In Situ Magnetohydrodynamic Energy Generation for Planetary Entry Vehicles

Hisham K. Ali[1] and Robert D. Braun[2]**

[1]hisham.ali@gatech.edu, [2]robert.braun@ae.gatech.edu, *Georgia Institute of Technology Space Systems Design Laboratory

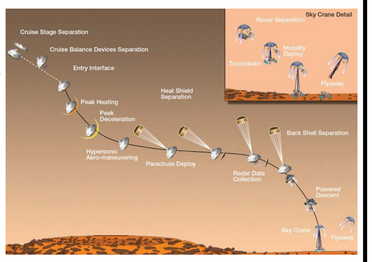
Introduction and Background

Abstract

Proposed missions such as a Mars sample return mission and a human mission to Mars require landed payload masses in excess of any previous Mars mission[1]. Whether human or robotic, these missions present numerous engineering challenges due to their increased mass and complexity. To overcome these challenges, new technologies must be developed, and existing technologies advanced. Mass reducing technologies are particularly critical in this effort. For example, the Mars Pathfinder entry vehicle dissipated approximately 92% of its kinetic energy during the hypersonic phase of its single pass entry profile[2]. Previous research conducted at NASA Langley Research Center studied the potential for reclamation of kinetic energy dissipated in this phase through magnetohydrodynamic power generation[3]. The proposed work aims to study the suitability of multi-pass entry trajectories for harnessing of vehicle kinetic energy through magnetohydrodynamic power generation from the high temperature entry plasma, reclaiming energy otherwise dissipated as heat. A systems analysis including the above elements is presented, analyzing tradeoffs between entry trajectories, available energy storage technologies, and system mass. These results will be compared with earlier work on the subject as presented in [3]. Potential mission configurations and power storage configurations are explored, with results including trajectories, percentage kinetic energy reclaimed, and additional system mass for various energy storage technologies.

Mars Entry, Descent, and Landing (EDL) Challenges

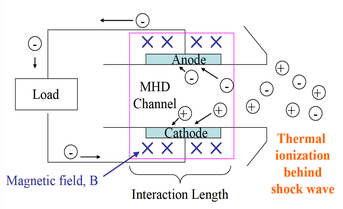
- Reduce velocity from several km/s to zero
- Requires large kinetic energy change, usually through atmospheric drag
- Relatively thin Martian atmosphere limits aerodynamic deceleration, but still causes significant thermal challenges
- High mass Mars landings prove difficult, require elaborate solutions

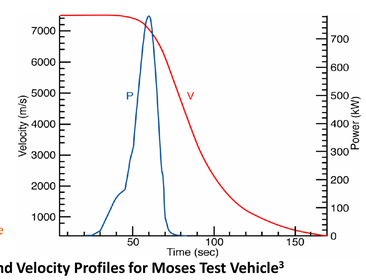


Mars Science Laboratory EDL (Image courtesy NASA)

Magnetohydrodynamic (MHD) Energy Generation and EDL

- Rapid atmospheric deceleration at hypersonic speed causes thermal ionization in the shock layer
- Numerous free electrons that can be influenced by magnetic fields in a MHD energy generator to create an electrical current
- MHD generator converts vehicle kinetic energy otherwise lost as heat into useful electrical energy, termed 'regenerative aerobraking'[3]





MHD Energy Generator and Power and Velocity Profiles for Moses Test Vehicle[3]

- MHD energy generation has potential to reduce overall system mass by converting normally wasted energy into electrical energy
- Want to study this problem for Mars planetary entry in a variety of cases, including direct entry and multi pass orbit cases
- Electrical energy storage system is critical

Methodology and Experimental Design

Calculating Power Available for MHD Energy Generation

- Power available for extraction via MHD energy generation varies as follows:

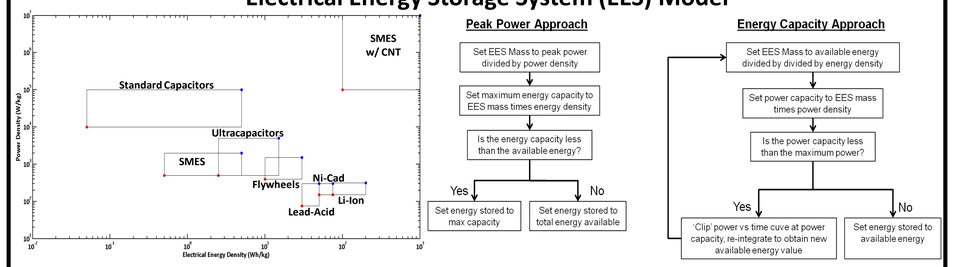
$$P_g \sim n_e u^2 B^2 A_c L_c$$

- Application of the above scaling law to trajectory velocity profile produces power generated versus time curve
- Magnetic field, area, and length scale left constant
- Power estimated from prior thermochemical code results[3]

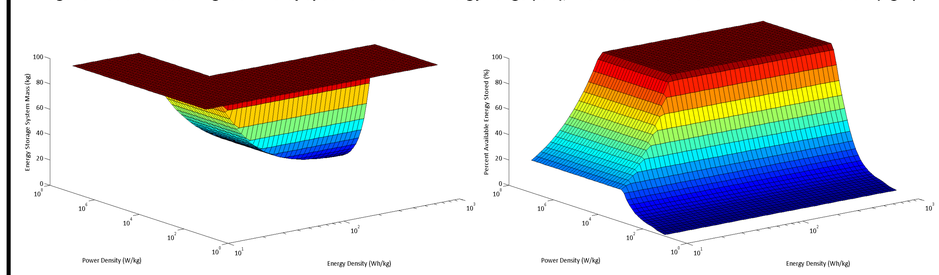
Test Vehicle Configurations

Property	Moses Test Vehicle[3]	Pathfinder	Mars Science Lab
Mass (kg)	1000	582	2800
C_D	0.40	0.40	0.67
A (m^2)	7.00	5.52	16.6
V_{entry}(km/s)	5.00	5.00	5.00

Electrical Energy Storage System (EES) Model



Ragone Plot Characterizing Each EES by Specific Power and Energy Range (left), EES Mass and Performance Model Flowchart (right)



EES Mass (left) and Performance (right) for Mars Pathfinder Class Profile[3], Constrained to 10% of Vehicle Mass, or 100kg

Generating Trajectories and MHD Power vs. Time Profiles

- Direct entry cases have consequence of very high power levels for a short period of time
- Multi-pass orbits allow for extraction of energy at moderate power levels for a longer period of time
- Multi-pass orbits generated experimentally by changing entry flight angle initial condition and integrating the following:

$$\ddot{\bar{r}} = -\frac{\mu}{|\bar{r}|^3}\bar{r} - \frac{\rho}{2\beta}\left(\dot{\bar{r}} \bullet \dot{\bar{r}}\right)\hat{\dot{\bar{r}}}$$

- Where β is the ballistic coefficient, given below as follows

$$\beta = \frac{m}{C_D A}$$

Moses Test Vehicle[3] Complete Passes	γ_{entry} (degrees)	Time in Atmosphere (s)
2	-5.50	1350
4	-4.65	2017
6	-4.05	2549
8	-3.60	2965
10	-3.20	3312

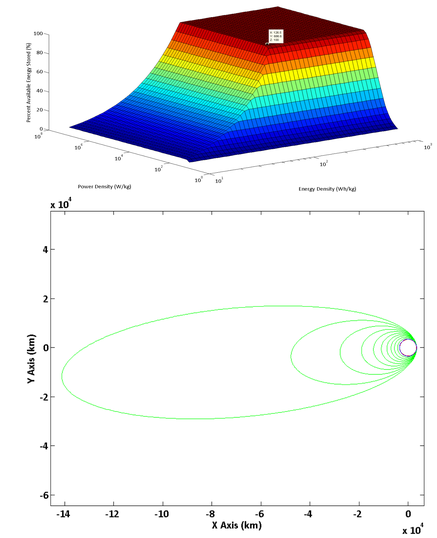
Pathfinder Complete Passes	γ_{entry} (degrees)	Time in Atmosphere (s)
2	-5.10	1313
4	-4.20	1900
6	-3.55	2346
8	-3.05	2676
10	-2.70	2961

Mars Science Lab Complete Passes	γ_{entry} (degrees)	Time in Atmosphere (s)
2	-5.00	1321
4	-4.10	1888
6	-3.50	2309
8	-2.95	2626
10	-2.55	2852

Results and Discussion

Complete Passes	Moses Test Vehicle[3] Energy Available (MJ)	Moses Test Vehicle[3] Energy Available Per Orbit (MJ/Pass)	Pathfinder Energy Available (MJ)	Pathfinder Energy Available Per Orbit (MJ/Pass)	Mars Science Lab Energy Available (MJ)	Mars Science Lab Available Per Orbit (MJ/Pass)
2	265.3	132.7	187.1	93.5	176.1	88.1
4	239.1	59.8	164.6	41.1	154.3	38.6
6	217.7	36.3	146.3	24.4	137.8	23.0
8	200.3	25.0	133.1	16.6	124.5	15.6
10	185.9	18.6	124.0	12.4	115.5	11.6

Seeded Multi-Pass Trajectories yield about 1 order of magnitude more energy than the 14MJ obtainable during the direct entry case for the Moses Test Vehicle[3]



Multi-Pass Trajectory and EES Performance for 10 Pass Mars Science Lab Orbit. Minimum EES performance for 100% Energy Storage at less than 10% Vehicle Mass Indicated by Data Cursor.

Conclusions and Future Plans

- Multi-pass orbits can yield orders of magnitude more available energy
- Storing this excess energy within a limited mass envelope proves difficult, even with forecasted advances in electrical energy storage
- MHD energy generation could thus prove even more useful for higher mass missions such as Mars Sample Return and Human Class missions
- Future plans include study of additional vehicle configurations, as well as investigation of implications for flight dynamics

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