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NUCLEAR POWER CONCEPTS FOR HIGH-POWER ELECTRIC PROPULSION MISSIONS TO MARS

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Under the Mars Transportation Assessment Study, NASA and DOE are performing analyses and generating concepts for crewed Nuclear Electric Propulsion (NEP) missions to Mars. This paper presents the results of trade studies and concept development for the nuclear electric power system, consisting of the fission reactor, radiation shielding, power conversion, heat rejection and power management & distribution (PMAD). The nuclear power team completed trade studies to evaluate different reactor and power conversion technologies and developed preliminary concepts for the crew shielding, waste heat radiators, and PMAD. The initial results suggest that a modified terrestrial microreactor combined with supercritical CO_2 *Brayton conversion could be used to perform the crew and cargo missions with satisfactory performance and modest risk.*

I. MARS NEP MISSION CONCEPT

Mission studies conducted by the Glenn Research Center (GRC) COMPASS Team identified the need for a 1.9 MWe power system to perform a 2-year round-trip crewed mission to Mars using a hybrid NEP/chemical propulsion architecture, as shown in Figure 1. The COMPASS studies evaluated multiple crewed mission opportunities spanning 2035 to 2042 that utilize a Low Earth Orbit (LEO) aggregation orbit, un-crewed LEO-to-Near Rectilinear Halo Orbit (NRHO) spiral where the NEP vehicle rendezvouses with the deep-space crew habitat, and 760-day opposition-type round-trip mission that includes a 30-day Mars stay. Additional mission analysis indicated that a duplicate NEP stage, using the same 1.9 MWe nuclear power system and EP thrusters but without the chemical propulsion, could perform pre-crew cargo missions delivering payloads of about 200t to Mars after a LEO spiral and 535-day one-way Mars trip.

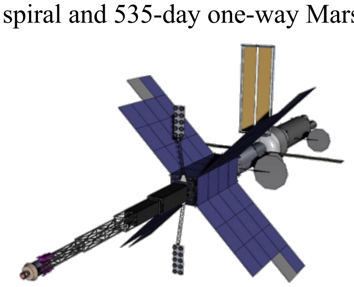

Fig. 1. Hybrid NEP/Chem Vehicle Concept

II. POWER SYSTEM CONCEPT

The reactor cooling method and power conversion choice is a major influence on system design and reliability. Figure 2 presents examples of the design space for reactor heat transfer and power conversion in nuclear fission systems. The three major primary heat transfer methods for space reactors are heat pipes, pumped liquid metal, and pumped gas. Heat pipes work on a passive two-phase evaporation/condensation cycle that requires no external power, while liquid metal or gas cooling requires drive pumps or compressors to circulate the fluid. The benefit of active cooling over passive heat pipes is flexibility in design and higher thermal throughput. Typical liquid metals used in pumped cooling loops are lithium, sodium, potassium, or a mixture of sodium and potassium (NaK). Gas-cooled systems have the option of directly coupling to a Brayton converter, simplifying the reactor heat transport. However, this leads to a single shared gas circuit for the reactor and power conversion, which impacts the system fault tolerance.

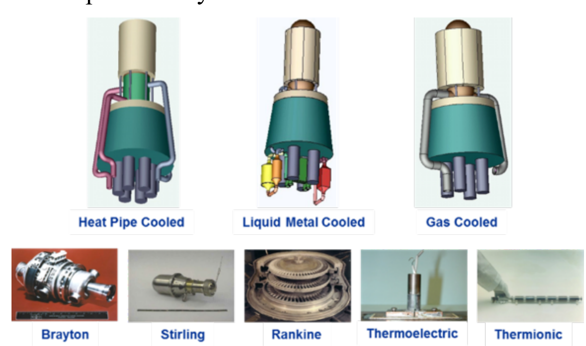

Fig. 2. Potential Reactor-Power Conversion Options

Among the power conversion options are Stirling, Brayton, and Rankine thermodynamic cycles, as well as thermoelectric and thermionic devices. Each option presents different characteristics on conversion efficiency and power throughput, and therefore on the system mass. On the low end of the efficiency scale, thermoelectric conversion has a long history of use in radioisotope power systems. However, the lower efficiency is a challenge for high power fission systems due to the larger reactor, radiation shield, and waste heat radiator. The Stirling cycle has high efficiency but does not scale well to higher power. HeXe Brayton systems fair better at higher power but the lower heat rejection temperature results in a larger radiator. A supercritical CO_2 (or perhaps other supercritical working fluid) Brayton system may perform better than the HeXe system but that technology has been mainly focused on terrestrial applications. A potassium Rankine cycle has the potential for high efficiency and heat rejection temperature, but the two-phase system design is a challenge and the maturity is low.

Rejecting the power conversion waste heat represents a major design challenge. The vacuum of space requires radiative heat rejection, which is dependent on large, bulky radiators. In fact, the limiting design factor for the reactor power system in this study was the stowed radiator volume that could be accommodated in a single launch vehicle. Preliminary radiator stowage concepts have indicated a maximum radiator area of approximately 2500 m^2 for the 8.4 m Space Launch System (SLS) fairing. The 2500 m^2 radiator limit proved to be the primary design constraint in determining the maximum NEP power output.

Figure 3 shows a parametric analysis of radiator area and system mass across a range of relevant power levels for three different reactor-Brayton combinations. System mass includes the reactor, shield, power conversion, heat rejection and PMAD. Given the 2500 m^2 SLS radiator limit, the 1200 K HeXe case (A) permits 1.6 MWe maximum power output, the 1200 K SCO_2 case (B) permits 1.9 MWe, and the 1500 K HeXe case (C) permits 2.9 MWe. The 1200 K SCO_2 case was selected as the study reference, supplying 1.9 MWe with a total system mass under 25 MT. While the 1500 K case may appear attractive from a performance standpoint, it introduces considerable development risk relative to the other two cases. The 1500 K reactor would require a new fuel form and refractory alloy cladding/structural material beyond what was demonstrated during the SP-100 Program. It would also require new higher-temperature materials for the Brayton converters and radiators beyond the current experience base for those technologies.

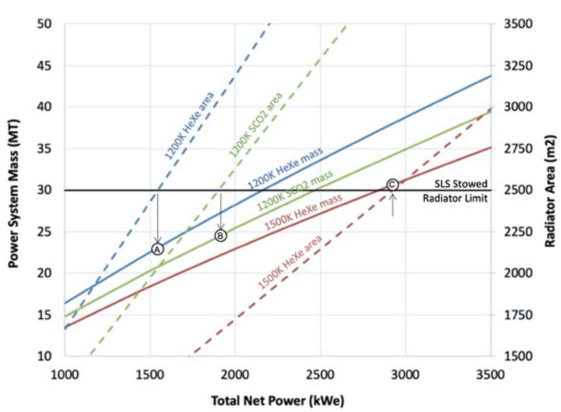

Fig. 3. Parametric System Analysis

II.A. Reactor and Shield Subsystems

The reactor concept in the parametric analysis above assumed a fast-neutron spectrum core with pin-type refractory-clad fuel using Highly Enriched Uranium (HEU). The DOE's Oak Ridge National Laboratory (ORNL) was added to the team to evaluate different reactor design options and fuel enrichment levels. They evaluated two reactor concepts: a) a fast-spectrum SP-100 derived system using UN pin fuel with pumped Li primary heat transport, and b) a derivative of the Transformational Challenge Reactor (TCR) using UN particle fuel in a solid SiC element with interspersed YH moderator. The TCR derivative could use either direct Brayton gas cooling or the primary Li loop, although the Li option was the preferred configuration for this study based on overall system reliability. Both the SP-100 and TCR reactor approaches were evaluated with HEU (93% enrichment) and High-Assay Low Enriched Uranium (HA-LEU, 19.75% enrichment).

The ORNL reactor study assumed a thermal power of 10 MWt, coolant outlet temperature of 1200 K, and operational life of two years at full power. The results showed the SP-100 HEU option to be the lightest mass reactor at approximately 2400 kg including fuel, vessel, reflector, instrumentation & control, and Li primary loop. The LEU version of the fast-spectrum SP-100 reactor was found to be prohibitively heavy. The HEU TCR option with YH moderator had a similar reactor mass as the fast-spectrum HEU SP-100, but the larger reactor diameter resulted a 70% increase in shield mass. The mass of the LEU TCR reactor with YH moderator was about twice the HEU version at 4800 kg and required the heaviest shield because of the large reactor diameter. However, the total 3500 kg mass increase (including the shield) for the LEU TCR option relative to the HEU SP-100 option did not significantly impact the mission design. The LEU TCR reactor shown in Figure 4 was selected as the reference approach for the mission study, with the HEU SP-100 as the study alternative. The 10 MWt thermal power rating provides approximately 40% thermal power margin at 1.9 MWe.

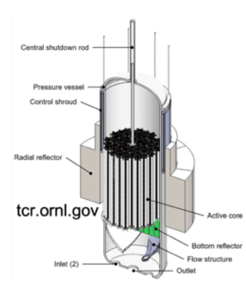

Fig. 4. TCR-Derivative Reactor Concept for NEP

A key challenge for the reactor is to shield the mixed neutron and gamma radiation field. The amount of radiation is directly correlated to the thermal power and operating duration of the reactor, which adds an additional motivation for high power conversion efficiency. The need for shielding is driven by both electronic and materials tolerance as well as human dose limits for crewed missions. Low-atomic-number materials like hydrogen, beryllium, lithium, and boron provide efficient shielding for the neutron flux, while high-atomic-number materials like tungsten or depleted uranium effectively shield the gamma flux.

For this study, ORNL compared several design variants for their effectiveness in attenuating radiation at three key locations: a) the Brayton units, b) the PMAD electronics, and c) the crew habitat. The starting point was a conical LiH/W shield with a 26 deg half angle that limited radiation to 25 krad and 10^{11} n/cm^2 at 50 m from the reactor (at the PMAD electronics) after two years of reactor operation. Further analysis revealed that this shield design was not sufficient for the crew habitat. Figure 5 presents the four shield configurations evaluated by ORNL. The LiH/W starting point assumed a constant shield thickness for the entire 26 deg half angle. The two compound shields assumed a thicker central section, or “plug” for increased protection of the vehicle centerline elements and crew habitat (within a 3 deg half angle). One of the compound shields assumed a combination of Be/B_4C/LiH/W, while the other assumed only LiH/W. The fourth shield option used LiH/W and retained the central plug but included cutouts in the perimeter to form a cruciform with four 26 deg extensions corresponding with the location of the radiator wings.

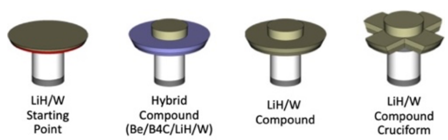

Fig. 5. Shield Options Evaluated

The desire to limit radiation at the crew habitat to 50 rem/yr became the driving requirement for shield mass. The ORNL analysis incorporated the benefits provided by the in-line Brayton engines, reactor boom, PMAD equipment, Xe propellant and tanks in attenuating crew radiation. The mass comparison among the four configurations revealed that the full-thickness LiH/W shield was the heaviest at 13800 kg, followed by the hybrid compound at 4800 kg, the LiH/W compound at 3500 kg and the LiH/W compound cruciform at 2800 kg. The compound cruciform was selected as the design reference, and the corresponding radiation flux maps are presented in Figure 6. This shield results in a total absorbed gamma dose at the Brayton converters and PMAD electronics after two years of operation of 100 Mrad and 25 krad, respectively. The effective human dose at the forward external face of the crew habitat is 3 mrem/hr, corresponding to 100 rem in two years. The total mass of the reference HA-LEU reactor and crew-rated radiation shield is about 7600 kg. The equivalent HEU-version is about 4100 kg.

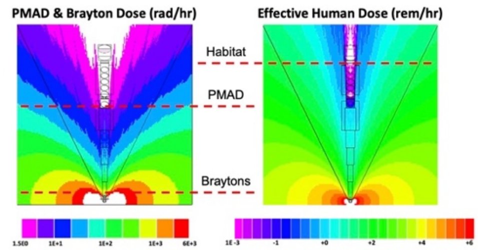

Fig. 6. Radiation Map for Compound Cruciform Shield

II.B. Power Conversion Subsystem

The power conversion trades comparing HeXe and Supercritical CO_2 Brayton favored the SCO_2 option. The SCO_2 option yielded a ~20% increase in power output for the same total radiator area. The reference 1.9 MWe power system concept assumes four SCO_2 Brayton converters each producing 25% of the total power, shown in Figure 7 coupled to the Li-cooled reactor through four liquid-to-gas heat exchangers. The use of a primary loop with separate HXs permits the system to produce partial power should one or more Brayton units fail. Each Brayton unit includes a turboalternator-compressor, recuperator, and gas cooler. The development of a ~500 kWe-class Brayton unit represents a significant scale-up from the experience base for HeXe Brayton technology, represented by the 10 kWe Brayton Rotating Unit (BRU), the 2 kWe mini-BRU, the 36 kWe converter for the Space Station Freedom Solar Dynamic Power Module, and the 100 kWe converter for the Prometheus/Jupiter Icy Moons Orbiter mission. Legacy HeXe Brayton technology, with superalloy hot-side materials that permit turbine inlet temperatures up to 1150 K, has undergone considerable NASA testing to demonstrate performance in relevant environments and for extended operating times (e.g., ~50,000 hours of BRU testing).

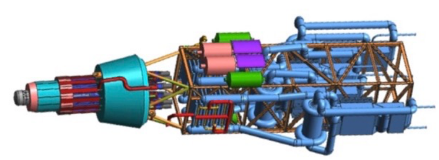

Fig. 7. NEP Reactor-Brayton Configuration

Conversely, SCO_2 Brayton development has focused on MWe-class power levels but has been mostly limited to terrestrial applications with systems that are not designed for space use. If SCO_2 Brayton is pursued for Mars NEP, the emphasis will be on adapting high power terrestrial technology and demonstrating performance in relevant environments. If HeXe Brayton is pursued, the emphasis will be on scaling the legacy technology to higher power levels. The four 500-kWe SCO_2 Brayton converters in the reference concept have a total mass of about 2100 kg.

II.C. Heat Rejection Subsystem

The heat rejection subsystem (HRS) assumes each Brayton converter has a dedicated pumped-NaK cooling loop and a one-fourth segment radiator assembly. The NEP radiators would operate at temperatures between 375 and 550 K and reject about 4 MWt. This temperature regime was studied extensively during the Prometheus and Fission Surface Power projects. Technology development was completed on high temperature Ti/H_2O heat pipes (both life testing and microgravity research), polymer-matrix composite (PMC) radiator panels (both sub-scale and full-scale thermal-vacuum tests), and pumped NaK fluid loops (at temperatures up to 875 K). Leveraging those developments, the NEP radiators use PMC panels with embedded Ti/H_2O heat pipes. The 2500 m^2 total NEP radiator surface is comprised of four radiator segments each having 17 individual radiator panels (~4 m x 5 m) that are coupled to the NaK coolant manifold, as shown in Figure 8 (for comparison, the total radiator area for the International Space Station is about 1200 m^2). The total mass of the NEP HRS concept is about 9500 kg with 68 radiator panels at ~100 kg each.

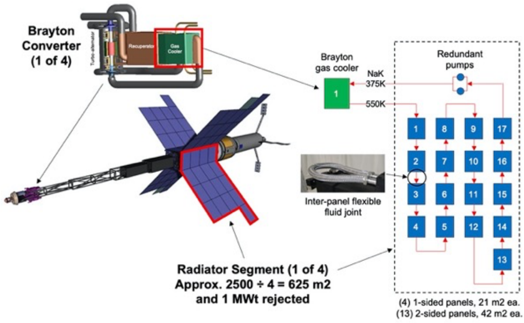

Fig. 8. NEP Radiator Configuration

II.D. PMAD Subsystem

The NEP PMAD electrical schematic is shown in Figure 9. The four Brayton units produce high frequency (~2.5 kHz) 3-phase power at 960 Vac that is transmitted through cables to the PMAD electronics located 50 m away. The power system produces sufficient electric output to power the EP thrusters, spacecraft bus, and system parasitic loads. Each Brayton has a dedicated PMAD channel with a high voltage AC bus that feeds the 650 Vdc Hall thruster direct drive units (DDU) and 120 Vdc spacecraft bus using the appropriate voltage conversion stages. Brayton rotor speed control is accomplished via a pulse-width modulated DC parasitic load radiator (PLR) that maintains a constant load on the alternator. The PLR is sized to reject the entire 500 kWe Brayton output (at 550 deg C) allowing the Brayton units to operate at full power even if there are no external loads. The four PLRs (~30 m^2 each) are located on the perimeter of the truss sections that comprise the reactor boom. The spacecraft receives power from the Brayton units, but also supplies power for startup and control via batteries and solar arrays. Startup power is delivered to a start inverter that allows the Brayton units to be electrically motored. The spacecraft also feeds power to the PMAD controller/processor that manages system operations and distributes DC power to the auxiliary loads (pumps, drive motors, etc.). Each of the four PMAD channels includes a cold plate and dedicated thermal radiator (~20 m^2 each) that rejects 15 kWt (~3%) at 100 deg C. The total PMAD mass for the four channels including cabling, electronics, and thermal management is about 5800 kg.

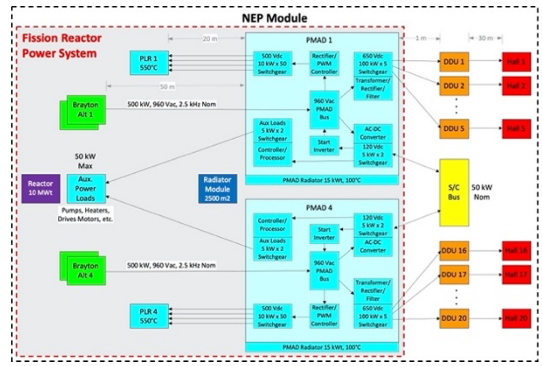

Fig. 9. NEP PMAD Schematic

III. CONCLUSIONS

Trade studies and analyses were performed to produce a nuclear electric power system conceptual design suitable for 1.9 MWe crewed Mars NEP missions. The reference concept uses a modified Li-cooled terrestrial microreactor with HA-LEU fuel, LiH/W crew-rated radiation shield, SCO_2 Brayton power conversion, pumped-NaK heat rejection with composite heat pipe radiators, and 960 Vac PMAD. Key design drivers were the maximum radiator size that could be accommodated in the SLS fairing, the high-voltage EP electrical interface and the crew radiation dose. The reference concept has a total system mass of about 25000 kg (~13 kg/kWe). The use of HEU for the reactor could reduce the system mass by 3500 kg (14%).

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