

Power Required for Potential Space Exploration

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Key Issues

● Onboard Power Infrastructures

- High Power Density: Performance enhancement, reduced weight, or increased functions
- Efficiency: > 40 %
- Long Operation Life: EOL > 30 years for deep space exploration, or EOL > 10 years for science missions
- Stability: No diminishing and no fluctuating power over time
- Energy Sources: Readily available for harvesting or onboard
- Systems: Simple and fault-tolerant

● Off-board Power (wireless)

- High Power Transmission: High intensity Gaussian beam
- Transmission Efficiency: > 80 %
- Beam Profile: No dispersion desirable
- Transmission Distance: > 1000 miles w/o loss of beam power
- Availability: Any where, any time



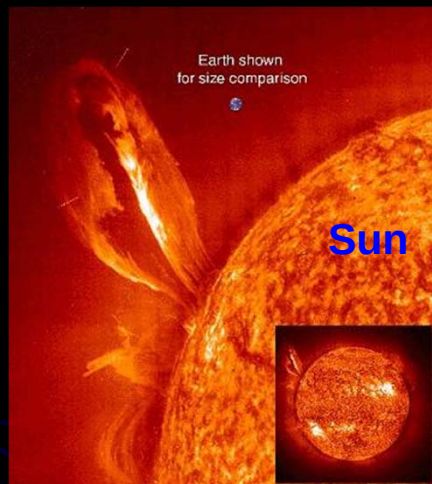
Physical Effects Utilized in Power Devices

- Light -** *Zeeman, Stark, Doppler, Raman, Brillouin, Nonlinear, Exciton, Bragg, Acousto-optic, Electro-optic, Magnetooptic, Bragg scattering, Bandgap, and Optical parametric*
- Acoustics -** *Doppler, Acoustoelectric, Acoustomagnetic, Diffraction, Masking, Bragg, Surface wave, Piezoelectric*
- Semiconductor -** *Tunneling, Zener, Schottky, Field, Gunn, Josephson, Bipolar, Impact avalanche, Hall*
- Magnetism -** *Superconducting quantum, Meisner, Barkhausen, Magnetocaloric, Temperature*
- Thermal -** *Seebeck, Peltier, Thomson, Pyroelectric, Pyromagnetic, Thermionic*
- Photovoltaic -** *Photovoltaic, Photoconductive, Photoelectron, Photoelectromagnetic, Pockels, Kerr, Bragg*
- Smart Materials-** *Piezoelectric, Magnetostrictive,, Electroplastic, Electrostrictive, Electro- or magneto rheological, Shape memory*
- Catalytic -** *Rate inducers, Metallic*
- Enzymes -** *Biological inducers or mediators for rate and reaction control*



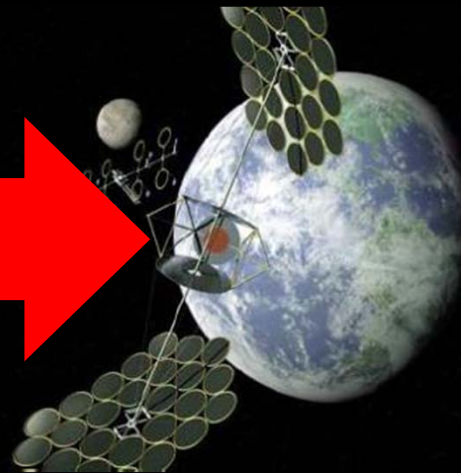
Energy Sources in Space

Solar Energy



- Burns 660 million tons/sec of H_2 .
- Leaves 600 million tons/sec of He.
- Gives off the rest as radiation.

d = 1 AU



174,000 TW of
sunlight hit the
earth every day

AM0 = 1370 W/m²
AM1 = 1353 W/m²

d = 1.52 AU



21,000 TW of
sunlight hit the
mars every day

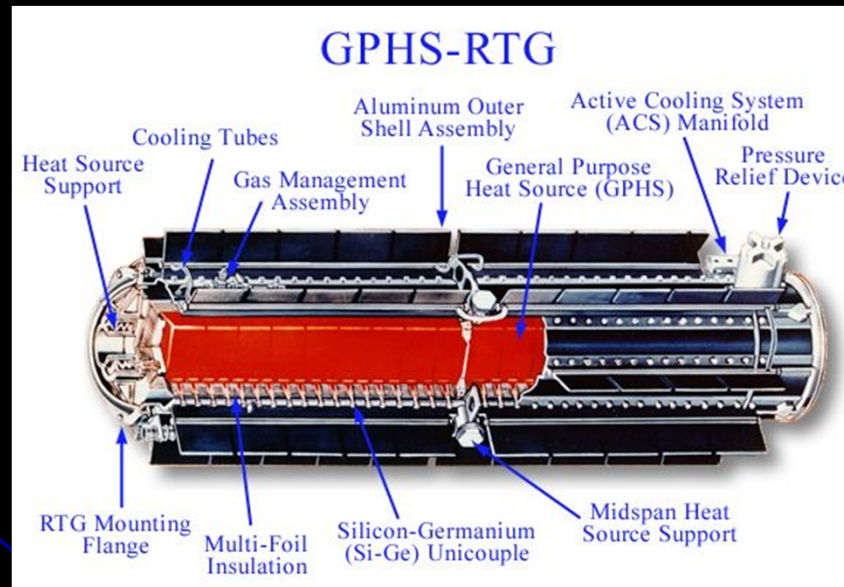
AM0 = 593 W/m²
AM1 = 588 W/m²

Energy Sources in Space

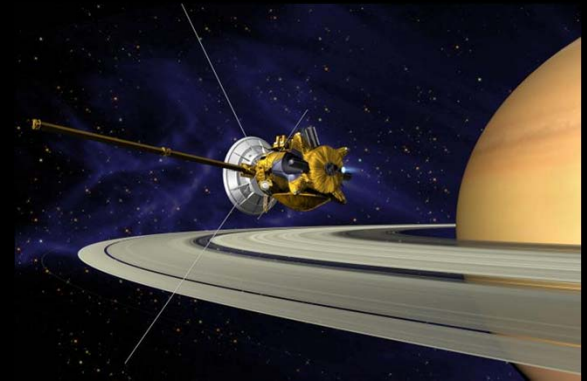
Nuclear Energy



Plutonium RTG pellet
glowing red-hot



Cassini (1997)



Huygens probe to Titan



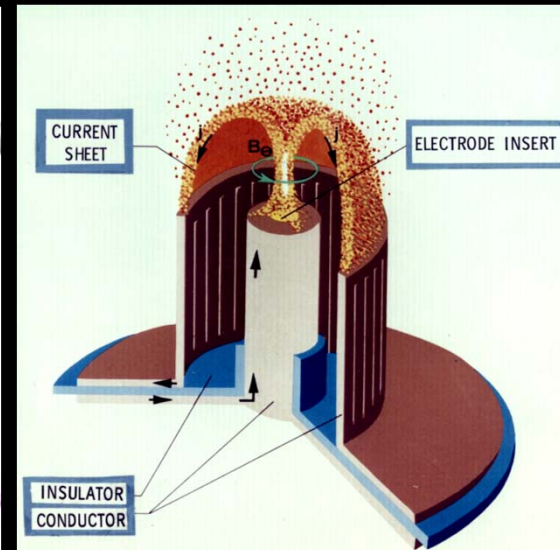
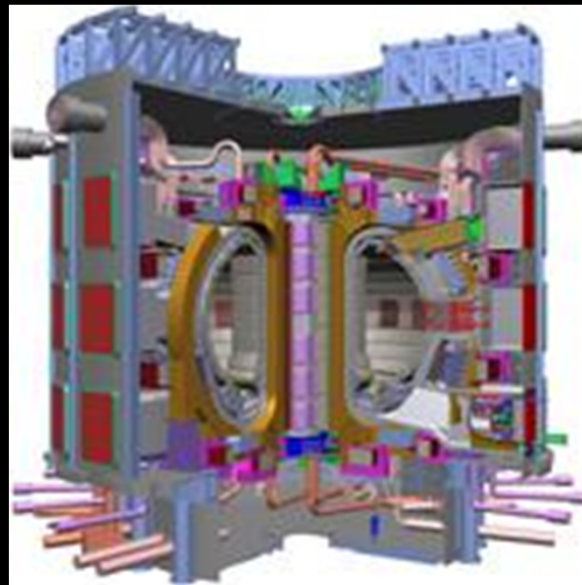
Radioisotopes & RTG Power

Element	Half-life (years)	Watts/g (thermal)	\$/Watt (thermal)
Polonium-210	0.378	141	570
Plutonium-238	86.8	0.55	3000
Cesium-144	0.781	25	15
Strontium-90	28.0	0.93	250
Curium-242	0.445	120	495

Name & Model	RTGs per User	Max Power (watts)	Max Heat output (watts)	Radioisotope	Fuel (kg)	Total Mass (kg)
SRG	in prototype phase, MSL	~110 (2x55)	~500	Pu238	~1	~27
MMRTG	in prototype phase, MSL	~110	~2000	Pu238	~4	26-34
GPHS-RTG	Cassini (3), Galileo (2) Ulysses (1)	300	4400	Pu238	7.8	55.5
MHW-RTG	Voyager 1 (3), Voyager 2 (3)	160	2400	Pu238	~4.5	39
SNAP-19	Viking (2), Pioneer 10 (4), Pioneer 11 (4)	35	525	Pu238	~1	13.6
SNAP-27	Apollo 12-17 ALSEP (1)	73	1480	Pu238	3.8	20
Beta-M	Soviet unmanned lighthouse	10	230	Sr90	.26	560

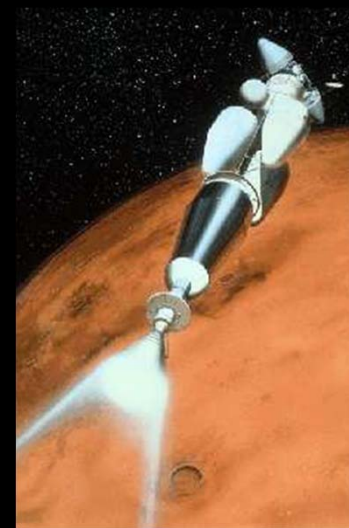
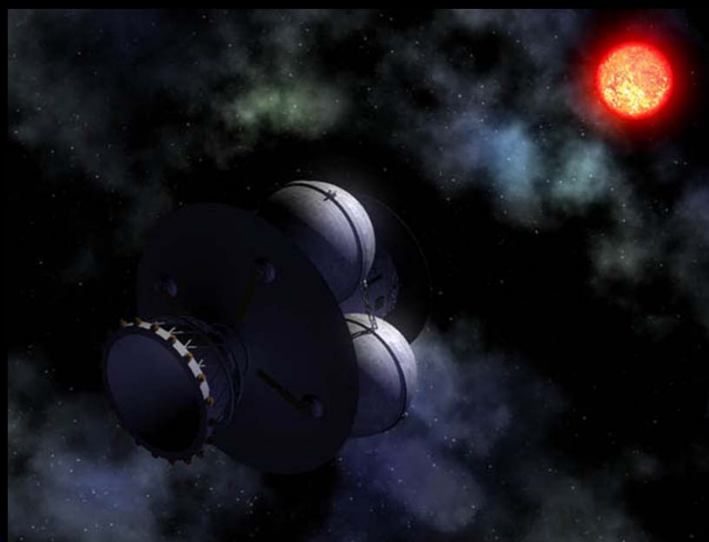
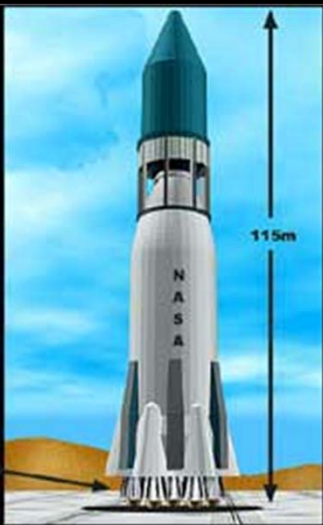
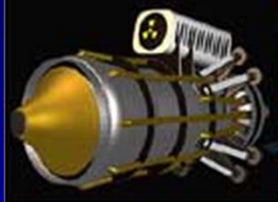


Fusion Reaction Power & Propulsion



**LIBERTY SHIP
GCNR-HLLV**
PERFORMANCE:
SSTO
1000 ton payload to LEO
Pollution Free
Reusable

Gas core nuclear
rocket engine



Battery and Fuel cell Technology

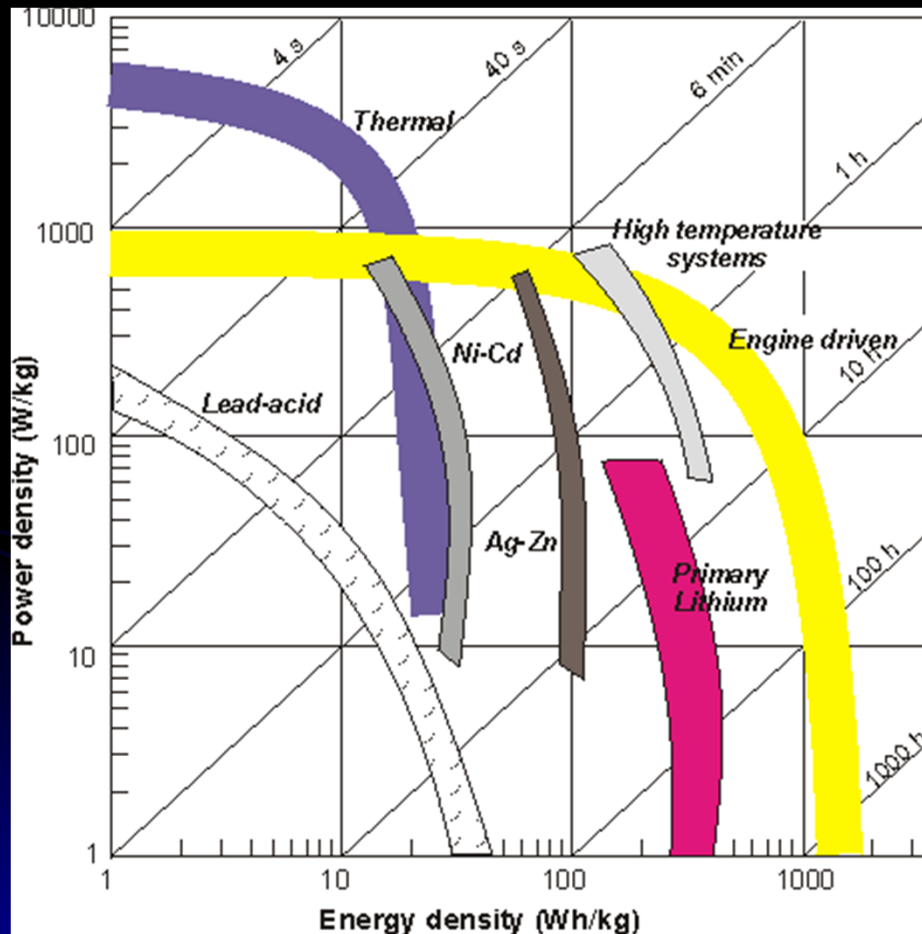


TABLE 2. BATTERY COMPARISON TABLE

Model	Chemistry	Whr/kg	Whr/L	P/S [†]
BB-2590U	Li-ion	84	109	S
L17	Li-ion	118	180	S
LI 1.5	Li-ion	136	128	S
LM11	LiMnO ₂	196	265	P
BA-x847A/U	LiMnO ₂	226	87	P
LMP 13.5	LiMnO ₂	308	107	P
Fuel Processor*	MeOH reforming	850	985	n/a

(Adapted from Feldman 1999)

*P= primary battery chemistry; S= secondary battery chemistry

* Assuming 14 day continuous use at 23 W_e output.

<http://www.pnl.gov/microcats/aboutus/publications/microchemical/holladayIECEC20074.pdf>

<http://www.corrosion-doctors.org/Batteries/Frames.htm>



Power Requirements

Power for Space Science:

- Power density - solar cells, fuel cells, batteries, & RTGs
- Life time (deep space exploration) - RTG
- Boost power capability - batteries and capacitors
- Efficiency - solar cells and RTG
- Cost - ???

Power for Space Propulsion:

- High I_{sp} (> 3000 s) - nuclear thermal, nuclear electric, chemical, solar thermal, solar sails, MPD, electrothermal, etc.
- Boosting power - nuclear electric, MPD, ion thrusters
- Boosting power - chemical, nuclear thermal, solar thermal. Electrothermal

Power for Aero-vehicles: microwave

- Power density -
- Life time -
- Efficiency -
- Cost -

chemical, battery, fuel cells, solar cells,

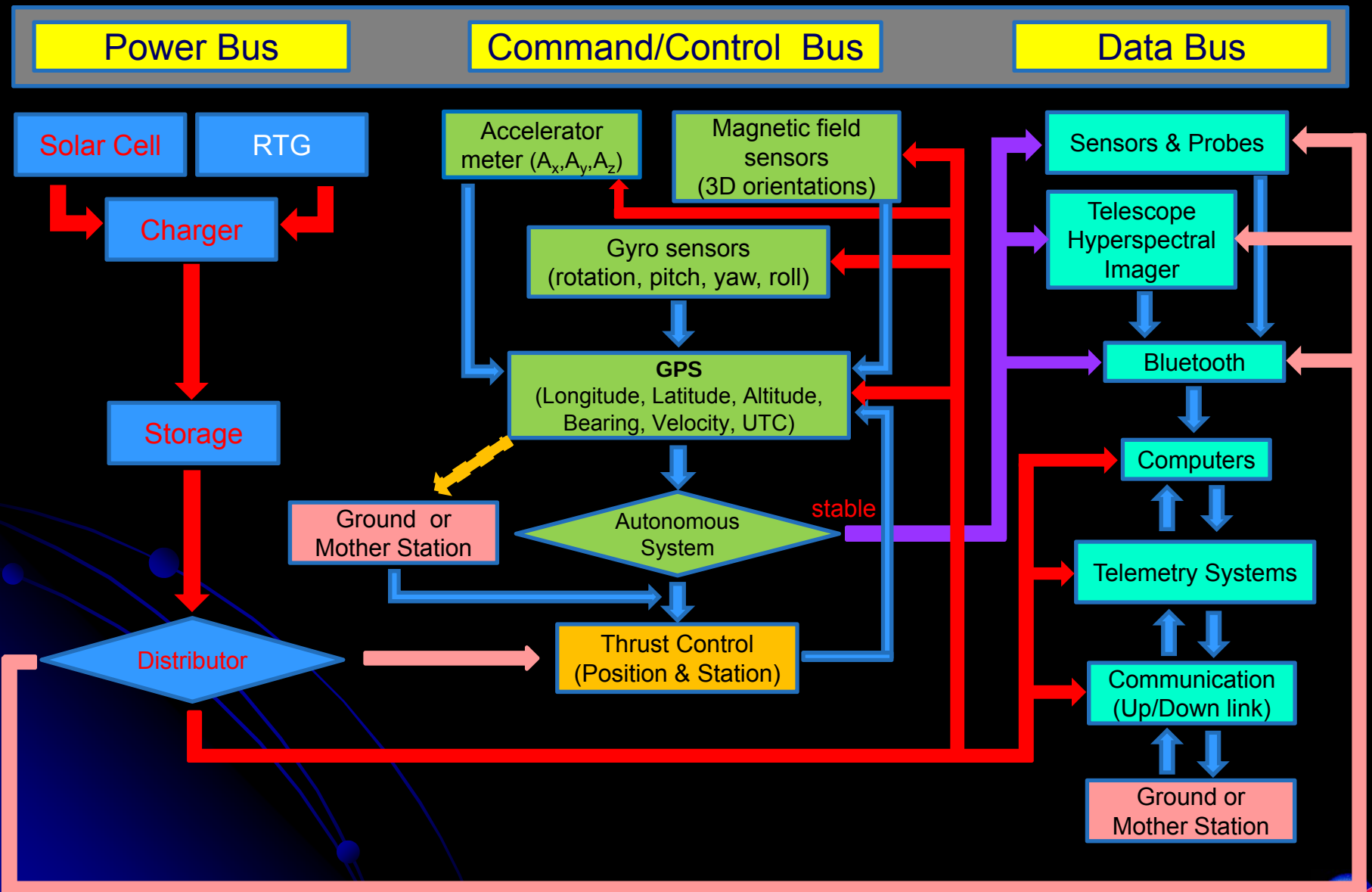
Power for Life Science:

- Life time - several years
- Leakage current free
- Bio-entanglement free
- Wireless inside or outside

battery, fuel-cells, TEG, or wireless



Bus Structures of Space Systems



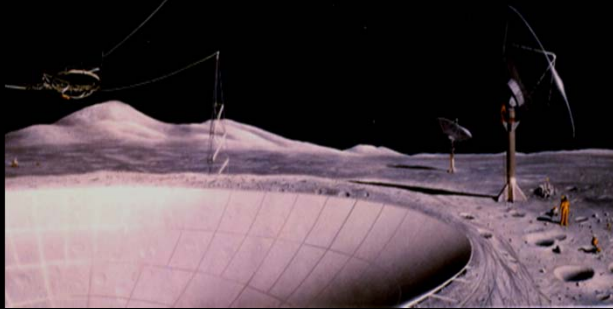
Power Need for Scientific Missions and Habitats

[thru Google Search Engine]



Lunar Exploration Base & Operation

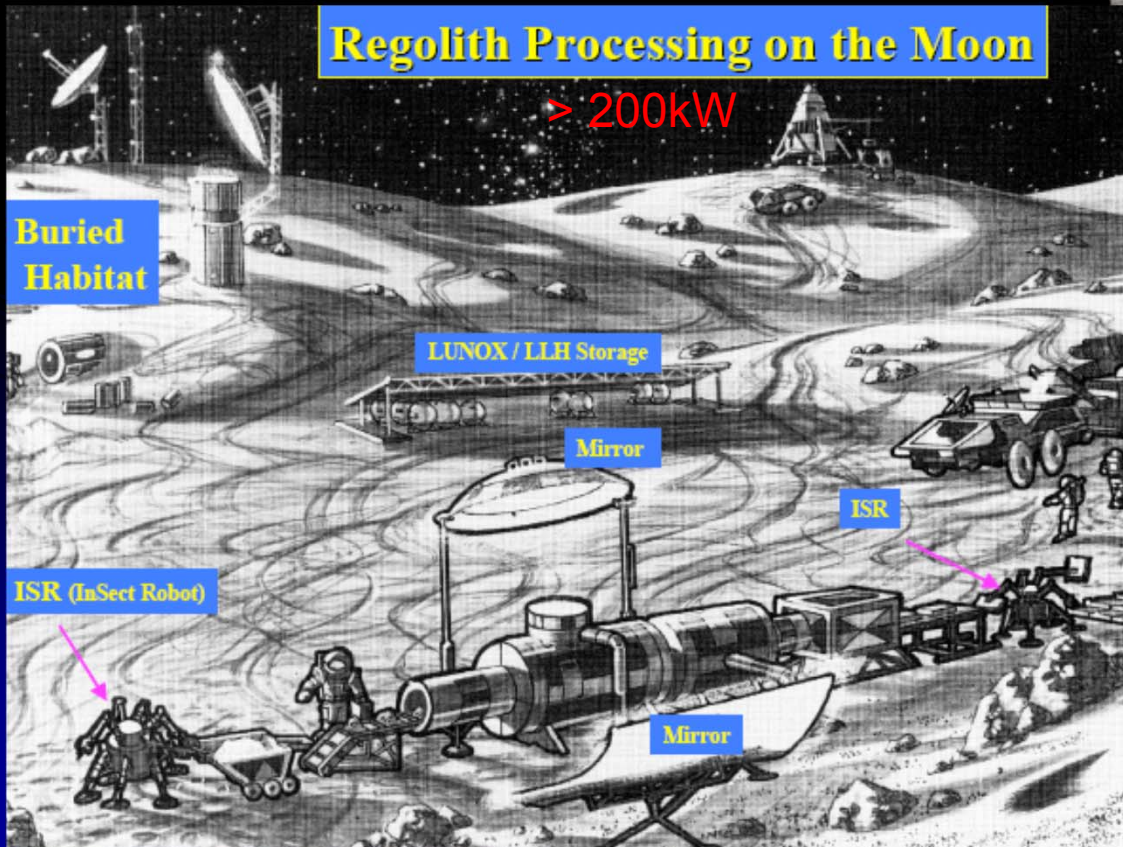
[thru Google Search Engine]



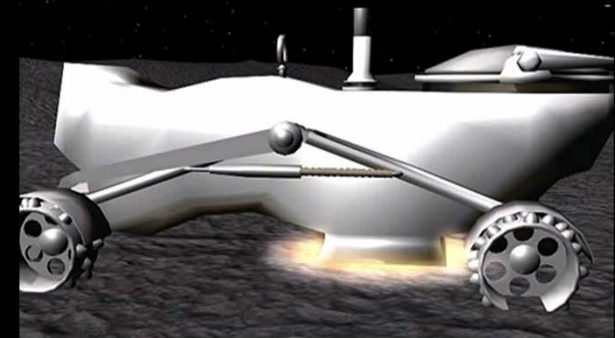
Crater transformed into Antenna, ~10kW



> 200kW



NASA Langley Research Center



Paving Robot, 100kW

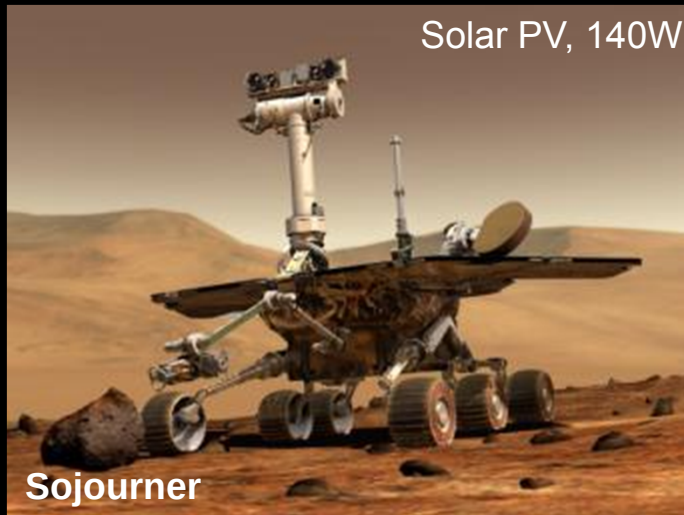


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Power for Lunar & Mars Rovers

Robotic Mission

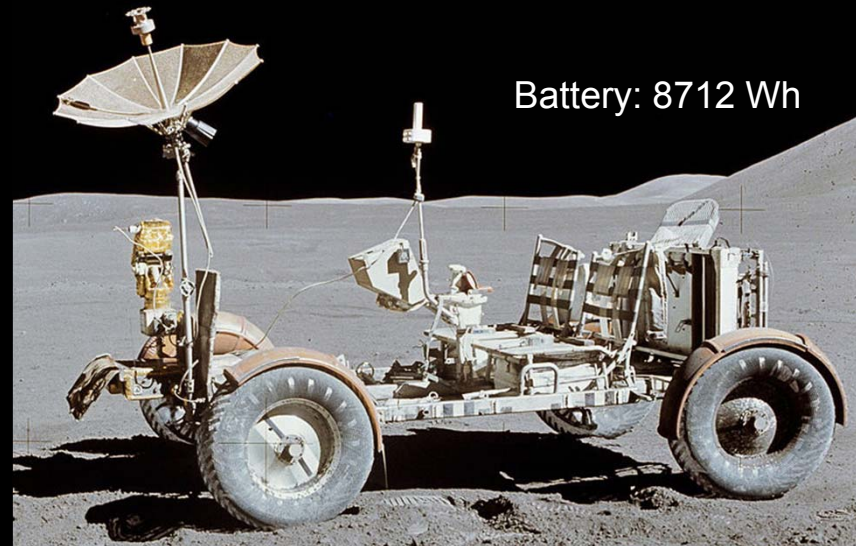
[thru Google Search Engine]



RTG, ^{238}Pu , ~ 2.5 kW



Battery: 8712 Wh



Lunar Rover-Manned land vehicle

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Helium-3 Mining

Helium-3

Neutrons	1
Protons	2
Parent Isotopes	^3H (β -decay)
Isotope Mass	3.016 u
Half Life	stable
Spin	$\frac{1}{2}+$
Availability	0.000137%

Resources

Earth Mantle	$\sim 10^6$ tons
Ocean Floor	4000 tons
Regolith	$\sim 10^6$ tons

Needs

U.S.A.	20 tons/yr (\$700B worth)
Others together	80 tons/yr

Aspiration (John Lasker, "Race to the Moon for Nuclear Fuel", Science, Space, Dec. 15, 2006)

U.S.A.	One of the justifiable space expeditions (2020) after all
China	Officially stated goal of Chinese lunar exploration program
Russia	Helium-3 mining plan by Russia's RKK Energia by 2020
Japan	Intended, but no details
India	Officially, but no details

Rationale

Fusion reactions involving Helium-3			
Reactants		Products	Q
First Generation Fuels			
$^2_1\text{H} + ^2_1\text{H}$	$\rightarrow$	$^3_2\text{He} + ^1_0\text{n}$	3.268 MeV
$^2_1\text{H} + ^2_1\text{H}$	$\rightarrow$	$^3_1\text{H} + ^1_1\text{p}$	4.032 MeV
$^2_1\text{H} + ^3_1\text{H}$	$\rightarrow$	$^4_2\text{He} + ^1_0\text{n}$	17.571 MeV
Second Generation Fuel			
$^2_1\text{H} + ^3_2\text{He}$	$\rightarrow$	$^4_2\text{He} + ^1_1\text{p}$	18.354 MeV
Third Generation Fuel			
$^3_2\text{He} + ^3_2\text{He}$	$\rightarrow$	$^4_2\text{He} + 2^1_1\text{p}$	26.2 MeV



Comparison: *ESP* vs. *PV Cells*

	PV Cells	ESP	Notes
Device Concept	Boeing's Spectro Lab Multi-junction	NASA LaRC's ESP Module	
Energy Source	Solar	Negatively charged lunar soil	
Unit Area	10 cm x 30 cm	10 cm x 30 cm	
Incident Energy	40 watts	147 watts*	*Both sun-lit and darkside operation
Efficiency	40 %	50 %*	*Efficiency of circuit is much higher (>80%)
Collected Power	16 watts	74 watts	
Operation under	Sun-lit side only	Sun-lit side and Dark side	
Energy Storage for Kick-off Power	No	Yes, for kick-off start	
Dust Mitigation	No	Yes	
Fabrication	Complex CMOS skill required	Fairly easy	In-house Fab



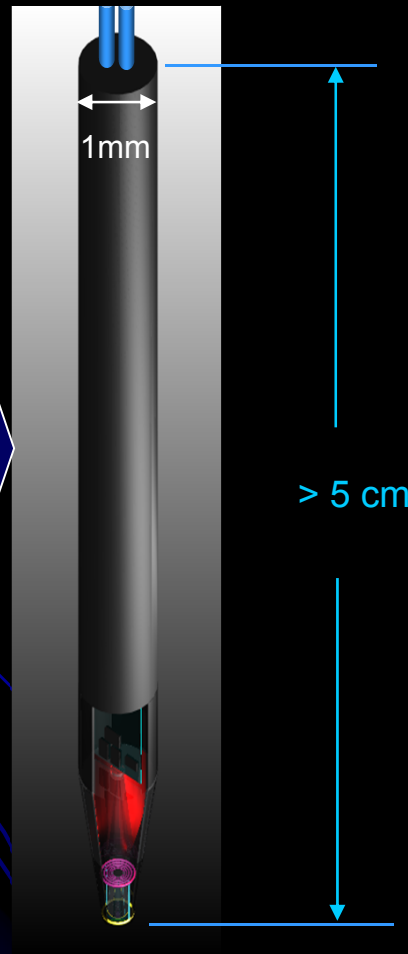
Micro Spectrometer (μ -SM) Applications

Medical Application for Neurosensing

Device Power: ~ 2 W

Medical Sensors:

- Tiny form factor < 1 mm
- Flexible pin
- Sensor fusion capable
- Power & telemetry
- Redundancy feature



For Space Exploration

Device Power: ~ 10 W

Leveraging Factors

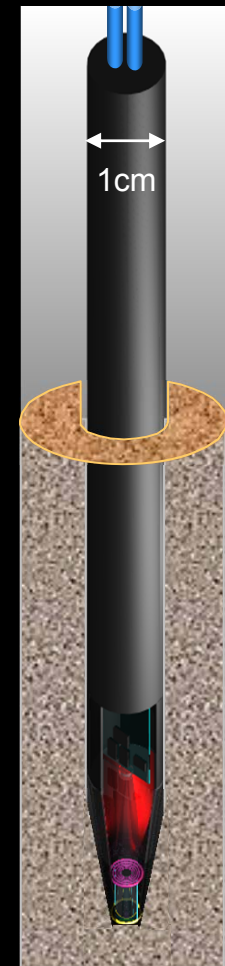
Space:

- μ -SM imbedded rover tires
- μ -SM imbedded Astronaut's shoes
- μ -SM imbedded canes or darts
- Hyperspectral imaging

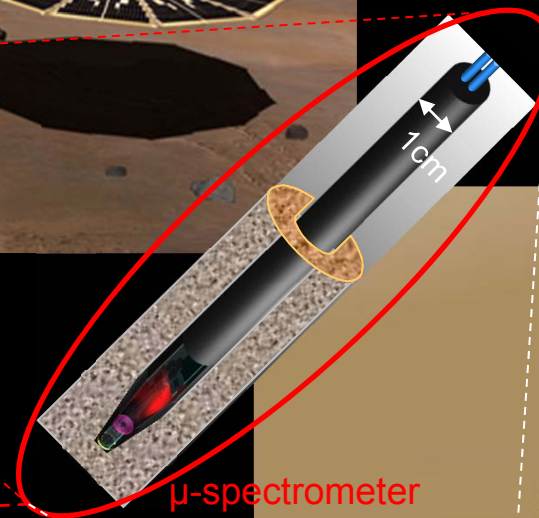
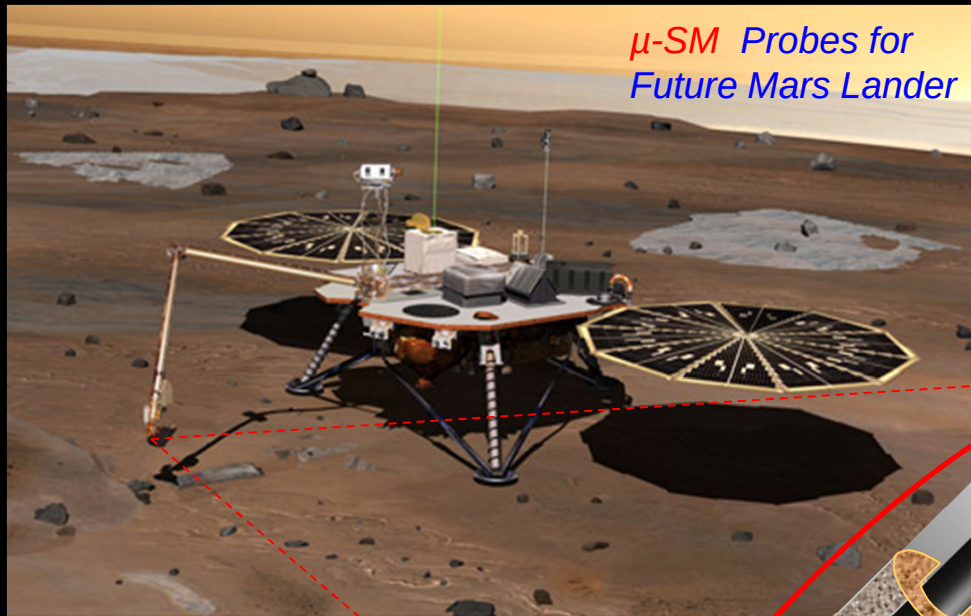
Aeronautics:

- Engine combustion monitoring
- Fuel leak detection
- Hyperspectral Lidar imaging

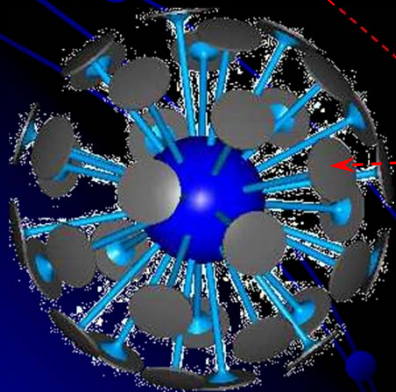
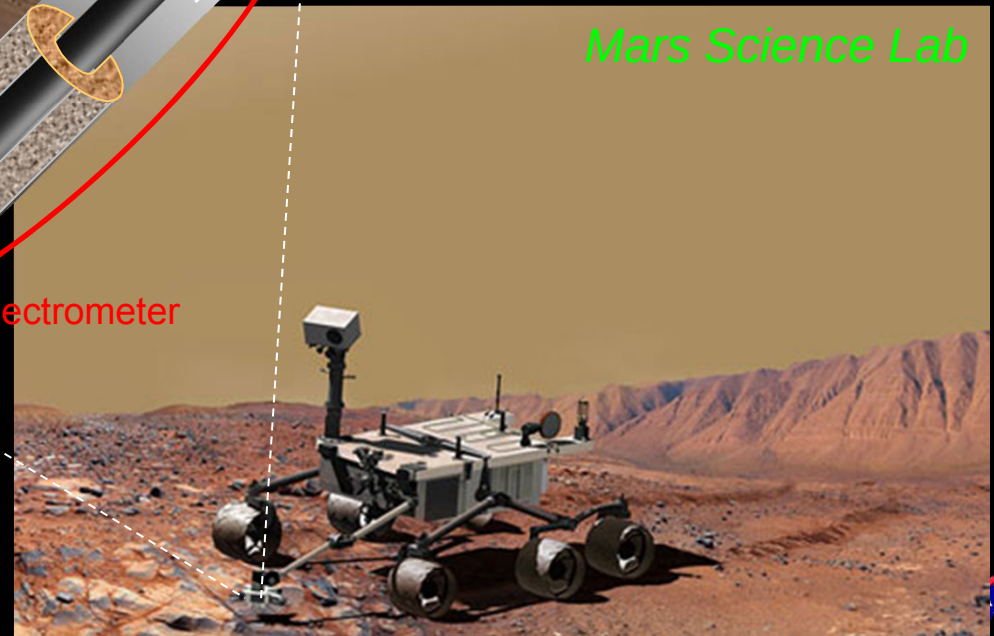
Can be used in
Tumble-weed type
planetary surface explorer



μ -Spectrometer (μ -SM) Applications Lunar & Mars Exploration



Mars Science Lab



μ -SM imbedded Tumbleweed Rover

Power for Earth and Space Science

Galaxy Evolution Explorer
(GALEX, Yonsei Univ.
partnered)



Solar PV, > 290W
Battery : ~ 250W at 28V

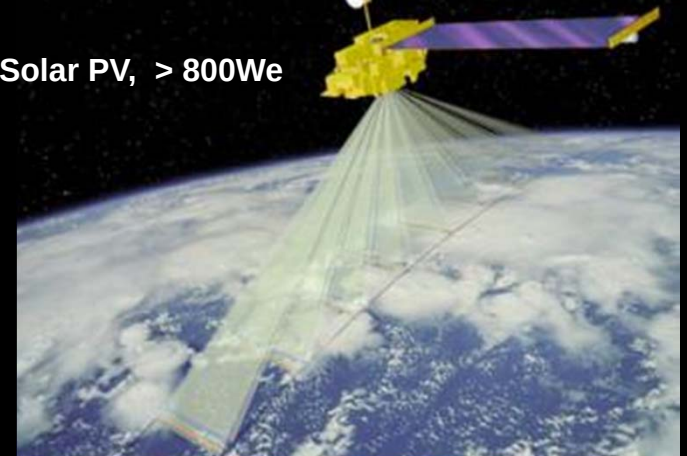
Cassini Spacecraft



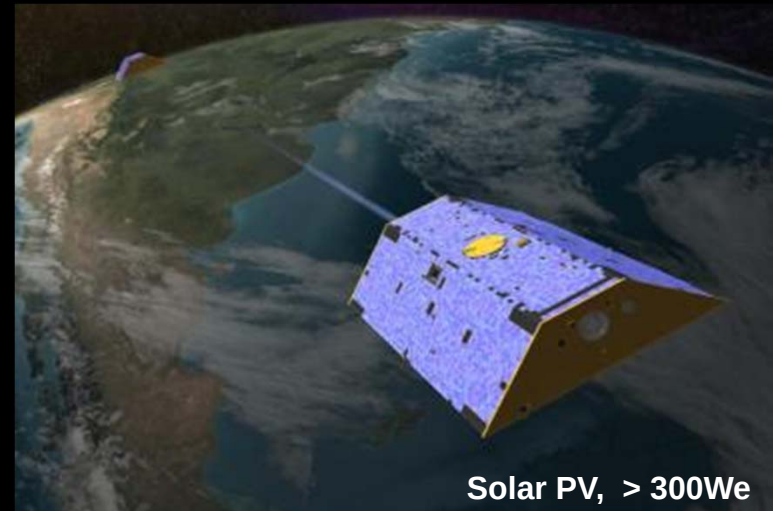
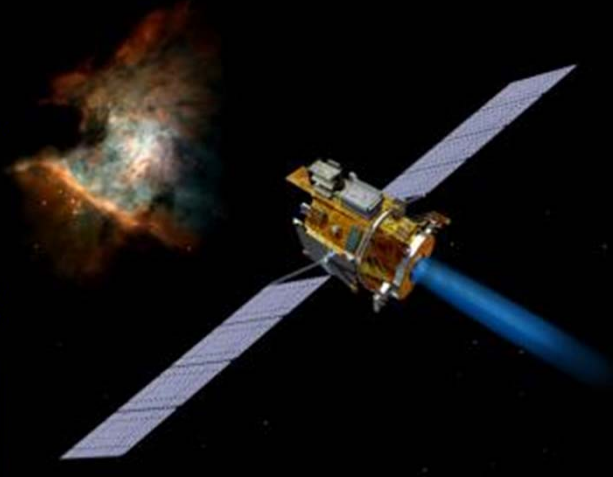
RTG, ^{238}Pu (72-lbs), ~1 kWe

Earth Observation Satellite

Solar PV, > 800We



NASA Langley Research Center



Solar PV, > 300We

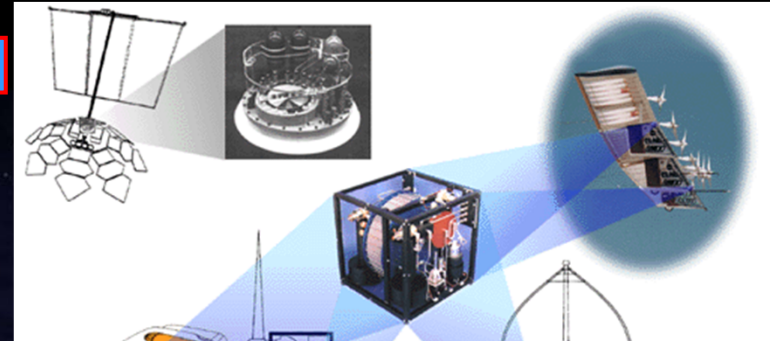
Power for Space Telescopes



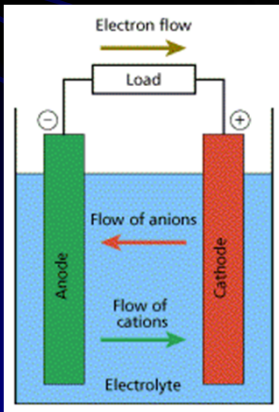
Power Sources for Spacecraft



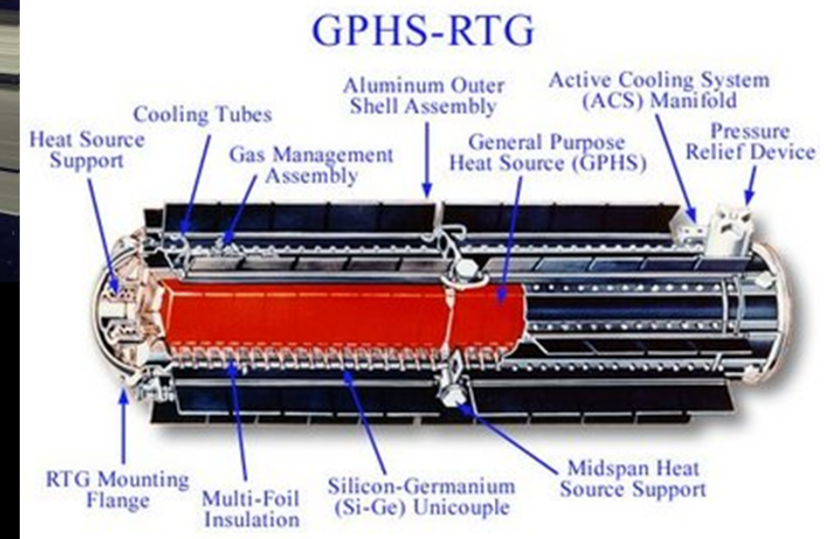
Fly-wheel Power Storage



Fuel Cells



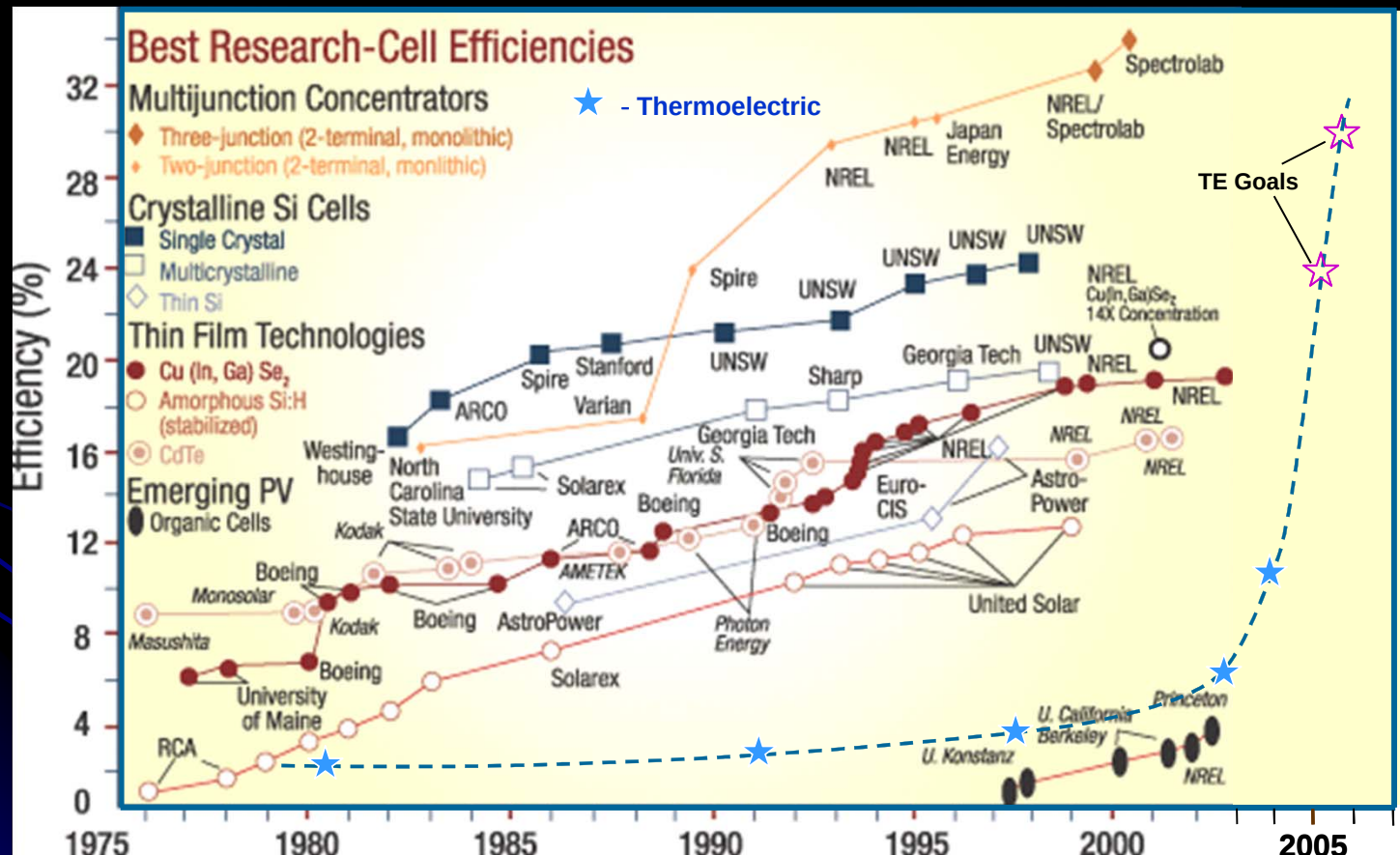
Canister-based Battery



Radioisotope Thermoelectric Generators (RTG)



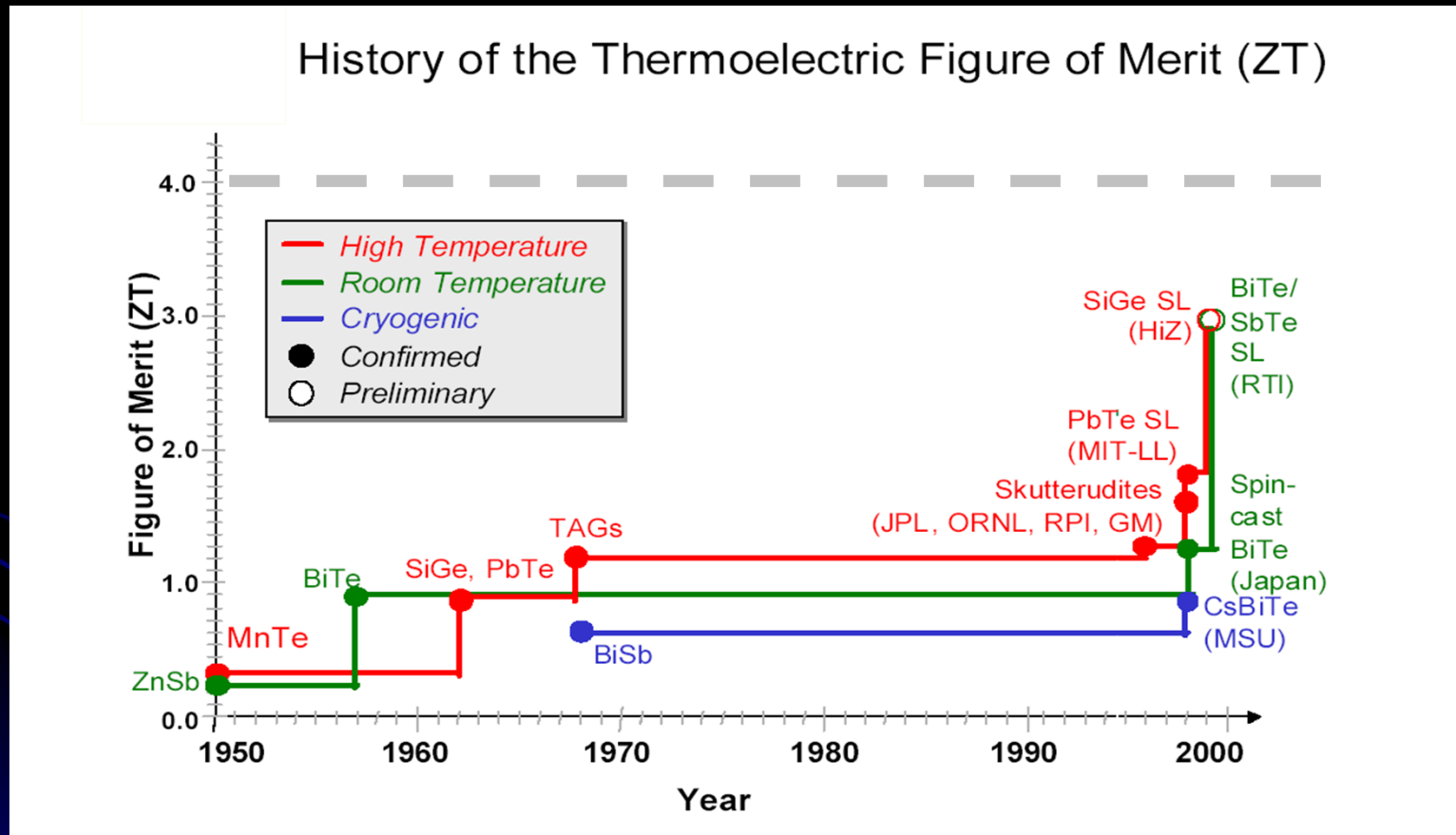
Efficiencies of State-of-the-Art Solar & Thermoelectric Cells



NREL Report, "Best Research-Cell Efficiencies", www.nrel.gov/pv/thin_film/docs/kaz_best_research_cells.ppt

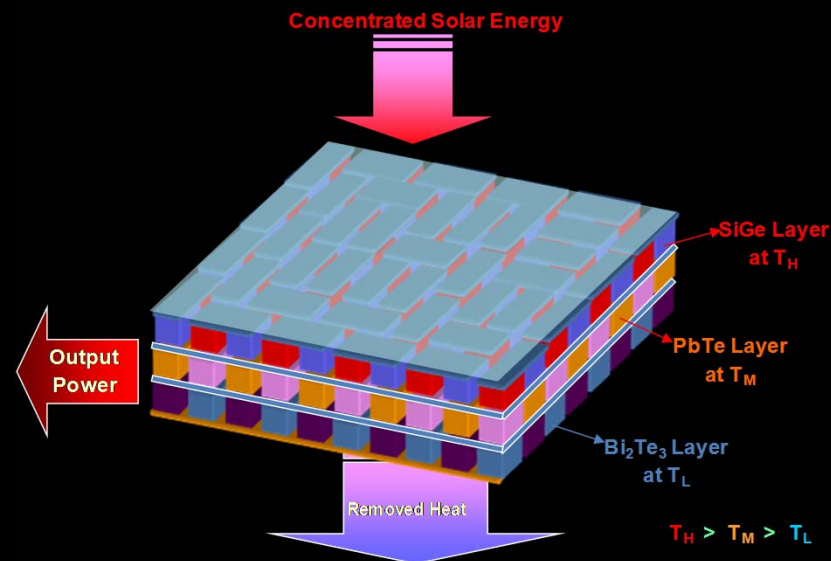
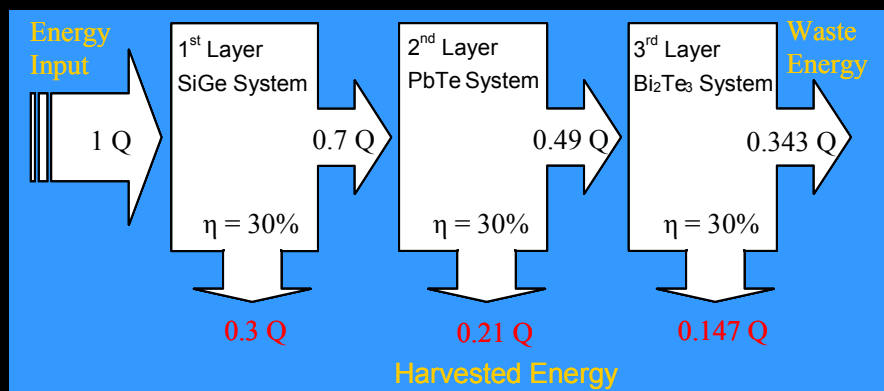
Historical Challenge for High Figure of Merit

Breaking away from the 188 years tradition by developing advanced thermoelectric (TE) materials with the TE figure of merit that exceeds 2.0



C.B. Vining, "Summary Report on ICT'99-the 18th International Conference on Thermoelectrics", 5th European Workshop on Thermoelectrics – ETS99, Pardubice, Czech, Sep. 20, 1999.

ATE Device for Solar Energy Conversion



TE Tandem System	TE FoM ≥ 1.5 $\eta = 10\%$		TE FoM ≥ 3.5 $\eta = 20\%$		TE FoM ≥ 4.5 $\eta = 30\%$		Solar Cells
	Loaded Energy, Q	η	Loaded Energy, Q	η	Loaded Energy, Q	η	η
1 st Layer (Hi T)	1Q in 0.9Q out	10 %	1Q in 0.8Q out	20 %	1Q in 0.7Q out	30 %	30 % (?) for membrane PV
2 nd Layer (Med T)	0.9 in 0.81Q out	10 %	0.8 in 0.64Q out	20 %	0.7 in 0.49Q out	30 %	
3 rd Layer (Low T)	0.81Q in 0.729Q out	10 %	0.64Q in 0.512Q out	20 %	0.49Q in 0.343Q out	30 %	
Cascade Efficiency	0.271Q Harvested	27 %	0.488Q Harvested	48 %	0.657Q Harvested	65 %	

40% Solar TE Power System Analysis

Power Output (kW)		304 kW	608 kW	1519 kW	15192 kW
Tandem TE	Active Area, ft ² (m ²)	2 (0.184)	4 (0.367)	10 (0.92)	100 (9.2)
	Cost of TE, \$1000/m ²	\$184	\$367	\$920	\$9200
	Concentrator - Aperture Area (m ²) - Diameter (m)	A = 802 m ² D = 32 m	A = 1605 m ² D = 45 m	A = 4010 m ² D = 71 m	A = 40100 m ² D = 226 m
	Power Network	as existed	as existed	as existed	as existed
	Cost of Mirror, \$30/m ²	\$24060	\$48150	\$120300	\$1203000
	Cost of Structure, \$50000/acre	\$10000 (0.2a)	\$20500 (0.41a)	\$51500 (1.03a)	\$515000 (10.3a)
	Total Cost, \$ \$/kW \$/kWh	\$23,244 \$126.64/kW 3.1 ¢/kWh	\$69,017 \$113.51/kW 3.1 ¢/kWh	\$172,720 \$113.70/kW 3.1 ¢/kWh	\$1,727,200 \$113.69/kW 3.1 ¢/kWh
Eco-Nano Solar Multilayer Solar PV	Active Area, ft ² (m ²)	802	1605	4010	40100
	Total Cost, \$ \$/kW \$/kWh				



Energy Cost Comparison

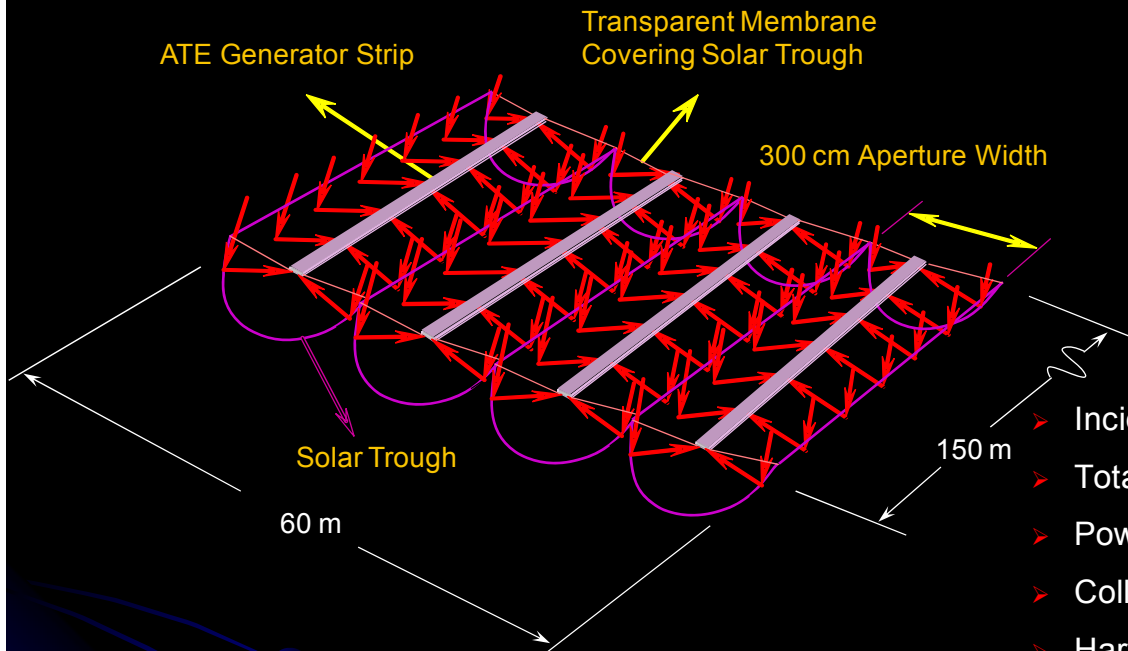
	Efficiency / Capacity factor	Capital cost	Cost in cents per KWh			Total cost
			O&M cost	Fuel Cost	Indirect cost	
Coal*	95	0.72	1	2.2	6.5	10.42
Nuclear*	95	0.9	1.4	0.76	0.25	3.31
Natural gas*	95	0.42	0.5	4.9	2.3	8.12
Silicon Solar*	15-20	17.1	1	none	--	18.1
Wind*	25-30	2.45	1	none	--	3.45
Eco Nano Solar	> 40	?	?	none	--	3.0??
Tandem TE	> 40	3.1	0.05	none	--	3.15

Average household ~ 10kW

*Source: renewableenergyworld.com



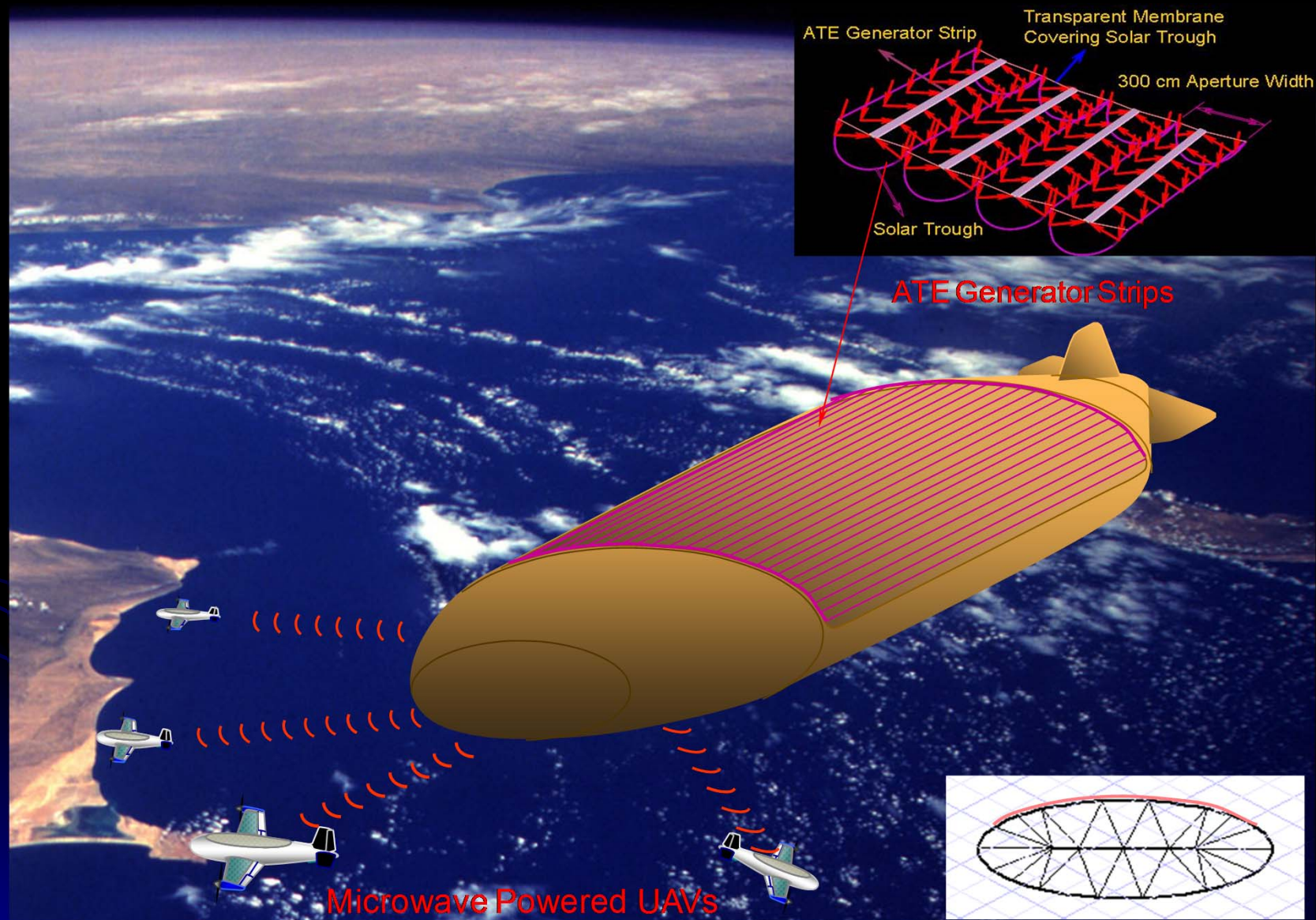
Solar Trough with 300 cm Aperture



➤ Incident Solar Power Flux:	1.353 kW/m ²
➤ Total Area of Solar Trough:	60 x 150 m ²
➤ Power Collected:	~ 12 MW
➤ Collective Losses (Orientation + Optical):	25 %
➤ Harvestable Power:	9 MW
➤ Losses by geometrical and Optical:	35 %
➤ Tandem Mode Efficiency of ATE (ZT~5):	65.7 %
➤ Power Output from Tandem ATE:	3.84 MW
➤ Power Conditioning Loss:	4 %
➤ Actual Useful Power:	3.7 MW

Sang H. Choi, James R. Elliott, Glen C. King, Yeonjoon Park, Jae-Woo Kim, Sang-Hyon Chu, and Kyo D. Song, "Power Technology for Application-Specific Scenarios of High Altitude Airships", Proceedings of AIAA 3rd International Energy Conversion Engineering Conference (IECEC), AIAA-2005-5529, Aug. 15-18, 2005.

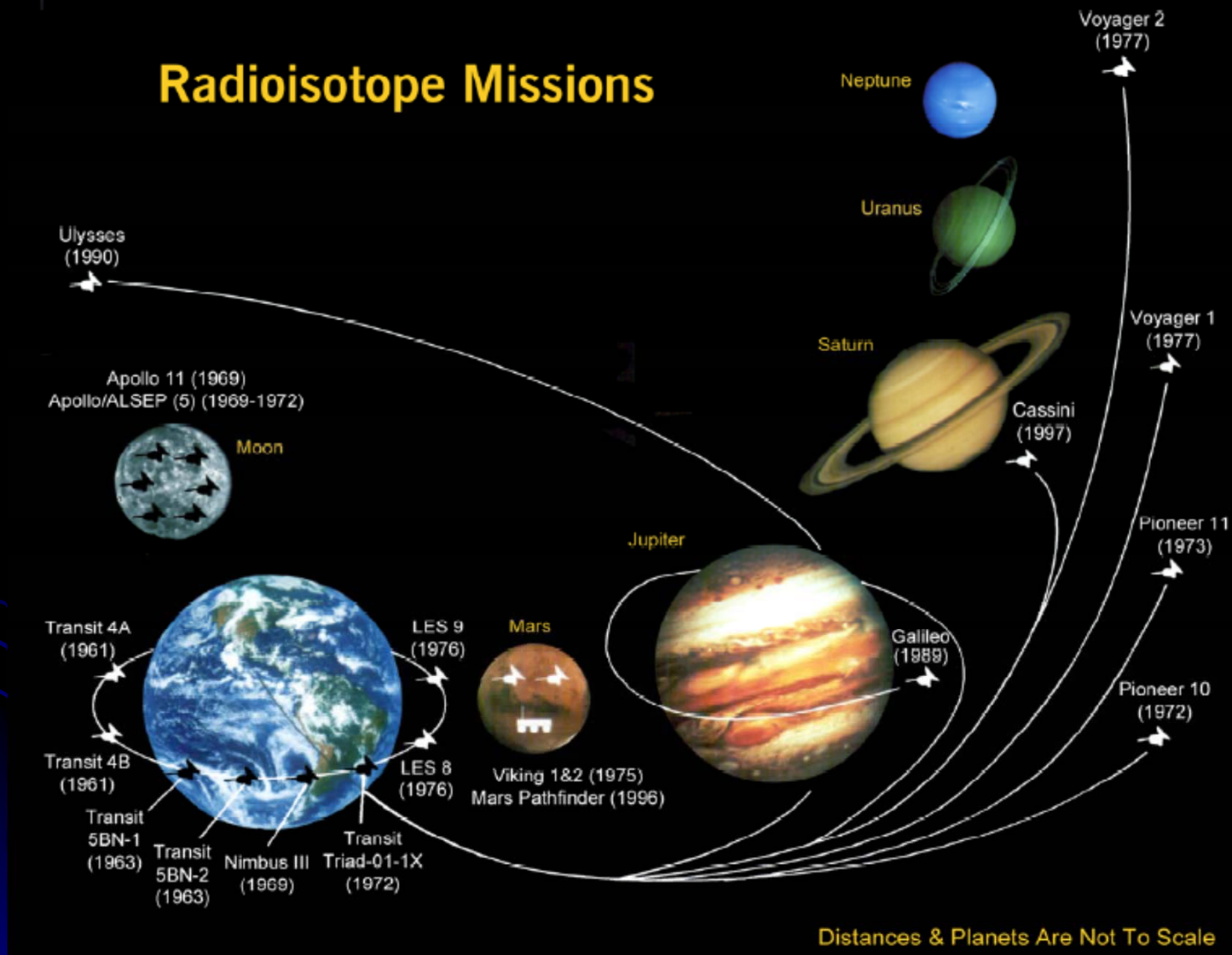
HAA Model with Ellipsoidal Cross-Section



Sang H. Choi et al. "Power Technology for Application-Specific Scenarios of High Altitude Airships", Proc. of AIAA 3rd IECEC, AIAA-2005-5529, 2005.

History of Space RTG Applications

Radioisotope Missions

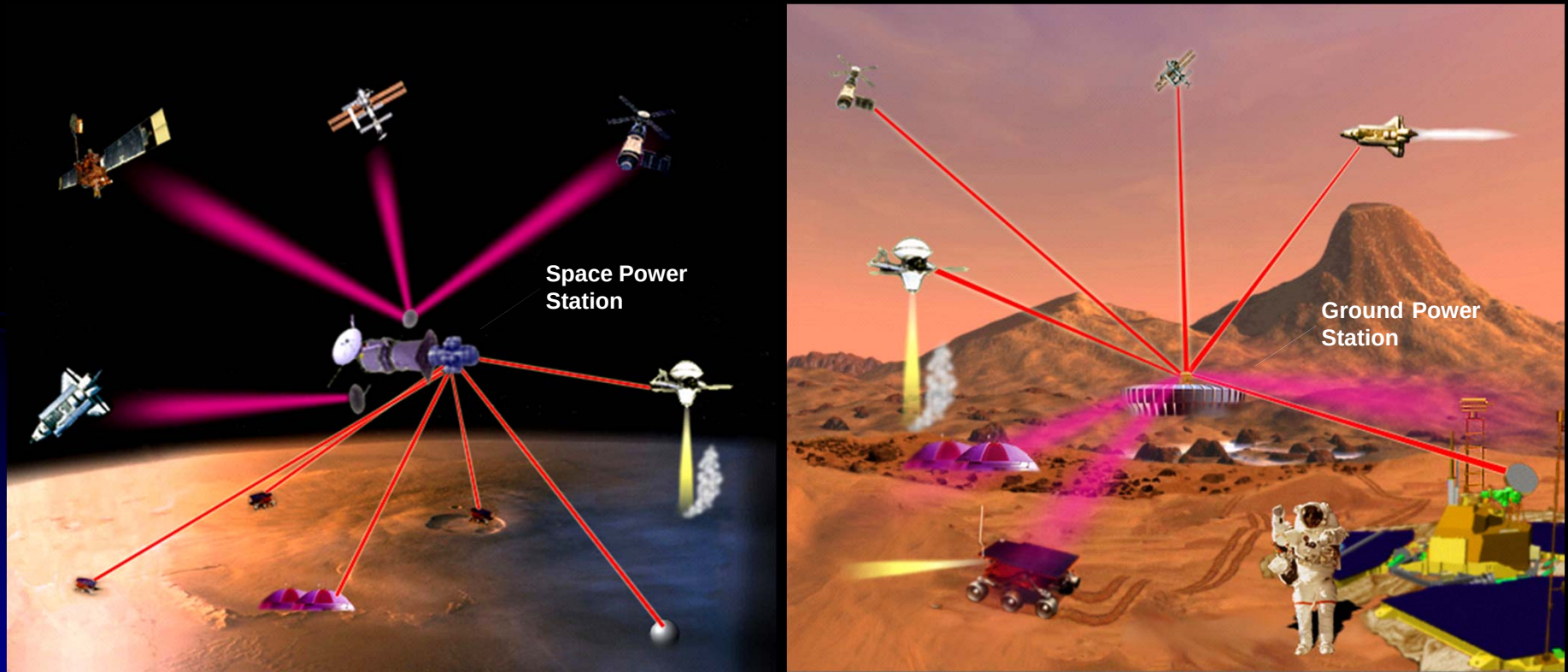


"Radioisotope Power for NASA's Space Science Missions" by Leonard A. Duzdzinski, Multi-Mission Radioisotope Thermoelectric Generator<<http://nuclear.gov/pdfFiles/MMRTG.pdf>> of Google

Advanced TE Power Generation and Transmission System

The proposed system encompasses three subsystems:

1. Radioisotope Power (RIP) subsystem
2. Advanced Thermoelectric Generator (ATEG) subsystem
3. Wireless Power Transmission (WPT) subsystem

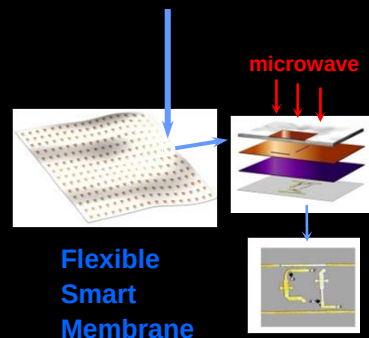
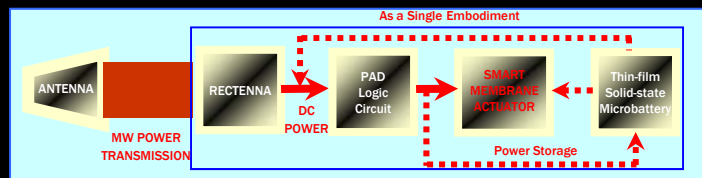


Artist's concepts of Mars space power station installed with WPT-ATEG system: space system (left) and ground system (right).

Wireless Power for Smart Membrane Structures

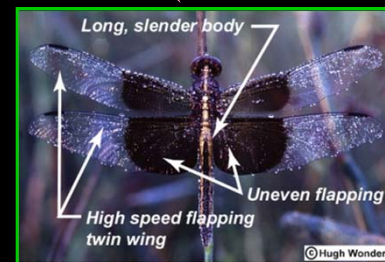
Microwave-driven Membrane Actuator Technology

Concept



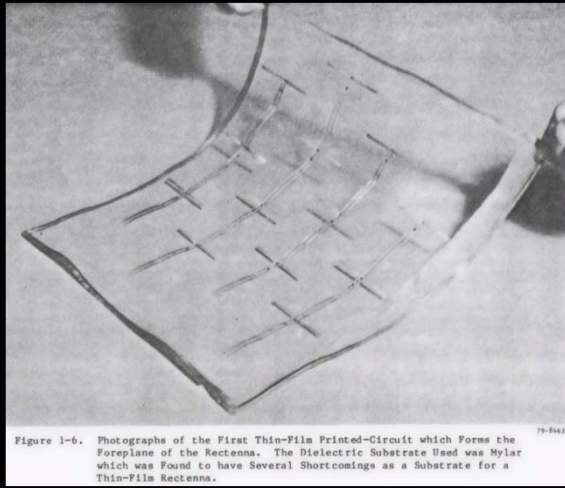
- Distributed piezoelectric actuators with rectenna patches.
- Control algorithm carried on MW signal enables actuators to be tuned for shape control.
- Power allocation and distribution (PAD) circuit imbedded actuators array allows smart power use.

Applications

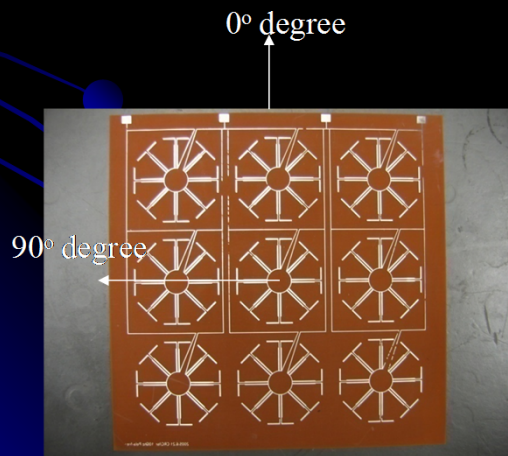
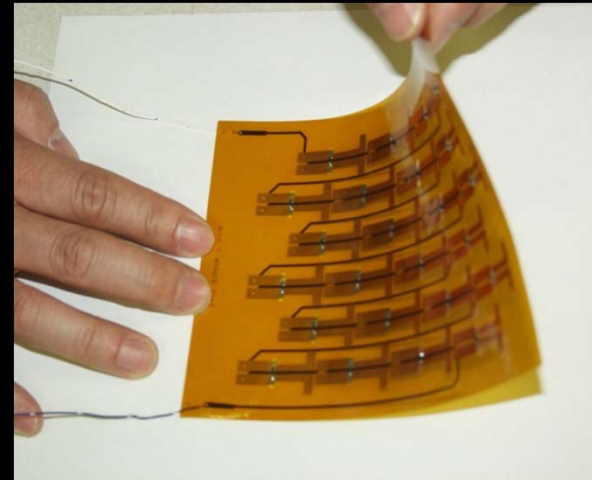


Sang H. Choi, Kyo D. Song, Walter Golembiewskii, Sang-Hyon Chu, and Glen C. King: "Microwave Power for Smart Material Actuators", IOP Journal of Smart Materials and Structures, Vol. 13, No. 1, pp38-48, February 2004.

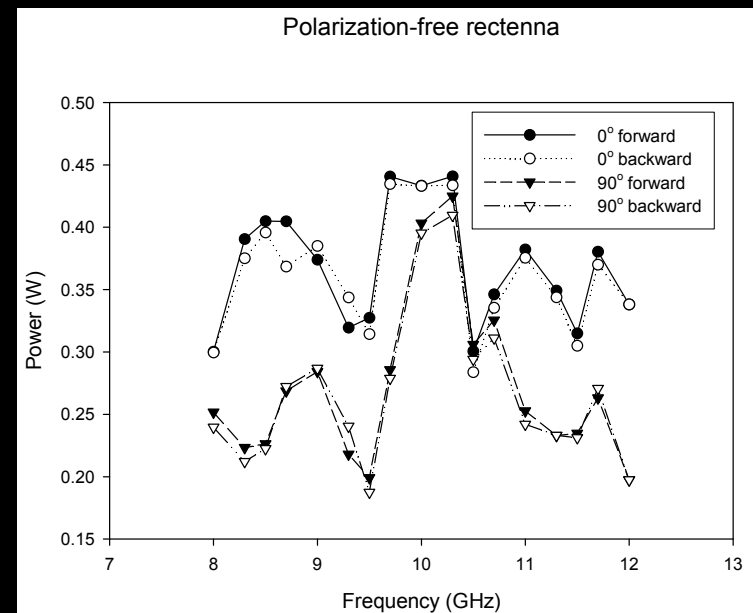
Thin-Film based Dipole Rectenna Array



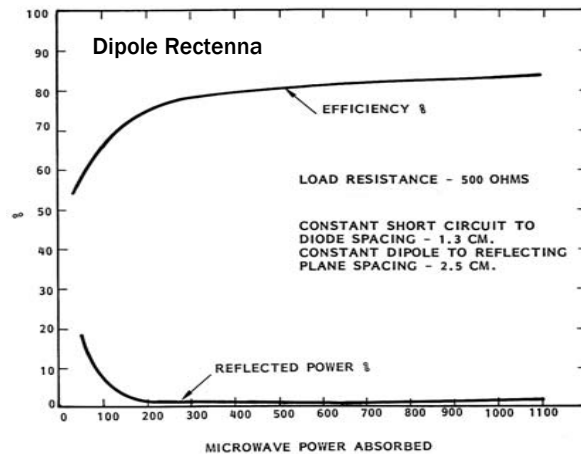
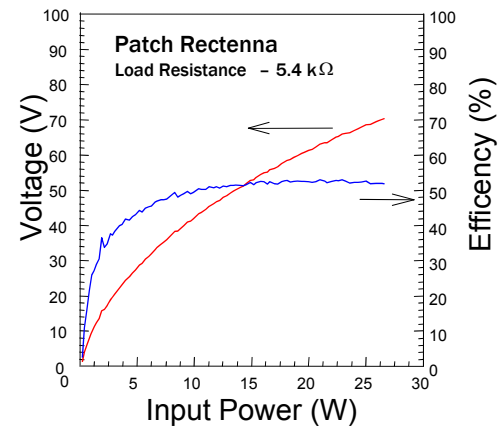
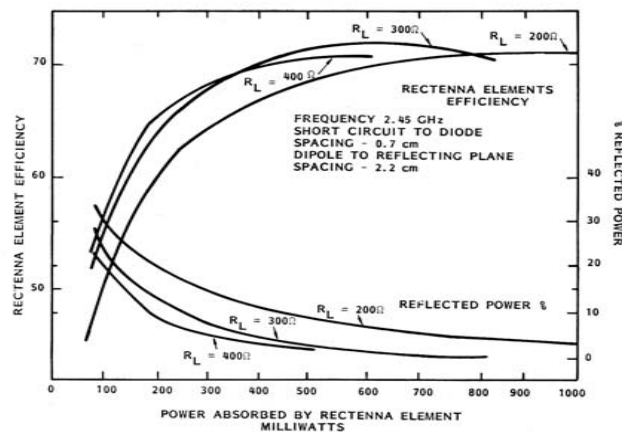
By William C. Brown, NASA CR179558, March 11, 1987



3 x 3 flexible rectenna



Rectenna Efficiencies

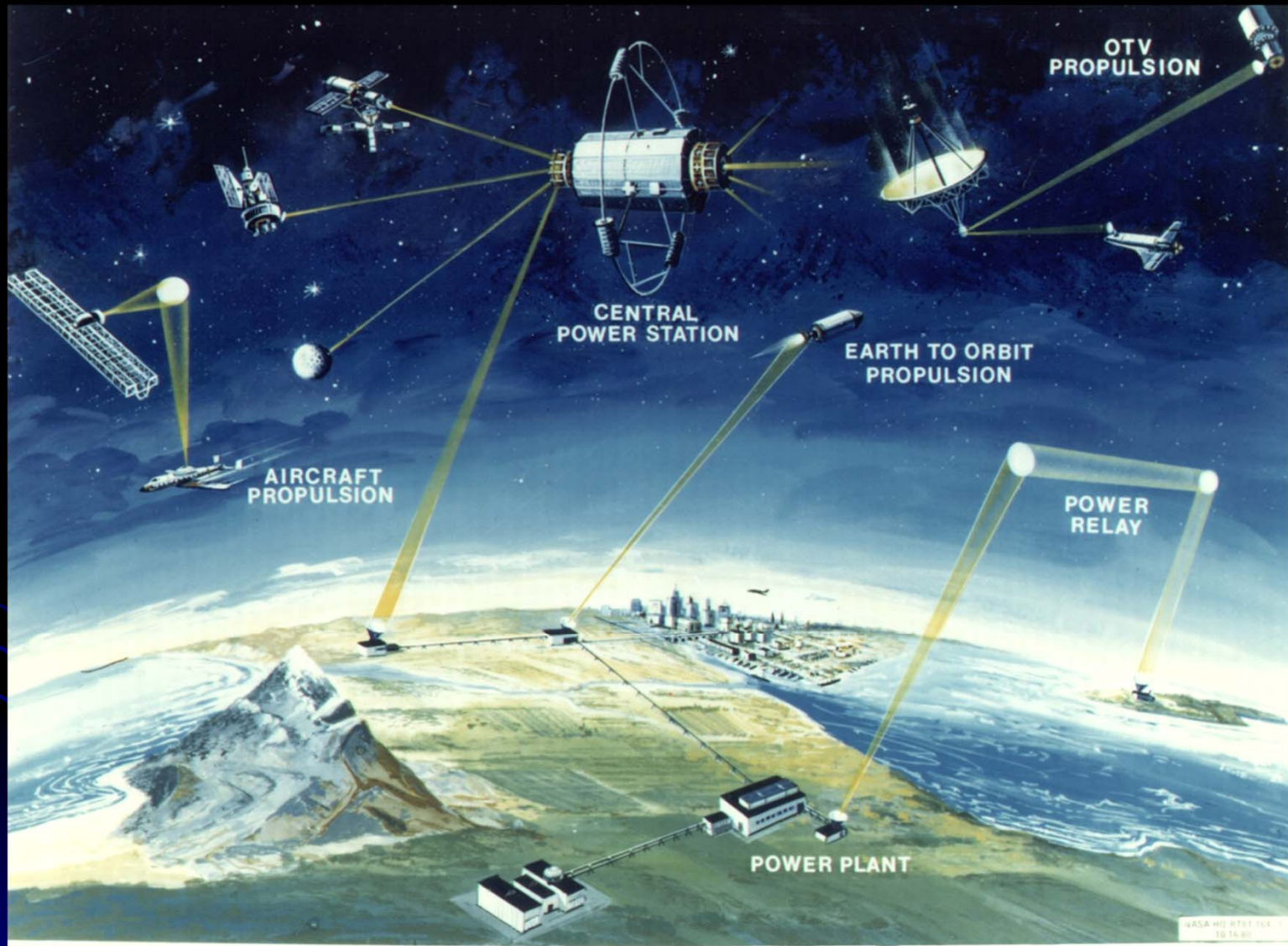


Patch Rectenna, measured at LaRC for 8.51 GHz

Dipole Rectenna, reported by William C. Brown,
NASA CR179558, March 11, 1987



Scenario of Laser Beam Power Transmission

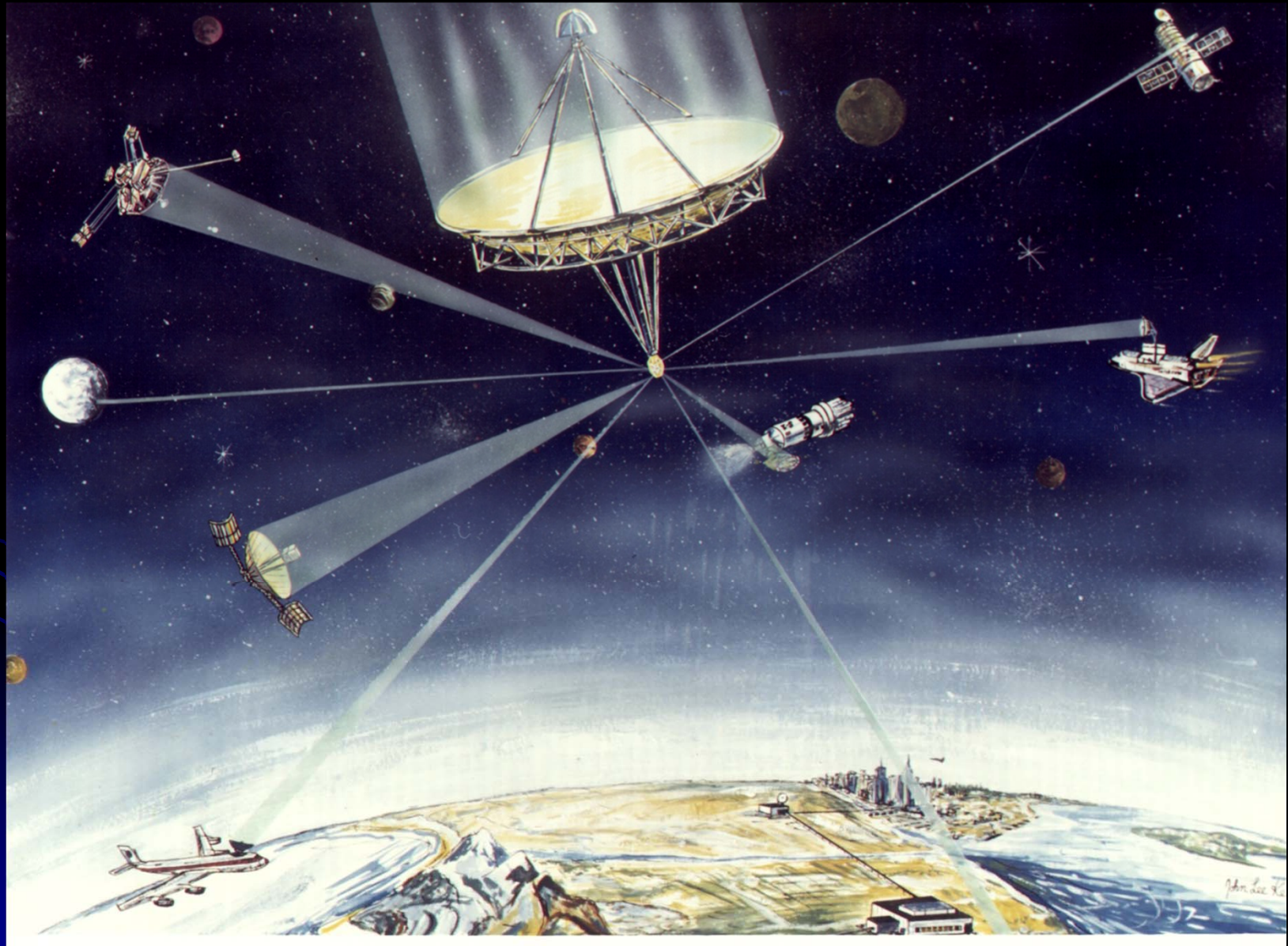


Williams, M. D., R. J. DeYoung, G. L. Schuster, S. H. Choi, J. E. Dagle, E. P. Coomes, Z. I. Antiniak, J. A. Bamberger, J. M. Bates, M. A. Chiu, R. E. Dodge, and J. A. Wise: "Power Transmission by Laser Beam from Lunar-Synchronous Satellites", NASA TM-4496, November 1993.

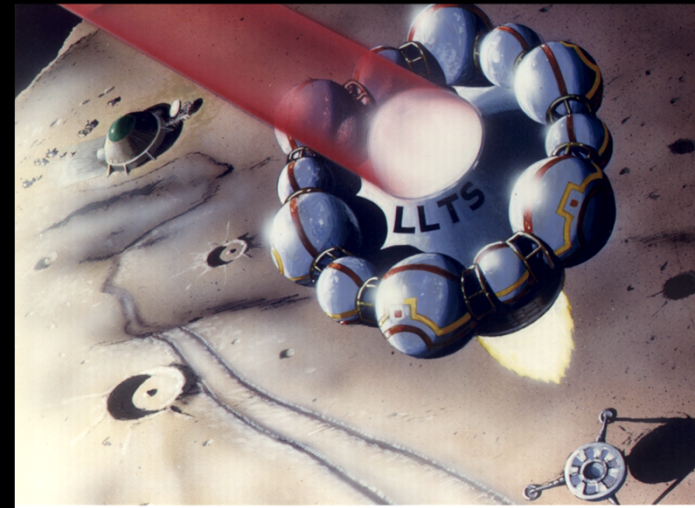
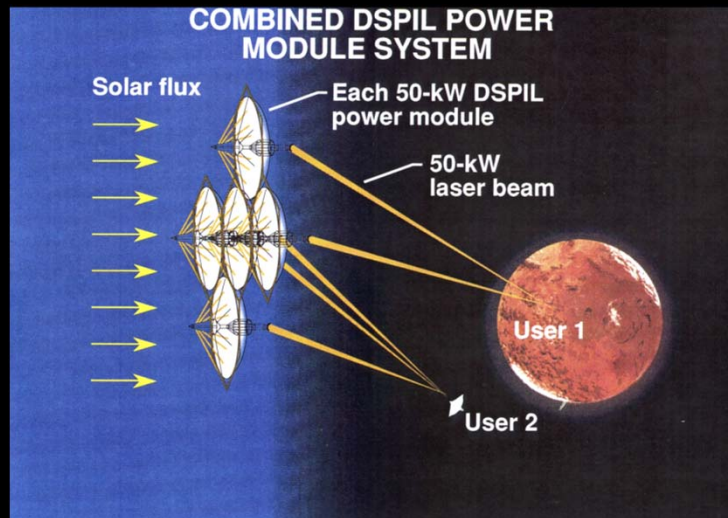


Solar Laser Beam Power Transmission

[NASA LaRC cartoon]



Laser Beam Power Transmission

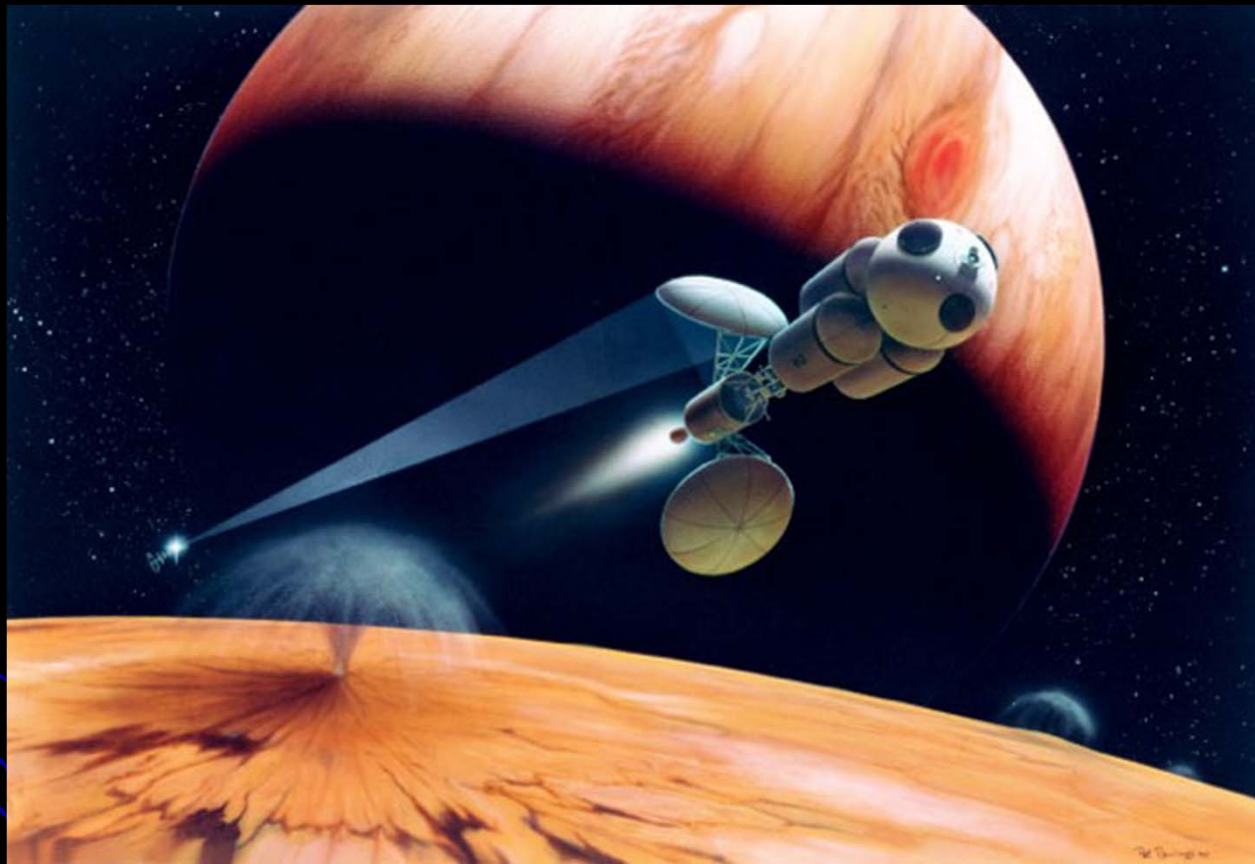


Choi, S. H.; Lee, J. H.; Meador, W. E.; and Conway, E. J.: "A 50-kW Module Power Station of Directly Solar Pumped Iodine Laser," *Journal of Solar Energy Engineering*, ASME, Vol. 119, p.304, Nov. 1995.



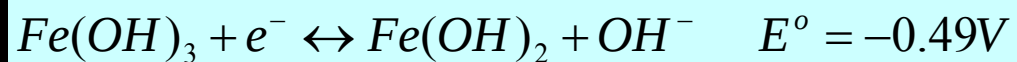
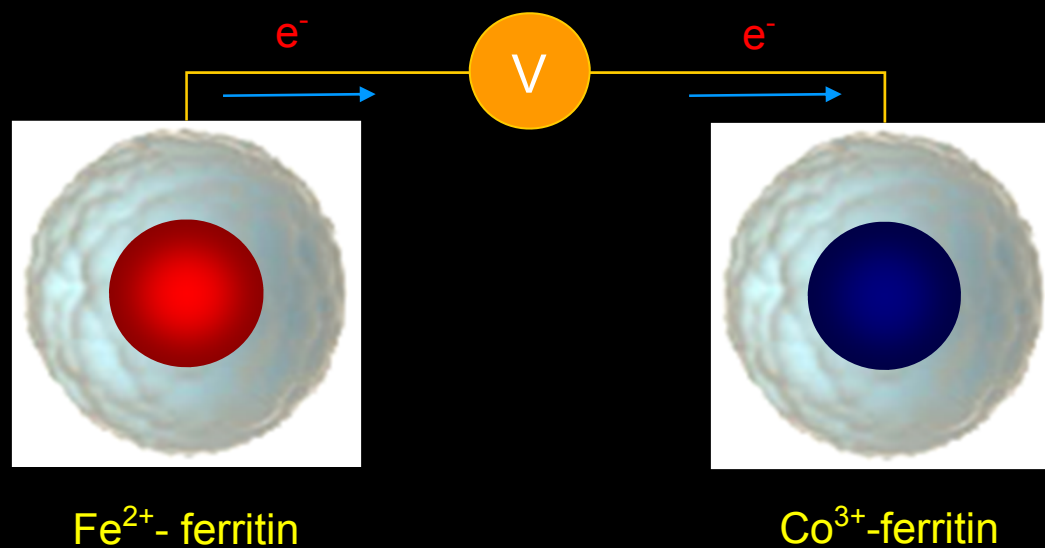
Choi, S. H., M. D. Williams, J. H. Lee, and E. J. Conway: "Diode Laser Power Module for Beamed Power Transmission," *Proceedings of the 26th IECEC*, Boston, MA, Aug. 4-9, 1991.

Laser Beam Power Transmission for Propulsion

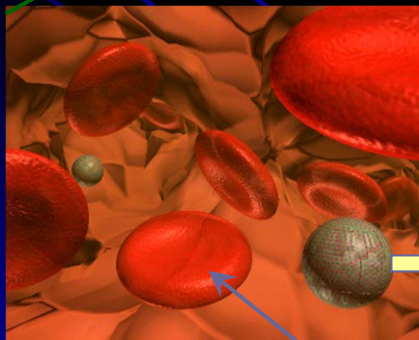
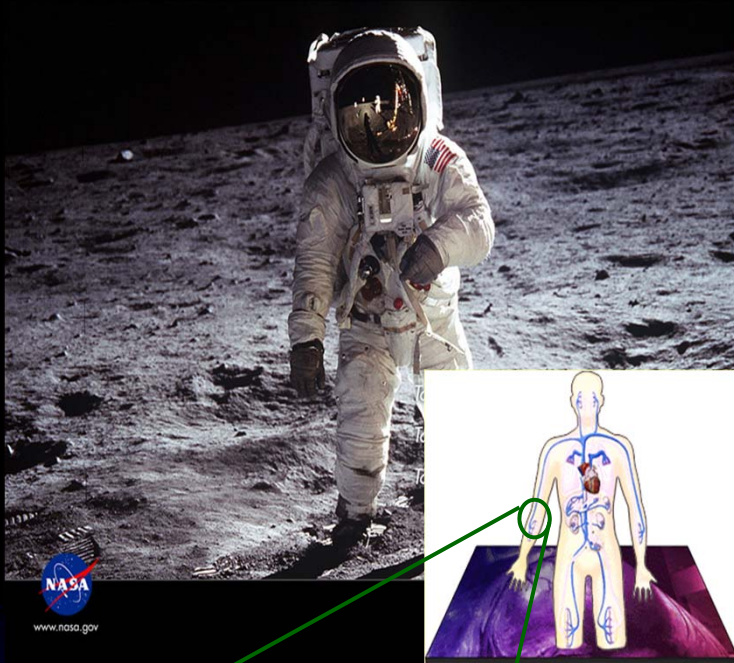


Laser power stations might one day propel spacecraft throughout the solar system. Credit: NASA/Pat Rawlings

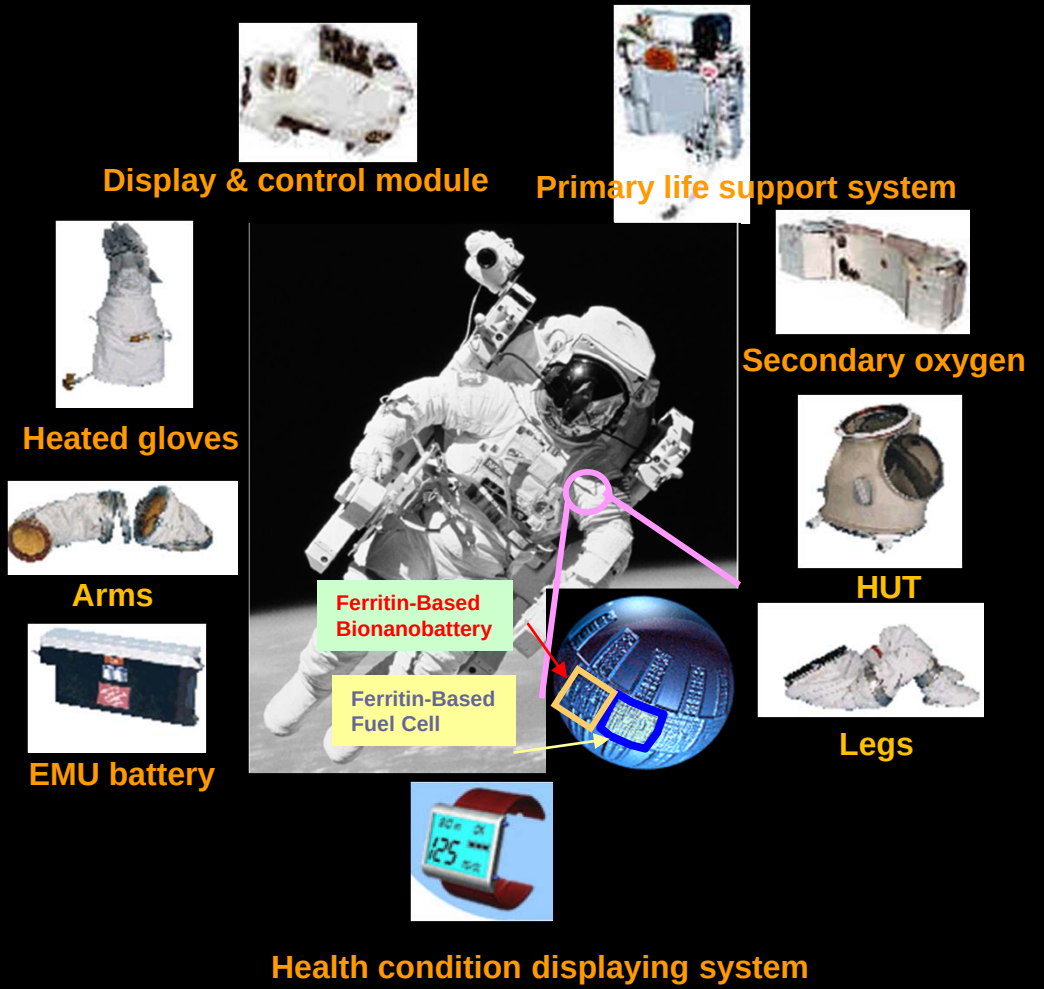
Bionanobattery Concept



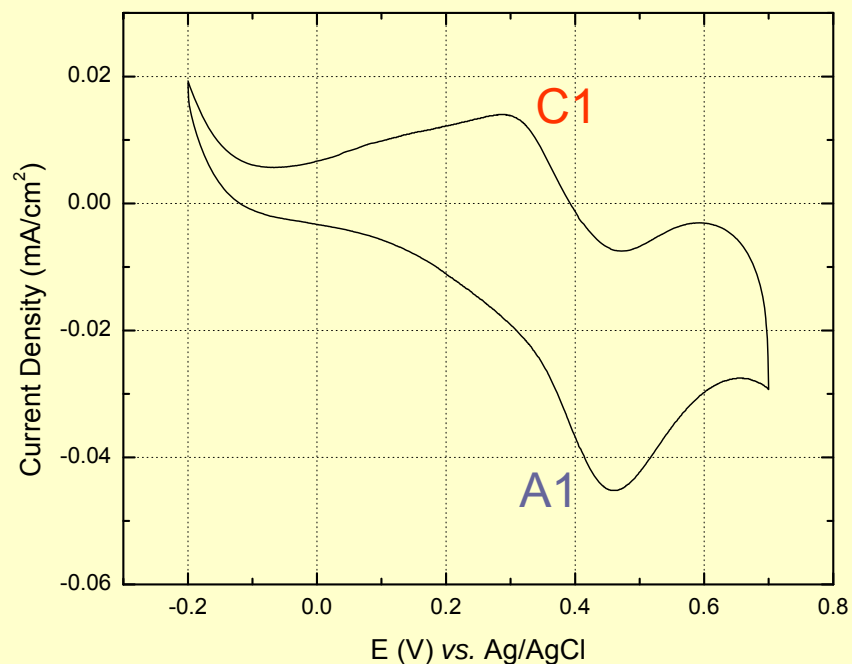
Bionanobattery and Biofuel Cells for Space Exploration Applications



Blood Vessel



Ni-Cored Ferritin

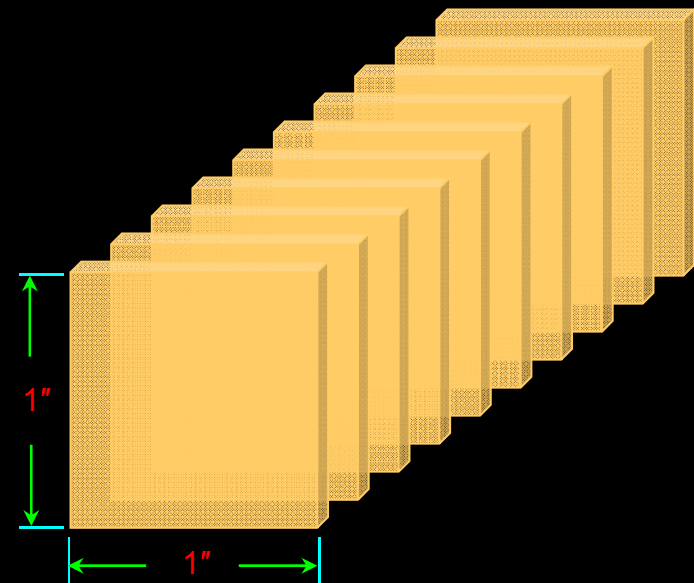
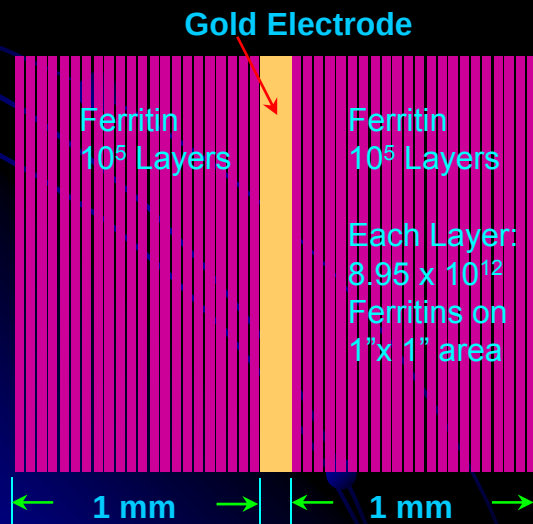


CV of physically adsorbed Ni-cored ferritin on Au electrode in 0.05 M phosphate buffer (pH 7.5 and pH 9.0) at the scan rate of 100 mV/s.

	Co	Mn	Ni
Fe	500 mV	480 mV	790 mV

Estimation of Electrical Output

- Electrode: 1"x1" gold films coated on both sides of a quartz slide
- Total number of ferritin on each layer of 1" x 1" area: 4.48×10^{12}
- Total available electrons: 2×10^{16} per layer = 3.2×10^{-3} Coulomb
- Charge Density per Electrode (2×10^5 layers): 640 Coulomb
- Cell Charge Density (array of 10 electrodes): 6400 Coulomb
- Operational Run-time: 6400 seconds when Fe^{2+} - Co^{3+} electrodes discharge 1 C/sec
- If we connect 10 gold electrodes together, then
 - Parallel connection: 0.79 V, 1 A (2844 mWh)
 - Serial connection: 7.9 V, 100 mA



Concluding Remarks

- ❖ Science missions needs highly efficient power system technology that has
 - High power density
 - Light-weight
 - Compact sizeto offer and enable:
 - Longer duration mission
 - More added mission categories
- ❖ Advanced thermo-electric materials with figure of merit (FoM) greater than 2 is necessary to enable long-term science missions using either radioisotopes or solar
- ❖ For deep space mission, solar PV cells are not suitable. RTG is a proven technology but requires higher efficiency.
- ❖ High capacity of new energy storage technology is necessary.
- ❖ Wireless power transmission (WPT) offers great flexibility of power management. Microwave WPT technology is matured, but w-band technology is desirable.
- ❖ WPT technology can subsidize solar or nuclear as energy sources to power client systems.

