Surrogate Reactor Modeling for Space Electrical System Mass Optimization

by

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Please insert your dedication here.

ACKNOWLEDGMENTS

It is customary for authors of academic books to include in their prefaces statements such as this: "I am indebted to ... for their invaluable help; however, any errors which remain are my sole responsibility." Occasionally an author will go further. Rather than say that if there are any mistakes then he is responsible for them, he will say that there will inevitably be some mistakes and he is responsible for them....

Although the shouldering of all responsibility is usually a social ritual, the admission that errors exist is not — it is often a sincere avowal of belief. But this appears to present a living and everyday example of a situation which philosophers have commonly dismissed as absurd; that it is sometimes rational to hold logically incompatible beliefs.

— David C. Makinson (1965)

Above is the famous "preface paradox," which illustrates how to use the `wbepi` environment for epigraphs at the beginning of chapters. You probably also want to thank the Academy.

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ABSTRACT

FIXME: basically a placeholder; do not believe

I did some research, read a bunch of papers, published a couple myself, (pick one):

1. ran some experiments and made some graphs,

2. proved some theorems

and now I have a job. I've assembled this document in the last couple of months so you will let me leave. Thanks!

0.1 Previous Space Reactor Work

Using nuclear technology to power space systems is not a new concept. Various space programs have been using nuclear technology for decades to power statellites and deep space probes.

Radioisotope Thermoelectric Generators

SP-100

Kilopower

The Kilopower reactor is a near-term reactor prototype under development at Los Alamos National Laboratory. The reactor was designed to achieve Technical Readiness Level 5 by 2017 [1]. The Kilopower project is a stirling engine system driven by a heat-pipe cooled core. The UMo core was manufactured at the Y-12 National Security Complex from 93%, High-Enriched Uranium (HEU). Kilopower is a relevant reference because it fills a similar mission profile as the current project. NASA's target for Kilopower was a 1-10 kWe unit. The core was successfully tested from November 2017 to March 2018 [2]. During the tests, the UMo core was operated at 800 C and 10 kWt power. While the cooling and power cycle systems differ from a direct-brayton cycle reactor, the Kilopower core design provided a good basis from which to design a direct-cooled fast reactor.

Other Fission Concepts

Nuclear Thermal Propulsion

Nuclear thermal propulsion is a promising alternative to chemical rockets for deep space missions. Nuclear thermal rockets improve the efficiency of traditional chemical rockets to drastically decrease the travel time to planets in the solar system.

0.2 Neutronic Constraints

A valid reactor design must meet certain neutronics constraints. The main neutronics constraint is reactivity. The reactor must be able to sustain a chain reaction from startup, to the final second of the 10 year lifetime. End of Life (EOL) reactivity was the target metric for the neutronic design of the core. It was important to determine which reactor parameters had the strongest impact on EOL k_{eff}. An n-dimensional sampling was performed to explore EOL k_{eff}dependence on various reactor parameters.

Neutronics Parameters

Homogeneous MCNP6.1 depletion models were used to analyze the EOL k_{eff}response to neutronics parameters (predictors). The core region was homogenized and surrounded by a graphite reflector. A large set of 5-dimensional predictors and EOL k_{eff}results was produced to investigate the neutronics parameter space. These predictors and their results helped develop an understanding of the reactor response to important design and operational parameters. High Throughput Computing capabilities at UW were used to perform 3901 depletion calculations with MCNP6.1. Each model represents a unique sampling in every dimension using the Latin Hypercube Sampling (LHS) technique. The LHS technique ensured even sampling for every dimension. The sampled and fixed dimensions/parameters are shown in Table 0.1.

Neutronics Sampling Results

The target metric for the neutronics sampling was an EOL k_{eff}equal to one. In order to determine the dependence of EOL k_{eff}on each swept parameter in Table 0.1, EOL $k_{eff}$was plotted against the parameters.

Table 0.1: Homogeneous Geometry and Depletion Parameters

Core Radius	10 - 50 [cm]
Reflector Thickness	15 [cm]
Core Aspect Ratio	1 [-]
Coolant Channel Radius	0.5 - 1 [cm]
Fuel Pitch to Coolant Channel D.	1.1-1.6 [-]
Fuel Enrichment	20% - 90% ^{235}U
Thermal Power	80-200 [kW]
Fuel Temp	300 [K]
Reactor Physics Code, Data	MCNP6.1, ENDF-7.2

Thermal Power

Initially, the result of greatest interest was the mass dependence on thermal power because thermal power was the coupling parameter with the power cycle. Figure 0.1 shows the relationship between thermal power and EOL k_{eff}.

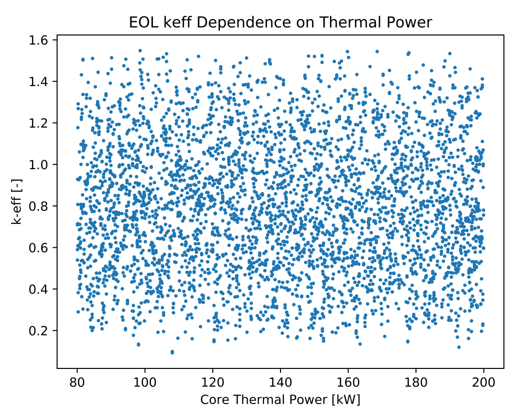

Figure 0.1: EOL k_{eff}Power Dependence

As shown in Figure 0.1, EOL $k_{eff}$is independent of core thermal power. This result is not surprising considering the depletion rates in the core. Assuming 1 MWd/gU is an achievable burnup, the reactor depletes approximately 1000 kg of uranium at 200 kW of thermal power. The depletion mass of uranium is negligigle compared to the mass of uranium required for the reactor to be critical at BOL. Thermal power is not a strong predictor of EOL criticality.

Uranium 235 Mass

0.3 Thermal Hydraulic Theory

The second constraint of a valid reactor design is coolability. The reactor must not melt and the integrity of the fuel must be maintained for the duration of the mission. To ensure the thermal hydraulic validity of a chosen design,

1D heat transfer and bulk-averaged fluid flow calculations were performed. The 1D heat transfer and fluid equations were coupled with analytical flux shape factors from nuclear engineering literature to determine the maximum extractable thermal power for each reactor design. A 1D resistance network is used to determine the maximum thermal generation for a given core design and temperature drop between fuel meat and coolant.

Flow Properties

All flow properties were axially averaged between their inlet and outlet values. The inlet and outlet flow conditions, thermal power, and mass flow rate are dictated by the power cycle configuration and requirements. Property tables for both CO2 and H2O coolants as a function of perssure and temperature were generated using EES and interpolated using SciPy's 2D interpolation functions. The interpolated properties included: thermal conductivity, density, viscosity, and specific heat.

Core Geometry

Important core geometry parameters were calculated. The coolant flow area, average distance of conduction in the fuel, volume fraction of cladding in coolant, number of coolant channels, convection surface area, LD, and the cross sectional area for conduction in the fuel. The core radius is set by a critical radius constraint dependent on the fuel fraction. This will be discussed in a later section.

Fuel area and volume is derived from the core radius and fuel fraction. Where AR is the core aspect ratio.

$$A_{fuel} = frac_{fuel} * r_{core}^2 * \pi \tag{1}$$

$$V_{fuel} = A_{cool} * AR * r_{core} \tag{2}$$

The fraction of cladding in the coolant is derived from the coolant channel radius and cladding thickness.

$$frac_{clad} = \frac{(r_{channel} + t_{clad})^2 - r_{channel}^2}{r_{channel}^2} \tag{3}$$

In a similar vein, coolant flow area is derived from the core radius, cladding fraction, and fuel fraction

$$A_{cool} = (1 - frac_{fuel}) * (1 - frac_{clad}) * r_{core}^2 * \pi \tag{4}$$

$$V_{cool} = A_{cool} * AR * r_{core} \tag{5}$$

The number of coolant channels is derived from the area of each channel and the core flow area.

$$N_{channels} = \frac{A_{cool}}{(r_{channel} + t_{clad})^2 * \pi} \tag{6}$$

The convection surface area is dervied from the channel radius, core length, and number of channels.

$$A_{conv} = 2 * r_{channel} * \pi * r_{core} * AR * N_{channels} \tag{7}$$

The length over diameter is derived from the channel radius and core length.

$$LD = \frac{r_{core} * AR}{2 * r_{channel}} \tag{8}$$

The average distance to conduction is derived from fuel area and number of channels.

$$R_{cond} = \frac{\sqrt{\frac{A_{fuel}}{N_{channels}}}}{2} \tag{9}$$

The cross sectional area for conduction in the fuel was conservatively estimated as the convection surface area. In reality, the cross-sectional area changes as heat transfers from the center of the fuel meat to the coolant channels.

These are the important equations defining the 1D geometry for a coolable reactor. Once the geometry has been defined, the flow conditions are modeled.

Flow Equations

Once the core geometry has been defined, the flow is characterized using bulk-averaged flow conditions and the reactor geometry. The mass flux, coolant velocity, Reynold's number, Nusselt number and average heat transfer coefficients are calculated.

Mass flux is derived from flow area and the mass flow rate dictated by the power cycle. Flow velocity can be calculate from mass flux and density.

$$\dot{G} = \frac{\dot{m}}{A_{flow}} \tag{10}$$

$$v = \frac{\dot{G}}{\rho} \tag{11}$$

The Reynold's number is derived from flow velocity, density, viscosity, and the characteristic flow length (channel diameter, D).

$$Re = \frac{\rho v D}{\mu} \tag{12}$$

The Nusselt number is calculated using the same correlations as EES. Laminar, turbulent, and transitional flows are all treated differently.

The average heat transfer coefficient is derived from the Nusselt number and thermal conductivity of the fluid.

$$\bar{h} = \frac{Nu k_{cool}}{D} \tag{13}$$

1D Thermal Generation Modeling

With a fully defined geometry and fully characterized flow, the maximum thermal output of the core is calculated. The maximum generation (at the center of the core) is calculated using a 1D resistance network. The three resistances in the network are: conduction in the fuel, conduction in the clad, and convection from the clad to the coolant. Gap and interface resistances were ignored.

Resistance to conduction in the fuel was approximated as plane wall conduction.

$$R_{fuel} = \frac{R_{cond}}{k_{fuel} A_{cond}} \tag{14}$$

$$R_{clad} = \log\left(1 + \frac{t_{clad}}{r_{channel}}\right) \tag{15}$$

$$R_{conv} = \frac{1}{2\bar{h} r_{channel} L \pi N_{channels}} \tag{16}$$

The maximum heat transfer rate at the fuel centerline was derived from the resistance network and the temperature drop. The temperature drop was determined by the maximum fuel temperature (estimated to be half the melting temperature of the fuel) and the bulk coolant temperature.

$$Q'''_{max} = \frac{dT}{R_{fuel} + R_{clad} + R_{conv}} \tag{17}$$

Finally, the thermal generation at fuel centerline is scaled by the axial and radial flux profiles to account for the cosine and bessel function shapes of the flux. The scaling factor was taken from El-Wakil's Nuclear Heat Transport.

$$Q_{gen} = Q'''_{max} * 0.275 \tag{18}$$

1D Thermal Hydraulic Calcuations

The governing equations above describe a coolable reactor design. A Python code was written to solve the system of equations defining the geometry, flow conditions, and 1D heat transfer in the reactor. The code utilizes Scipy's optimization package. The 'optimize_scalar' function is used to guess fuel fraction values. For each fuel fraction, the above equations are used to determine Q_{gen}, an error exists between Q_{gen} and the required thermal reactor output dictated by the power cycle requirements. The optimization function minimizes the squared difference between Q_{gen} and the thermal power requirements. When the solver converges on a fuel fraction, the code returns a coolable reactor design. Since the core radius was set by a critical radius constraint, this reactor is also neutronically valid for the duration of the 10 year mission. The thermal hydrauilc code also calculates the mass of each reactor. This mass includes fuel, cladding, coolant, reflector material and the pressure vessel. The pressure vessel thickness was calculated as a function of pressure and outer core radius (including the reflector) for stainless steel at $\tilde{7}$00K.

Reactor Mass Modeling Results

DISCARD THIS PAGE

COLOPHON

This template uses Gyre Pagella by default. (I used Arno Pro in my dissertation.)

Feel free to give me a shout-out in your colophon or acks if this template is useful for you. Good luck!

REFERENCES

[1] Gibson, Marc A., Steven R. Oleson, David I. Poston, and Patrick McClure. 2017. NASA's Kilopower reactor development and the path to higher power missions. In *2017 IEEE Aerospace Conference*, 1–14. Big Sky, MT: IEEE.

[2] Poston, David Irvin. 2018. KRUSTY Test Results. Tech. Rep. LA-UR–18-23685, 1435544.