Analysis of Liquid Hydrogen Propellant Density on Microwave Thermal Rocket Structural Margins

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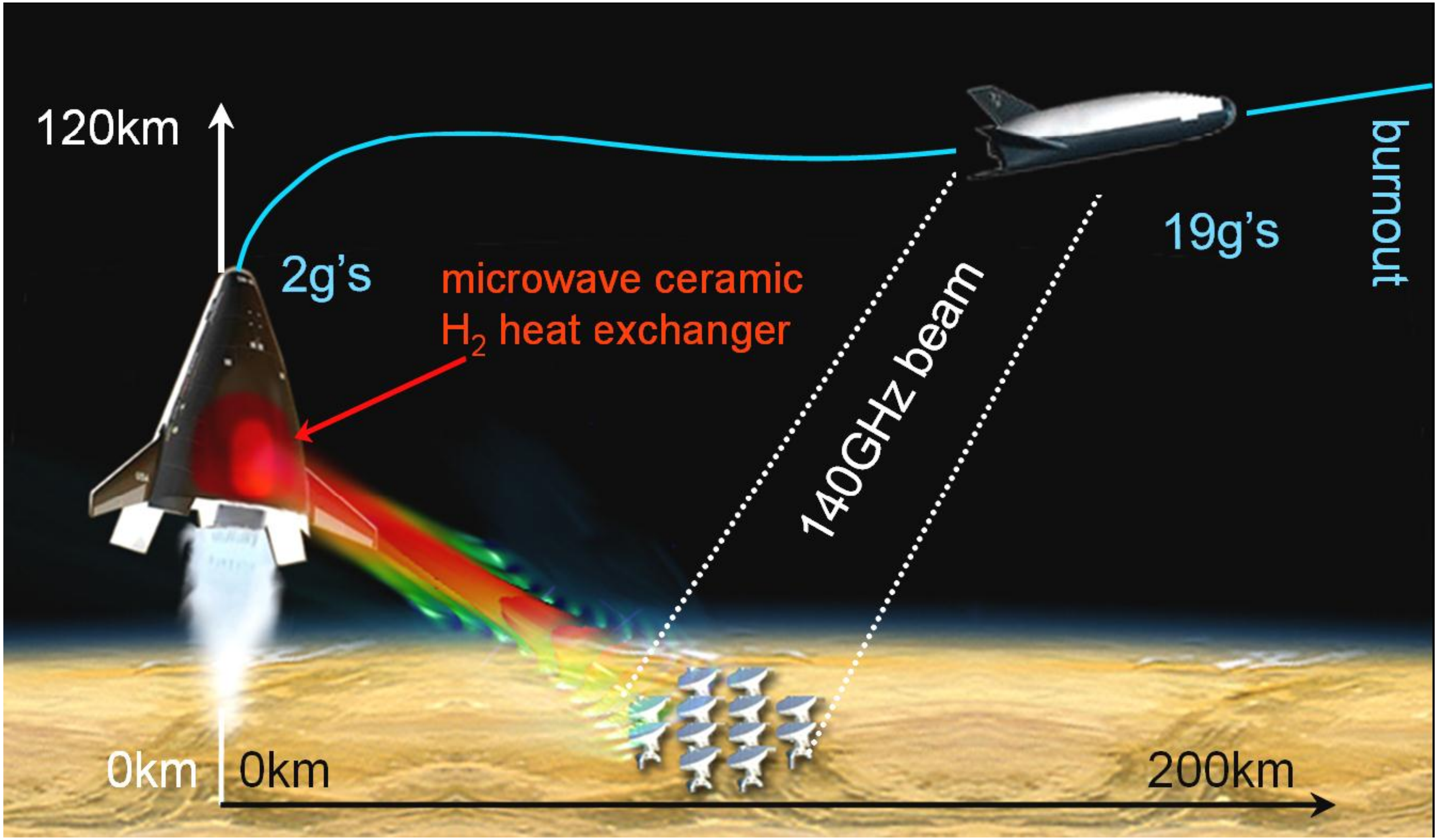
Basic Concept

- Utilize Ground Based Phased Microwave Array to Power Spacecraft to Orbit
  - Order of 100 Mega Watts Required!
- High Specific Impulse and Thrust to Weight Ratio
  - Calculations Yield Isp 900s, T/W > 50
- Hydrogen propellant, High heat capacity, 14 J/gK
- Note: Lower propellant temperature, but higher Isp

$$u_e = \sqrt{2c_p\left(T_0 - T_e\right)}$$

- Note: Microwaves can be replaced by lasers or onboard nuclear power
  - General category of “thermal” rockets

Basic Concept



Parkin, K. L. G., The Microwave Thermal Thruster and Its Application to the Launch Problem, PhD dissertation, California Institute of Technology, Department of Aeronautics, May 2006.

Motivation & Objective

- This is not a presentation on developing beamed energy propulsion, but rather analyzing its advantages **assuming** the technology works
- Debate has arisen over the payload fractions obtainable
- Lower LH_2 (70 vs 1,000 kg/m^3) density propellant yields heavier tanks and turbopumps than L0x/RP1
- John Carmack of Armadillo Aerospace eloquently posed this thought experiment:
  - If I took a rocket that used pure LH_2 fuel and filled up the giant tank with high density L0x/RP1. I would have a mass fraction sufficiently good to achieve SSTO with an Isp below 300s.
- Further criticism of the MTR came from the comparisons typically done between chemical and thermal rockets
  - Jordan Kare and others have used composite tanks in their designs to compare with existing vehicles.[2]
- As a result a study was done to better compare vehicles

[2]Kare, J. T., "Laser Powered Heat Exchanger Rocket for Ground-to-Orbit Launch," *Propulsion and Power Journal*, Vol. 11, No. 3, 1995, pp. 535-543.

Analysis

- Two comparisons were made:
  1. Conservative: Assume currently available tank materials and pumps
  2. Optimistic: Stretch the state of the art and allow for superior materials and pumps
- It is critical that everything remain consistent in the comparison
- Further debate has arisen as to what the fair metric of comparison should be for a low cost vehicle
  - Is it payload fraction? Or more related to Vehicle Volume?
  - A parameter ψ was introduced which is the payload fraction divided by the structural mass fraction

$$\psi = \frac{\text{Maximum Payload}}{\text{Structural Mass}}$$

- A vehicle must be robust in order to be reusable and low cost
- Robustness is achieved by adding structural margins to the load bearing components and by adding redundant components to the vehicle.

Analysis

- To clarify this, suppose for example there are two vehicles that both must achieve orbit.
  - Vehicle one has a very high specific impulse and only 50% of the gross lift-off weight (GLOW) is fuel and 30% is structural mass for the tanks, pumps etc, and the leftover mass for payload is 20%.
  - Suppose vehicle two has a lower specific impulse and 90% of the GLOW is fuel; however, 2% is structural mass and 8% is payload.
  - A priori vehicle one seems more attractive due to its much higher potential payload; however, Ψ for the two vehicles are respectively .66 and 4.
  - Without knowing more specifics on reentry and g forces, vehicle two seems more attractive for reusability due to the higher mass margins for the components.
- Note: This is analysis is coarse for rules of thumb thinking

General Vehicle Parameters				
Propulsion System	MTR (2g)	MTR (1g)	LO_x/kerosene	LO_x/LH_2
Mission Delta Velocity	9.6 km/s	9.6 km/s	9.3 km/s	9.6 km/s
Vehicle at Liftoff	10,000 kg	10,000 kg	10,000 kg	10,000 kg
Specific Impulse	900 s	900 s	350 s	450 s
Propellant Mass	6,633 kg	6,633 kg	9,664 kg	8,866 kg
Vehicle at Burnout	3,367 kg	3,367 kg	664 kg	1,134 kg

Tank Mass

- Tank analysis
  - Space shuttle tanks, LH_2 density 70 kg/m^3
  - A conservative estimate generated from the Aluminum Lithium 2195 for the Super Light Weight Tank[1]

$$\text{Conservative Tank Mass} = \frac{1}{5}\text{Mass } LH_2$$

  - For an optimistic comparison, the composite tanks are estimated to have:

$$\text{Optimistic Tank Mass} = \frac{1}{10}\text{Mass } LH_2$$

  - LOx/LH_2 has a bulk density of 358 kg/m^3. and the mass ratio of the tank is roughly 0.039.
  - LOx/RP1 has a bulk density of 1,011 kg/m^3. and the mass ratio of the tank is roughly 0.015.
- Pump Analysis
  - Involved some detailed scaling calculations; however, a few examples were found that matched the specifications

1. Baker, D., Jane's Space Directory 2004-2005 20th EDITION , Jane's Information Group Inc., Virginia, USA, 2004, pp. 321, 351, 360, 563-564, This information was taken from the Launch Vehicle Propulsion 15 of 16 section, France Societe Europeenne de Propulsion, Boeing Space Division and United Technologies Pratt and Whitney (Liquid Propulsion).

Pump Mass

Pump	Propellant	Stages n	Density kg/m^3	$\dot{m}$ kg/s	Q m^3/s	N_r r/s	Power (W)	Pressure (Pa)	Mass (kg)
Turbopumps based on existing engines[3]									
Vulcain	LO_x	1	1140	226	0.198	1434	3.30×10^6	1.52×10^7	130
Vulcain	LH_2	2	70	36	0.520	3632	1.19×10^7	1.62×10^7	240
P&W RL10A-3-3A	LO_x	1	1140	14	0.012	1371	8.80×10^4	4.62×10^6	11
P&W RL10A-3-3A	LH_2	2	70	3	0.040	3433	-	7.72×10^6	34
SSME	LO_x	1	1140	408	0.358	2983	1.79×10^7	2.96×10^7	261
SSME	LH_2	3	70	68	0.971	3559	4.62×10^7	4.20×10^7	351
Turbopumps designed for Nuclear Thermal Rockets[8]									
Axial 1,743	LH_2	3	70	17	0.243	6877	3.22×10^6	1.10×10^7	49
Cent 1,743	LH_2	1	70	17	0.243	6992	3.47×10^6	1.10×10^7	50
Axial 4,480	LH_2	5	70	37	0.529	6688	1.75×10^7	2.72×10^7	149
Cent 4,480	LH_2	2	70	37	0.529	6720	1.87×10^7	2.72×10^7	154

3. Baker, D., Jane's Space Directory 2004-2005 20th EDITION , Jane's Information Group Inc., Virginia, USA, 2004, pp. 321, 351, 360, 563-564, This information was taken from the Launch Vehicle Propulsion 15 of 16 section, France Societe Europeenne de Propulsion, Boeing Space Division and United Technologies Pratt and Whitney (Liquid Propulsion).
8. Bissell, W. R. and Gunn, S. V., \Turbopump Options for Nuclear Thermal Rockets," AIAA Paper 92-3858, July 1992.

Vehicle Mass Comparison

Propulsion System	MTR (2g)	LO_x/Kerosene	LO_x/LH_2
Conservative Vehicle Mass Estimations			
Al 2195 Tank	1,327 kg	140 kg	345 kg
SSME Turbopump	500 kg	-	-
Heat Exchanger	60 kg	-	-
Nozzle and Thrust Chamber	141 kg	-	-
Complete Propulsion System	-	212 kg	300 kg
Total Component Mass	2,028 kg	352 kg	645 kg
Maximum Payload Mass	1,339 kg	312 kg	489 kg
Maximum Payload Fraction	13.4 %	3.12 %	4.89 %
Structural Parameter Ψ	0.66	0.89	0.76
Optimistic Vehicle Mass Estimations			
Propulsion System	MTR (1g)	LO_x/Kerosene	LO_x/LH_2
Composite Tank	663 kg	70 kg	173 kg
1 X Axial 4,480 Turbopump	150 kg	-	-
Heat Exchanger	30 kg	-	-
Nozzle and Thrust Chamber	72 kg	-	-
Complete Propulsion System	-	197 kg	260 kg
Total Component Mass	915 kg	267 kg	433 kg
Maximum Payload Mass	2,452 kg	397 kg	701
Maximum Payload Fraction	24.5 %	3.97 %	7.01 %
Structural Parameter Ψ	2.68	1.49	1.62

Conclusion

- With existing technology LOx/RP1 does the best
- With stretches in technology or lower thrust there is an advantage to thermal rockets
- With superior materials etc the thermal may be advantages
  - Many technological hurdles
  - New systems need to be much better than state-of-the-art in order to replace the existing infrastructure
  - Conservative Psi with LOx/RP1 density and Isp 900 s is 8.6!
- May be useful as a second stage or with denser, lower Isp propellants
- Currently Dr. Kevin Parkin and Stanford graduate student David Murakami are working on developing a heat exchanger propulsion system at NASA Ames
- Key area for academic research: Structures!!

Future Work

- Increase fidelity of analysis
- Two main areas of focus
  - Decide on a vehicle configuration, wings etc
  - 1. Find structural mass more accurately including wings, spars, not just tanks, pumps, nozzles etc
  - 2. Estimate heat shield mass!
  - Take a serious look at using the heat exchanger as a heat shield!!
- Smaller Issues
  - Better estimate tank masses
  - Look more into the psi parameter and see if it makes sense with a considerable payload
  - Also look briefly at propellant costs etc. LOx is 5 cents/pound, RP1 50 cents, LH_2 is $3!

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