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Abstract. *A conceptual reactor system to support Multi-Megawatt Nuclear Electric Propulsion is investigated within this paper. The reactor system consists of a helium cooled Tungsten-UN fission core, surrounded by a beryllium neutron reflector and 13 B_4C control drums coupled to a high temperature Brayton power conversion system. Excess heat is rejected via carbon reinforced heat pipe radiators and the gamma and neutron flux is attenuated via segmented shielding consisting of lithium hydride and tungsten layers. Turbine inlet temperatures ranging from 1300 K to 1500 K are investigated for their effects on specific powers and net electrical outputs ranging from 1 MW to 100 MW. The reactor system is estimated to have a mass, which ranges from 15 Mt at 1 MW_e and a turbine inlet temperature of 1500 K to 1200 Mt at 100 MW_e and a turbine temperature of 1300 K. The reactor systems specific mass ranges from 32 kg/kW_e at a turbine inlet temperature of 1300 K and a power of 1 MW_e to 9.5 kg/kW at a turbine temperature of 1500 K and a power of 100 MW_e.*

Keywords: Space Reactor, Power Conversion, Radiator, Electric Propulsion.

I. INTRODUCTION

The United States of America nor any other nation on earth has ventured beyond Low Earth Orbit (LEO) since the Apollo 17 mission undertaken in December of 1972. However, the presidential administrations of George W. Bush and Barack Obama have both challenged NASA to push beyond LEO to explore different celestial bodies such as the moon, Mars and Near Earth Asteroids (NEO's). Advancement in space propulsion is key to enabling travel to distant non-terrestrial bodies and will inevitably require fission power sources to achieve the required kinetic jet powers for high thrust high specific impulse missions. In fact the current presidential administration of Barack Obama has made space nuclear power and propulsion development a key part of the National Space Policy of the United States of America.[1]

Two of the dominant nuclear propulsion concepts are Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP). An NEP engine is a system where electricity is produced within a fission reactor; the electricity from the reactor is then used to ionize a propellant, which is accelerated out of a nozzle via an electrostatic force or a magnetic field.[2] Nuclear Electric Propulsion can enable missions with a specific impulse of many thousands of seconds; however, power conversion inefficiencies and the physics of high specific impulse systems, produce very low thrust to weight ratios. Nuclear Electric Propulsion engines can produce a much higher specific impulse than conventional NTP engines; however, the low thrust to weight ratios typical of NEP engines can produce mission durations much longer than that of NTP systems and can vastly increase the Initial Mass in Low Earth Orbit (IMLEO) over that of NTP engines. An electric propulsion system must have a power source with a specific mass of 5 kg/kW_e or less in order to enable rapid transit times to celestial targets that compare with that of NTP and even chemical rocket engines.[3]

Many studies have been conducted to investigate the design and achievable specific masses associated with an NEP reactor system. However, one must bound the scope of a study to that of either a Research and Development (R&D) plan or an Engineering and Development (E&D) plan. An R&D plan does not necessarily have to conclude with the construction of a working reactor and can investigate the fundamental science behind subsystems required to achieve a specific mass of 5 kg/kW$_e$, no matter the cost or development risk. An E&D plan differs in the fact that the project can only conclude with the successful construction of a reactor system with the desired specific mass. An E&D approach must minimize risk associated with the differing subsystems and must also achieve key milestones within an allocated budget and schedule. Some previous NEP studies have shown it may be possible to construct NEP reactors with a specific mass of 5 kg/kW$_e$; however, many subsystem technologies selected were very high risk and may require budgets of tens of billions of dollars to develop.[4] This paper will investigate the design of an NEP reactor and subsystems from an engineering development approach where development risk is minimized while still yielding an advanced reactor with the minimum reasonable specific mass.

II. FISSION CORE

A helium cooled fast spectrum reactor was chosen for its resistance to thermal spectrum poisons and its advantageous material properties. This study has chosen a tungsten-uranium-mononitride (W-UN) CERMET fuel material due to the very high corrosion resistance and creep strength of tungsten at elevated temperatures, coupled with the high creep strength and thermal conductivity of UN.[5,6,7,8] The fuel geometry selected for this study was a prismatic style fuel, with a flat-to-flat distance of 3.51 cm, each fuel hex containing 37 coolant channels. Each coolant channel is lined with a 0.025 cm thick cladding tube consisting of a W-25Re alloy. Each fuel element is 83 cm in length where the first 20 cm consists of a beryllium-oxide axial neutron reflector, fabricated to the same geometry as the fuel element, and the remaining 63 cm consists of the fueled portion of the element.

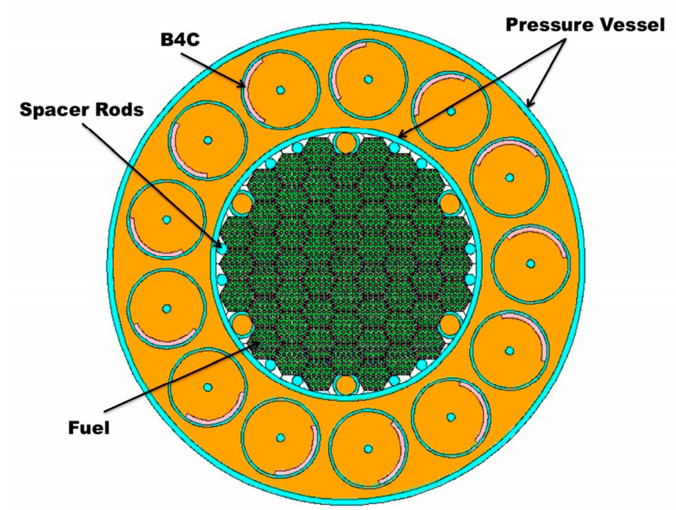

FIGURE 1. Top Down View of an MCNP Rendered Multi-Mega-Watt (MMW) Reactor Model.

The fuel elements are surrounded by a 0.64 cm thick Ti-8Al-1Mo-1V pressure vessel, which is also surrounded by a beryllium (Be) radial neutron reflector. Thirteen control drums are encased within the Be reflector, each comprised of a 0.25 cm thick B_4C neutron sheath which wraps around a 120^0 section of the control drum. The entire fission core is surrounded by another 0.7 cm thick Ti-8Al-1Mo-1V pressure vessel. The core is designed to have approximately \$4.00 of excess cold clean reactivity at start up, with a control swing of approximately \$12.00 in the control drums. The W-25Re cladding tubes also helps keep the reactor deeply subcritical in the event of a water submersion scenario, even if the control drums are in their most reactive position. Figure 1 displays an MCNP rendering of the fission core top view at midplane with all thirteen control drums in the critical position. Analytical calculations were used to estimate the radius of the coolant channels required to absorb the reactor thermal power for the appropriate helium flow rate. The coolant channel radius was then used in an MCNP5 model to determine the reactor dimensions and mass required to achieve the appropriate amount of excess reactivity. The fission core mass as a function of reactor electrical power was then fit to an analytical equation, which is shown in Equation 1, where *M* represents the core mass in kilograms and *P* represents the electrical power in megawatts. Equation 1 was developed by the use of hand calculations to help determine the required coolant channel radius and mass flow rate which achieves a peak temperature within the fuel elements of 1800 K. The coolant channel radius was fed into the MCNP criticality code to determine the required reactor radius and mass.

$$M = 20.375P + 945 \tag{1}$$

III. SHIELDING

Multi-megawatt fission power systems produce copious quantities of both gamma and neutron radiation, which must be shielded to protect either a human or robotic payload aboard a spacecraft. While the typical annual dosage allowed on earth for radiation workers is approximately 5 rem/year, space operations will inevitably require larger allowable doses. At the present time it is not known what radiation doses will be allowable for astronauts; however, for the purposes of this study a dose rate of 15 rem/year was been assumed. Instead of encapsulating an entire spacecraft in a radiation attenuation medium, a shield of the appropriate dimensions is placed between the reactor and craft, such that a radiation shadow is produced that encompasses the entire spacecraft. In order to reduce the shielding requirements a variable geometric attenuation distance between the shield and spacecraft has been assumed.

A combination of a Lithium-Hydride (LiH) and Boron Carbide (B_4C) will be used to attenuate and absorb neutrons scattering within the shield material. The boron within the B_4C is enriched to 90% B^{10} in order to increase the effectiveness of the shield. An initial tungsten shield 1.5 cm thick is used at the front end of the shield to absorb the gamma rays produced in the reactor. Multiple LiH and B4C layers are stacked on top of each other to attenuate the dose to a 15 rem/year limit. The number of layers increases as the reactor power increases yielding different shield masses. Each LiH layer is 2 cm thick, followed by a 0.25 cm thick layer of B_4C.

An MCNP5 model of the space reactor attached to the shield was used to predict the level of neutron and photon dose to a sphere of water with a volume of 3.2 cm^3.[9] The density of the LiH was assumed to be 0.78 g/cc, the tungsten was assumed to have a density of 19.3 g/cc and the B_4C was assumed to have a density of 2.5 g/cc. The MCNP5 code determined the track length estimate of flux and then used the ANSI 6.1 flux to dose conversion to determine the estimate of dose for the spherical water volume. The code was run several times for varying shield thicknesses by adding LiH and B_4C layers, at differing separation distances between the water volume and shield. A FORTRAN code was written to extrapolate the mass of a shield required to yield a 15 rem/year dose rate at a given geometric attenuation distance. The shield mass was increased by 15 % over the initial estimate to account for void space needed for piping required to cool the shielding material. Over the range of 1 MW_e to 100 MW_e and geometric attenuation distances ranging from 10 m to 100 m, the net shielding mass was found to range from 50,000 kg to 88,000 kg as shown in Figure 2.

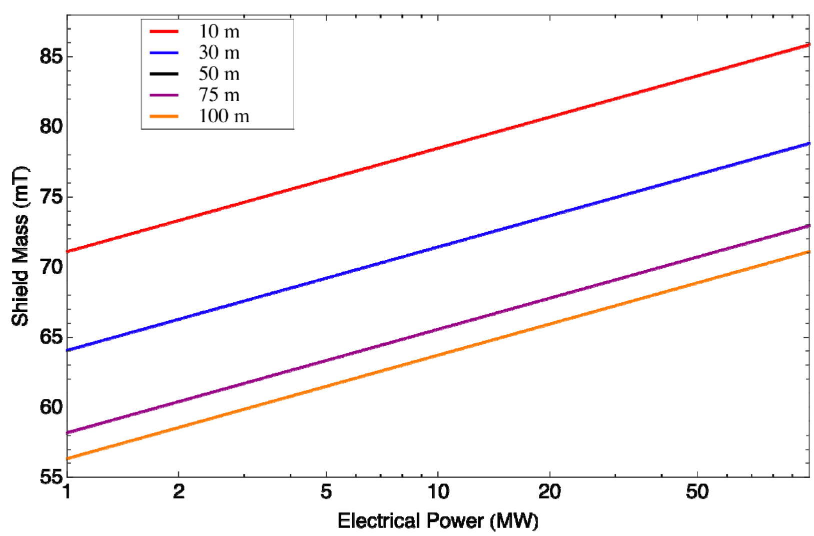

FIGURE 2. Shadow Shield Mass as a Function of Electrical Power for Various Attenuation Distances.

IV. POWER CONVERSION

A dynamic power conversion system was assumed at the beginning of the analysis in order to reduce the amount of heat to be rejected and increase the efficiency of thermal to electric energy conversion. Many different types of dynamic power conversion systems exist for uses in space applications to include, Stirling engines, Brayton engines, Rankine engines and MHD energy conversion. Stirling engines offer enormous potential for energy conversion at inlet temperatures below 1000 K; however, multi-megawatt systems require much higher temperatures in order to minimize the mass of the heat rejection system. Rankine engines are ideal for the energy conversion of high temperature fluids, but require the handling and separation of two-phase flows, which is very problematic in a microgravity environment such as space. Magneto-Hydro-Dynamic (MHD) energy conversion methods offer enormous potential for future low mass energy conversion systems; however, they currently exist as a very immature technology.

Brayton engines are the only system that can be developed further for space applications with an acceptable level of risk within the context of an E&D program. A typical Brayton engine consists of a heat source, which in this case is a reactor, a fluid (in this case helium) carries thermal energy from the reactor to a turbine, where energy is extracted and transformed into electricity within an alternator. The heat not transformed into electricity is rejected to space by a radiator. The fluid then leaves the radiator and flows to the compressor, where energy is added to restore the fluid to the proper temperature and pressure prior to re-entering the fission core for re-heating. For the purpose of mechanical simplicity the turbine, compressor and alternator all exist on a common shaft. A regenerator can be added to increase conversion efficiency; however, the addition of a regenerator comes at the price of added mass. As will be discussed in the next section, the increased efficiency will decrease heat rejection temperature and can increase the mass of the heat rejection system. Figure 3. demonstrates the basic layout of a simple Brayton engine.

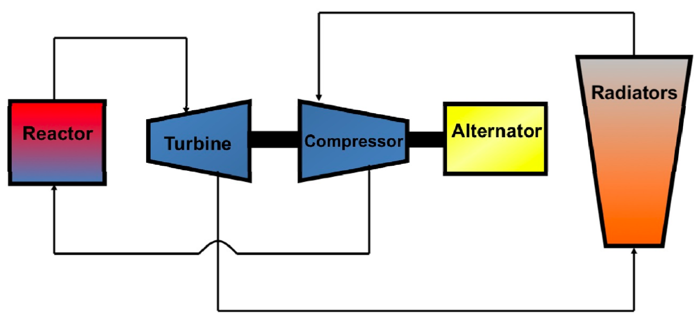

FIGURE 3. Schematic of a Simple Brayton Power Conversion Cycle.

The mass of a single shaft Brayton engines used in space power applications must be minimized. The National Aeronautics and Space Administration (NASA) has led many studies to determine the state of the art in power conversion technology and the specific mass associated with the different concepts.[9,10,11] Figure 4 represents a compilation of differing Rankine and Brayton engine concepts and their specific masses as a function of turbine inlet temperature. The trend of decreasing specific mass as a function of temperature is clearly evident, indicating the need for very high turbine inlet temperatures in order to reduce the system to an acceptable mass. Nevertheless, it is not reasonable to assume that any known refractory super-alloy can withstand the centripetal acceleration of a spinning turbine blade for many months without succumbing to the effects of creep at temperatures above 1800 K. Also the effects of increased corrosion kinetics become very severe at such high temperatures, so it is assumed that no E&D program will consider a turbine inlet temperature greater than 1500 K, which still represents a serious challenge and risk to a development program. The Brayton data points within Figure 4 were curve-fit to a second order temperature dependent polynomial shown in Equation 2. The temperature dependent polynomial gives an estimate of a power conversion systems specific mass (α) in units of kg/kW$_e$ as a function of temperature (T) in units of Kelvins.

$$\alpha = -5.893 \bullet 10^{-6} T^2 + 5.829 \bullet 10^{-3} T + 12.19 \tag{2}$$

Helium is one of the best choices as a coolant and energy transfer mechanism for long duration Brayton power cycle applications. Mixtures of helium and xenon as well as helium and neon may be considered due to the fact that they reduce pressure losses and thereby the compressor mass by increasing the molecular mass of the fluid. However, the addition of xenon and neon to a fluid also decreases the thermal conductivity and specific heat of the fluid; which decreases the energy transfer within the fission core. The addition of xenon or neon to a core can also induce corrosion of the turbine blades which can be detrimental over long durations missions. This study has chosen to use high purity helium as a coolant within the Brayton engine and has also chosen to forego the possible use of a regenerator to reduce system mass.

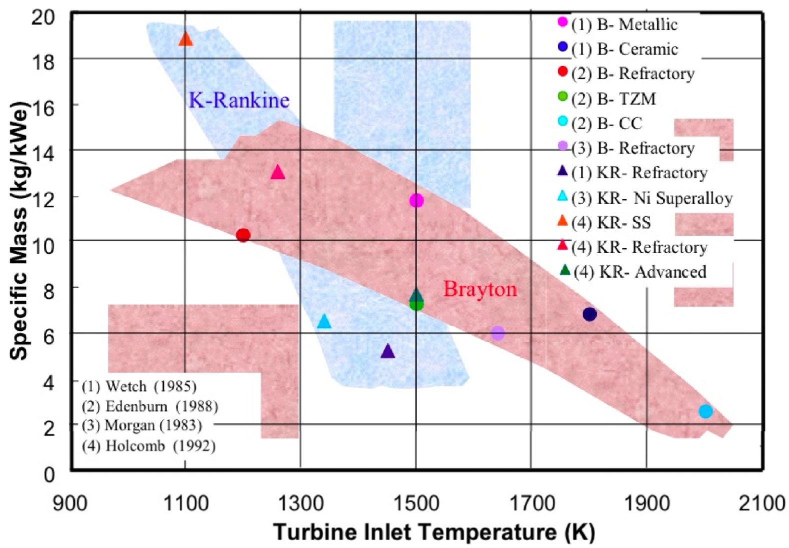

FIGURE 4. Plot of Power Conversion Cycle Specific Power as a Function of Turbine Inlet Temperature.[9,10,11]

V. HEAT REJECTION

Unfortunately for the design of any power conversion system, the laws of physics prevent the conversion of all heat within a system into electricity. Some fraction of the energy released by a reactor will remain in the coolant after it leaves the power conversion turbine. If this heat is not rejected from the system, it will compound upon itself every time the coolant cycles through the system and eventually melt the reactor and associated components.

In space the only method to reject heat is via radiative energy transfer, which is controlled by the Stefan-Boltzman equation shown in Equation 3 where P represents the radiated power, ε represents surface emissivity of the radiator, σ represents the Stefan-Boltzman constant (5.669×10^{-8} W/m^{2}K^4), A represents the radiator surface area and T_h as well as T_c represent the radiator hot side temperature and the blackbody (space) temperature respectively.

$$P = \varepsilon\sigma A\left(T_h^4 - T_c^4\right) \tag{3}$$

Equation 3 clearly shows that there is a robust tug of war in minimizing the radiator surface area and thereby the mass of a radiator. If one can maximize the power conversion efficiency and thereby reduce the excess power to be radiated, the radiator surface area can be decreased. However, when the conversion efficiency is increased to decrease the power to be radiated, the hot side temperature is decreased which can increase the required radiator area.

A FORTRAN code was written to evaluate the helium temperature and pressure at every point within a simple brayton engine for reactors of varying electric powers ranging from 1 MW to 100 MW. The temperature of the coolant entering the radiator was assumed as the hot side temperature in Equation 3 with a cold side temperature of 25 K. The code assumed a perfect emissivity of 1.00 and then determined the amount of excess thermal power residing in the flow entering the radiator. The FORTRAN code then analytically solved for the required radiator area needed to reject the excess heat. The required radiator area was then plotted over the range of 1 MWe to 100

MWe for turbine inlet temperatures of 1300 K, 1400 K and 1500 K, which is shown in Figure 5. The required radiator areas ranged from 290 m^2 at 1500 K and 1 MW_e to 14,000 m^2 at 1300 K and 100 MW_e.

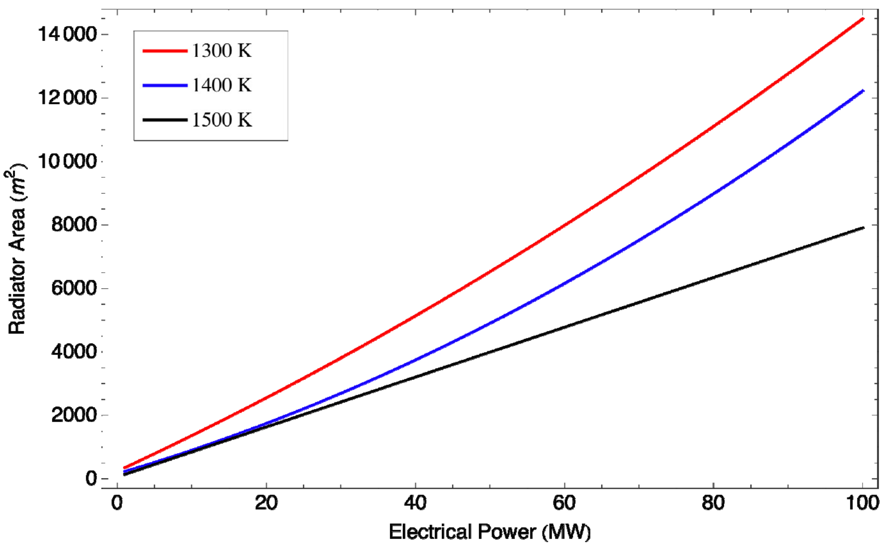

FIGURE 5. Required Radiator Surface Area as a Function of Electrical Power for Turbine Inlet Temperatures of 1300 K, 1400 K and 1500 K.

The surface area required for heat rejection shown in Figure 5 will be the same for any type of radiator, assuming the material emissivity is the same. However, different radiator concepts exist, that offer a range of radiator areal mass densities. The two prime candidates for radiator technologies are the liquid drop radiator and the heat pipe radiator. The liquid drop radiator operates by ejecting hot liquid metal droplets from a top-side shower. The surface area of the droplets acts as the radiator; however, many of the droplets end up radiating energy into one and another. The droplets fall onto a collector which then sends the liquid to a heat exchanger where they absorb thermal energy from the cold side of the Brayton turbine and repeat the cycle.[12] Unfortunately, the risk of fluid loss during free fall is too great of a risk for serious consideration in this study.[13]

The heat pipe radiator operates via the use of a pipe, liquid and wick. The liquid in the heat pipe convectively absorbs heat from the cold side end of the Brayton turbine. The heated liquid is then transported up the wick by the action of surface tension, which branches out to panels, which reject the heat to space. Once the liquid is cooled by radiation, it is recycled to the turbine cold side, where it absorbs energy and repeats the process.[13] Heat pipe radiators have been robustly tested and have been selected for development in current NASA programs.[14,15] Various technology studies have claimed that heat pipe radiators might be built for areal mass densities ranging from 3 kg/m^2 to 6 kg/m^2; however, the a value of 4.5 kg/m^2 may be more reasonable for a development program. Long duration heat pipe radiators must also be reinforced by a carbon Kevlar weave in order to protect against long duration micro-meteoroid damage. Due to the known performance and current testing of heat pipe radiators, the heat pipe radiator was selected for the heat rejection system in this study with an assumed areal mass density of 4.5 kg/m^2[(14-16)].

VI. REACTOR SYSTEM MASS

A reactor system was selected to use a W-UN CERMET fission core. The core was surrounded by two titanium-alloy, pressure vessels with a radial neutron reflector consisting of beryllium, which was embedded with thirteen B_4C control drums. A segmented shield consisting of tungsten, LiH and B_4C was selected to attenuate the neutron and gamma flux such that the crew never received a dose rate exceeding 15 rem/year from the reactor. A single shaft brayton engine was selected for the conversion of heat into electricity along with a carbon reinforced heat pipe radiator as a heat rejection system.

The net system mass can now be estimated as a function of power by using Equation 1 for the reactor mass, Figure 2 to determine the shield mass, Equation 2 for the power conversion mass and the combination of Equation 3 and an area mass density of 4.5 kg/m^2 for the radiator mass. For further purposes in this study the shielding geometric attenuation distance is assumed to be 25 meters.

The mass and specific mass of the reactor system was tabulated over the electrical power range of 1 MW to 100 MW. For the purposes of brevity the power dependent plot of reactor system mass and the subsystem mass breakdown is not shown. However, the power conversion system dominated the mass breakdown and accounted for approximately 60% of the entire system mass at nearly all powers investigated. The specific mass of the reactor system was found to range from 32 kg/kW_e at 1 MW_e and a turbine inlet temperature of 1300 K to 9.5 kg/kW_e at 100 MW and a turbine inlet temperature of 1500 K. The system designed from an Engineering Design standpoint fell far short of the desired specific mass of 5 kg/kW_e.

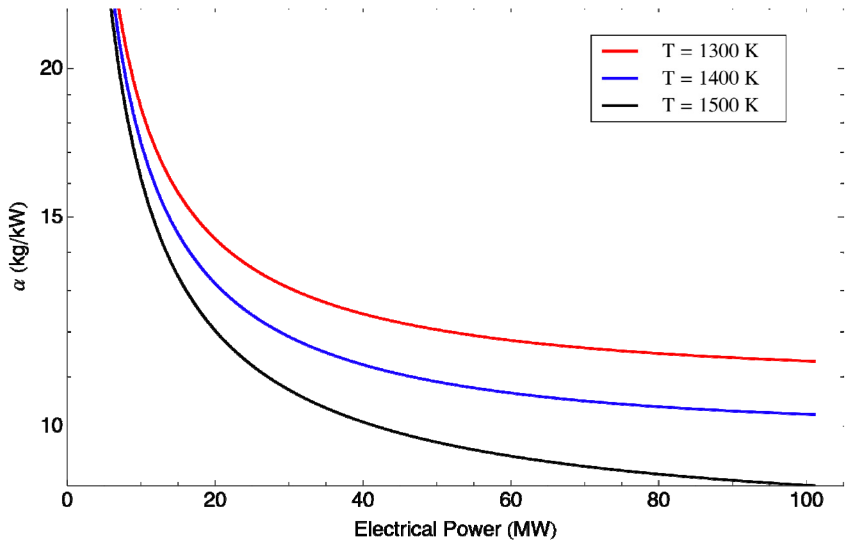

FIGURE 6. Reactor System Specific Mass over the range of 1 to 100 MW_e for Turbine Inlet Temperatures of 1300 K, 1400 K and 1500 K.

CONCLUSION

A reactor system was conceptually designed in a method where risky and possibly very expensive subsystem development was passed over in favor of lower risk subsystems. The fuel type selected for development was a tungsten-uranium-mononitride CERMET fuel fabricated to a hexagonal cross section. The core was comprised of lattices of the W-UN fuel elements, each consisting of 37 W-25Re clad fuel channels of varying radii depending on the power level. The spacecraft was shielded by the combination of a geometric attenuation distance and a segmented tungsten, LiH, B_4C shield, such that the dose never exceeds 15 rem/year. A single shaft brayton engine with no recuperators or regenerators was selected as the power conversion technology using a helium coolant with turbine inlet temperatures ranging from 1300 K to 1500 K. A carbon reinforced heat pipe radiator was selected as the prime candidate for excess heat rejection and an areal mass density of 4.5 kg/kW_e was assumed. The reactor specific mass was determined to range from 9.5 kg/kW_e to 32 kg/kW_e at electrical powers ranging from 1 MW to 100 MW and turbine inlet temperatures ranging from 1300 K to 1500 K. Previous studies have shown that for NEP rockets to compete with NTP and chemical rocket engines a power system specific mass of 5 kg/kW_e may be required. Based on the results of this study it may not be feasible based on current technology to build NEP engines for robust manned space transportation with current technology. However, future research into ultra high temperature Brayton engines or MHD energy conversion, may vastly decrease the system net mass and allow the achievement of a 5 kg/kW_e specific power at some time in the future, but this will likely involve a substantial financial and technical investment.

NOMENCLATURE

α = specific mass (kg/kW$_e$)
ε = emissivity
σ = Stefan-Boltzman constant (5.669 x 10^{-8} W/m^{2}K^4)
A = surface area (m^2)
M = mass (kg)
P = Power (MW)
T = temperature (K)

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