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High-Energy-Utilization, Dual-Mode System Concept for Mars Missions

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A high-energy-utilization, dual-mode, electric power and propulsion system concept is described for a future crewed missions to Mars. The system uses a gas-cooled, nuclear reactor heat source and closed Brayton cycle (CBC) engines to convert thermal power to electricity. The He–Xe working fluid for the CBCs is also the nuclear reactor coolant. The fuel temperature and the inlet temperatures of the He–Xe of the nuclear reactor core and the CBC engines are kept almost constant during the propulsion and electric power modes to minimize thermal stresses. The temperature of the He–Xe exiting the nuclear reactor core is kept at least 200 K below the maximum fuel temperature. The electric power generated is kept the same during the propulsion and the power modes, but the reactor thermal power in the former could be several times higher. During the propulsion mode, the system's electric power, minus ~ 1–5 kW$_e$ for housekeeping, operates a variable specific impulse magnetoplasma rocket (VASIMR). In addition, the reactor's thermal power, plus more than 85% of the heat load of the CBCs' radiators, is used to heat hydrogen. The hot hydrogen is mixed in the plasma exhaust of the VASIMR to provide both high thrust (>4000 N) and I_{sp} > 45,000 N ·s/kg (~ 4,500 lbf ·s/lbm), potentially reducing the travel time to Mars to 3 months. The system's electric power could also be used to support surface exploration of Mars. A dual-mode system based on the Pellet-bed reactor has a specific energy utilization of 400–500 W/kg and no single point failure. The system can be tested fully assembled in a ground facility using electric heaters in place of the nuclear reactor. Operation and design parameters of a 40-kW$_e$ prototype are presented to illustrate the operation principle and demonstrated performance potential of the dual-mode system concept.

Introduction

TO minimize the exposure of astronauts to space ionizing radiation while in route to Mars, the travel time should be reduced below the 6 months projected using solid core nuclear thermal propulsion systems having a specific impulse $I_{sp} \leq 10{,}000$ N · s/kg (1.0 N · s/kg = 0.09806 lbf · s/lbm). Therefore, future shorter crewed missions to Mars would require using high specific impulse propulsion ($I_{sp} > 30{,}000$ N · s/kg) systems. Such high I_{sp}, however, is not achievable with solid core nuclear reactors and direct hydrogen thermal propulsion (~3000 K) (Refs. 1–3). Although other options such as the gas core and nuclear fusion[4,5] could potentially operate at significantly higher I_{sp} (up to 50,000 N · s/kg), they require major investment and long lead time to develop and demonstrate the technology (>15 years).

A projected crewed mission to Mars in the years 2012-2016 needs to rely on off-the-shelf technologies and those requiring short lead time (<5–10 years) to develop as well as a great deal of engineering innovation in system design and operation. Current consensus among astronauts is to reduce the travel time to Mars to about 3 months, with an access to electric power for housekeeping while in route and on the surface of Mars for exploration and experimentation.

These challenging operation and performance requirements could be met using high-performance plasma thrusters that utilize a large fraction of the thermal and electric power of a nuclear reactor system. A very promising plasma propulsion device for interplanetary exploration missions is the variable specific impulse magnetoplasma rocket (VASIMR).[6,7] This open-ended, rf-heated, mirrorlike plasma device could vary the thrust and the I_{sp} via mixing neutral gas, such as hot hydrogen, in the high-temperature exhaust plasma, providing high thrust for orbit maneuvering and planetary escape, as well as high I_{sp} for shorter travel time. The VASIMR technology could potentially cut travel time to Mars to 96 days. For a 10-MWe VASIMR, having an exhaust nozzle diameter of 10 cm and an efficiency of 60%, injecting hot hydrogen in the plasma exhaust could provide a thrust of 4500–420 N at a specific impulse of 50,000–300,000 N · s/kg, respectively.[8]

Recent analyses of crewed missions to Mars using VASIMR, however, necessitates the development of nuclear reactor power systems with a very high specific electric power of 200–250 W$_e$/kg. To achieve such high specific electric power, the efficiency of converting the reactor's thermal power to electricity would need to be more than 60%. This conversion efficiency far exceeds the capabilities of current energy conversion technology and any projected in the intermediate future. On the other hand, high-energy utilization, including both electric and thermal power, of more than 70% is possible using dual-mode electric power and propulsion nuclear reactor systems.

This paper describes a high-energy-utilization (HEU), dual-mode electric power and propulsion system concept for meeting the aforementioned ambitious performance requirements for shorter (≤3 months) crewed missions to Mars. Also presented and discussed are the calculated performance parameters of a 40-kW$_e$ prototype that could be used for ground testing, in conjunction with a scaled down VASIMR, for concept verification. In such testing, the nuclear reactor could be replaced with electric heaters while the entire system is fully assembled and instrumented. The data generated in these tests could be used in developing and verifying models for scaling the system design to the multimegawatt electric level required for a crewed mission to Mars.

System Design

The proposed HEU, dual-mode, electric power and propulsion system employs a gas cooled pellet-bed reactor (PeBR) as the heat source.[9,10] The PeBR core could be divided into three or more equal, neutron and thermal coupled sectors. Each sector is self-contained, independently cooled, and hydrodynamically and thermally coupled to one closed Brayton cycle (CBC) engine, or more, for generating an equal fraction of the nominal electric power of the system. This system design eliminates a single point failure because the failure

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Table 1 Operation parameters of CBC engine designs for space applications

Operation parameter	Brayton cycle demonstrator	(BRU)	High-performance engine	Dynamic isotope power system
Cycle efficiency, %	27	28.5	31	31
Power output, kW_e	3	10.5	30	1.4
Thermal power input, kW_{th}	11.1	32.8	96.7	4.8
Shaft speed, rpm	64,000	36,000	52,000	52,000
Compressor inlet pressure, kPa (psia)	3.1 (4.5)	16.3 (23.7)	21.8 (31.6)	26.2 (38)
Compressor inlet temperature, (R)	277 (500)	300 (540)	262 (473)	303 (546)
Compressor pressure ratio	2.3	1.9	1.61	1.89
Turbine inlet temperature, (R)	1111 (2000)	1144 (2060)	1033 (1860)	1089 (1960)
Recuperator efficiency, %	90	95	96	84
Working fluid flow rate, kg/s	0.0771	0.38	0.0862	0.685
Working fluid type, gm/mole	Argon 39.9	He–Xe 83.3	He–Xe 83.8	Argon 39.9

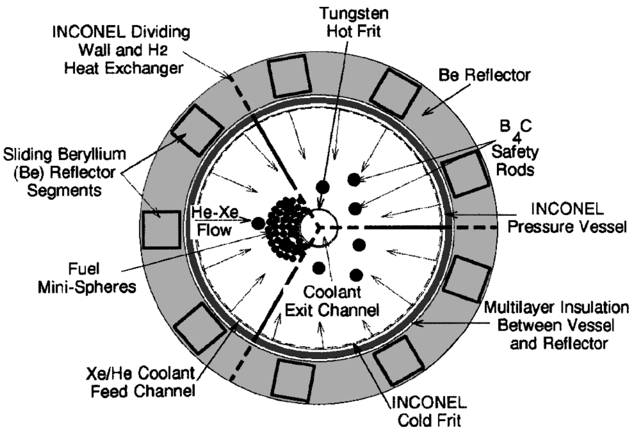

Fig. 1 Radial cross section of the PeBR core for the 40-kW_e prototype dual-mode system.

of an energy conversion loop does not impair the performance of the other loops, hence enhancing the system's reliability.

The PeBR core is packed with spherical fuel elements [mini-spheres ~2 mm in diameter (see Fig. 1)]. The fuel elements are composed of ZrC-coated (U, Zr)C fuel microspheres (~500 μm in diameter) dispersed in graphite at a volume fraction as high as 50% (Ref. 9). The random packing fraction of the fuel elements in the reactor core is about 62.5%. A gas mixture made of 70-mol% helium and 30-mol% xenon (He–Xe) cools the reactor core and serves as the working fluid for the CBC engines. The technology of CBC engines is mature and some units have undergone thousands of hours of testing in a simulated space environment without failure (Table 1) (Ref. 11 and personal communication from T. Ashe of the Allied-Signal Aerospace Company of Phoenix, Arezona, October 1993).

Separate bleed lines in the coolant loops control the amount of He–Xe circulating through the PeBR core sectors during the electric power and the propulsion modes. In the propulsion mode, the fraction of the working fluid flowing through the reactor core increases commensurate with the reactor thermal power. The bleed fraction of the working fluid decreases to almost zero at the peak operating thermal power of the reactor in the propulsion mode. The fraction of the He–Xe circulating through the reactor core during the electric power mode could be less than 0.20. In this mode, the reactor thermal power is also much lower (<20%) than the nominal design value in the propulsion mode. The coolant bleed lines concept helps maintain the temperatures of the fuel and the structure materials in the PeBR core almost the same during both the electric power and the propulsion modes. This operation feature avoids inducing any thermal or structure stresses, hence enhancing the system's reliability and prolonging its operational lifetime.

Safety and Design Features

The PeBR, HEU, dual-mode, electric power and propulsion system offers many additional safety and operations advantages:

1) It avoids design and startup complexities as well as the temperature limitations associated with using liquid-metal cooled reactors due to the need to incorporate a subsystem to thaw the working fluid at startup and to pressurize the coolant loop to achieve high temperatures.

2) It could be operated at high temperatures (>2000 K) not achievable with liquid-metal cooled reactors.

3) Because of its simple design, the PeBR can be launched fueled or empty. It can also be fueled, emptied, and refueled while in space. These options can be exercised very readily with the minispheres fuel elements (Fig. 1) with an easily sliding graphite surface.[9] This design and operation feature of the PeBR would reduce the overall operation cost by extending the useful lifetime of the power system beyond that achievable with a single reactor core.

4) The reactor core is divided into equal sectors, and each sector is hydrodynamically coupled to a separate CBC engine, hence eliminating a single point failure in the reactor coolant and electric power generation loops.

5) The inert He–Xe working fluid poses no compatibility concerns with the structure materials of the CBCs, coolant loop, and the reactor core and of the fuel elements.

6) The reactor temperature is maintained almost constant during the electric power and propulsion modes to avoid causing thermal stress in the reactor core and structure components of the nuclear reactor.

7) The PeBR is passively cooled after shutdown with the aid of liquid-metal heat pipes inserted in the radial Be reflector (Fig. 1). (Ref. 10).

8) Despite the complexity of the hydrogen flow and heating loop, all control of the hydrogen flow is while in the liquid phase, upstream of the heat rejection radiators (Fig. 2).

9) The CBC heat rejection radiator is sized for the electric power level of the system, which is a small fraction of the system's total thermal power in the propulsion mode. As a result, the mass of the heat rejection radiators is a small fraction of the total system mass. The radiators' size and mass, however, would increase with the electric power of the system.

Note that the proposed HEU, dual-mode, electric power and propulsion system concept can utilize any gas-cooled solid core nuclear reactor with similar operation, safety, and redundancy features as the PeBR.

To better illustrate the design and operation principles of the proposed HEU, dual-mode, electric power and propulsion system, the following section describes the design and the performance parameters of a 40-kW_e prototype based on the PeBR. Detailed neutronic, thermal hydraulic, and safety analyses of this system have been performed.[10,12,13] The calculated design and performance results are also summarized in the next section.

40-kW_e Prototype System

The 40-kW_e prototype system employs three 13.33 kW_e, He–Xe CBC engines of the rotating type [Brayton rotating unit (BRU) in Table 1]. These engines have slightly different operation parameters than the one listed in Table 1. The inlet temperatures of the He–Xe

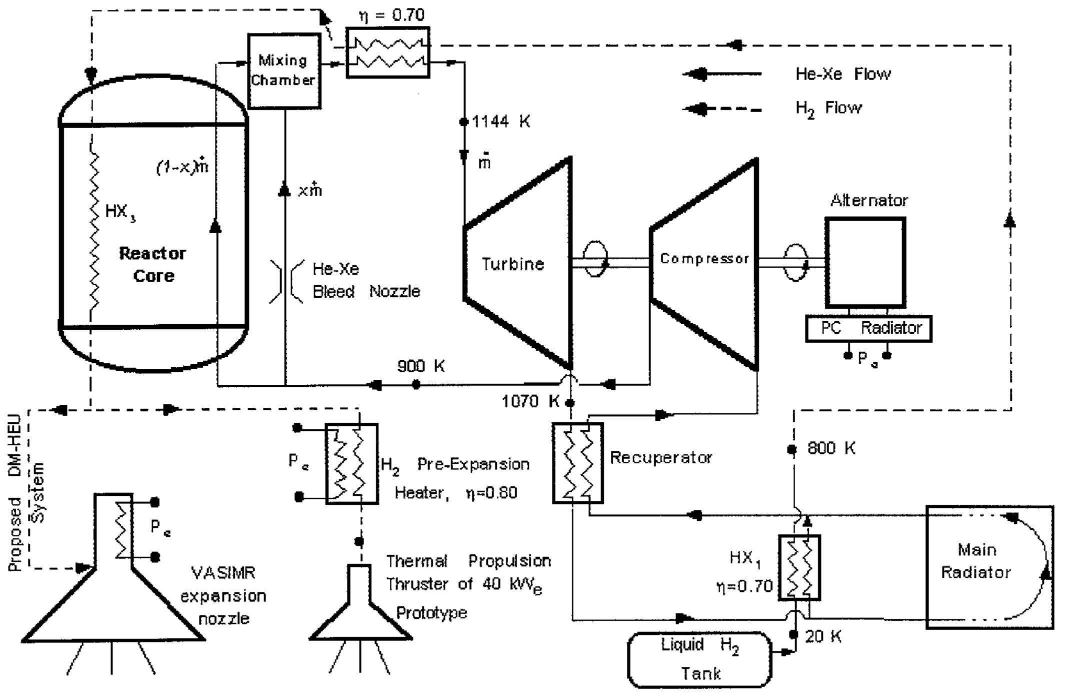

Fig. 2 Line diagram of an energy conversion and thermal-hydraulic loop of the 40-kW$_e$ prototype system, with in-core heating of the hydrogen.

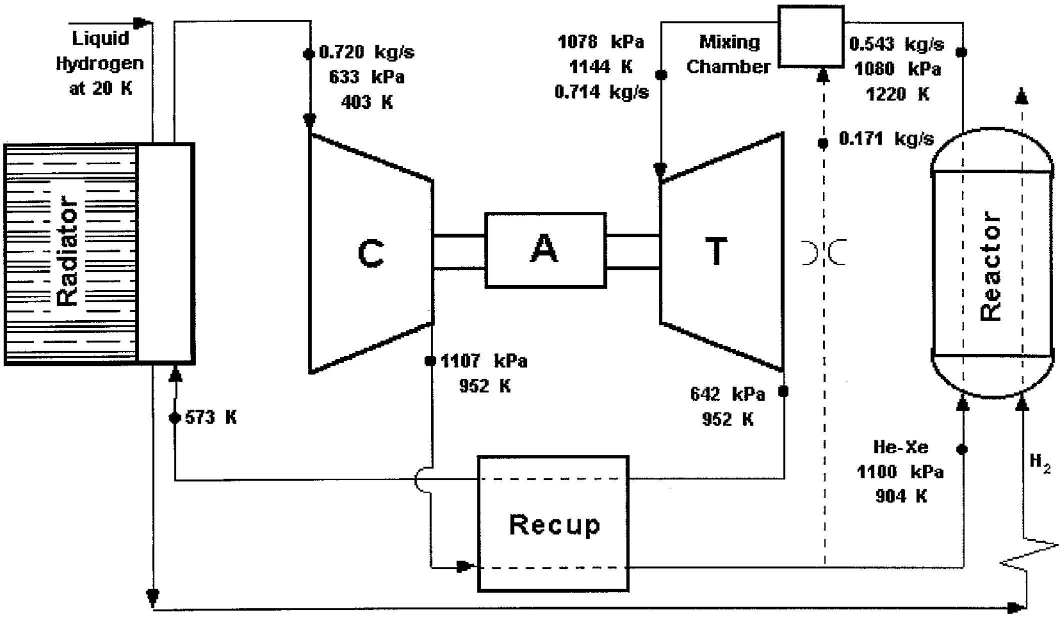

Fig. 3 Schematic and operation parameters of a BRU-type CBC engine.

working fluid to the PeBR core and the CBC engines of 900 and 1144 K, respectively, are dictated by the design and the structure material of the latter (Ashe personal communication cited earlier). The inlet and exit temperatures of the He–Xe gas mixture in the PeBR core and its inlet temperature to the CBC engines are also kept constant during both the electric power and propulsion modes. A radial cross section of the PeBR core for the 40-kW$_e$ prototype system and a schematic of the 13.33-kW$_e$ CBC units are shown in Figs. 1 and 3, respectively.

A number of these CBC units were tested successfully in the 1970s at NASA John H. Glenn Research Center at Lewis Field for 36,000 h in a simulated space environment without any performance degradation (see Fig. 3) (Ashe personal communication cited earlier). All of the technologies required to implement these CBC engines in a HEU, dual-mode, electric power and propulsion system are proven and mature. No technology breakthrough is required, only engineering implementation (Ashe personal communication cited earlier).

Table 1 lists the operation characteristics of other more efficient engines that have also been designed and fabricated. The specific power of some of the BRU-type engines are compared in Fig. 4 at turbine inlet temperatures of 1144 and 1400 K (Ashe personal communication cited earlier). Table 1 indicates that the technology of CBC units with a conversion efficiency of 31% is also available for increasing the system's specific power beyond those presented later, using BRU units with 22.5% efficiency.

As shown in Fig. 4, a 100-kW$_e$ CBC engine operating at a turbine inlet temperature of 1144 K has 30% higher specific power (47 W$_e$/kg) than the 13.33-kW$_e$ engines (36 W$_e$/kg) used in the 40-kW$_e$ prototype. Increasing the inlet turbine temperature also

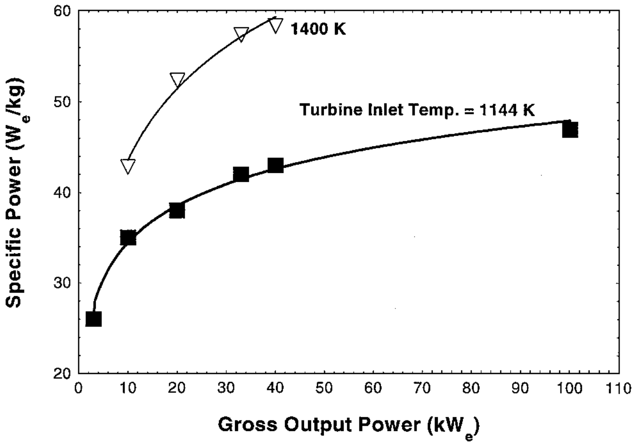

Fig. 4 Specific electric power of a CBC-BRU type engines.

increases the CBC engine's specific power. Figure 4 shows that for a 50-kW$_e$ CBC engine, increasing the inlet turbine temperature from 1144 to 1400 K increases the engine's specific power by ~35%, from 43 to 58 W$_e$/kg.

Power Mode Operation

During the electric power mode, a fraction x of the He–Xe mass flow rate from the compressor at 900 K is bled off, before entering the PeBR core, to the mixing chamber located at the exit of the reactor. The remainder of the working fluid $(1 - x)$ flows through the reactor core sectors (see Fig. 2) (Ref. 12) to remove the heat generated by nuclear fission. The He–Xe gas mixture flows radially in the reactor core sectors and exits through three separate central channels, each connected to a core sector and a separate CBC engine. The temperature of the coolant exiting the reactor core is kept at least ~100–200 K below the maximum fuel design temperature. This temperature could be as much as 2000–2400 K, for long operation lifetime[3] because the melting temperature of the (U–Zr)C fuel in the coated microspheres is more than 3500 K.

On exiting the reactor core, the heated He–Xe is mixed with the cooler bled fraction in the mixing chamber to adjust its temperature to the CBC engines inlet temperature of 1144 K (see Fig. 2). This inlet temperature is maintained constant during both the electric power and propulsion modes of operation. In the propulsion mode, the temperature of the He–Xe gas mixture exiting the reactor core and its fraction flowing through the core are higher than during the electric power mode. In this case, the countercurrent hydrogen flow through exchangers (HX$_2$) lowers the temperature of the He–Xe exiting the mixing chamber to the desired CBC turbine inlet temperature of 1144 K.

Propulsion Mode Operation

In the propulsion mode, liquid hydrogen in pumped from the storage tank at 20 K. It is boiled off and the hydrogen gas is heated in exchangers (HX$_1$), which are integral parts of the heat rejection radiators of the CBC engines (Fig. 2). In these exchangers, the hydrogen flow captures >70% of the radiators' heat load. In the 40-kW$_e$ prototype, in which the efficiency of the CBC engines is 22.5%, the fraction of the heat rejection recovered by the hydrogen flow in exchangers HX$_1$ equals ~96 kW$_{th}$. The thermal effectiveness of exchangers HX$_1$ for heating hydrogen could be as much as 95%, increasing this thermal energy recovery in exchangers HX$_1$ from 96 to 123 kW$_{th}$.

This hydrogen preheating feature is a key to increasing the thermal energy utilization of the system from only 22.5% in the electric power mode to >70% in the propulsion mode.[14] Another advantage of this design/operation feature is that the hydrogen boiling in exchangers HX$_1$ is external to the nuclear reactor, hence avoiding causing transient changes in the reactor operation and control by flowing and boiling liquid hydrogen in the PeBR core.

The hot hydrogen gas exiting exchangers HX$_1$ enters exchangers HX$_2$ to be heated further by the hot He–Xe exiting the mixing chamber in the propulsion mode of operation (Fig. 2). The temperature of the hydrogen exiting HX$_2$ could be as high as 1600–2000 K, depending on the design maximum fuel temperature in the core and the hydrogen mass flow rate. On exiting exchangers HX$_2$, the hydrogen is heated further in the three heat exchangers incorporated into the dividers of the reactor core sectors (Fig. 1). In-core heating of hydrogen could increase its temperature by an additional 200–400 K, depending on the reactor thermal power and the hydrogen flow rate. For reliable long-time operation, the temperature of the hydrogen exiting the PeBR core sectors was limited to about 200 K below the maximum fuel temperature. As indicated earlier, such fuel temperature could be as high 2400 K. The calculations presented in the following section, however, were performed at conservative maximum fuel temperatures of 1600 and 2000 K (Ref. 13).

The hot hydrogen exiting the PeBR in-core heat exchangers could expand through a high-thrust nozzle in a thermal-propulsion-only option following a failure of the VASIMR. The latter is the primary, high-performance, propulsion option. To increase the specific impulse and thrust for the thermal propulsion option, the electric power, minus 1–5 kW$_e$ for housekeeping, could be used to increase the temperature of the hydrogen exiting the in-core exchangers by an additional 50–150 K, before entering the expansion nozzle (see Fig. 2 and Table 2).

Table 2 Performance parameters of 40-kW$_e$ prototype for electric power and thermal propulsion

Steady-state system parameters	H_2 flow rate 5.0 g/s	H_2 flow rate 10.0 g/s
Reactor thermal power in power mode, kW$_{th}$	178	178
Maximum fuel design temperature, K	1610	1636
Electric output in power and propulsion modes, kW$_e$	40	40
Reactor thermal power in propulsion mode, kW$_{th}$	251	355
In-core mass flow rate of He–Xe gas, %	35.7	24.5
Calculated maximum fuel temperature, K	1610	1636
Temperature of He–Xe exiting reactor core, K	1590	1615
Temperature of H_2 entering reactor core HXs, K	520	270
Temperature of H_2 exiting reactor core HXs, K	1425	1381
Temperature of H_2 at inlet of expansion nozzle, K		
Without preexpansion electric heating	1425	1381
With preexpansion electric heating	1777	1557
Specific impulse, lbf · s/lbm (N · s/kg)		
Without preexpansion electric heating	658 (6452)	647 (6344)
With preexpansion electric heating	735 (7207)	687 (7737)
Thrust, N		
Without preexpansion electric heating	32	63
With preexpansion electric heating	36	67

Because of the low I_{sp} in the thermal propulsion option (<7800 N · s/kg), it is only done as a contingency measure in the event the VASIMR fails (Table 2). In the latter, the hot hydrogen exiting the PeBR in-core exchangers is mixed with the plasma exhaust, to achieve both high thrust and significantly higher I_{sp}. In this case, the system's electric power, minus ~1–5 kW$_e$ for housekeeping, is used to operate the VASIMR.

The following section presents and discusses the performance parameters of the 40-kW$_e$ prototype for the thermal-propulsion-only option, with and without preexpansion electric heating of the hydrogen exiting the PeBR in-core exchangers (see Fig. 2). Although the results are not directly applicable to the high-performance option using VASIMR, they demonstrate that high-energy utilization fractions can be achieved (Fig. 2).

Performance Parameters of the 40-kW$_e$ Prototype

An integrated nuclear reactor's point kinetics, thermal hydraulics, and performance model of the 40-kW$_e$ prototype system was developed and used to investigate the system's operation in the electric power and the propulsion modes, as well as during operation transients. These transients include nuclear reactor startup from a cold state and changing the reactor operation from the power to the propulsion mode.[13] The system model consisted of several interactive building blocks as follows: 1) six-group reactor point kinetics model with a linear, negative-temperature, reactivity feedback; 2) lumped transient thermal model of the nuclear reactor core, the He–Xe thermal-hydraulics loop, and the hydrogen heat exchangers ; and 3) energy conversion and thermal propulsion performance model.

During both the electric power and the propulsion modes of operation, the temperature of the He–Xe working fluid at the inlet of the CBC engines is maintained the same at 1144 K. The total flow rate of the He–Xe working fluid is also maintained constant during both modes at 2.444 kg/s (0.81 kg/s per CBC engine) (Fig. 2). Table 2 lists the operation and performance parameters of the 40-kW_e prototype in the electric power and thermal propulsion modes, with and without preexpansion electric heating of the hydrogen (see Fig. 4).

The calculations presented in this section and the performance parameters listed in Table 2 were based on the following conservative assumptions:

1) In hydrogen flow in the in-core exchangers during the propulsion mode absorbs only 10% of the reactor thermal power.

2) Thermal effectiveness of exchangers HX_1 and HX_2 is only 70%. As indicated earlier, an effectiveness of 90–95% is readily attainable for gas/gas heat exchangers.

3) Maximum hydrogen exit temperature from the reactor core is limited to 200 K below the maximum fuel temperature in the reactor core (<1650 K). This temperature for the PeBR fuel, however, could be raised safely to 2500 K, resulting in a much higher performance than that reported in Table 2.

4) Hydrogen flow rate is limited by its required exit temperature from the in-core exchangers. Therefore, raising the maximum fuel temperature in the PeBR during the propulsion mode to 2500 K would significantly increase the hydrogen flow rate and temperature, resulting in higher thrust and I_{sp} than those reported in Table 2.

5) In the thermal propulsion mode, all electric power, minus 1.0 kW_e for housekeeping, is used for further heating of the hydrogen exiting the reactor core, at an efficiency of 80%. This efficiency of could be easily increased to 90–95%.

Performance Envelope

The performance envelopes of the 40-kW_e prototype for maximum fuel design temperatures of 1600 and 2000 K are compared in Fig. 5. The reactor thermal power during the power mode, $P_0 = 177\ kW_{th}$, increases during the propulsion mode by 250–450%, depending on the hydrogen flow rate, without exceeding the maximum fuel temperatures of 1600 and 2000 K, respectively. The left and right boundaries of the operation envelopes in Fig. 5 represent

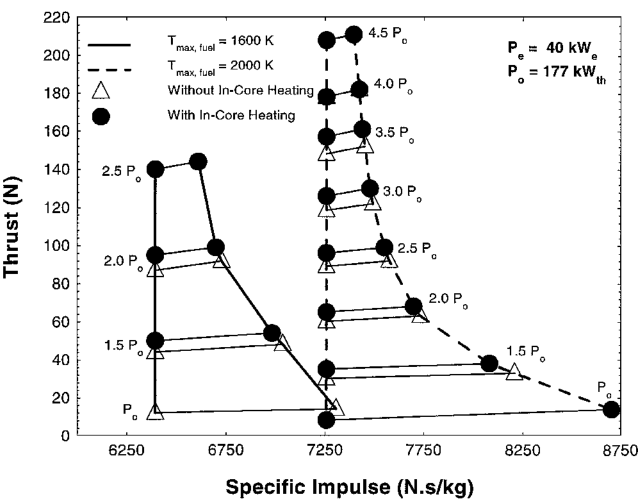

Fig. 5 Performance parameters of 40-kW_e prototype, with and without in-core heating of hydrogen.

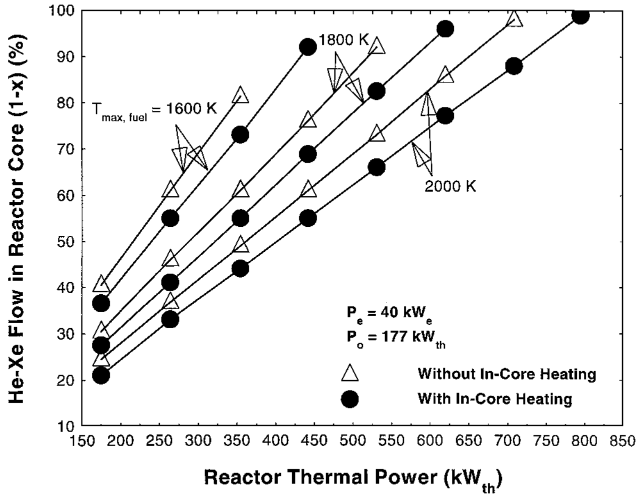

Fig. 6 Estimated fractions of He–Xe working fluid in the PeBR core during the electric power and thermal propulsion modes.

the performance parameters during the thermal propulsion mode, without and with preexpansion electric heating of hydrogen, respectively. The difference in performance (thrust and I_{sp}) between the left and right boundaries of the envelopes decreases as the reactor thermal power in the propulsion mode increases or the electric power becomes a smaller fraction of the system's total power.

Note that in-core heating of the hydrogen slightly increases both the delivered thrust and I_{sp}. When the reactor thermal power in the propulsion mode was identical to that during the electric power mode ($P_0 = 177\ kW_{th}$), only the results with in-core heating of hydrogen are presented in Fig. 5. The corresponding propulsion parameters are represented by the lower boundary of the operation envelopes. Similarly, the top boundary of the operation envelopes represents the propulsion parameters corresponding to the highest reactor thermal power achievable during the propulsion mode with in-core heating of the hydrogen. Increasing the maximum fuel temperature from a modest 1600 to 2000 K increases the area of the performance envelope of the system, shifts it to the right (higher I_{sp}), and raises its top boundary (higher thrust).

Energy Utilization Fraction

Increasing the maximum fuel design temperature in the reactor core and implementing in-core heating of the hydrogen increases the fraction of the He–Xe working fluid flowing through the PeBR core (Fig. 6) and the utilized fraction of the reactor thermal power during the propulsion mode (Fig. 7). The results presented in Fig. 6 show the effect of increasing the maximum fuel temperature on the mass flow rate fraction $(1 - x)$ of the He–Xe gas mixture in the reactor core during the propulsion mode. With in-core heating of the hydrogen, the fraction of He–Xe flowing through the reactor core in the propulsion mode is lower than without in-core heating of the hydrogen. In-core heating of the hydrogen is assumed to consume 10% of the reactor thermal power (Fig. 1). This percentage, however, could be higher, depending on the design of the in-core heat exchangers and the flow rate of the hydrogen.

Figure 6 shows that, for a maximum fuel temperature of 1600 K, the fraction of the mass flow rate of He–Xe in the reactor core is 0.41 and 0.37, with and without in-core heating of the hydrogen, respectively. In these cases, the reactor thermal power in the propulsion mode was the same as in the power mode ($P_0 = 177\ kW_{th}$). At the highest reactor thermal power in the propulsion mode, the fractions of the He–Xe flowing through the PeBR core, with and without in-core heating of the hydrogen, increase to 0.92 and 0.82, respectively.

Figure 7 shows that, for a maximum fuel design temperature of 1600 K, the system's energy utilization fraction in the propulsion mode was about 0.54 and 0.51, with and without in-core heating of the hydrogen, respectively. The reactor thermal power was

Table 3 Mass estimates of the 40-kW$_e$ prototype system

System component	Mass, kg
Nuclear reactor	336
Radiation shadow shield	350
CBC engines, power conditioning, radiator, and heat exchangers	930
Additional structure and subsystems	84
Total	1700.0

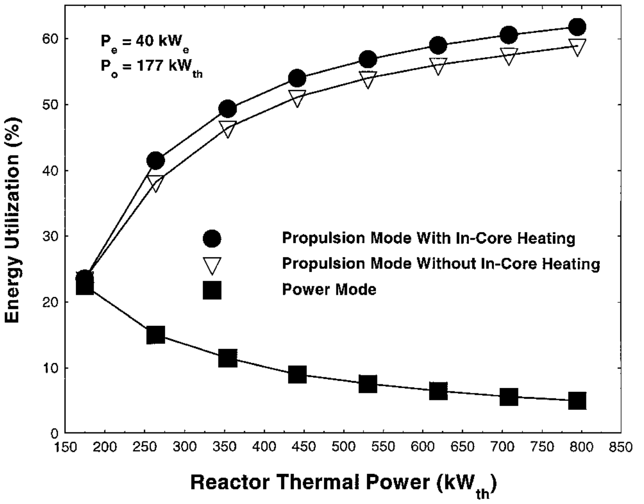

Fig. 7 Estimates of the energy utilization in the 40-kW$_e$ prototype system.

442 kW$_{th}$. When the maximum fuel design temperature was increased to 2000 K, the energy utilization fraction of the system increased to 0.62 and 0.59 in the propulsion mode, with and without in-core heating of the hydrogen, respectively (Fig. 7). The reactor thermal power in this case also increased to 800 kW$_{th}$. These energy utilization fractions could exceed 0.85 because the effectiveness of exchangers HX$_1$ and HX$_2$ increases from the assumed value of 70% in the present analysis to 95%, which is possible with the current technology of compact heat exchangers.

Mass Estimates

Table 3 lists the mass estimates of the components of the 40-kW$_e$ prototype. The reactor mass of 336 kg was been determined based on detailed neutron calculations.[13] The estimated mass of the shadow shield in Table 3 is based of those reported for similar systems.[15] The radiation shadow shield consists of a thin tungsten front layer for gamma shielding followed by a thick layer of depleted lithium hydride (LiH) neutron shield.[16] This shadow shield has a half-cone angle less than 10 deg and is contained in a stainless-steel canister. The estimated shield mass is 350 kg for a reactor thermal power of 1000 kW$_{th}$ and separation distance of the payload of ~10 m. The mass estimates in Table 3 exclude those of the propulsion subsystem, the hydrogen storage tank, the associated piping, and the liquid hydrogen pump. The estimated total mass of the system in Table 3 may be shown later to be on the conservative side.

For a maximum fuel design temperature of 2000 K and exchangers HX$_1$ and HX$_2$ effectiveness of only 0.7, the specific electric power of the 40 kW$_e$ system is estimated at ~23.5 W$_e$/kg. However, the system's specific energy utilization is as much as 440 W/kg in the propulsion mode. Increasing the exchangers' effectiveness to 0.9–0.95, which is technically achievable at present for gas–gas heat exchangers, could increase the specific energy utilization of the system beyond 500 W/kg.

In summary, using an HEU, dual-mode, electric power and propulsion system, in which hot hydrogen is mixed in the exhaust plasma of a VASIMR, a reliable, redundant, and lightweight spacecraft can be designed for future crewed mission to Mars. The high thrust and very high I_{sp} (>35,000 N · s/kg) of this HEU-VASIMR system could cut the projected travel time to Mars to about 3 months.[6,8] This is only half the projected travel time with a solid core nuclear reactor and hydrogen thermal propulsion.[1–3,9]

Summary and Conclusion

An HEU, dual-mode, electric power and propulsion system concept, powered by a gas-cooled nuclear reactor and employing a VASIMR device is proposed for potentially reducing the travel time to Mars to ~3 months. The system generates the same electric power during the power and the propulsion mode, and in both modes, the maximum fuel temperature and the inlet temperature of 1144 K to the CBC engines are kept constant. The working fluid of the CBC engines for generating high-voltage, ac electric power is a He–Xe gas mixture. This gas mixture, which serves as the reactor coolant, is chemically compatible with the reactor core and CBC structural materials. The present HEU system does not have a single point failure. The reactor core is divided into three self-contained, but neutronically and thermal hydraulically coupled sectors. The dividers of the core sectors contain heat exchangers for heating the hydrogen propellant. Each core sector has an independent He–Xe and hydrogen flow loops, a separate set of CBC engines, and a separate heat rejection radiator and attached heat exchanger. The latter is used to boil off the liquid hydrogen pumped from the storage tank and to preheat the hydrogen gas in the propulsion mode.

The hydrogen gas exiting the radiator's preheating heat exchangers is heated further by the hot He–Xe gas exiting the reactor core in the propulsion mode. In this mode, the mass flow rate fraction of the He–Xe in the reactor core increases from <0.2, during the electric power mode, to close to 0.95, commensurate with the reactor thermal power. The reactor core temperatures are kept almost constant in the electric power and the propulsion modes to avoid causing structural stress.

The hydrogen exiting the high-temperature He–Xe heat exchangers could be heated further in the nuclear reactor by flowing through heat exchangers placed in the dividers of the core sectors. The hydrogen exits the in-core exchangers at 1700–2300 K, depending on the reactor thermal power, the hydrogen flow rate, and the maximum fuel design temperature. The hot hydrogen is mixed with the plasma exhaust of VASIMR to achieve high thrust and $I_{sp} \geq 35{,}000$ N · s/kg. In case the VASIMR fails, a thermal-propulsion-only option could be used, in which the hot hydrogen exiting the reactor core exchangers can be heated further using the system's electric power, minus 1 kW$_e$ for housekeeping, then flown through an expansion nozzle. This thermal propulsion backup option enhances the system's reliability and could deliver thousands of Newtons of thrust at an I_{sp} of up to 8000 N · s/kg.

The calculated performance parameters of a 40-kW$_e$ prototype system that uses the thermal-propulsion-only option have shown that energy utilization fractions of 0.6–0.8 are possible when the maximum fuel temperature is 2000 K. At this temperature, the reactor thermal power in the propulsion mode could be raised to ~450% that during the electric power mode, resulting in a system's specific energy utilization in excess of 400 W/kg. Increasing this value to more than 500 W/kg is possible by simply increasing the effectiveness of the hydrogen heat exchangers in the system from 70% to 85–95%, which is achievable with today's technology.

In conclusion, an HEU, dual-mode, electric power and propulsion system concept using a gas-cooled nuclear reactor and VASIMR offer unique performance, safety, and reliability features for future crewed missions to Mars. By mixing neutral hot hydrogen in the plasma exhaust of VASIMR, high thrust and very high I_{sp} (>35,000 N · s/kg) could be achieved. Such high I_{sp} would cut the travel time to Mars to 96 days, instead of the 6 months projected for solid-core nuclear reactors and hydrogen thermal propulsion. The HEU/VASIMR system could be developed and tested fully assembled in a ground facility, by replacing the nuclear fuel in the PeBR core with electric heaters. The technology of the PeBR, and similar gas core nuclear reactors, and of the CBC engines is proven and mature, and no technology breakthrough is required. Most of the development needs, however, are related to the VASIMR technology.

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