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The Mars Hopper: a radioisotope powered, impulse driven, long-range, long-lived mobile platform for exploration of Mars

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Abstract. *Planetary exploration mission requirements are becoming more demanding. Due to the increasing cost, the missions that provide mobile platforms that can acquire data at multiple locations are becoming more attractive. Wheeled vehicles such as the Mars Exploration Rovers have proven extremely capable but have very limited range and cannot traverse rugged terrain. Flying vehicles such as balloons and airplanes have been proposed but are problematic due to the very thin atmospheric pressure and the strong, dusty winds present on Mars. The Center for Space Nuclear Research (CSNR) has designed an instrumented platform that can acquire detailed data at hundreds of locations during its lifetime - a Mars Hopper. The Mars Hopper concept utilizes energy from radioisotopic decay in a manner different from any existing radioisotopic power sources—as a thermal capacitor. By accumulating the heat from radioisotopic decay for long periods, the power of the source can be dramatically increased for short periods. The platform will be able to "hop" from one location to the next every 5-7 days with a separation of 5-10 km per hop. Preliminary designs show a platform that weighs around 52 kgs dry, i.e. empty of propellant, which is the condition at deployment. Consequently, several platforms may be deployed on a single launch from Earth. With sufficient lifetime, the entire surface of Mars can be mapped in detail by a couple dozen platforms. In addition, Hoppers can collect samples from all over the planet, including gorges, mountains and crevasses, and deliver them to a central location for eventual pick-up by a Mars Sample Return mission. The status of the Mars Hopper development project at the CSNR will be discussed.*

Keywords: radioisotope power, Mars Hopper, thermal rocket

I. INTRODUCTION

Planetary exploration mission requirements are becoming more demanding. Due to the increasing cost, missions that provide mobile platforms that can acquire data at multiple locations are becoming more attractive. The Mars Exploration Rovers, Spirit and Opportunity, have performed remarkably for 5 years and have covered 4.8 and 10.7 miles, respectively. The Phoenix lander has sampled the Martian surface close to the northern polar cap of Mars but only at one location. Spot sampling at a few locations, especially locations that are safe landing sites, will not provide an accurate geophysical map of Mars. In addition, if humans are ever going to land on Mars, we must produce a much more detailed map of the resources, terrain and subsurface in order to know where to land.

More ambitious technologies must be developed and methods created to increase the science return for each launch, thus increasing the scientific value for the money spent for each mission. Several previous studies have proposed the use of "hoppers" powered by one means or another [1-5]. However, these concepts suffered from either short range (solar electric powered) or relatively short operational durations (chemical propellants carried from Earth). Conceivably, a long duration, robust Hopper can be placed on the surface of Mars that could acquire highly detailed data from the surface and subsurface, travel large distances to multiple sites and perform this task repeatedly. Such a platform enables an entire planetary surface to be accurately mapped and sampled with higher resolution than from orbiting platforms. In addition, if several such platforms could be simultaneously deployed from a single launch vehicle, a surface network of science stations would be possible that could provide long term assessment of meteorological conditions.

The CSNR is developing an instrumented platform that can acquire detailed data at hundreds of locations during its lifetime - a radioisotopic thermal rocket (RTR) Mars Hopper. The platform will be able to "hop" from one location to the next every 5-7 days with a separation of 5-10 km per hop. Each platform will weigh around 52 kgs dry, i.e. empty of propellant, which is the condition at deployment. Consequently, several platforms may be deployed on a single launch from Earth. With a lifetime estimated at 5-7 years, the entire surface of Mars can be mapped in detail by a couple dozen platforms. Furthermore, the basic platform could be deployed to Europa or Titan with alterations-- the propulsion system and operations essentially will be the same.

The design of the Hopper is meant to be simple and robust in order to enable a long life and hundreds of landings. Currently, the CSNR is leading a team composed of CSNR staff, INL staff, and three universities to build a prototype Hopper to demonstrate the concept. The prototype will have an electrically heated core coupled to a tank of liquid CO_2. The liquefaction of Martian CO_2 is being demonstrated by the Utah State University. The power conversion subsystem to power the CO_2 liquefaction is being examined by the University of Idaho. Thermal isolation and heat transfer are being modeled by the Oregon State University and CSNR staff. This paper summarizes the results to date of these efforts.

II. CONCEPT

The Mars Hopper concept utilizes energy from radioisotopic decay in a manner different from any existing radioisotopic power sources—as a thermal capacitor. Radioisotope sources have very high specific energy, J/kg, while having rather low specific power, W/kg. For example, Pu-238 has roughly 160,000 times the specific energy of high explosives (10 MJ/kg) but only produces around 0.4 kW/kg. By accumulating the heat from radioisotopic decay for long periods, though, the power output from the source can be dramatically increased for short periods. Thus, a radioisotopic thermal rocket (RTR) is possible.

The envisioned operational sequence is to utilize the 1 kWt decay heat from 2.5 kgs of PuO_2 to heat a block of beryllium to high temperatures. While the heating is taking place, some of the thermal power is converted to 250 W of electrical power to run a cryocooler. The cryocooler takes in the Martian atmosphere and liquefies it at roughly 2.8 MPa. The liquefied CO_2 is transferred to a tank which is held at 270 K. Once full, the power convertor is turned off and the core is allowed to increase in temperature. After the peak temperature of 1200 K is reached, a valve opens and gaseous CO_2 is pressure fed into the core. The gas is heated, expanded through a nozzle, and allowed to produce thrust. One half of the CO_2 propellant is "burned" for ascent. After a ballistic coast, the remaining propellant is used for a soft landing. Once landed, the process repeats.

III. CORE DESIGN

One of the features of the core design is the decoupling of the heating process from the blow down process in the rocket. Radioisotope particulate will be dispersed uniformly throughout a tungsten matrix material. A single rod of this material will be located at the center of a cylindrical core of beryllium. The beryllium contains the flow channels for the blow down mode. The radioisotope matrix will not be exposed to the flowing exhaust.

The current design assumes the use of old Pu-238 that is below the NASA specifications for Radioisotopic Thermoelectric Generators (RTGs) with regard to power density. However, several other radioisotopes such as Cm-244 or Am-241 could also be used. Although RTGs have been launched on several vehicles for the past few decades, encapsulation of the Pu-238 in case of launch abort is an ever-present issue. Recent developments in the fabrication of tungsten-rhenium (W-Re) materials at the CSNR indicate that a solid, tough, high-temperature matrix can be formed to encapsulate the radioisotopes [6,7]. The W-Re encapsulation process will prevent the dispersion of the radioisotopes if exposed to the destructive forces associated with spacecraft re-entry and launch abort scenarios. Because the tungsten matrix concept is also applicable to use in the nuclear thermal rocket and in surface power reactor fuel, the CSNR is promoting the material as a "universal encapsulation" for any radioisotopic material.

The remainder of the core is composed of beryllium to act as the thermal capacitor. Beryllium has a density of 1.85 g/cm^3, a melting point of 1551 K, thermal conductivity of 200 W/m-K (at 298 K), and a specific heat of 1825 J/kg K (at 298 K). Beryllium has a unique combination of high thermal conductivity and very high heat capacity. As shown in Table 1, beryllium is significantly superior to the other metals in both areas. Based on the published properties of beryllium, the CSNR was able to make estimates for core mass and size sufficient to contain enough energy to allow the Hopper to reach large ranges. The current core consists of 6.07 kg of beryllium to hold 14.8 megajoules of heat. The core dimensions are 7.28 cm radius by 30 cm long. The core is assumed to have flow channels for the CO_2 coolant running along the axis and equally spaced. The volume fraction of the flow channels to the entire core volume is 25%.

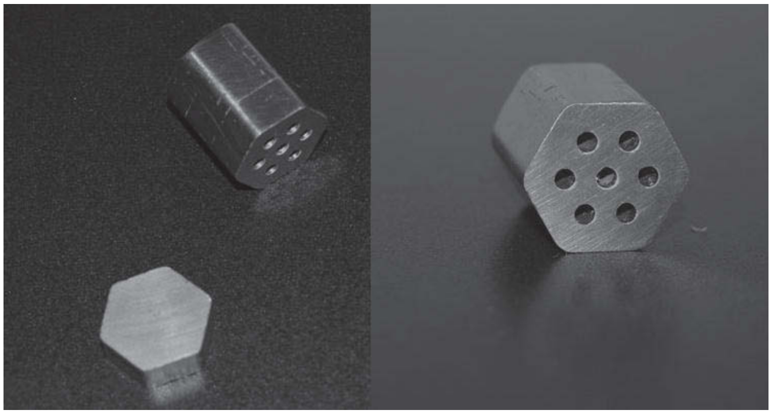

Figure 1. Tungsten samples loaded with CeO_2 (40% vol.) reminiscent of a nuclear thermal rocket fuel element. The CeO_2 acts as the PuO_2 simulant [6]. The sample without flow channels has density 90% of the theoretical value.

As seen in Table 1, the heat capacity of beryllium is the dominant characteristic. In fact, the capacity increases dramatically with temperature as shown in Figure 2. This dependence on temperature makes the core temperature calculation as a function of propellant mass flow nonlinear. The remarkable ability of beryllium to hold heat enables the Mars Hopper concept.

TABLE 1. Comparison of fundamental properties of candidate matrix materials.

Material	T_{melt} (K)	Thermal Conductivity (W/m-K)	Heat Capacity (J/kg-K)
Carbon	3823	165	710
Tungsten	3695	173	130
Beryllium	1551	200	1820

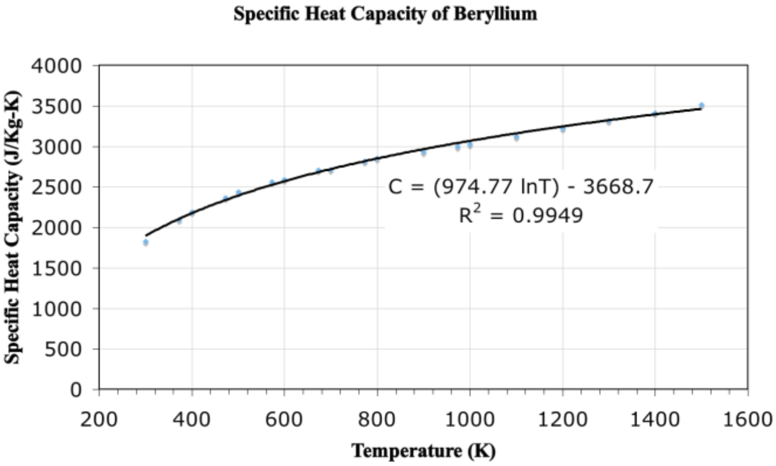

Figure 2. Specific heat capacity of beryllium as a function of temperature. Plot of data taken from [8].

The kinetics of the interactions of Beryllium in a high temperature CO_2 environment favor the production of surface layers of BeO. As such, prolonged exposure may result in some surface erosion during propellant flow. In order to mitigate the risk of erosion of the matrix during operation, specifically in the flow channels, and to improve the handling requirements for the components, a protective coating of Hastelloy C-276 will be applied. More specifically, the coefficient of thermal expansion and stability at 1200 K are closely matched between C-276 and beryllium so as to ensure integrity over the range of operational temperatures required of the RTR system.

Initial calculations of the time dependent heat transfer provided an indication as to the diameter of the beryllium mesh relative to the flow channels. Initial designs of the "fuel" elements were reminiscent of the 19 hole hexagonal cross section elements in the Rover/NERVA nuclear rocket cores. However, discussions with the manufacturer indicated that they could not guarantee complete coating of the flow channels with the Hastelloy. Bare beryllium could easily react with the CO_2 or other gases and erode into the exhaust stream. This might possibly expose the researchers in the lab to beryllium oxides or particles. Consequently, the CSNR acquired specially shaped beryllium rods coated with a 50 micron Hastalloy layer. The rods are shown in Figure 3. The rods have a round cross section with four flats ground at the 90 degree points to create flow channels between the rods.

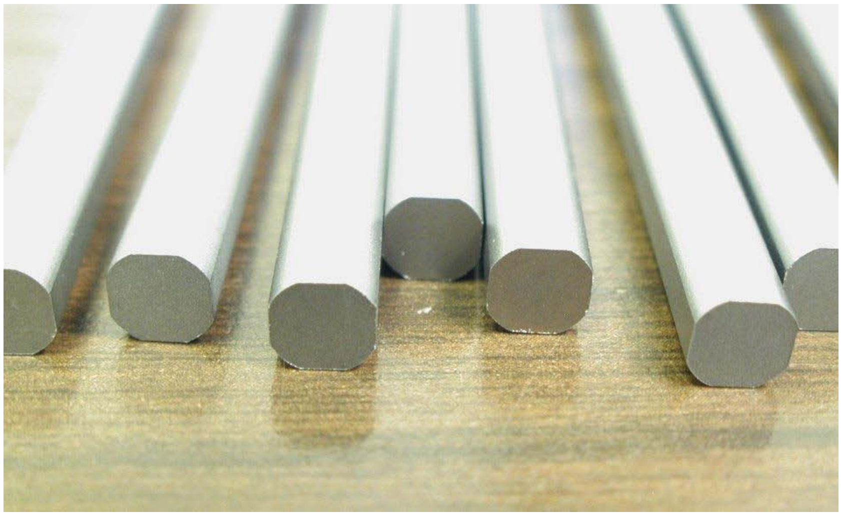

Figure 3. Photograph of finished cylindrical Be elements prior to shipping to Los Alamos National Laboratory.

In order to keep the temperature uniform across the core and to reduce the surface temperature to a level where radiative emission is consistent with the thermal power generated by the isotope, the beryllium core is surrounded by a layer of insulating material, possibly zirconia or aerogel, on the sides and top. The core and zirconia layer rest on a "disk" of zirconia that connects to the pressure vessel. The thickness of this disk is variable but needs to support the core during launch and landing while allowing the least amount of thermal conduction away from the core as possible.

IV. SUBSYSTEM ASSESSMENTS

To complete this project, a team has formed from INL, the Center for Space Nuclear Research, and three universities- Utah State, Oregon State, and the Univ. of Idaho. The major issues that have to be resolved are thermal isolation of the beryllium core, heat transfer from the core to the propellant, choice of insulator materials, design of the core with respect to flow channel size and number, testing and validation of the material behavior during the thermal cycle. In addition, assessment of the benefits of the Hopper concept to space exploration missions is needed to attract participation by NASA HQ and NASA centers.

Operation of the Mars Hopper will be significantly different than previous platforms. The basis of the concept requires many, perhaps hundreds, of thermal cycles. In addition, a substantial temperature range will be encountered by the engine materials during each cycle. Finally, the ability to thermally isolate the core from the pressure vessel places a significant requirement on the design. All of these features necessitate innovative solutions.

However, preliminary efforts indicate that a Hopper can be designed than requires relatively few parts, utilizes local resources, and can repeatedly perform significant jumps.

The major issues which have been examined are: 1) power conversion, 2) CO_2 liquefaction, and 3) thermal management.

IV.1. Power Conversion

The CSNR is currently evaluating the least massive method to use the heat from the core to drive a power conversion system generating the electricity to drive the cryocooler. Two primary options have been identified that can provide power: 1) Stirling engines and 2) open cycle Brayton. The baseline assumption is to use two of the engines being developed for the Advanced Radioisotope Stirling Generator (ASRG) for NASA. The ASRG is a dual piston engine that generates 140 W of electrical power. Total mass of the engines is around 2 kg each.

Alternatively, the idea of using the local Mars atmosphere as a working fluid in a Brayton cycle could enable a lower mass power conversion system. Potentially, an open cycle system that simply heats the incoming, compressed CO2 with the core heat, expands it through a turbine, and exhausts it back to the atmosphere could produce a simple, robust system.

The comparison of power conversion cycles is being examined by Dr. John Crapeau and his students at the University of Idaho.

IV.2. CO_2 liquefaction

The Hopper concept requires that a low mass, low power carbon dioxide (CO_2) liquefaction system be designed to function in the propulsion system of a Mars exploration vehicle. The liquefaction system will collect CO_2 gas from the Martian atmosphere over a period of 7-8 days. To prove the feasibility of this liquefaction system, a testing environment has been developed. Due to the high pressure ratio needed and low power available to compress the necessary CO_2, a mechanical compressor was unable to complete the task. The most successful approach was to freeze the CO_2 to a heat exchanger using a cryocooler to remove the heat. The frozen CO_2 would then be heated and pressurized in a closed volume (an intermediate pressure vessel) to make liquid CO_2. As a result the system is light weight, 13.5 kg (dry), and low power, 242 W. This process also provides for 22 kg of liquid CO_2 to be collected in 7-8 days. With minimal moving parts the system will have a long lifetime. To simulate the Martian environment, the CO_2 will be supplied directly to an intermediate pressure vessel at 4 mbars and 300 K where it will freeze to the copper foam cold tip. The liquefaction system will run its cooling and heating cycles 379 times over an 8 day period which produces .06 kg of liquid CO_2 per cycle.

The design that meets the requirements:

- weighs 6.5 kg (less than the required 28 kg);
- uses 220 W (less than the required 250 W);
- liquifies 0.6 kg in 10 hours (extrapolating this amount and considering the use of two cryocooler systems results in a total of 22 kg being liquified in seven and a half Martian days);and
- provides a low maintenance system with minimal moving parts

This effort is being pursued by Dr. Steven Hansen and his student team at the Utah State University.

IV.3. Thermal Management

Three major issues exist in thermal management: 1) Thermal isolation, 2) Heat transfer to the propellant, and 3) Thermal cycling.

The thermal isolation of the low power thermal source is critical for the core to reach the required temperature in a practical time period. The heat transfer requirement impacts the length and mass of the core. The thermal cycling qualification element of the design will impose lifetime limits for the entire system.

A preliminary proof of principle thermal-hydraulic analysis was performed for the Mars Hopper concept. The analysis was performed to obtain a general behavior on the thermal system mass with several materials that are under consideration. This model, based on the carbon aerogel insulation, allows us to eliminate the vacuum gap between the beryllium and the titanium shell and results in a much lower mass system. The Star-ccm+ software was extensively used to perform the computational fluid dynamics simulation while the GAMBIT software was used to generate the structured mesh.

A 3D simulation of a steady-state blow-down calculation was performed to estimate the average pressure drop across the core channels. This result was then subsequently used as the boundary condition for a following 2D axi-symmetric case to perform a volume averaged transient thermal calculation.

IV.3.1. Configuration

The preliminary design of the Hopper core consists of 1056 coolant channels. Based on a specific coolant channel configuration, a 22.5 degree azimuthally symmetric model was constructed using SolidWorks. Since a steady-state calculation was being performed, a thermal boundary condition of 1200 K was applied at the flow-region and solid-region interfaces (i.e. no beryllium and PuO_2/W matrix exists in this model). Refer to Figure 4.

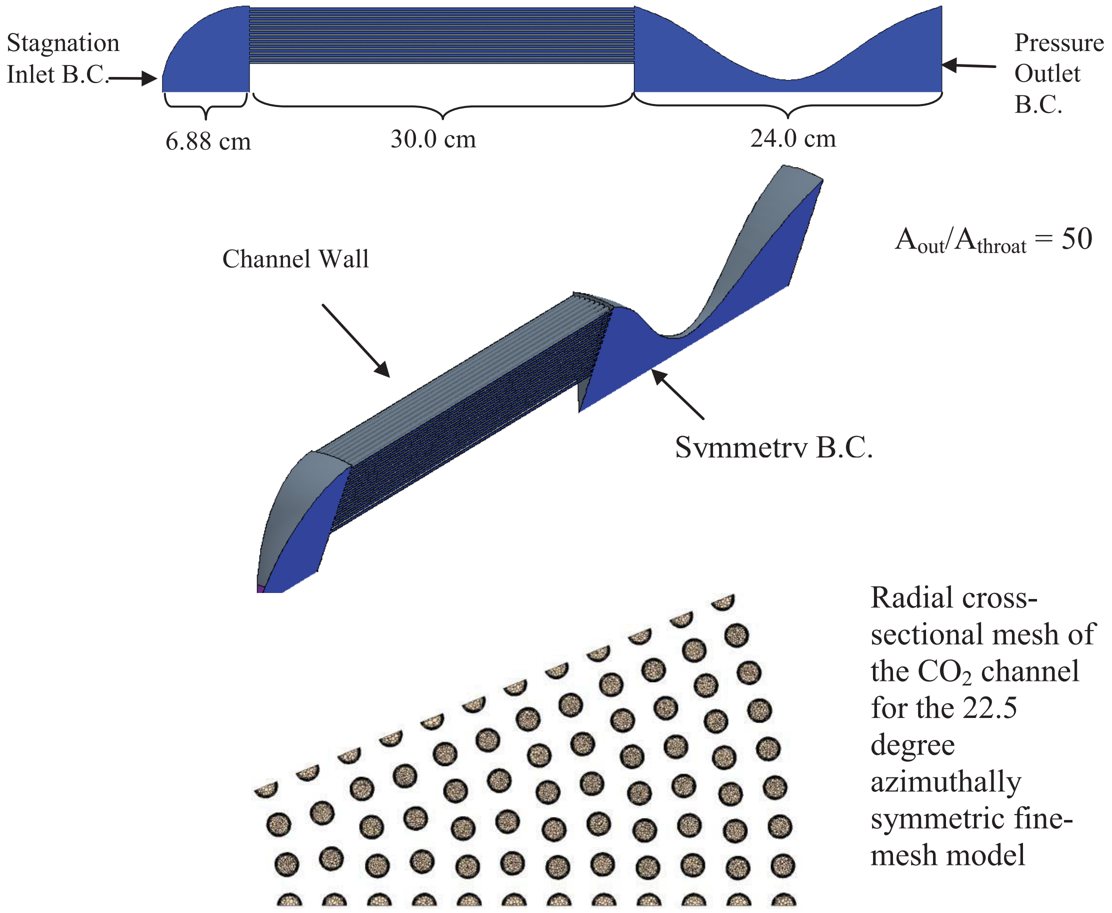

Figure 4. Geometry of 3D 22.5 Degree Symmetry Hopper

IV.3.2. Thermal-Analysis of Steady-State Hopper with Preliminary Configuration

A steady state thermal analysis of the preliminary Hopper system was performed to gain a rough estimation in the initial design parameters and material choice for the detailed engineering optimization and design study. This study includes conductive, convective and radiation heat transfer mechanisms. To reduce the CPU requirements, the CO_2 channels and beryllium was lumped and volume averaged and mass averaged properties were used. Additionally, the CO_2 filling the system (from the worst case scenario of vacuum breach) is treated as an incompressible solid with CO_2 material properties defined at 0.01 Martian atmosphere.

A simple parametric study was performed on the carbon based aerogel insulator thickness as shown in Figure 5.

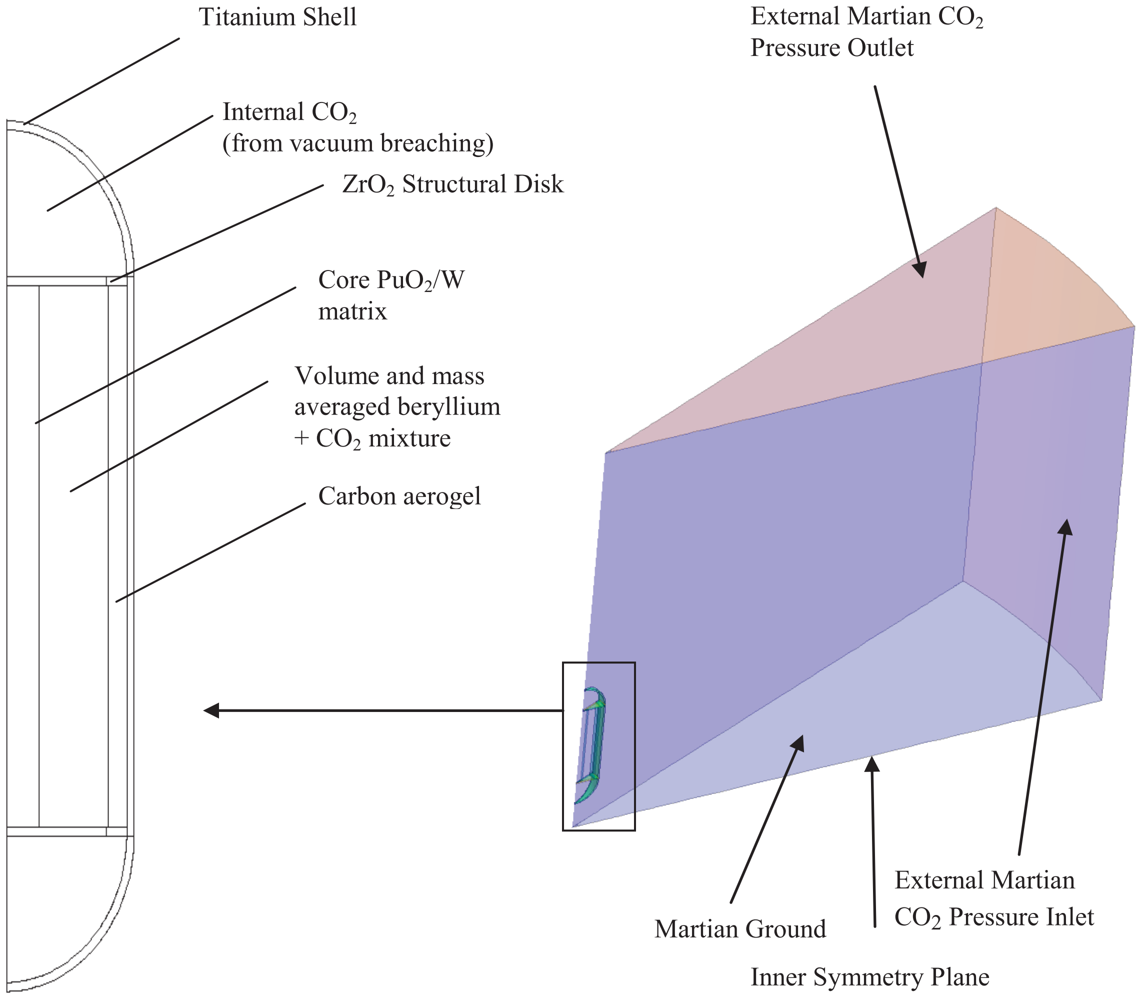

Figure 5. Hopper 3D SS Heat Transfer Analysis Geometry

The current steady-state heat-transfer model consists of a cylindrical Hopper core, an upper and lower plenum (no nozzle), titanium shell and a ZrO_2 support disk. Fixed dimensions were used for the titanium shell thickness and ZrO_2 support disk while varying the aerogel thickness in order to achieve an average core temperature of over 1200 K. The component dimensions are given in Table 2.

IV.3.3. Heat-Transfer Results

This study included the natural convection cooling from the average Martian atmosphere as well as radiation heat transfer. For the radiation heat transfer model, a surface to surface (S2S) model was used. The S2S radiation model becomes applicable to this study due to the intrinsically low density of the Martian atmosphere. The calculation assumes that the absorption and reflection (scattering) of photons with the atmospheric CO_2 is negligible.

In the situation where sufficiently dense CO_2 is encountered, the discrete ordinance method must be used with the appropriate absorption and scattering cross sections for CO_2 in multi-group approximation or homogenized single group analysis. Core average temperature, average titanium shell surface temperature and the total stored thermal energy in the core are given for the three thicknesses of aerogel in Table 3.

TABLE 2. Dimensions for Components

Parts	**Values (cm)**
Fuel Radius	2.305
Beryllium+CO_2 Radius	6.88
Fuel Length	30
Plenum Radius	7.88, 8.13, 8.38
ZrO_2 Disk Inner Radius	6.78 (0.1 cm overlap with Be)
ZrO_2 Disk Outer Radius	7.88, 8.13, 8.38
ZrO_2 Thickness	0.5
Titanium Shell Thickness	0.5
Aerogel Thickness	1.00, 1.25, 1.50

TABLE 3. Heat Transfer Results

Thickness [cm]	Core Average Temperature [K]	Average Radiation Temperature [K] (Titanium)	Stored “Usable” Thermal Energy [MJ]	Thermal System Mass [kg]
1.00	1262.3	730.0	10.2	13.4
1.25	1320.0	723.0	11.2	13.6
1.50	1340.0	715.2	11.6	13.7

As seen in the table, the overall core temperature increases non-linearly as the insulator thickness is increased. The average surface titanium radiation temperature decreases due to the increased surface area. Three varying thicknesses of insulator were investigated for two reasons:

1. To obtain a trend in the peak core average temperature with respect to insulator thickness.
2. To provide an envelope of excess thermal energy for future detailed design. As power conversion units, CO_2 tank (with CO_2 in it) and other instrumentation are included, a greater heat sink and increased surface area for heat loss to the atmosphere will be produced.

An approximate usable thermal energy was calculated based on the specific heat of the beryllium and core PuO_2/W matrix. The thermal energy is usable in a sense that the core temperature cannot drop lower than the beryllium minimum design temperature of 700 K.

This effort is being pursued by the CSNR in collaboration with Dr. Andrew Klein and his students at Oregon State University.

V. ESTIMATED PERFORMANCE

Preliminary results show that a platform carrying a 10 kg payload can hop repeatedly over the Martian surface until some part fails and the craft falters. From a power supply standpoint, the Hopper can operate for decades with the interval between hops growing with time. Initial results indicate that the Hopper could cover over 5-10 km each time. In this scenario, roughly one half of the liquefied propellant is expended during the ascent. The craft then coasts on a ballistic trajectory reaching a peak altitude >1.4 km. At the appropriate altitude after reaching the peak in the ballistic trajectory the engine restarts, i.e. a propellant tank valve opens and the craft descends. As a consequence of the reduced mass during the descent phase, roughly 5% of the propellant is left as a contingency at touchdown. Assuming a thermal power provided by the radioisotope of roughly 1000 W, the ship should be able to repeat the cycle every 5-7 days.

As a result of the range/performance calculations, a point design was developed that set the scale for the masses of components of the Hopper as shown in Table 4.

TABLE 4. Mars Hopper Point Design

Overall	
Total energy stored (J)	1.48e7
Isotope thermal power (W)	1000
Core max temperature (K)	1200
Core Specifications	
Mass Pu-O2 (kg)	2.5
Mass tungsten matrix (kg)	4.55
Length tungsten source (m)	0.30
Radius tungsten source (m)	0.0129
Beryllium mass(kg)	6.068
Outer beryllium radius (m)	0.0728
Thickness of insulation (m)	0.015
Inner pressure vessel rad. (m)	0.1868
Pressure vessel wall (m)	0.001
Core length (m)	0.30
Rad curvature of plenums (m)	0.1268
CO2 tank radius (m)	0.183
Nozzle length (m)	0.3
Total ship length (m)	1.50
Engine specs	
Mass payload (kg)	10
Mass guidance (kg)	12
Mass pressure vessel (kg)	3.0
Mass power convertor (kg)	4
Mass batteries (kg)	5
CO2 tankage (kg)/fraction	1.926/.077
CO2 Propellant mass (kg)	25
Structure mass(kg)/fraction	3.03/.04
Total ship mass dry (kg)	50.744
Total launch mass (kg)	75.744
Performance	
Acceleration factor	3.6
Mass flow rate (kg/s)	1.094
Initial thrust (NT)	1461.6
Initial jet power (w)	976684.
Total burn time (s)	22.86
Range (km)	6.06

VI. SUMMARY AND CONCLUSIONS

Significant progress has been made on all fronts in the project. Computational models for the thermal isolation and the heat transfer issues have been built in both STAR-CCM+ and COMSOL codes. These multiphysics codes are required due to the time-dependent coupling of thermal, fluidic and structural conditions. In addition, the CO_2 liquefaction system has been designed. Furthermore, the design of a test rig to validate the heat transfer from the beryllium core to the CO_2 has been accomplished but may be altered due to concerns of handling hot beryllium in the Center for Advanced Energy Studies building. Finally, beryllium rods coated in Hastelloy have been acquired. More completely, the following tasks have been accomplished:

1) Identification of science missions for the Hopper by the CSNR Summer Fellows. The Fellows assessed the feasibility of a Hopper on the moon Europa, designed a Mars sample return mission enabled by the Mars Hopper, and designed a 10 kWe pulsed power system with a specific mass of 16 kg/kWe for application in Low Earth Orbit;
2) Thermal isolation modeling – steady state temperature profiles of the core with various insulators has been accomplished; a STAR-CCM+ model has been built that includes the core, the pressure vessel, the CO2 storage tank, and the Martian atmosphere;
3) Heat transfer models – time dependent heat transfer calculations for CO2 at various entrance pressures have been completed for 2 mm diameter flow channels using Matlab, STAR-CCM+ and COMSOL;
4) Power conversion systems - various power conversion cycles have been assessed for use with the Hopper and the masses estimated;
5) CO_2 liquefication system design – a cryo-cooler based system that uses 250 W has been designed that can provide sufficient CO_2 in a 7 day interval;
6) Beryllium rods – beryllium rods with two different cross sections have been delivered– circular and hexagonal cross sections.;
7) Test rig design – a test rig has been designed that would raise the beryllium rods to 1200 K and flow CO_2 through the rods. However, concerns about using beryllium at elevated temperatures in the CAES building have been raised; discussions with the Los Alamos National Laboratory's Beryllium Test Facility (BTF) indicate that cold flow tests can be executed at INL but that hot flow tests should be executed at the BTF. Consequently, the test rig must be altered to adapt to the LANL system; and
8) Heat source development- the electrically heated tungsten rod heat source has been designed and discussions with the NASA Marshall Space Flight Center have been initiated.

Preliminary results indicate that a small, compact system with relatively few parts can be designed that will utilize the in-situ Martian resources to "hop" around the surface. Such a probe will enable high-fidelity data to be acquired at hundreds of sites over a period of a few years. Potentially, this system can travel from the equator to a pole in two years. Thus, a comprehensive set of data using the same instruments can be acquired over much of the surface of Mars. In addition, depositing several of these platforms on Mars will allow the entire surface to be mapped within a decade using only a few launches from Earth. Finally, the proof of concept for this system can be performed using electrically heated cores with a modest investment.

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VII. REFERENCES

[1] E. SHAFIROVICH, M. SALOMON, and I. GOKALP, "Mars hopper versus Mars rover", Acta Astronautica, 2006, 59, 710 – 716.

[2] S. MONTMINY, S. DUPUIS, and H. CHAMPLIAUD, “Mechanical design of a hopper robot for planetary exploration using SMA as a unique source of power”, Acta Astronautica, 2008. 62, 438–452.

[3] P. FIORINI and J. BURDECK, “Minimalist jumping robots for celestial exploration”, The International Journal of Robotics Research, 2003, 22, 653–674.

[4] G.A. LANDIS and D. LINNE, “ A Mars rocket vehicle with *in-situ* propellant production”, *J. Spacecr. Rockets* **38**, 730–735, 2001.

[5] D.R. YU, X.W. LV, J. QIN, W. BOA, and Z.L. YAO, “A carbon dioxide thermal rocket that utilizes an indigenous resource in raw form for Mars exploration”, *Proc. Inst. Mech. Eng. G J. Aerosp. Eng.* **224**, 271–281., 2010.

[6] R. C. O’BRIEN, et al., “Spark Plasma Sintering of simulated radioisotope materials within tungsten cermets, Journal of Nuclear Materials”, 2009, 393(1), 108-113.

[7] R. C. O’BRIEN, et al., “Safe radioisotope thermoelectric generators and heat sources for space applications, Journal of Nuclear Materials”, 2008, 377(3), 506-521.

[8] P.J. KARDITSAS and M.J. BAPTISTE, "Thermal and Structural Properties of Fusion Related Materials". United Kingdom Atomic Energy Agency (UKAEA - Fusion)