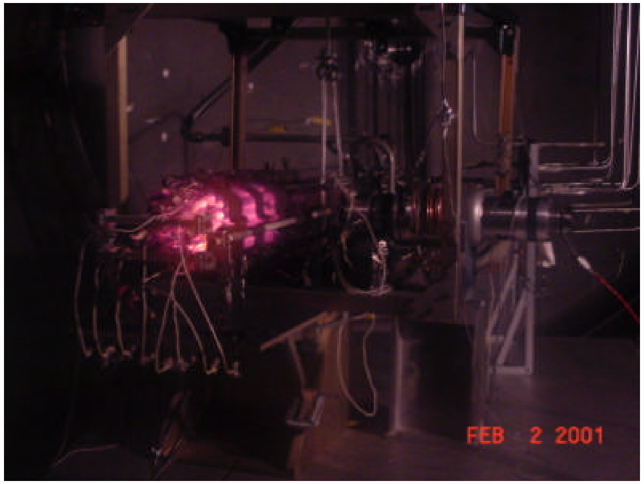
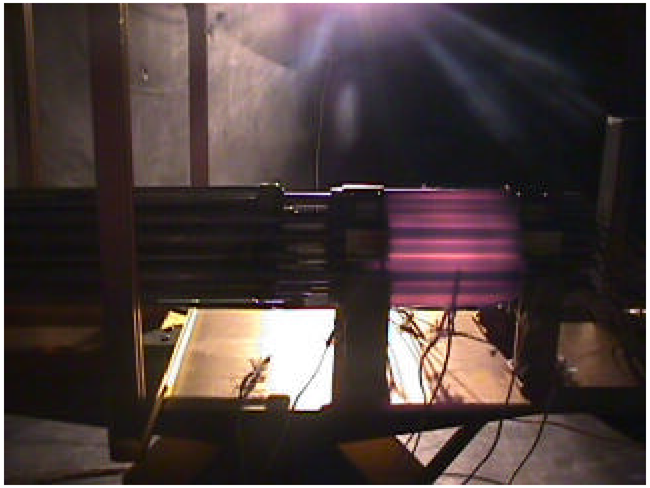
NASA/JPL/MSFC/UAH 12th Annual Advanced Space Propulsion Workshop



April 3 - 5, 2001



The Safe Affordable Fission Engine (SAFE) Test Series

Melissa Van Dyke, Mike Houts, Ivana Hrbud, Jim Martin, Ricky Dickens, Eric Williams, Roger Harper, Gene Fant, Tom Godfroy, Kevin Pedersen Jose Roman, and Pat Salvail

Marshall Space Flight Center

David Poston, Jim Lee, and Bob Reid

Los Alamos National Laboratory

Ron Lipinski, Steve Wright, and Roger Lenard

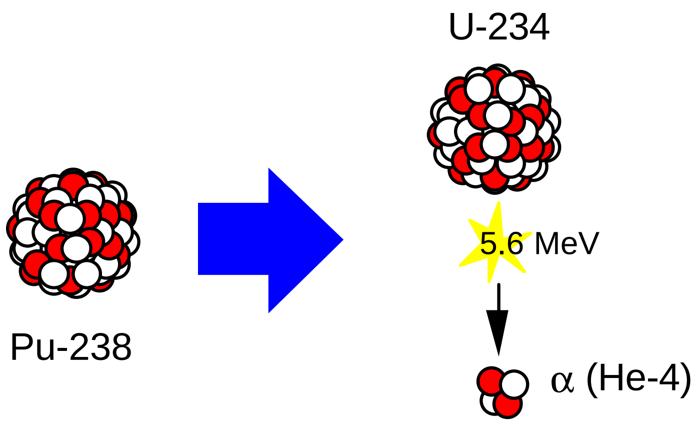
Sandia National Laboratories

Peter Ring

Advanced Methods and Materials

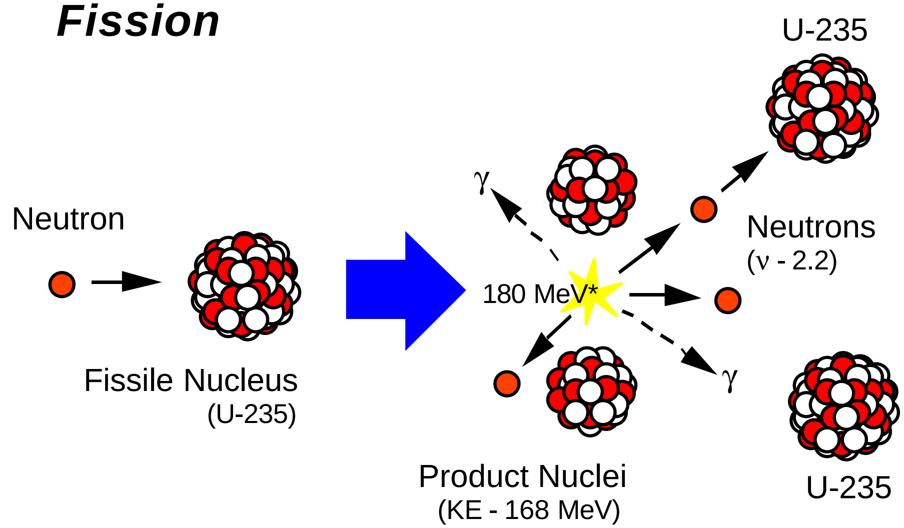
Nuclear processes for space applications

Radioisotope Decay



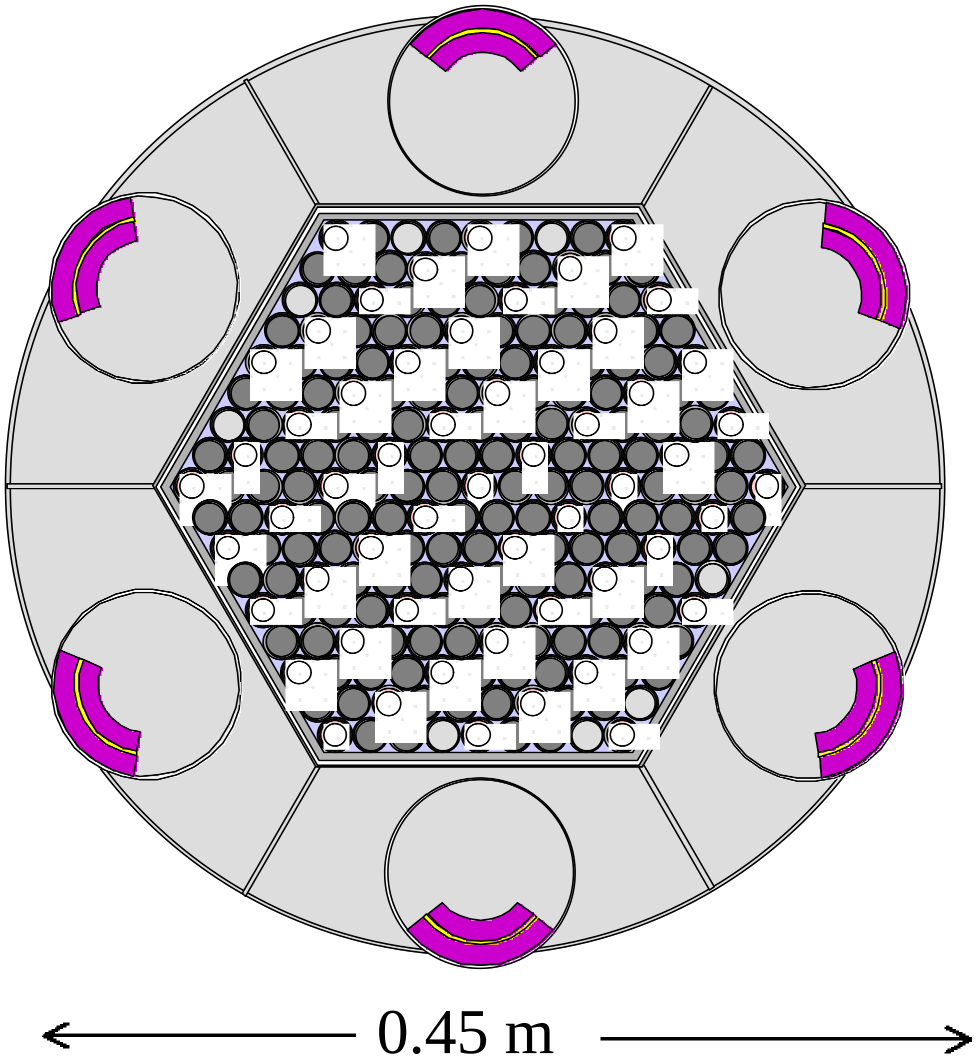
- Long history of use on Apollo and space science missions - 44 units launched by U.S. over last 40 years (RTGs), also numerous RHUs.
- Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238).
- Small portion of heat energy (6%-20%) converted to electricity via passive or dynamic processes.
- 0.558 W/g Pu-238.

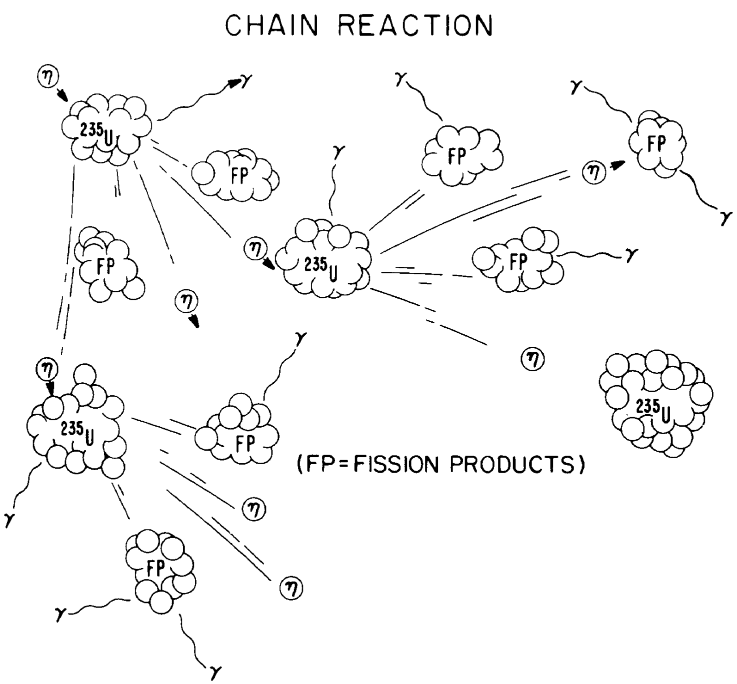
Fission



- Many U.S. technology programs over last 50 years - only one unit (SNAP-10A) was flown. *Former U.S.S.R. flew over 30.*
- Heat produced from neutron-induced splitting (fission) of Uranium (U-235).
- At steady-state, 1 of the 2 to 3 neutrons from reaction causes a subsequent fission in a “chain reaction” process.
- Heat converted to electricity, or used directly to heat a propellant.
- System can be designed to operate at very high power density. System can also be turned off as desired.

How Fission Systems Work

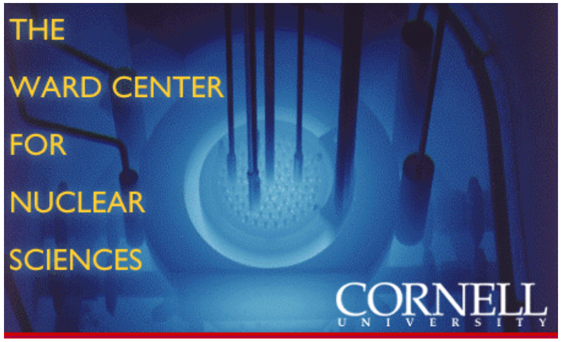


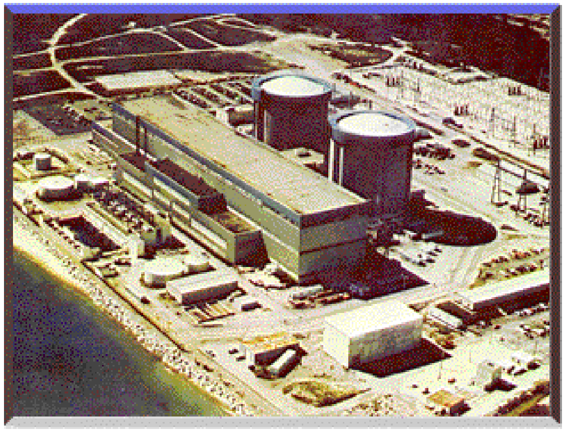


Why Fission?

Fissioning a coke can full of uranium yields 50 times the energy contained in the Shuttle External Tank.

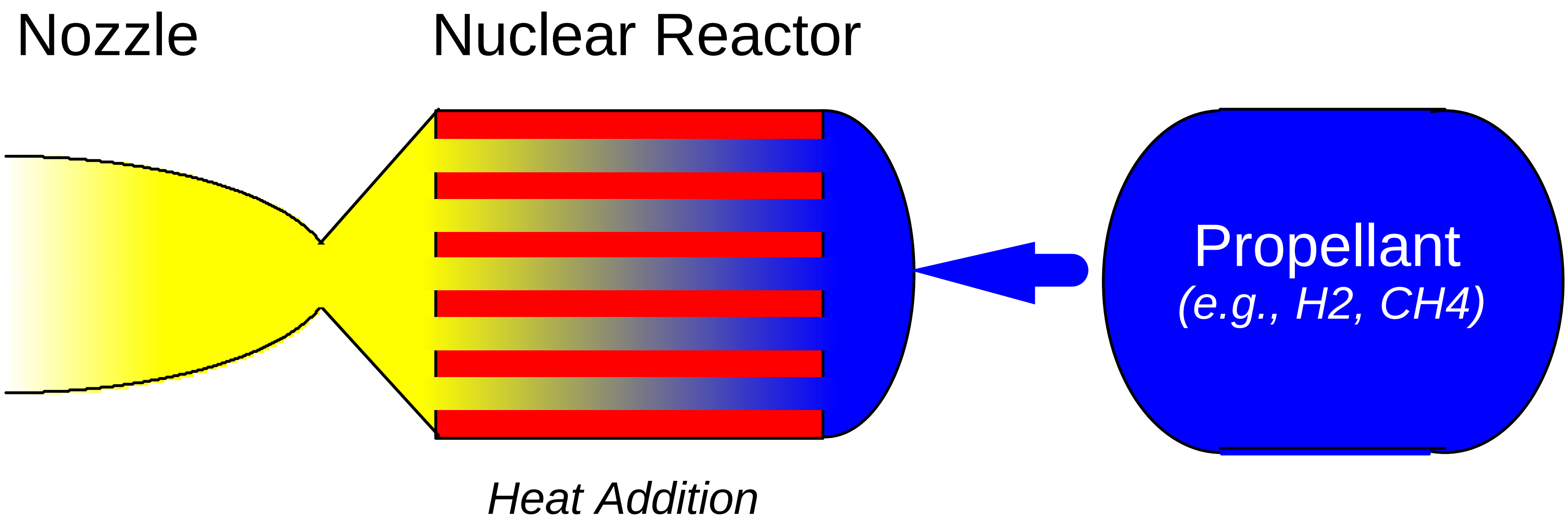
= 50 x





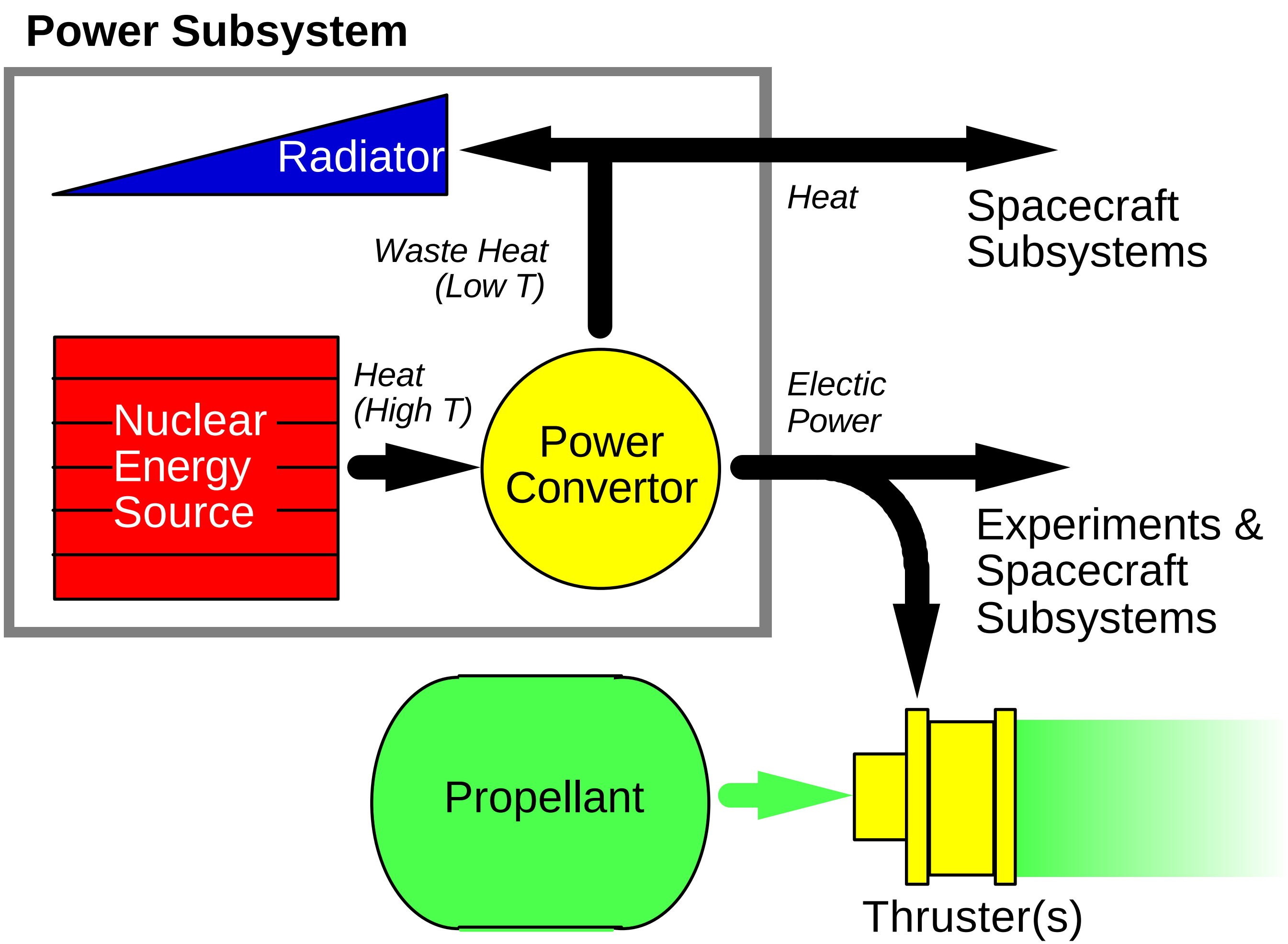
- Safe reliable systems operating since 1942.
- Self-sustaining fission reaction: right materials, right geometry.
- Government, industry, university and international experience.
- Safe development and operation.
- Virtually non-radioactive at launch.
- Insensitive to solar proximity or orientation.
- Scales well to very high power levels.
- Demonstrated 40,000,000,000 J/g fuel.

Nuclear Thermal Propulsion (NTP)



Propulsion Research Center

Fission Electric Propulsion (FEP)



Space Fission Power and Propulsion Status & History

Propulsion Research Center

• **Only US flight SNAP-10A, 1965. Former Soviet Union - 33 flights. Numerous other programs that did not lead to flight.**

▪ Solid-Core Nuclear Rocket Program ▪ Medium-Power Reactor Experiment (MPRE) ▪ Thermionic Technology Program ▪ Space Nuclear Thermal Rocket Program ▪ SP-100	▪ SNAP-50 / SPUR ▪ High-Temperature Gas Cooled Electric Power Reactor (710 Reactor) ▪ SPAR / SP-100 ▪ DOE 40 kWe Thermionic Reactor Program ▪ Air Force Bimodal Study	▪ Advanced Liquid Metal Cooled Reactor ▪ Advanced Space Nuclear Power Program (SPR) ▪ Multi-Megawatt Program ▪ Thermionic Fuel Element Verification Program

• **50 years of space fission technology development can be incorporated in modern systems.**

•**Non-nuclear advances (e.g. light weight structures, deployable radiators, power conversion) can also be incorporated in modern systems.**

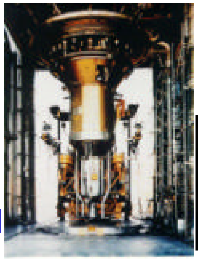
• **Operational facilities exist for developing fission systems. Launch approval process in place. Nuclear system design codes highly developed.**

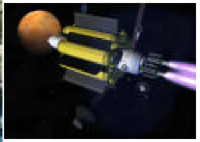
• **Utilization of "Phase 1" systems will enable development of much higher performance systems. Evolution of fission systems potentially analogous to space solar power and other space technologies.**

Three Phase Approach to Fission Propulsion

GOAL: **Develop fission propulsion to enable rapid, affordable access to any point in the solar system.**

Phase I





Phase II

Phase I: First Fission Propulsion System

- Focus on safety, cost, schedule.
- No new nuclear fuel development - utilize existing nuclear technology.
- No need for new or significantly modified facilities.
- Operate within established limits on core components and fissile fuel: temperature, power density, burnup and radiation damage in relevant environment.
- Highly testable. Full performance testing of flight unit through non-nuclear ground testing (e.g. heaters).
- Complete significant system development prior to first nuclear test, including component and system-level testing. Utilize space nuclear technology that has been proven over the past five decades.
- Fission energy source enables orbiters, sample returns / other missions of interest.
- Most Phase 1 components traceable to Phase 2 and Phase 3 systems - initiate key technology tasks for Phase 2 systems.

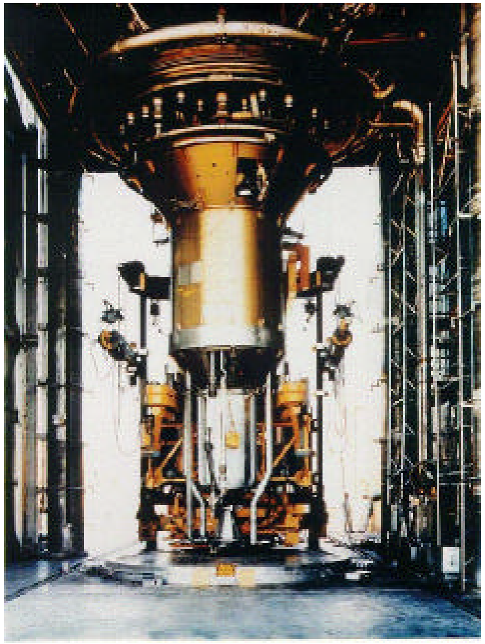
Three Phase Approach to Fission Propulsion

GOAL: **Develop fission propulsion to enable rapid, affordable access to any point in the solar system.**

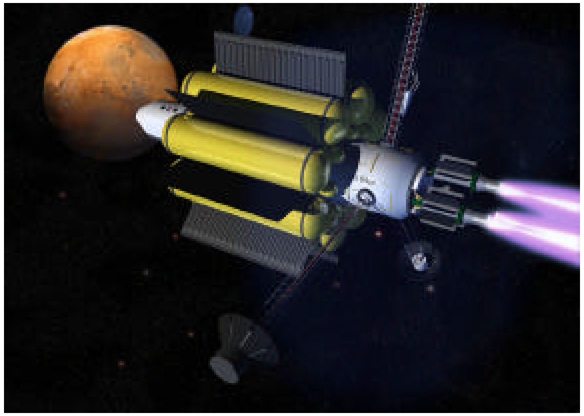
Phase II: Advanced Human Exploration

- Development of fuels and other nuclear components
- Significant facility construction or modification (Government/Industry)
- Feasibility issues with performing full-thrust ground test of flight unit
- User base developed in Phase 1 helps sustain Phase 2

Phase III



Phase II



Phase III - Highly Advanced Human Transportation

- Significant advances in basic technology may be required (e.g. materials, fissile fuels, pumps, flow control, energy conversion)
- Significant ground facility construction or modification
- Significant new space infrastructure required
- In-space propellant re-supply
- Full system requires multiple launches
- Realistic ground testing (research and development) difficult to perform.

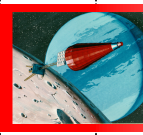
Emphasis on near-term science missions and evolution to advanced applications

Propulsion Research Center

2000	2010	2020	2030	2040

Phase 1

- 10-100 kW NEP
- 10-100 kW spacecraft & surface powerplants


Robotic Outposts
Neptune Orbiter
Europa Lander
Titan Explorer
Saturn Ring Observer
Comet Nucleus S/R
Interstellar Precursor

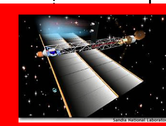
Kuiper Belt Exploration
Triton Lander
Europa Ocean Science Station
Pluto Orbiter
Large Asteroids
Io Volcanic Observer
Advanced S/R Missions
Advanced Outposts

SPACE SCIENCE MISSIONS

Phase 2

- 1-100 MW, 1-10 kg/kW NEP
- 850-950 s Isp solid-core NTR
- Multi-MW space & surface powerplants





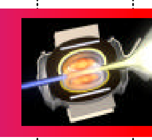
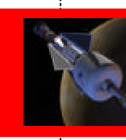
HUMAN/ROBOTIC EXPLORATION

Mars Exploration
Cislunar Transportation
Lagrange Point Access
Near-Earth Asteroids
Interstellar Precursors

Rapid Mars Transportation
Human Outpost Establishment
Human Interplanetary Exploration
Interstellar Probes

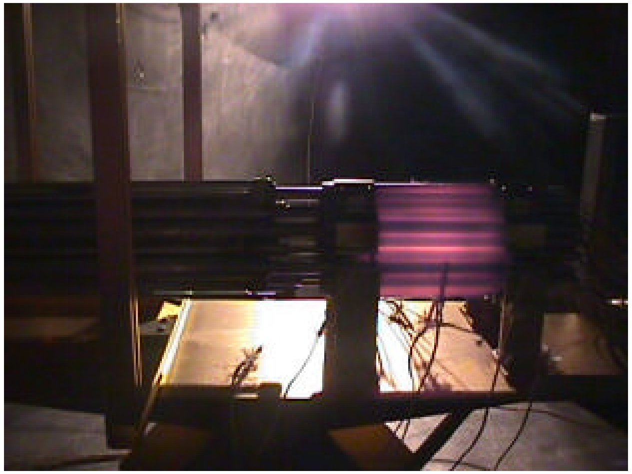
Phase 3

- 100-1000 MW, 0.1-1 kg/kW NEP
- >2000 s Isp gas/plasma-based NTR

Fission Systems Can Be Safe to Develop and Launch

- Maximize development accomplished via non-nuclear testing.
- Utilize nuclear facilities that are currently operational.
- Fission systems pose no radiological hazard prior to extended operation at full power.
- Fission systems contain order of magnitude less radioactivity at launch than Mars Pathfinder's Sojourner Rover, which was itself totally safe.
- Launch safety - straightforward methods for precluding inadvertent fission system start.
  - Launch with part/all of fuel separated from core.
  - Passive neutron spectral shift.
  - In-core neutron absorbers.
  - Ex-core control system.

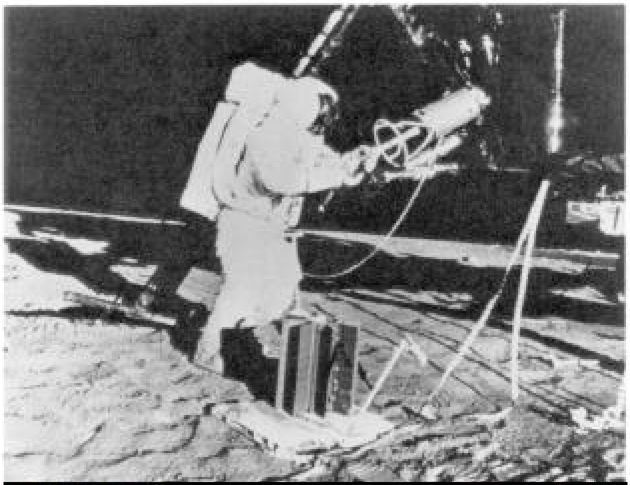


SAFE-30 full core primary heat transport test. Resistance heaters mimic heat from fission.

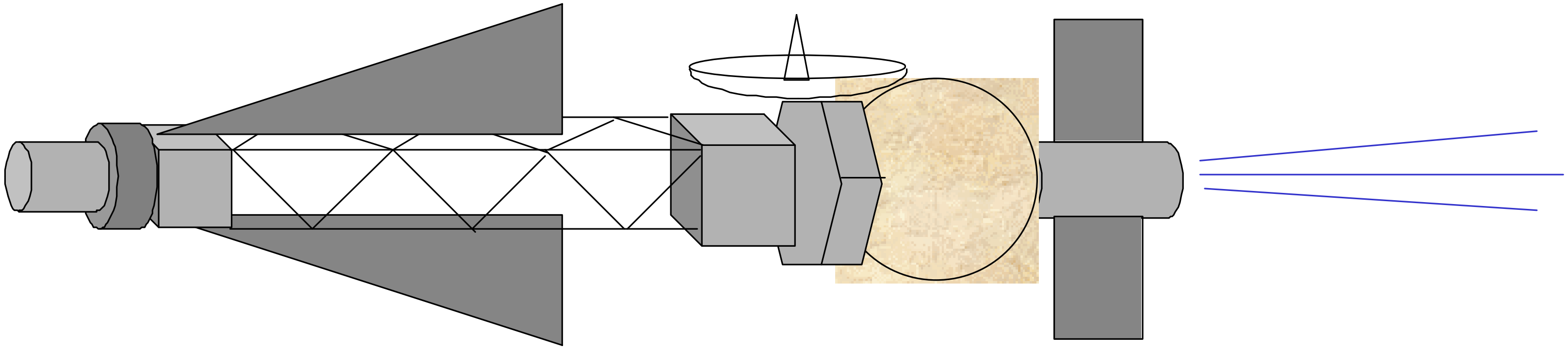
Loading uranium fuel into a fission system (Sandia National Laboratories).

Benefits and Potential of Fission Systems for Space Applications

- Enable missions which increase understanding of solar system and universe.
- Enhance astronaut safety.
  - reduce trip times (less zero-g and cosmic radiation exposure);
  - reliable, power-rich environment;
  - better landing site characterization.
- Long history of terrestrial power plant use proves safety and benefits of fission technology.
- Recent energy supply concerns may re-invigorate interest in fission systems.

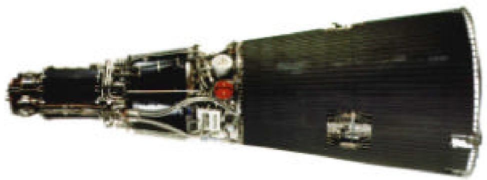


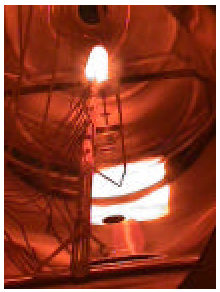
Observations Related to FEP

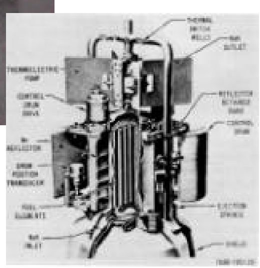


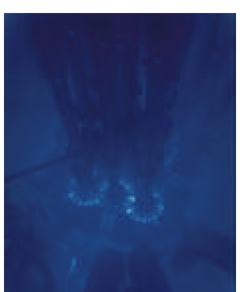
1. All outer solar system missions will be nuclear powered (choice of fission vs radioisotope).
2. FEP energy source can be used to provide abundant energy to payload.
3. FEP eliminates need for RTGs.
4. FEP adds mission flexibility in certain areas (trajectory, targets of opportunity, launch date).
5. System optimized for safety, cost and schedule. Option for safe, higher performance system also available.
6. Requires Delta-IV 4040 class vehicle. 8100 kg to 1000 km orbit.

Subsystem TRL for Phase 1 Space Fission









Fuel

• Large database on W, Mo, and SS-clad uranium dioxide at required temperature, power density, linear heat rate, neutron fluence, and burnup. UO_2 pin fuel reactor flown in space (TOPAZ 1), UO_2 operated above required temperature. UO_2 fuel pin design will be optimized.

Heat Transport / Power Conversion

• Liquid metal heat pipes flown in space. Terrestrially operated at beyond required temperature, neutron fluence, lifetime, and power density. Stirling engine under development for ARPS, units up to 3 kWe available (cluster units or evolve power level for high power application). Previous Brayton development at GRC, ongoing commercial utilization of Brayton technology.

Light Weight, Deployable Radiators

• Dynatherm ammonia capillary pumped loop radiator used on Hughes 702 satellite. 3.8 kg/m^2. Optional upgrade to water capillary pumped loop.

Other Components

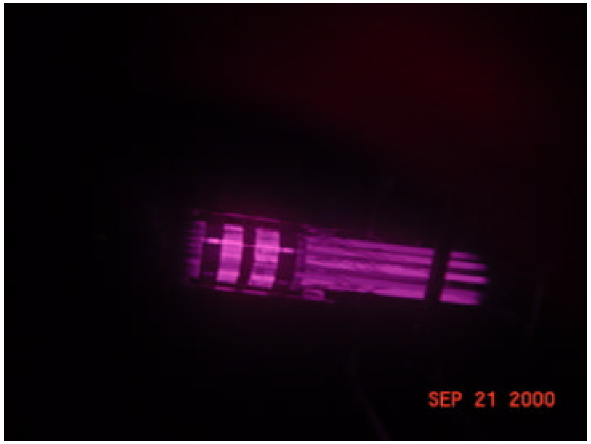
• Passively cooled radiation shields and neutron reflectors flown in space. Other components for operational system also flown (will upgrade). US fission flight in 1965. 33 Russian fission flights.

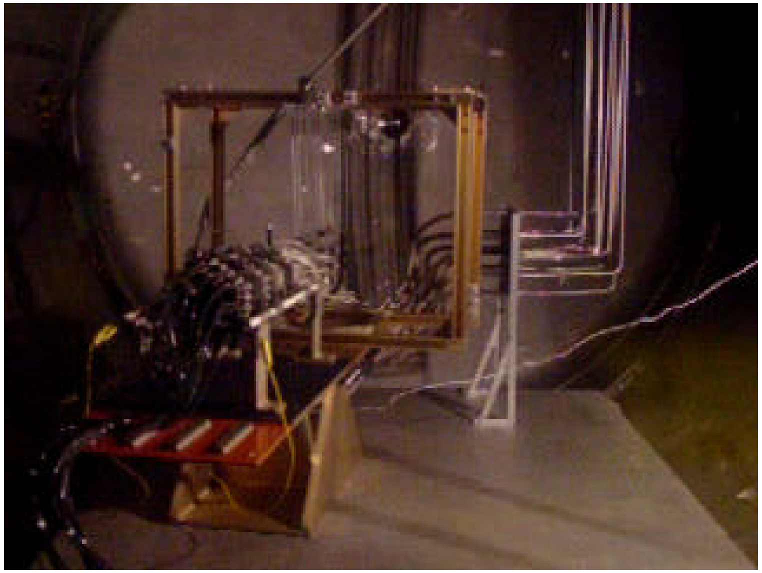
Required Test Facilities Operational) - No Significant Modifications Needed for Space Fission Systems up to 1000 kWt

• Non-nuclear NASA facilities.
• Los Alamos National Lab's Critical Experiment Facility.
• Sandia National Labs' Area V and Annular Core Research Reactor.
• Idaho National Engineering & Environmental Lab's Advanced Test Reactor.

Fission Systems
Ongoing Research - Phase 1

Propulsion Research Center

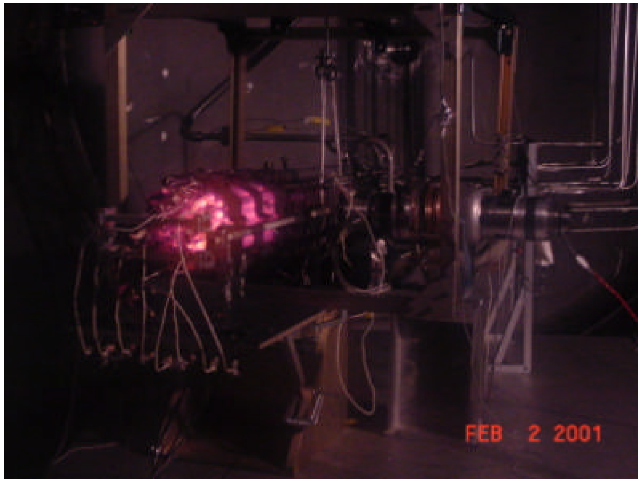




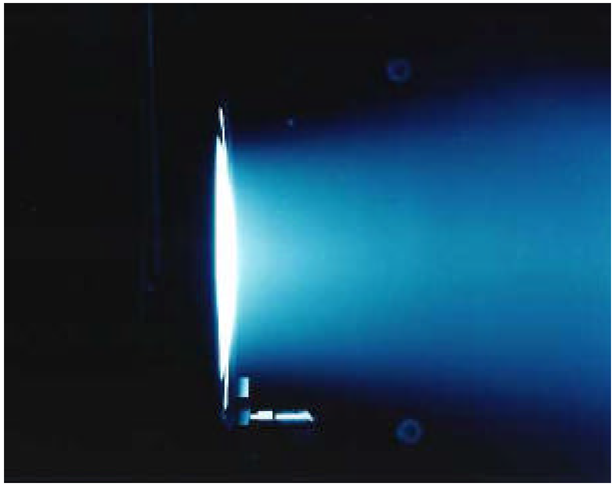
SAFE-30 Test Status

- Isothermal heatpipe operation. High power (17.1 kW) at high temperature (>1000 K). Demonstrated high-temperature CO_2 compatibility.
- Stirling engine coupled to SAFE-30, operated at full power.
- Fifteen restarts as of February, 2001.
- Remaining tests include direct thermal propulsion.
- SAFE-30 utilizes materials and geometry required for fission system core / primary heat transport.
- First realistic full-core / primary heat transport test of US space fission system since 1969.

Fission Systems
Ongoing Research - Phase 1



End-to-End NEP Demonstrator



End-to-End NEP Demonstrator Objectives:

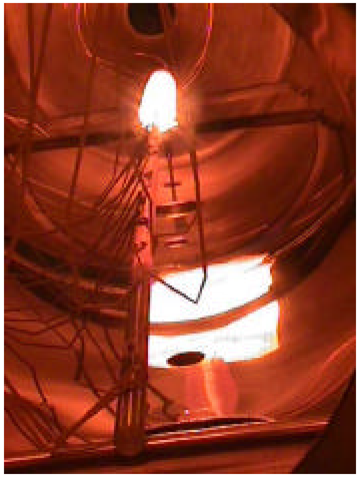
- Couple a near-prototypic fission core, a Stirling power conversion system, and an advanced ion thruster into an integrated propulsion system.
- Demonstrate an integrated, high efficiency fission propulsion system using resistance heaters to closely mimic heat from fission.
- Use knowledge gained from computer modeling and hardware-based technology assessment to devise more advanced systems.

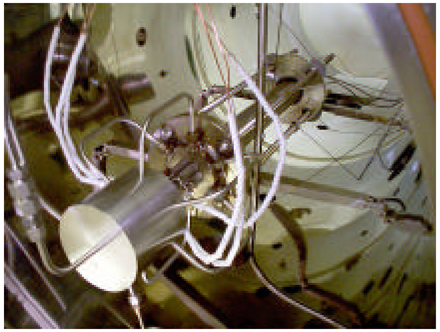
•End-to-End Demonstrator Subsystems:

- 30 kWt Safe Affordable Fission Engine (SAFE-30) core (Los Alamos National Laboratory)
- 350 We Stirling Engine (Stirling Technology Company / GRC)
- Advanced ion thruster / test chamber (Jet Propulsion Laboratory)

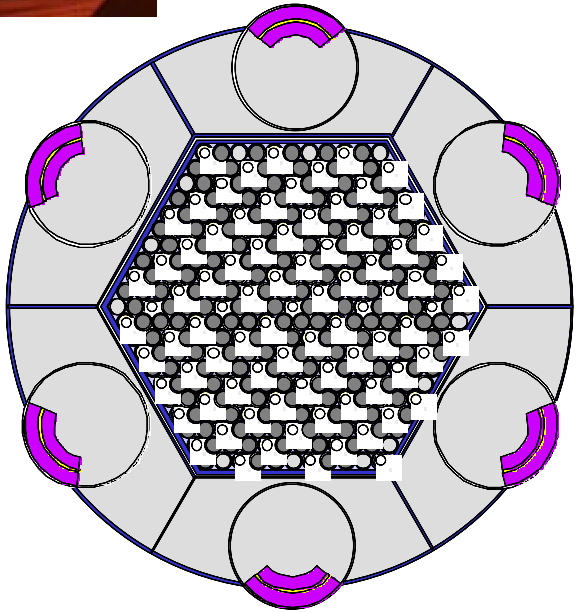
Fission Systems
Ongoing Research - Phase 1

SAFE-300 Preliminary Design / Fabrication Research

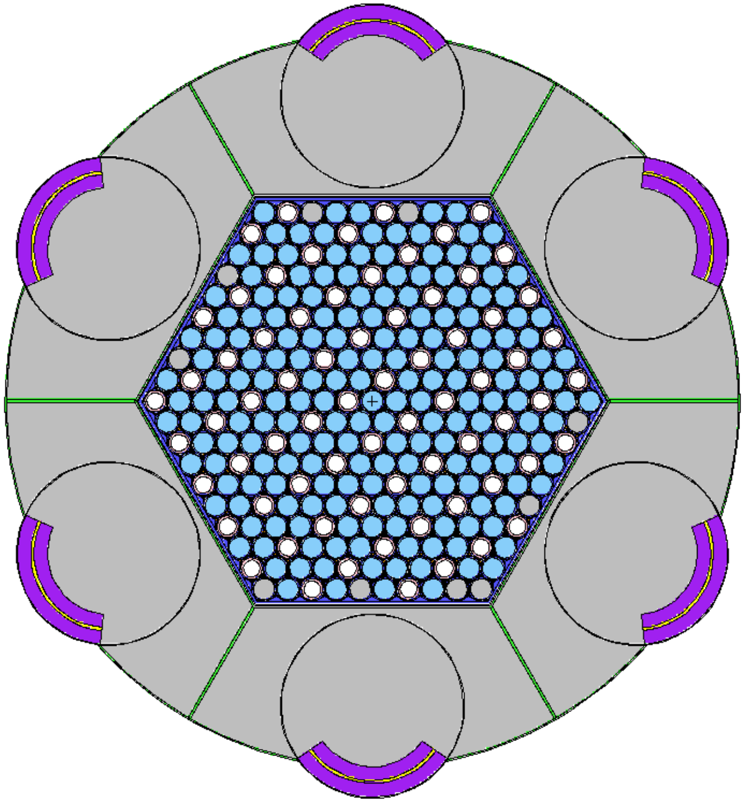


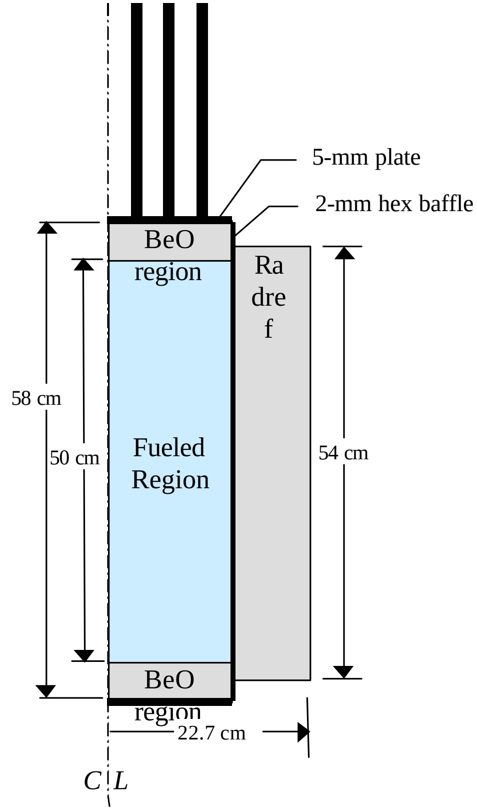


- High-Temperature SAFE Module Tests Completed in FY00.
- > 1750 K Core Module Temperature.
- > 1450 K Heatpipe Temperature.
- Direct thermal propulsion mode.
- Fast start of heatpipe (room temp to >1400 K in < 1 hr).
- Multiple restarts.
- Operates within established burnup and radiation damage limits, no nuclear technology development. Realistic full-thrust tests at NASA facility.
- Passive safety via in-space fueling or choice of core materials.
- No new or significantly modified facilities required for development.



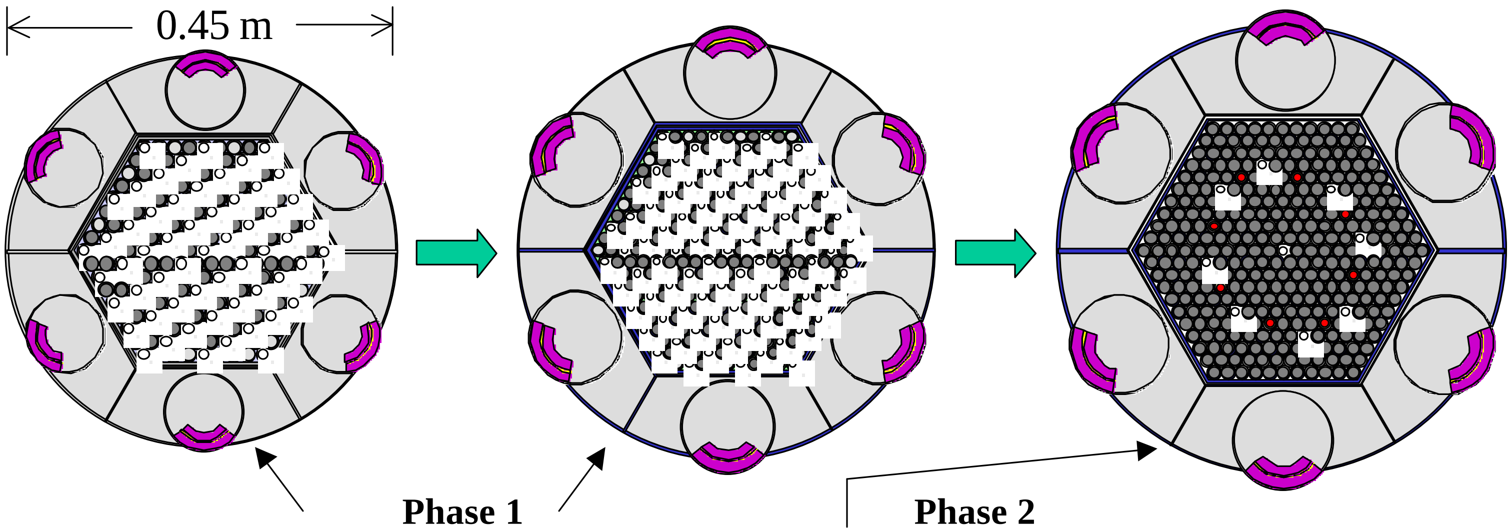
SAFE-300 Geometry





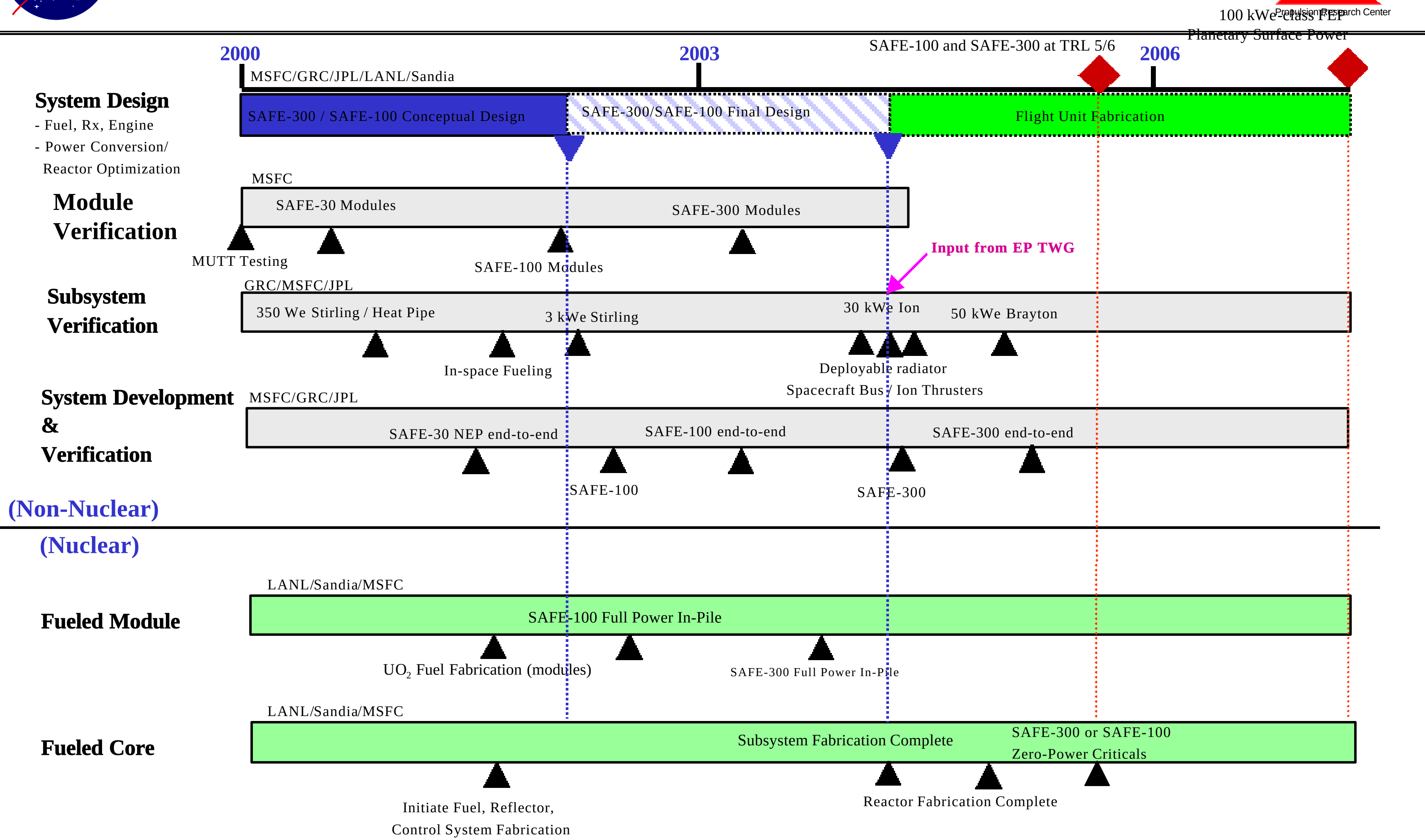
Evolutionary 20 to 4000 kWe Space Fission Program

Utilization of Phase 1 Fission System Enables Follow-on System Development



	20 kWe Surface	SAFE-300 (~100 kWe Space)	400 kWe Space	4 MWe Space
Fuel Form	Pin (Pellets)	Pin (Pellets)	Pin (Pellets)	Pin (Pellets)
Pin Diameter	~1.7 cm	1.59 cm	~1.27 cm	~0.5 cm
Number of Pins	~150	191	~400	~3000
Fuel Material*	UO_2	UO_2	UO_2	UO_2
Clad Material	SS	Mo	Mo	Mo
Axial (in-pin) Reflector	BeO	BeO	BeO	BeO
Radial Reflector	Be	Be	Be	Be
Shield	LiH/W	LiH/W	LiH/W	LiH/W
Power Conversion	Stirling (ARPS-based)	Brayton	Brayton	Brayton
Primary Heat Transport	Heat pipes	Heat pipes	Flowing gas	Flowing gas
Backup cooling/power	Heat pipes	Heat pipes	Heat pipes	Heat pipes
Launch Safety (primary)	Passive Spectral	Passive Spectral	Passive Spectral	Safety Rods
Radiator	Deployable	Deployable	Deployable	Deployable
Control	Drums (B_4C)	Drums (B_4C)	Drums (B_4C)	Drums (B_4C)
Development Facilities	Existing	Existing	Existing	Significant Mod

Phase 1 Space Fission Propulsion



Fission Systems
Potential Research - Phase 2

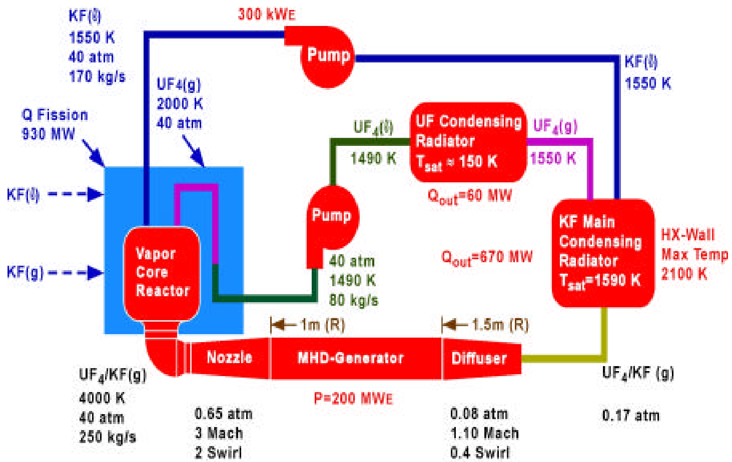
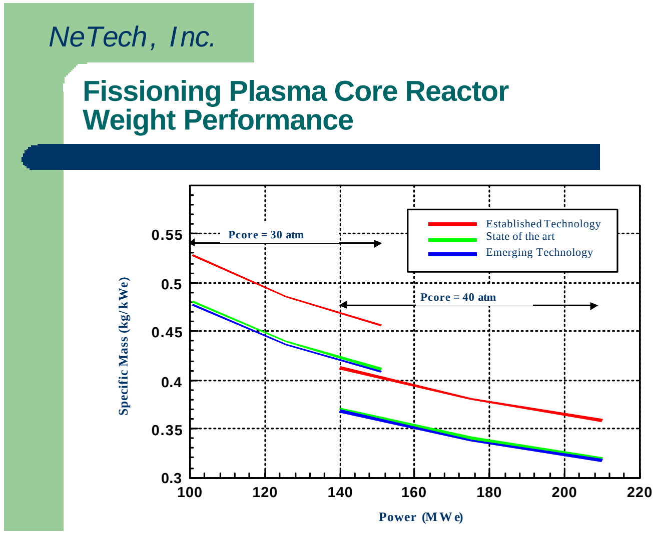


Illustration of a 200 MWe gas core reactor with MHD energy conversion in a closed Rankine cycle (specific mass 0.37 kg/kWe.)

High Performance Closed-Loop System



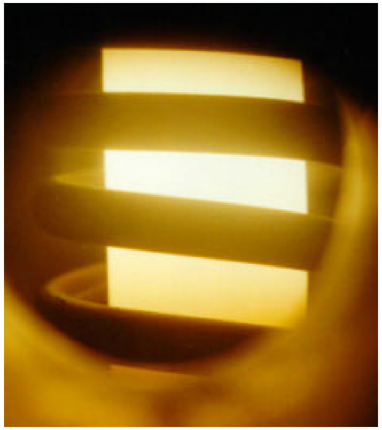
Integrated propulsion system capable of high specific power (> 1 kW/kg) at high power (>50 MWe) and high specific impulse (>> 3000 s).

Vapor Core / MHD system :

Safety: Launch, Operation, and End-of-Life
Operability
Core design / control
High temperature waste heat rejection
Direct drive of thrusters

Fission Systems
Potential Research - Phase 2

Propulsion Research Center



NTR and Fuels:

• Recapture coated-particle graphite matrix fuel technology used in Rover/NERVA full-core nuclear tests. Capable of >850 s Isp for > 1 hr using modern engine cycles.

• Initiate advanced fuels research capable of extremely high temperature operation (>925 s Isp for > 1 hr using modern engine cycles).

• Research on "bimodal" fuels. Short duration, high temperature operation inter-mixed with long-duration, lower-temperature operation.

• Investigate options for using extraterrestrial resources to enhance capability of NTRs. GRC-led Lunar oxygen Augmented Nuclear Thermal Rocket (LANTR) tests have demonstrated significant thrust augmentation.

Observations / Conclusions

- Fission technology has the potential for enabling rapid, affordable access to any point in the solar system. A viable development path needs to be chosen.
- Affordable, near-term systems with good performance can be developed using established nuclear technology and state-of-the-art power conversion and spacecraft components. These systems are applicable to near-term missions of interest.