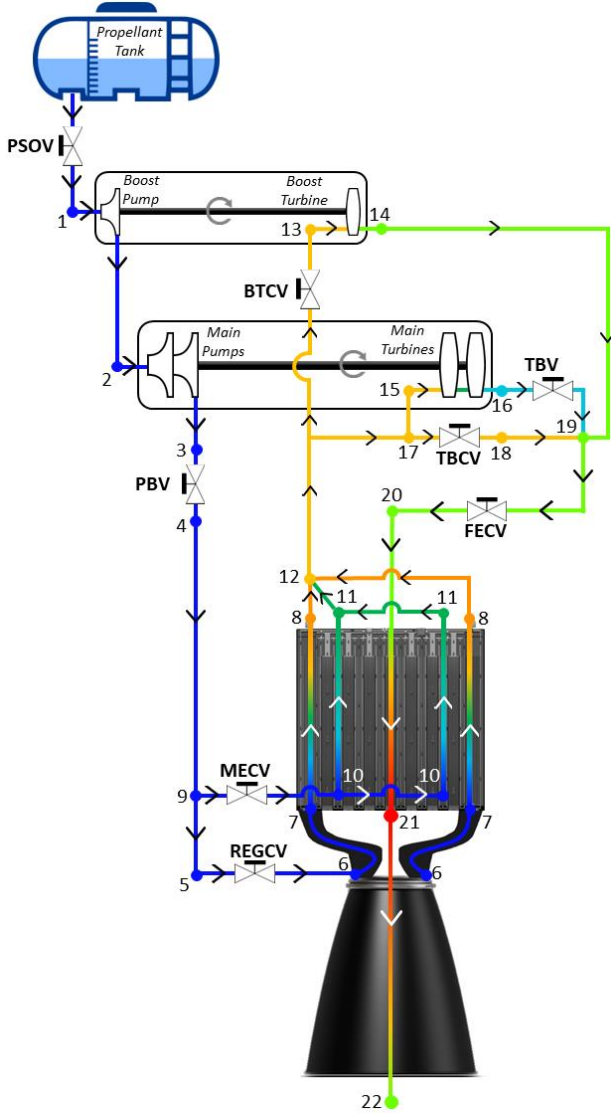


Fig. 1. H-NTP Testing Reference Design Schematic¹.

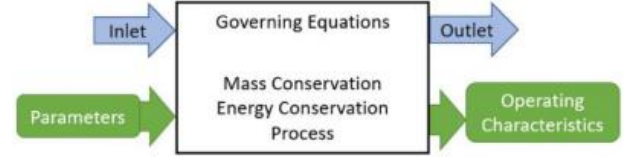


Fig. 2. Arbitrary Engine Component Schematic

The engine components use various user input parameters and the power shape for the reactor (provided by neutronics analysis) to determine the thermal performance of the reactor. Eq. 1 shows the calculation for the surface temperature of a cooling channel, where δQ is the differential heat added to the node, h is the convective heat transfer coefficient, A_s is the wall area, and T_s is the surface temperature. Eq. 2 shows the calculation for maximum temperatures in any solid surrounding a cooling channel in the reactor, where d_{co} is the outer diameter of the representative solid, d_{ci} is the inner diameter of the representative solid, k_f is the thermal conductivity of the solid, and Δx is the length of the channel element. The maximum temperature is averaged with the wall temperature to determine a representative temperature for the material. This temperature then informs which cross-section library is selected in the neutronics analysis for the given material. Further, the neutronics analysis also uses the propellant temperatures and pressures to determine the cross-section library and the propellant atom density.

$$\delta Q_i = h \Delta A_s \left[T_{si} - \frac{T_i + T_{i+1}}{2} \right] \quad (1)$$

$$T_{f_{max_i}} = \frac{\delta Q \ln\left(\frac{d_{co}}{d_{ci}}\right)}{2\pi k_f \Delta x} + T_{si} \quad (2)$$

II.B. Neutronics

A Python script uses OpenMC's Python API to build a representation of the TRD for neutronics analysis. The general configuration of the TRD is used; however, all dimensions are provided by the user input files, easily allowing for parametric sweeps on various geometry parameters. The ENDF/B-VII.1 Evaluated Nuclear Data Library⁵ provides the neutron cross-sections for all isotopes.

The materials attached to the TRD-like geometry are provided by a material card generator developed for OpenMC, which provides an optional porosity correction to the material from Eq. 3, where ρ_{TD} is the theoretical density and P is the porosity of the material. The density for all solids is taken as the room temperature density because thermal expansion is ignored for the neutronics analysis. The thermal hydraulics analysis performed by the X-NTP model provides the temperature used to select the cross-section library. The number of values in each temperature row defines the axial temperature discretization of each component in the active core.

$$\rho = \rho_{TD}(1 - P) \quad (3)$$

Two sensitivity studies provide the run-time settings for OpenMC. Figure 3 shows a Shannon Entropy convergence study which illustrates that with a course mesh, the fission site distribution converges after 10 iterations. Since it's impossible to have an infinitely fine mesh for the sensitivity study, this study uses 50 inactive cycles to assure that the error from the source term convergence is minimized. Figure 4 shows a separate sensitivity study where the maximum relative uncertainty in any heating tally was found by varying the particle count. The computation time is found using AMA's computational cluster. A particle count of 50,000 allows the maximum relative uncertainty to stay below 5%

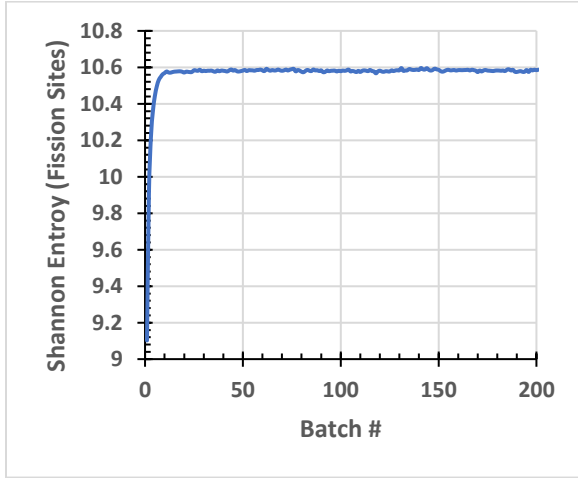


Fig. 3. Convergence of Shannon Entropy from fission sites during inactive batching.

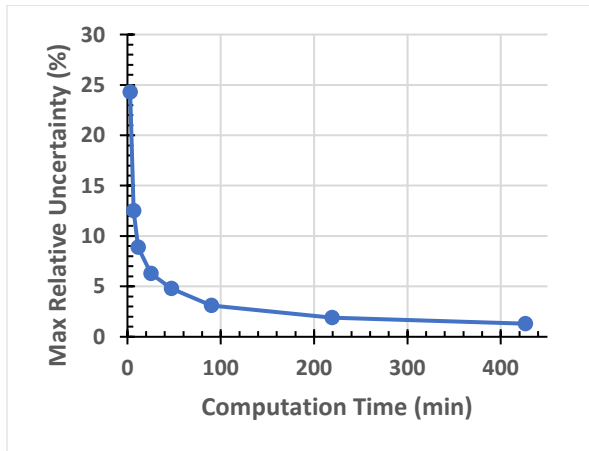


Fig. 4. Maximum relative uncertainty in heating tallies by varying particle count.

OpenMC records the heat shape, flux shape, and criticality of the reactor during the neutron transport simulation. The magnitude of the heating and flux values are determined by the reactor design and is driven by the temperature limits of the materials used in the active core. The heating shape is then provided to the X-NTP model to complete the Picard iteration loop.

II.C. X-NTP Model and OpenMC Coupling

A coupling interface allows for seamless communication between the X-NTP model and OpenMC for use of a TRD-like design. Figure 3 shows the solution flow diagram as seen from the coupling interface.

The coupling interface takes parameters from the X-NTP model through three input files, summarized in Table I. These files are written by the X-NTP model and supplied to the coupling interface.

TABLE I. Coupling Interface Input Files

Static Inputs	Dynamic Inputs	Axial Inputs
Geometry Dimensions	Core Power	Solid Temperatures
Material Identifiers	N/A	Fluid Temperatures
Solver Options	N/A	Fluid Pressures

The interface then takes the values from the input files while using additional information from the material card generator and material properties module to build the TRD-like case in OpenMC. The results from the OpenMC case are manipulated by the post-processor to create a useable file for the X-NTP model. This forms an output file, summarized in Table II. Figure 4 illustrates the entire solution flow.

TABLE II. Coupling Interface Output File

Output File
Axial Power Shapes
Axial Flux Shapes
Effective Neutron Multiplication Factor

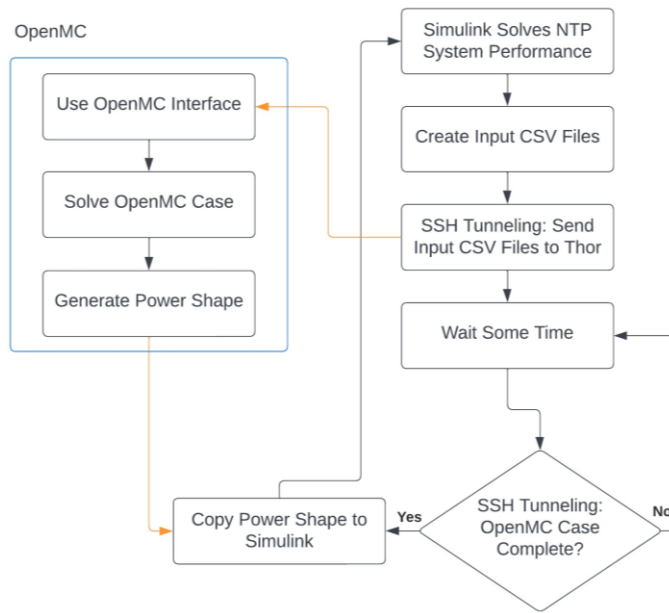


Fig. 4. Solution Flow Diagram of Coupling Interface

The X-NTP model is the driver of the entire Picard iteration loop. It is responsible for creating the input files for the coupling interface, instructing the coupling interface to start, holding until OpenMC has complete its simulation, and reading the resulting output files to receive the new power shape.

III. RESULTS

Detailed results to be added in final paper.

IV. CONCLUSIONS

Conclusions from final results to be added in final paper.

ACKNOWLEDGMENTS

This work was supported by NASA’s Space Technology Mission Directorate (STMD) through the Space Nuclear Propulsion (SNP) project. This work was funded under Contract No. 80LARC23DA003.

REFERENCES

1. Nikitaeva, D., Smith, C. D., and Duchek, M., “Engine Cycle Comparison for Alternative Propellant Nuclear Thermal Propulsion Engines,” Las Vegas, Nevada, 2023. <https://doi.org/10.2514/6.2023-4715>
2. Nikitaeva, D., Smith, C. D., and Duchek, M., “Effects of Heat Transfer Coefficient Variation on Nuclear Thermal Propulsion Engine Performance,” ANS NETS, Idaho Falls, Idaho, 2023.

3. Romano, P. K., Horelik, N. E., Nelson, A. G., Forget, B., and Smith K., “OpenMC: A State-of-the-Art Monte Carlo Code for Research and Development,” *Ann. Nucl. Energy*, 82, 90-97 (2015).
4. Gustafson, J., Kreicicki, M., Swanson, R., Zilka, B., and Witter, J. K., “Space Nuclear Propulsion Fuel and Moderator Development Plan Conceptual Testing Reference Design,” Virtual Event, 2021.
5. Chadwick, M. B., et. al., "ENDF/B-VII.1: Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data", *Nucl. Data Sheets* 112 (2011) 2887.