An Overview of Advanced Concepts for Launch

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This briefing presented an overview of advanced concepts for launch at AFRL. It explored “the” launch problem and “the” nanoLaunch problem, then discussed advanced concepts for cost effective launch/nanoLaunch.
An Overview of Advanced Concepts for Launch

Marcus Young
Jason Mossman

USC Engineering Honors Colloquium
Feb. 24, 2012
1. Advanced Concepts at AFRL

2. “The” Launch Problem

3. “The” nanoLaunch Problem

4. Advanced Concepts for Cost Effective Launch/nanoLaunch
1. Advanced Concepts at AFRL

• Air Force Research Lab
• Advanced Concepts Group
• What is an Advanced Concept?
• AFRL Does: Research and Develop Advanced Tech.
• AFRL Does Not: Manufacture or Use Advanced Tech.
"Enable Future AF Missions Through the Discovery and Demonstration of Emerging Revolutionary Technology"

- Propulsion
  - Power
  - Thermal Control
  - Launch
  - Near Space
  - In Space
    - Breakthrough Physics
      - Small ($m_s < 500\text{kg}$)
      - Medium ($500\text{kg} < m_s < 5,000\text{kg}$)
      - Large ($m_s > 5,000\text{kg}$)

- 15-50 Years
- Technology Push
  - System Test, Launch & Operations
  - System/Subsystem Development
  - Technology Demonstration
  - Technology Development
  - Research to Prove Feasibility
  - Basic Technology Research

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**Advanced Concepts Group**

**USC Activities**

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**CHAFF**

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**HEATS**

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**Cubesat Propulsion (Future?)**

- Nanosat: \( m_p = 1-10 \text{kg} \).
- Cubesat: Adhere to specs.
- Lightweight
- Cheap
- Fast
- Simple
- Risk O.K.
- Wrong Orbit.
- Limited/No Propulsion.

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**Air Breathing Satellite (Future?)**

- Dip lower (150km) to collect propellant.
- Dramatic increase in achievable \( \Delta V \).
- Scooping at 7.8km/s is difficult problem…
1. Identify Key Metric. ($/Performance)
2. Identify Enabling Threshold. (10x Reduction)
3. Identify Technology Required to Cross Metric. (Many)
- Insufficient Modeling Available.
- Require Unknown Breakthroughs.

\[ P(t) = \frac{1}{1 + e^{-t}} \]

**Cell Phone Example**

1983 → 2011
2. “The” Launch Problem

• Space Operations Process
• Typical Launch Parameters
• Recent Launch Statistics
• Lessons Learned
Delta IV Heavy Launch

Figure 2-6. Delta IV H Sequence of Events for LEO Mission (Western Range)
Typical Launch

- Responsiveness:
  - Now: years → Want: weeks/days.
  - Solids (Minotaur I) → Launch in Days.

- Launch Involves Extreme Numbers and is Extremely Difficult.
- Rockets Are an Inefficient and Expensive Way to Launch.
- Rockets Are All We Have.

### Typical Launch Magnitudes

<table>
<thead>
<tr>
<th></th>
<th>Falcon I</th>
<th>Saturn V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload (LEO) [kg]</td>
<td>450</td>
<td>119,000</td>
</tr>
<tr>
<td>Cost [$]</td>
<td>$7M</td>
<td>$1.1B (2011$)</td>
</tr>
<tr>
<td>Cost/mass [$/kg]</td>
<td>$15,600</td>
<td>$9,200</td>
</tr>
<tr>
<td>Height [m]</td>
<td>22.25</td>
<td>110.6</td>
</tr>
<tr>
<td>Diameter [m]</td>
<td>1.7</td>
<td>10.1</td>
</tr>
<tr>
<td>Wet Mass [kg]</td>
<td>3.32x10^4</td>
<td>3.03x10^6</td>
</tr>
<tr>
<td>Payload Fraction</td>
<td>1.4%</td>
<td>3.9%</td>
</tr>
<tr>
<td>ThSL [MN]</td>
<td>0.343</td>
<td>34</td>
</tr>
<tr>
<td>Pthroat [GW]</td>
<td>0.85</td>
<td>130</td>
</tr>
</tbody>
</table>

### Typical Launch Breakdowns

#### Energy Efficiency

$$\eta_{en} = \eta_{int} \cdot \eta_{pr} \cdot \eta_{me} \cdot \eta_{dr} \cdot \eta_{g}$$

#### Mass Breakdown

$$M_{lo} = M_{fuel} + M_{str} + M_{pay}$$

- $M_{fuel}$ (85%)
- $M_{str}$ (14%)
- $M_{pay}$ (1-4%)

#### $\epsilon$ Efficiency

$$\epsilon_l = \epsilon_{r&d} + \epsilon_{ve} + \epsilon_{go} + ... + \epsilon_{en}$$

- $\epsilon_{r&d}$ (50%)
- $\epsilon_{ve}$ (30%)
- $\epsilon_{go}$ (20%)
- $\epsilon_{en}$ (0.01%)

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Space Operations

~10% costs due to launch
- Small number of unique launches.
- Standing army for facilities/vehicles.
- Increase total number of launches.
- Increase launch/vehicle (all fly same).
- Need competition.

~25% costs due to spacecraft
- Nearly all space hardware is unique.
- Extremely low risk tolerance.
- Increase capabilities/mass.
- Expand cubesat paradigm.
  - Well defined specification.
  - Risk accepted.

~65% costs due to ground ops.
- Large ground workforce.
  → Automation, Simplification.

Space operations is much more than just the launch day.
Free launch → still 90% of space operation cost.
Cheap launch is a critical part.
**MIL and CIV Space**

**Why?**

- Wide Range of Applications for Both MIL and CIV.
- Core Metric is $ per Mission Performance.
- Launch is a Key Component of $.

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**2000 – 2010 Launch Missions (Military)**

- PNT 23%
- Comm 15%
- NRO 25%
- Research / Technology 27%
- Weather 4%
- Early Warning 6%

**2000 – 2010 Launch Missions (Civilian)**

- Science / Exploration 49%
- Comm 30%
- Observation 10%
- Weather 11%

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MIL and CIV Space
How Often?

~15 Total US Launches/Year (1/4 of World). MIL & non MIL Roughly Equal.

Historical Trends and Candidate Applications Require Few Launches.

2000–2010 U.S. Averages

| MIL | 7.4 |
| CIV | 8.0 |

(U.S.) 15.4/yr

Worldwide Launches

- 1957 – 2009: 4,621
- 2006 – 2009: 259
- ‘06–’09 avg.: ~65

Large Missions

- Apollo → 13 (6 yrs).
- Shuttle → 135 (30 yrs).
- ISS → 105 (13 yrs).
- GPS → 62 (33 yrs).

- SBSP(GW) ~ 100 (<10 yrs)
- Virgin Galactic ~ 70 (suborb)
MIL and CIV Space Where To?

2000 – 2010 Launch Destination (Military)
- GEO: 27%
- GPS: 24%
- Polar: 20%
- LEO 50-85 deg: 12%
- LEO < 50 deg: 10%
- Highly Elliptical: 7%

2000 – 2010 Launch Destination (Civilian)
- GEO: 34%
- Earth Escape: 19%
- Polar: 27%
- LEO 50-85 deg: 6%
- LEO < 50 deg: 9%
- Highly Elliptical: 4%
- MEO: 1%

- Large Range of Destinations Required for Missions.
- Not Condensable to Single Site and Vehicle.
•~10 Vehicles for MIL and CIV launches.
•No Launch Vehicle Used More than 5.7x per Year (Delta II).
“The” Problem
Launch Costs

Historical Launch Costs (Parkin, 2006)

- 1/10 Cost May Yield Market Elasticity and Further Reductions.
- 1/10 Cost May Also Enable Candidate Markets.

→ Reduce Launch Costs by One Order of Magnitude. (At Current Rates)

Space Based Solar Power

Need < $100 $/kg. Slight Increase in Rates.

Space Tourism

- 3/4 price for transport.
- $23M for 30 day stay.
- America’s Space Prize.
- Man Rated!
Reducing Costs

Cost of Launch

(Taylor: AIAA-2004-3561)

Common Solutions

- **Reusability**
  - Payback (~10s).
  - High Reliability.
  - Shuttle: “Weekly Launches”
  - Inspect & Rebuild.

- **SSTO**
  - LOx/LH₂: m_s < 10%
  - Advanced Structure/Tank.
  - Aerospike.
  - Sensitive Design Space.

**Can We Avoid Launching?**

- Reuse orbital mass → DARPA Phoenix.
- Avoid launching → MDA Corp.
- Avoid launching → Lockheed Martin HAA.
Recent and Future Options

- Recent/Active Launch Vehicles Follow Trend and Haven’t Improved Towards Goal.
- Near-Term Solutions Hope to Demonstrate Improvement, but do NOT Achieve the Goal.

**Launch Cost ($ Million)**

- **SpaceX Falcon 9**
  - $m_{pay} = 10,450kg (LEO)
  - Cost = $56.0M
  - Lox/RP1
  - Simple Design.
  - Limited Parts.
  - 2 successes.
  - > 30 sch. (→ 2017)

- **Antares**
  - $m_{p,LEO} = 5,000kg (2012)

- **Stratolaunch**
  - $m_{p,LEO} = 6,100kg (2016)

- **SLS**
  - $m_{p,LEO} > 70,000kg (2017)
3. The nanoLaunch Problem
Nanosatellite Operations (Cubesats)

- Nanosatellite: $m_{\text{sat}} = 1 – 10$ kg.
- Cubesat: Adheres to specs.
  - Simplified Design.
  - Specified Release.
  - System Unification.
- Very Short Time-Scales.
- Very Low Cost.
- Accept Higher Risk.
- Limited Functionality, Propulsion.
- Dropped off in Wrong Orbit with Little/No Propulsion.

Need Dedicated Nanolauncher.

- Must Maintain Paradigm
  - Simple, Responsive, Very Low Cost
- BUT
  - Cost/kg increases with decreasing size.
  - Uncertainties → hard to accurately deliver.

Real need for responsive, cost effective nanolaunch.

Acceptable solution possible in near term.

Better solution needed for long term.

Cost = $20.5M + 9,100$/kg$ * m_{\text{pay}}$

$20.5M to launch nothing!

Garvey Spacecraft

2-Stage NLV
10kg to 250km polar.
LOX/Densified C$_3$H$_6$.
$\text{d} = 0.65m$
$h = 7m$
$T_{\text{h1}} = 20kN$
$l_{\text{sp}_{\text{s1}}} = 212\text{s}$
Cost $\sim$ $1M$. 

“Conventional Design”
4. Advanced Concepts for Launch

New Combustion Reactants
• Advanced Propellants/Oxidizers
• Air Breathing Concepts

Onboard, but Separate Energy Storage
• Nuclear Thermal Upper Stage

Beamed Energy
• Solar Thermal Upper Stage
• Laser Booster
• Microwave Booster

Launch Assist
• Gas Dynamic Guns
• Railguns

Mechanical Assistance
• Space Platforms and Towers
• Space Elevator

Breakthrough Physics

Not Covered
• Skyhook
• Space Escalator
• Rotovators
• Orbital Ring
• Launch Loop
• Space Fountain
• Maglev
• Ram Accelerator
• Slingatron
…
Evaluation Technique

### Ideal Process

<table>
<thead>
<tr>
<th>Concept</th>
<th>Cost</th>
<th>Performance</th>
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<tbody>
<tr>
<td>Rank #1</td>
<td>???</td>
<td>???</td>
</tr>
<tr>
<td>Rank #2</td>
<td>???</td>
<td>???</td>
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</table>

### Practical Process

- Simple, Systematic Evaluation.
  - Fundamental & Rules of Thumb.
- Subset of Probable & Visible Technologies.
- Accept Researcher’s Estimates.
  1. Technical Feasibility.
  2. Current Status. (*Magnitude of Scaling*).
    - $/kg for payload > 500kg
    - $/kg for payload < 10kg (Nanolaunch)

**Difficulties**

- Large uncertainties.
  - Uncertainty > Advantage.
- Large changes in designs.
- Rough performance estimates.
- Cost models inadequate.

**Technical Feasibility**

<table>
<thead>
<tr>
<th>LTF</th>
<th>nTF</th>
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<tbody>
<tr>
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**Magnitude of Scaling**

<table>
<thead>
<tr>
<th>nMS</th>
<th>LMS</th>
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<tr>
<td>&gt;100x</td>
<td>&gt;100x</td>
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<tr>
<td>10-100x</td>
<td>10-100x</td>
</tr>
<tr>
<td>&lt;10x</td>
<td>&lt;10x</td>
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</table>

**Cost Advantage**

<table>
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<th>nCA</th>
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</thead>
<tbody>
<tr>
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<td>None</td>
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<tr>
<td>Net?</td>
<td>Net?</td>
</tr>
<tr>
<td>Clear</td>
<td>Clear</td>
</tr>
</tbody>
</table>

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Distribution A: Approved for public release; distribution unlimited.
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Advanced Propellants

**Exemplar Status**

**Lithium-Fluorine-Hydrogen**

60:1 Nozzle.
Included Mixing.
Isp = 509s
P_c = 750 psia
Th = 8,896N

**Li/F_2/H_2**

**Envisioned Design**

E/m_{mH} = 138MJ/kg
H_2/mH = 3
Height = 50m
m_{pay} = 25MT
GLOW = 126MT
T_{ch} = 3240K
Isp = 911s

**Pros**

- Higher stored energy.
- Higher reaction temp.
- Higher specific impulse.
- Less fuel.
- More payload or smaller vehicle.
- Fewer stages → SSTO.

**Cons**

- Low m usually low ρ.
- High E/m less stable.
- Propellant reactivity.
- Much more expensive.
- May need new nozzles.
- Many requirements to meet.

**Eval.**

- LTF
- LMS
- LCA
- nTF
- nMS
- nCA

**Concept Description**

- Isp ∝ \sqrt{\frac{T}{m}}
- Theoretical Isp
  - Gamma = 1.15
  - P1/P2 = 750

**Distribution A: Approved for public release; distribution unlimited.**

PA Clearance Number XXXXX
Air Breathing Concepts

**Concept Description**

\[ m_{ox} >> m_{pay} \]

- **Turbojets**
- **Ramjets**
- **Scramjets**
- **Rockets**

**Engine Specific Impulse (Isp)**

- **Hydrogen Fuel**
- **Hydrocarbon Fuel**

**Exemplar Status**

**X-51 WaveRider**

- Scramjet
  - hydrocarbon
  - \( h = 15.2 \text{km} \)
  - \( M = 4.5 - 5 \)
  - 120 kg of JP-7
  - \( \Delta t = 140 \text{s} \)
  - \( L = 7.9 \text{m} \)
  - \( m_{dry} = 1814 \text{kg} \)

- **Pros**
  - Use atmospheric oxidizer.
  - Avoid bringing \( O_2 \).
  - (30% for STS).
  - More payload or smaller vehicle.
  - Advertised at reusable.
  - “SSTO”

- **Cons**
  - Multiple modes required.
  - Flow path integration.
  - Ignition/Transition.
  - Low Thrust-to-Weight (2 vs. 75)
  - Longer flight times.
  - Aero-thermal heating.

- **Envisioned Design**

- **Scramjet**
  - hydrocarbon
  - \( h = 15.2 \text{km} \)
  - \( M = 4.5 - 5 \)
  - 120 kg of JP-7
  - \( \Delta t = 140 \text{s} \)
  - \( L = 7.9 \text{m} \)
  - \( m_{dry} = 1814 \text{kg} \)

- **GTX**

- **Lazarus (G.Tech):** $15,000/\text{kg} @ 12/\text{yr}!, \sim$6B to first vehicle.

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PA Clearance Number XXXXX
# Propellant: Nuclear

## Concept Description

- **Fission**: $7 \times 10^{13}$ J/kg
- **Fusion**: $6 \times 10^{14}$ J/kg
- $\sim 10^7 - 10^8 >$ chemical

![Diagram of a nuclear reactor with a nozzle and turbine pump](image)

### Exemplar Status

**Hexagonal Fuel Elements**

- Met requirements for manned Mars mission.
- Total test time 115 minutes, 24 starts.
- Saturn upper stage: 155,000kg to LEO.
- Full power test @ 1100MW.
- $T_{\text{core}}$: 2272 K.
- 25,000 – 250,000lb thrust are validated.

**NERVA NRX**

<table>
<thead>
<tr>
<th><strong>Pros</strong></th>
<th><strong>Cons</strong></th>
<th><strong>Eval.</strong></th>
</tr>
</thead>
</table>
| - Separate energy storage and ejecta.  
  - Optimized ejecta.  
  - High Isp  
  - High T & High Isp upper stage.  
  - Reduce 1st stage size.  
  - Enabling for larger interplanetary missions. | - Inert mass.  
  - Expensive.  
  - High T Hydrogen.  
  - Radioactive Plume.  
  - Sociopolitical Concerns. |  

## Envisioned Design

**SNTP**

**Pebble Bed**

- Radioactive Plume
- $\text{Th/W} \sim 25-35:1$
- $T_{\text{ex}} = 2750K$
- Isp = 925-950s
- $\text{Th} = 0.2$-$0.37\text{MN}$
- $t_{\text{fire}} = 200$-$1050s$

![Diagram of a pebble bed reactor](image)

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**PA Clearance Number**: XXXXX
Solar Thermal Upper Stage

Concept Description

Exemplar Status

Full ground test completed in 1997; TRL = 6.

- 117 burns, 2-27 min
- 320 hours RAC at T
- $I_{sp} = 758 \text{ s}$
- $T_{exhaust} > 2000 \text{ K}$
- 90% effective heat exchanger

Tested RAC, system for power gen, distribution, & management, solar concentrator, and cryogen feed/storage

ISUS EGD @ NASA LeRC

Pros

- Upper stage: propulsion and power for satellite.
- More responsive than EP.
- Moderate $F_n$, high $\eta$.
- Step-down launch vehicle
- Save up to 60% cost.
- Titan IV → Delta III save ~$200M.
- Low mass power system
- Thermal storage
- No safety/political issues
- Technology proven in ground tests, TRL = 6.

Cons

- High $T$ operation.
- $H_2$ storage, but methane and ammonia are higher density, lower efficiency options
- 0.1 degree pointing accuracy required
- Temperature change during thruster firing
- May require batteries as well.

Envisioned Design

Propulsion, RAC, power systems validated by EGD. Space test planned, 1999...

- Various sizes envisioned
- 14,400 kg, 5000 kg payload
- 160 N @ 800 s Isp
- 30 days LEO – GEO
- 15,000 W @ 100 W/kg thermionics

Uses: Upper stage that stays with satellite, refuelable/reusable stage, move defunct or stranded satellites, delivery to ISS.
**Beamed Energy Laser**

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### Concept Description

- Capital (CAPE) is assembled and sieved at a LEO assembly facility (crowd or robots).
- Supply vehicles rendezvous with Space Station and other future facilities.
- Independent packets go directly to LEO.
- Baseline expandable vehicles discarded.
- Vehicles could be reused.

### Exemplar Status

10kW Pulsed CO₂ Laser.
- m = 50.62g
- d = 12.2cm.
- h = 71m.
- spin > 10,000rpm.
- ΔT = 12.7s.

### Envisioned Design

Multiple 10kW fiber lasers.
- 120-160MW total laser power.
- R < 400km.
- \( P/A_{HX} = 10\text{MW/m}^2 \)
- \( T_{exit} = 2000K \)
- GLOW = 2800kg.
- \( m_{pay} = 80-100\text{kg} \)
- System Cost ~ $2 Billion

---

### Pros

- Low Density Propellant.
- Power Levels ~1MW/1kg in LEO.
- Many Individual Sources.
- High Installation costs.
- Fixed Installation.
- Weather Limited.
- Laser Clearinghouse.
- Aiming/Tracking.

### Cons

- Leave energy storage on ground.
- Better optimized ejecta.
- Higher specific impulse.
- Many candidates:
  1. Heat Exchange
  2. Plasma Formation
  3. Laser Ablation
  4. Photon Pressure
- SSTO
- Reusable

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**Distribution A: Approved for public release; distribution unlimited.**

PA Clearance Number XXXXX

27
Beamed Energy
Microwaves

Exemplar Status

- Plasma Formation
- Heat Exchanger
- SRM Augmentation

Oda

P = 1MW
f = 110 GHz
\( \Delta t = 0.175\text{ms} \)
\( C_m = 395\text{ N/MW} \).
m = 9.5 – 19.5g
\( \Delta x = 30\text{cm} \)
h < 0.5m
\( v_o < 3\text{m/s} \)

Envisioned Design

Propellant: LH\(_2\)
Isp\(_{\text{vac}}\) : 800
Th/W : 50
m\(_{\text{LO}}\) : 636kg
m\(_{\text{pay}}\) : 30kg
HX size: 3.3x6.7m
\( P_{\text{HX}}\) : 140MW
\( f_{\text{mw}}\) : 170 GHz
BF Cost: $760M

Pros

- Mass & Energy on ground.
- Better Optimized Ejecta.
- More Payload.
- Low Consumables Cost.
- SSTO.
- Reusable.
- Thorough System Analysis.

Cons

- Low density propellant.
- Power Levels
  ~1MW/1kg in LEO.
- High installation cost.
- Fixed installation.
- Many sources required.
- Beam attenuation.
- Weather.

Eval.

- LTF
- LMS
- LCA
- nTF
- nMS
- nCA

Concept Description (Parkin)

Distribution A: Approved for public release; distribution unlimited.
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Launch Assist
Gas Dynamic Gun Launch

Exemplar Status

Stage 1: Gas Dynamic Gun
Stage 2: Solid Rocket Motor
- 570 HARP Shots.
- Demonstrated payloads.
- h ~ 180km
- m ~ 85kg
- V ~ 3.6km/s
- Δt_{reload} ~ 1 hour
- Cost ~ $3000/launch
- Installation cost: $2M (1960s)

- multipoint ignition system.
- fluid filled SRM.

HARP

Envisioned Design

- Gun adequate.
- Martlet improvements.

- m_{shot} = 1300kg
- m_{pay} = 90kg (LEO)
- V = 1.2 – 1.8km/s
- a_{peak} = 5,000 gees.

Project Babylon
2,000kg to 200km for $600/kg.

Pros

- Mature technology.
- Mass & Energy on ground.
- Payload mass fractions.
- Low consumables cost.

Cons

- High T,P Operation.
- a_{peak} ~ 5,000 gees.
- V_{max} ~ 3km/s
- Fixed installation.
- Aero-thermal Heating.

Eval.

LTF
LMS
LCA
nTF
nMS
nCA

Project Babylon
2,000kg to 200km for $600/kg.

Distribution A: Approved for public release; distribution unlimited.
PA Clearance Number XXXXX
Launch Assist Railguns

Concept Description

- Exemplar Status
  - IAT-UT
  - 5.4g projectile
  - \( V_{ex} = 5.2 \text{km/s} \)
  - \( L = 7 \text{m launcher} \)
  - \( E_{ex} = 73 \text{kJ} \)

- Envisioned Design
  - \( V > 7.5 \text{km/s}, E > 10 \text{GJ}, m_{pay} = 250 \text{kg}, L > 1 \text{km}, \text{System cost} > \$1 \text{B}, \text{10,000 launches} \rightarrow \$530/\text{kg}. \)

Pros

- Mass & Energy on Ground.
- Increased Payload Fraction.
- Low Consumables Cost.
- Fast Cycle Time.

Cons

- High Acceleration.
- High Installation Cost.
- Pulsed Power System Must be Developed.
- Aero-thermal Loads.
- Fixed Installation.
- Harsh Environment.

Eval.

- LTF
- LMS
- LCA
- nTF
- nMS
- nCA

Distribution A: Approved for public release; distribution unlimited.
PA Clearance Number XXXXX
Space Platforms and Towers

Concept Description

Energy/Mass [MJ/kg] vs. Altitude [km]
- Circular Orbit Kinetic Energy
- Potential Energy
- Total Mechanical Energy

Pros
- Above atmosphere.
- Above winds.
- Minor ΔV benefit.
- Multiple candidates.
  1. Solid
  2. Inflatable
  3. Electrostatic

Cons
- Extreme materials requirements.
- Must Support Launch Vehicle & Launch.
- Winds/Weather.
- Single Launch Site.

Exemplar Status
- World's Tallest Structure
  - Burj Khalifa (828m)
- York Univ. (7m)
- Pegasus, Mount Everest, Near Space Dirigible, LEO (400km), GEO, Space Tower

Envisioned Design
- h = 100km
- Steel?
- t_{\text{build}} < 1 yr
- Cost: “cheap”

Distribution A: Approved for public release; distribution unlimited.
PA Clearance Number XXXXX
Space Elevator

### Concept Description

**Liftport**

- **Ribbon to Counterweight**
- **Climber**
- **Beamed Power**

### Exemplar Status

**LaserMotive**

Space Elevator Games
- $h = 1\text{km}$
- $v_{cl} = 2\text{m/s}$
- $\eta_{DC-DC} = 10\%$
- $P_{cl} = 1\text{kw}$.

### Envisioned Design

**Brad Edwards**

- $C_{D&B} \sim $10B
- $C_{\text{elec}} \sim $250/kg
- $t_{D&B} = 15$ years
- 1m wide ribbon.
- $T_{\text{climb}} = 8$days.
- $m_{\text{pay}} = 11,800$kg

### Pros

- No stored energy required.
- No propellant/launch.
- Low consumables.
- Reusable.

### Cons

- Long tether.
- $L \sim Xx C_E$
- Tensile Strength ($\sim 100\text{GPa}$!)
- Installation Cost.
- Micrometeoroids/Debris.
- Weather.
- Atomic oxygen.
- Power/Beaming Efficiency.

### Eval.

- LTF
- LMS
- LCA
- nTF
- nMS
- nCA

**Distribution A: Approved for public release; distribution unlimited.**

PA Clearance Number XXXXX
Breakthrough Physics

Millis, 2009

[Diagram showing various categories and statuses of breakthrough physics concepts.]

- Large Number of Concepts.
- Some May be Useful for Propulsion in the Long Term.
- Nothing Immediately Applicable to Saving $$$.

E/m ~ 9x10^16 J/kg
m/year ~ 10ng
$/m ~ $25B/g
E/V_{stor} ~ 10^{11}part/cm^3
(15kJ/l)
E_{stor}/E_{in} ~ 10^{-10}

Distribution A: Approved for public release; distribution unlimited.
PA Clearance Number XXXXX
# Summary for Launch

<table>
<thead>
<tr>
<th>Concept</th>
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<th>LMS</th>
<th>LCA</th>
<th>Primary Challenges for Launch</th>
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• **Save $ “Now”**. Solar Thermal Upper Stage.
• **Build “Now”**. NTP Upper Stage, Gun Launch.
• **Research Now**. BEP (Laser, Microwave), Launch Assist, Adv. Propellants.
• **Avoid**. Complexity, Multiple Breakthroughs,
• **Alternative Missions**. Space Tug or Rapid Delivery of Robust Payloads.
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**Summary for nanoLaunch**

- **Save $ “Now”**. NONE.
- **Build “Now”**. Gun Launch.
- **Alternative Missions**. Space Tug or Rapid Delivery of Many Small Payloads.
- **Cubesat Paradigm**. (simple, specs., accepted risk, cheap) must be kept.