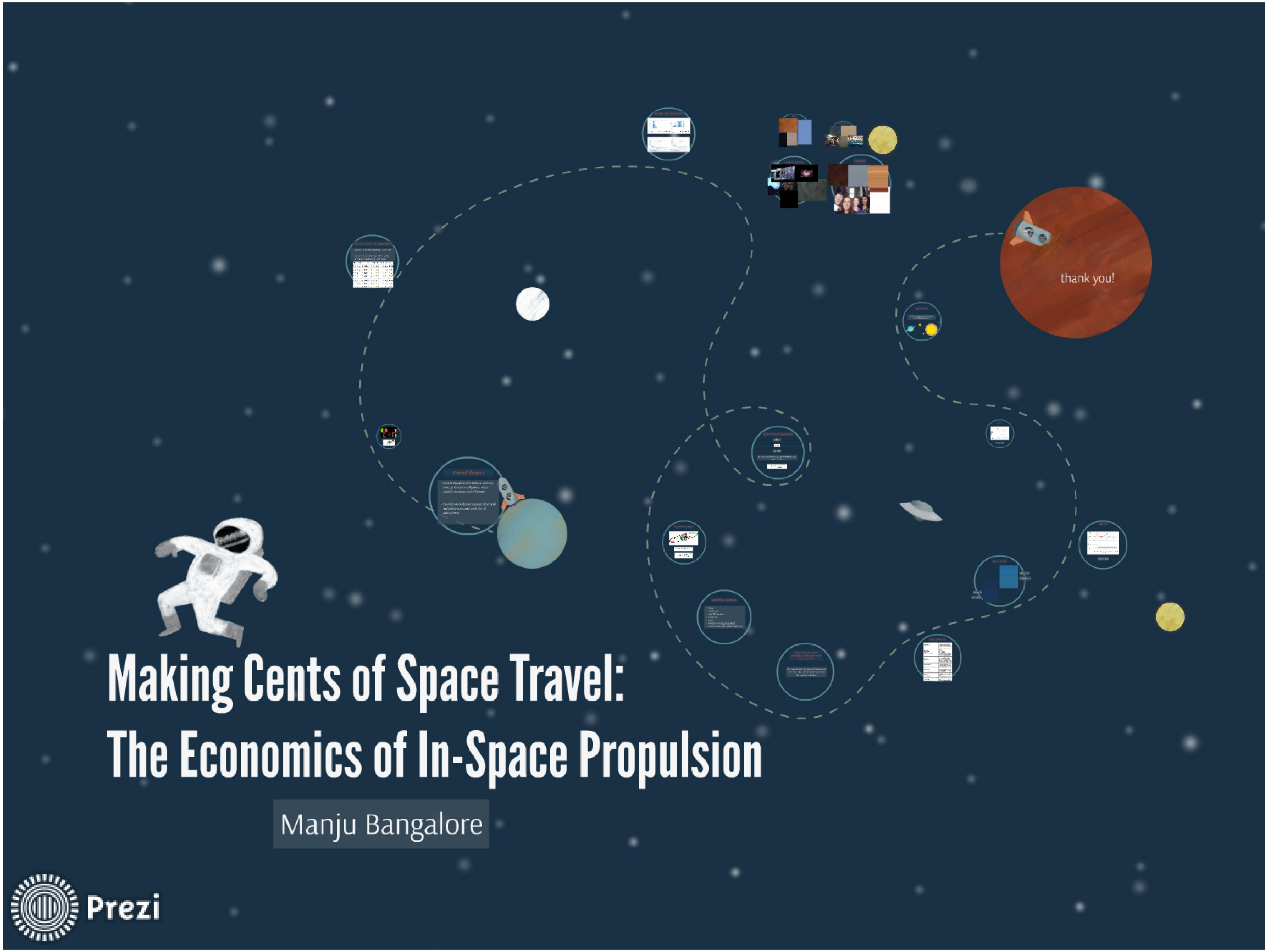
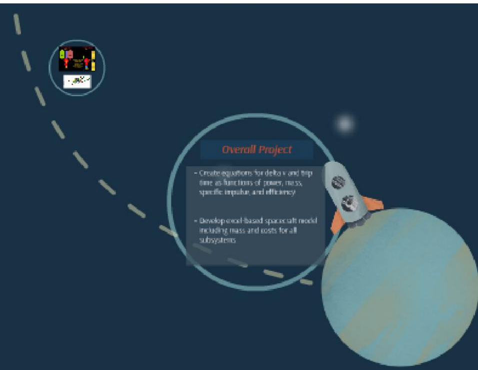
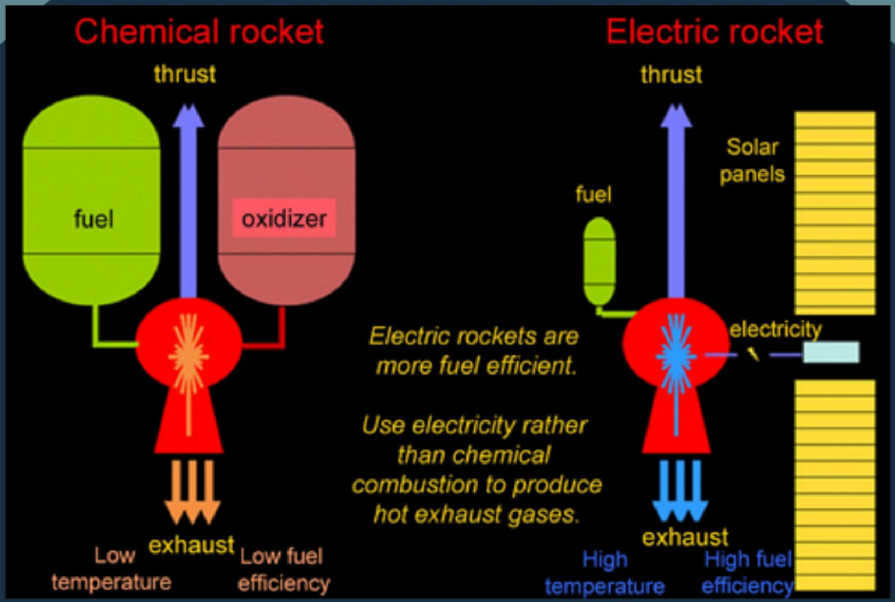
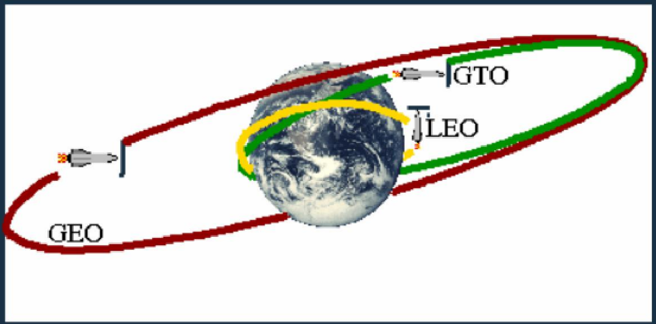

thank you!
Making Cents of Space Travel:
The Economics of In-Space Propulsion
Manju Bangalore
Prezi



Making Cents of Space Travel: The Economics of In-Space Propulsion

Manju Bangalore


Chemical rocket
thrust
fuel
oxidizer
exhaust
Low temperature
Low fuel efficiency
Electric rocket
thrust
fuel
Solar panels
electricity
exhaust
High temperature
High fuel efficiency
Electric rockets are more fuel efficient.
Use electricity rather than chemical combustion to produce hot exhaust gases.


GTO
LEO
GEO

Prezi

Overall Project

- Create equations for delta v and trip time as functions of power, mass, specific impulse, and efficiency
- Develop excel-based spacecraft model including mass and costs for all subsystems

Procurement of Equations

- Utilized SEPSPOT, MATLAB, and Excel
- Cases vary by orbit, specific impulse, efficiency, shadowing, and power

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	casenu	M0	P0	Isp	Eff	f0	Time	SMA	Ecc	Incl	Mass	RPow	Pow	Flunc	Per	dV	acc
2	1	4000	0.5	800	30	9.53E-07	28.72	42158	0.00021	0.001	2858.4	1	0.48	0.1	23.929	2.6362	9.55657E-09
3	17	4000	0.75	800	30	8.26E-11	19.16	42164	0	0	2858	1	0.73	0.1	23.934	2.6372	1.43349E-08
4	5	4000	0.5	900	30	5.68E-14	32.9	42164	0	0	2966.5	1	0.48	0.1	23.934	2.6381	8.49473E-09
5	21	4000	0.75	900	30	8.35E-10	21.93	42164	0	0	2966.8	1	0.73	0.1	23.934	2.6373	1.27421E-08
6	37	4000	1	900	30	2.07E-07	16.45	42161	4.00E-05	0	2966.8	1	0.97	0.1	23.932	2.6373	1.69895E-08
7	53	4000	1.25	900	30	3.74E-12	13.16	42164	0	0	2966.7	1	1.21	0.1	23.934	2.6377	2.12368E-08
8	85	4000	1.75	900	30	2.92E-09	9.4	42164	3.00E-05	0.001	2966.7	1	1.69	0.1	23.934	2.6376	2.97316E-08
9	9	4000	0.5	1000	30	2.72E-11	37.04	42164	0	0	3057.1	1	0.49	0.1	23.934	2.6363	7.64526E-09
10	25	4000	0.75	1000	30	1.75E-08	24.71	42164	3.00E-05	0.001	3056.9	1	0.73	0.1	23.934	2.6369	1.14679E-08
11	41	4000	1	1000	30	2.63E-12	18.53	42164	0	0	3056.8	1	0.97	0.1	23.934	2.6374	1.52905E-08
12	57	4000	1.25	1000	30	3.41E-11	14.83	42164	0	0	3056.7	1	1.21	0.1	23.934	2.6375	1.91131E-08
13	73	4000	1.5	1000	30	4.60E-11	12.36	42164	0	0	3056.7	1	1.45	0.1	23.934	2.6375	2.29358E-08
14	89	4000	1.75	1000	30	7.87E-09	10.59	42165	1.00E-05	0	3056.7	1	1.69	0.1	23.935	2.6375	2.67584E-08
15	29	4000	0.75	1100	30	1.35E-10	27.49	42164	0	0	3132.6	1	0.73	0.1	23.934	2.6367	1.04254E-08
16	61	4000	1.25	1100	30	8.08E-10	16.5	42164	0	0	3132.4	1	1.21	0.1	23.935	2.6374	1.73756E-08
17	93	4000	1.75	1100	30	4.18E-12	11.79	42164	0	0	3132.2	1	1.69	0.1	23.934	2.638	2.43258E-08
18	1	4000	0.5	1200	30	3.75E-12	45.38	42164	0	0	3197.5	1	0.49	0.1	23.934	2.6351	6.37105E-09
19	129	4000	1.5	1200	30	6.99E-08	15.14	42163	0.00018	0.01	3197	1	1.45	0.1	23.934	2.6371	1.91131E-08
20	161	4000	1.75	1200	30	7.54E-10	12.98	42164	1.00E-05	0	3196.8	1	1.69	0.1	23.934	2.6377	2.22987E-08
21	33	4000	0.75	1200	30	3.44E-10	30.28	42164	2.00E-05	0	3197.1	1	0.73	0.1	23.934	2.6366	9.55657E-09
22	65	4000	1	1200	30	4.46E-14	22.72	42164	0	0	3197	1	0.97	0.1	23.934	2.637	1.27421E-08
23	9	4000	0.5	1400	30	9.03E-07	53.7	42169	0.00028	0.019	3301.3	1	0.49	0.1	23.939	2.6358	5.4609E-09
24	105	4000	1.25	1400	30	1.42E-08	21.53	42163	5.00E-05	0.001	3301	1	1.21	0.1	23.934	2.6371	1.36522E-08
25	137	4000	1.5	1400	30	3.59E-10	17.94	42164	0	0	3300.9	1	1.45	0.1	23.934	2.6373	1.63827E-08
26	169	4000	1.75	1400	30	9.11E-13	15.38	42164	0	0	3300.8	1	1.69	0.1	23.934	2.6376	1.91131E-08
27	41	4000	0.75	1400	30	4.82E-10	35.87	42164	1.00E-05	0	3301.2	1	0.73	0.1	23.934	2.6363	8.19135E-09
28	73	4000	1	1400	30	3.23E-15	26.9	42164	0	0	3301	1	0.97	0.1	23.934	2.6368	1.09218E-08
29	113	4000	1.25	1600	30	3.06E-13	24.88	42164	0	0	3381.2	1	1.21	0.1	23.934	2.6369	1.19457E-08
30	145	4000	1.5	1600	30	1.46E-14	20.74	42164	0	0	3381.1	1	1.45	0.1	23.934	2.6373	1.43349E-08
31	17	4000	0.5	1600	30	3.95E-08	62.04	42163	3.00E-05	0	3382	1	0.49	0.1	23.933	2.6332	4.77829E-09
32	177	4000	1.75	1600	30	2.61E-13	17.78	42164	0	0	3381.1	1	1.69	0.1	23.934	2.6373	1.6724E-08
33	49	4000	0.75	1600	30	2.36E-09	41.42	42164	1.00E-05	0	3381	1	0.73	0.1	23.935	2.638	7.16743E-09
34	81	4000	1	1600	30	1.30E-08	31.1	42163	2.00E-05	0	3381.3	1	0.97	0.1	23.934	2.6364	9.55657E-09
35	121	4000	1.25	1800	30	7.07E-10	28.24	42164	0	0	3445	1	1.21	0.1	23.934	2.6367	1.06184E-08
36	153	4000	1.5	1800	30	2.77E-09	23.54	42164	2.00E-05	0.001	3444.9	1	1.45	0.1	23.934	2.637	1.27421E-08
37	185	4000	1.75	1800	30	2.61E-12	20.18	42164	0	0	3444.9	1	1.69	0.1	23.934	2.6373	1.48658E-08
38	57	4000	0.75	1800	30	2.21E-12	47.02	42164	0	0	3445.3	1	0.73	0.1	23.934	2.6352	6.37105E-09

Graphs for Equations

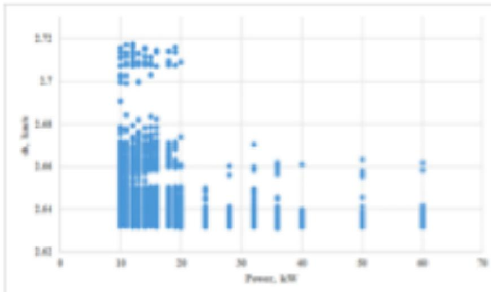


Figure 1. Power versus ΔV for GTO to GEO with shadowing on.

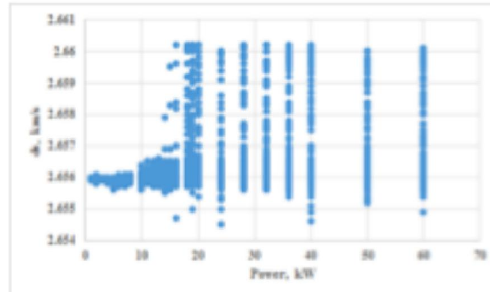


Figure 2. Power versus ΔV for GTO to GEO with shadowing off.

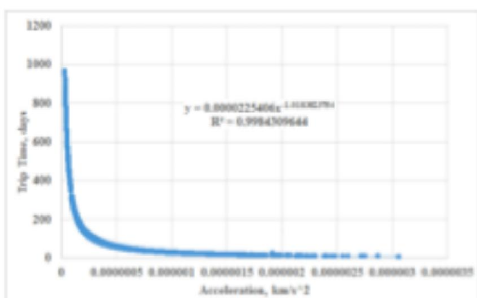


Figure 3. Trip time in terms of acceleration for GTO to GEO shadow on.

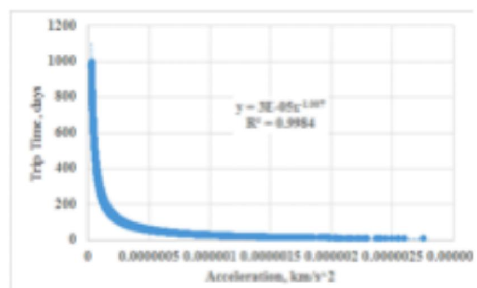


Figure 4. Trip time in terms of acceleration for GTO to GEO shadow off.

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GTO to GEO Equations

Delta V

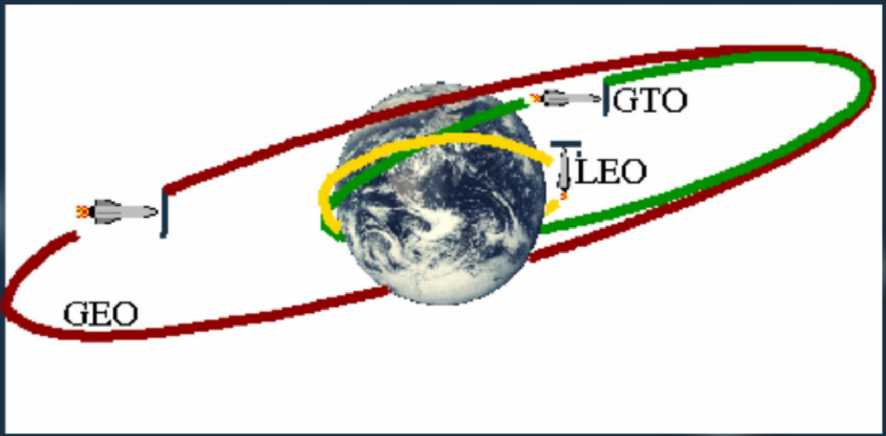
$\Delta V = 2.65$

Trip Time

as a function of start mass, power, efficiency, and specific impulse:

$$t = (2\times10^{-5})\left(\frac{2\eta p}{m_o g I_{sp}}\right)^{-1.018}$$

Incremented Apogee



$$c = -0.44\ln(a) + 5.6203$$

$$t = (c)(2\times10^{-5})\left(\frac{2\eta p}{m_o g I_{sp}}\right)^{-1.018}$$

When does low-thrust propulsion make more sense than chemical?

We have to look at mass utilization and the time-value of the mission to find the optimal solution.

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Sensitivity Analyses

- Power
- Start mass
- Specific impulse
- Efficiency
- Cost
- Revenue ($k/kg) of payload
- Launch costs (for specific vehicles)

Spacecraft Model

Propulsion Wet Mass, kg	979.7339566. This was found by adding the tank mass, the propellant mass, and the total propulsion dry mass.
SEP Radiator Mass, kg	17.76669319. This was found by subtracting the PPU efficiency from 1 and multiplying it by the maximum SEP power and 1000, dividing it by 5.67 x 10^{-8}, multiplying it by radiator emissivity, dividing it by the difference of the radiator temperature to the fourth and the environment temperature to the fourth, dividing it by two, and multiplying it by the radiator areal density.
Battery Mass, kg[11]	0.001333333
Power BOP Mass, kg	40. This is an estimate.
Avionics Mass, kg	50. This is an estimate.
Dry Mass w/o Structure and Tanks, kg	912.7709984. This is the sum of the total propulsion dry mass without tank, the array mount and tilt mass, the SEP radiator mass, the battery mass, the power BOP mass, the avionics mass, and the solar array mass.
Structure Mass, kg	139.4382183. This is calculated by multiplying the structures percentage by the sum of the dry mass without structure and tanks and the tank mass.
Delta V, km/s	2.65. This is derived from the SEPSPOT curves.
Ideal Final mass, kg	3655.5632362. This was found by taking the exponential of the product of 1000 and the ΔV and the reciprocal of the gravitational constant multiplied the specific impulse and multiplying it by the initial mass.
Starting specific power, W/kg	0.01. This was found by dividing the maximum SEP power by the start mass.
Starting acceleration, m/s2	4.41726E-07. This was found with the Rocket Equation. The calculation was 2 times the efficiency and power of the spacecraft divided by g, the initial mass, and the specific impulse.
Total Propellant Mass, kg	373.713861. This is the propellant residual mass added to the difference of the start mass and final mass.
Propellant Residual Mass, kg	29.27712275. This is the difference of the start and final spacecraft mass multiplied by the propellant and residuals percentages.
Required Propellant, kg	344.4367383. This is calculated by subtracting the final mass from the initial mass.
Tank Mass, kg	16.81712375. This is calculated by multiplying the total propellant by the tank mass fraction.
Trip Time, Days	66.77740889. This is derived from the SEPSPOT curves.
Total SEP Wet Mass, kg	1442.740201. This is the sum of the dry mass without the structure and tanks, the structure mass, the tank mass, and the propellant mass.
Non-SEP Mass, kg	2557.259799. This is the total SEP wet mass subtracted from the initial mass.
Partial SEP Cost, $K	$94,240.71. This is the sum of costs of the solar array, the product of the hardware per string and the

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Launch Vehicles

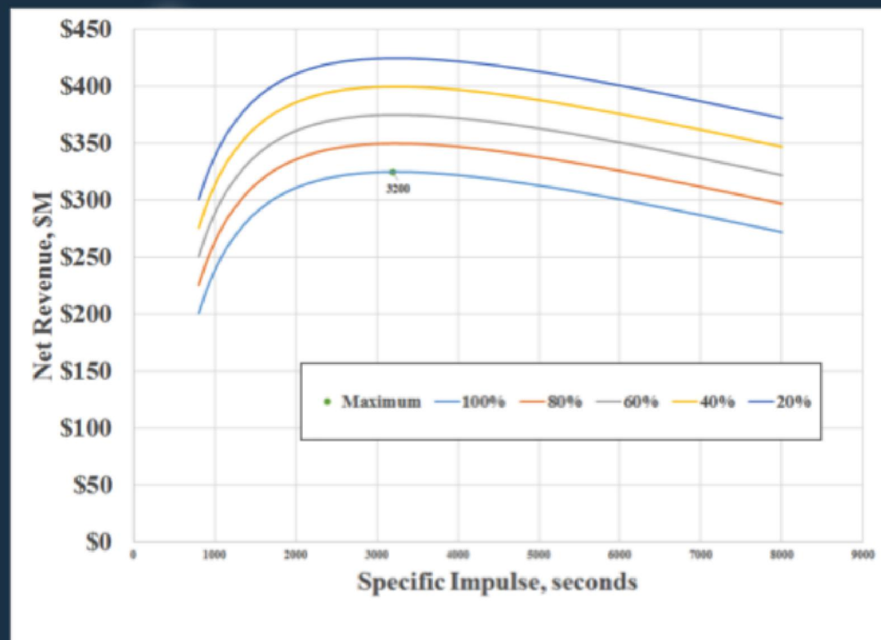
Atlas V 551

$190 million

Falcon 9

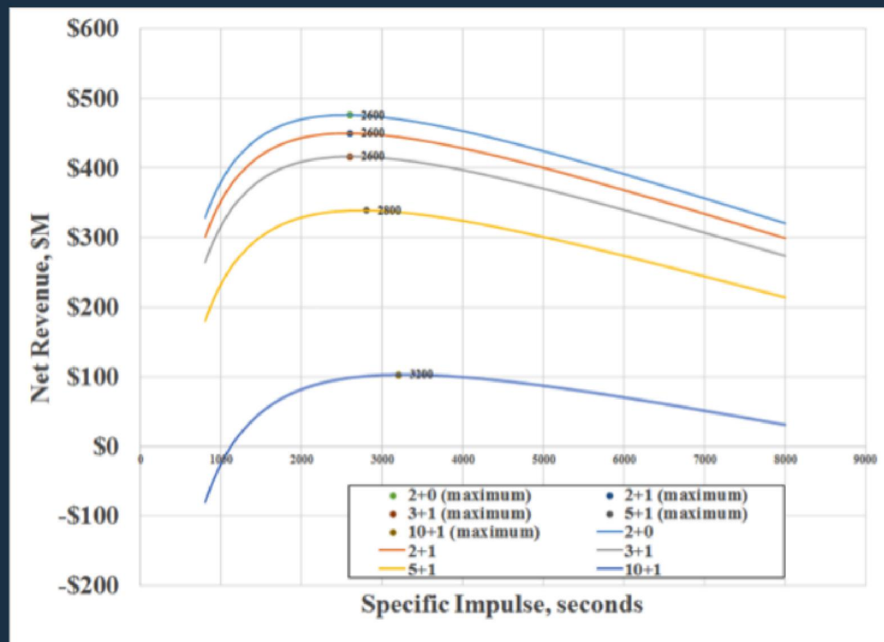
$61 million

Falcon 9



launch cost

Atlas V 551



thruster quantity

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Applicability
Will be used to guide future space architecture assessments.
*
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thank you!
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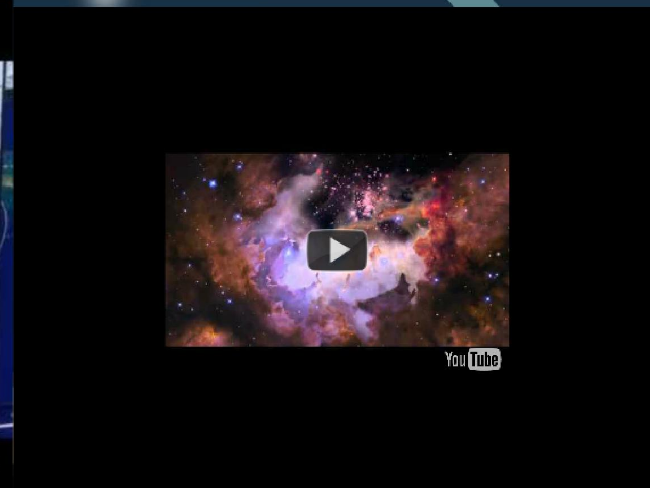
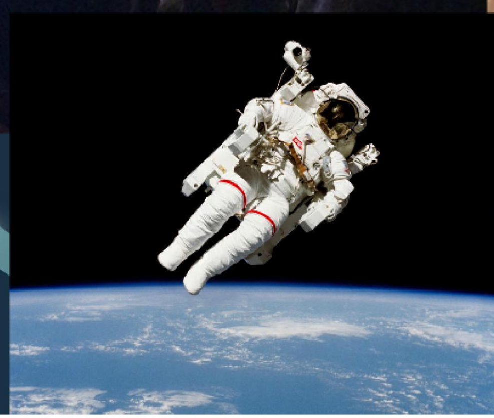
CineSpace and Hoot





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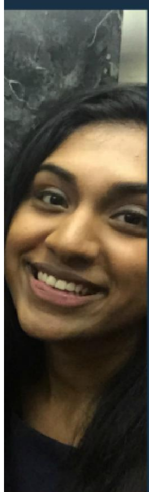
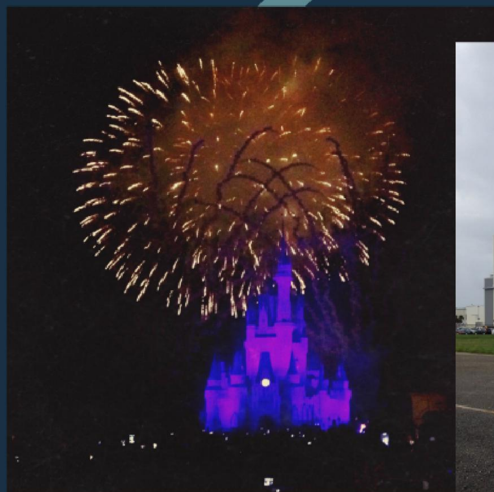
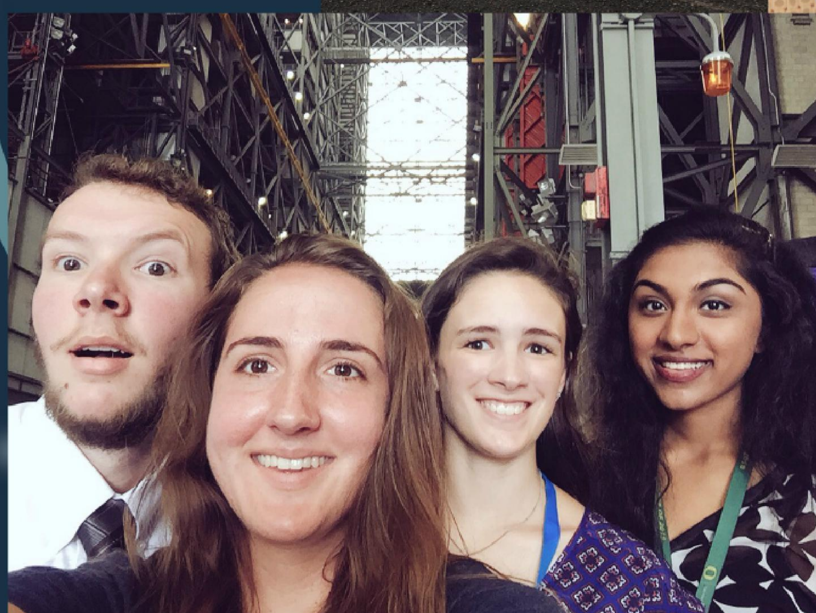
Florida







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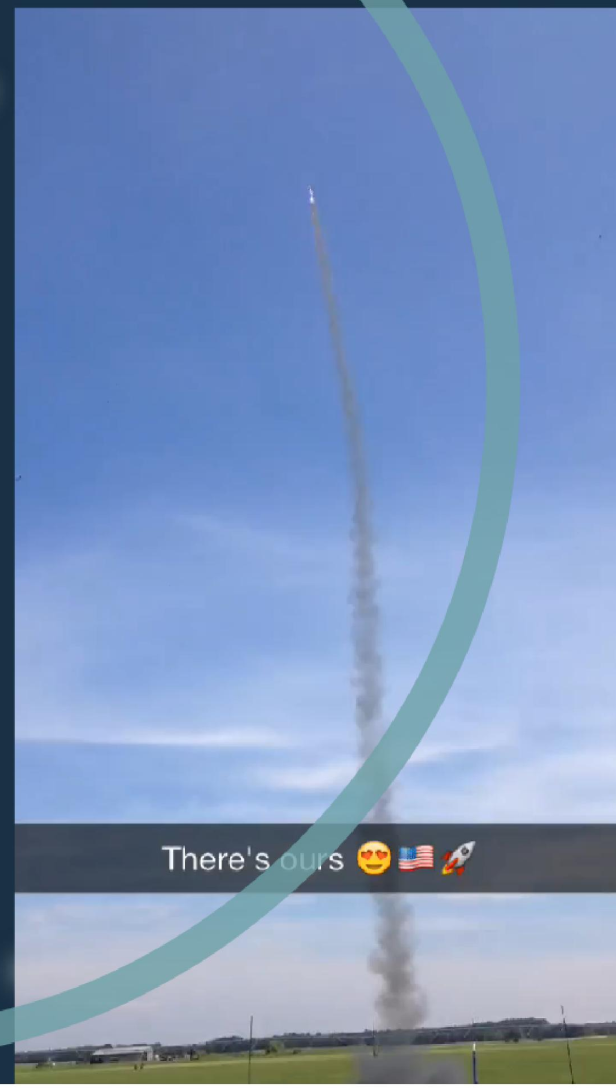
Fun



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Michoud and Johnson