Towers for Earth Launch

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Fifteen kilometer tower

(9.3 miles)

Size a 15 km tower to support launch weight of space-shuttle (2000 t):

Structural material:
Graphite epoxy: Lc = 107.5 km *No taper needed*
tower mass 280 tons

Cast steel: Lc = 15.4 km *taper required*
tower mass 5300 tons (taper ratio 2.6)

alternative: a 10 km tower on a 5-km mountaintop

Why launch from a fifteen kilometer tower?

Single stage to orbit means that mass ratio is very sensitive to small changes in performance

much of the improvement is due to lower air pressure:
15 km gets you above 83% of the atmosphere

Advantages of high-altitude launch:

(1) Start at a fraction of the altitude needed to get to orbit

a. Initial potential energy

b. Gravity losses for first part of launch not incurred

(2) Start at a lower atmospheric pressure.

a. Reduced atmospheric drag loss

b. Vehicle can be designed with less attention to aerodynamics.

c. More optimum trajectory curves toward horizontal faster

d. Max-Q occurs at a much lower pressure; lower aerodynamic stress

e. Aerodynamic vibrations lower; allows less robust (lighter) payload

f. Wind loads on vehicle in flight much lower

g. Acoustic loads much lower

h. Cryogenic storage easier (lower conduction and convective heating)

i. Shroud jettison can occur earlier

(3) Lower pressure means rocket operation is closer to vacuum

a. Higher performance out of the rocket nozzle at launch

b. Higher expansion ratio possible; less design compromise needed

(4) Start at a lower gravity

a. Lower gravity losses due to lower gravity and higher thrust/weight ratio

(5) Above the weather means no compromises needed for weather

a. Fewer delays for weather

b. Above lightning hazard

c. less robust design needed

Advantages of high-altitude launch

Examine in detail 4 of these advantages:
1a. initial potential energy
5a. gravity loss
2a. atmospheric drag
3a. rocket engine performance

Comparison: launch from a 15-km tower compared to sea-level

Single stage to orbit means that mass ratio is very sensitive to small changes in performance

Baseline SSTO for calculation:

ΔV to orbit = 9 km/sec (includes drag, gravity, and trajectory losses)

H_2-O_2 propulsion, I_{sp} = 425 sec. [V_e = 4.16 km/sec]

Theoretical mass ratio:
Mf/Mi = exp[-ΔV/gIsp] = exp[-

Vehicle mass (structure, engines, avionics, payload)
= 11.5% of gross lift-off mass
Payload = 2% of gross lift-off mass

Potential energy:

15 km tower gives a potential energy velocity of mgh = 225 kJ/kg
Required launch energy is 40.5 MJ/kg
Tower provides 0.56% of orbital energy
This is equivalent to:
ΔV = 11 m/sec
negligible

Gravity Loss

Shuttle: gravity loss 800 m/sec. Titan IV: gravity loss 750 m/sec.
Gravity for a 15 km tower is 99.4% as strong as gravity on the ground; this gives us a 0.45% decrease in gravity loss, and another 0.45% decrease due to higher thrust/weight

ΔV = 7 m/sec
negligible.

Drag

atmospheric density exp[-15/8.4] = 16.8% of baseline

Drag loss = $K_d\ C_dA/W_o$,
For β(burnout)=30°, C_d=0.5, A=75 m^2, W_o (GLOW)=950,000 kg and I_{sp}(vac)=450 sec, drag loss = 230 m/sec drag loss
A 15 km tower will multiply this loss by a factor of 0.168. Improvement:
ΔV = 191 m/sec

Improved Engine Performance

$$I_{sp}/I_{sp(vac)} = 1 - \varepsilon P_o/[P_c C_{f(vac)}]$$

or, in terms of practical parameters:

$$I_{sp}/I_{sp(vac)} = 1 - A_e P_o/F$$

A_e = exit area
P_o = atmospheric pressure
F = thrust

(Does not include additional gains possible by increasing expansion ratio)

Specific impulse at sea-level (SL) and in vacuum (vac)

Atlas:
Rocketdyne MA-5 sustainer: 309 sec vac, 220 sec SL [V/SL = 140.5%]
Rocketdyne MA-5A booster: 295 sec vac, 263 sec. SL [V/SL = 112.2%]
Delta:
RS-27A: 302 sec vac, 255 sec SL [V/SL= 118.5%]
Shuttle:
SSME at 100%: 2091 kN vac, 1668 kN SL [V/SL thrust = 125.4%]
Soyuz:
RD-107: 314 sec vac, 257 sec SL [V/SL = 122.2%]
RD-108: 315 sec vac, 248 sec SL [V/SL = 127.0%]
Energia/Zenit
RD-170/171: 336 sec vac, 308 sec SL [V/SL = 109.1%]
Tripropellant
RD-701 (mode 1): 415 sec vac, 330 sec SL [V/SL = 125.8%]

Total gain in effectove ΔV: 405 meters per second

The bottom line for payload:

<u>Baseline SSTO:</u>

Payload+vehicle fraction = exp[-9/4.161]= 11.5%
of which 2% is payload and 9.5% vehicle

<u>Tower Launched SSTO</u>:

Payload+vehicle fraction = exp[-(8.595)/(4.161)]= 12.7%
of which 3.2% is payload, and 9.5% vehicle

Tower launch increases payload to orbit by 60%

The bottom line for payload:

Detailed calculation of example SSTO:

Empty vehicle mass 10% of Gross lift-off weight
Payload mass 2.45% of Gross lift-off weight

Tower Launched SSTO:

Tower height km	Payload (% of GLOW)	Fractional increase
0	2.45	-
5 km	3.08	**+26%**
10 km	3.65	**+49%**
15 km	4.13	**+69%**
20 km	4.54	**+85%**
25 km	4.90	**+100%**

Tower launch increases payload to orbit by 60%

A convenient measure of a material's strength to weight ratio is the characteristic length Lc. This is the ultimate strength σ divided by the density ρ times the acceleration of gravity at the Earth's surface.

$$Lc = \sigma/\rho g$$

The physical meaning of L_c is the length at which a length of constant cross section will fail under its own load, under a uniform force of one gravity.

Table 1 Compression Material Characteristics

Material (* with safety factor)	Strength (GPa)	Density (kg/m^3)	Lc (km)	Lc* (km)
Grey Iron	1.2	7446	16.5	13.2
Cast Steel	1.2	7800	15.4	12.3
TiC	2.76	4000	70.3	35.2
Graphite/Epoxy	1.7	1610	107.5	53.8
Quartz fabric	0.46	1716	27.2	13.6
S-Glass	0.66	1909.9	35.2	17.6
Boron/Epoxy	2.43	2020.6	122.5	66.3
Glass polyimid	0.55	2214.2	25.3	12.7
WC Carbide	4.48	15500	29.4	14.7
B_4C	2.85	2500	116.1	58.1
SiC/Epoxy	2.33	2248	98.5	49.8

References: Handbook of Tables for Applied Engineering; Handbook of Composites, George Lubin