# THERMOPHOTOVOLTAICS FOR IN-SPACE NUCLEAR POWER

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## ABSTRACT

In-space nuclear fission power systems are under consideration for missions that require MWe scale power. Recent work in Thermophotovoltaic (TPV) cells indicates that they may be a mass efficient option for converting a nuclear reactor's thermal energy into electrical energy. This paper reviews literature on the history of in-space TPV and trades TPV against a Brayton Cycle in the context of a conceptual Earth-to-Mars transportation system. The selection of the heat engine primarily impacts the design of the nuclear reactor, power system, and thermal system, so the impact to these subsystems is considered. The electrical power output per mass is compared between these two alternatives, and qualitative differences are discussed.

## TPV PAST AND PRESENT

TPV cells are photovoltaic cells that convert infrared light into electrical energy. They were first invented in the early 1960s, and their in-space applications were considered at least as early as 1970.[1] More recently, radioisotope TPV (RTPV) has become viewed as the clear choice to produce a higher specific power than the incumbent radioisotope thermoelectric generator (RTG) technology for <1 kWe systems.[2][3] NASA issued contracts for RTPV development in 2003, and tests combined with modelling indicated that an RTPV system (at 20% efficiency) would indeed have greater specific power (16 W/kg) than alternative radioisotope power systems (<4 W/kg) even when radiator mass is included.[4] TPV efficiencies have improved since those tests were conducted. Recent developments have increased TPV efficiency to as high as 40% with a ~2400 K emitter and a 300 K cell, and researchers see a plausible path forward (higher substrate reflectivity with an "air bridge" approach) to efficiencies as high as 56% at emitter temperatures of ~2500 K.[5] Modelling estimates the 40% efficient TPV would become 27% efficient if the cell temperature were changed to 600 K to accommodate a high temperature radiator. High emitter temperatures were a crucial feature for the improved efficiency, and these temperatures are most easily obtained with the use of a nuclear reactor.[5] It's notable that a 2500 K gray body emitter radiates at an areal power density that is ~1,300 times greater than the solar flux at 1 AU, so TPV do not need as much surface area as solar arrays when TPV is used with a high temperature heat source.

TPV's application in high-power systems (like nuclear fission) has been in question primarily due to two challenges that face its implementation.[3][4] First, TPV efficiency decreases as cell temperature increases (Figure 1) while radiator mass and area decrease with increasing temperature.  This dilemma forces a compromise that results in suboptimal TPV efficiencies and larger radiators. This challenge also exists for Brayton systems, but historically TPV has traded unfavorably versus Brayton systems for high-power, nuclear fission applications. Second, the radiation tolerance of TPV is not well characterized for the radiation environment present near a nuclear fission reactor.[2] However, it is notable that TPV has been stress tested with Cm-244 for over 120 days and data indicates the neutron damage in a low-power radioisotope environment would result in less than 1% degradation per year of operation.[3] Radiation testing at neutron and gamma ray fluxes characteristic of a shielded fission reactor are necessary to understand TPV's resilience to this environment.

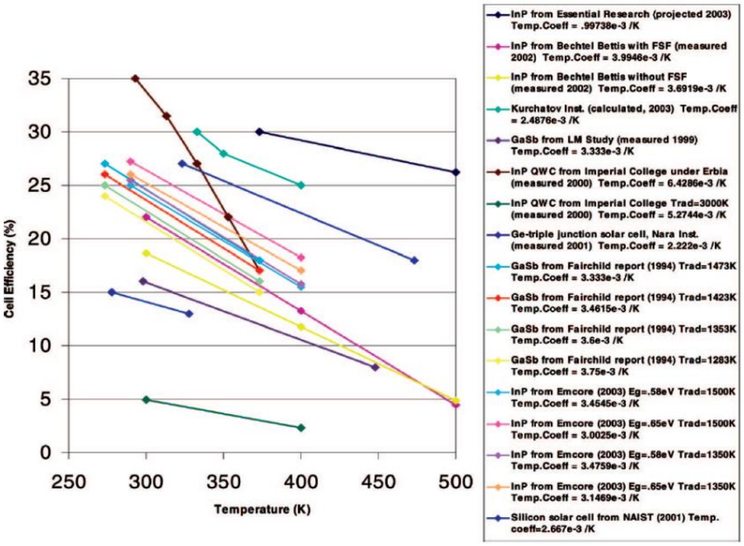

*Figure 1: Cell efficiency vs cell temperature*[2] *Note: The variation in cell efficiency is due to variation in cell designs as well as variation in emitter temperature (Trad, which is the hot-side temperature for TPV).*

The first challenge, TPV cell efficiency, is a function of quantum efficiency (QE), the photon overexcitation factor ($F_0$), bandgap ($E_g$), open circuit voltage ($V_{oc}$), fill factor (FF), cold-side, cell temperature ($T_c$), and hot-side, emitter temperature ($T_h$) as described by Equations ( 1 and ( 2. Together, these equations describe how cell efficiency decreases as cell temperature increases, and cell efficiency increases as emitter temperature increases (with all else equal). Please note that some of the variables are a function of temperature and these equations assume the cell's short circuit current is greater than its dark current.

$$\eta_{cell} = QEF_0 \frac{V_{oc}}{E_g} FF \tag{1}$$

$$\frac{V_{oc}}{E_g} = 1 - \frac{T_c}{T_h} + \frac{kT}{E_g} \ln\left[\frac{T_h}{T_c}\right] \tag{2}$$

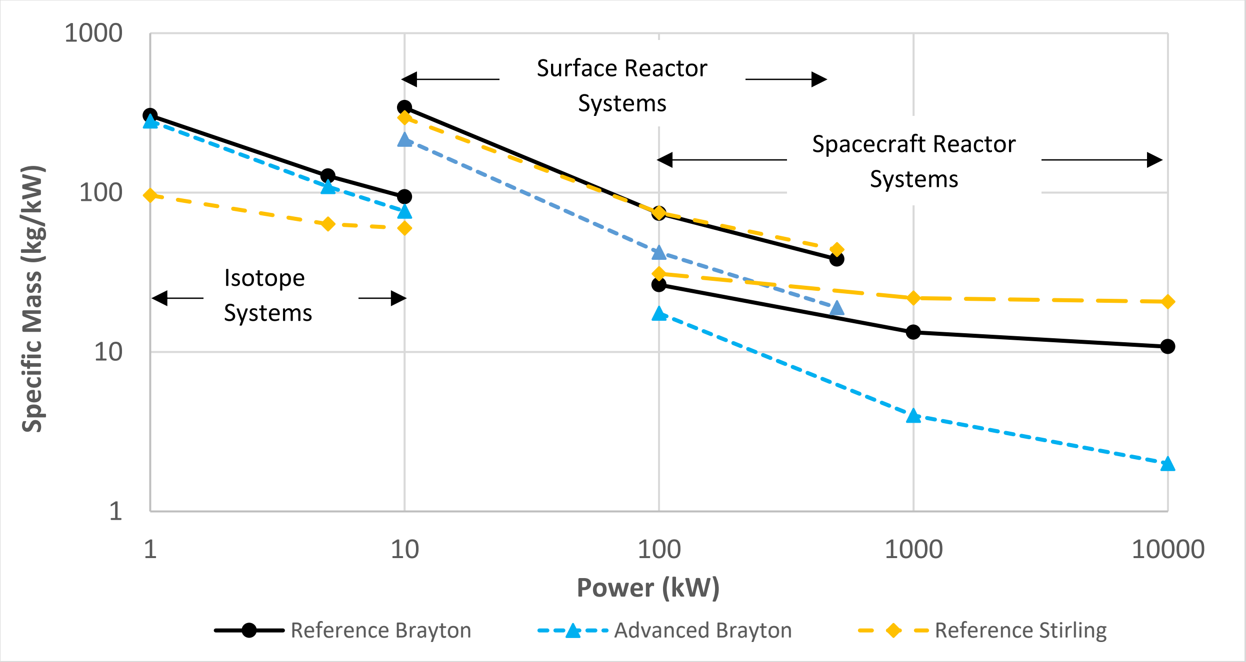

*Figure 2: Heat Engine Performance versus power and application[6]*

Recent developments in TPV have demonstrated efficiencies above 40% which is significantly higher than other solid state heat engine alternatives.[5] High efficiencies were obtained by combining several features that are known to improve TPV efficiency including: high-performance multi-junction architectures with bandgap tunability enabled by high-quality metamorphic epitaxy and the integration of a highly reflective back surface reflector (BSR) for band-edge filtering.[5] These developments has stimulated some interest and curiosity about whether high-temperature, high-efficiency TPVs could improve in-space nuclear power systems. In-space applications will require higher cell temperatures, and models indicate that this TPV system would have an efficiency of around 27% with an emitter temperature of 2673 K and a cell temperature of 600 K. It is necessary to compare TPV performance against alternative heat engines to answer this question. Brayton systems are typically baselined for NEP systems, because they are considered to have greater technical maturity and reduced complexity than Rankine systems, and Brayton systems offer greater mass efficiency than Stirling at MWe power levels as shown in Figure 2.[6] Therefore, a brief overview of in-space Brayton technology is discussed next.

## BRAYTON ENGINES PAST AND PRESENT

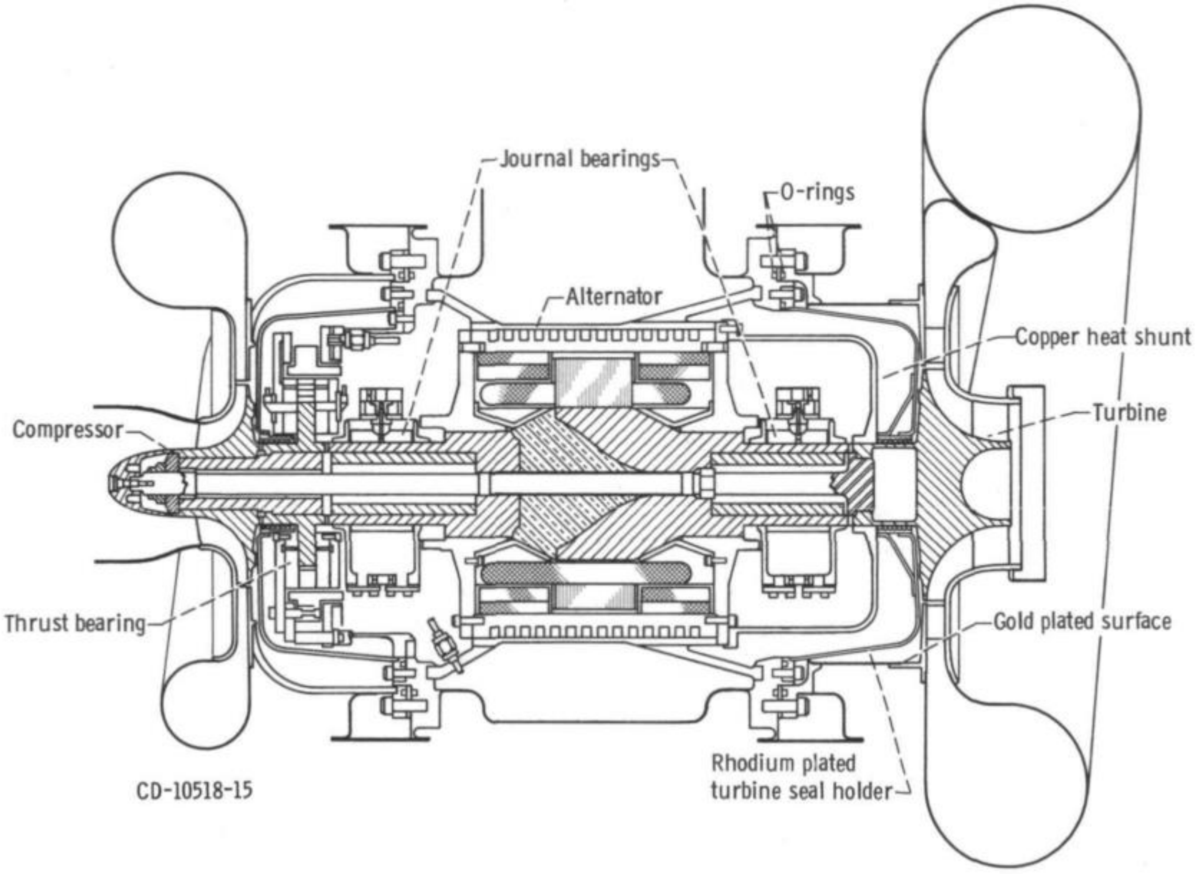

*Figure 3: Brayton Rotating Unit (BRU)* [7]

The history and evolution of Brayton power conversion systems is covered by several sources.[6][7][8] NASA's Brayton Rotating Unit (BRU) Project developed the first Brayton technology for space applications in the 1960s as part of the in-space nuclear power push during that time. Early BRU designs used an 83.8 molecular weight (MW) He-Xe mixture (to have similar fluid properties as Krypton) and produced 10 kWe at 35 krpm with a turbine inlet temperature of 1144 K and a compressor inlet temperature of 540 K.[7] The efficiency of these early BRUs reached up to 32% with a 65 kg BRU and a 95% effective, 200 kg Brayton Heat Exchanger Unit (BHXU). These BRUs were extensively endurance tested. In total, the BRUs were operated for approximately 50,000 hr to demonstrate their reliability and long life.[8] The follow-on Mini-BRU Project lasted from 1974 to 1978 to develop high-efficiency BRUs at lower power levels (500 to 2100 W). The Mini-BRU was baselined in the Department of Energy's (DOE) 1.3 kWe Brayton Isotope Power System (BIPS).

Brayton technology was again developed for in-space use in the 1980s to turn concentrated solar energy into electricity on NASA's Space Station Freedom (SSF).[8] The system was designed to produce 36 kWe with a turbine inlet temperature of 1034 K and a compressor inlet temperature of 338 K with a 40 MW He-Xe mixture. The turboalternator was designed to spin at 32 krpm. Designs were completed, but flight hardware was not fabricated for SSF. Ground tests were completed and demonstrated the feasibility of the system. A flight unit was developed for use on the Mir space station in the 90s, but it never flew.

In the 2000s, NASA again showed interest in Brayton nuclear systems. This time it was for a science mission, Jupiter Icy Moons Orbiter (JIMO), to explore three of Jupiter's moons. The primary science target was Europa, where a sub-ice ocean of liquid water could potentially contain life. The Brayton nuclear power system was expected to produce 200 kWe of power, but JIMO was cancelled. Before cancellation, a 2 kWe Brayton Power Conversion Unit (BPCU) technology development system was tested and provided 1100 VDC to drive an ion electric thruster.[8]

During the 2020s the Fission Surface Power (FSP) project considered a Brayton system but concluded a Stirling engine is superior (in terms of mass and TRL) for both the Lunar or Martian 10 & 20 kWe systems, and the Kilopower project also developed a Stirling engine instead of a Brayton engine for tests they conducted in 2018.[9][10] The Kilopower and FSP decisions are consistent with work that indicates Brayton engines are superior to Stirling engines at NEP power levels as shown previously in Figure 2. Interest in Brayton engines remains strong today for high power systems like Nuclear Electric Propulsion (NEP).

## COMPARING TPV TO A BRAYTON FOR NEP

A NEP element consisting of a nuclear reactor, power conversion system, telescoping truss structure, Hall propulsion system, bus power system, avionics system, and thermal system was considered in a preliminary Advanced Concepts Office (ACO) internal study. The master equipment list (MEL) from this study was used as the basis for comparing a TPV heat engine with a Brayton heat engine.

The mass efficiency of the NEP Reactor-Power-Thermal (RPT) subsystems are largely driven by their operational temperatures. The heat engine’s power conversion efficiency increases as the reactor temperature increases and decreases as the radiator temperature increases. The radiator’s area and mass decrease as its radiating temperature increases. For the Brayton NEP, the reactor maximum temperature was limited by the perceived maximum operational temperature of the Brayton’s turbomachinery (1400 K), and the radiator inlet and outlet temperatures (605 - 460 K) were selected to minimize the mass of the interdependent RPT subsystems and provide a cooling flow to the alternator.

TPV does not have the same temperature limit as the Brayton heat engine. It has efficiently operated at emitter (analogous to Brayton turbine inlet) temperatures of 2673 K.[1] The reactor temperature can operate at these temperatures for the required 25,000 hours. However, the TPV cell diodes leak current at higher cell temperatures, so the radiator cannot substantially increase in temperature. A mathematical simulation of the TPV reported in Nature indicates that its efficiency would be around 27% with an emitter temperature of 2673 K and a cell temperature of 600 K.[1] Therefore, these state and performance metrics were used in the analysis of the TPV system.

TPV has some qualitative advantages and disadvantages when compared with Brayton engines. These advantages include: 1) easier to implement artificial gravity due to significantly less rotational inertia in the power system, 2) small, flexible, modular TPV cells enable different form factors and potentially easier integration with Nuclear Thermal Propulsion (NTP) systems, 3) manufacture of these cells can begin immediately, and 4) scaling TPV systems to new and changing power level requirements is relatively easy. The primary qualitative disadvantage of TPV when compared to a Brayton engine is that it requires higher reactor temperatures to obtain similar efficiencies.

### Power System

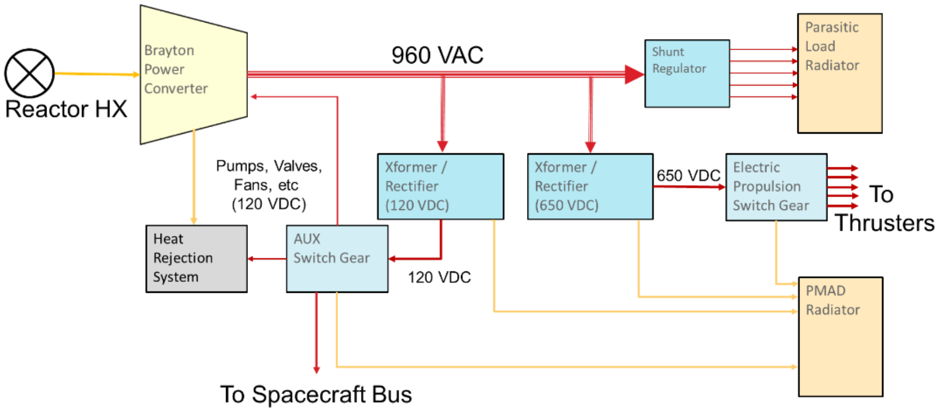

*Figure 4: Brayton NEP power system configuration*

First, we will consider the Brayton NEP power system. Figure 4 illustrates the configuration of a Brayton power system for a 3.1 MWe nuclear electric vehicle. There are 4 separate Brayton power units on the vehicle, each with its own Power Management and Distribution (PMAD) system. Each unit can produce 788 kWe to power (7) 100 kW Hall thrusters along with auxiliary spacecraft loads. Thus the 4 units together can power 28 thrusters at max power.

The 4 Brayton power units are connected to a common 10 MWt reactor supplying heat through a molten Lithium fluid loop. These 4 units are also connected to a common Heat Rejection System, which cools the Brayton working fluid after the useable power is extracted from it. The Brayton engine is designed to run at a particular, pre-determined speed (e.g. 36 krpm). Its main mechanical load is the alternator rotor, which is rotated against the force of the magnetic field generated by current flowing to the Brayton's electrical load. When that load changes quickly – say because one of the thrusters is turned off – the mechanical load on the alternator will drop quickly as well. This will cause the turbine, compressor and alternator assembly to speed up dramatically. To avoid that (and precisely control the shaft speed), the shunt regulator senses the change in the electrical load, and switches in additional parasitic loads in parallel with the operational loads to keep the overall power load the same. These parasitic loads are embedded in the parasitic load radiator, a carbon-carbon radiator operating at 1000 – 1200 K to radiate the excess power to space.

The alternator generates 788 kWe at 960 VAC. A transformer rectifier unit (TRU) converts this 960 VAC to 650 VDC for the Hall thrusters. Another TRU converts the 960 VAC to 120 VDC to power the auxiliary spacecraft loads.

The size and performance of the Brayton power units were estimated using physics-based tools. Each component of the power unit is modelled individually and integrated with a component-based design tool. The component models were derived from "Power Management and Distribution (PMAD) Model Development" final report.[14]

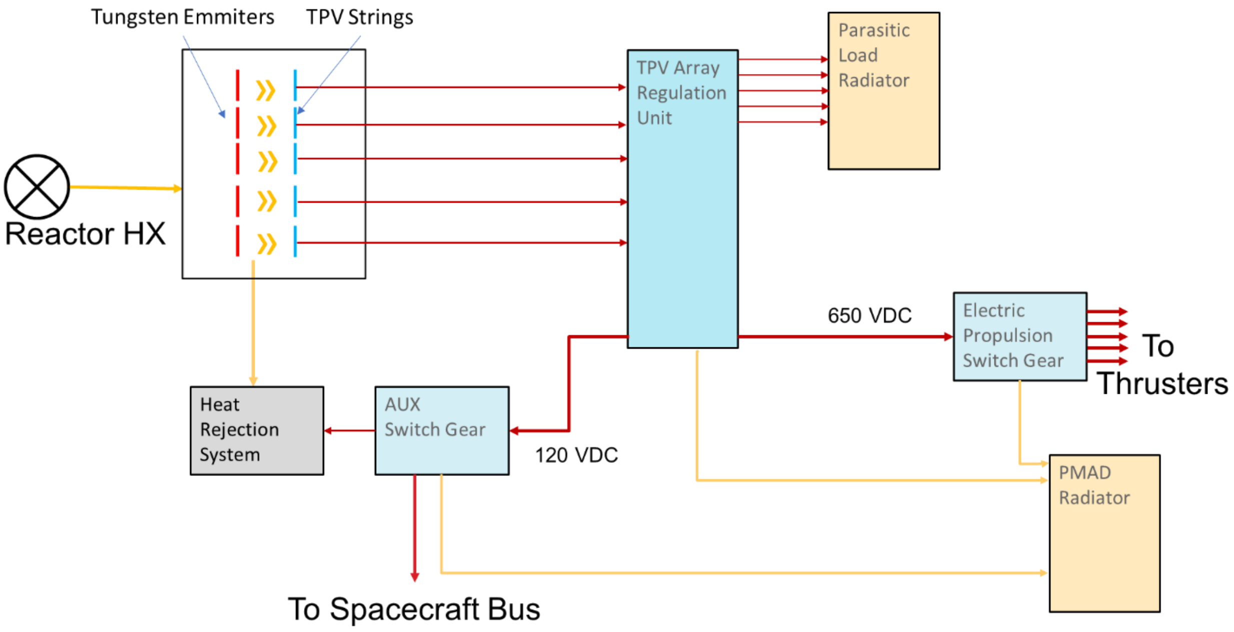

*Figure 5: TPV NEP power system configuration*

Now we will consider the TPV NEP power system. Figure 5 illustrates the same 3.1 MWe NEP vehicle (28 100kW Hall Thrusters) powered by a nuclear TPV power system. In this configuration, 1,050 small, rectangular channels extract electrical power from the thermal radiation of a much hotter 10 MWt reactor. Each channel has 4 thin tungsten emitters heated to 2673 K by the fission reaction. When heated, the emitters radiate light in the long-wave visible and infrared spectrum to immediately adjacent TPV cells. The cells convert the irradiance into electric power (27% conversion efficiency). Cooling fluid is run along the cell's other side to cool the TPV cells and wiring.

The TPV cells are connected in series into strings. Each string is essentially a current source – that is, it produces a specific current that depends on the irradiance. The voltage of the string depends on the resistance of the load. Both the Hall thrusters and the spacecraft loads require a constant voltage source (650VDC and 120VDC respectively). The TPV Array Regulation Unit (ARU) converts and regulates the TPV output to provide the required constant voltages. It does this by switching needed TPV strings to the loads while switching unneeded strings to elements of the parasitic load radiator which converts the power switched to it into heat and radiates that heat to space.

Each of the 2 output power busses – 120 VDC and 650 VDC – are distributed to the loads using a switchgear. Heat from power regulation and switching losses is rejected via the PMAD radiator.

The total power system predicted mass decreases by 4 mT if TPV cells are used instead of a Brayton, but the lower TPV efficiency results in a lower electrical power output.

## Nuclear System

### *Background*

NASA has considered a variety of fission reactor designs for NEP applications over the years, due to their ability to operate in the absence of sunlight, as well as their high power density potential. For the purposes of this report, the NEP-Chem vehicle architecture from an in-house design study by the ACO in late 2021 through early 2022, will be considered. The ACO study focused specifically on the NEP element of the NEP-Chem vehicle architecture, with the following ground rules and assumptions (GR&A):

- Design for a crewed, short-stay (opposition-class) Mars mission
- Use a 1400 K, HALEU (High-Assay, Low-Enriched Uranium) $UO_2$-fueled, Lithium heat pipe reactor
- Use a Brayton cycle power conversion system with a He-Xe working fluid
- Assume two electric propulsion (EP) thruster types for consideration:
  - 100-kW Xenon Hall thruster
  - 1-MW Lithium Magnetoplasmadynamic (MPD) thrusters.

While the GR&A provide a broad-based set of expectations for the design of the reactor and power conversion elements, some reactor-specific assumptions were also implemented, also based on the COMPASS team study.[11] These assumptions are highlighted due to their immediate relevance to the TPV implementation in the reactor element:

- The nuclear startup power was not to exceed 2.5 kW for more than 1 hour
- The baseline case features a HALEU (19.75% enrichment) reactor with a pumped lithium heat transport interface and refractory materials in the cladding/structural elements.
- The reactor heat exchange system includes multiple heat exchangers that transfer thermal energy from the Lithium loop to the HeXe heat exchangers, that in turn serve the individual Brayton power converters.
- Reference shadow shield featured a LiH/W composite, with 25krad at the payload point (assuming a 50m payload) separation after 2 years at full power.

### Methodology

Implementing a TPV system in place of the Brayton power conversion subelements can occur in a variety of configurations. Two candidates considered for the scope of this report are:

- Attaching TPV components to an internal shield covering the reactor
- Attaching TPV components to heat pipe or equivalent thermal energy conduits (pumped metal, other working fluids) that extend from the reactor, through the shadow shield

Estimating the impact on the reactor architecture when changing to TPV systems will primarily focus on the shielding requirements, and the changes in shielding mass needed to accommodate the TPV system.

A basic shielding estimation change is obtained using composite shield mass equations that are part of an in-house ACO software modeling code developed in 2017, in turn derived from the Space Propulsion Analysis and Design handbook and adjusted for NEP-scale flux considerations and operating temperatures.[12] Because of the limitations in shield estimates using this method, a more detailed radiation analysis was performed, and will be provided in a concurrently published report.[13]

### Results

The initial estimate for the additional shielding mass needed to accommodate the first TPV housing option is approximately a minimum addition of 532.8 kg to the reactor assembly assuming a LiH/W composite shield configuration. This includes a 30% mass margin for the shielding components and structural attachments. Although this adds a statistically significant mass to the NEP element, it is minor in comparison to the reported NEP shadow shielding estimate of ~3500 kg for the baseline NEP reactor configuration.[11]

With the second option, the pre-existing shadow shield would stand as a starting point for the radiation shielding required for the TPV. However, the final dose rate that the TPV system would experience is dependent upon the design of the heat transfer system used to transfer energy to the TPV assembly. The anticipated radiation dose for the power conversion system can be expected to range from 10-6000 rad/hr, depending on positioning of the TPV system outside the shadow shield.[11] Assuming a conservative estimate with regards to the TPV positioning, the aforementioned 532.8 kg mass would serve as the upper bound for the estimated TPV shielding mass needed.

Some of the limitations with this analysis approach arise from the models being used to evaluate the shielding requirements. The ACO in-house modeling system used, does not factor a more in-depth, 3-dimensional analysis of the neutron and gamma flux fields and ways to optimize shielding configurations. Additionally, shielding compositions may need to be updated to reflect newer assessments on the radiation shield trade space in terms of material composition, long term performance, and ease of manufacturability. As mentioned before, the concurrently published report provides a more detailed analysis of the estimated required shielding mass for protecting a TPV system.[13]

## Thermal System

The NEP element converts reactor thermal energy into electrical power and radiates all waste heat to space. The thermal subsystem is responsible for moving heat through the power system as well as maintaining temperatures for power electronics and propulsion hardware (valves, drive electronics, tanks, and feed lines). The thermal subsystem includes heat pipes, fluid loops, heat exchangers, and radiators, but the most massive element of the thermal subsystem is the radiator that removes waste heat from the heat engine, and it was impacted by this trade. The area required for this radiator is defined by equation ( 3 ) where $Q_{waste}$ is the waste heat that must be removed from the heat engine, $\varepsilon$ is the radiator's emissivity, $\sigma$ is the Stefan-Boltzmann constant, $T_{rad}$ is the radiator temperature, $T_{space}$ is the cosmic microwave background temperature, and $\phi_{solar}$ is the worst case solar flux, $\alpha$ is the radiator's absorptivity, and $A_f$ is the ratio of the radiator's sunlit projected area to the radiators total area.

$$A = \frac{Q_{waste}}{\varepsilon\sigma\left(T_{rad}^4 - T_{space}^4\right) - A_f \alpha \phi_{solar}} \qquad (3)$$

The radiator's surface area increases as more waste heat is produced, and the TPV's lower efficiency results in more waste heat and a larger radiator. Therefore, the radiator area and mass increase for the TPV case by approximately 22%.

## RESULTS AND CONCLUSIONS

A NEP element consisting of a nuclear reactor, power conversion system, telescoping truss structure, Hall propulsion system, bus power system, avionics system, and thermal system was considered by an ACO internal study. The MEL generated by this study was modified to account for the changes necessary to switch from a Brayton to a TPV power conversion system. The predicted mass and electrical power output of both NEP elements were calculated. The electrical power divided by the system dry mass for the NEP element that used TPV was ~12% lower than the NEP element that used a Brayton power conversion system which implies a lower acceleration and performance is achievable when using the TPV assumed in this comparison. The TPV cells we considered were highly optimized cells for a high emitter temperature but were never intended to operate at the high cell temperatures required by a NEP element. It is possible that TPV cells designed for our specific application (600 K cell temperatures in particular) could perform better than the cells developed by NREL and MIT for other applications.[5] ACO plans to do a more detailed Brayton versus TPV trade in the future.

In contrast with this apparent performance disadvantage, TPV has more qualitative advantages than disadvantages when compared with Brayton engines. These advantages include: 1) easier to implement artificial gravity due to significantly less rotational inertia in the power system, 2) small, flexible, modular TPV cells enable different form factors and potentially easier integration with Nuclear Thermal Propulsion (NTP) systems, 3) manufacture of these cells can begin immediately, and 4) scaling TPV systems to new and changing power level requirements is relatively easy. The primary qualitative disadvantage of TPV when compared to a Brayton engine is that it requires higher reactor temperatures to obtain similar efficiencies.

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