OPTICAL NUCLEAR ELECTRIC PROPULSION. V. Patel[1], R. Davis[2], N. Campbell[3], C. Runco[1], and S. Howe[4]. [1]Texas A&M University (vkp93@tamu.edu), [2]University of Idaho, [3]University of Florida, [4]Center for Space Nuclear Research.

Introduction: Nuclear Electric Propulsion (NEP) is an enabling technology for long-term space operations that require high power levels. Previous designs have large specific masses (mass/power) which make them economically unattractive, many moving parts which make them hard to maintain, and high temperature coolants which require exotic materials. A 12 kWe/kg system operating at 236 kWe was designed by optimizing each subsystem with respect to system specific mass relative to power level and photovoltaic (PV) cell array temperature. A design tool was created that related different PV cell temperatures and power levels to specific mass. The tool took into account many reactor designs that were studied to find critical, coolable dimensions. Methods for efficient light transport between the nuclear reactor and PV array were implemented. PV arrays with heat rejection systems were designed and included in the tool. Auxiliary systems were studied to be included in the final design.

Design Overview: The optical nuclear electric propulsion system was designed using a nuclear heat source to heat an emitting surface to 2200K. This surface is coated with selective emitters that emit a spectrum that is designed for use with triple-junction photovoltaic cells. A mirror system transfers the light emitted by the surface around a shadow shield to a photovoltaic array, which generates electricity for use with electric engines. A view of the system is shown in Fig. 1.

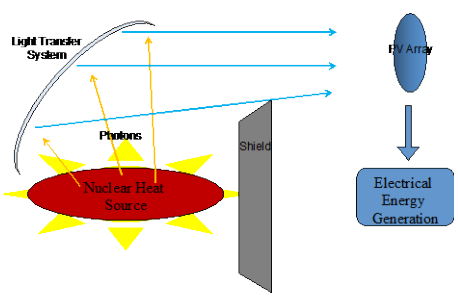

Figure 1: Overview of Optical NEP

Nuclear Reactor: A tungsten cermet fuel (47WRe-50UO_2-3Th_2) in a cylindrical configuration surrounded by BeO reflector is used as the nuclear core. The tungsten fuel and the reflector were chosen because of their good heat transfer characteristics and high melting temperatures.

Many core configurations were studied using MCNP5 for neutronics and MATLAB for heat transfer calculations. To form a design space, several properties were varied such as the fissile isotope (U^{235} or U^{233}), fuel mixes (50% or 60% fissile fractions), fuel dopants (Ta or Re), core shapes (Spherical or cylindrical), and reflector properties (material, position, dimensions).

The reactor study found a set of minimum mass cores corresponding to different power levels constrained to a maximum temperature of 3000 K and a surface temperature of 2200 K. The specific masses as a function of power for the different cores created are shown in Fig. 2. The U^{233} fuel with a 60% volume fraction was found to achieve the lowest specific mass that included the important Re dopant.

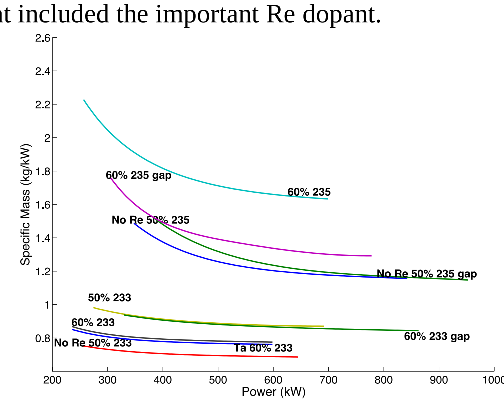

Figure 2: Specific Mass vs. Power for Many Reactor Configurations

Light Transfer System: A Light Transfer System (LTS) was developed to direct the flow of photonic energy being emitted from the radiating nuclear reactor to an array of photovoltaic cells. Ensuring minimal energy losses in this transfer was vital in reaching high overall system efficiency.

The LTS had to be designed to direct light from a distributed source to the PV arrays that were behind the shadow shield while maintaining low system mass. This resulted in extended source complications that rival current work in the non-imaging optics research community [1]. A MATLAB script was created based initially on the Direct-Method of 2D Free-Form Reflector Design [2] and modified for extended source considerations. Using the axisymmetric geometry of the LTS, specifically the spatial distribution of source (core) and target (PV), as an input, the code solved for an ideal mirror made of specific conic sections.

Designs were tested by numerical experiments in COMSOL (v4.3). This analysis applied Hamiltonian Optics in COMSOL's Mathematical Particle Tracing Module to achieve ray-tracing simulations that enabled design validation and system analysis. A parametric study was conducted varying many design aspects such as mirror size, eccentricity, focal distance, PV array distance and size, as well as material considerations such as mirror reflectivity and core absorptivity.

Results from the parametric study were used to form a relationship for the variation of light transport efficiency and system mass as a function of PV array distance from the core. This work led to a light transport system design with over 95% efficiency.

Photovoltaic Cell Array: The PV array must efficiently convert the light from the reactor to electricity. Many variables contribute to the conversion efficiency, most importantly: the spectrum of the light, the composition of the PV cell material, and the temperature of the PV cell.

A literature review of selective emitters and PV cells was used to select a good combination of materials to increase photovoltaic conversion efficiency. The power produced by these combinations was calculated with the emissivity corrected Plank law for each emitter-PV cell pair [3]. This calculated power was then divided by the total power produced from the selective emitter surface to find power conversion efficiency. Using a Yb, Ho, Er selective emitter mix with a triple junction (Si-InGaAs(n)-InGaAs(ext)) PV cell, a conversion efficiency of 51% was achieved. There are many host materials that the selective emitters can be bound in that allow for high temperature operations [4].

Auxiliary Systems: Additional required systems such as shielding, extendable truss, radiator, and power management were also considered.

Shielding. A tool was developed that found required LiH and W thicknesses to shield a payload to a desired radiation dose. The analysis followed the works in [5], which used MCNP to develop neutron and gamma attenuation lengths for W and Be from a reactor source. These attenuation lengths allowed the shield mass to be estimated for any distance away from the payload. A minimum mass was found where the mass added by increasing the distance away from the payload was larger than the decrease of shielding mass required at that distance.

Extendable Truss. The support structure that all the subsystems attach to needs to be lightweight and separate the payload and the reactor. An inflatable truss that was designed for large space telescopes and radars [5] was found to fit the needs. The truss mass was estimated from data found.

Radiator. Two methods of heat removal are considered viable: a radiator similar to the JIMO mission consisting of an array of heat pipes with a NaK eutectic coolant, and routing the coolant to other areas of the spacecraft (e.g. the back of the PV cell array) to take advantage of the additional surface area as radiative transfer surfaces. It was found that the PV temperature array at 140 °C could provide very good heat transfer rates. The loss of power conversion efficiency with higher temperatures [7] in the PV cells was found to be outweighed by the ability to decrease the radiator mass.

Power Management and Distribution. A PMAD system is needed to regulate electrical output and distribute power from the PV cells to the engines. A scaled version of the International Space Station's PMAD was used as a reference for this design.

Engines. Several engines were considered, including Hall Effect (HiPEP), magneto-plasma dynamic, and microwave thrusters. The HiPEP was found to best fit the power output of the designed NEP.

Final Design Tool & Conclusions: The final optimization was found to be a function of reactor power, mission duration, and PV array temperature. Figure 3 shows several power levels and how PV cell temperature affects the total specific mass while assuming a 10-year mission duration. Table 1 shows the subsystem masses for the 12 kWe/kg configuration.

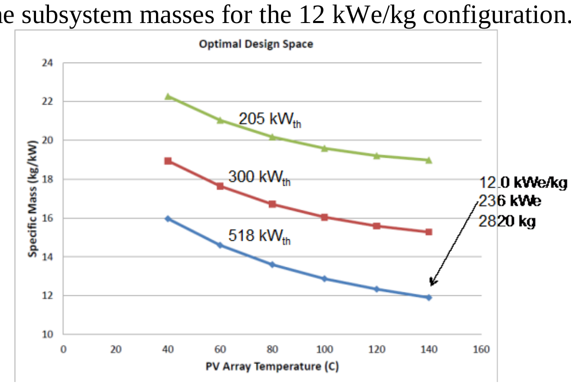

Figure 3: Final Design Space

Subsystem Component	Mass	
Reactor	590	21
Radiation Shield	46.6	2
Truss	93.6	3
Thermal Radiator	334	12
PV Array	410	15
Mirror	1181	42
PMAD	165	6
Total	2820	

Table 1: System Mass

References:

[1] Fournier F. (2010) Ph.D. Thesis University of Central Florida [2] Canavesi C. et al. (2012) *Optics Letters*, 37(18) [3] Datas A. et al. (2007) AIP Conf. Proc. 890:227 [4] Chubb D. ISBN. 0444527214, pp. 98-104 [5] Bruno C. (2008) ISBN: 1563479516, pp. 195-198 [6] Darooka D. K. et al. (2001) AIAA-2001-1614 [7] Durisch W. et al. (2007) Solar Energy Materials and Solar Cells, Volume 91, pp. 79-84