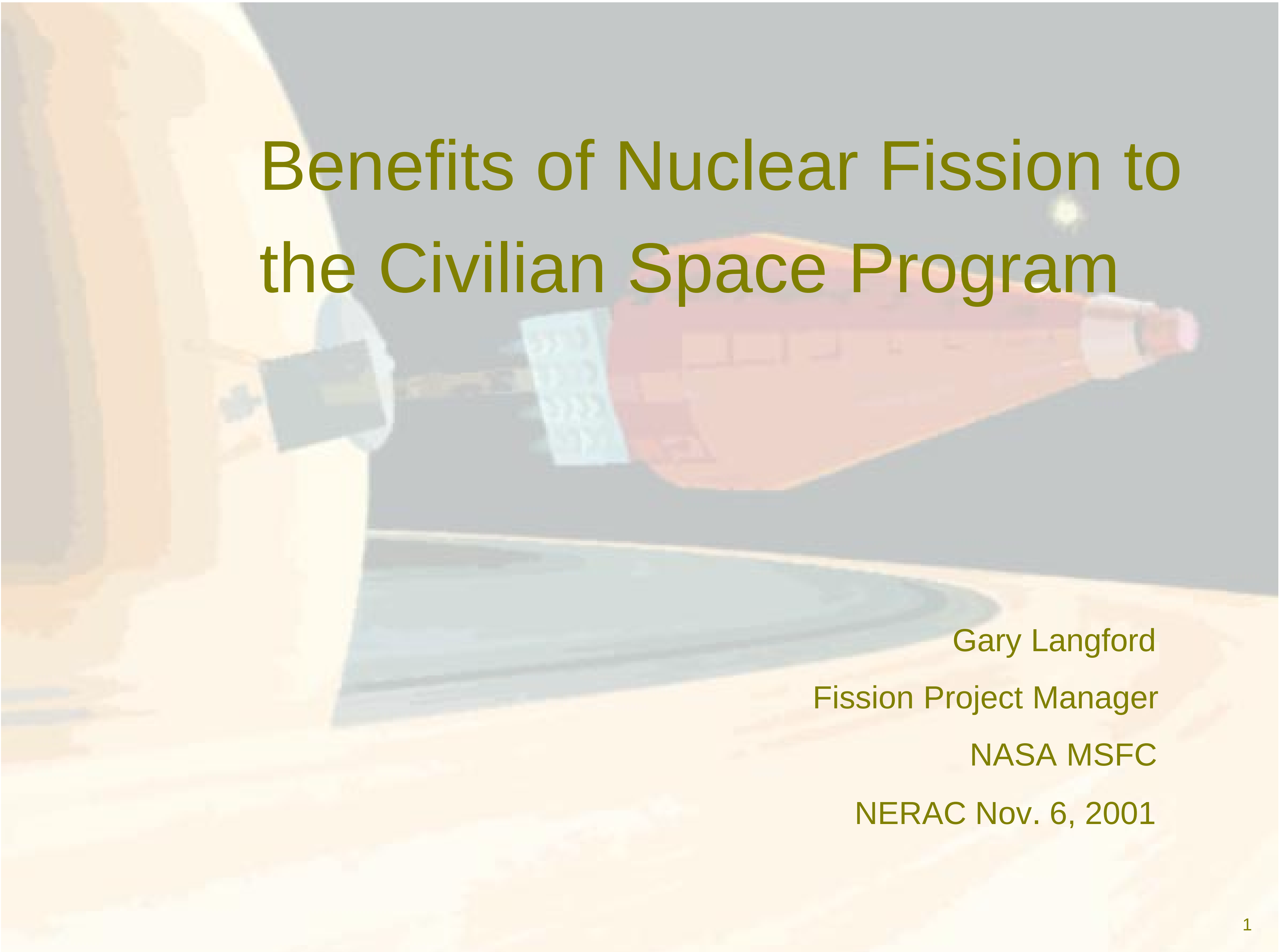


Benefits of Nuclear Fission to the Civilian Space Program

Gary Langford

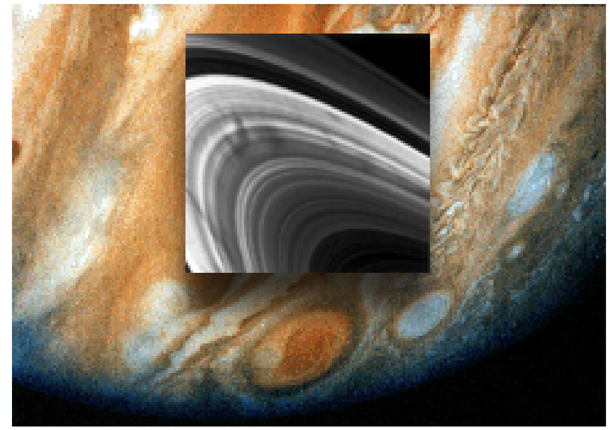
Fission Project Manager

NASA MSFC

NERAC Nov. 6, 2001

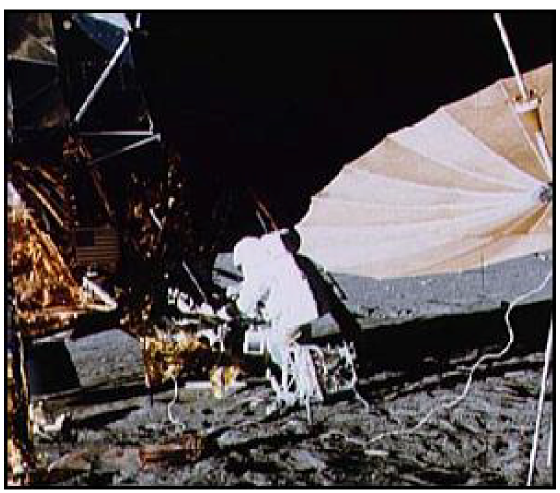
Uses of Nuclear Fission in the Civilian Space Program

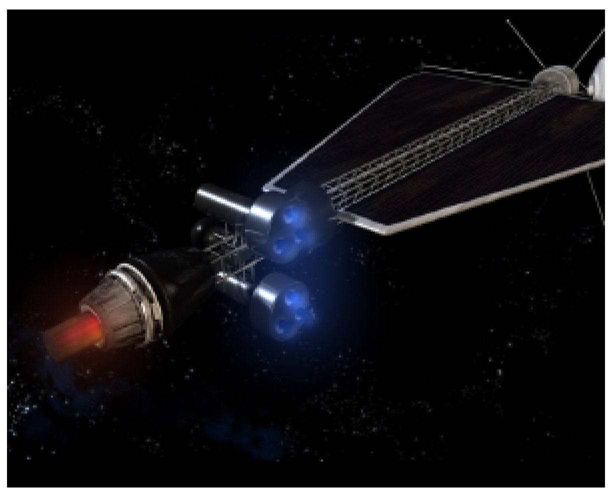
- Outer solar system exploration.
- Planetary or lunar surface missions (robotic or human).
- High-performance propulsion for human missions.

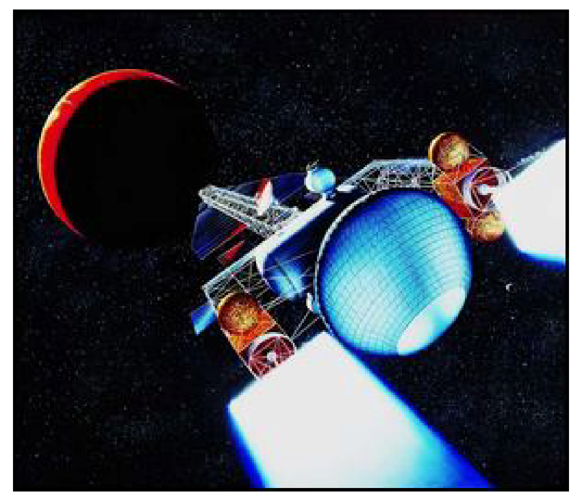


- Advanced applications.

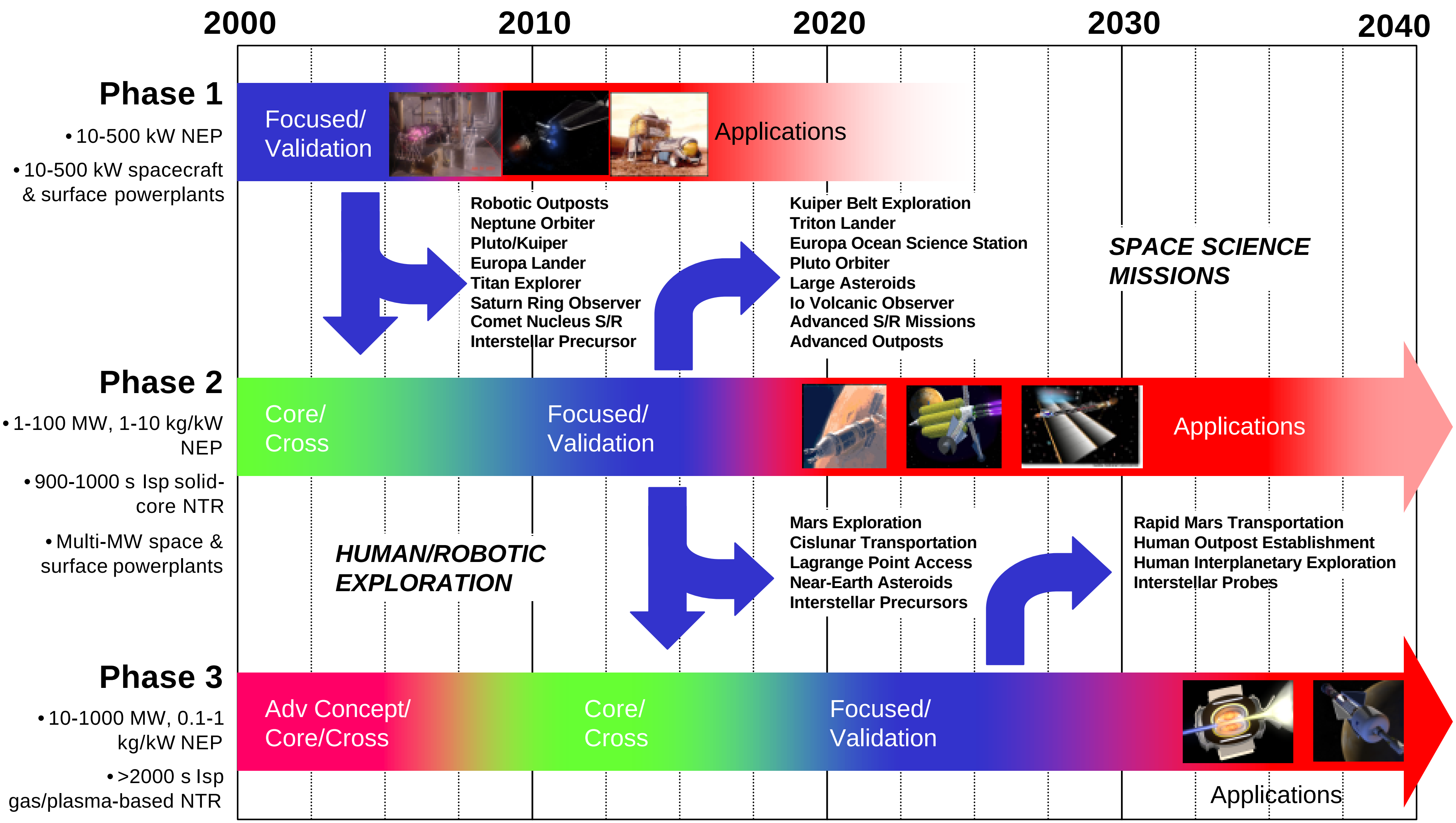
  Highly advanced propulsion, extremely high power surface applications.



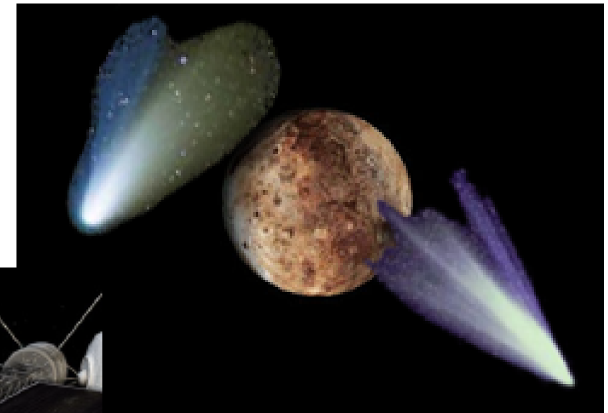


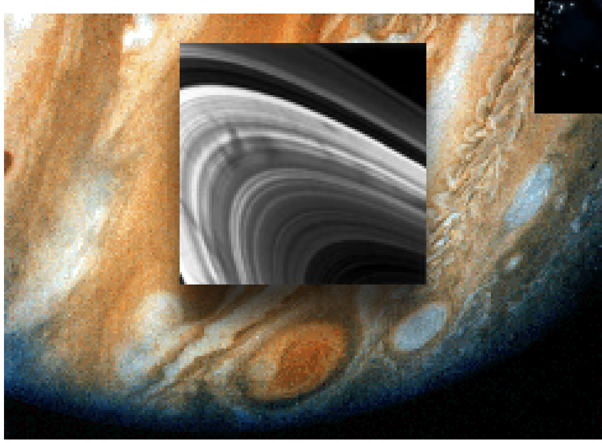


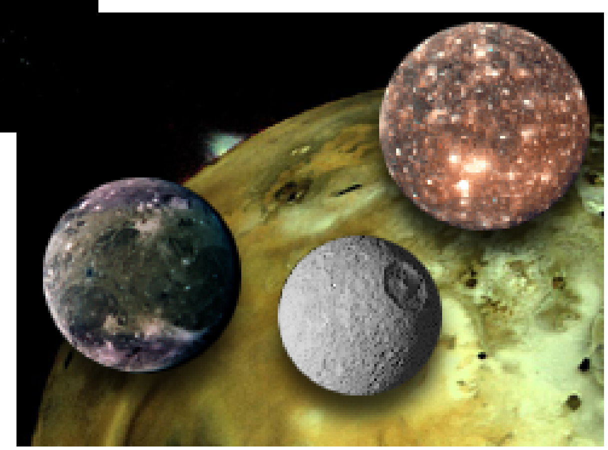
Top-Level Fission Roadmap



Outer Solar System Exploration







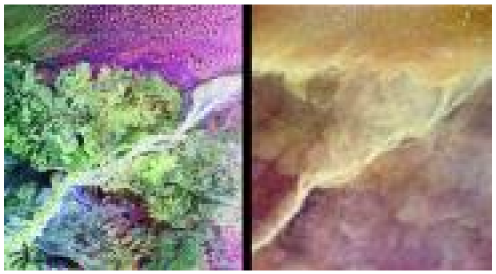
Challenges of Outer Solar System Exploration

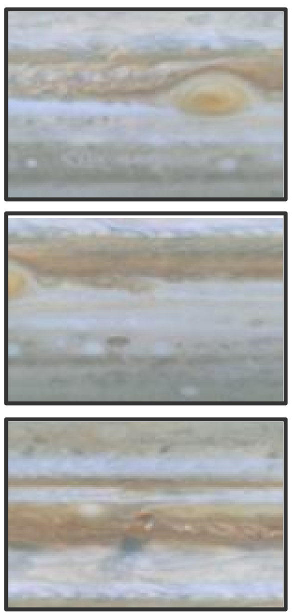
Characteristic	Challenge	What we need:
Distance	Solar power is infeasible	Power where it's needed
	Flight times are long and gravity assist opportunities can be rare	Highly efficient electric propulsion
	Mass is limited, data rates are low	Increased payload/data return
Environmental extremes	Radiation and temperature	Increased mass for shielding and heat for thermal control
	Atmospheric and subsurface conditions	Robust mission and system designs that avoid or tolerate hazardous regions
	Particle hazards	
Exploration of complex, interactive systems	Giant planet/ring/satellite/ magnetosphere systems	New types of science and systematic study of multiple targets & processes
	Pluto/Charon and the Kuiper belt	

Power is the only thing that will enable us to meet these challenges… and only space nuclear systems can provide it

New Science Will Be Enabled by High Power Capability

The reactor power source that enables NEP can also fundamentally alter the way we study solar system bodies



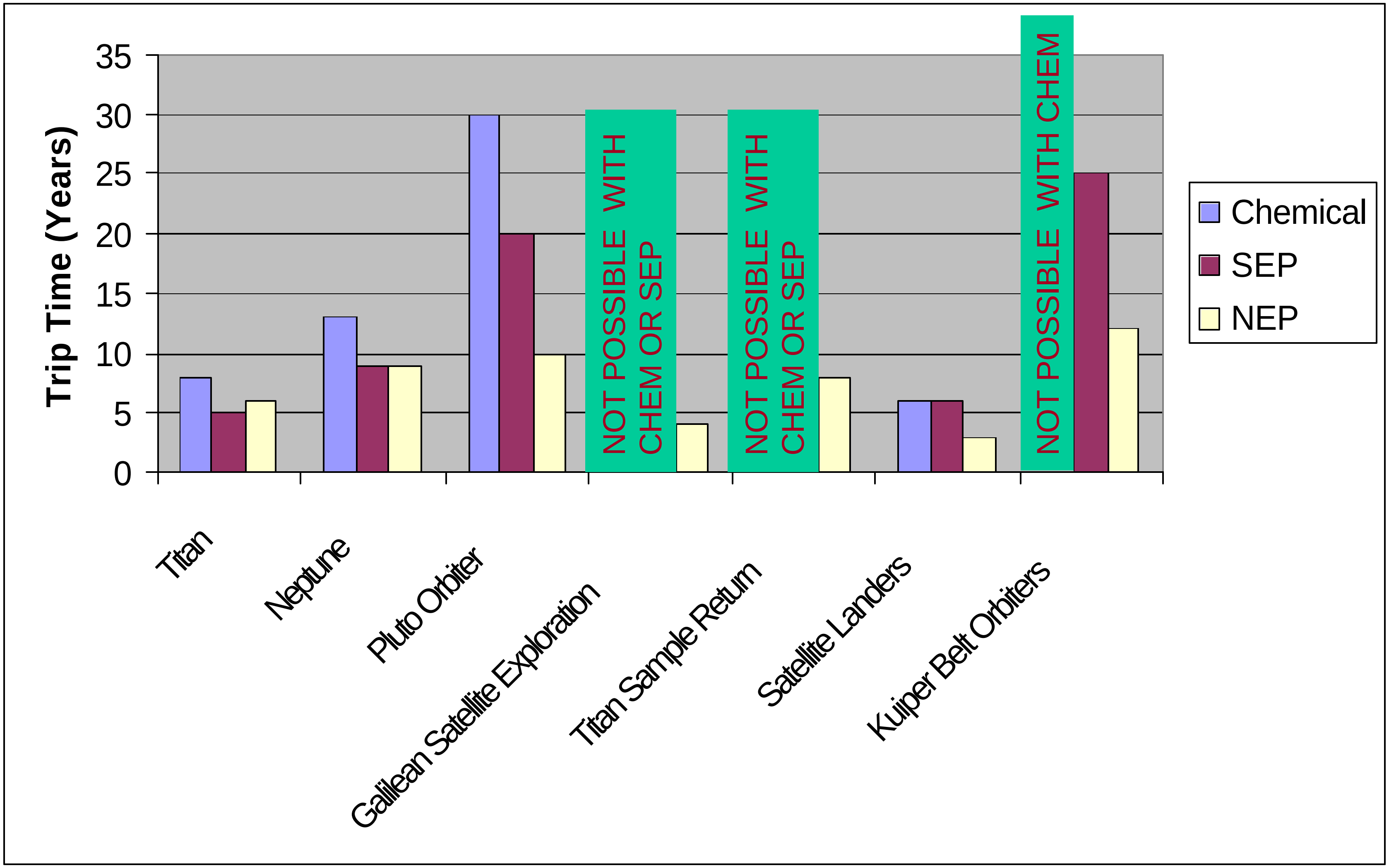


- Much of our science program has been conceived under the assumption that power and mass are extremely limited…*we can break this paradigm*

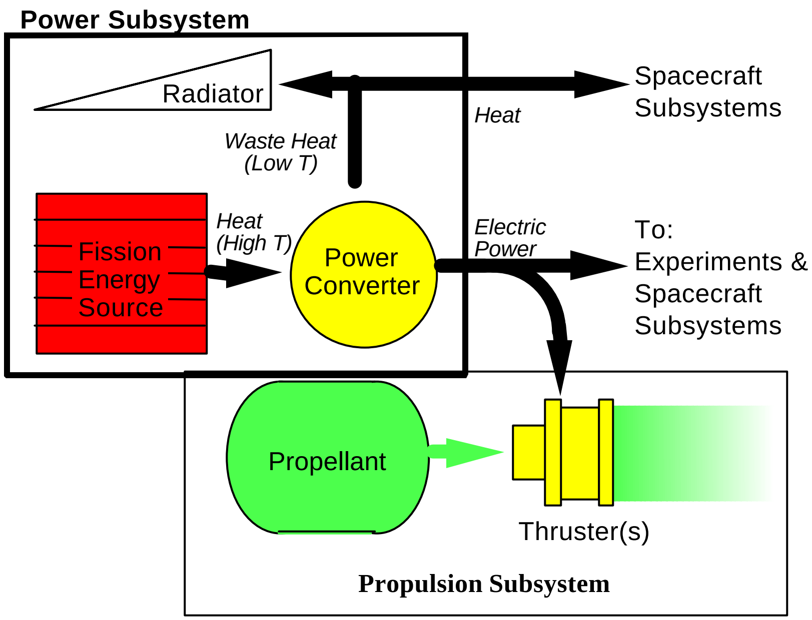
- Examples of new science areas that might be enabled/enhanced by higher power:
  - Active radar – Synthetic Aperture Radar, deep ice sounding, bistatic radar
  - High-precision deep atmosphere and ring occultations

- Examples of use of much higher data rates
  - High resolution optical/spectral and radar maps
  - High time resolution plasma/radio wave studies
  - Atmospheric and ring dynamics ("movies")
  - Auroral movies: detailed interactions between magnetosphere, solar wind and planet's atmosphere

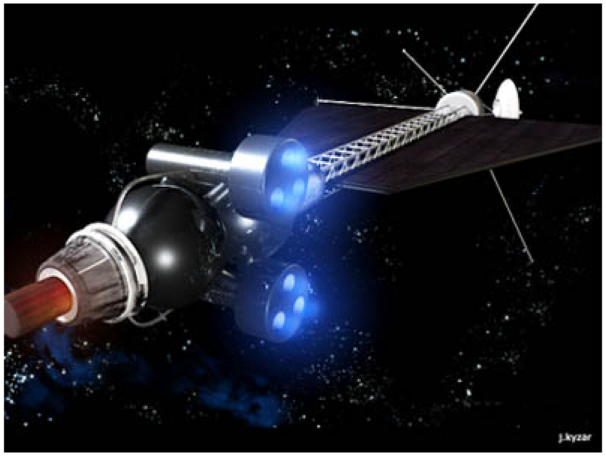
NEP Enables Many Missions and Significantly Reduces Trip Time for Many Missions



Converting Fission Energy to Thrust

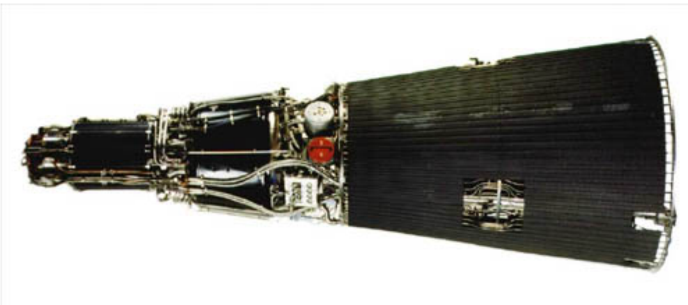


- Power is generated in fuel by fission reactions
- Fission reaction rate (power) actively and passively controlled by neutron balance
- Power converted in-core (thermionics) or transferred ex-core to power conversion subsystem
- Shield attenuates radiation that escapes reactor
- Electricity generated by power converter sent to propulsion subsystem
- Waste heat generated by power converter rejected by radiator
- Electric propulsion subsystem converts electricity into thrust by accelerating propellant-derived plasmas



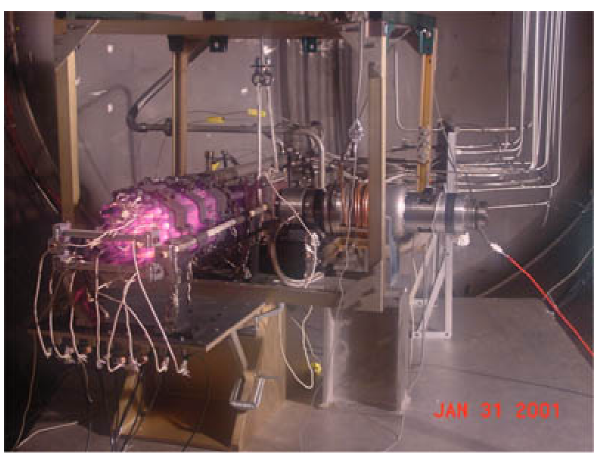
Pluto/Charon orbiter
spacecraft concept

NEP Technology Has A Rich Heritage



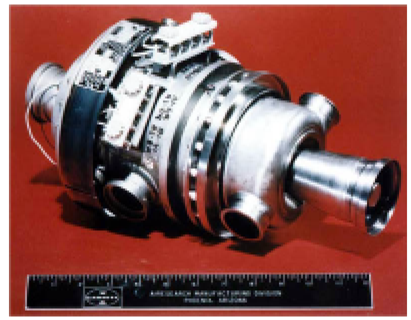
Space Fission Reactor

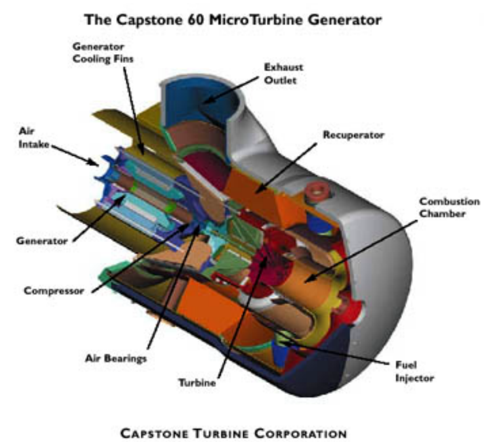
- Technology from over 15 major US programs
- 33 Soviet / 1 US flight
- Choice of proven fuel forms (UO_2 or UN)
- Advanced design & modeling techniques

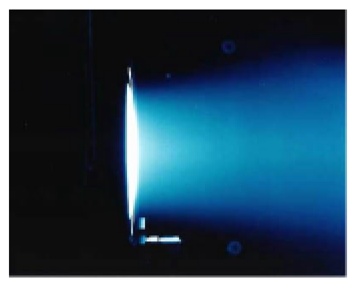


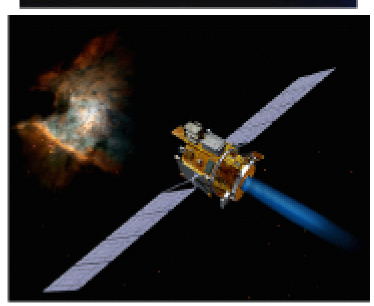
Power Conversion

- 2 kWe Brayton tests completed
- Established industry base for terrestrial Brayton systems
- Thermionic conversion developed in US and Russia, flown in space (TOPAZ)





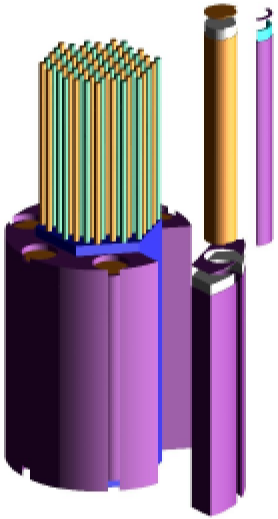


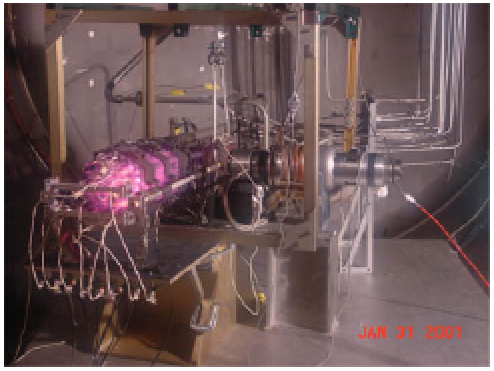


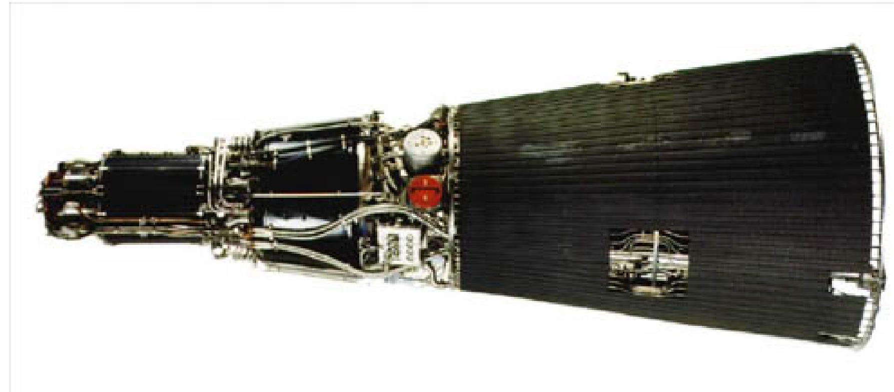
Electric Propulsion

- DS-1 flight of ion thruster
- DS-1 ground test unit
- Next generation ion thruster

Reactor Options







Safe Affordable Fission Engine (SAFE)

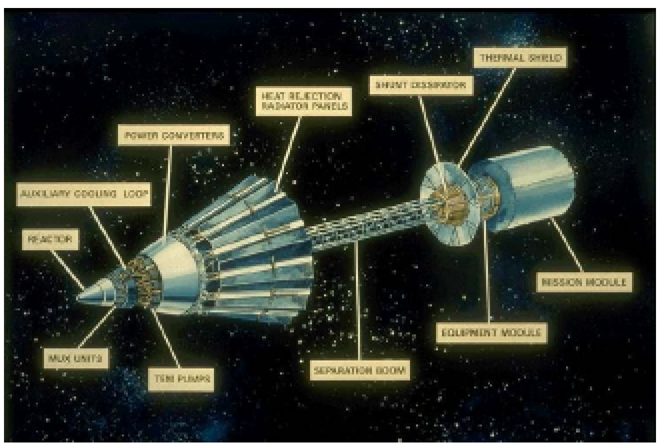
Testable, use existing technology and facilities

Key technologies evolve to high power levels

Testable Multi-Cell In-Core Thermionics

Thermionic systems flown in space (TOPAZ 1)

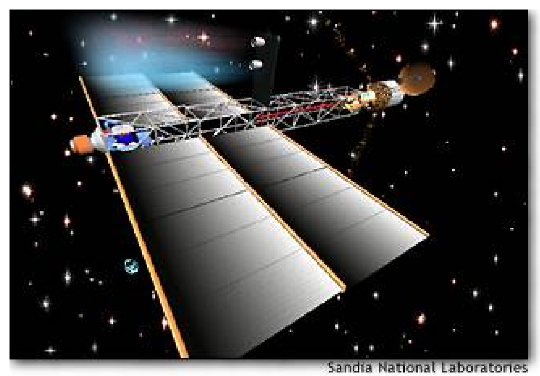
High temperature heat rejection, structure SS

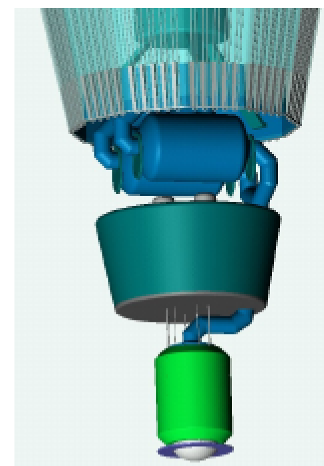


Liquid Metal (i.e. SP-100)

Significant program 1983 - 1994

Pre-conceptual designs up to 75 MWt

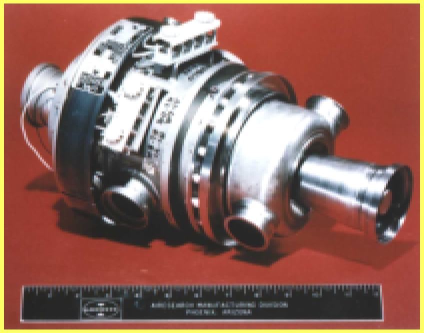




Direct Gas-cooled

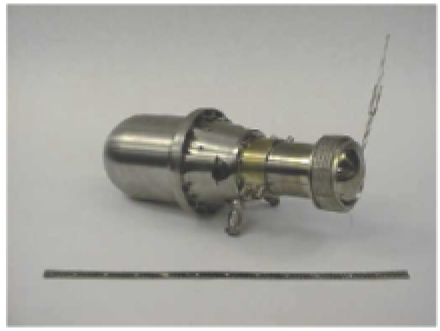
Direct coupling of core and Brayton cycle

Power Conversion Options



Closed Brayton

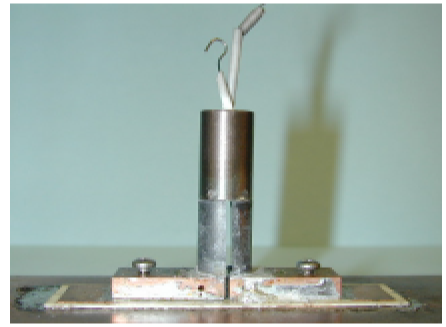
- **Heat engine with rotating turbine-compressor at 30-60 krpm**
- **High efficiency (20-30%)**
- **Relative high maturity, but not flight proven**
- **Engine prototypes built at 2 and 15 kW**
- **Scales well to high power**
- **Well suited for high voltage applications**
- **Turbine Inlet 1150K (superalloys), Comp. Inlet ~425K**



Free-piston Stirling

- Heat engine with reciprocating piston at 60-80 Hz
- High efficiency (20-25%)
- Relative high maturity , but not flight proven
- Current flight dev't for 100 W class radioisotope power system
- Well suited for low to medium power applications
- Thot 925K (superalloys), Tcold~450K

NEP power level somewhat high for Stirling



Thermoelectrics

- Electrical potential produced by dissimilar materials exposed to temperature difference
- SiGe or PbTe unicouples (flight proven) or segmented TE (advanced)
- Low efficiency (5-10%)
- High maturity in RTG at power levels < 300 W
- Poor scaling to high power
- Thot 1275K (refractory alloys), Tcold~575K

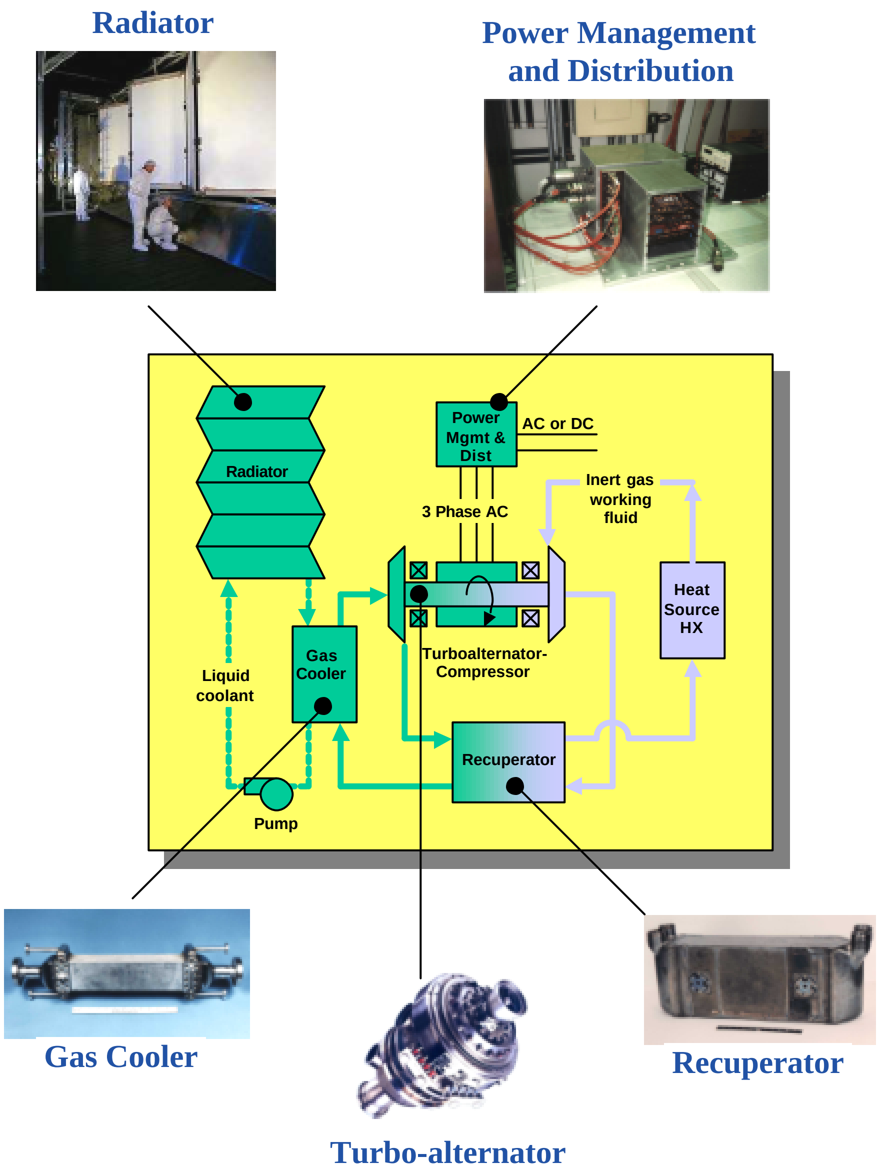
Efficiency too low for candidate reactors

Thermionics

- **H**eated emitter passes electrons to cooled collector across very small cesium-filled gap
- Typical in-core configuration has converter with fuel
- Used in Russian Topaz Reactors (6 kW)
- Moderate efficiency (8-15%)
- Emitter 1800K(refractory alloys), Collector 1000K
- High temperature waste heat rejection offsets moderate efficiency

Lifetime issues must be resolved

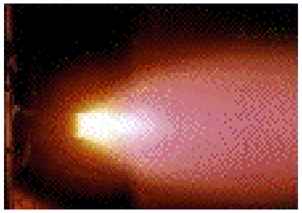
Brayton Power Subsystem



- Functional Description
  - Converts reactor heat into electrical power via multiple Brayton converters
  - Rejects waste heat to space via radiator
  - Processes and distributes power to loads via Power Management & Distribution
- Physical Description
  - Turbine, compressor and alternator on single shaft at 30-60 krpm
    - High temperature, inert gas working fluid
    - Non-contacting foil bearings
    - Nickel-based superalloys
    - 20-30%cycle efficiency with recuperator
  - Lightweight composite radiator panels reject waste heat to space
    - Pumped liquid coolant
    - Variable temperature heat rejection
  - PMAD interfaces with thruster power processing unit.
    - Accepts multi-kilovolt, 3ø AC from alternator
    - Provides speed and voltage control, startup power for Brayton
    - Distributes regulated power to PPUs

Electric Thruster Options

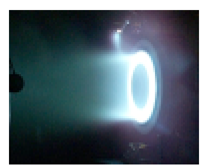
Electrothermal



- Arcjets: 400 to 1200 sec Isp
  - 2 kW N2H4
  - 30 kW NH3
- Used in commercial GEO applications

Electrostatic

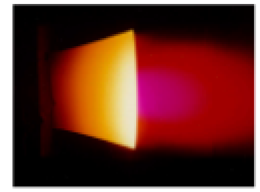
- Gridded Ion: 2500 sec to 70,000 Isp
  - NSTAR/DS-1 Flight Proven
    - 3100 sec Isp
    - 2.3 kW
    - >130 kg Throughput
  - Lab Models
    - Up to 70,000 sec Isp
    - Up to 20 kW
    - >70% Efficiency



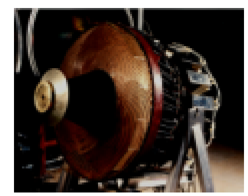
- Hall
  - 1600 sec Isp
  - High Isp (3000 sec): Life?

Electromagnetic

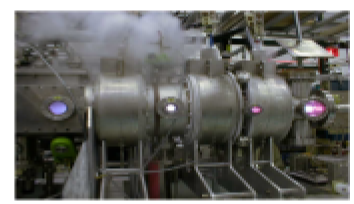
- MagnetoPlasmaDynamic



  - 2000 to 12,000 sec Isp
  - 200 kW to 1 MW
  - Demonstrated life: <2000 hours



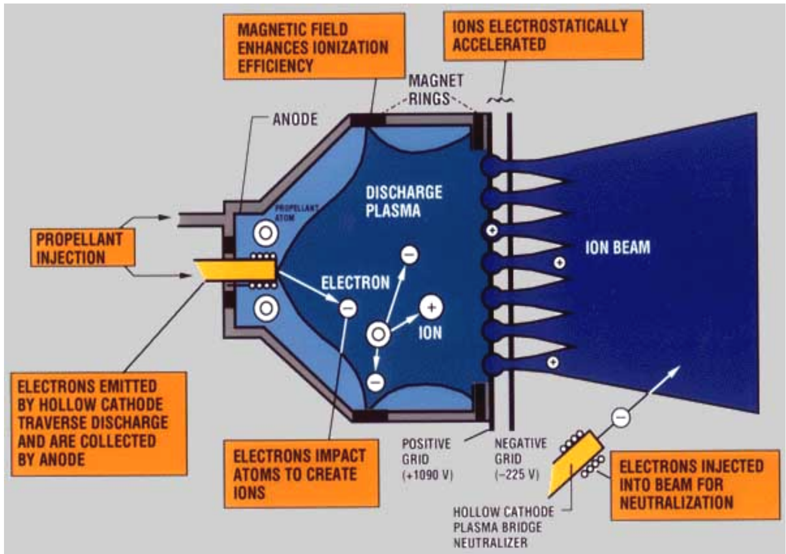
- Pulsed Inductive Thruster
  - 4000 to 8000 sec Isp
  - 40 to 200 kW Pulsed

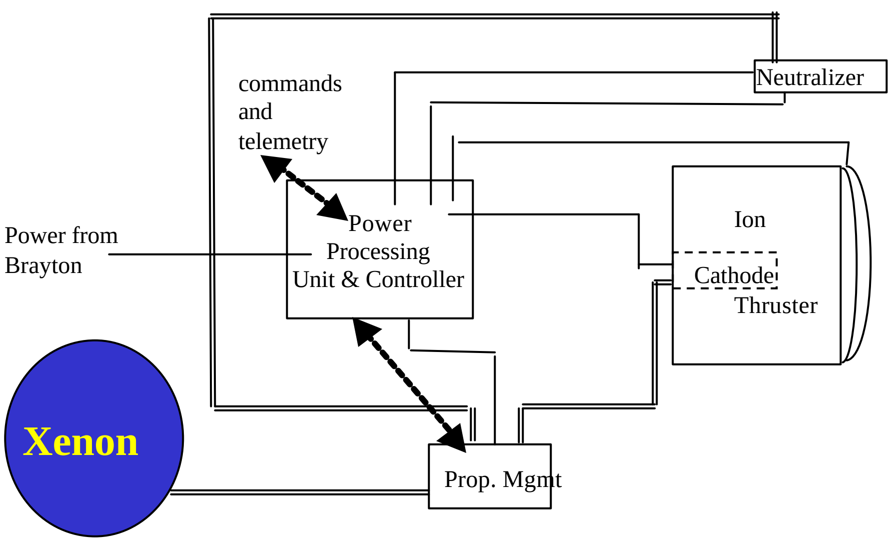


- VASIMR
  - 3000 to 30,000 sec Isp
  - > 100 kW

Trade studies will determine best choice

High Isp Ion Propulsion System





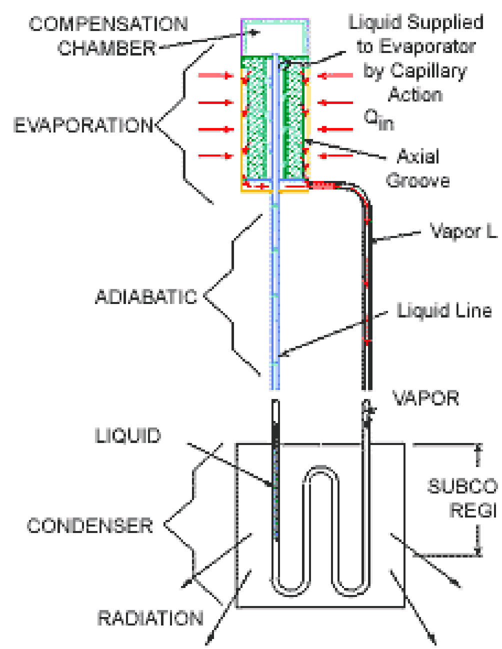
- Functional Description
  - Provides High Isp thrusting for S/C delivery and maneuvering
  - Accepts High Voltage AC power from Brayton System
- Physical Description
  - Gridded Ion Thruster
    - Creates ions using a Cathode in isolated chamber
    - Accelerates ions using high voltage grids (electrostatic field)
    - Neutralizes exhaust using cathode
  - Power Processing
    - Voltage converter (AC to DC)
    - Controller
  - Xenon Feed System
    - High Pressure Carbon overwrapped tanks
    - Plenum or regulator or proportional valve flow control

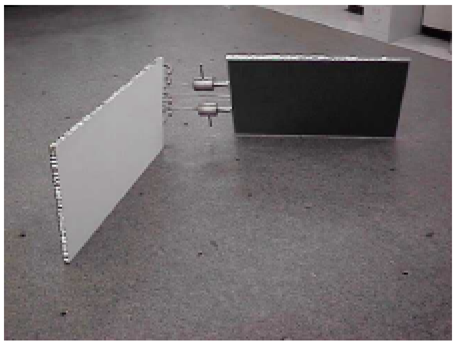
Additional Elements

Systems Integration

Light Weight, Deployable Radiators

- Light-weight deployable radiators exist with the capability of ~2.0-2.5 kg/kWth at temperature
- Can use water, pyridine, methanol, or ammonia system with low cost materials and fabrication
- Independent testing can be performed. Testing of a 50 cm by 75 cm ultra-high thermal conductivity graphite fiber and high temp Cyanate Ester matrix material at MSFC at end of CY01
- Space systems have already flown
  - Dynatherm ammonia capillary pumped loop radiator (3.8 kg/m^2) used on Hughes 702 satellite
  - Other options (eg. thermacore water, pyridine, or methanol loop heat pipe) available if desired.

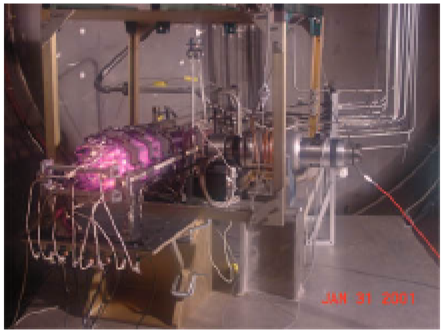




Other Components

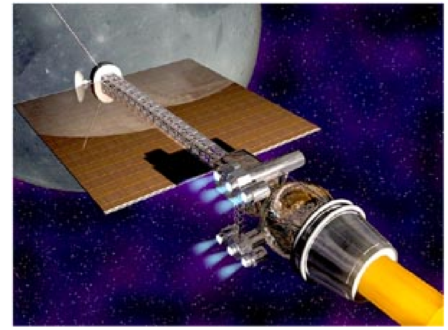
- Passively cooled radiation shields and neutron reflectors flown in space. Other components for operational system also flown (upgrade if desired). US fission flight in 1965 and 33 Russian fission flights.
- Control system (rotating drums) flown in space. Sliding reflector control devised under SP-100.

NEP Investments Can Evolve to Meet Future NASA Needs

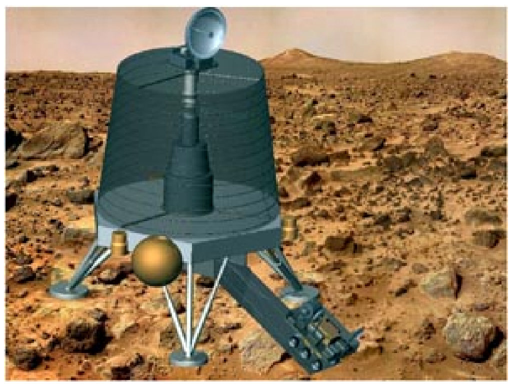


Mid-Term Nuclear Electric Propulsion System

- Enables key outer solar system missions
- Highly testable on ground
- Utilize established technology and existing facilities

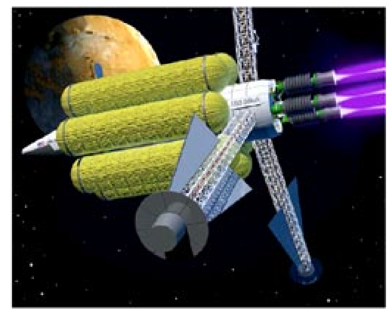


Future Need: Surface Fission Power Supply



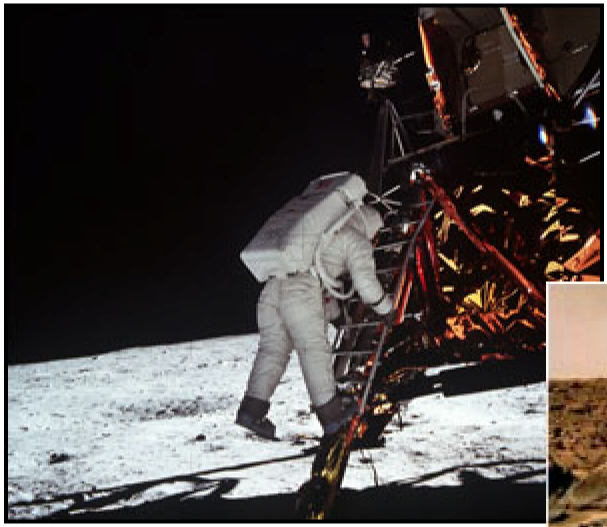
- Enables high-power Mars surface science
- Highly testable on ground
- Utilizes established technology, existing facilities

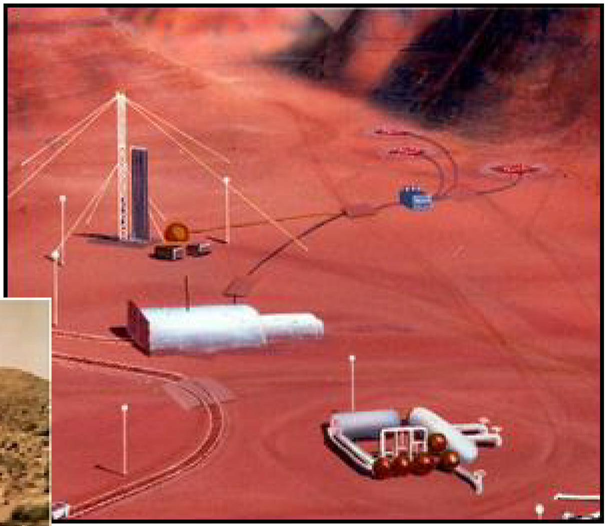
Future Need: NEP For Human Exploration

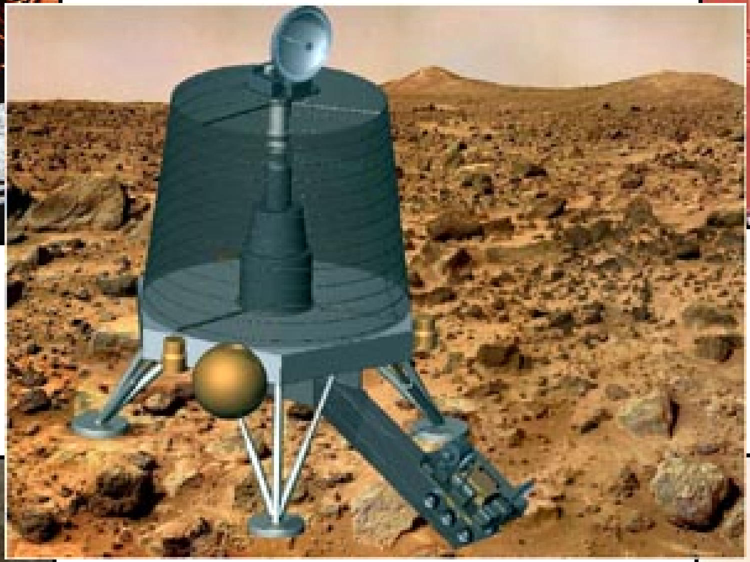


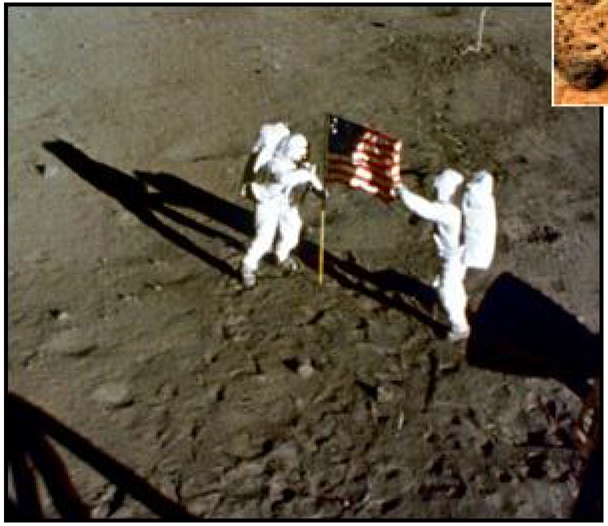
- Enables rapid human Mars exploration and advanced outer solar system missions
- Moderately testable on ground; extension of established technology
- Utilizes existing, modified, or new facilities

Surface Power Systems





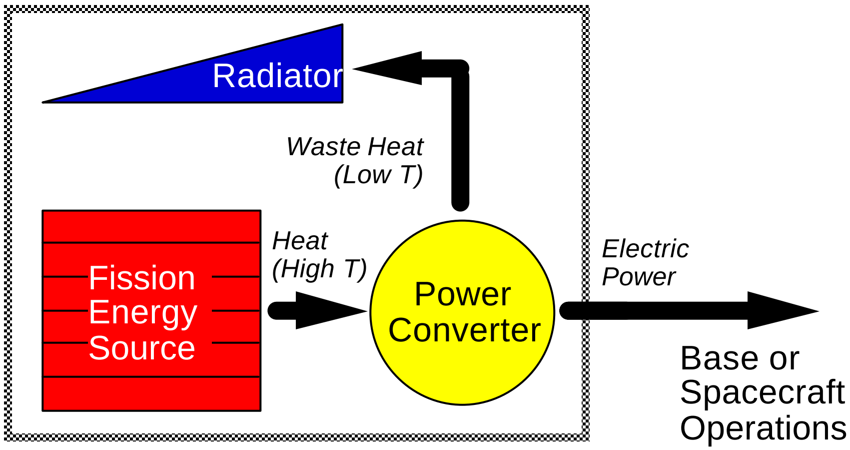




Nuclear Fission for Surface Power

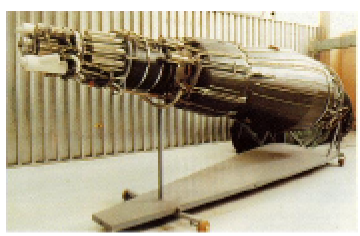
Surface Electric Power Generation

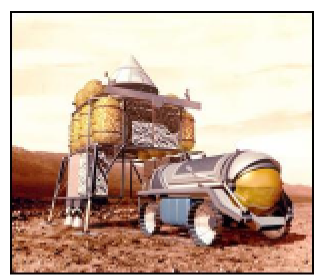
Power Subsystem



- Compact, flexible, high-energy density power source for remote, long-duration operations.
  - Robust spacecraft power supply
  - Robotic Mars outposts and colonies
  - Human Mars surface operations
- Suitable for situations requiring power levels >10 kilowatts - *power-rich environments*

TOPAZ fission-based thermionic power supply





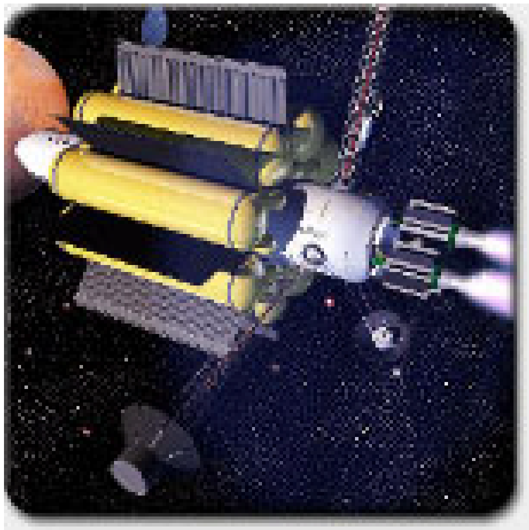
Surface power systems for human Mars exploration

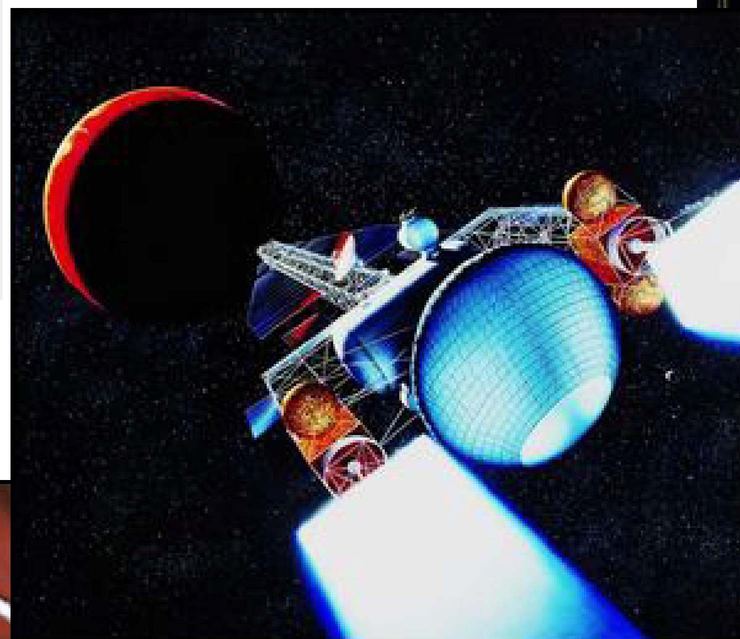
Fission Surface Power

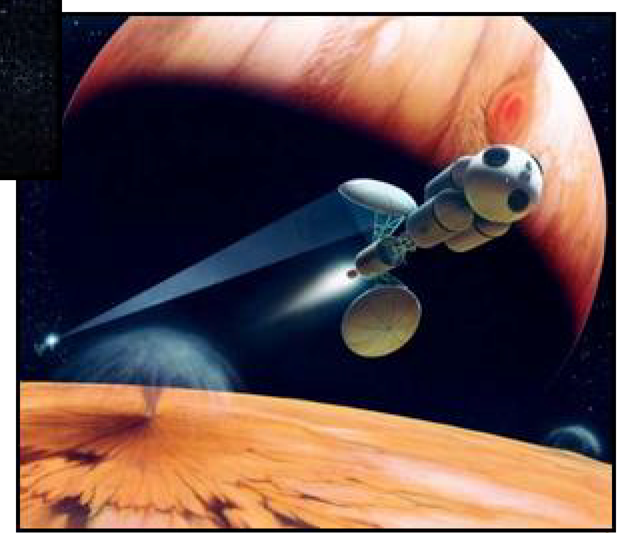
- Moderate to high power (3 kWe through > 1000 kWe).
- Full power at all latitudes.
- Full power through all seasons.
- Full power at night.
- Full power during / after dust storms.

Space fission systems provide a power-rich environment on planetary surfaces. Fission systems can enable deep drilling, robotic colonies, in-situ resource utilization and other advanced robotic missions, as well as providing a safer, power-rich environment for human missions.

Propulsion for Human Exploration / Advanced







The Energy Density of Fission Systems Can Enable High-Performance Propulsion and Advanced Applications

- 82 Billion Joules per gram of uranium fissioned.
- Excellent scaling potential. Specific power greater than 1 kW/kg at power levels above 50 MWe.
- If appropriate thrusters developed, 10 MWe fission systems could enable 90 day Earth-Mars transits. 100 MWe systems could enable <45 day transits.
- Rapid access to all points in the solar system enabled by high specific power, high specific impulse fission systems.
- Advanced fission applications include large-scale in-situ resource utilization, comet or asteroid trajectory change, and terraforming.

Development of high specific power nuclear fission electric propulsion would enable large-scale exploration, development, and utilization of the solar system. Fission systems can eventually enable a highly advanced space program

Summary:

Nuclear Systems Provide a Strong Benefit to the Space Program

- All missions beyond Mars have relied on nuclear power (radioisotope to date).
- Beyond Jupiter, solar power alone is infeasible.
    - Some limited and highly focused Jupiter science is achievable using solar power…but exploration of the Galilean satellites is not.
- Radioisotope and fission power systems are required for a robust outer solar system exploration program.
- Fission system technology also enables power-rich surface exploration, high performance propulsion for human missions, and advanced applications.

Development of nuclear fission electric propulsion will *revolutionize* our ability to study the outer solar system's natural laboratories, to explore planetary surfaces, and to rapidly propel humans to any point in the solar system.