Reenergizing US Space Nuclear Power Generation

Center for Space Nuclear Research Seminar
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The Story

- US space dominance will require access to space power ~ 200kWe
- Solar energy is not practical over 100 kWe
- Past attempts to revitalize space nuclear reactor technology have failed
- Still somewhat of a negative development environment
- Russians are back in the game in a big way
- So let's do something different, build a new space engine
- Do it quickly
- Rapid prototype/development approaches are presented that strengthens stakeholder interest and diffuses negative political environment
- Expensive but necessary?

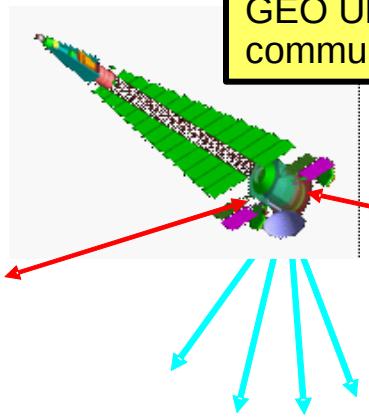
Current funding not likely
Use as a basis for design courses

Future Space Mission Power Needs

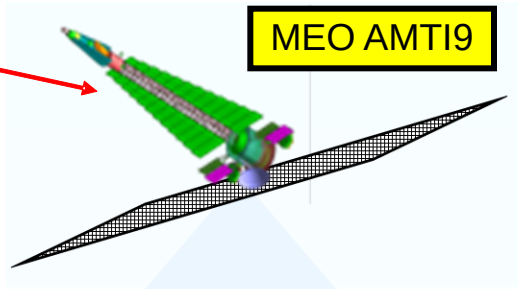
- Examples of game changing space dominance missions with 200 kWe availability

Missions
Space Control – Constant orbit repositioning using electric propulsion
Power available for payloads when not thrusting
• Geostationary orbit (GEO) Ultra-high bandwidth and secure comms/processing
• Mid Earth Orbit (MEO) Air Moving Target Indication (AMTI) against LO UAVs
• 10,000 km range high power (kWe) transmission beaming
• Multiple High Altitude Nuclear Detonation (HAND) radiation remediation using electrostatic (ES) tethers

GEO Ultra high capacity communications and processing

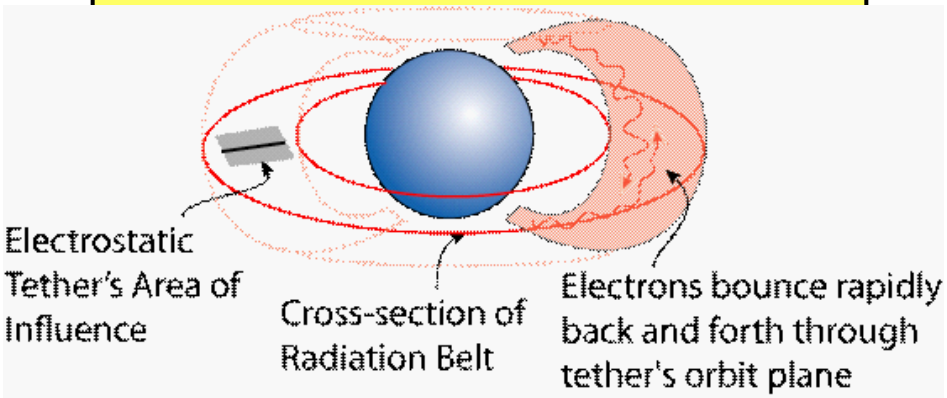


MEO AMTI9



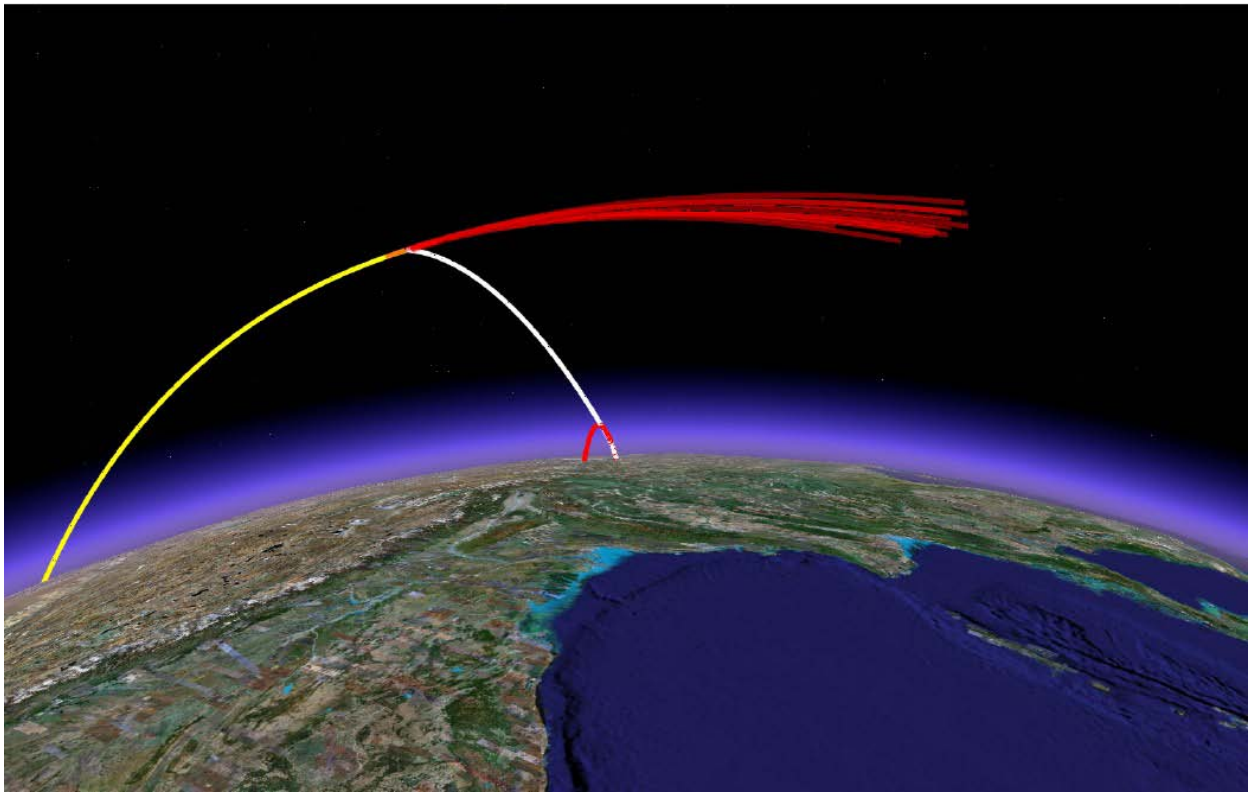
kWe power beaming

ES tether multi HAND radiation remediation



Space Control

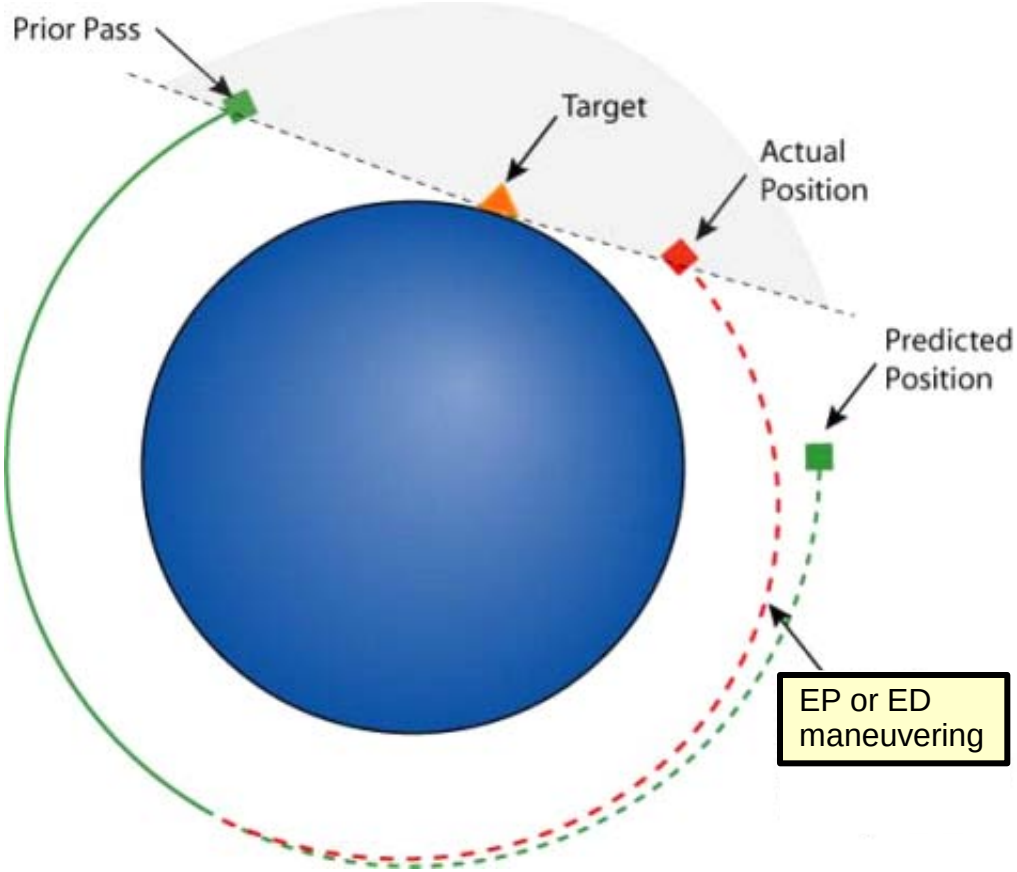
- Access to space critical to our national security
  - China's successful ASAT Demos
  - Ground based EW probing by unknown actors
- Key is Space Situational Awareness (SSA) is using a Space Object Surveillance and Identification (SOSI) system



  - Fuses optical, radar, signal intelligence, other sensors and supporting information
  - US tracks ~18,000 object
  - Provides data to attack a satellite

Space Control (cont.)

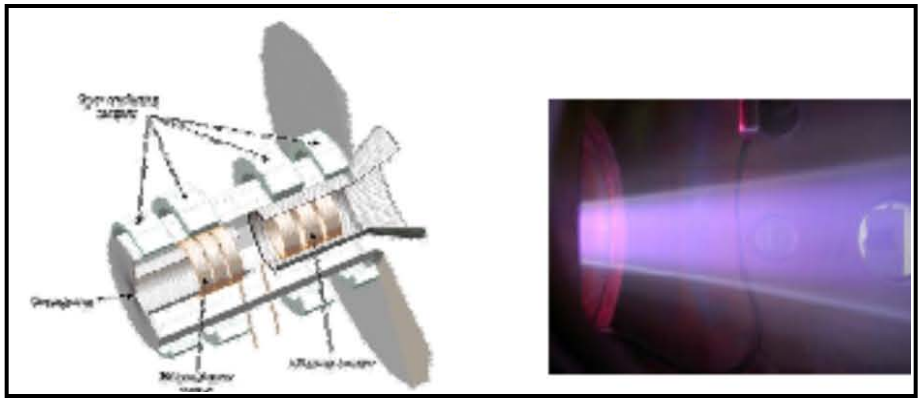
- Adversary SSA improving as SOSI system's upgrade
- To track an object as it departs the field-of-view an estimate is made on where the object will reappear
- Estimation process does not perfectly model perturbations, including maneuvers
- Optical sensors are used for GEO (degraded by weather and optical field of view limitations)
- Radar and optical sensors are used for LEO (Optical degraded as above and radar by timing)

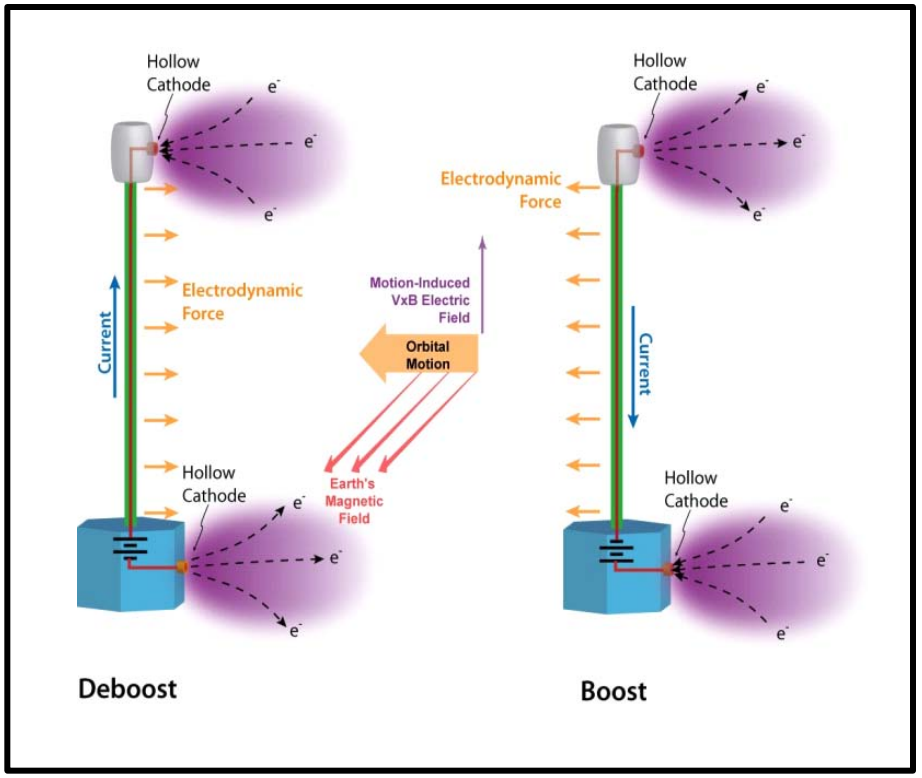


- Sufficient maneuvers that change altitude and/or inclination will cause SOSI track loss unless prior knowledge of the amount and when the change was initiated

Long Duration Propulsion

- Changing orbit requires energy, go with high Isp propulsion
  - Electric propulsion (EP) - accelerate particles
  - Electro-dynamic (ED) tethers - Create a Lorentz force induced thrust
- ED tethers
  - Long wire with current produces thrust from Lorentz force
  - Produces more thrust then EP system at same power
  - Ops envelop to <1500 km and at lower inclinations.
    - Altitude restrictions required for completing the circuit using the higher density plasma of the ionosphere
    - Lower inclinations optimized thrust with the magnetic field orientation and strength





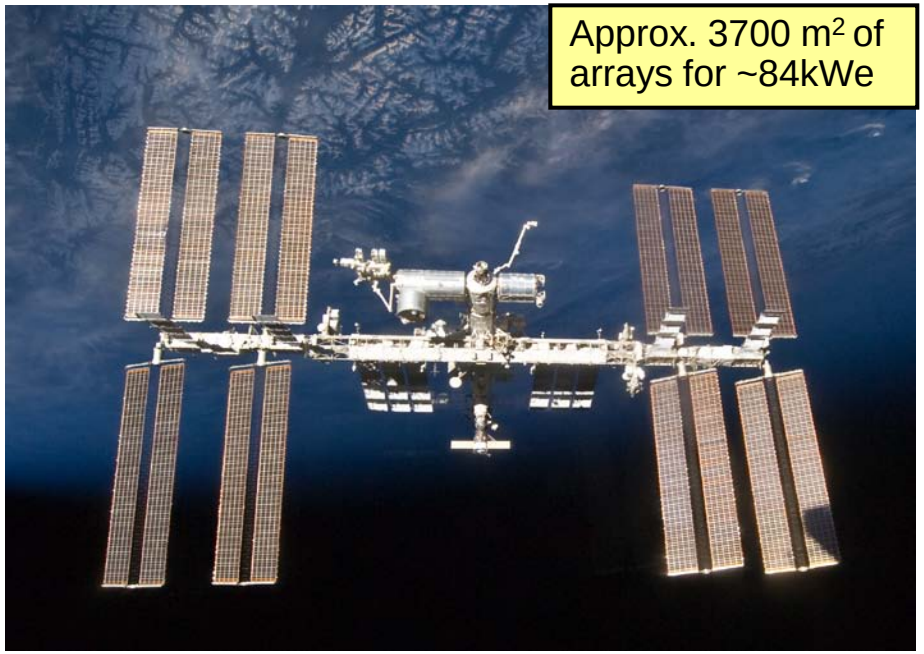
EP Induced Orbit Changes (per orbit/day)

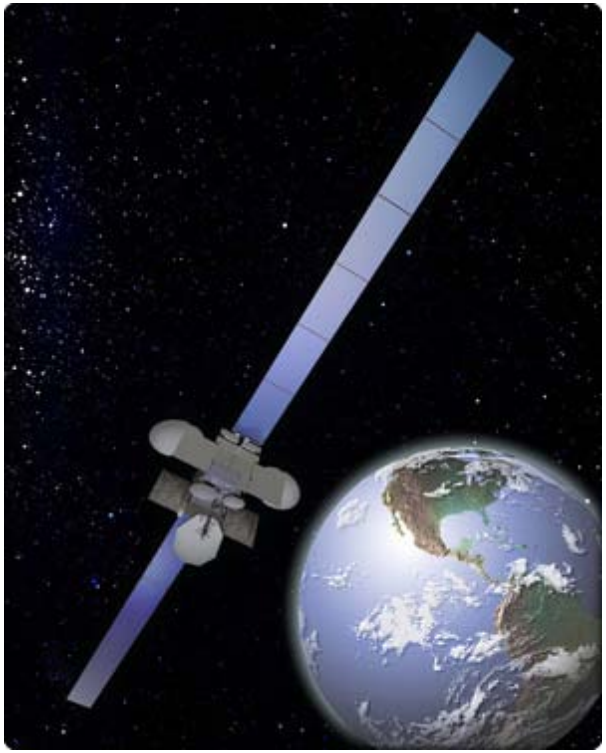
Mass (kg)	Thrust +/- (N) for entire orbit period	Initial Orbit (km)	Orbits per day	Incl. (deg.)	Max. change (loss or gain) per orbit or day (km)(2)	Max. difference in time (early or late) to same point after one orbit or day (sec)	Max. Incl. change per orbit or day (deg.)
Electric Propulsion (1)							
LEO							
15,000	5	1,000	~14	51.6	4/56	3/44	.011/.15
10,000	5	1,000	~14	51.6	6/89	4/59	.016/.22
MEO and GEO							
15,000	5	10,000	~4	28.7	46/185	44/177	.053/.21
10,000	5	10,000	~4	28.7	68/279	66/264	.078/.31
10,000	5	GEO	1	0	1151/1241	1770/1770	.128/.51
Electro-Dynamic Tethers (1)							
LEO							
15,000	17	1,000	~14	28.7	14/197	16/225	.014/.191
10,000	17	1,000	~14	28.7	21/290	23/320	.020/.281

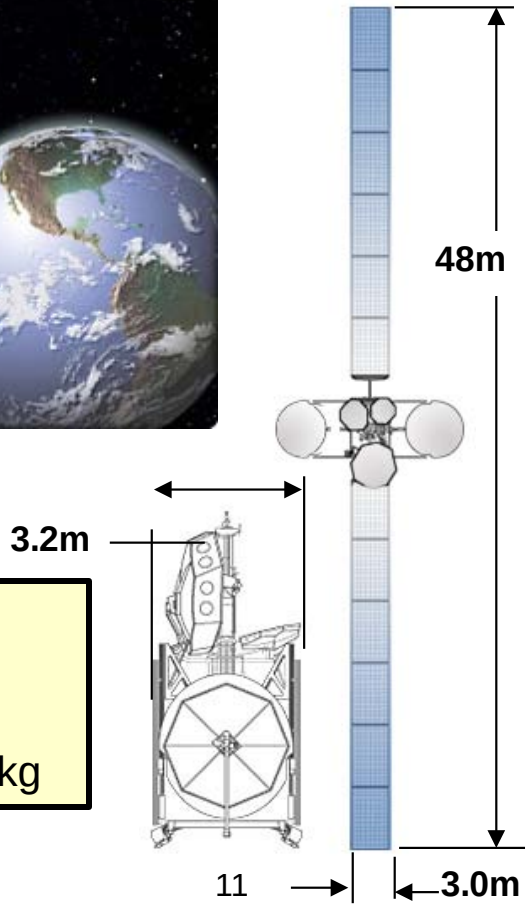
(1) EP Isp ~7000 sec., ED tether Isp ~40,000 sec.

(2) Non-optimal thrusting (Thrust pointed along fore and aft of vehicle)

Why Not Solar?







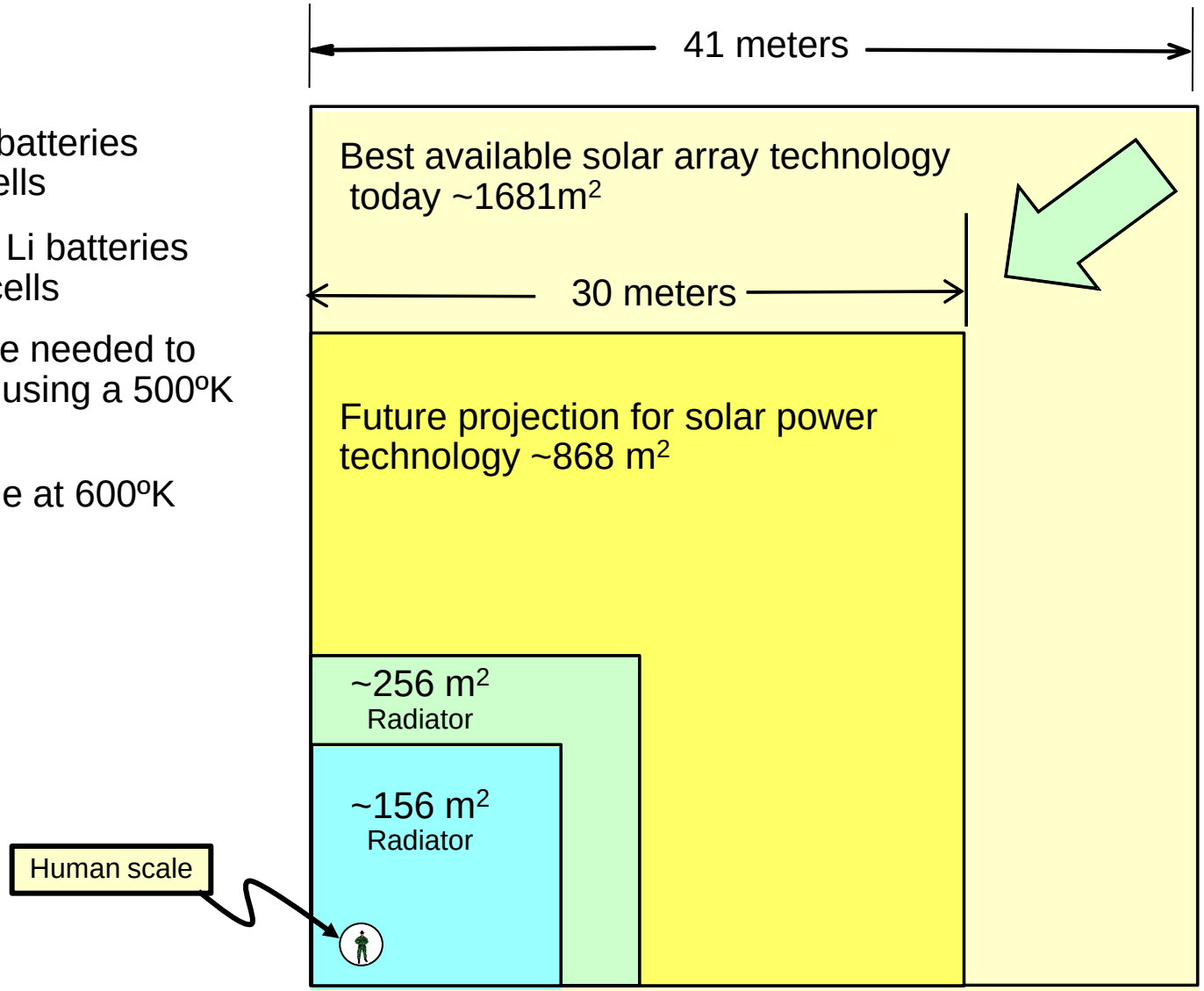
ISS
α= 220
Mass for 27 kWe is 5,938 kg
α=181
Mass for 200 kWe is 36,393 kg

Galaxy IIIc
α= 64
Mass for 15 kWe is 962 kg
Mass for 200 kWe is 12,508 kg

α = kg/kWe Smaller is better

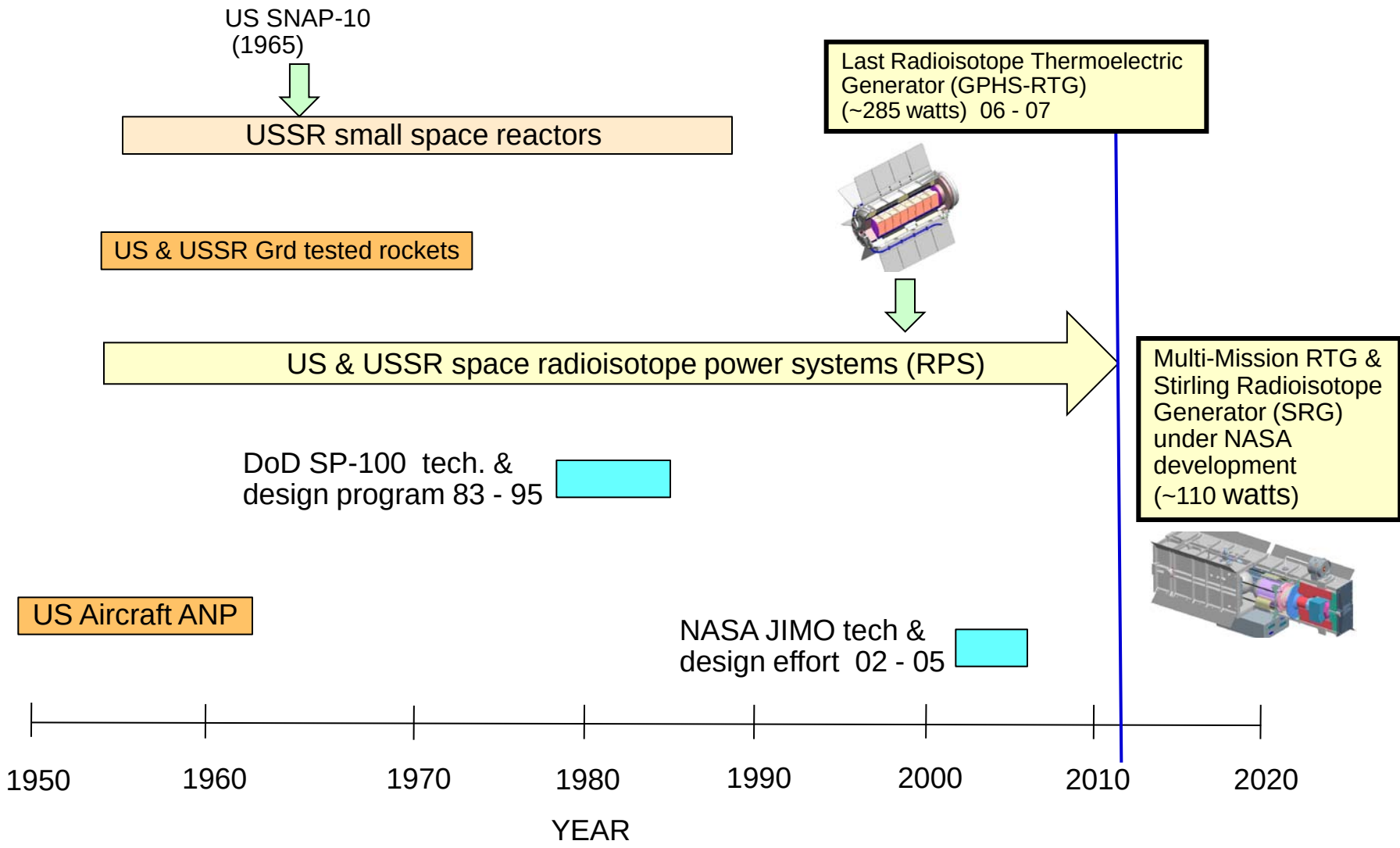
200 kWe Solar Array Size vs. NEP Radiator Size

- Solar array NiH batteries and 18% EOL cells
- Solar array Adv. Li batteries and 35 % EOL cells
- NEP radiator size needed to radiate 800 kWt using a 500ºK rejection temp.
- NEP radiator size at 600ºK rejection temp.



Sources: (Angelo, 1985 and Wertz, 1999)

Nuclear Aerospace - Last Six Decades

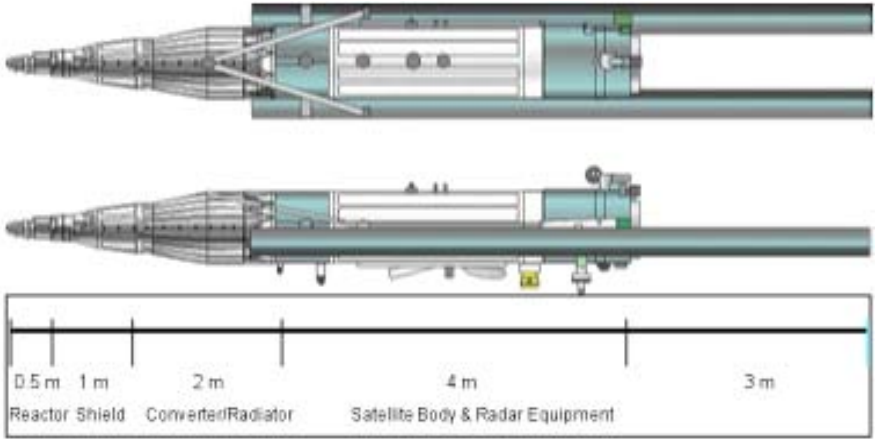


Sources: (Abelson, 2005)

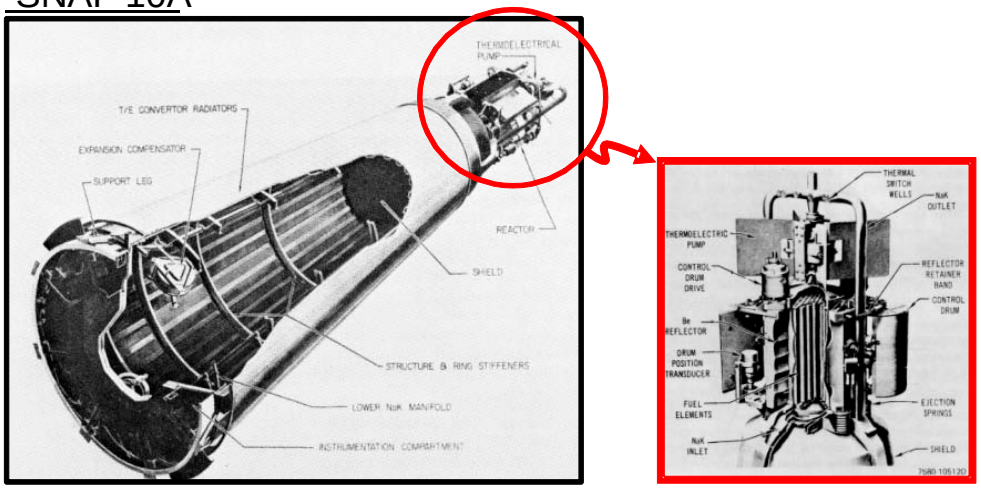
Nuclear Space Reactors Flown In Space

	USA	USSR
	SNAP-10A	RORSAT
Initial Flight	1965	1967
Number Flown	1	31+
Power kWt	46	~100
Power kWe	0.65	~5
Conversion	Thermoelectric	Thermoelectric
Fuel	U-ZrHx	U-Mo
kg^{235}U	4.3	25 - 35
Mass (kg)	435	~390
Coolant	NaK	NaK
~ α (kg/kWe)	670	78

RORSAT

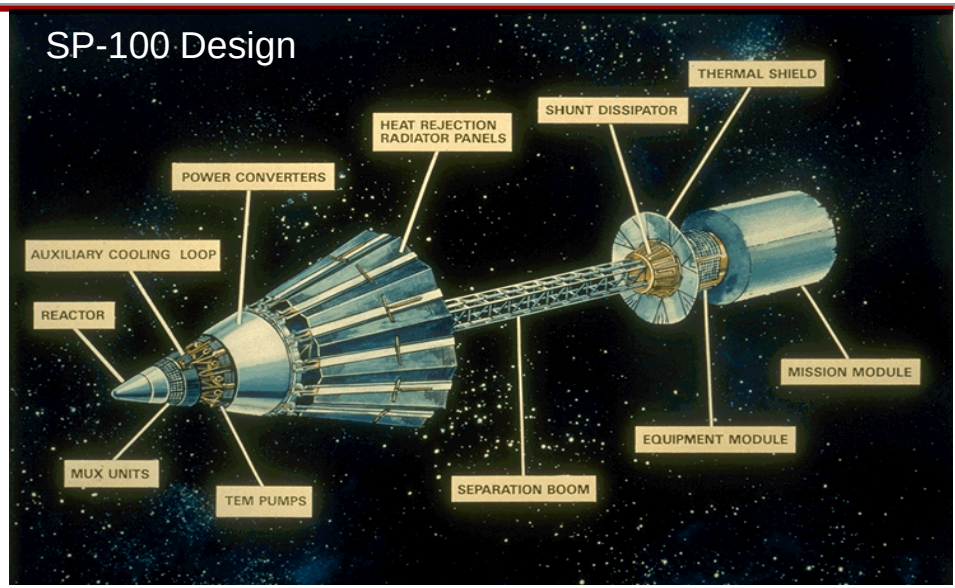


SNAP-10A



Sources: (Angelo, 1985 and Kulcinski 2004)

SP-100 (1983 to 1995)



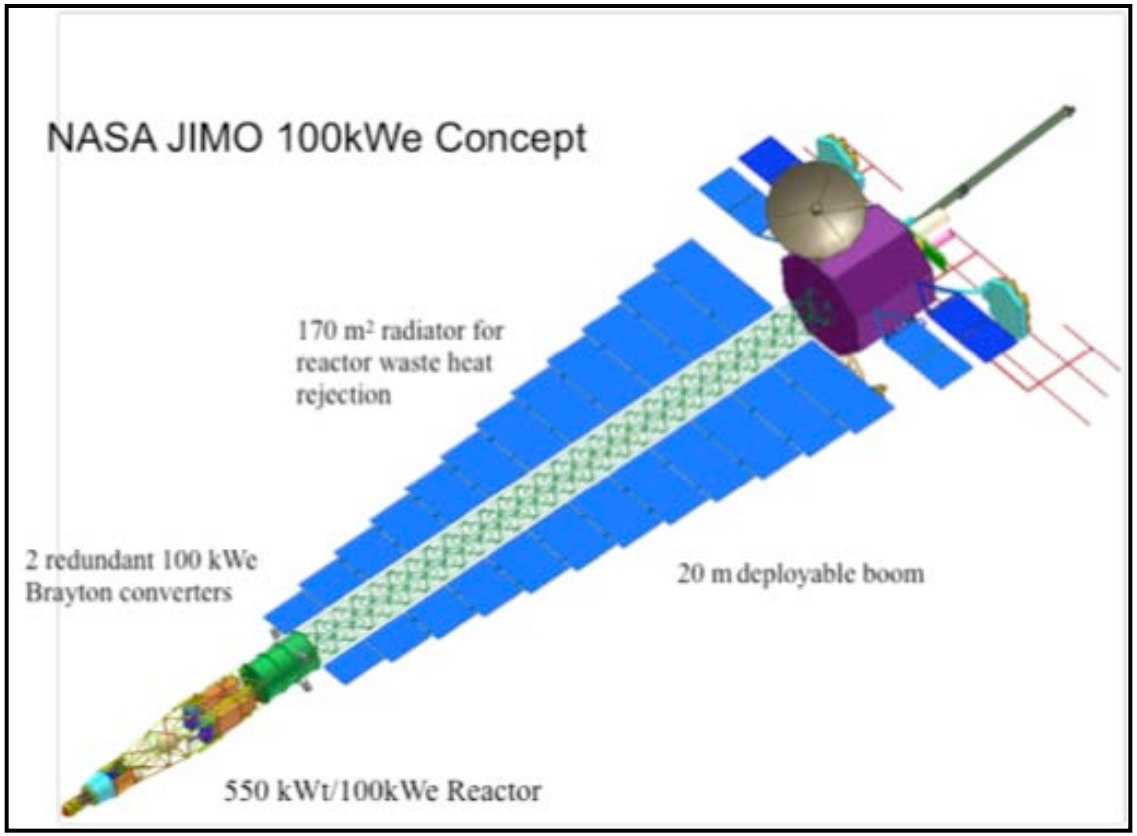
- $727M (08 dollars[1]): NASA, DoE, DoD (DARPA)
- Key features:
  - Liquid lithium (Li) metal cooled
  - 2.3 MWt for 100 kWe (4.3%) using thermo-electrics
  - α ~ 40 to 54, 106 m^2 of heat pipes radiator
- Modular design
  - Addressed different users/missions
  - Couple the reactor, shield and heat rejection radiators to different energy extraction devices to get different power conversion efficiencies
  - Compatible with a wide variety of space environments and launch vehicles
- Approach required significant technology development and increased both program cost and schedule
- Missions evaporated during development
- No complete end-to-end prototype tested in a space simulated vacuum environment to "wow" investors of full system level capabilities as a return on their multi-year investment

- Approach may have contributed to a classic "time-to-market" failure

(1) Inflation factor from 1995 to 2008 is 1.39

Prometheus/JIMO (2002 – 2005)

- $128.5M Phase A completed
- Key features:
  - 200 kWe nuclear reactor with Ion and Hall electric propulsion thrusters (NEP)
  - Design for 20 years (10 years plus 10 at half power)
  - Gas-cooled reactor with redundant pairs of Brayton turbo-alternators
  - 5875 kg , α ~ 30.
  - 1500 kg payload
  - 12,000 kg of Xenon propellant
  - Docking interface for on-orbit docking ***three launches*** were necessary to assemble spacecraft
  - ***Aero-shell*** (jettisoned prior to reactor start-up) safety device to keep reactor together during an unplanned reentry back to earth.



NEP for deep Solar System exploration and increased maneuverability at destinations

Today's Development Environment

- Legacy issue
  - 80+ nuclear devices flown ~10 accidents involving spacecraft with some sort of nuclear device (Two events resulted in terrestrial contamination)
  - Publicity caused a large negative attitude towards entire discipline
  - Cost for SNAP-10 flight program (~$357M in 2008[1] dollars)
  - Cost for SP-100 technology program (~$727M in 2008[2] dollars)
  - Last two US attempts (SP-100 and Prometheus/JIMO) to reenergize space nuclear reactors failed
- Need for future high power space systems exists but that by itself does not appear to provide a strong enough mission pull
- Threat environment to US space dominance (China, Russia, India, others) rapidly accelerating
- Russians are back in the space nuclear reactor game, $150M/FY10

(1) 1966 to 2008 inflation multiplier 5.847 (2) 1995 to 2008 inflation multiplier 1.39

Development Environment (cont.)

- Status
  - NASA and DoE have budgeted $10M (FY10) for space nuclear power technologies in a variety of small projects
  - Hard to justify the need to rebuild space nuclear reactor fabrication and fuel manufacturing and testing infrastructure without an actual flight program identified and future flight programs planned
  - Manned mission to the moon is gone (pushed surface nuclear power systems) and manned missions to Mars still stalled out
- Current budget priorities and projected costs?
  - Recent Obama administration interest requested the NASA surface nuclear reactor projects be slightly redirected towards flight systems
  - Congressional interest potentially weak in a deficit mitigation environment
  - Academia just can't get this size project to happen
- However, is there still a US government/industrial capacity to do the job?
  - Design, develop, manufacture and test and evaluation facilities, fuel sources and talent (demographics)

Going Forward

- How to go forward given these constraints
  - Repackage concept
    - Build an engine that happens to use nuclear power
    - Nuclear electric propulsion
  - Build it in a way that is different then before?
    - Rapid development approach
    - Intermediate real system level products
  - Cultivate key stakeholders
    - Involve then in the entire development process
  - Educate the value of the technology
    - Race with the Russians?
    - Importance of space dominance for our future

Example: Rapid Prototyping/Development Features

- Minimize requirements definition, work with stakeholders, get quickly into development
- Build a prototype, demonstrate it, get stakeholder feedback, address in follow-on cycle
- Repeat the process, evolving product and gradually adding capabilities, until stakeholders are satisfied
- Assumption - More time and cost effective to work with the product than to spend getting requirements stabilized.
- Positives
  - Cost reduction by minimizing requirements definition
  - Stakeholder involvement leads to "buy-in", perhaps even to design compromises
  - Requirements continually evolve
  - Failure or program termination in later cycles still results in system level capabilities demonstration

Used often in software development, relevant here?

Rapid Prototyping/Development Features (cont.)

- Risks and mitigations
  - How many build and test cycles will be required?
    - ***Agree on a finite number with stakeholders.***
  - Difficult to plan and establish a schedule and budget for executive control
    - ***Continuous dynamic planning***
  - May break down if it is large complex systems are involved with many development teams
    - ***Minimize teams***
  - May break down if too many stakeholders are involved
    - ***Limit stakeholders***
  - May end up with only a prototype
    - ***Continuous planned knowledge extraction into virtual value added products (e.g. design tools)***

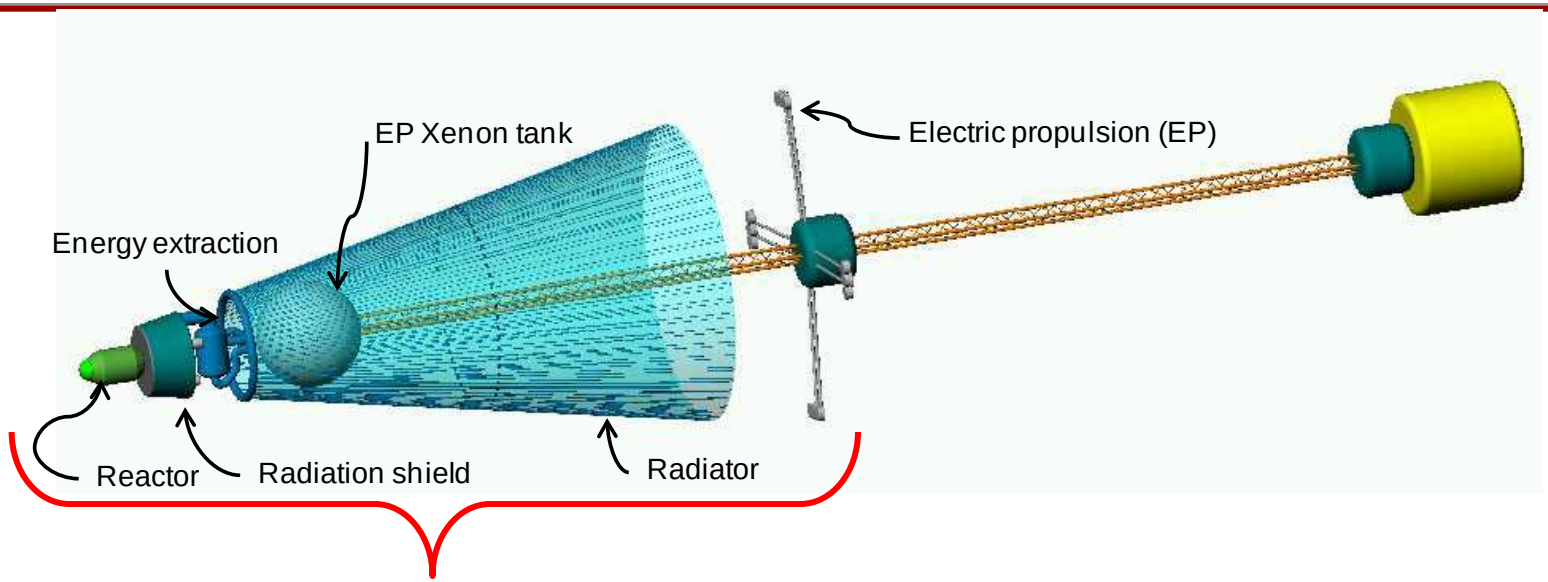
Ref: www.maxwideman.com, project management wisdom

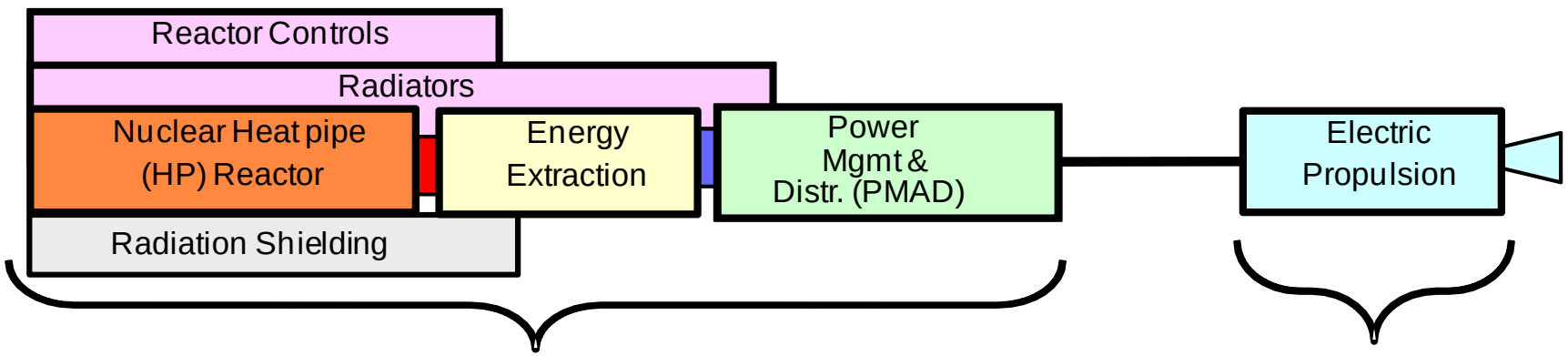
Reenergize – New Approach

- Build an space engine (happens to be nuclear power) in a ***rapid development/prototype manner*** with intermediate system level products to cultivate key stakeholders, educate the value of this technology, maintain US space dominance and minimize surprises from the Russians
- Two approaches presented next
- Key features
  - Stringent scope, cost and schedule control with early planning for next cycle
  - Designed for launch and space environment
  - Continuous full scale testing in space simulation environment
  - Continuous value added assessment
  - Power extraction subsystem enhancements developed in parallel
- Simple yet elegant engine design
  - Minimum moving parts (e.g. heat pipe reactors, energy extraction approaches, etc.)
  - Continuous mass optimization
- Critical, lean management and execution team
  - Industry integrator
  - Split facilities for system level integration, test and evaluation
  - Continuous flight article cost and schedule modeling
  - Extensive and continuous stakeholder analysis

Design, build, test….Design upgrade, build, test…eventually fly

Nuclear Electric Propulsion Engine





α = total mass (kgs)/ available electric power (kWe)

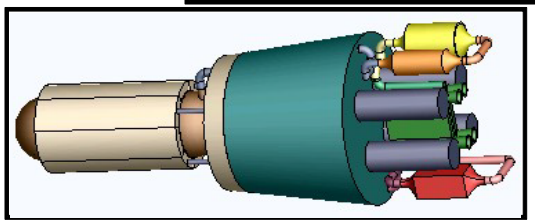
Total mass = $mass_{reactor} + mass_{shield} + mass_{radiators} + mass_{energy\ extraction} + mass_{PMAD} + mass_{controls}$

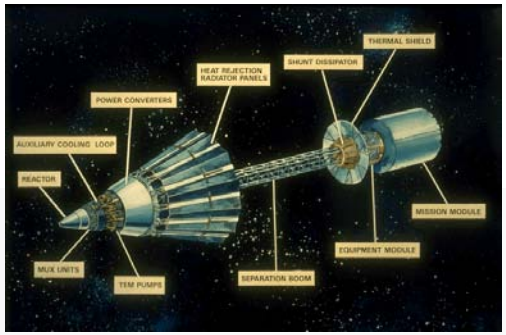
- Thrust (Newtons)
- Isp (seconds),
- Thrust density (N/m^2)

Sources: Artwork courtesy of LANL

Space Nuclear Reactor Types

Liquid-metal-cooled

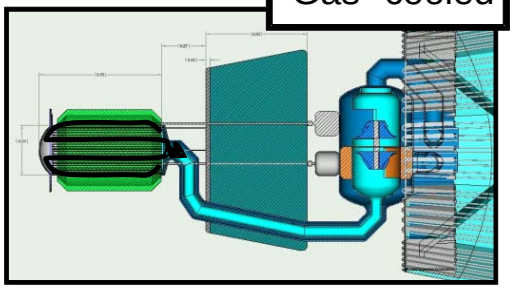


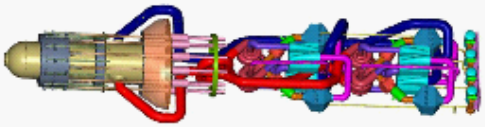


SP-100 (1995 scalable design from 10kWe to 1MWe)

- α ~ 54kg/kWe
- Liquid lithium metal cooled
- Rankine Cycle
- Life: 7 years
- Lithium hydride + tungsten shield

Gas-cooled

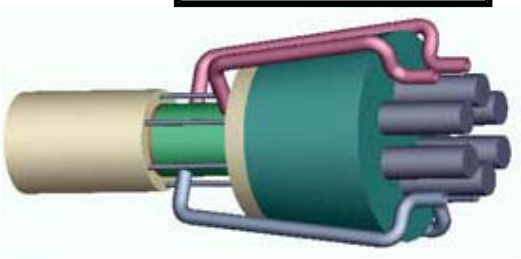


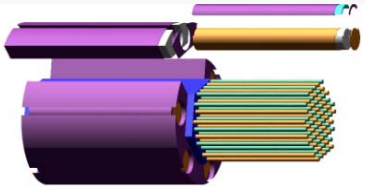


IO (2005 scalable design from 20 to 300kWe)

- α ~ 46kg/kWe
- Gas cooled
- Brayton Cycle
- Life: 10 years full + 10 year partial power
- Lithium hydride shield

Heat pipe-cooled



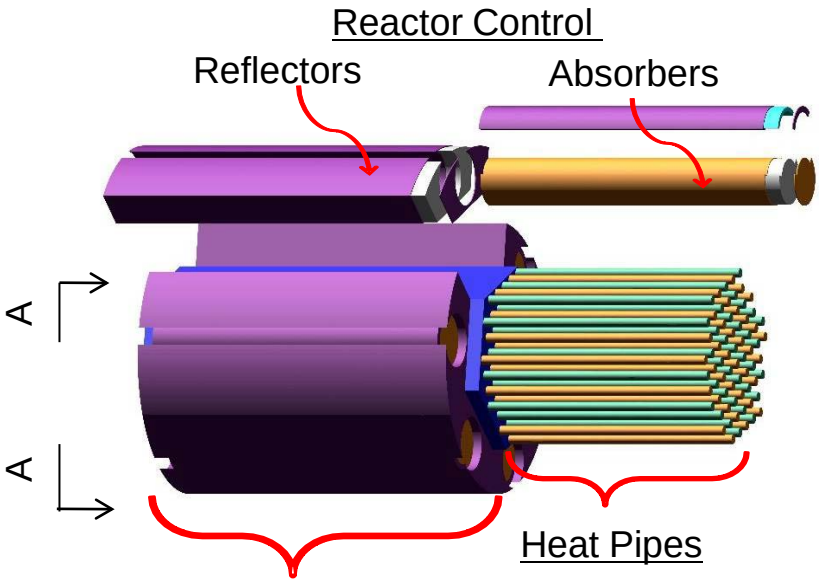


Current study (2011 scalable design from 25 to 200kWe)

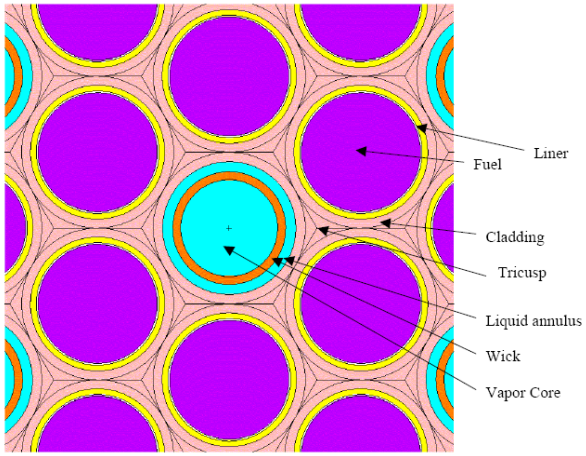
- α ~ 40kg/kWe
- Heat pipe cooled
- TPV or Stirling Cycle
- Life: 10 years full
- Lithium hydride + tungsten shield

Sources: (Obal, 2004) Artwork courtesy of LANL

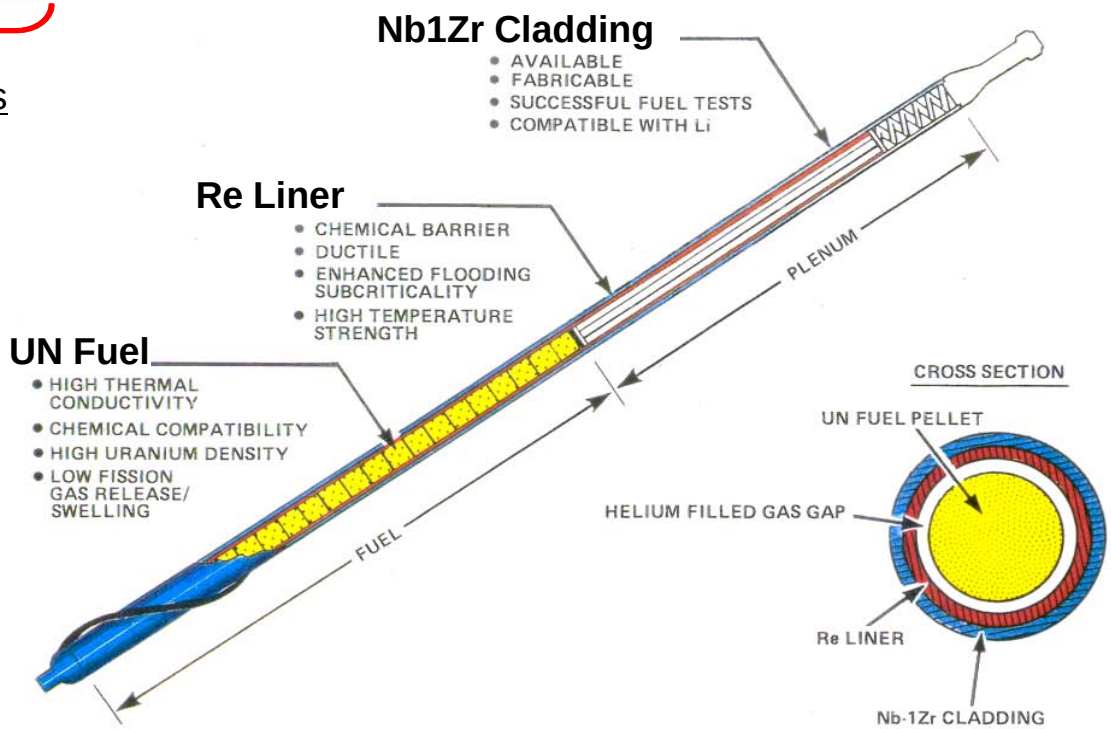
Details of a Heat Pipe Reactor



Heat Pipe



Cross Section A -A

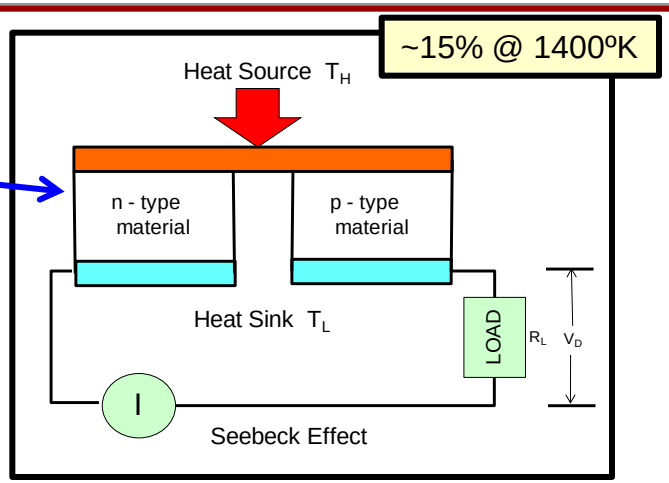


Sources: Artwork courtesy of LANL & University of CA, Greenspan, 2008

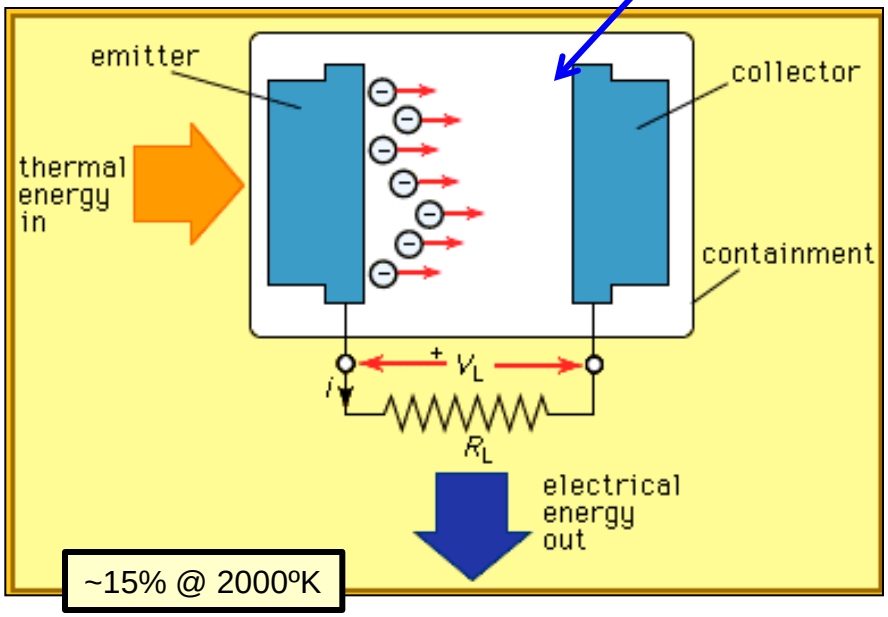
Energy Extraction Approaches

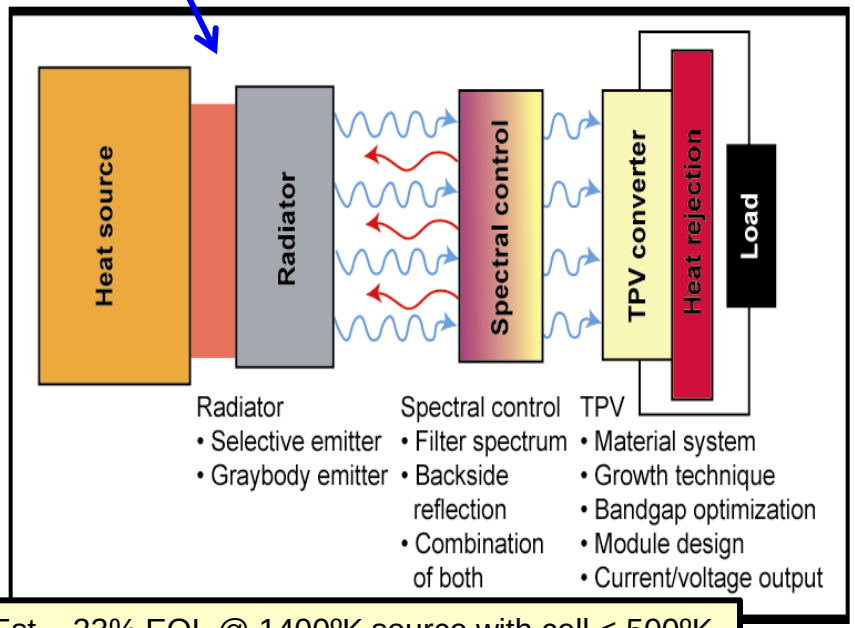
- Produce heat
  - Radioisotope decay
  - Nuclear Reactors

- Direct Conversion
  - Thermoelectric
  - Thermo-photovoltaic
  - Thermionic



SNAP-10A, SP-100





Q-Dot Est. ~23% EOL @ 1400ºK source with cell < 500ºK

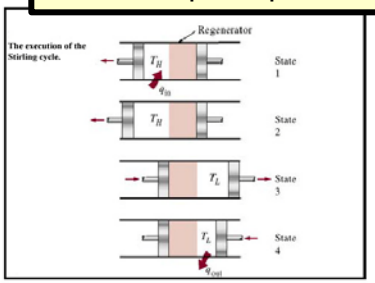
Sources: (Angelo, 1985, Teofilo, 2007),

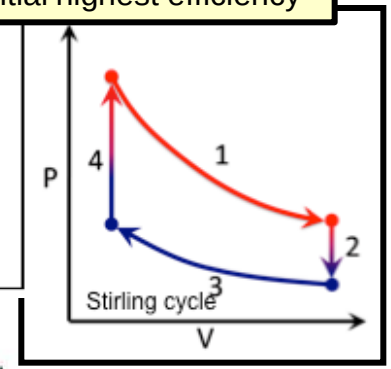
Energy Extraction Approaches

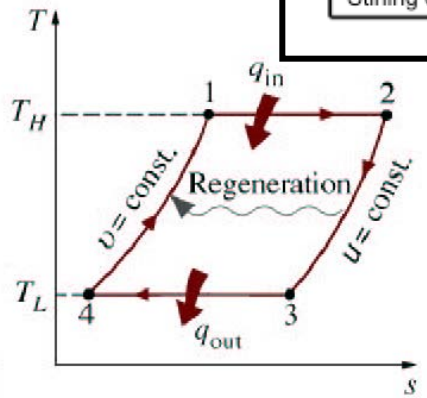
- Produce heat
  - Radioisotope decay
  - Nuclear Reactors

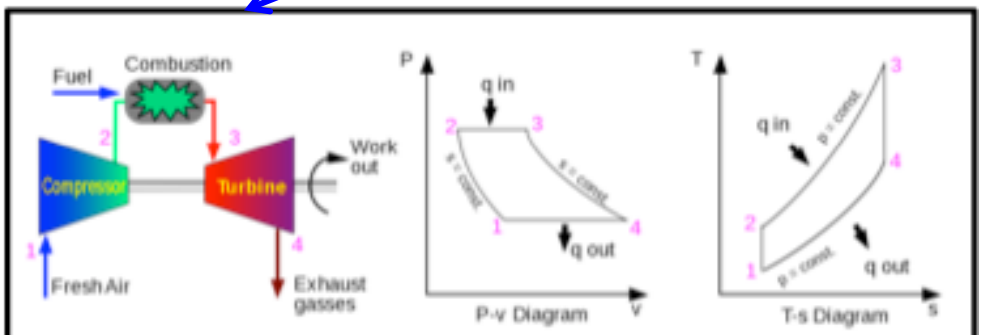
- Thermodynamic cycles
  - Stirling
  - Brayton
  - Rankine

Minimum parts potential highest efficiency

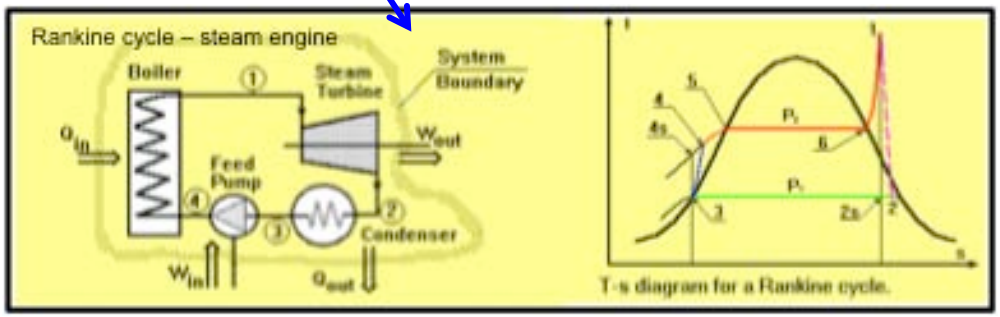








Brayton cycle – gas turbine



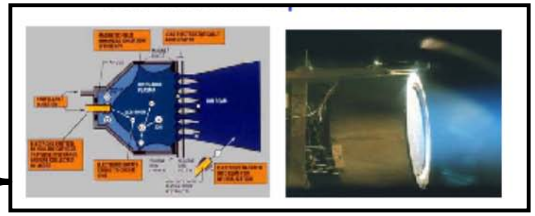
Sources: (Angelo, 1985, Teofilo, 2007),

Electric Propulsion Concepts

- Isp = Thrust/weight flow rate and is a measure of the energy content of the propellant, types of electric propulsion systems, High Isp and thrust

Type	Isp (sec.)	Thrust (max)(N)	Power (kWe)
NASA GRC HIPEP (low)	6000	0.460	25
NASA GRC HIPEP (high)	9620	0.670	39.3
NASA NEXIS	8700	0.517	27
VHITAL 160 (Mode 1, two stage tech.) 1	6000	0.650	25
Electro dynamic tether	40,000	4.5	25

(1) VHITAL Mode 2: Isp, 8000, Thrust 0.710N at 36kWe

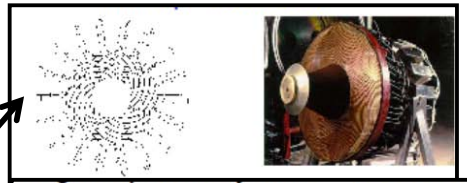


Ion thruster

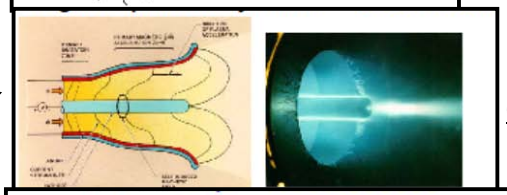
Hall thruster w/induction

Type	Isp (sec.)	Thrust (max) (N)	Power (kWe)
Pulsed Inductive thruster (NuPIT)	3000 - 10000	5	200
Li-MPDT ALFA	4250	4	192
VASIMR (VX-200)	5000 - 10000	5.7	200

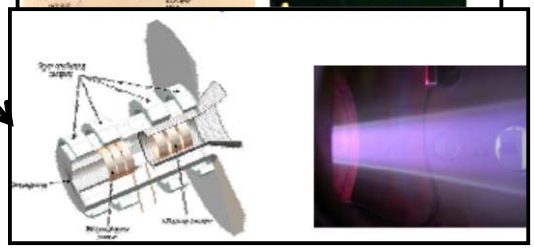
There are no wall outlets in space



Pulsed inductive thruster



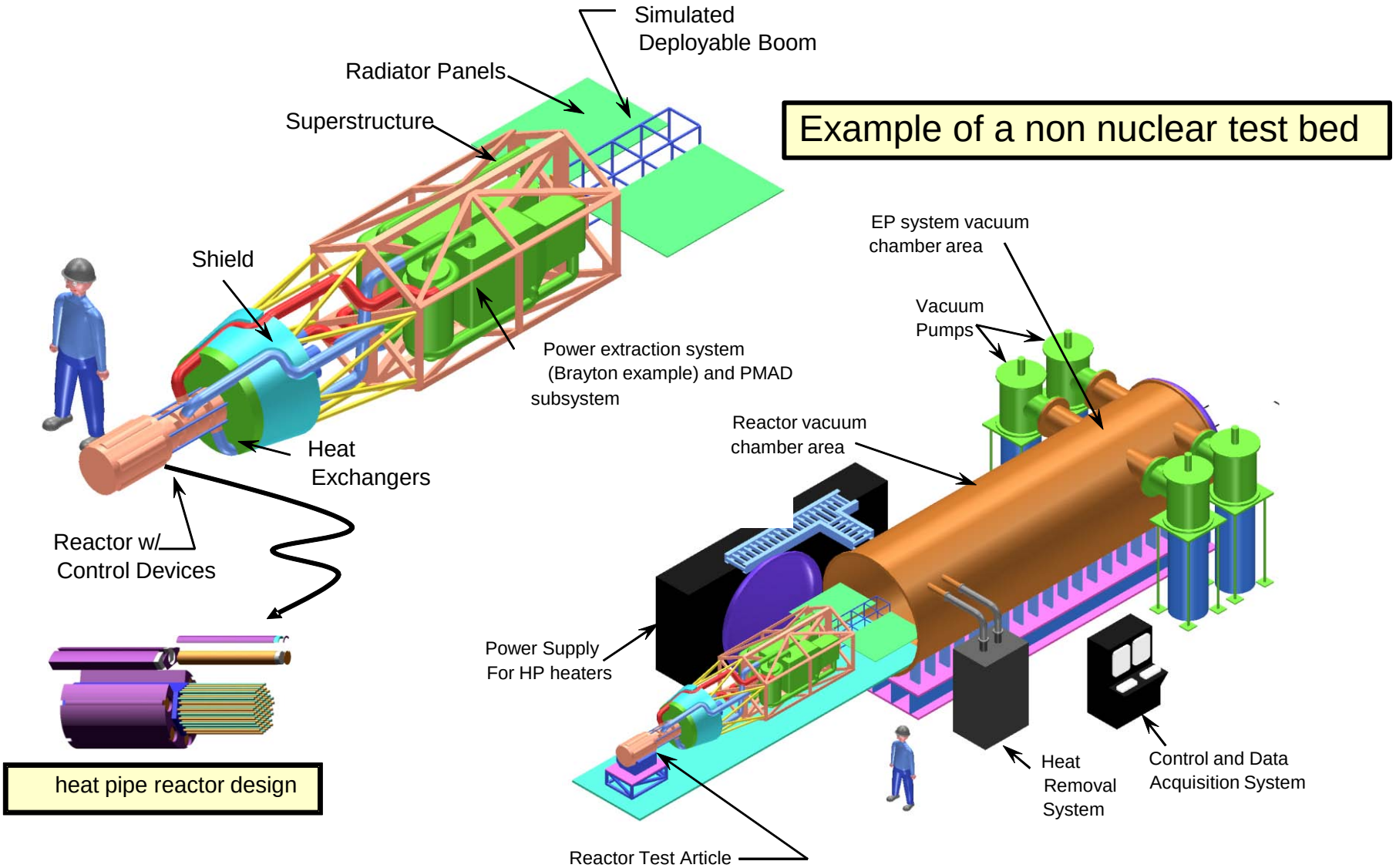
Magneto plasma dynamic thruster



VASIMR thruster

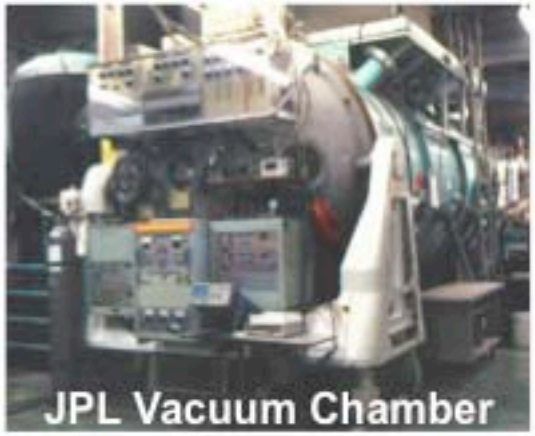
Sources: (Teofilo, 2007, Auweter-Kurtz, 2005, Cassady, 2008)

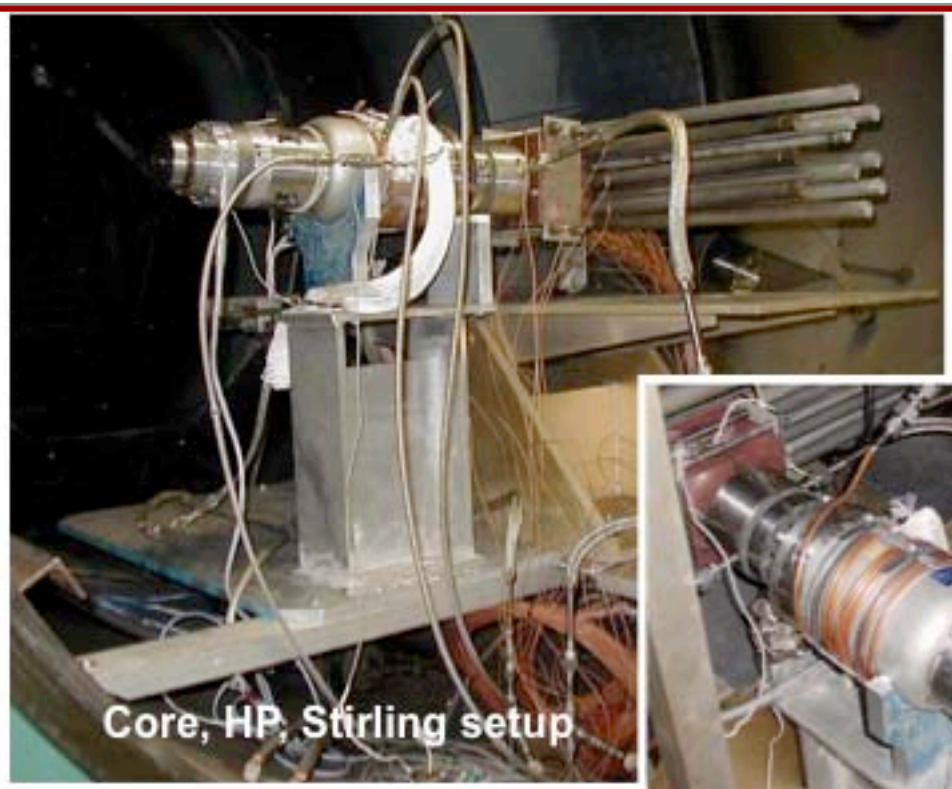
NEP Engineering Design Unit (EDU) Ground Test Concept



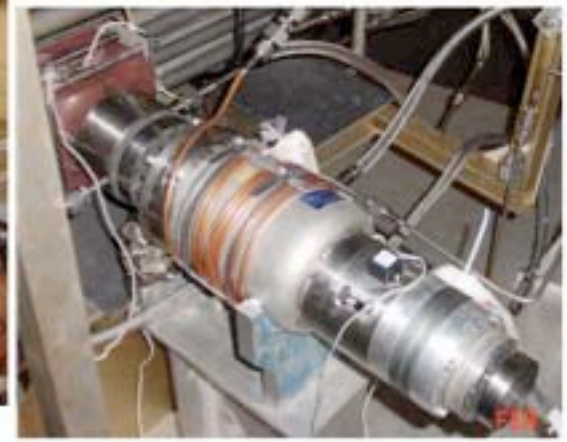
Source: Artwork courtesy of LANL 2004

NASA SAFE-30 NEP Test Program 2003





Core arrangement



HP to Stirling heater head arrangement

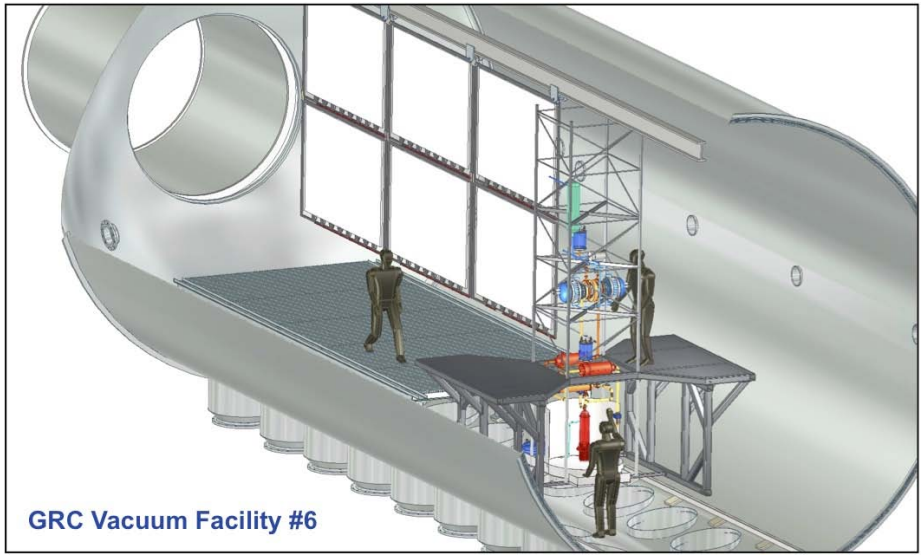
- First pioneering effort for end-to-end testing of a space NEP
- Stainless steel 1020°K reactor using Na heat pipes
- Directly connected to Stirling engine operating at 923°K
- 30 kWt to produce 350 We (1.2%) fed to 17cm NSTAR like ion engine

Ion propulsion engine

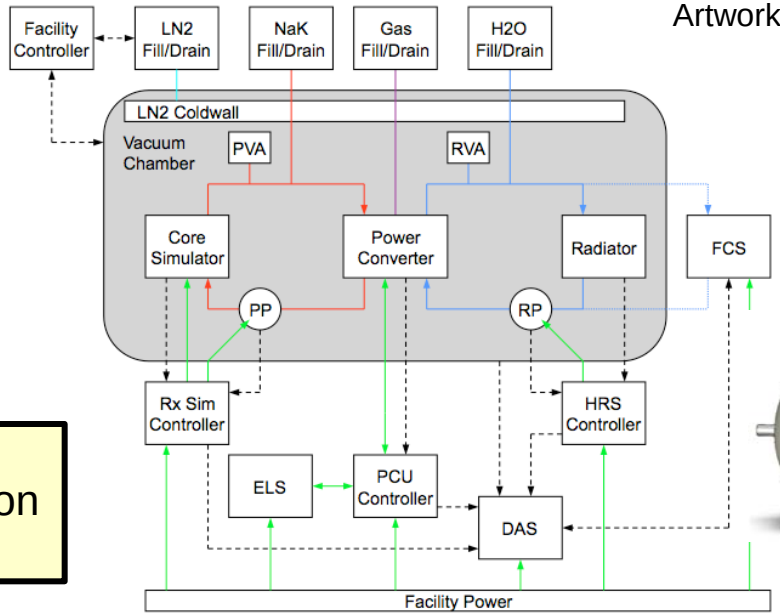
Source: (Hvbud, 2003), Photos courtesy of NASA

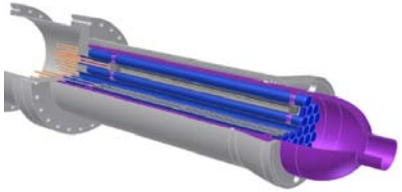
NASA/DoE Fission Power Systems Tech. Demo. Unit

- Current work-in-progress "non nuclear" reactor test program
  - Coalition of GRC, MSFC, LANL, INL, ORNL and SNL
- Details
  - End-to-end system test in thermal (LN_2 cold walls) vacuum (21 x 7.6 m)
  - Power output goal 10 kWe
  - Simulated NaK liquid metal reactor pumped using annular linear induction pump (no moving parts)
  - Free piston Stirling energy extraction
  - Water space radiator
  - PMAD and high fidelity hardware & prototypic controls SW
  - Satisfy requirements for TRL 6

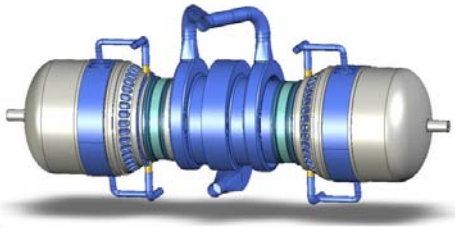


Artwork courtesy of NASA GRC





Core simulator



Dual head Sirling engine

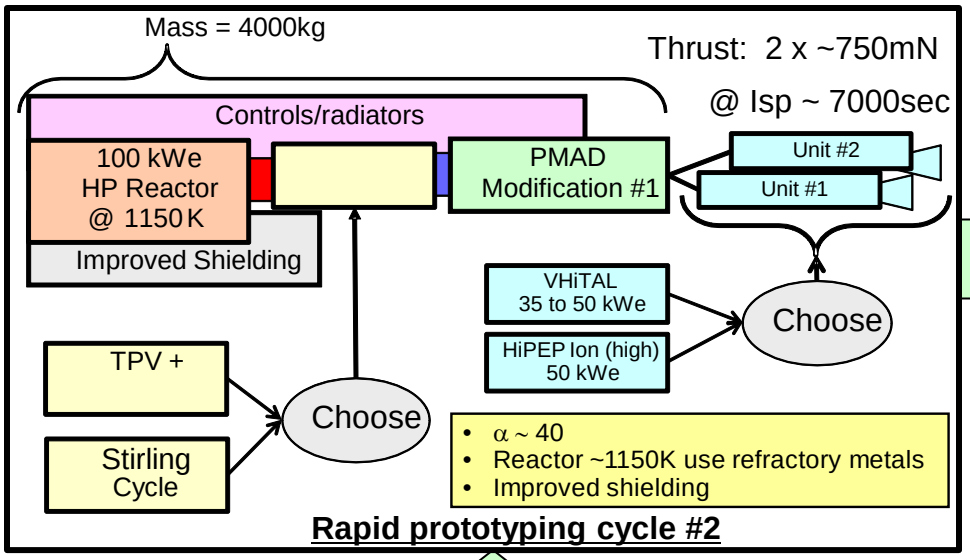
Key challenges: liquid metal heat transport, electric power generation and waste heat removal

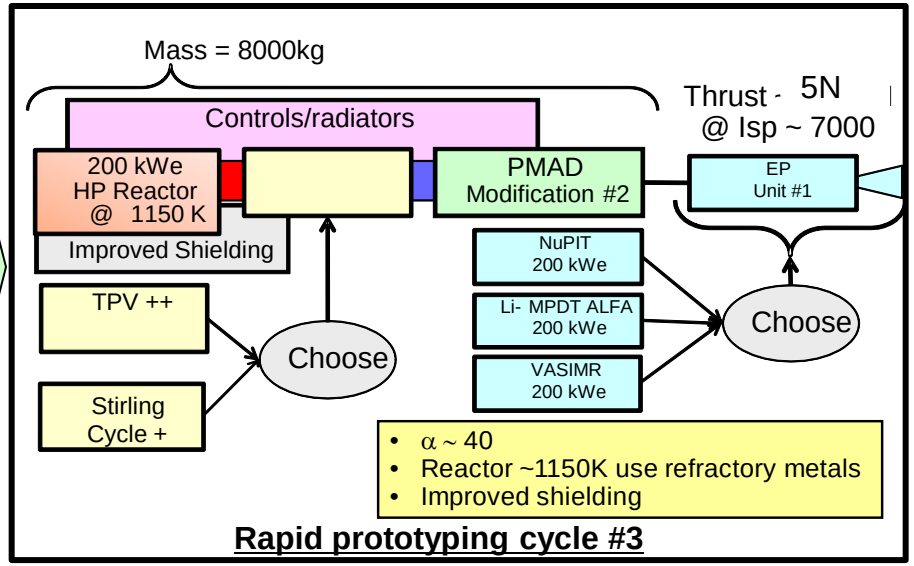
Source: Mason (2011)

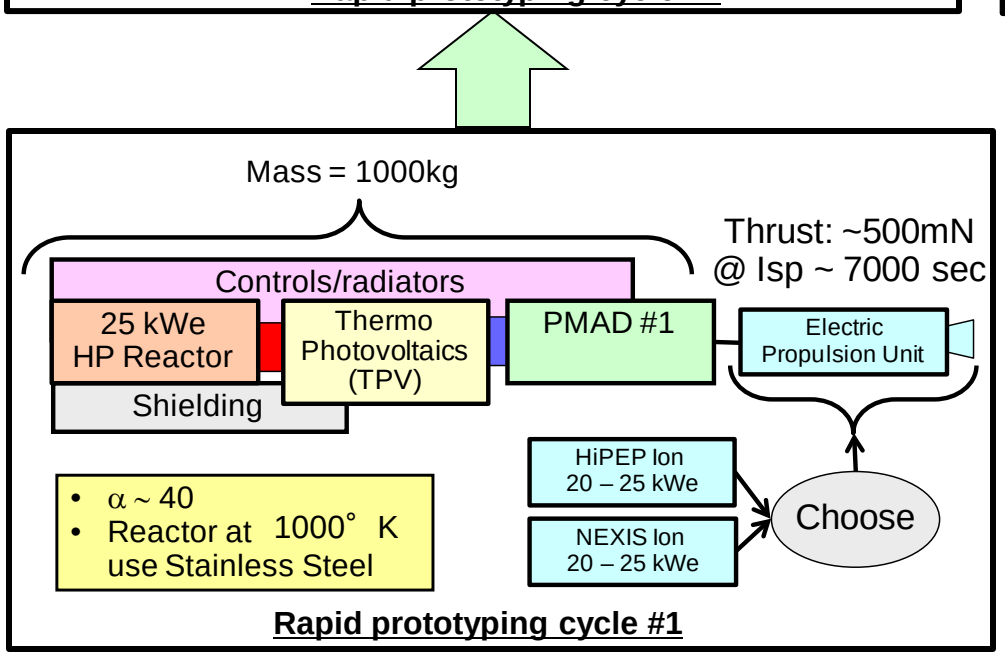
Two Ways to Proceed

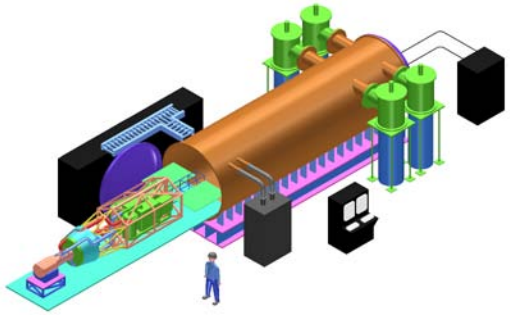
	Approach A: Low Risk (Low to high power)	Approach B: High Risk (Warm to hot temperature)	
α (kg/kWe)	Constant: 40	Decreasing: 40, 35, 30	
Mass (kg)	Increasing 1000 to 8000	Decreasing: 8000 to 6000	
Temperature ° K	Slight increase: 1000 to 1150	Large increase: 1150 to 1400	
Energy Extraction	TPV or Stirling choice for cycles #1 to #3	TPV or Stirling cycle #1 Stirling cycle #2, #3	
Power (kWe)	Increasing: 25, 100, 200	Constant: 200	
Thrust	Increasing: 500mN to 5N	Constant: 5N	
Cost	First cycle: $440M	First cycle: $800M	Total for either ~ $1.2B to $1.3B
Cycle Duration	36/36/36 months	48/36/36 months	
Benefit	High TRL cycle #1 for earliest low cost flight demo	Most thrust after cycle #1, mass optimized system after cycle #3	

Approach A: NEP Rapid Prototyping Cycles



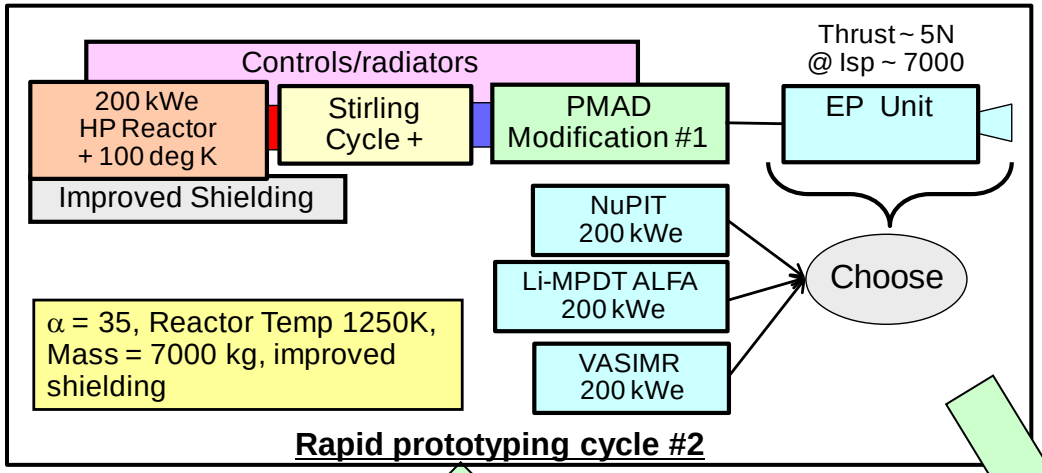






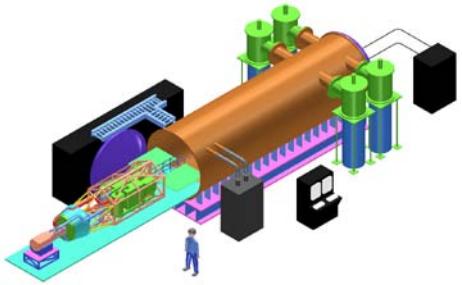
- Constant: α & Isp, increasing: thrust, reactor power, mass and temperature
- Low mass allows for early flight demo after RP cycle #1
- High heat pipe reactor TRL at 1150K

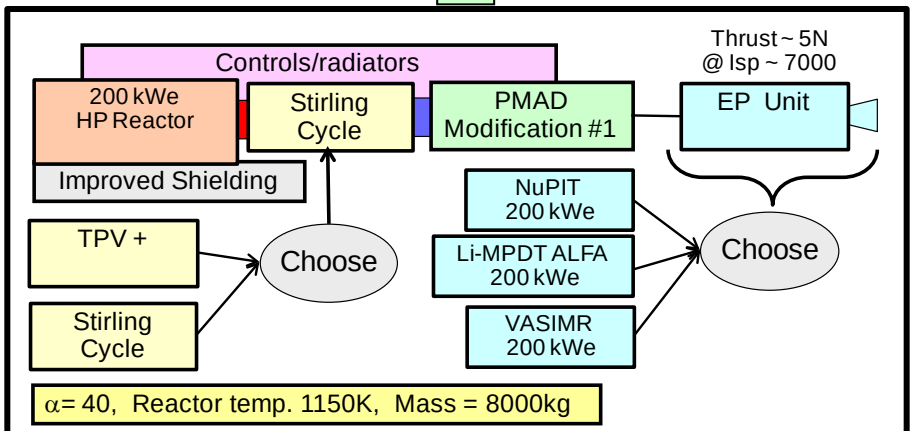
Approach B: NEP Rapid Prototyping Cycles



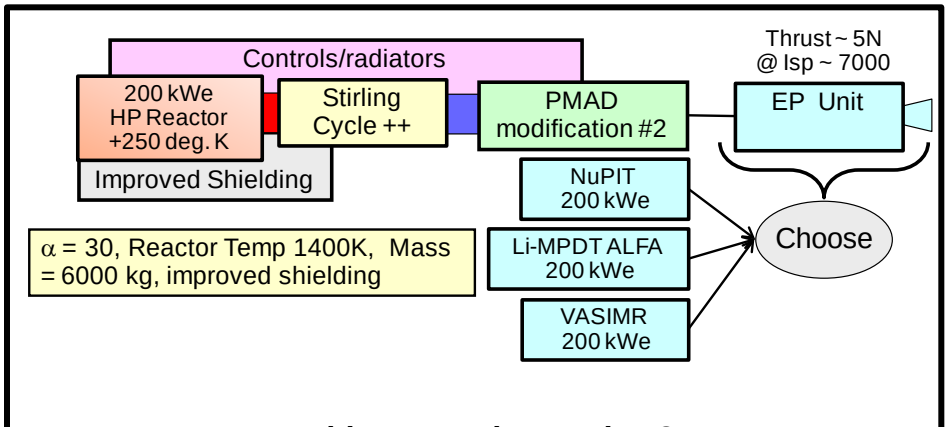
Rapid prototyping cycle #2

- Constant: power, thrust & Isp, decreasing: α with increasing reactor operating temperature
- Max NEP performance system after cycle #1
- Highest performance NEP after cycle #3



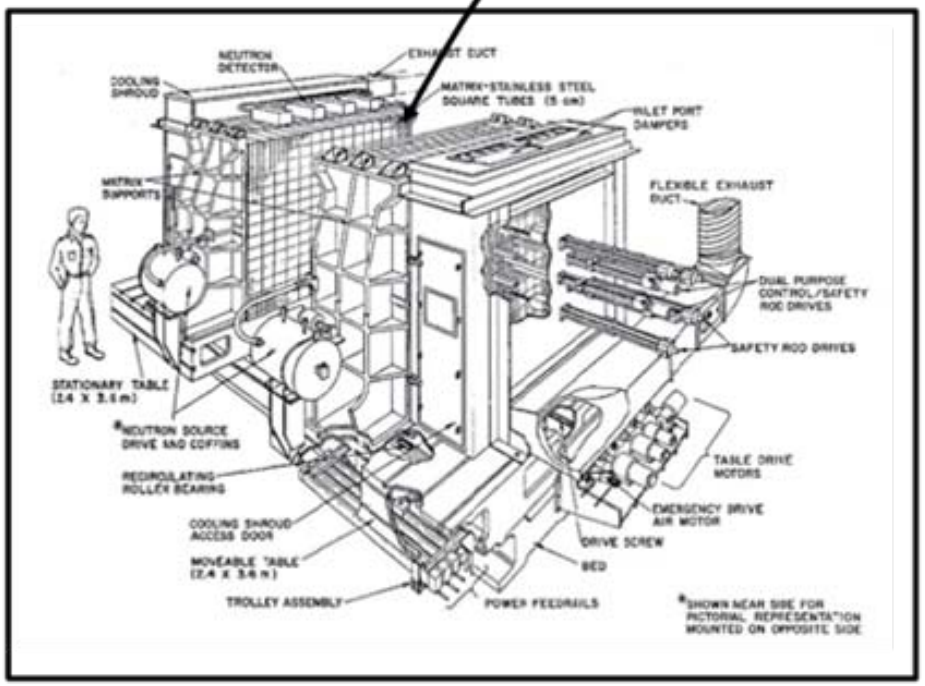


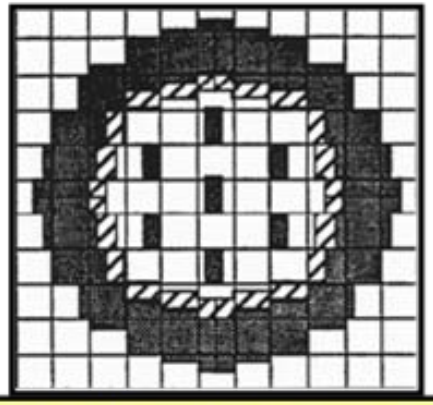
Rapid prototyping cycle #1



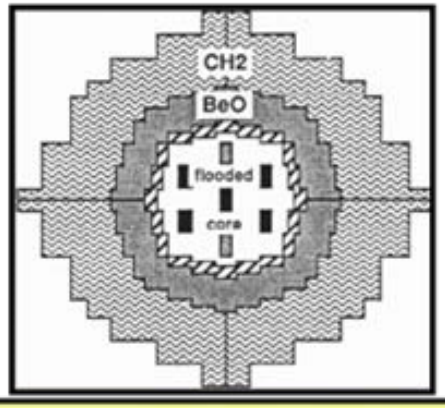
Rapid prototyping cycle #3

Zero-Power Physics Reactor





SP-100 Phase B configuration
BE reflectors fully closed



SP-100 Phase C configuration
Simulated flooding due to launch failure and ocean impact, CH_2 used as simulated water

Summary

- For space dominance, space power ~ 200 kWe and above
- Solar power is not practical much above 100 kWe
- Russians are getting back into space nuclear reactors business should there be a concern?
- Are rapid prototyping/development/spiral approaches the way to accelerate this technology
  - Keep stakeholders support?
  - Minimize negative political pressures?
  - Manage the cost and schedule?
- NEP engines are expensive, worth the cost?
- Do we have the infrastructure and talent to build NEPs?

Academic Considerations

- Graduate engineering students
  - Space vehicle design
  - Nuclear reactor design
  - Electric propulsion design
  - Thermal analyses
  - Power analyses
  - Radiation / shielding design
  - Core physics
  - Orbit mechanics
- AFIT has an interest in developing graduate course(s)
- Potential interest from other universities
  - Maintain some interest in problem
  - Challenging engineering problem for students

Develop talent in case future need and funding exists

Acknowledgements

Mr. Phil Springmann (Orbit perturbation analysis)
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4100 North Fairfax Ave,
Arlington, VA

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Previous work in 2003 and 2004
Dr. Janet Sater (Materials and shielding)
Dr. Mike Rigdon (Materials, shielding and nuclear technology)

Dr. Robert P. Hoyt (Electro-dynamic and electrostatic tethers)
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Bothell WA, 98011-8804
http://www.tethers.com

Professor William Saylor (Nuclear materials and technologies)
USAFA
Colorado Springs, CO

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Reenergizing US Space Nuclear Power

Center for Space Nuclear Power Seminar
September 2011
Backup

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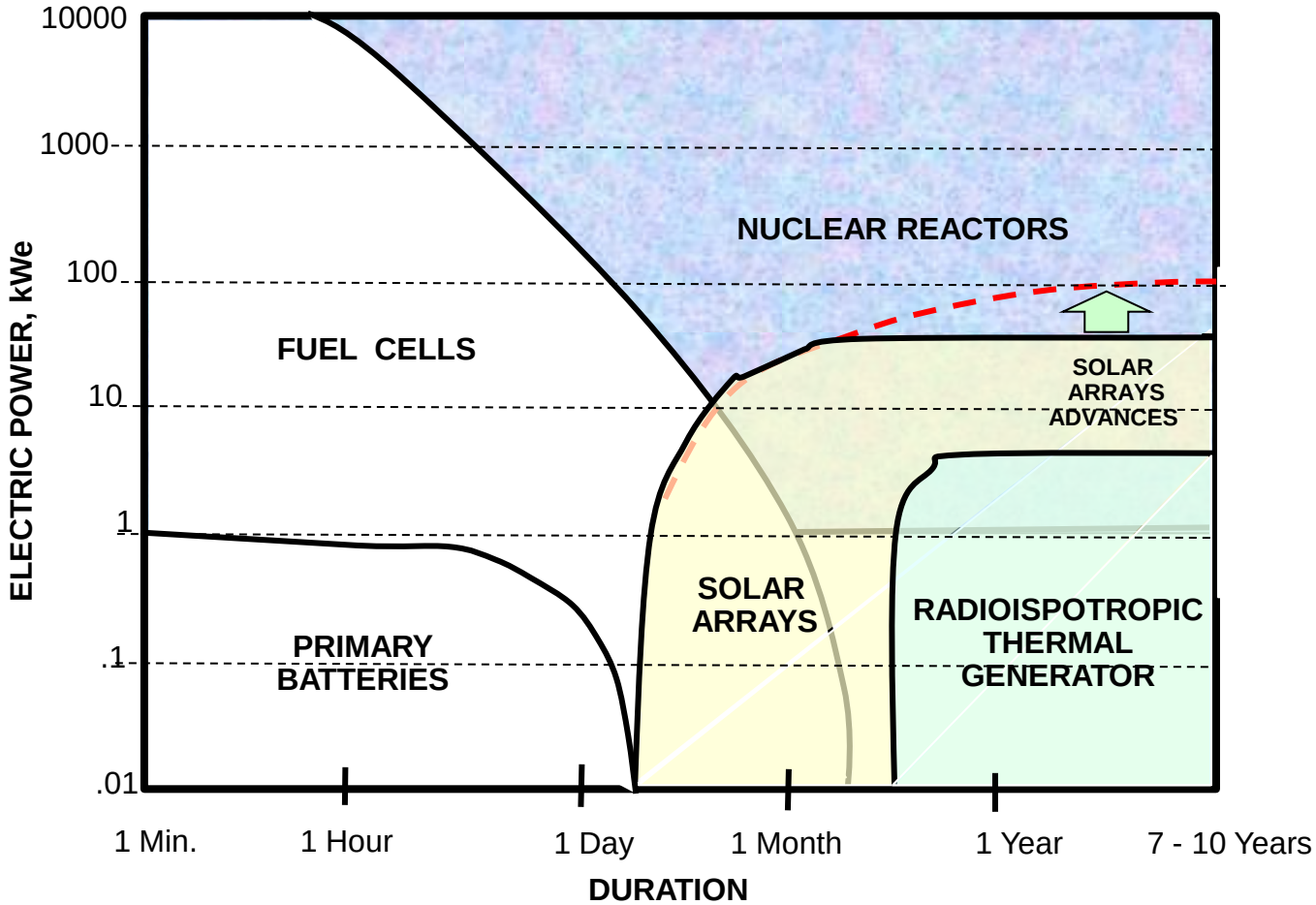
Backup

Space Power Choices

- Advances in non-nuclear space power technologies have improved
- ***<u>Nevertheless, this chart is inadequate by itself to sell investors on space reactor nuclear power</u>***



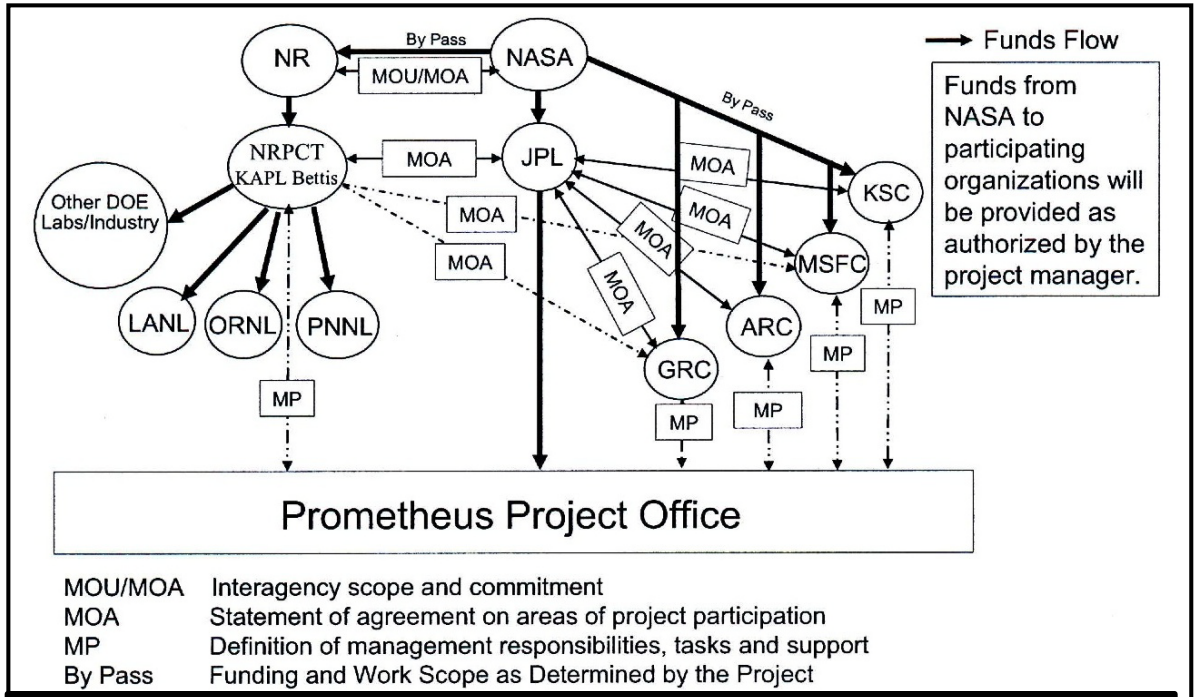
- Space mission's ROI to commercial investors or solves a DoD need that no other technology can do is more likely to aid in obtaining the funding to transition this power technology into space operations

SOSI Degradation

- SOSI at GEO is primarily optical, weather constrained with optical narrow field of view
  - Example:
    - 5N thrust for one day for 10,000 kg vehicle changes GEO orbit by 1159 km and early/delay of arrival time by 1770 seconds
    - The distance traveled along track (circumference): 5,442 km/day or 7.4 deg/day
    - 49 days to travel around the GEO belt
    - Could also reposition in the 3 degree dead belt after 24 days (Estimated 0.128 deg/day inclination change)
- 5N thrust activated at the right time (correlated with weather patterns) for a few days would degrade most SOSI systems
- SOSI at LEO is primarily radar with some optical and SIGINT support
  - Typical systems use “predictive techniques”, spot checking objects as they enter and reenter certain sectors
  - Do not track continuously
- 5N thrust activated at the right time can degrade this SOSI approach
- 1150 kg of Xenon provides about 183 days of fuel, given EPs with Isp of 7000 seconds

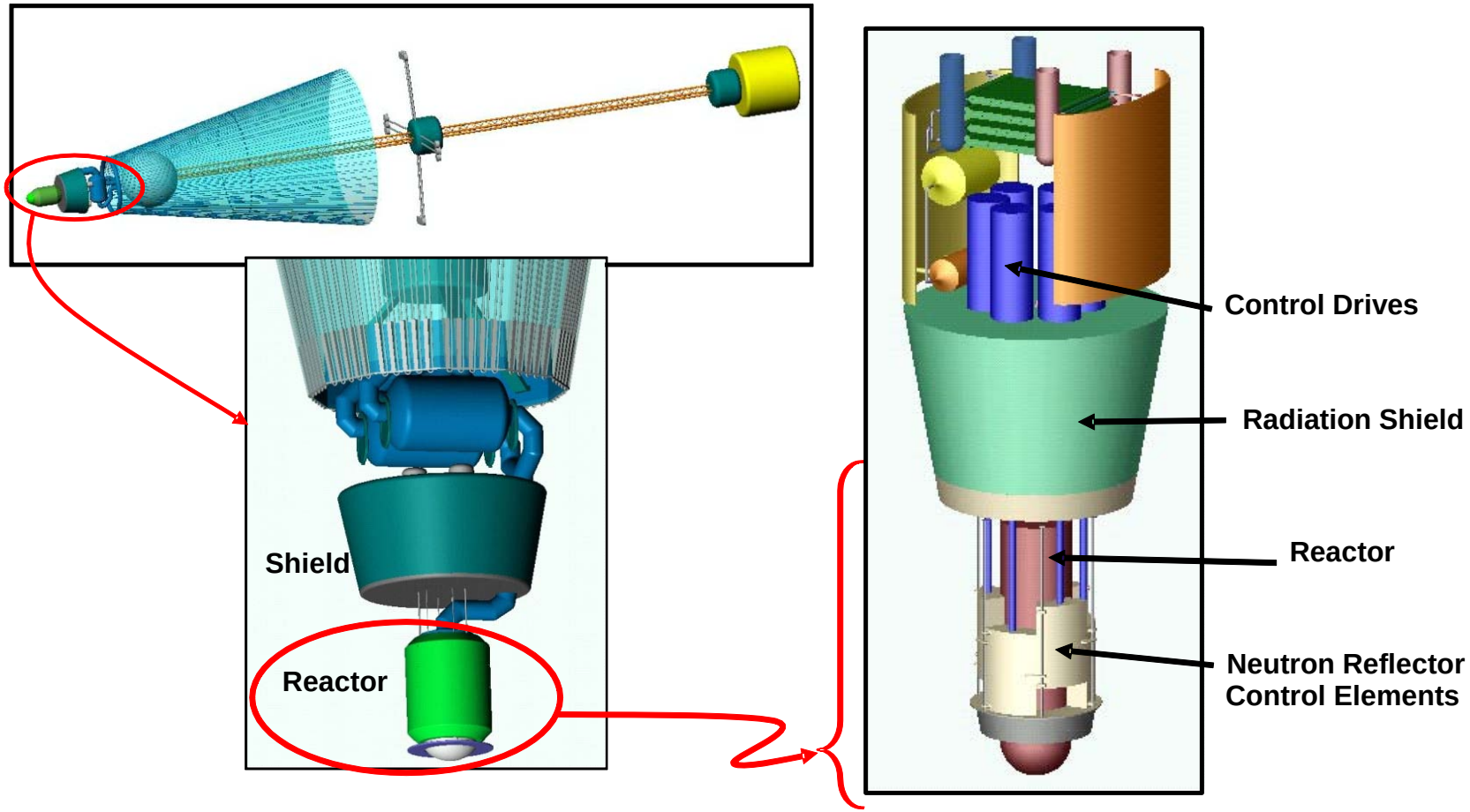
Prometheus - Program Management Challenges/Decisions

- Worried about skills in key areas
- Quickly built a very large team
  - Impact: team may have grown to quickly adding complexity and delay in critical decision making
  - Not conducive to creating a cost effective, agile and efficient organization
- Naval Reactors labs was to produce the reactor, never built a space nuclear reactor
- Early coupling of JIMO mission design requirements to NEP, unvested in mission unique technologies
  - Impact: lack of funds to develop an end-to-end NEP demo using off-the-shelf components
  - Demo may have been enough to make the case to stakeholders that the program had reached a level of momentum worth continuing.
- To be launched in 2015, 12 years from Phase A study
  - Impact: May have been excessive given today's turbulent budgetary environment (key administration and congressional stakeholders would of most certainly changed over that period).



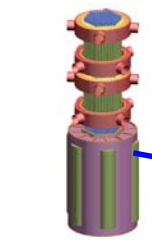
- JPL, NASA HQ, DoE NE, four DoE Naval Reactors labs, eight NASA centers, NGST, six DoE labs, 31 universities and 14 subcontractors

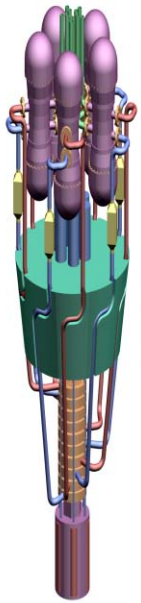
Space Nuclear Reactor Details



Sources: Artwork courtesy of LANL 2004

Approach A: Cycle #3 Details





Mass ~ 8000kg

Controls/radiators

200 kWe
HP Reactor

Improved Shielding

PMAD
Modification #2

Thrust ~ 3 to 5N
@ Isp ~ 7000

EP
Unit #1

TPV ++

Stirling
Cycle +

Choose

NuPIT
200 kWe

Li-MPDTALFA
200 kWe

VASIMR
200 kWe

Choose

Magneto-plasma dynamic

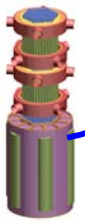
Pulse Inductive Thruster

VASIMR

- $\alpha \sim 40$
- Reactor ~1150K use refractory metals
- Improved shielding

Sources: : (Cassady, 2008 and Teofilo, 2007) Artwork courtesy of LANL 2005, Photos courtesy of NASA

Approach B: NEP Rapid Prototyping Cycle # 3 Details



Controls/radiators

200 kWe
HP Reactor
+ 250 ° K

Improved Shielding

Stirling
Cycle ++

PMAD
modification #2

Thrust ~ 5N
@ Isp ~ 7000

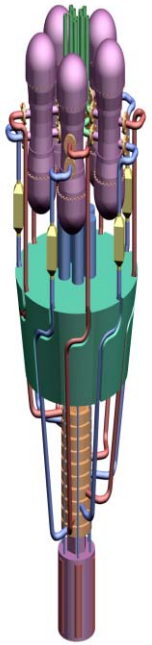
EP Unit

NuPIT
200 kWe

Li-MPDT ALFA
200 kWe

VASIMR
200 kWe

Choose



Magneto-plasma dynamic

Pulse Inductive Thruster

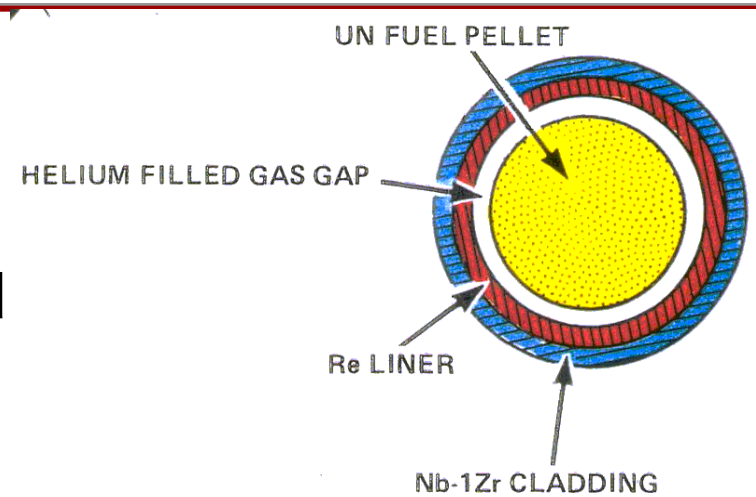
VASIMR

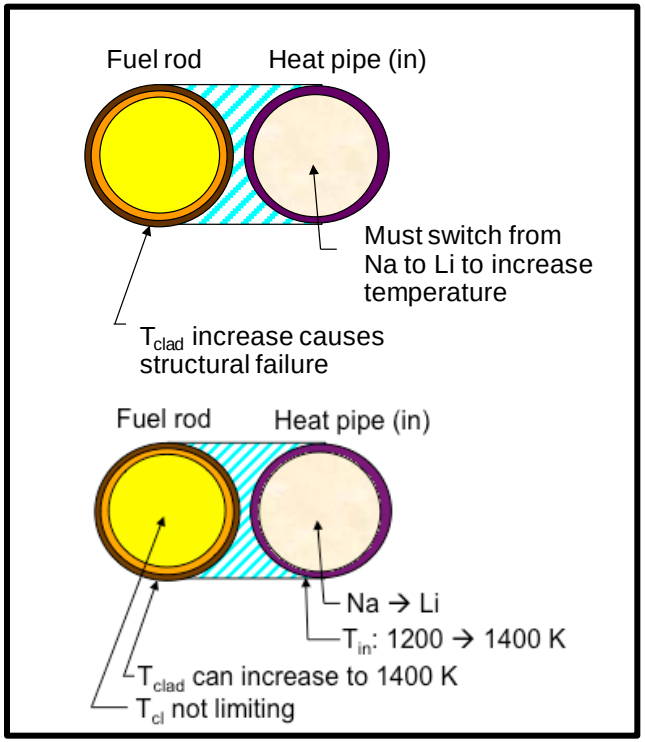
α = 30, Reactor Temp 1400° K, Mass = 6000 kg, improved shielding

Sources: Artwork courtesy of LANL 2005, Photos courtesy of NASA

Challenges in Raising Reactor Temperature

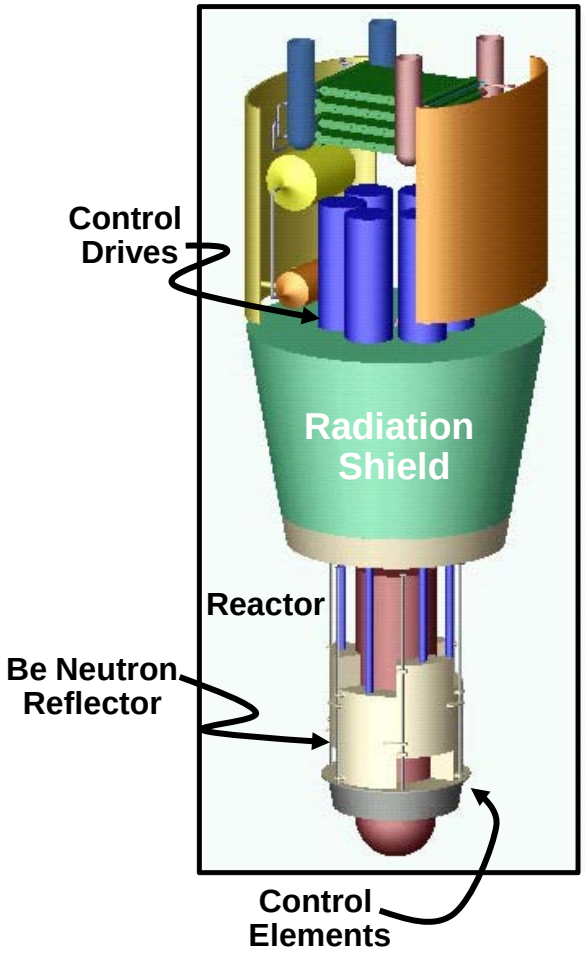
- Higher operating temperatures
  - Improved heat transfer – less radiator area/mass
- Traditional heat pipe nuclear fuel rod design uses UN fuel a Re liner and Nb1Zr cladding.
  - Nb1Zr cladding exhibits creep at these higher temperatures
  - New refractory metal alloys need to be investigated
- Elevated temperatures accelerated corrosion and lithium heat pipe failure due to contaminates
  - Improve manufacturing and NDI technology of Lithium heat pipe for less than 10 ppm of contaminates





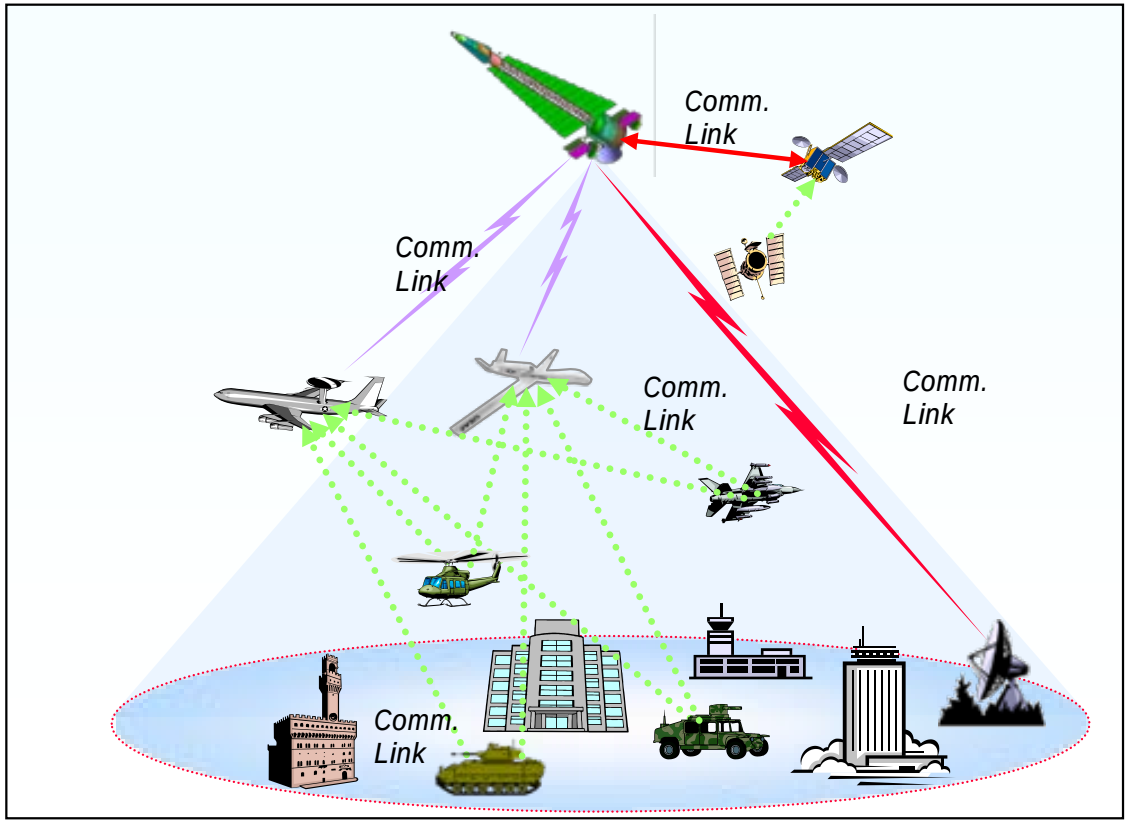
Challenges in Raising Reactor Temperature (cont.)

- LiH: primary radiation shield
  - Exhibit as much as ~25% swelling when irradiated < 600° K
  - Start dehydrogenation when above 800° K.
  - Need to investigate new materials
- Be and BeO radial reflectors are known not to perform that well in a high-flux neutron environment.
  - Be should be <~823° K to minimize void swelling
  - BeO should be > ~600° K to minimize microcracking
  - Need to investigate other advanced materials



GEO Communication Possibilities

RF capability - space to ground		
Power (kWe)	Number of transponders (36 MHz equil. @ 230 watts each capable of 90 Mbps)	
40	174	15.6 Gbps
Laser Comm - space to space		
5	50 Mbps/watt	250 Gbps
Cryo electronic processing		
50	1000 to 1 cooling for 50 watts of 10 to 65° K electronics	On board latency free ATM switching and processing
Spacecraft		
105	Bus, propulsion, protection and reserve	

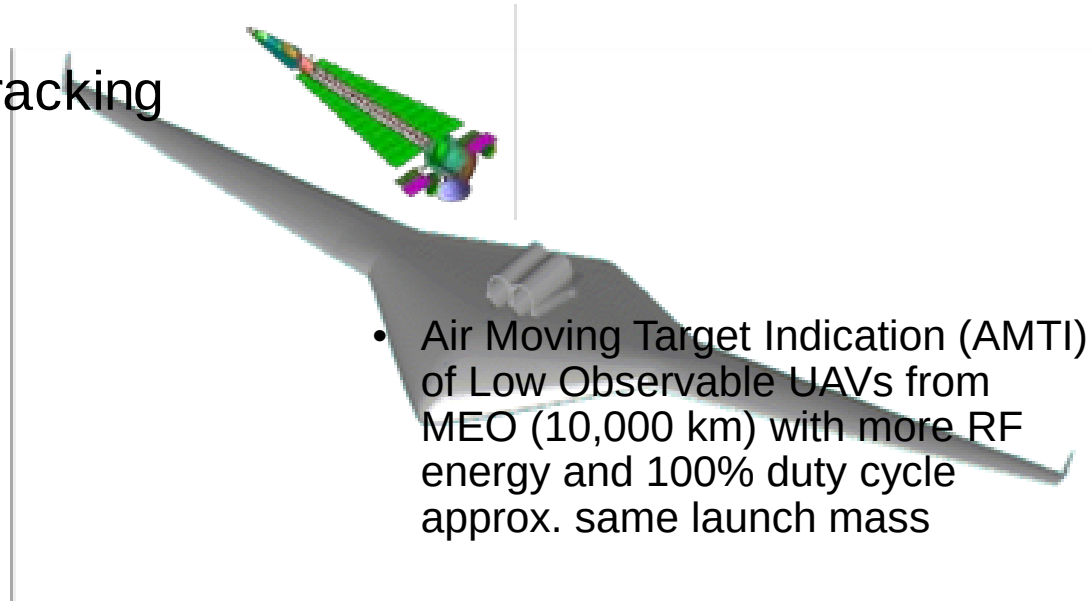


- World 2015 demand is 7150 transponders (36 Mhz equivalent at 90 Mbps) @ ~ 230 watts each requires ~ 1,644 kWe
- Nine nuclear reactor spacecraft versus hundreds of satellites from a power point of view

Source: (Obal, 2004)

Tracking Low Observable UAVs/Cruise Missile from 10,000 km

Trip-Wire/Tracking



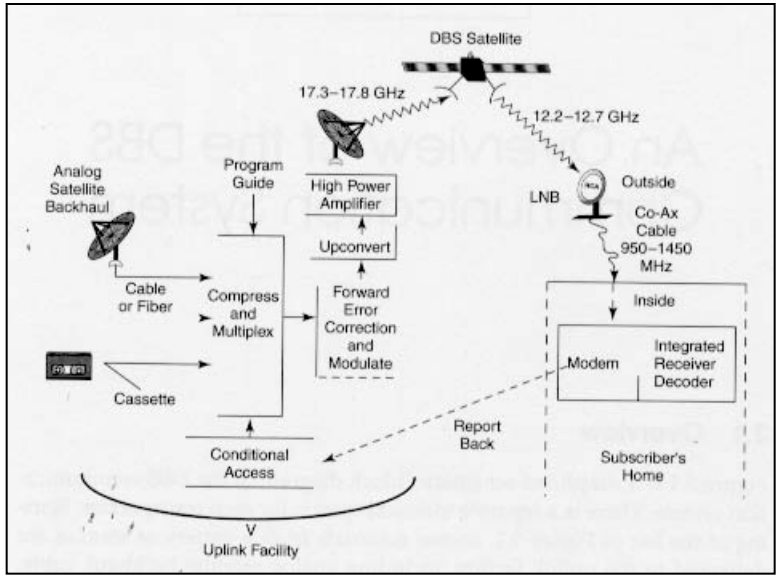
- Air Moving Target Indication (AMTI) of Low Observable UAVs from MEO (10,000 km) with more RF energy and 100% duty cycle approx. same launch mass

- Solar power of 25 kWe RF (- 5 dBsm) to Nuclear 100 kWe RF (-11 dBsm) an improvement of -16 dBsm is possible

40x increase in available EOL RF power and 100% duty cycle over 2015 PV/battery technology

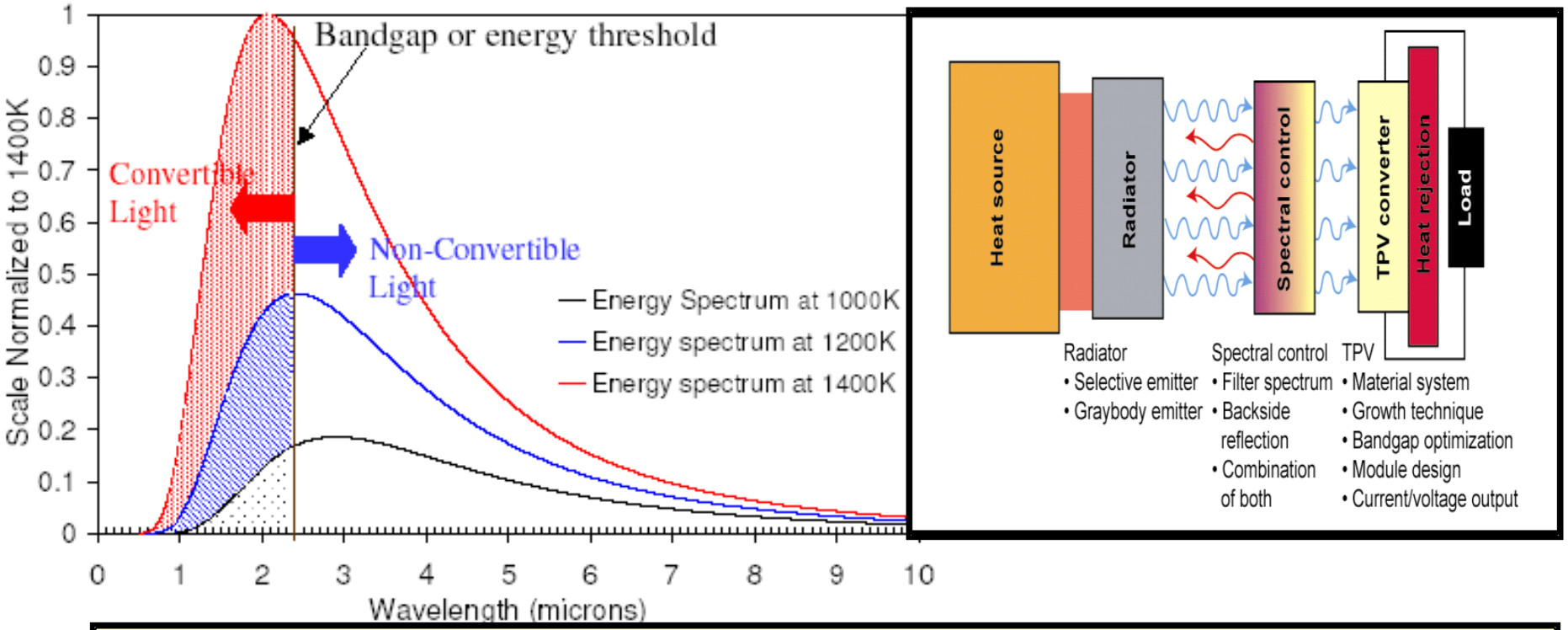
Example: Direct Broadcast Satellite (DBS-1) Communications DIRECTV - 1993 Technology

- Bent Pipe Satellite
  - Receives, transponds the signal and retransmits it
    - Uplink 17.3 - 17.8 GHz, Downlink 12.2 - 12.7 GHz
      - 500 MHz provides for 16 transponders @ 24 MHz analog BW and 5 MHz spacing
  - Using Quatenary Phase Shift Keying (QPSK) results in 2 bits/symbol
  - A 24 MHz signal can push 20 mega-symbols per sec
    - Therefore, one transponder transmits 40 Mbps
  - Using a knock down factor of 0.589 (low power case) gives:
    - ***16 x 40 x 0.589 = 377.28 Mbps***
    - ***Power: 16 x 120 watts = 1.9 Kw***



Band	Frequency GHz
L	1 - 2
S	2 - 4
C	4 - 8
X	8 - 12
K_u	12 - 18
K_a	18 - 30

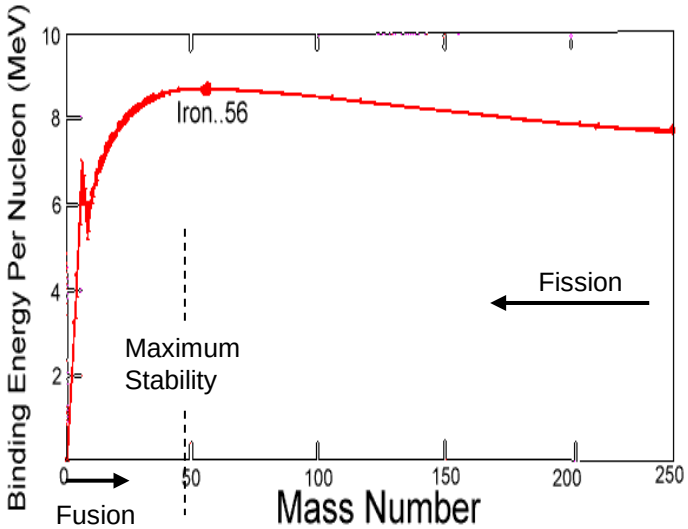
Thermal Photovoltaic (TPV) Power Extraction

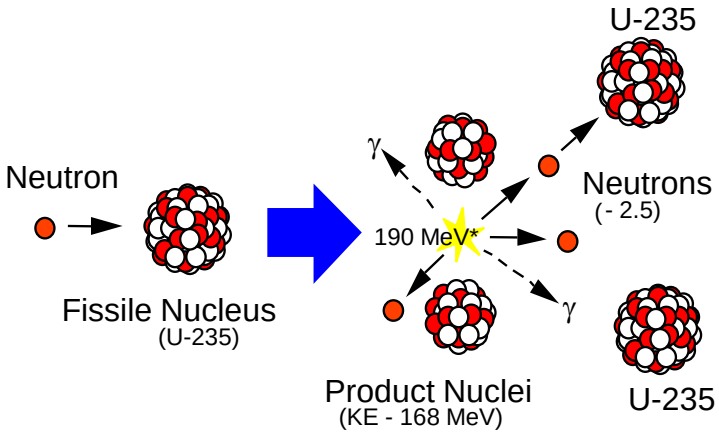


The key feature of TPV is that there are no moving parts proving inherent reliability and simplicity. However serious limitations include; conversion efficiency at elevated operating temperatures and large scale manufacturing. The quantum dot architecture shows promise in resolving many of the TPV issues of operating at high temperatures.

Source: (Teofilo, 2007)

Nuclear Fission Process





- Neutron absorbed by heavy nucleus, which splits to form products with higher binding energy per nucleon
- Difference between initial and final masses = prompt energy released (190 MeV).
  - *Fissile* isotopes (U-233, U-235 and Pu-239) fission at any neutron energy
  - Other actinides (U-238) fission at only high neutron energies
- Fission fragment kinetic energy (168 MeV), instantaneous gamma energy (7 MeV), fission neutron kinetic energy (5 MeV), Beta particles from fission products (7 MeV), Gamma rays from fission products (6 MeV), Gamma rays from neutron capture (~7 MeV).
- For steady power production, 1 of the 2 to 3 neutrons from each reaction must cause a subsequent fission in a *chain reaction* process.

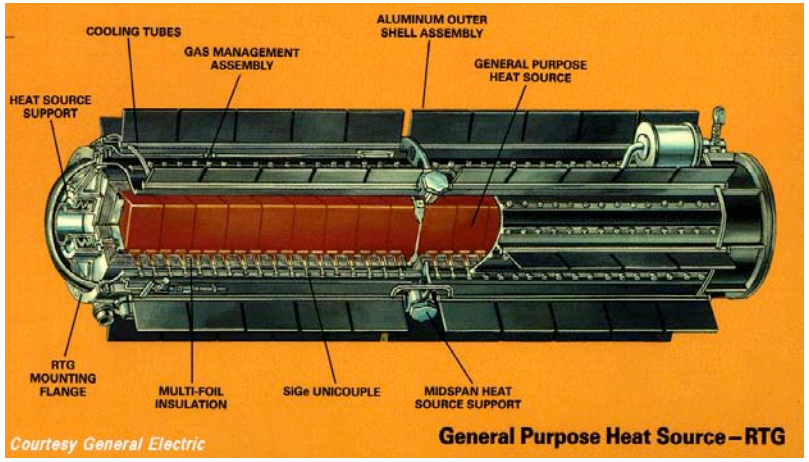
- 180 MeV prompt useful energy (plus 10 MeV neutrinos)
- Additional energy released in form of fission product
  - Beta particles
  - Gamma rays
  - Neutron capture gammas
- ~200 MeV total useful energy

Radioisotope Thermoelectric Generator (RTG)

# of Launches	# of RTG's	Power Level/Unit W_e	Mission	Time Period
5	5	2.7 (1), 25 (2) 30 (1)	TRANSIT (Navigation)	1961-4, 72
1	2	40	NIMBUS (Meteorology)	1969
6	6	70	APOLLO (Lunar Exploration) [Apollo-11 Heat Source only]	1969-72
2	8	40	PIONEER-10,11 (Interplanetary)	1972-3
2	4	40	VIKING-1,2 (Mars)	1975
2	4	150	LES (Communication)	1976
2	6	150	VOYAGER-1,2 (Interplanetary)	1977
1	2	275	GALILEO (Jupiter)	1989
1	1	275	ULYSSES (Sun)	1990
22	38	3,360 (Tot)	Total	1961-90
Mission Failures With RTG's				
1	1	25	TRANSIT (Satellite Failed to Achieve Orbit)	1964
1	2	40	NIMBUS (Vehicle Destroyed During Launch)	1968
1	1	70	APOLLO-13 (Mission Aborted Enroute to Moon)	1970

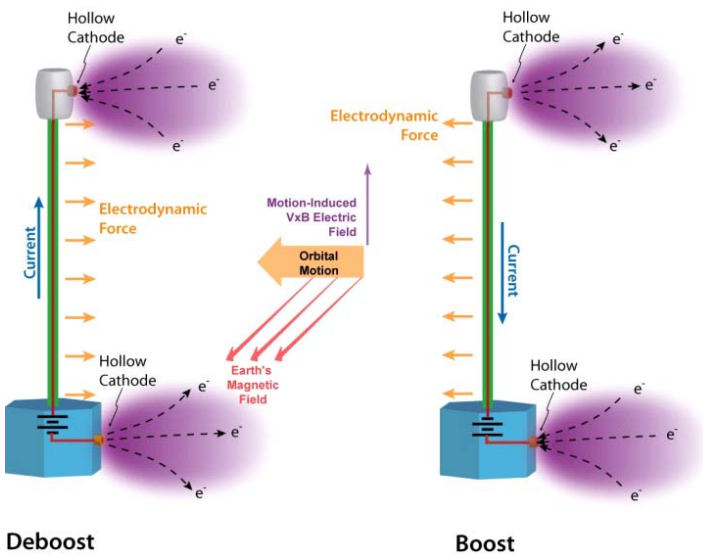
After G. L. Bennett (1995), p. 515 in CRC Handbook of Thermoelectrics, ed. D. M. Rowe, CRC Press

- 38 RTGs in space by 1990
- SC problems resulted in mission failures not RTGs
- RTGs flown by the U.S. used Plutonium-238 as the radioisotope to provide the thermal power in the heat source

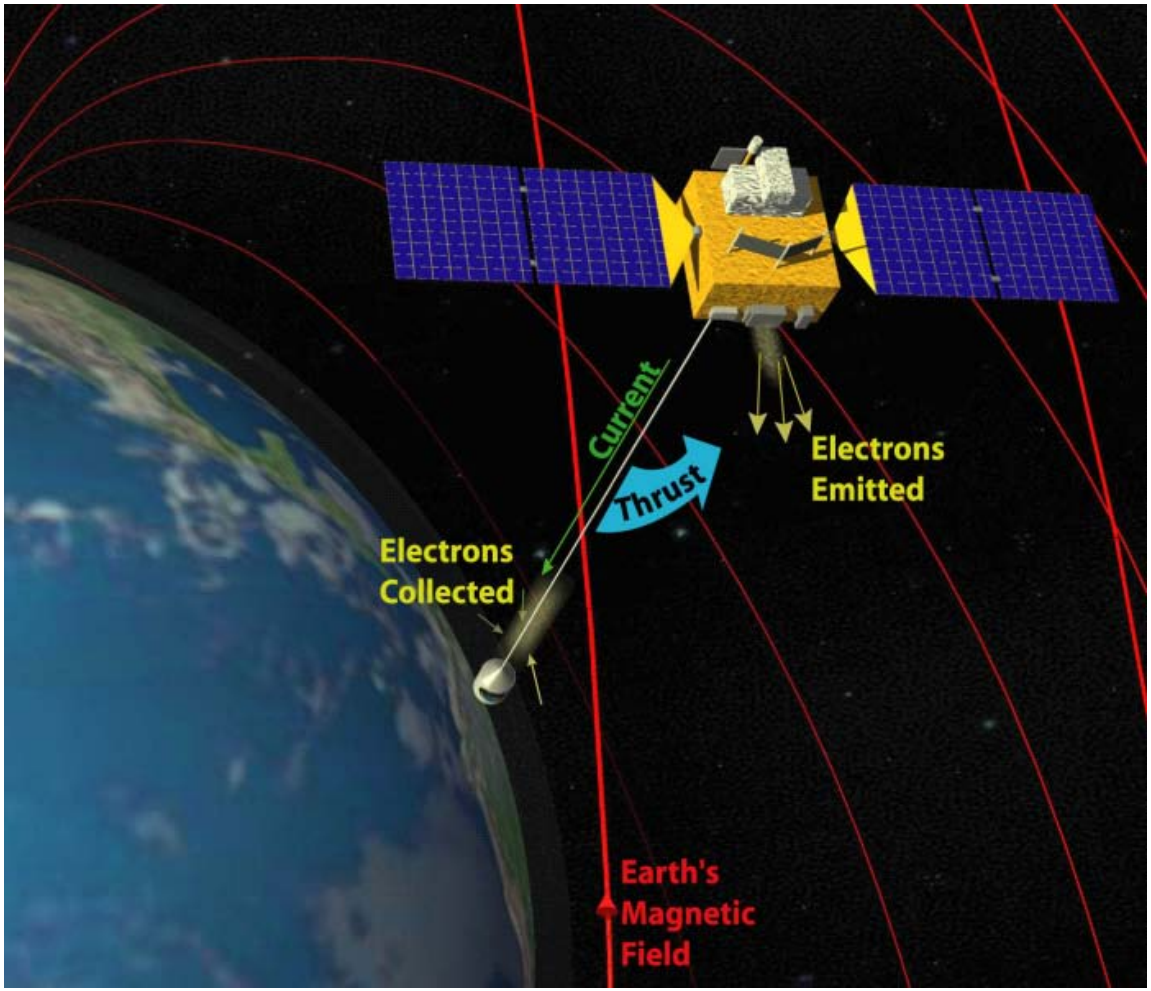


- Plutonium-238 satisfies the various safety and operational criteria.
  - Plutonium-238 decays primarily by emitting alpha particles, which are completely absorbed in the heat source to produce the heat; hence, no special radiation shielding for these alpha particles is required
- Radioisotope has an appropriately half-life of about 87.8 years
  - Power density that reduces the number of curies per gram while still permitting reasonable sizes for the heat source and long operational lifetimes

Electro-Dynamic (ED) Tether Propulsion



Two Hollow Cathode Plasma Contactor (HCPC) and bare wire system



Sources: (Hoyt, 2008)

Comparison Of Solar And Nuclear Power

	25 kWe (100 kWt)			100 kWe (400 kWt)			200 kWe (800 kWt)			
	Solar		Nuclear	Solar		Nuclear	Solar		Nuclear	
	Today	Future		Today	Future		Today	Future		
Mass (kg)	1955	815	1000	7819	3261	4000	15638	6521	8000	6000
Operating Temp. (K)	NA	NA	1000	NA	NA	1150	NA	NA	1150	1400
Solar or radiator size (m^2)	211	108	~81	844	434	~132	1688	868	~265	~128
α kg/kWe	78	33	40	78	33	40	78	33	40	32

Nuclear power systems become more practical above 100 kWe at 100% duty cycle, even with advances in solar power technology, primarily due to radiator versus solar array size

Superior value

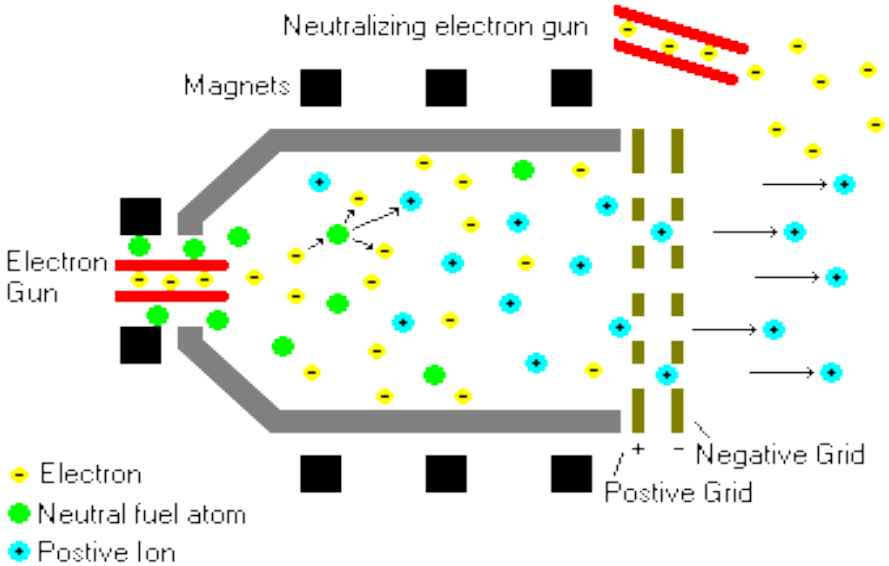
Example: Spiral Model Iteration Features

- Each phase starts with a design goal and ends with a stakeholders progress review
- Analysis and engineering efforts are the applied in the next phase, focused on the end goal of the project.
- Details
  - The system requirements are defined in as much detail as possible, usually involves interactions with stakeholders
  - The first prototype is created from the preliminary design of the system
    - All possible (and available) alternatives are analyzed and strategies to use them are decided
    - Identify and resolve all the possible development risks
    - When risks indicate uncertainty in requirements, prototyping is used to find out possible solutions in order to deal with requirements changes
  - First prototype is usually an approximation of the final product.
- The next prototype is evolved by
  - Evaluating the previous prototype in terms of its strengths, weaknesses, and risks
  - Define the requirements then plan, design, build and test next prototype

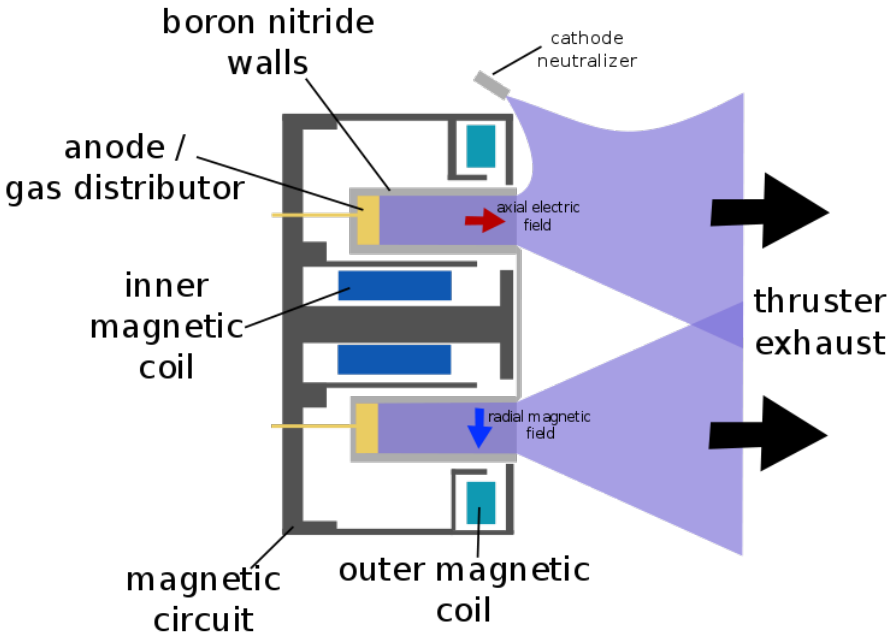
Ref: Boehm, Barry, 1986 "A Spiral Model of Software Development and Enhancement"

Electric Propulsion

- Electro-static Ion thrusters



Gridded Ion Thruster

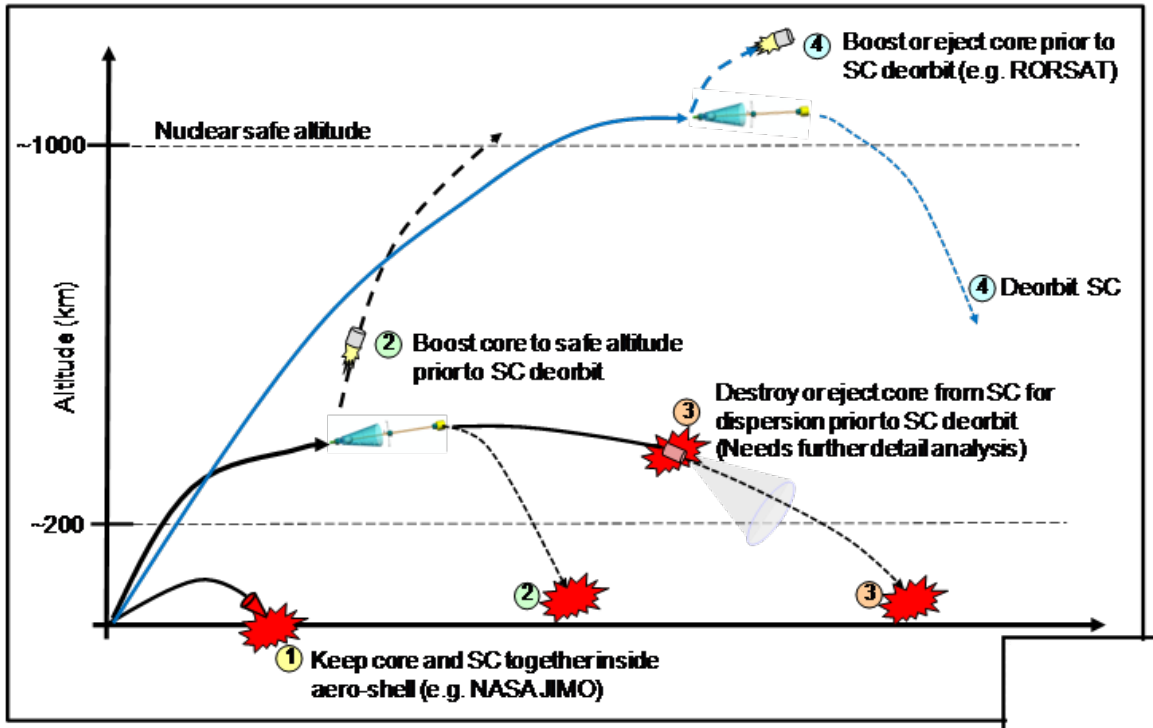


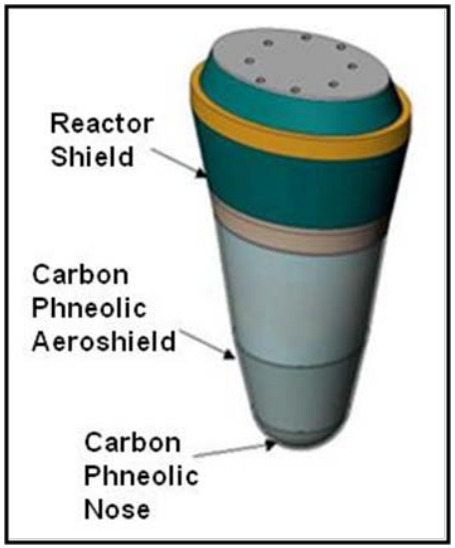
Hall Effect Thruster

More thrust then Gridded Ion

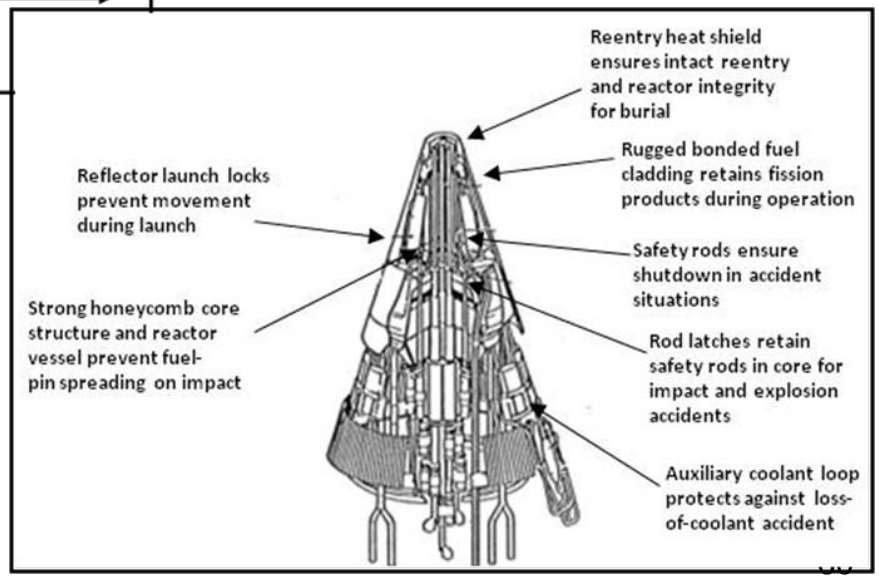
Drawings courtesy of Wikipedia

Safe Reactor Core Placement Strategies





NASA Prometheus/(JIMO) Reentry Shield Design



SP-100 Reentry Safety Design