Appropriately Ambitious Aerospace Goals:
Keynote Address to the Turning Goals Into Reality Conference

NASA Marshall Space Flight Center

18 May 2000

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My Job—"Helping Stretch Your Mind"

- Say You Want a Revolution
- Broaden the Aeronautics Constituency
- Allow For the MNT Scenario
- We Can Afford to Go
- Getting There is Not Enough

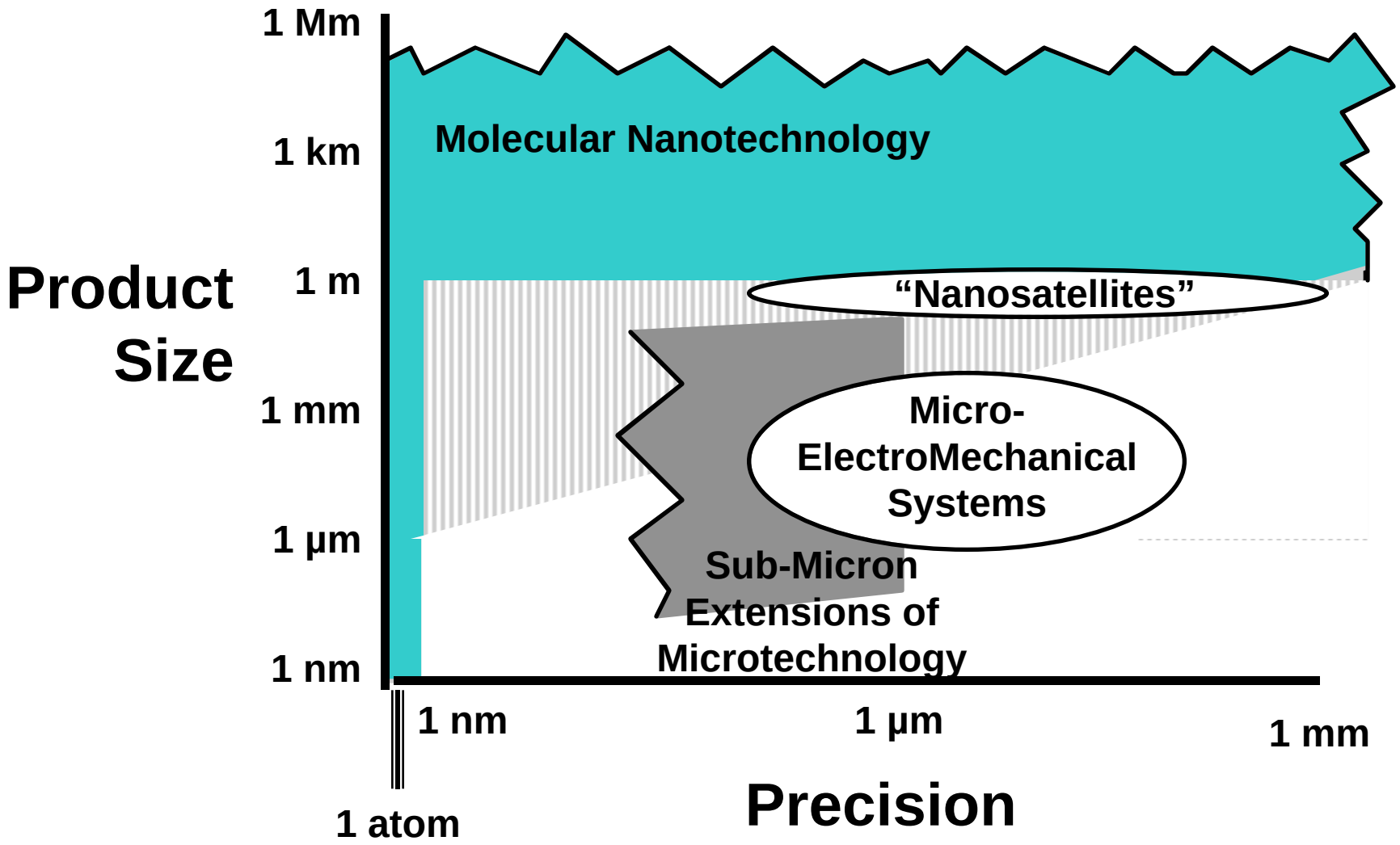
Pergamit and Peterson's Law

- If you're looking 30 years out and it "sounds like science fiction," it may be wrong; but if it doesn't sound like science fiction, it's definitely wrong.

Say You Want A Revolution

- **Say You Want a Revolution**
  - **Molecular Nanotechnology (MNT) Represents a Real Revolutionary Technical Leap**
- **Broaden the Aeronautics Constituency**
- **Allow For the MNT Scenario**
- **We Can Afford to Go**
- **Getting There is Not Enough**

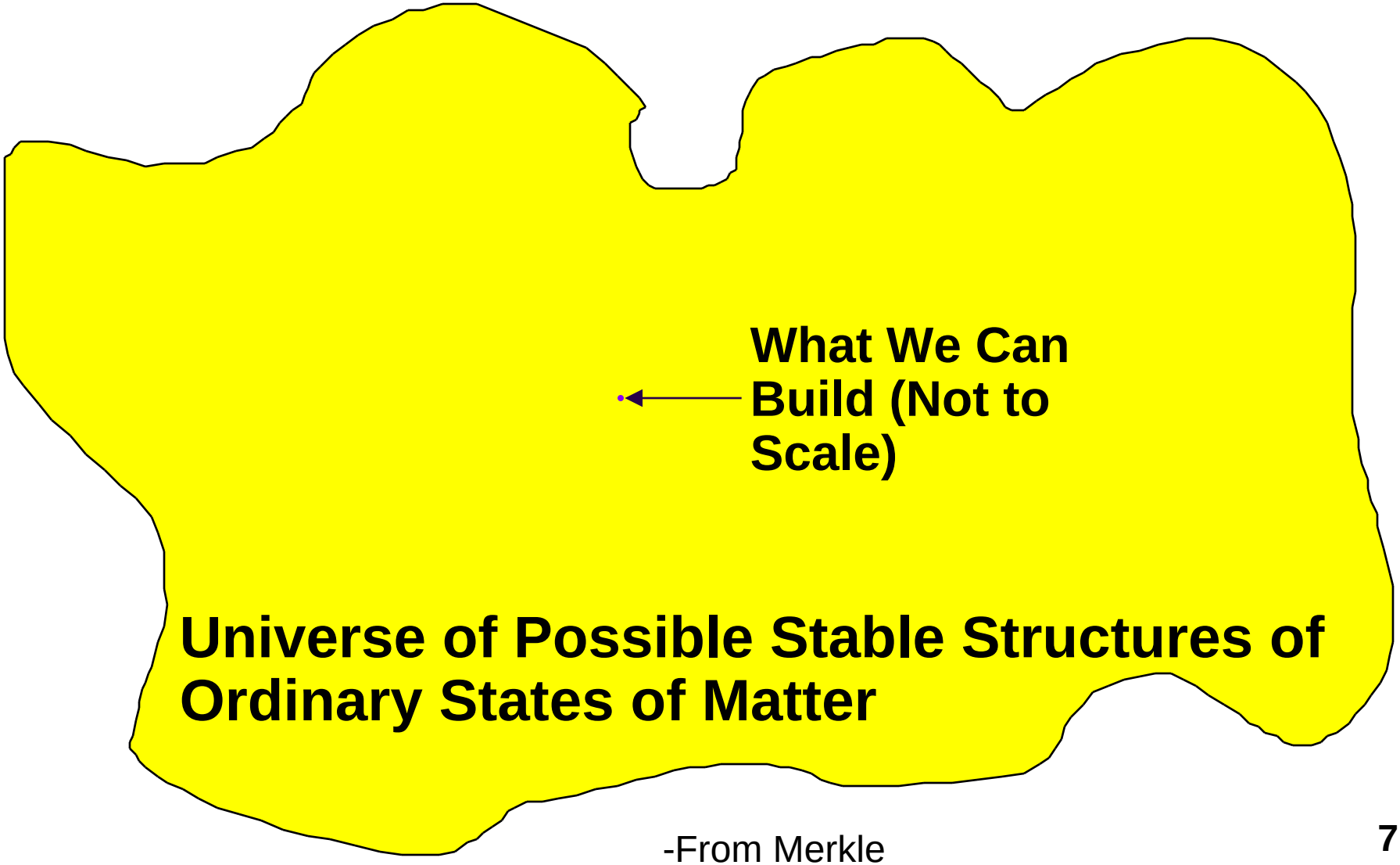
Different Meanings of "Nanotechnology"



Molecular Nanotechnology

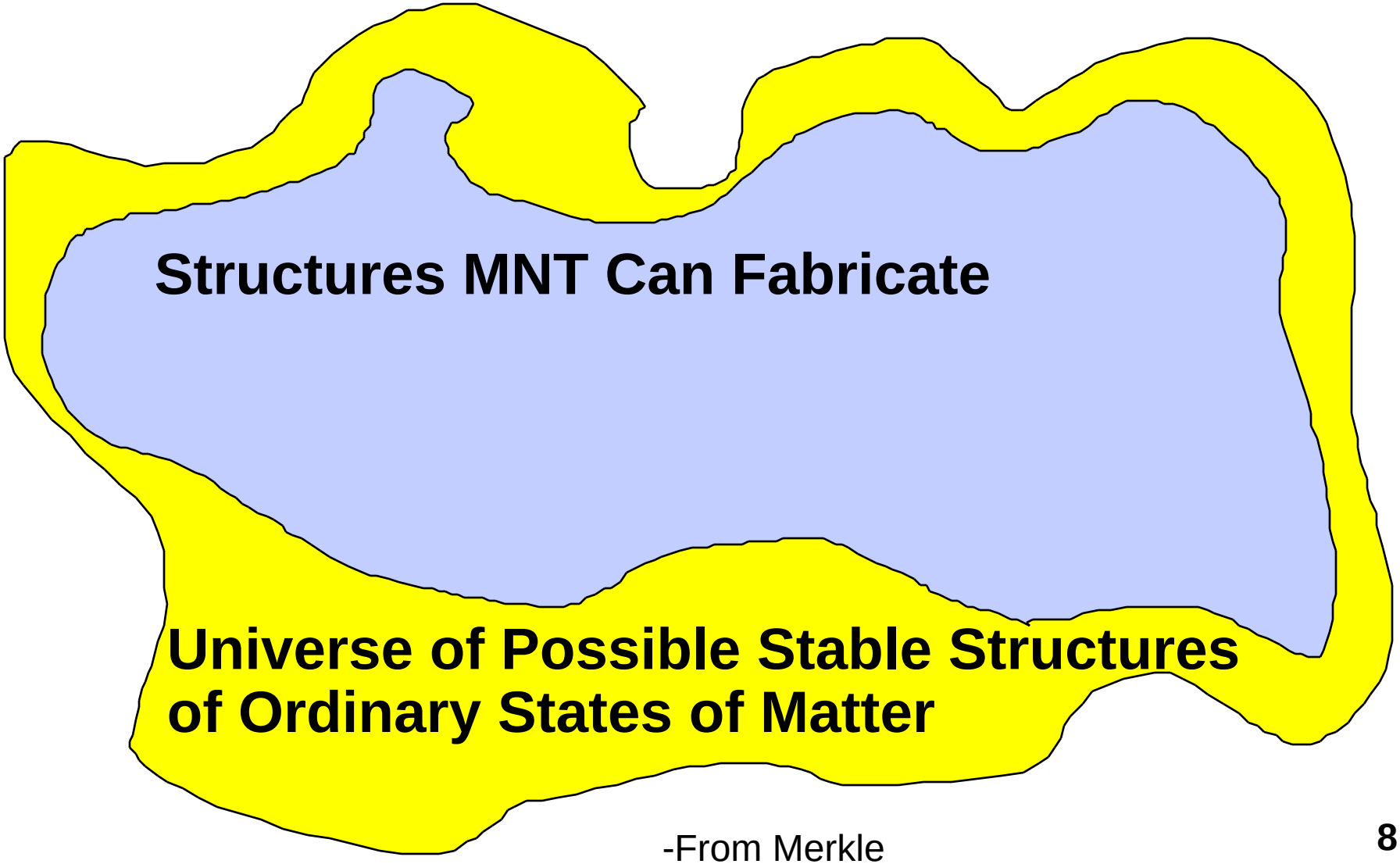
- **The Emerging Ability to Design and Build Systems to Atomic Precision**
- **Merkle's Goals**
  - » **See http://www.zyvex.com/nano/ For More on MNT from Dr. Ralph Merkle**
  - – **Almost Every Atom In Its Place**
  - – **Manufacturing Costs Near Raw Material And Energy Costs**
  - – **For a Broad Range of Structures**

The Space Of Structures



-From Merkle

We Want a “Healthy Bite”



-From Merkle

Broadening the Aeronautics Constituency

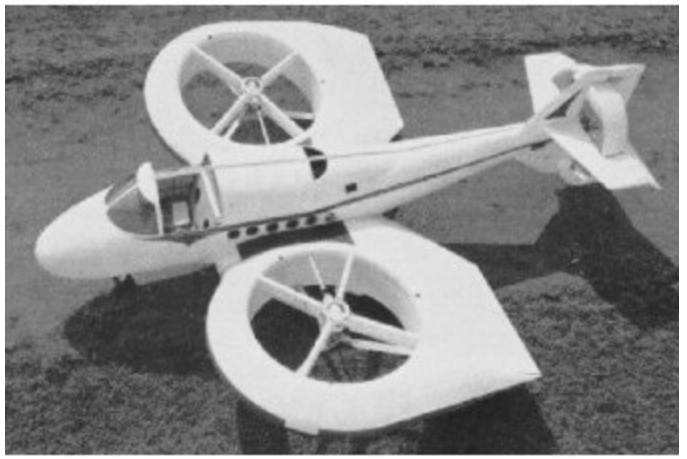
- Say You Want a Revolution
- Broaden the Aeronautics Constituency
  - Making Personal Flight Widely Available
    - » Taken From The Work of Dr. J. Storrs Hall, at http://www.imm.org/Reports/Rep004.html
  - Small Fliers Broaden the Range of Applications
    - » Not Discussed Here
- Allow For the MNT Scenario
- We Can Afford to Go
- Getting There is Not Enough

Aircars: The Dream

GA

The Jetson's

Supercar



Omniplane

Ford Volante

Avrocar

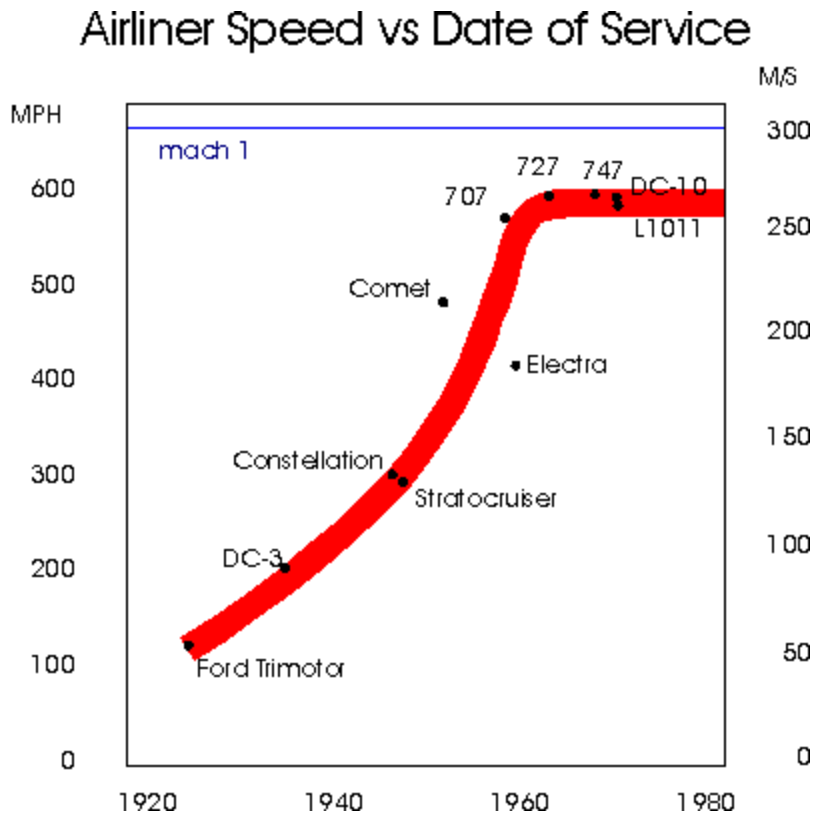
Ryan XV5

Moller's Skycar

Harrier

--Hall, http://www.imm.org/Reports/Rep004.html

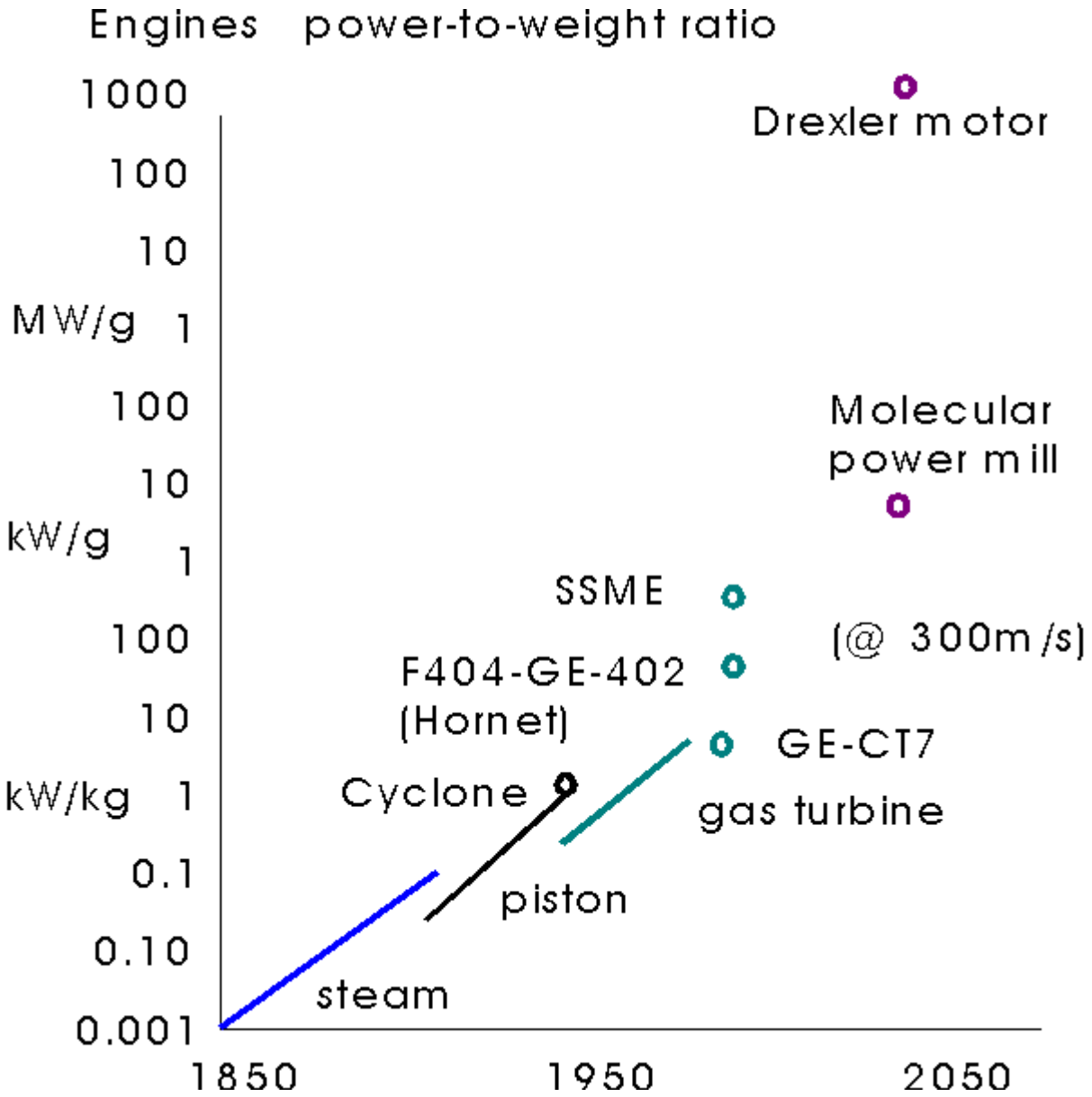
Airliner Speed Versus Date of Service



- **High Altitude, High Subsonic Speed Forms a "Sweet Spot"**
  - **Design Target for This Aircar**

--Hall, http://www.imm.org/Reports/Rep004.html

Engine Power-to-Mass Ratios



--Hall, http://www.imm.org/Reports/Rep004.html

- **High Power to Mass Allows Widely Embedded Actuation**
- **Power Mill Provides Direct Electric Power for Drexler Motors**
  - **Benign Emissions from Power Mill (E.g., Water)**

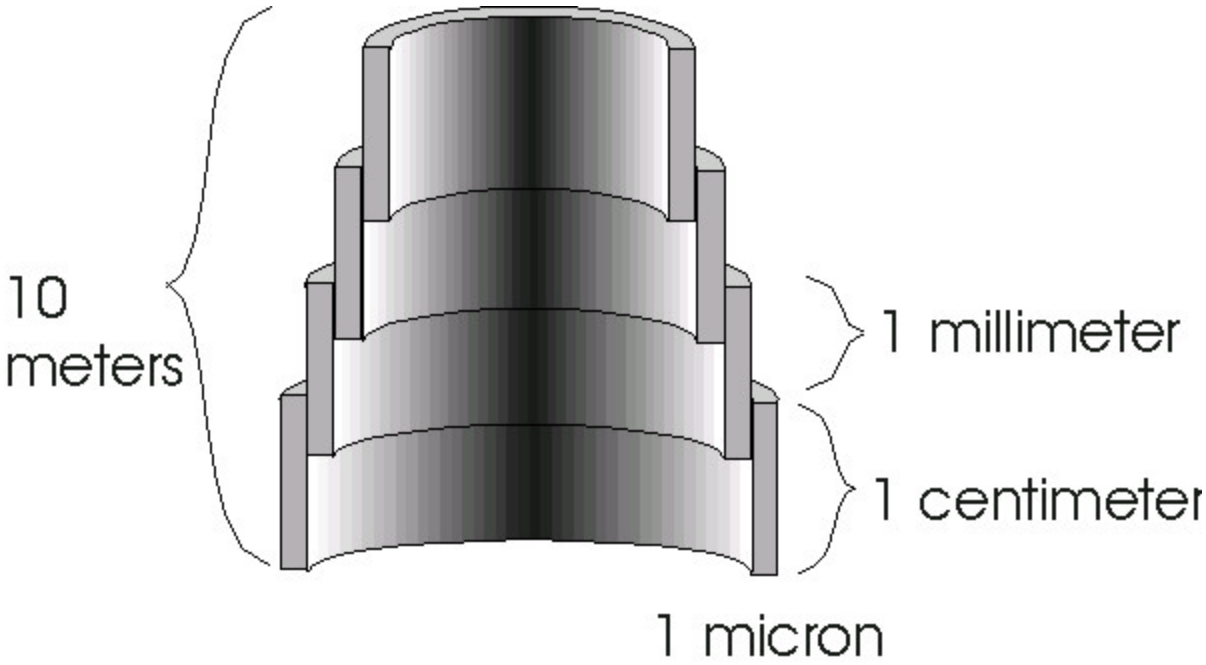
Emissions

Shape Change Vehicle

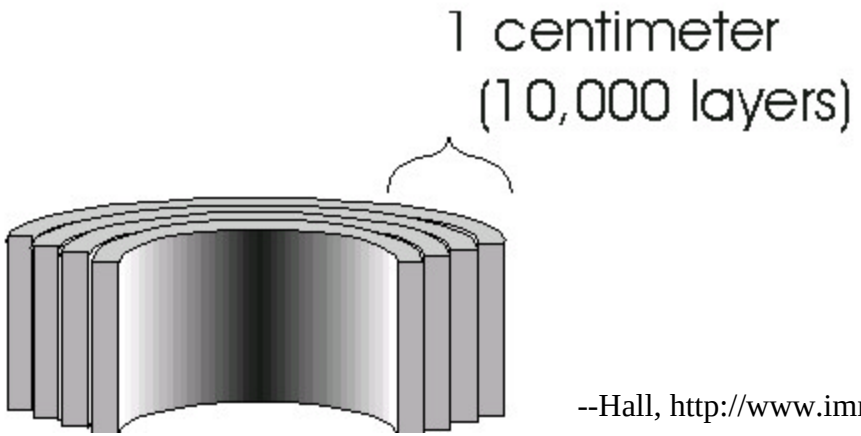
--Hall, http://www.imm.org/Reports/Rep004.html

- **For a Pre-Defined Set of Shapes, Develop Laminar Flow Model, Then Implement in Thin Diamondoid Sheets Powered by Embedded Drexler Motors**
  - **Low And Slow Wings**
  - **High And Fast Wings**
  - **Disappearing Wings for Ground Storage**
  - **Pull in All Extensions for Flight Regime**

Extensible Legs

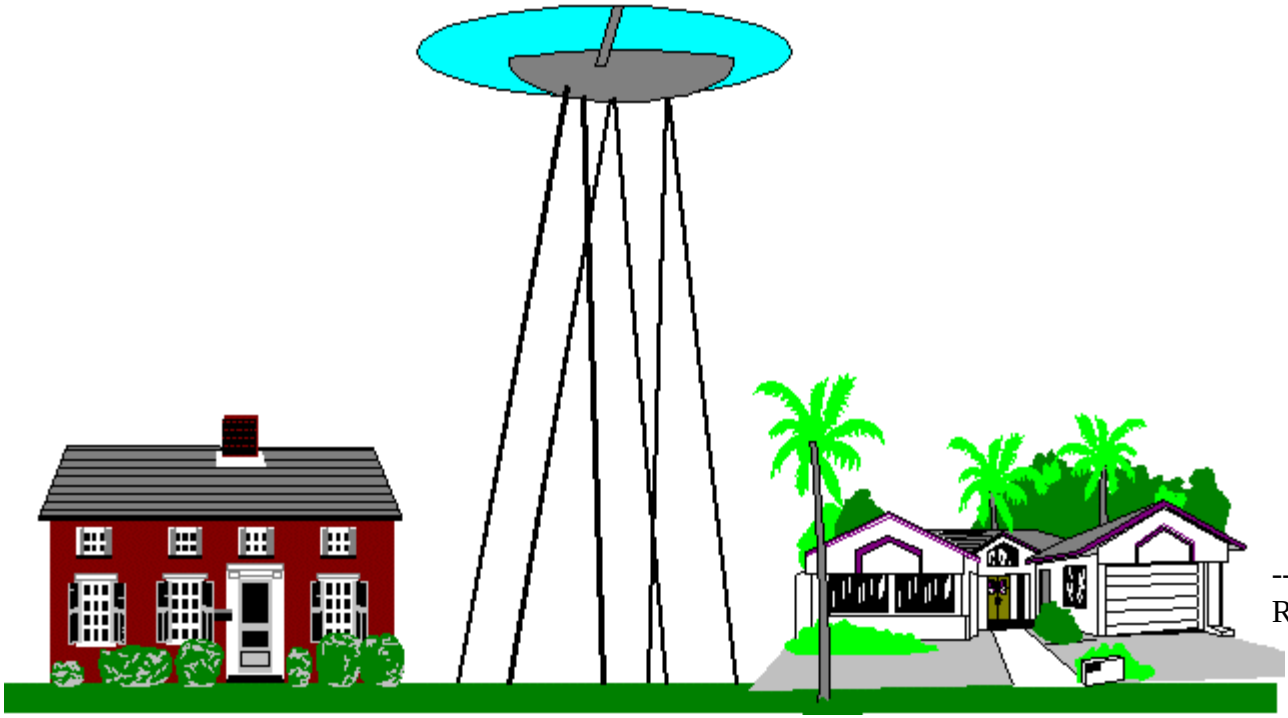


- **Very Simple Example of the Laminar Flow Design Approach**



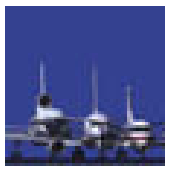
--Hall, http://www.imm.org/Reports/Rep004.html

Quiet Takeoff and Landing

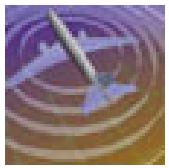


--Hall, http://www.imm.org/Reports/Rep004.html

- **Residential Takeoffs and Landings**
  - **More Car-like Trip Numbers and Distances**
- **Blue Skirt is “Fan Cloth”**
  - **1.5 mm Ducted Rotors, Powered By MNT Motors**
  - **Produces Vertical Lift With Low Noise**



Throughput

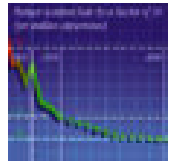


Noise

Other Aircar Uses of MNT

- **Surface of Small Rotating Devices Simulate Stationary Boundary**
  - **Lower Drag**
  - **Higher Device Speeds Generate Thrust**
- **Engine-On to Engine-Off Automated Flight Control**
  - **Using Massive Improvement in Computing Power**
- **Molecular Manufacturing Fabricates Complex, MNT Products at a Low Marginal Cost**

HSR



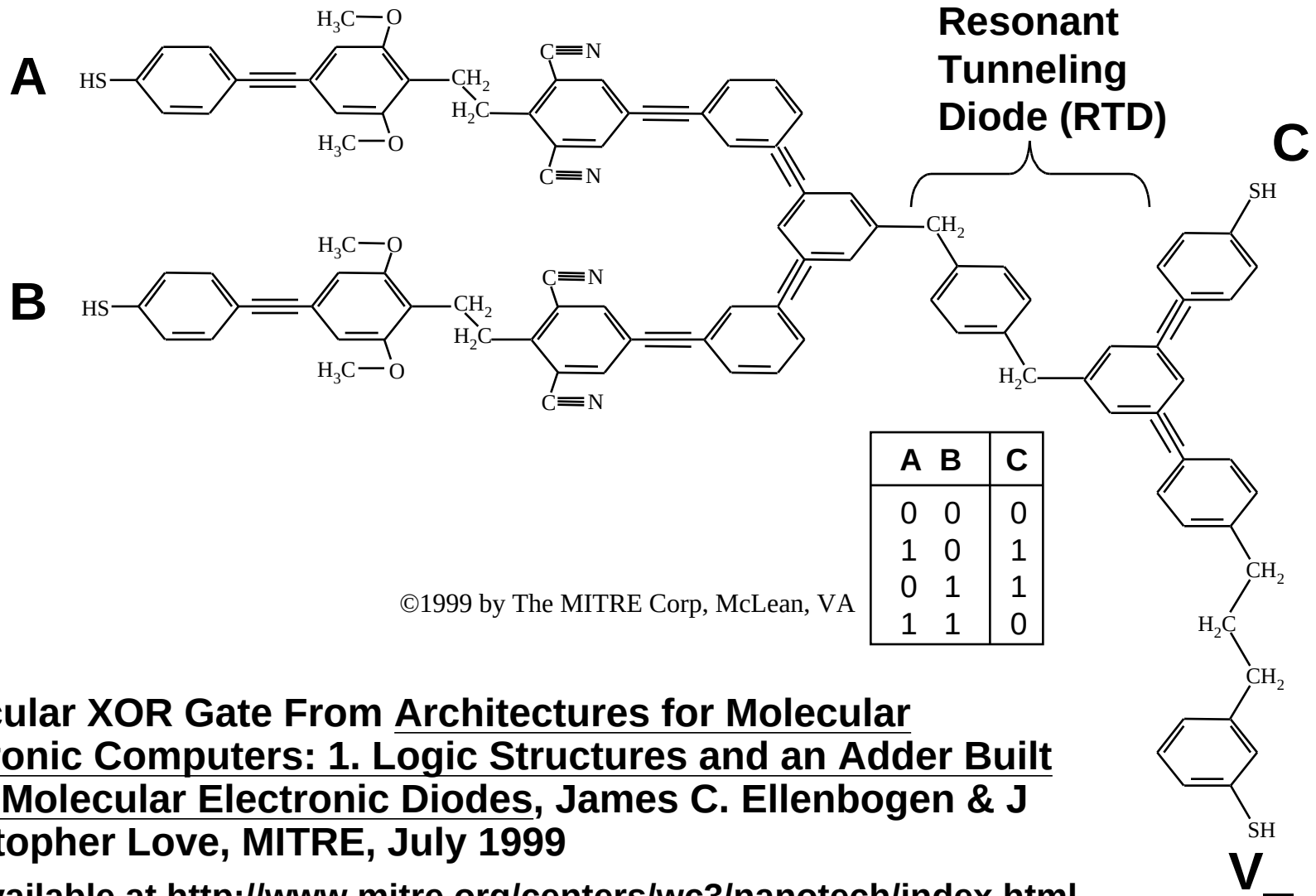
Safety

Reduced Cost

Allow For the MNT Scenario

- Say You Want a Revolution
- Broaden the Aeronautics Constituency
- Allow For the MNT Scenario
  - Span This Trade Space When Developing Tools
- We Can Afford to Go
- Getting There is Not Enough

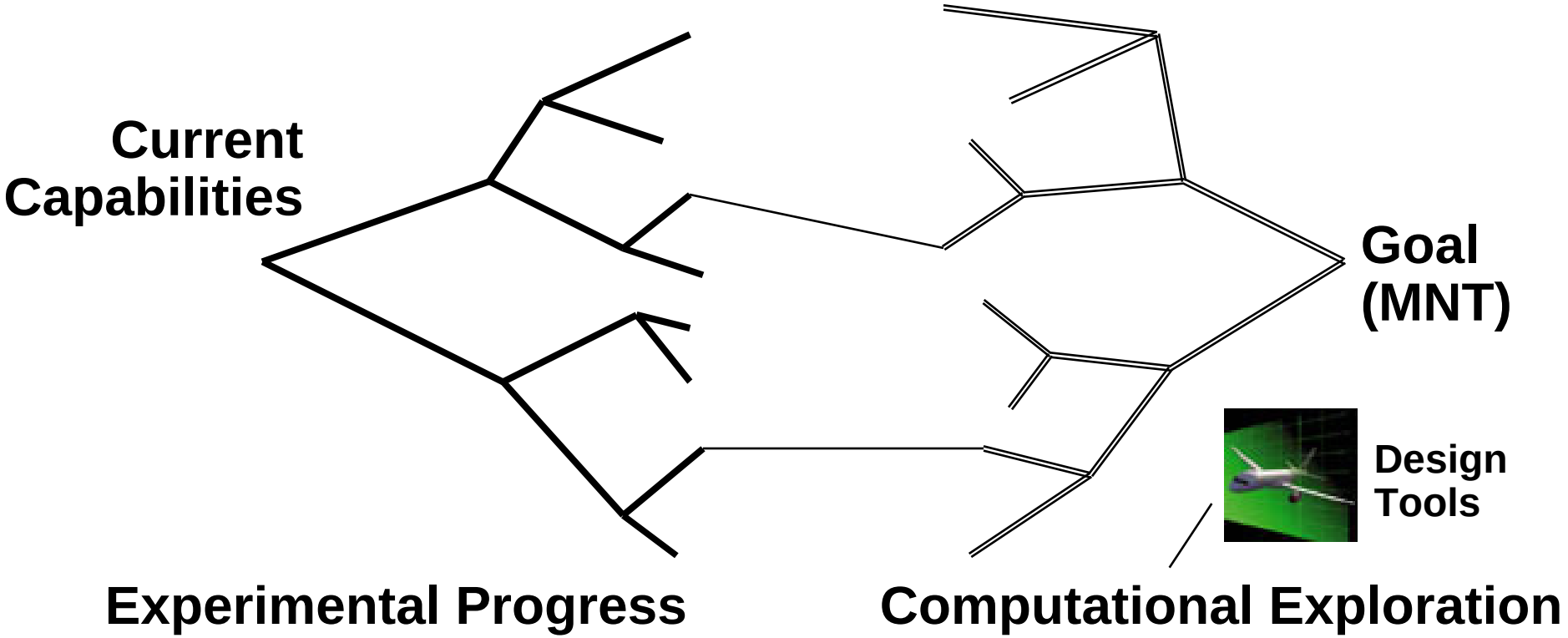
Molecular Electronics Provide the Basis for MNT to Improve Computers



A	B	C
0	0	0
1	0	1
0	1	1
1	1	0

- **Molecular XOR Gate From Architectures for Molecular Electronic Computers: 1. Logic Structures and an Adder Built From Molecular Electronic Diodes, James C. Ellenbogen & J Christopher Love, MITRE, July 1999**
  - **Available at http://www.mitre.org/centers/wc3/nanotech/index.html**

“Meet In the Middle”



- **Analytic Tools Are Good for Exploring Paths Back From One’s Goal, While Experimental Progress Moves Forward**
  - **Based on Original Figure by Merkle**

We Can Afford to Go

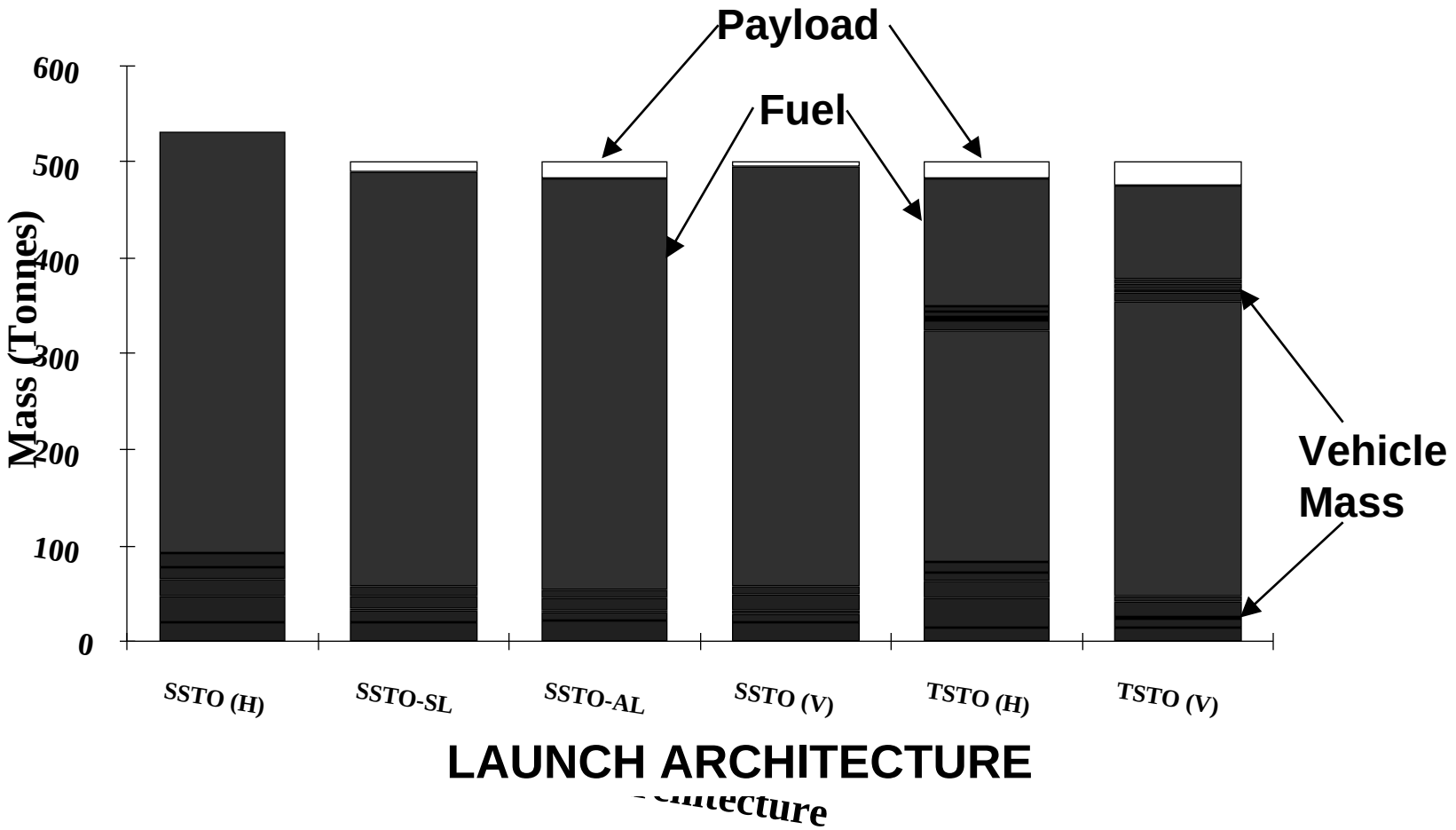
- Say You Want a Revolution
- Broaden the Aeronautics Constituency
- Allow For the MNT Scenario
- We Can Afford to Go
  - Earth Launch Rockets
  - Skyhooks and Towers
  - Spacehooks
  - Solar Electric Ion Engines

Space Access

In Space

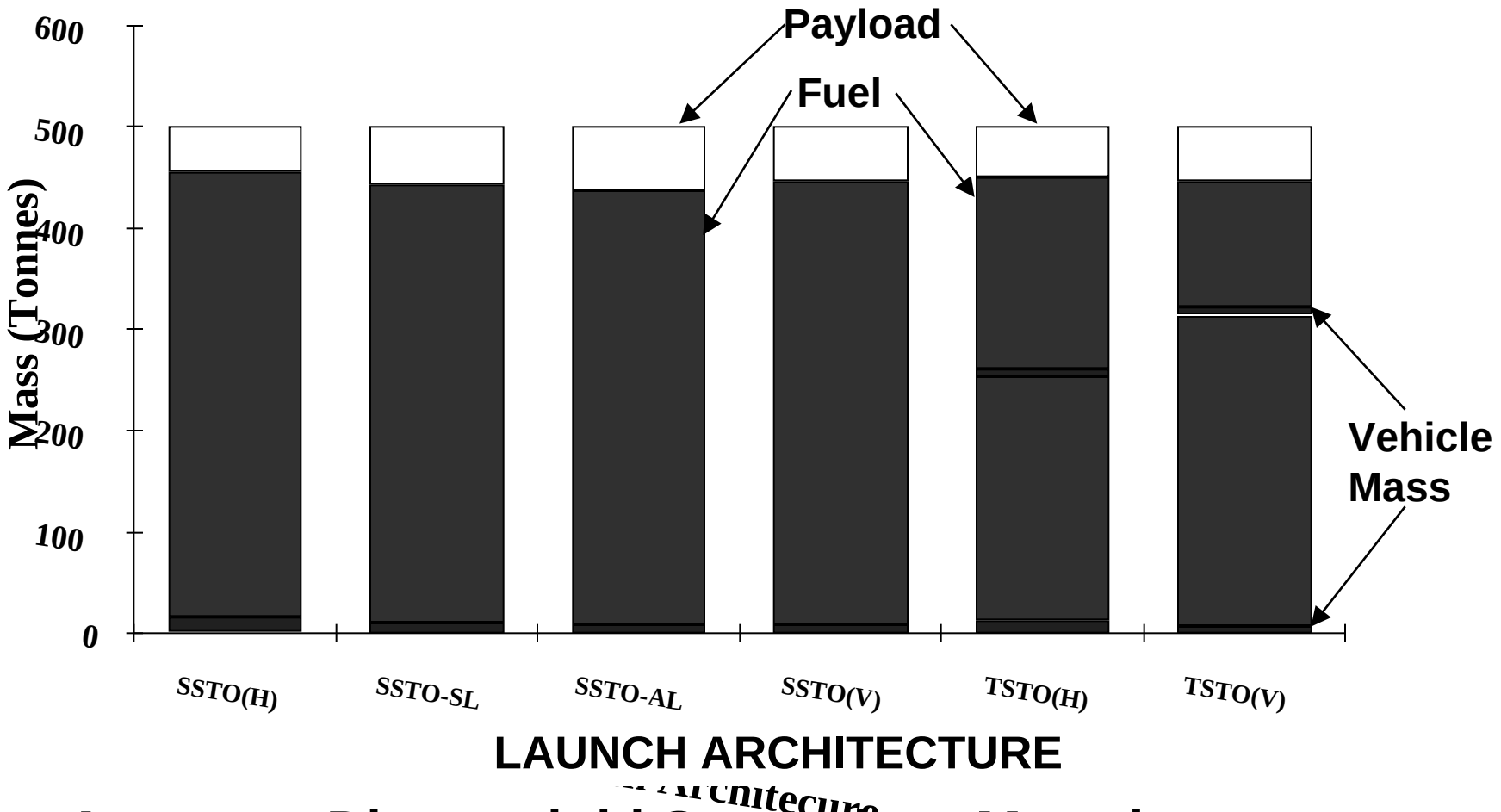
- Getting There is Not Enough

Earth Launch With Current Technology



—FromShkadov et al., ***Acta Astronautica***, **35**:1, 47-54, 1995

Earth Launch With MNT



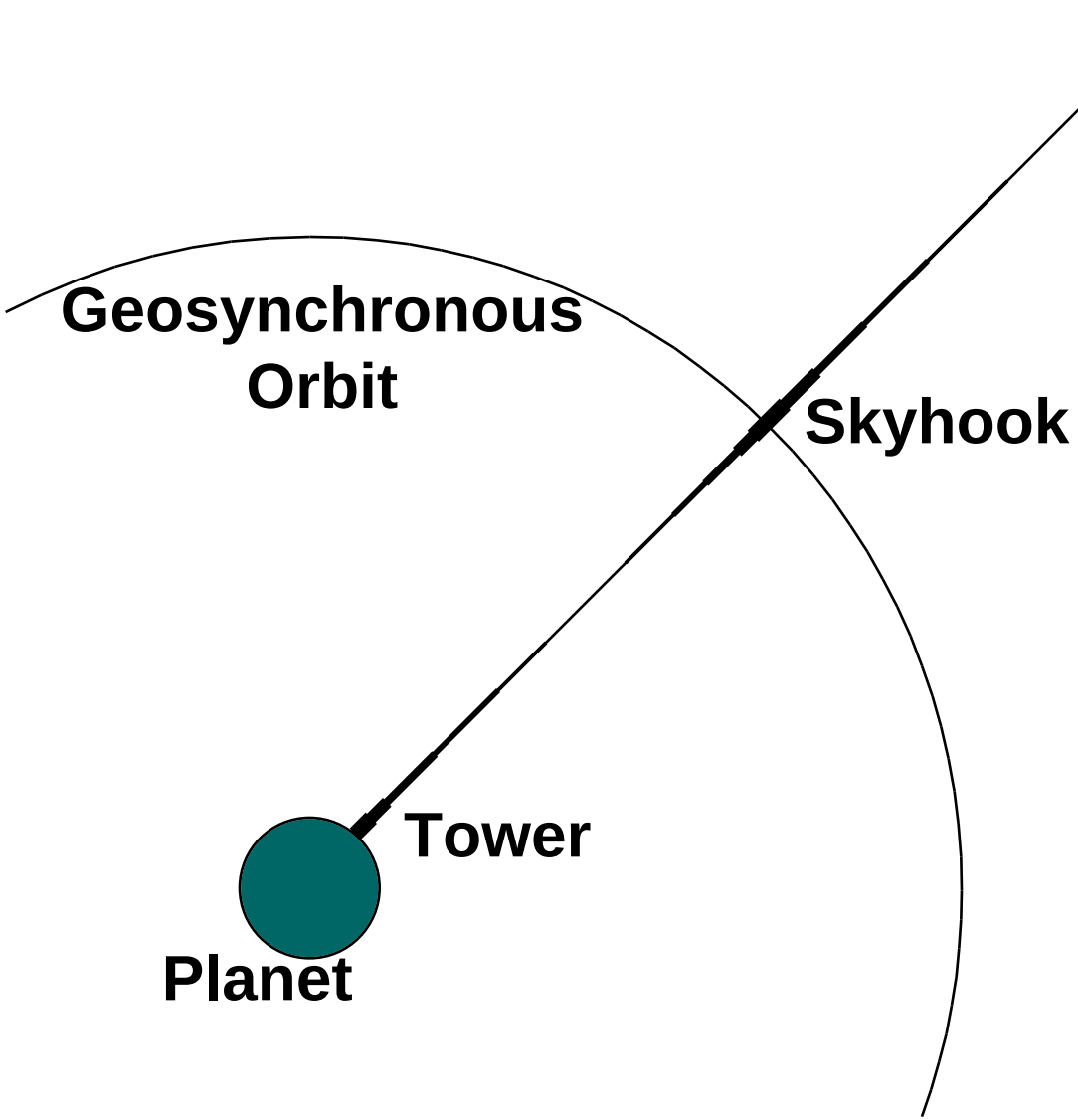
- **Assumes Diamondoid Strength-to-Mass in Place of Titanium**

Cost Advantages of MNT for Earth Orbit Launch

- **Conventional Costs**
  - **$16,000 / kg**
- **More Payload Per Launch**
  - **$5,000 / kg**
  - **Model of Same Cost per Launch**
- **Much Lighter Dry, Empty Mass**
  - **$185 / kg**
  - **Model of Same Lifetime Cost Per kg of Vehicle**
- **Lower Manufacturing Cost**
  - **$4 / kg**
  - **Based on Applying MNT Cost Model to Total GLOW**

Based on McKendree, "Implications of Molecular Nanotechnology Performance Parameters On Previously Defined Space System Architectures," 1995, at http://www.zyvex.com/nanotech/nano4/mckendreePaper.html

Skyhook—Tower



- **Landis and Cafarelli Show That A Skyhook—Tower Combination Can Mass Much Less Than A Skyhook Alone**
  - **For MNT Materials, A Tower Alone Is Often the Lowest Mass**
  - **Tower Uses Active Stabilization to Prevent Buckling**

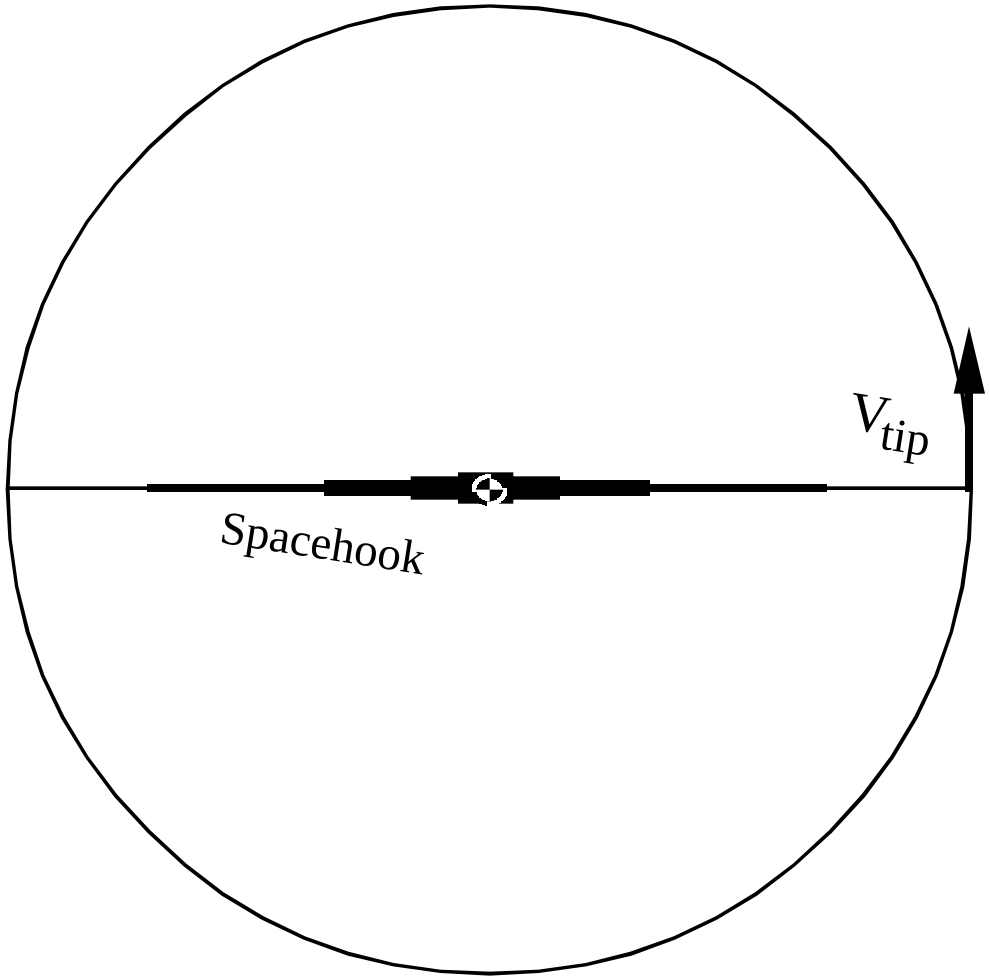
Buckytube Skyhook-Tower Performance

Planet	Ratio of Structure Mass to Payload Mass	Estimated Lift Payback Time (Earth Days)
Mercury	32.7	182
Venus	550.0	19,433
Earth	38.3	32
Moon	5.2	10
Mars	2.6	1

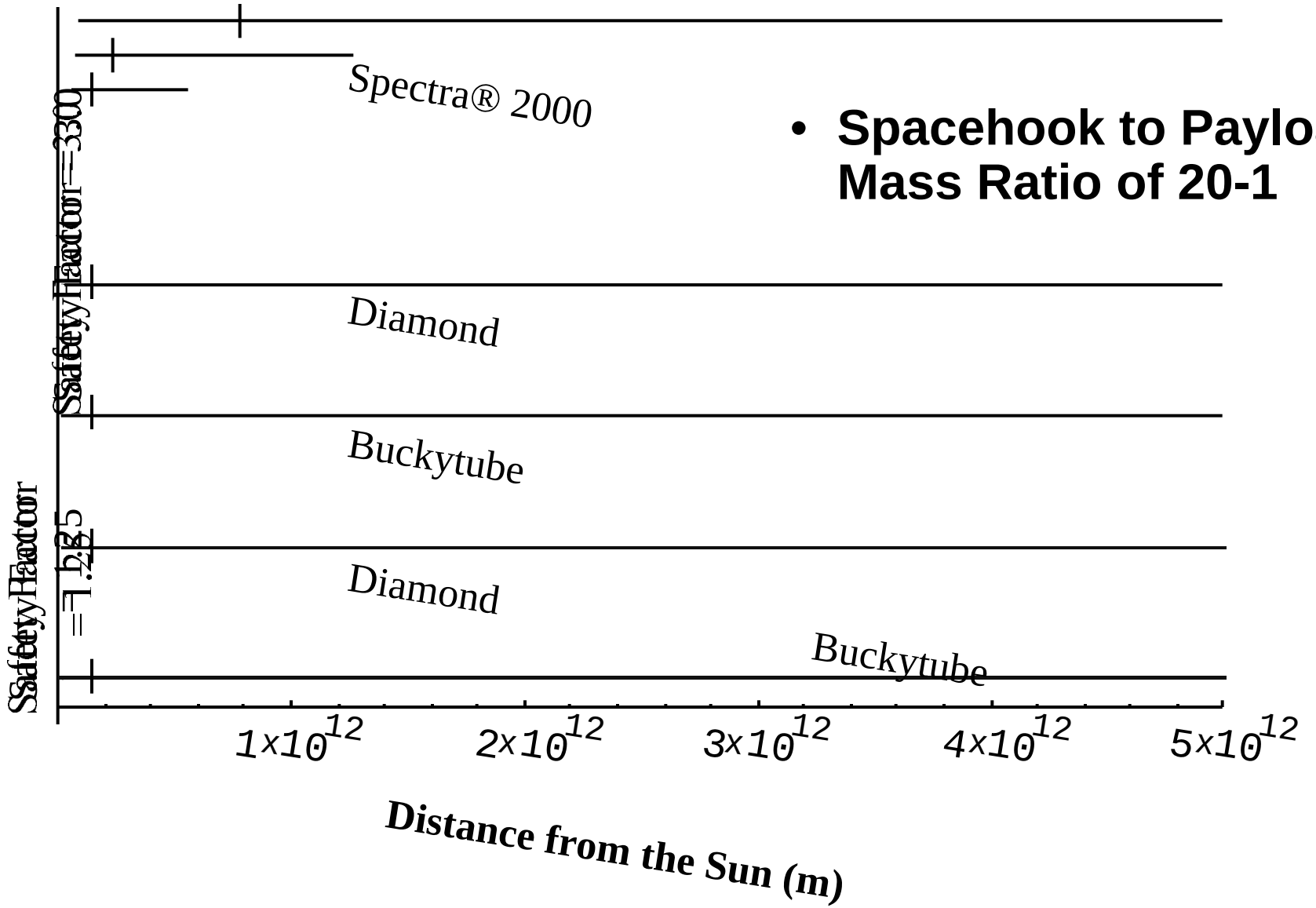
- MNT Monitoring and Repair Allows a 1.25 Safety Factor

Spacehooks

Safety Factor 3.00	Vtip (km/s)
Spectra® 2000 20-1	2.1
Diamond 20-1	3.9
Buckytube 20-1	6.0
Spectra® 2000 100-1	2.8
Diamond 100-1	5.2
Buckytube 100-1	8.1
Safety Factor 1.25	
Diamond 20-1	6.0
Buckytube 20-1	9.3
Diamond 100-1	8.0
Buckytube 100-1	12.5

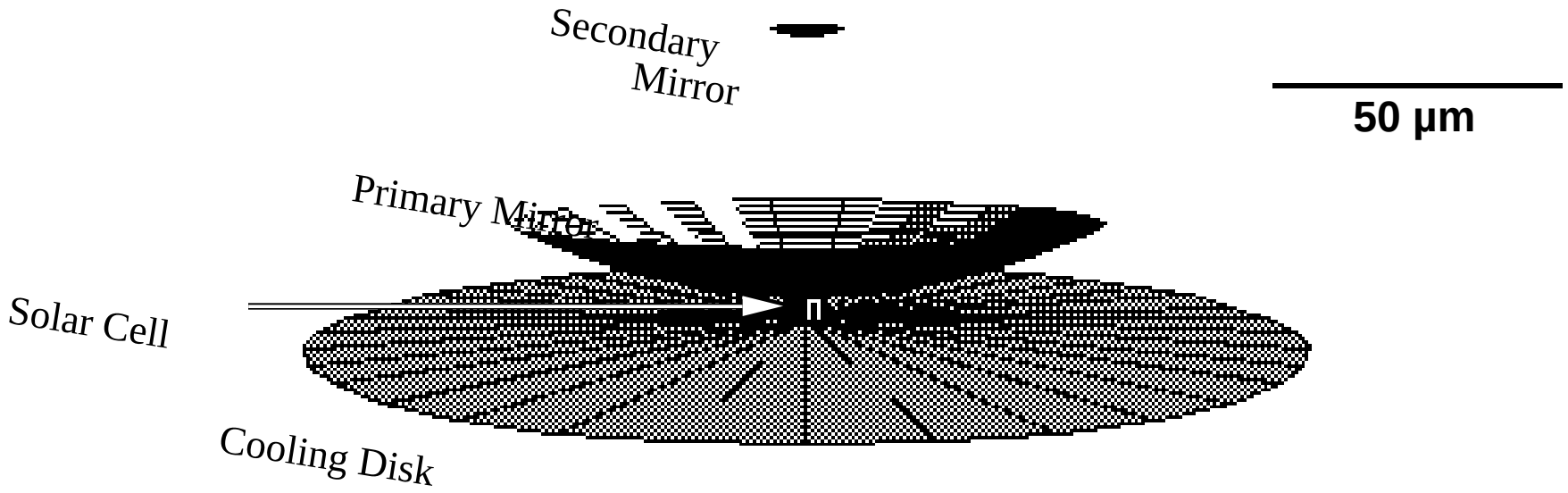


Solar System Reach for Spacehooks in Elliptic Planetary Orbits



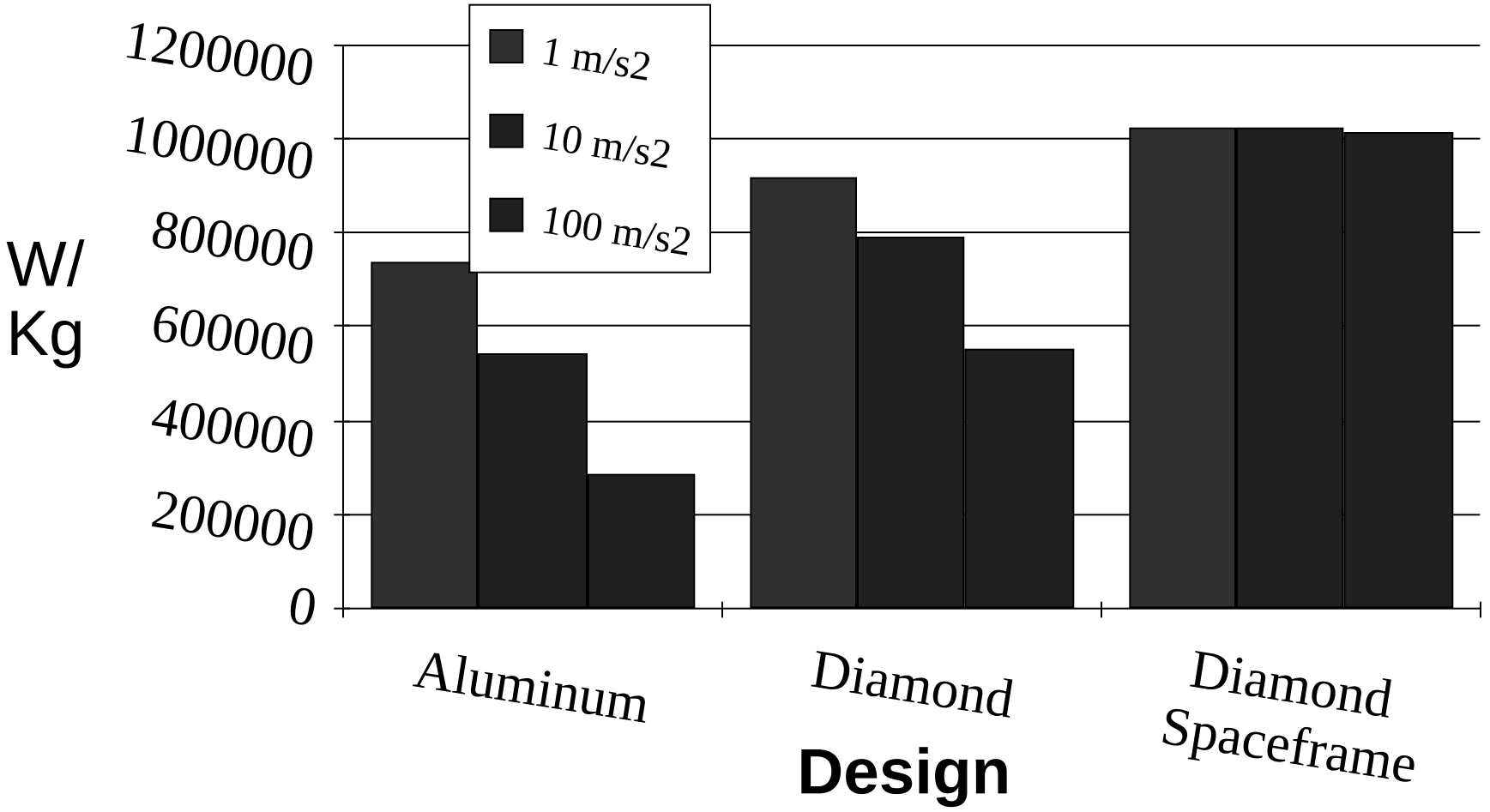
- **Spacehook to Payload Mass Ratio of 20-1**

Solar Concentrator

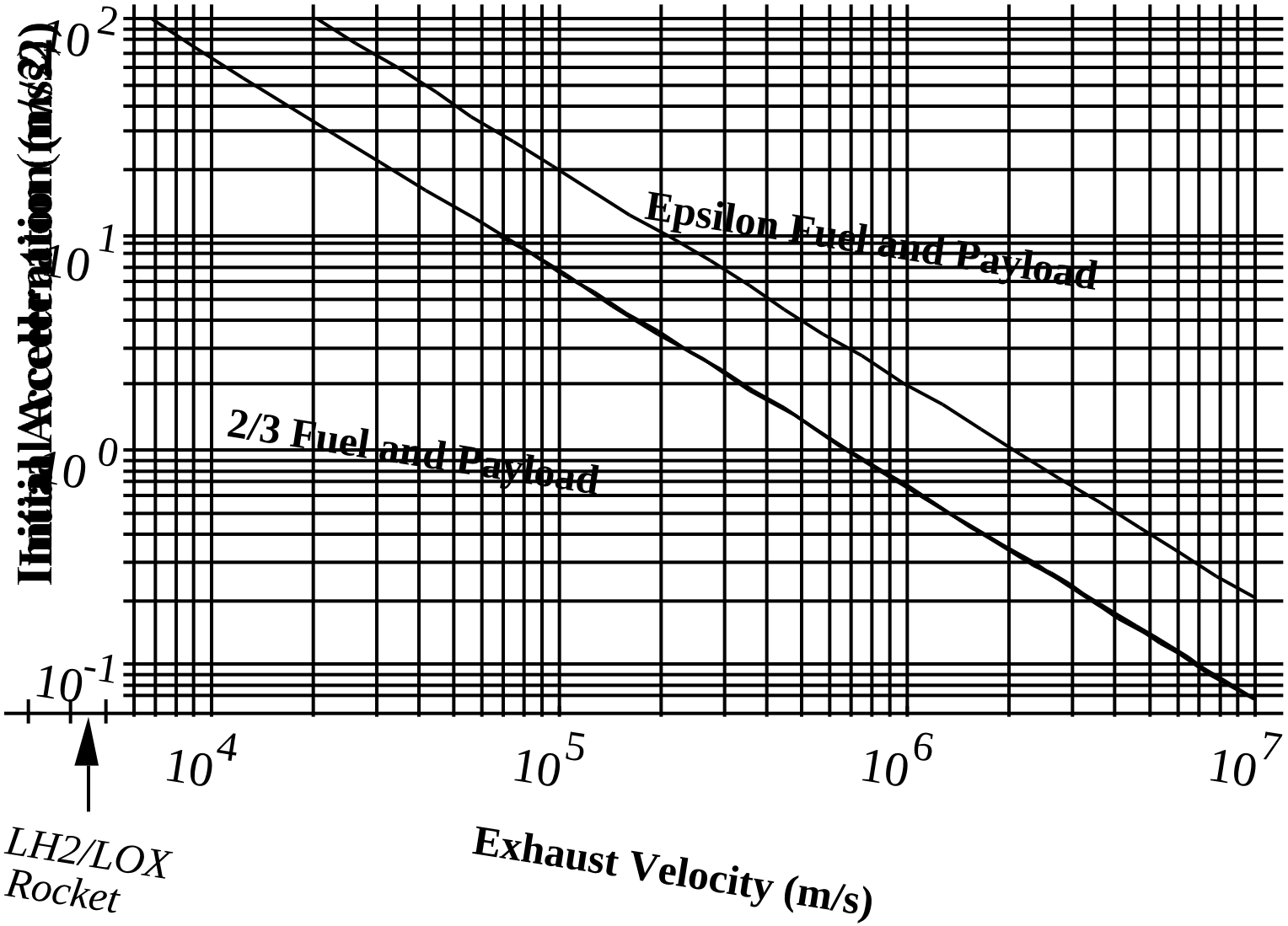


- **Optimized for 1 AU**
- **Primary Mirror Contains the Bulk of the Mass**
  - **40 nm Al, Plus Support Backing**
- **Support Struts Not Shown**
- **Up to 1 MW/kg Solar Panels (at 1 AU)**

Specific Power of MNT-Based Solar Concentrators



Performance of MNT-Based Solar Electric Ion Engines



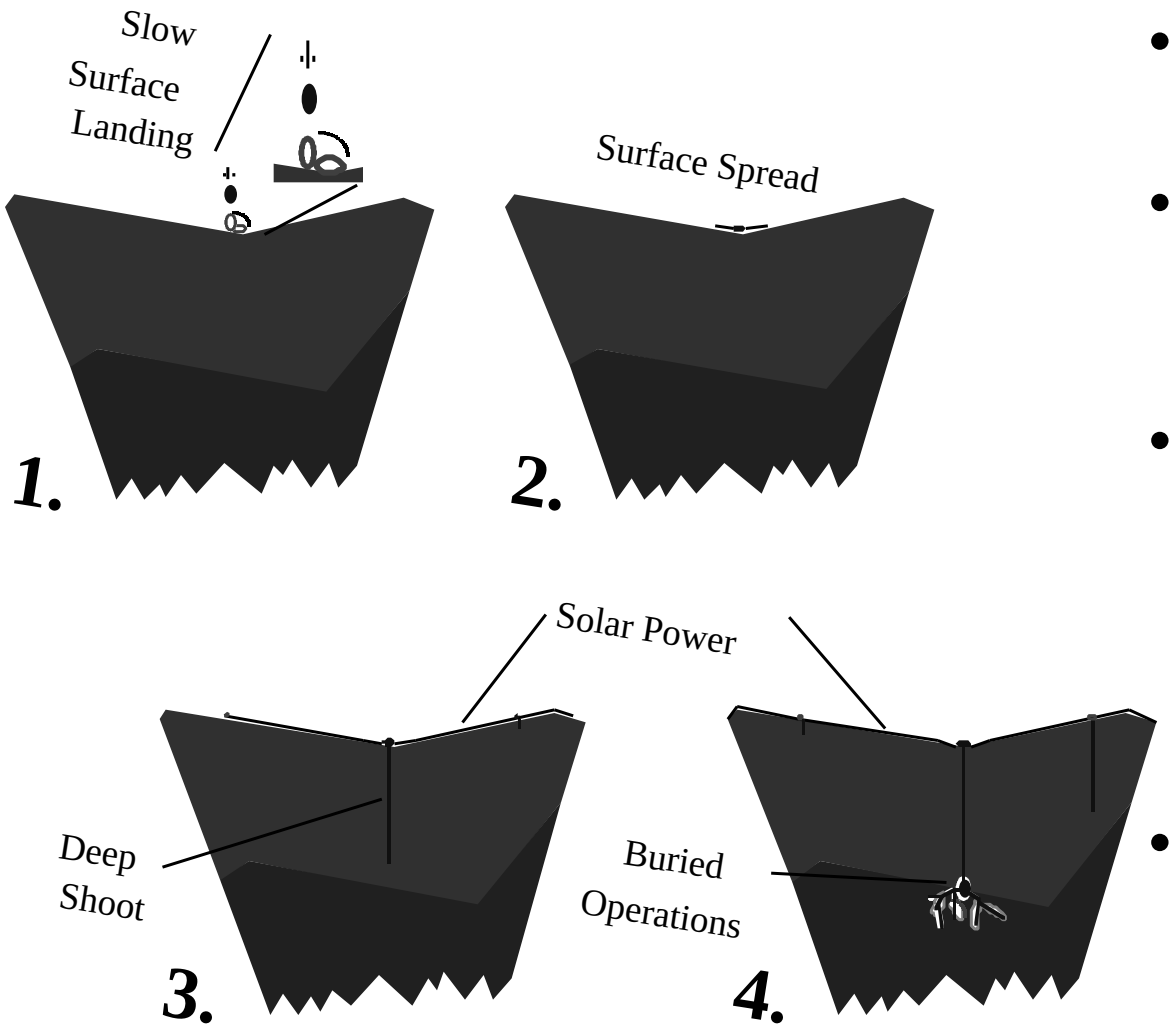
Diamond Space-frame Solar Panel Design

(~1 MW/kg)

Getting There is Not Enough

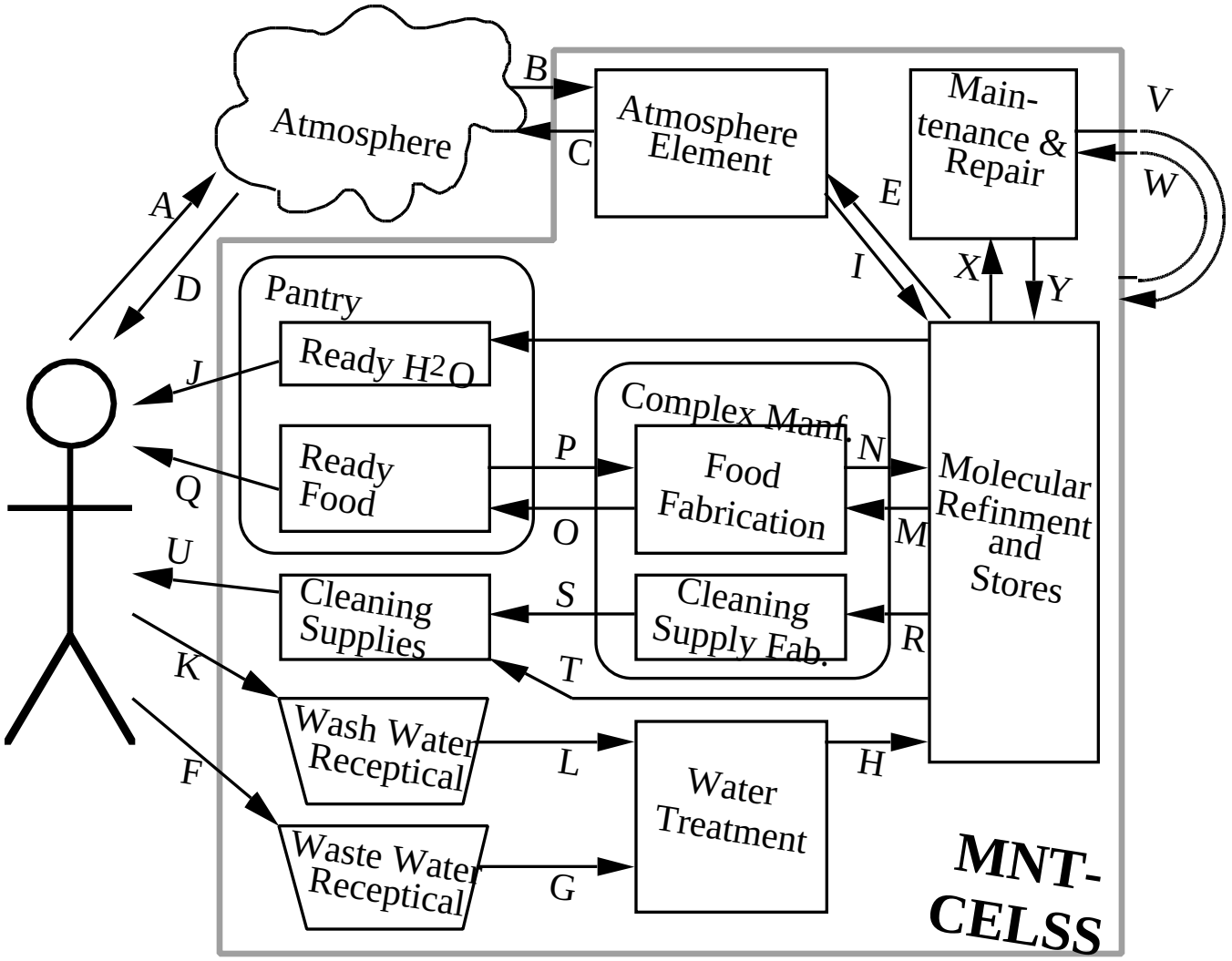
- Say You Want a Revolution
- Broaden the Aeronautics Constituency
- Allow For the MNT Scenario
- We Can Afford to Go
- Getting There is Not Enough
  - Extra-Terrestrial Resource Utilization (e.g., Asteroid Mining)
  - Closed Environment Life Support
  - Self-Repair Using On-Board Remanufacture
  - Flexible Operations (Logical Core Architecture)
  - Space Colonies

"Small Seed" MNT Asteroid Mine Architecture



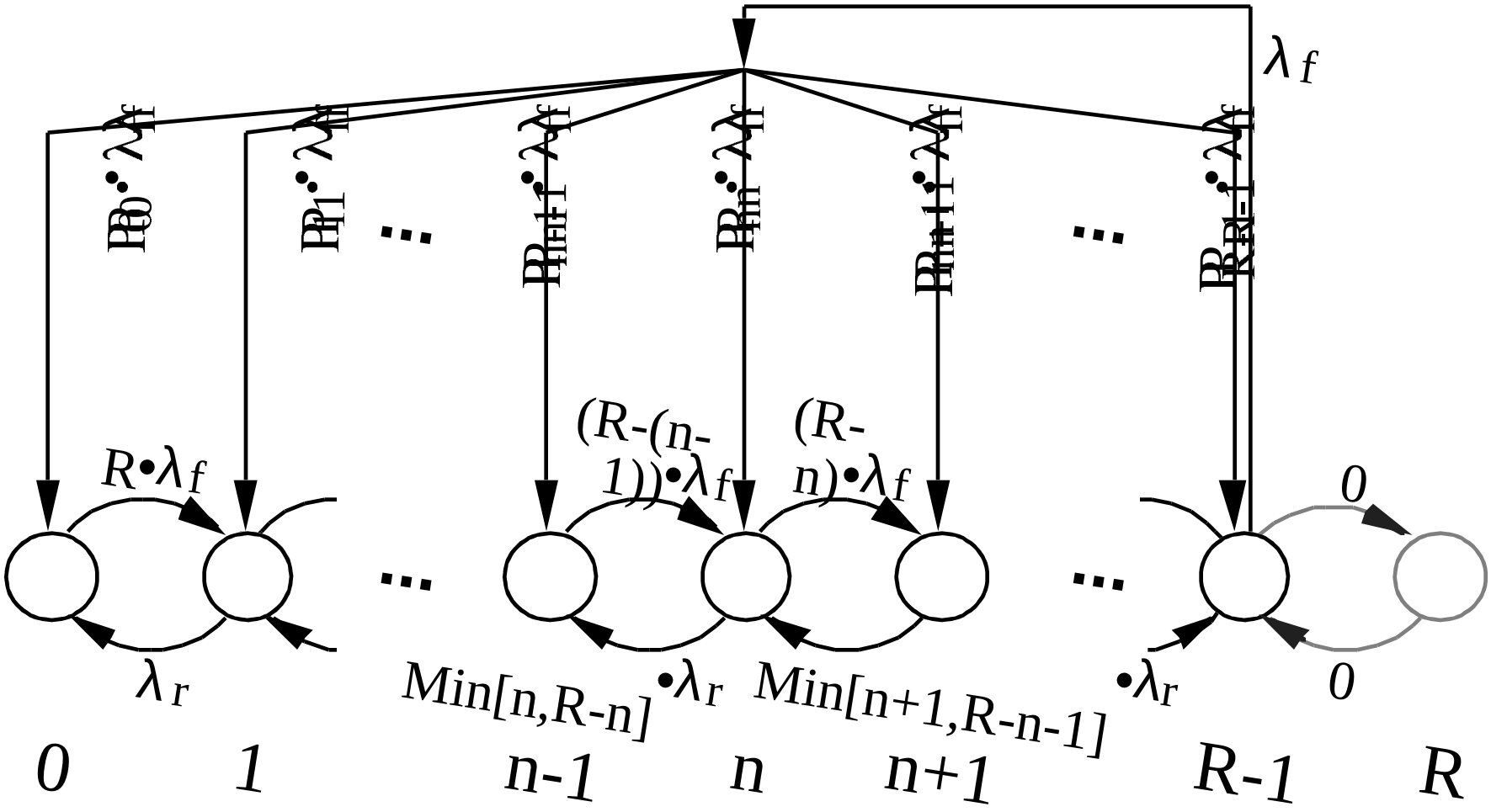
- **Individual Seeds Have Low Mass**
- **Many Per Satellite Are Feasible**
  - **$P_{Survive}$ Can Be Low**
- **Objective is Bootstrapping Consumption of a Small Carbonaceous Body**
- See McKendree, ***JBIS***, **51**, 153-160, 1998 for Other Options

Closed Environment Life Support System Through Direct Remanufacture



- **Back of the Envelop Performance Estimates**
  - **Per Capita Mass of ~0.6 - 6 kg**
  - **Per Capita (Line) Power of ~1.3 - 13 kWe**
  - **Range is Design Margin Of Up to a Factor of 10**

Single Module-Type Model of System Repair Through On-Board Component Remanufacture



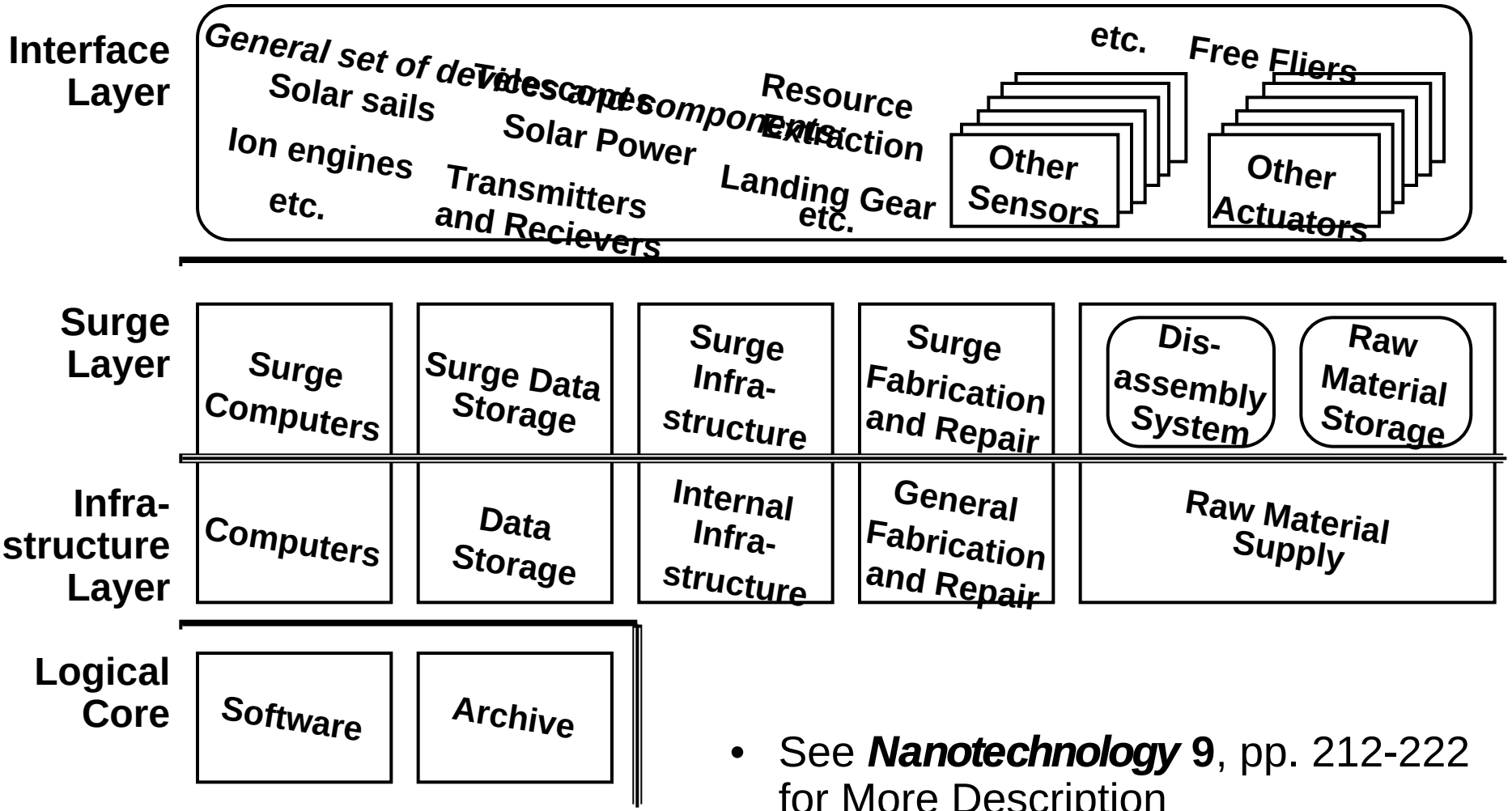
Performance of Self-Repair Model

Number of Modules	ATTF= 10 Years	ATTF= 2.8 Years	ATTF= 0.2 Years	ATTF= 24 hours
1	1.0×10^{1}	2.8×10^{0}	2.0×10^{-1}	2.7×10^{-3}
2	4.4×10^{5}	3.4×10^{4}	1.8×10^{2}	3.7×10^{-2}
3	1.3×10^{10}	2.7×10^{8}	1.0×10^{5}	3.1×10^{-1}
4	5.6×10^{14}	3.3×10^{12}	9.0×10^{7}	3.9×10^{0}
5	2.0×10^{19}	3.3×10^{16}	6.3×10^{10}	3.9×10^{1}

ATTF Range from Radiation Damage Estimates

- ATTF = Average Time To Failure (λ_f)
- Average Time to Repair (λ_r) of 1 Hour
- Schedule Replacement Greatly Outperforms Replacement on Failure

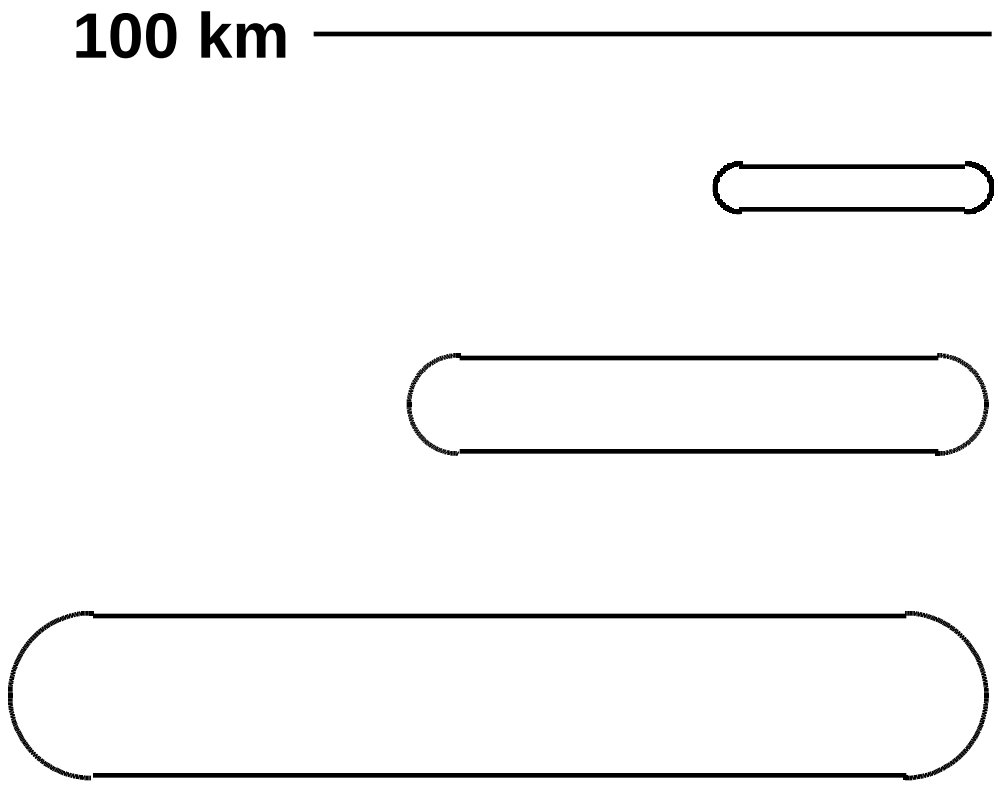
Logical Core Architecture



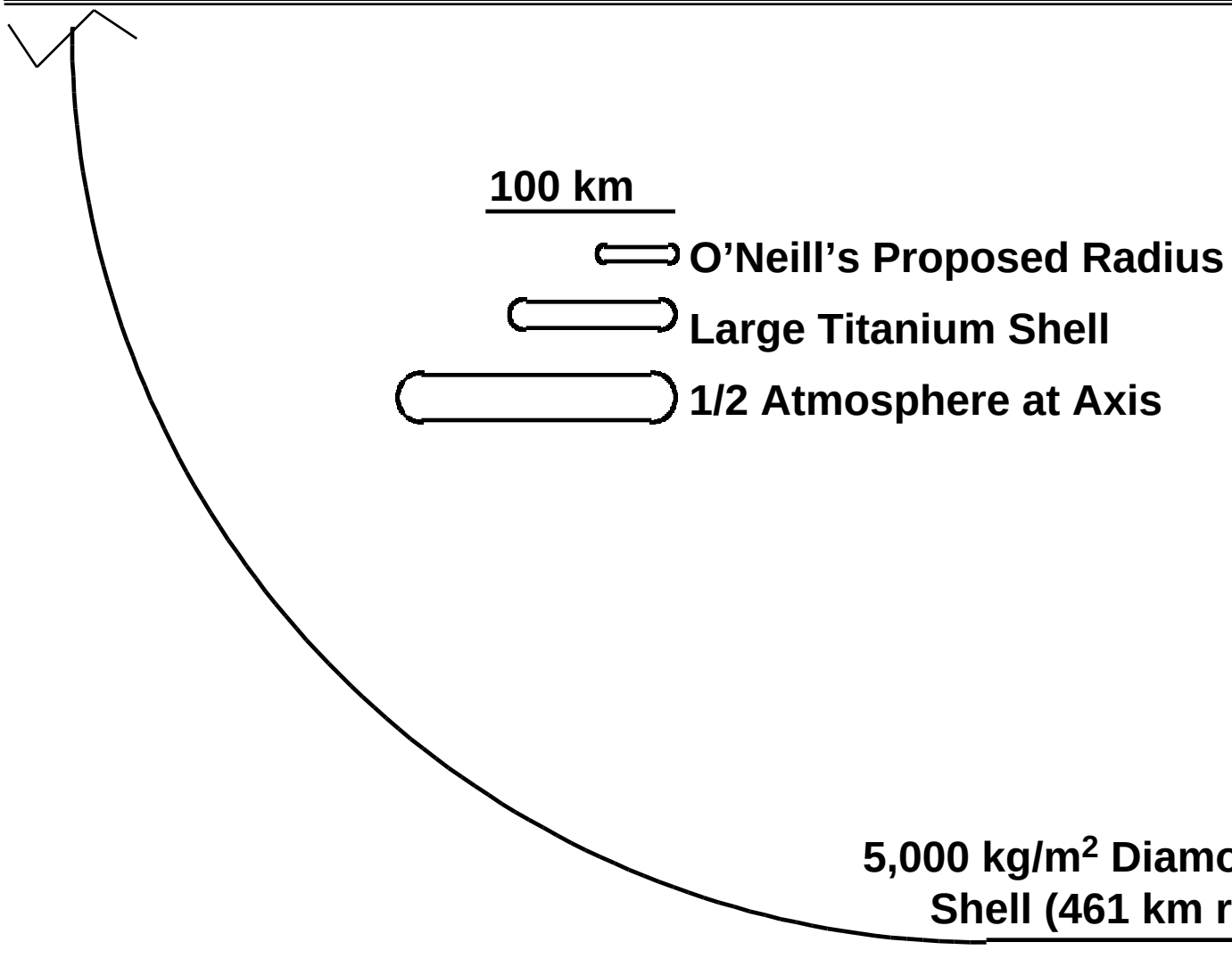
- See ***Nanotechnology* 9**, pp. 212-222 for More Description


The Vision of O’Neill Style Colonies

Several O'Neill-Style Colonies



An O'Neill-Style Colony Using Diamond



Characteristics of a Diamond Colony

- 461 km radius
- 4,610 km long cylinder section, plus endcaps
- Diamondoid Shell
  - 1.4 m thick
  - 5000 kg/m^2
  - 50% safety factor
  - 8 x 10^{16} kg
- 9.8 m/s^2 simulated g level on the inner surface
  - 22.7 minute rotation period
  - 2 1/8 km/sec rim speed
- ~6.7 10^{12} m^2 habitable surface area
- Population of ~40 billion people

Characteristics of a Buckytube Colony

- 1,120 km radius
- 11,200 km long cylinder section, plus endcaps
- Buckytube Shell
  - 2.1 m thick
  - 5000 kg/m^2
  - 50% safety factor
  - 4.7 x 10^{17} kg
- 9.8 m/s^2 simulated g level on the inner surface
  - 35.4 minute rotation period
  - 3.3 km/sec rim speed
- ~3.9 10^{13} m^2 habitable surface area
- Population of ~250 billion people

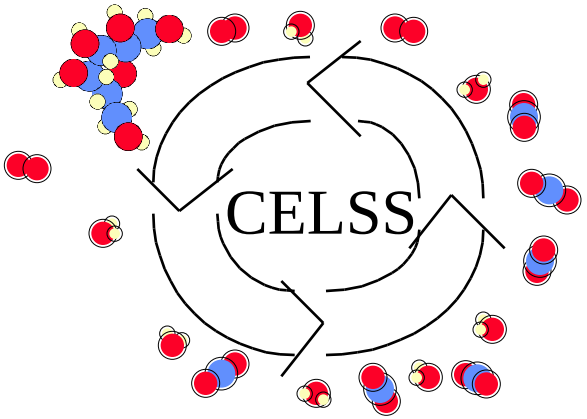
Space Colony Practicalities

- **Ceres Contains Enough Carbon for ~12 Buckytube Colonies or ~60 Diamond Colonies**
  - **High Estimate of Ceres' Carbon Would Provide For ~75 Buckytube or 370 Diamond Colonies**
- **Need ~1.65 x 10^6 kg of Atmosphere per Colonist**
- **Metals and Especially Silicates Are More Abundant and Appear to Have Fewer Uses. Thus More and Smaller Metal and Silicate Shell Colonies Are Likely To Be More Desirable**
- **Mirror Design Adds Complications**

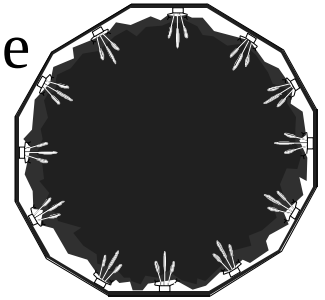
Penultimate Laws

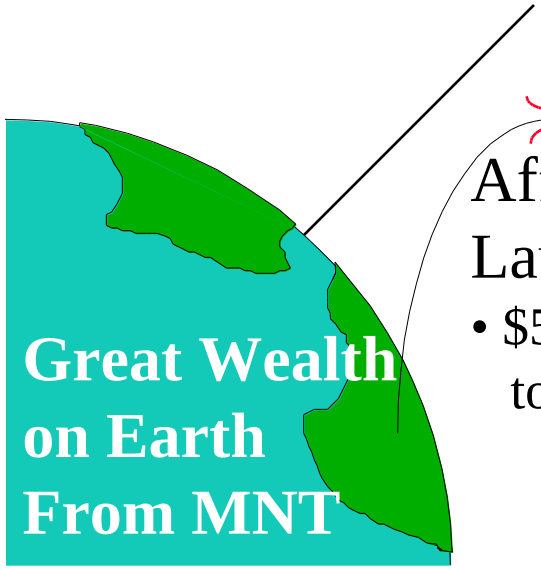
- If God Had Wanted Us to Go Into Space, He Would Have Given Us More Money
  - Space Funding Catechism of the Aerospace Industry
- Molecular Nanotechnology Will Vastly Reduce the Cost of Goods, Which Is Equivalent to Making Us All Much Richer
  - McKendree's MNT Finance Observation
- God Want's Us to Go Into Space
  - McKendree's Space Finance Corallary

Why MNT Will Make Space Settlement Affordable



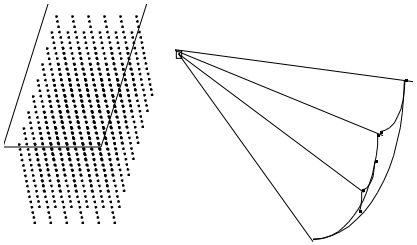
In Situ Resource Utilization (Space Manufacturing)



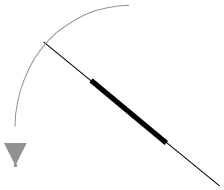


Affordable Launch

- $5-$0.5/kg to orbit



Efficient Interplanetary Travel



Concluding Law

- **Question:**
  When Will We Develop Molecular Nanotechnology?
- **Answer:**
  Just Before We Colonize the Solar System

—Globus's Fourth Timing Postulate

– From Globus et al., JBIS, **51**, pp. 142-152. 1998.

Recommendations [1 of 2]

- **Say You Want a Revolution**
  - **A Really Revolutionary Technical Leap Would be MNT**
    - **10 Year Goal: Develop an Assembler**
    - **25 Year Goal: Demonstrate Everything Else in This Talk—In the Field**
- **Broaden the Aeronautics Constituency**
  - **Personal Aircar Appears Practical with MNT**
    - **Potential Should be Reflected in all Aeronautics Goals**
  - **Research Small Flyers**

Recommendations [2 of 2]

- **Allow For the MNT Scenario**
  - **Provide Adequate Flexibility in Design Tools**
  - **Prefer Solutions That Scale to A World with MNT**
- **We Can Afford to Go**
  - **Pursue Buckytube and Diamond-Based Systems in the Out Years**
- **Getting There is Not Enough**
  - **Need Some Technical Research Goals For Space Operations**
    - » **Extra-Terrestrial Resource Utilization**
      - **In-Situ Propellant Propulsion for a Start**
    - » **Closed Environment Life Support**

Questions?