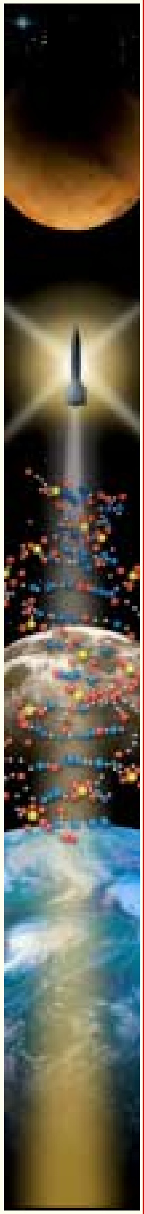
Technological Hurdles



Capabilities we need:

In-space transportation

- Safe, efficient, economical
- Multi-use; robotic and human capabilities

Crew health and safety

- Countermeasures to environmental effects
- Medical autonomy

Human/robotic tools

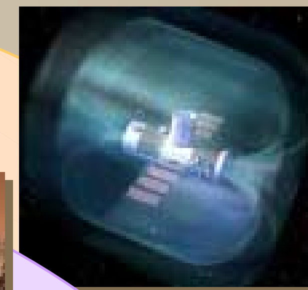
- On-site intelligence; dramatically higher productivity
- Power for flexible, productive operations

Space vehicle performance

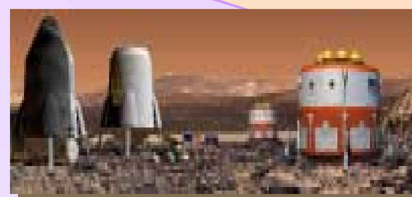
- Low mass, self-healing, self-assembling
- Automated reasoning, smart sensing, reliable

Stepping Stones

Go anywhere, anytime



Sustainable Planetary Surfaces
Going Beyond and Staying



- Traveling out to ~1.5 AU, and beyond
- Staying for indefinite periods
- Enabling sustainable scientific research
- Living and working on another planet

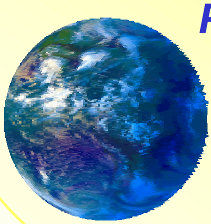
Accessible Planetary Surface
Going for Visits

- Traveling out to 1.5 AU
- Staying for 1000 days
- Enabling tactical investigations
- Visiting and working on another planet

Earth's Neighborhood
Getting Set by Doing

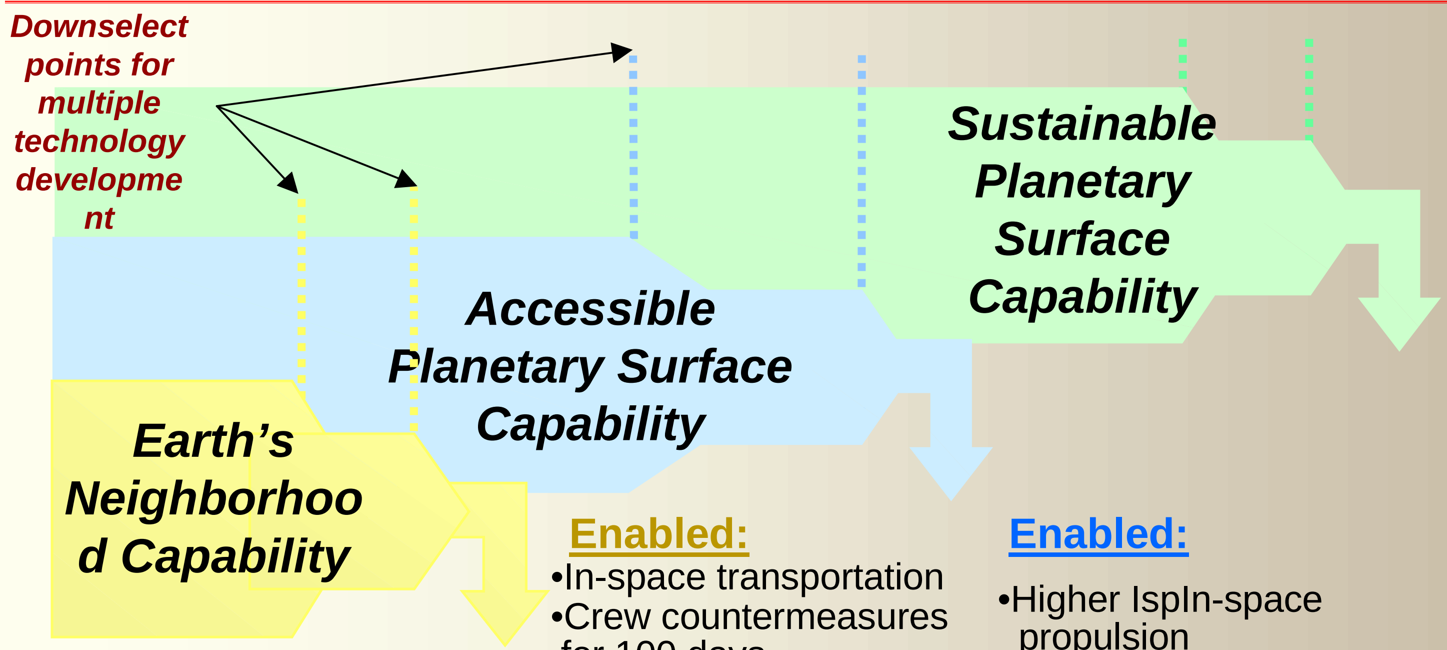
- Traveling up to 1.5 million km
- Staying for 50-100 days
- Enabling huge optical systems
- Living in deep space

Earth and LEO
Getting Ready



- Space Station Experience
- Solar System Learning
- Technology Advancements

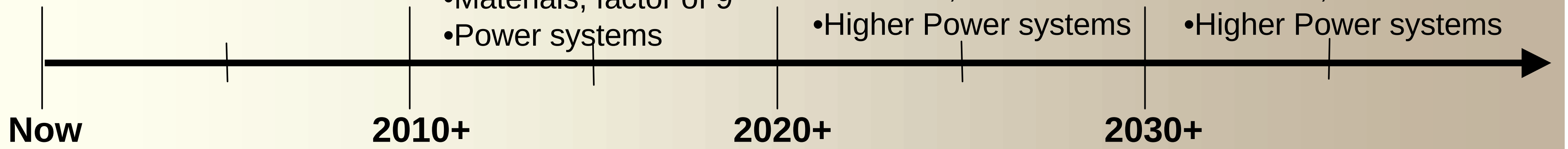
Progressive Exploration Capabilities



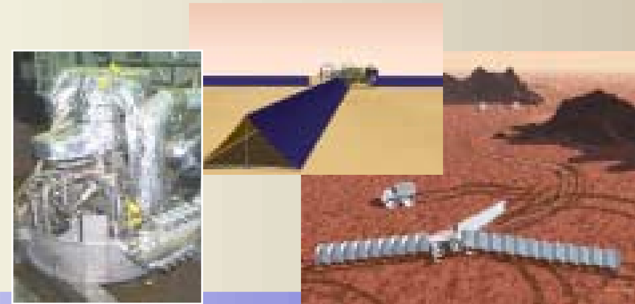
Enabled:
- •In-space transportation
- •Crew countermeasures for 100 days
- •Health care
- •Integrated Human/ robotic capabilities
- •EVA
- •Closed water/air systems
- •IVHM
- •Advanced habitation
- •Materials, factor of 9
- •Power systems

Enabled:
- •Higher IspIn-space propulsion
- •Crew countermeasures for longer duration
- •Health care
- •Robotic aggregation/assembly
- •Sustainable habitation
- •Micro/Nano avionics
- •ETO @ <$1000/lb
- •Materials, factor of 40
- •Higher Power systems

Enabled:
- •Higher IspIn-space propulsion
- •Crew Countermeasures for indefinite duration
- •Sustainable health care systems
- •Intelligent systems, orbital and planetary
- •Closed life support
- •Permanent, reuseable habitation
- •ISRU for consumables and spares
- •ETO @ <$1000/lb
- •Materials, factor of 40
- •Higher Power systems



Power System Technologies



	Now	*5-10 Years*	*15-25 Years*
Applications	• LEO/GEO satellites • Earth & planetary science missions • International Space Station	• Mars Outposts • Libration point observatories • Electric propulsion	• Human missions far from Earth • High power electric propulsion
Capabilities	•Short duration/low power Mars surface PV •100w class RTGs •10-100kW near-Earth PV	•kW class Mars surface PV •10-100+kW surface nuclear •Higher efficiency/low mass PV for in-space	•Multi-MW PV and nuclear dynamic systems for space •Robust, high power surface systems

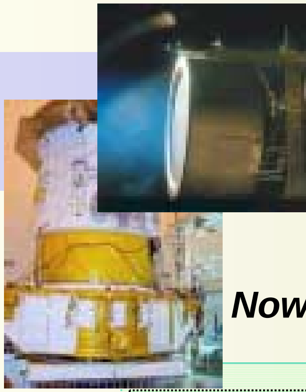
High Payoff Technology Candidates

- Thin film and high efficiency PV cells/arrays
- Advanced dyanmic and static conversion
- High density energy storage
- High efficiency power management/distribution

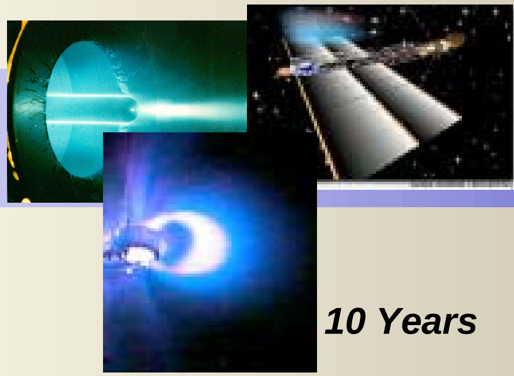
National Benefits:

Advanced power systems increase the reliability and reduce the mass and cost of NASA, military and commercial satellites and spacecraft

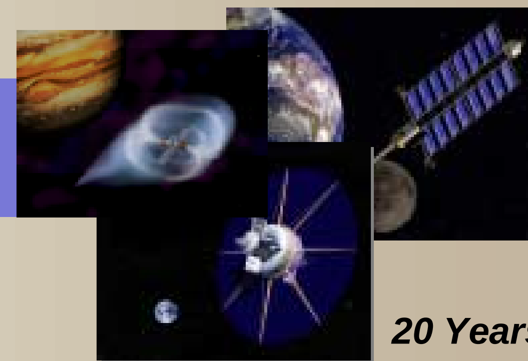
In-Space Transportation Technologies



Now



10 Years



20 Years+

	Now	*10 Years*	*20 Years+*
Application Missions	Humans to LEO. Upper Stages for LEO-to-GEO and robotic missions	Human mission capability for near-Earth space Robotic missions anywhere in the solar system	Safe, low-cost human and robotic exploration of the solar system
Metrics:			
Safety & Reliability	~1/200 failure probability	100X safer	10,000X safer
Mass	Chemical state-of-the-art	3X - 5X reduction	10X reduction
Cost	$3000/kg LEO-to-GEO	$1000/kg - $300/kg	$300 - $100/kg

Leading Candidate Technologies:

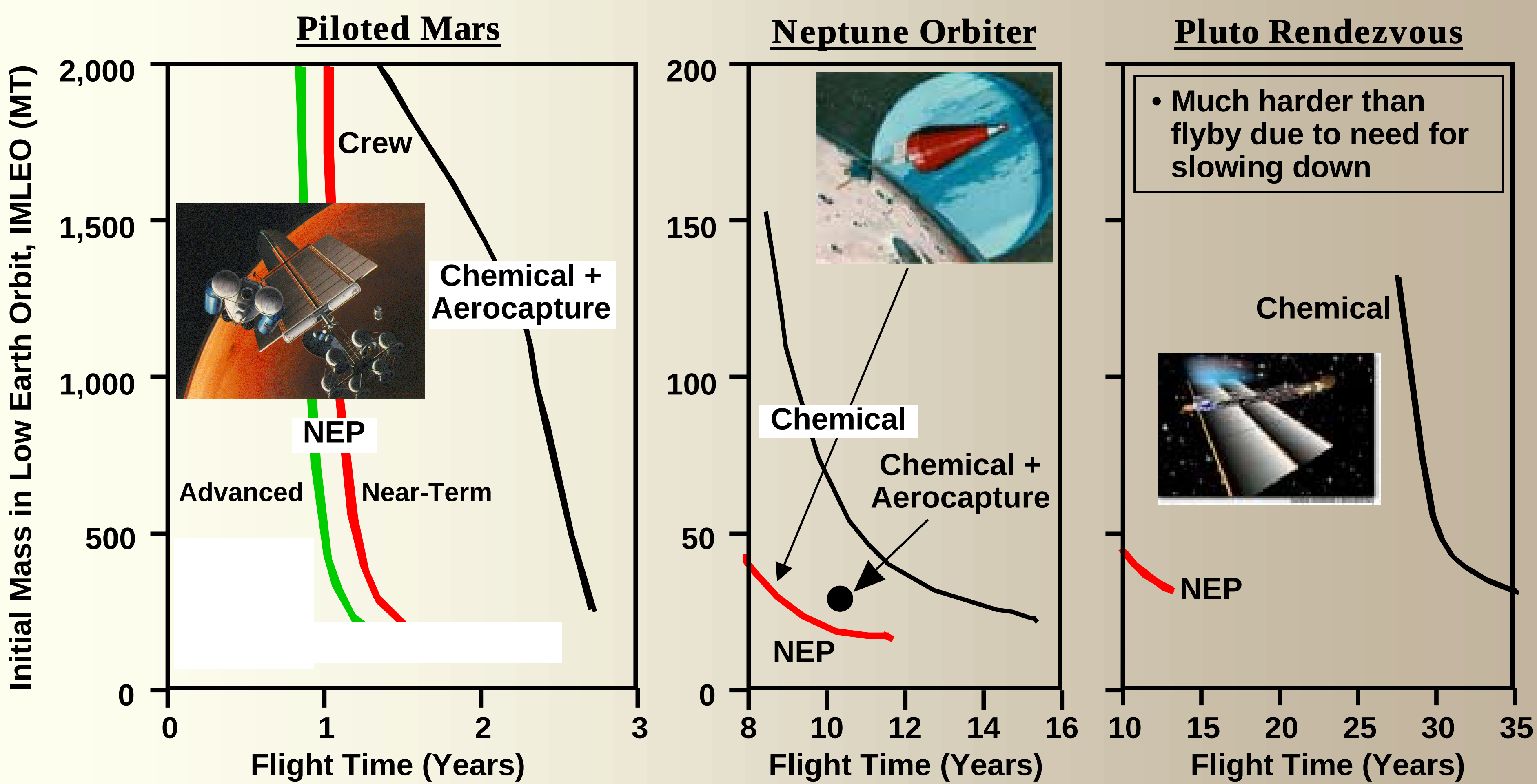
- High power electric propulsion (Isp: 3500 - 10,000 sec; power: 100 kW - 1 MW)
- Aeroassist and aerocapture (mid L/D aeroshells; ballutes)
- Plasma sails for efficient interplanetary transfer and inherent radiation protection
- Fission propulsion for reduced IMLEO and enhanced crew safety
- Momentum Transfer Tethers to provide a reusable in-space infrastructure for robotic and human exploration
- High energy density materials and advanced chemical fuels to increase Isp and reduce propulsion system mass

National Benefits:

Lower cost and more reliable space transportation for commercial enterprises (e.g., communications, resource monitoring, tourism) and defense needs

Electric Propulsion Benefits for Robotic and Human Missions

- NEP can provide both IMLEO and trip time benefits for piloted and robotic missions
- Significant enhancements from advanced power and thruster technologies
- Cannot use SEP or Solar Sails for orbit rendezvous missions significantly beyond Mars (no sunlight !)



Example: Propulsion Technology Down-select

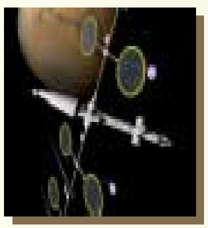
Option 1: Multiple Small NTR Engines

√

Option 2: Nuclear Electric Propulsion

√

Option 3: Solar Electric Propulsion



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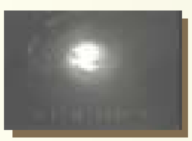
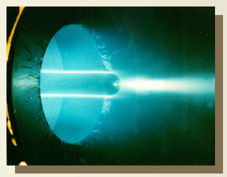
Option 4: HEDM Chemical Propulsion



X

Good Progress … With Breadboards in the Lab...



√

√

R&D Fails

New Option 4: M2P2

√

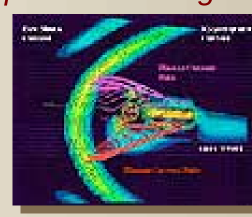
?

Studies Determine Large NTR Needed - - Requiring New Facilities for R&D; Deferred as Later Option

Good EP Progress; Reactor Issues ...

Good Progress...

Rapid M2P2 Progress



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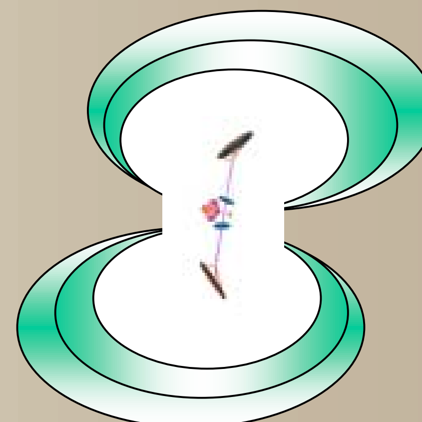


Starting Options → **Initial Down-select** → **Additional Down-select** → **Flight Demo**

Crew Health & Safety: Medical Care

Space First Aid

Now

Space Clinic

10 years

Space Hospital

20 years

	Now	10 years	20 years
Application Missions	Short duration missions in low Earth orbit	Extended missions in Earth's Neighborhood	Long-duration missions to more distant destinations
Metrics: *Diagnosis/Prognosis*	Limited to tele-diagnosis of obvious problems	Tele-diagnosis & prognosis	Autonomous, on-site diagnosis, prognosis & self repair
Medical Treatment	Triage only, abort to Earth for secondary care	Limited in-space treatment, abort to Earth for tertiary care	In situ cyberdoc capability, in-space tertiary care
Human Performance	Enhancement limited to data processing	Telerobotics capability with haptic interfaces	Interactive, variable-autonomy research support

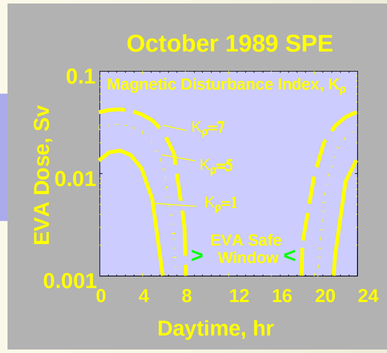
Leading Candidates Technologies:

- Miniature biochemical imaging and analysis labs for studying space-induced effects at the cellular and molecular level
- Self-guided nano-scale and non-invasive astronaut state-of-health monitors, nano-scale therapy effectors
- Virtual reality training with haptic interfaces and human-robot symbiots to enhance human performance
- Biological pharmaceutical production in space, use of local raw materials
- Digital human models for cyber diagnosis, treatment & surgery

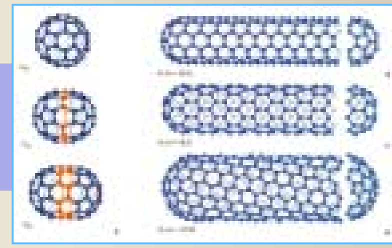
National Benefits:

Direct application to medical systems on Earth, such as telemedicine in remote environments, pharmaceuticals with extended shelf-life, small and portable diagnostic equipment, biosensors for body function monitoring, trauma advances like artificial blood.

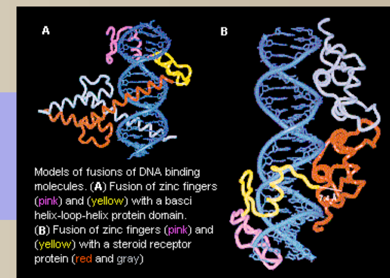
Crew Health & Safety: Radiation Protection



Flight rules



Optimal shielding materials



Biomolecular Intervention

	Now	***10 years***	***20 years***
Application Missions	Short duration missions in low Earth orbit	Extended missions in Earth's Neighborhood	Long-duration missions to more distant destinations
Metrics:			
Uncertainty in cancer risk	600%	120%	50%
Radiobiological database	10% complete	50% complete	100% complete
Solar flare strategies	40% complete	75% complete	100% complete
Model Validation	High altitude balloons	Int'l Space Station	Beyond Van Allen Belts

Leading Candidates Technologies:

- Biomolecular risk prediction; molecular surveillance
- New structural materials with optimal shielding properties with significant improvement over aluminum
- Electromagnetic shields, including electrostatic, magnetic, and plasma shields from innovative propulsive techniques
- Pharmacology: antioxidants, antisense drug discovery, ribozymes
- Biomolecular intervention, such as stem cell replacement

National Benefits:

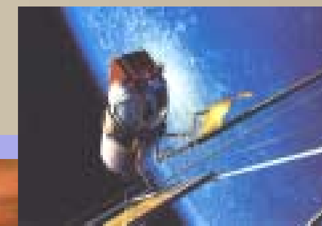
Direct contribution to the diagnosis, prevention and treatment of cancer.

Improvement in safety for military and civilian travel on high altitude aircraft.

“Breakthrough” Robotics/EVA Technologies

Now

5-10 years



10 - 20 years

pplication Missions

Metrics:
Human/robotic Optimization
Deployment Characteristics
Typical Capabilities

Now

HST Servicing
International Space Station

- Very limited
- Very low precision/complexity
- Advanced tools, with zero autonomy

5-10 years

Simple deployment
Resecure and recovery

- High communication bandwidth
- Low precision/complexity
- Robots/spacesuits with high dexterity and limited autonomy

10 - 20 years

Complex ‘free space’ science facilities
Planetary surface exploration

- Highly-integrated partnership
- High precision structures/complexity
- Robots enhance human senses, intelligence, adaptibility, autonomy

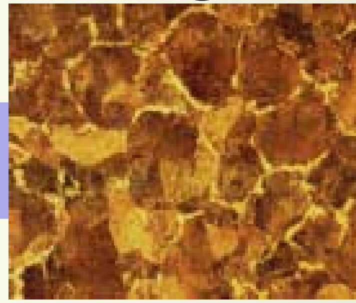
Leading Candidate Technologies:

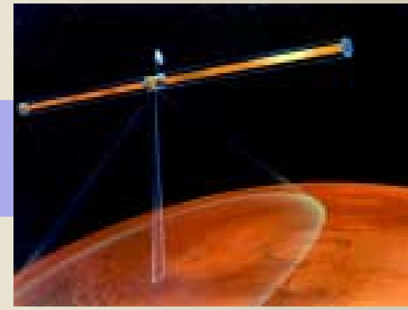
- Advanced fabrics for spacesuits: high strength-to-flexibility ratio
- “Smart fabrics” for spacesuits, with embedded sensors and control systems
- Advanced materials for robots: high strength-to-weight ratio
- IT: increased autonomy of robotic systems, with optimized integration with humans
- High communication bandwidth among robots and humans
- Advanced sensors: multiband vision, increased dexterity and delicacy, multi-level feedback systems

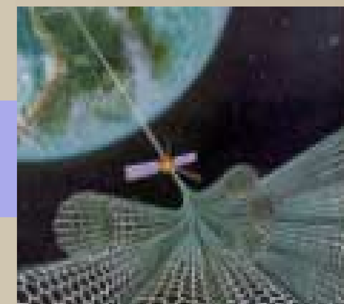
National Benefits:

Optimized human/robotic partnerships applied to hazardous environments on Earth, including deep-sea exploration, fire/chemical/radiation hazards, remote medical/surgical care, virtual reality systems, and military/police combat.

“Breakthrough” Materials Technologies


Aluminum — **_Now_**


Thin-film radar antenna — **_5-10 years_**


Nanotube Space Elevator — **_15-25 years_**

	Now	5-10 years	15-25 years
Application Missions	Small robotic missions International Space Station	Large-aperture robotic missions Light-weight launch vehicles	Low-mass, smart structures for human & robotic exploration
Metrics:			
Strength-to-Mass Ratio	Aluminum - 1x	10x	1000x
Deployment.	Very low precision	Low precision	High precision structures
Embedded Elements	Antennas, some sensors	Add: Receivers, transmitters, interconnects	Add: Propulsion, processors, actuators, etc.

Leading Candidate Technologies:

- Carbon Nanotubes with up to 1000 times greater strength/mass
- Carbon nanotube microfibers with 40x stiffness/mass
- Thin-film materials with 1% nanotube whisker reinforced polymers results in dramatic improvement in thin film properties
- Wide bandgap semiconductors for high temperature environments, high-power circuitry, and high-strength MEMS devices
- Silicon carbide & elastomeric foams for self deploying & complex space structures
- Zeolites, carbon molecular sieves, etc. for in situ propellant production and air/water revitalization

National Benefits:

Benefits all facets of standard of living and national defense, such as medical, all forms of transportation, computing, energygenration and distribution, military vehicles, etc.

“Breakthrough” Earth-to-Orbit Technologies

Now

10 yrs

20 yrs

	Now	10 yrs	20 yrs
Application Missions	Human and robotic access to Low Earth Orbit (LEO)	Safe, reliable access to LEO for human and robotic missions in near-Earth space.	Safe, reliable and truly low-cost access to space supporting human exploration throughout the solar system
Metrics:			
Safety	1/200 risk of failure	100X safer	10,000X safer
Cost	$7000/lb - $10,000/lb	$1000/lb	$100/lb
Flight Rate	4 (Shuttle) - 25 (ELV) per year	>20 (Crew) - 100 (cargo) per year	100 - 1000 per year TOTAL

Leading Candidate Technologies:

- High Energy Density Materials and Advanced Chemical fuels to dramatically increase Isp
- Launch assist to reduce propellant requirements
- Modularity of design for increased reliability and design redundancy
- Partial pump-fed engines using lightweight materials
- Elevators (rotating and/or fixed) as reusable ‘upper stage’ infrastructure
- Annular Aerospikes

National Benefits:

Lower cost and more reliable space transportation for commercial enterprises (e.g., tourism, industrialization, and entertainment) and defense needs