Nuclear Energy for the Space Exploration Initiative

- Basic Premise - Nuclear Energy will be required and can be safely provided for power, heat, and propulsion for manned exploration spacecraft, bases, rovers, and robots

- System requirements, design plans, capabilities, and safety considerations will be discussed by panel members (and the audience):

Ron Creel (Moderator) - Set the stage with some historical perspective - Nuclear power and heat sources were safely used on previous lunar missions

Dr. Jaime Reyes (Lockheed) - Describe RTG and RHU utility, designs, and space mission experience

Dr. Robert Zubrin (Mars Society) - Nuclear power for Mars propulsion, habitats, and rovers.

Tom Kessler (Boeing) - Nuclear propulsion for distant missions (JIMO, etc.)

Roger Lenard (Sandia) - Safety considerations for Nuclear use in Space, including the role of DOE and Naval Reactors

Nuclear Energy for the Exploration Initiative

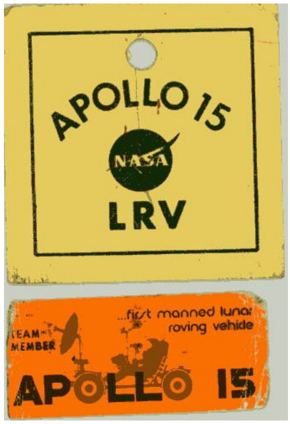
Apollo Lunar Roving Vehicle and Russian Rover Nuclear Experiences

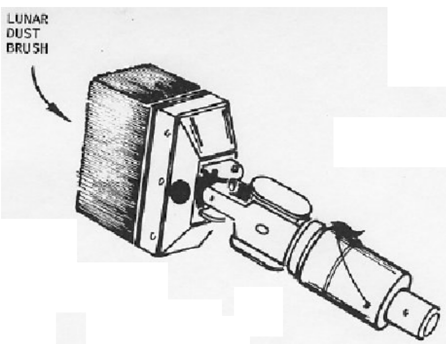
May 30, 2004

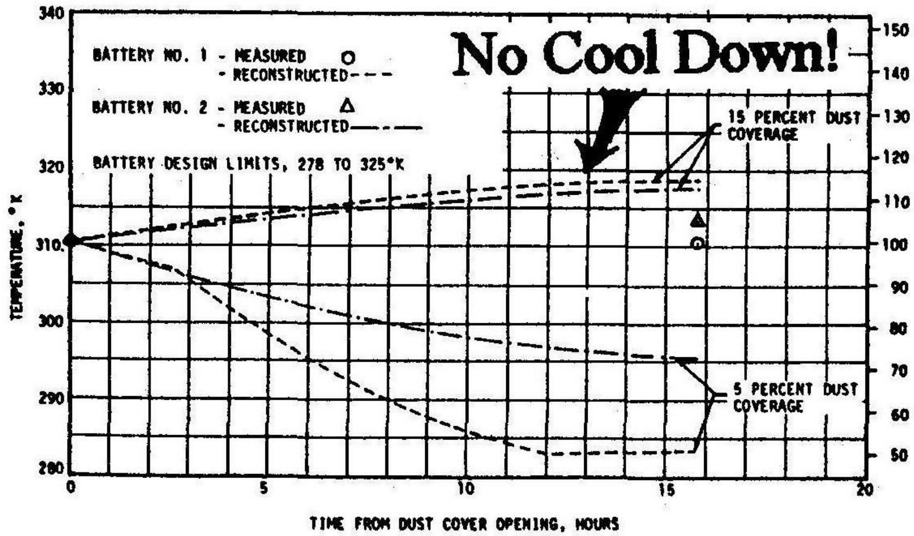
Ron Creel, Science Applications International Corporation (SAIC) discussed charts excerpted from his “Back to the Future” ISDC-2004 presentation.

Future Moon Rover Challenge 1 – Design Around Bad Effects Of Dust

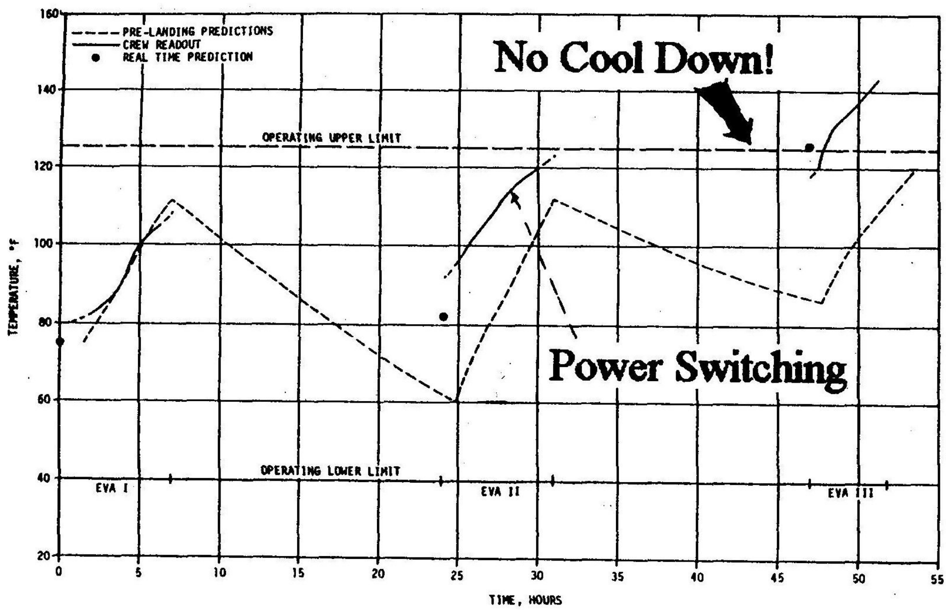
- Dust On Apollo LRV's Severely Reduced Battery Cooldowns – Brushing Radiators Was Ineffective
- Based On Cumulative Dust Effects, Astronauts Stated That They Doubted Longer Missions Were Possible



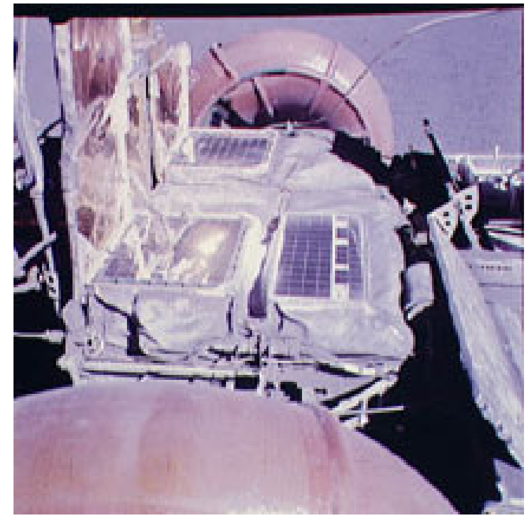




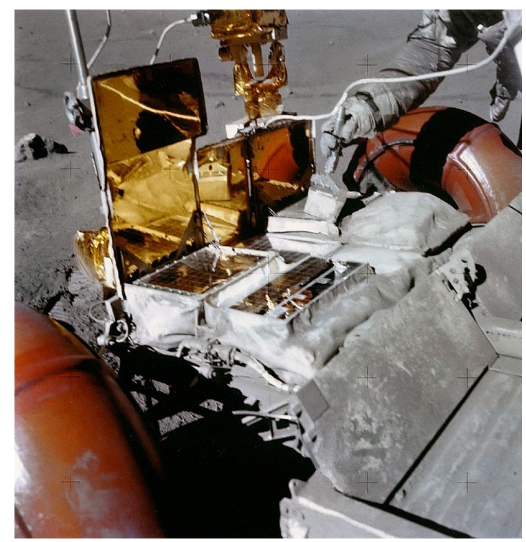
LRV Battery Temperatures During Cooldown 2



Battery No. 2 Temperature



Dust On Radiators



Astronaut Brushing Dust From Radiators

Future Moon Rover Challenge 2 – Design For Extended Cold/Hot Missions

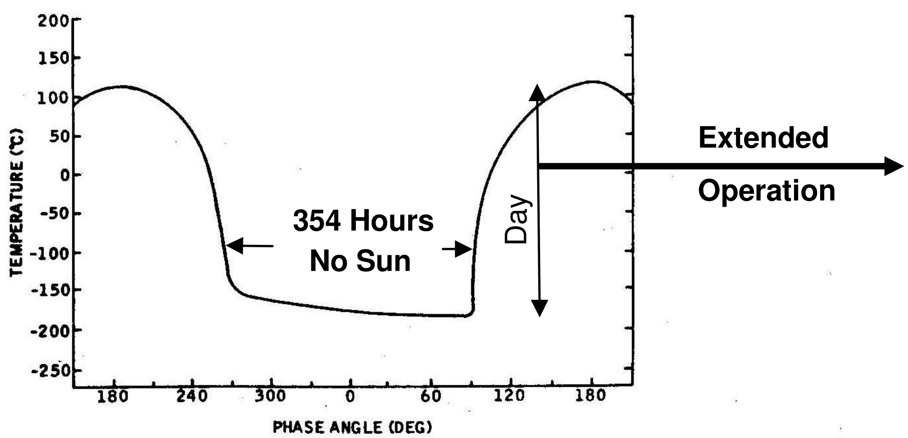
- Extended Operation In Much Colder And Warmer Environments Than Apollo LRV's

Lunar Night

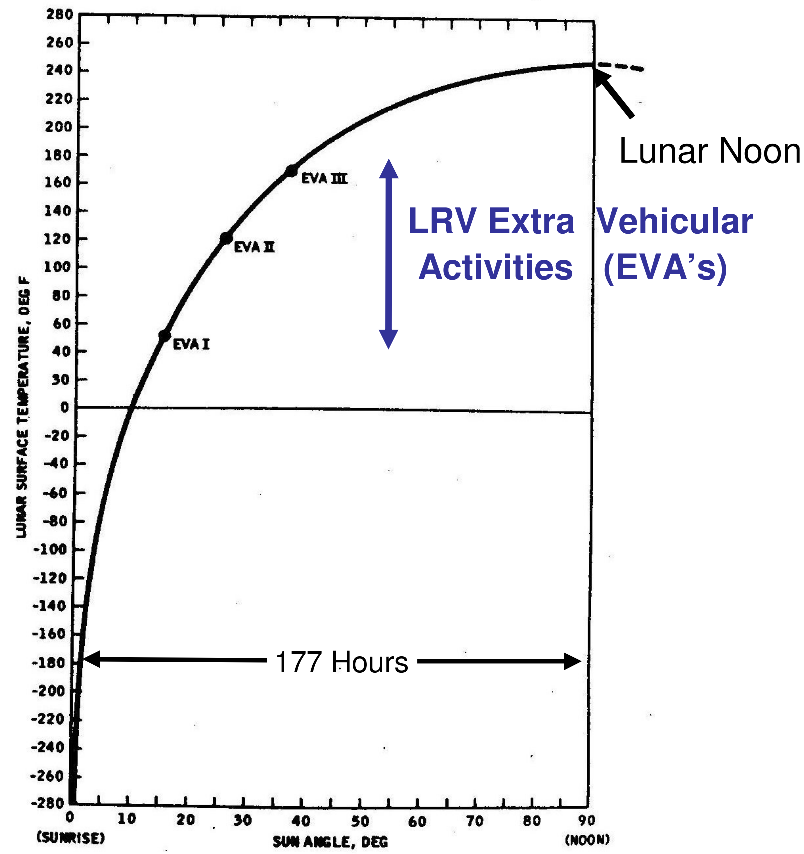
- 354 Hours Without Solar, Moon Heating
- Surface Temperature = -280 Deg. F

Lunar Day

- 354 Hours With Solar, Moon Heating
- Max. Surface Temp. = +250 Deg. F



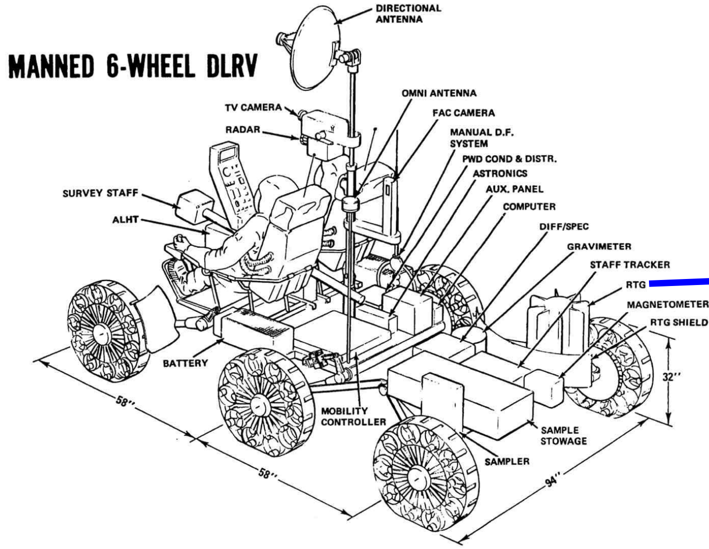
Temperature of the Moon. The average temperature of the Moon as a function of phase, or time, is shown here. The exact shape of the curve varies somewhat with geographical position on the Moon and is determined by the thermal properties at each position.

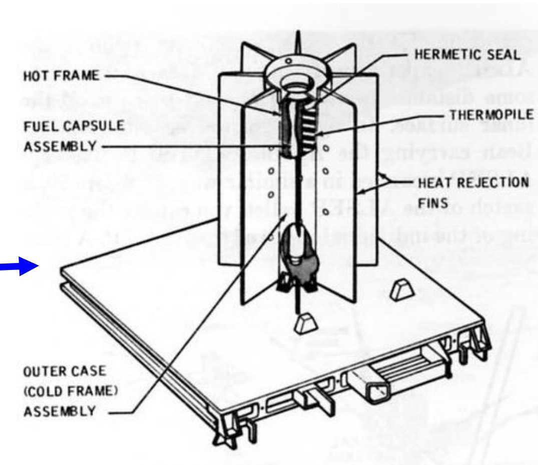


The temperature of the Taurus-Littrow site shown as a function of the Sun angle. Note that EVA 1 at +17° Sun angle should have +50° F, EVA 2 at +27° Sun angle should have +110° F, and EVA 3 at +37° Sun angle should have a temperature of +160° F.

Nuclear Energy To Meet Moon Thermal Challenges

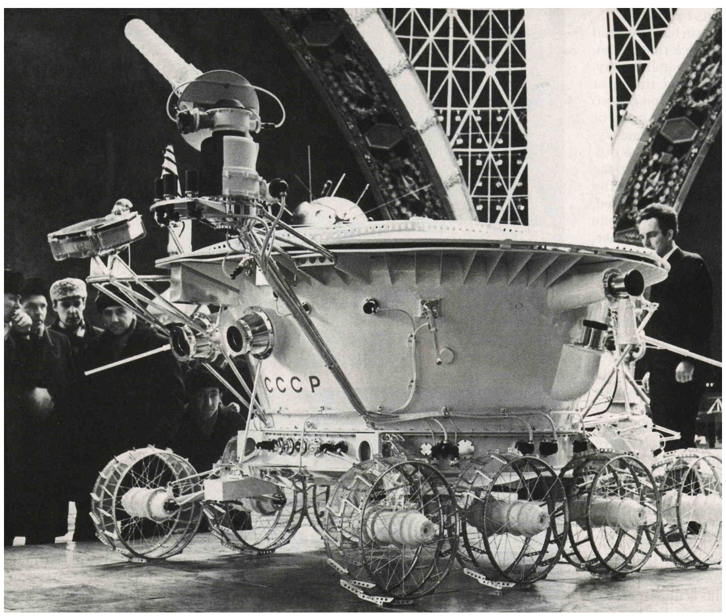
- Nuclear Power Sources Were Used On Apollo, Studied For Dual Mode Rovers



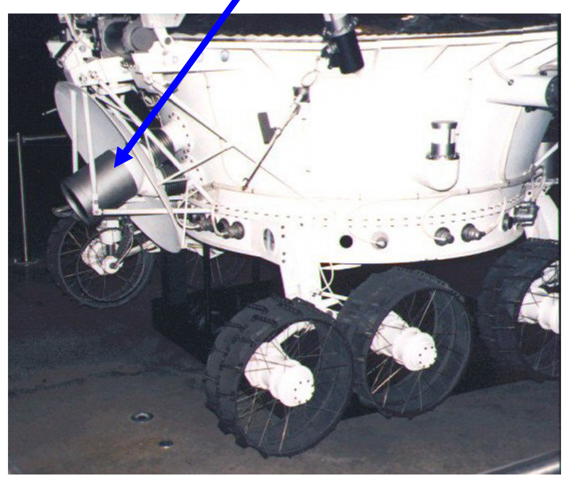


Radioisotope Thermal Generator. This equipment provides all of the power used by the ALSEP. It furnishes continuously about 70 watts.

- Russians Successfully Used Nuclear Isotope Heat Sources On Their Lunokhod (Moonwalker) Robotic Rovers



Isotope Heater



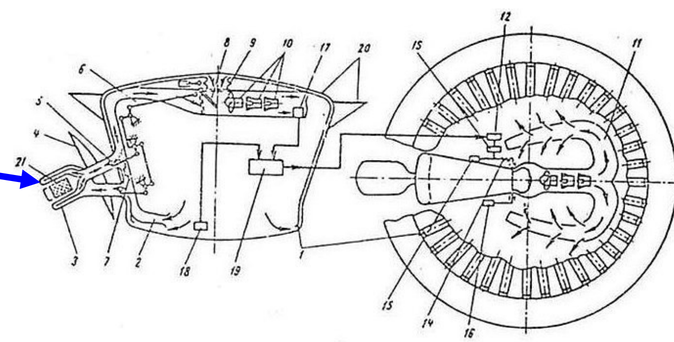
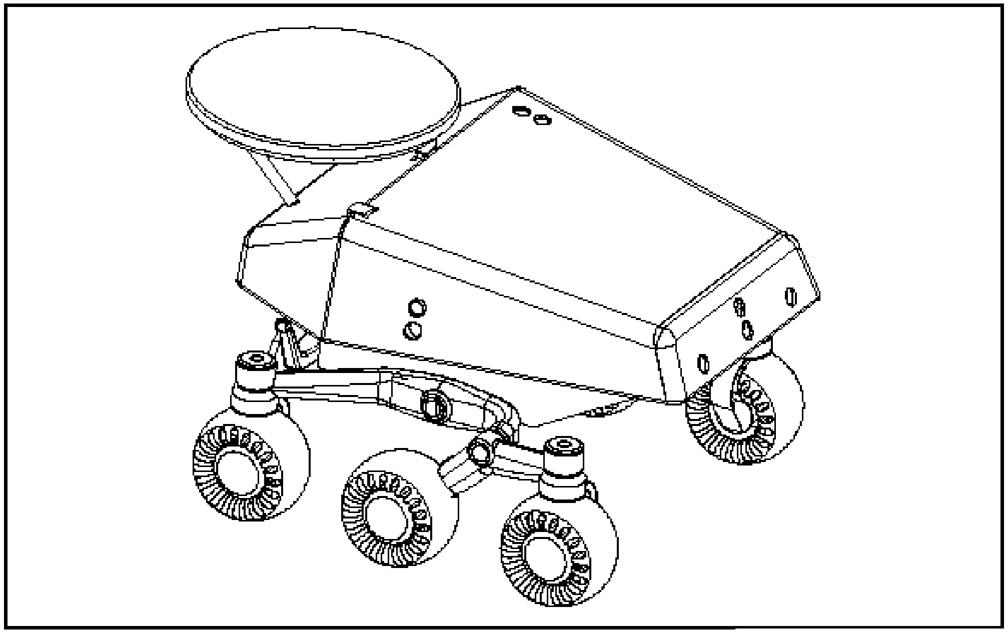


Diagram of lunokhod heat regulating system. 1) air passages of cold channel; 2) air passage of hot channel; 3) heating unit (HU); 4) HU shield; 5) HU "blinds"; 6) control of HU blinds; 7) baffle plate; 8) baffle; 9) connecting sheath; 10) three-step fan; 11) collector; 12) baffle drive; 13) step mechanism; 14) spring traction; 15) cam mechanism; 16) angular movements sensor; 17) SE1 sensing element; 18) SE2 sensing element; 19) radiator-cooler; 20) collector of HU blow-off system; 21) fuel cell.

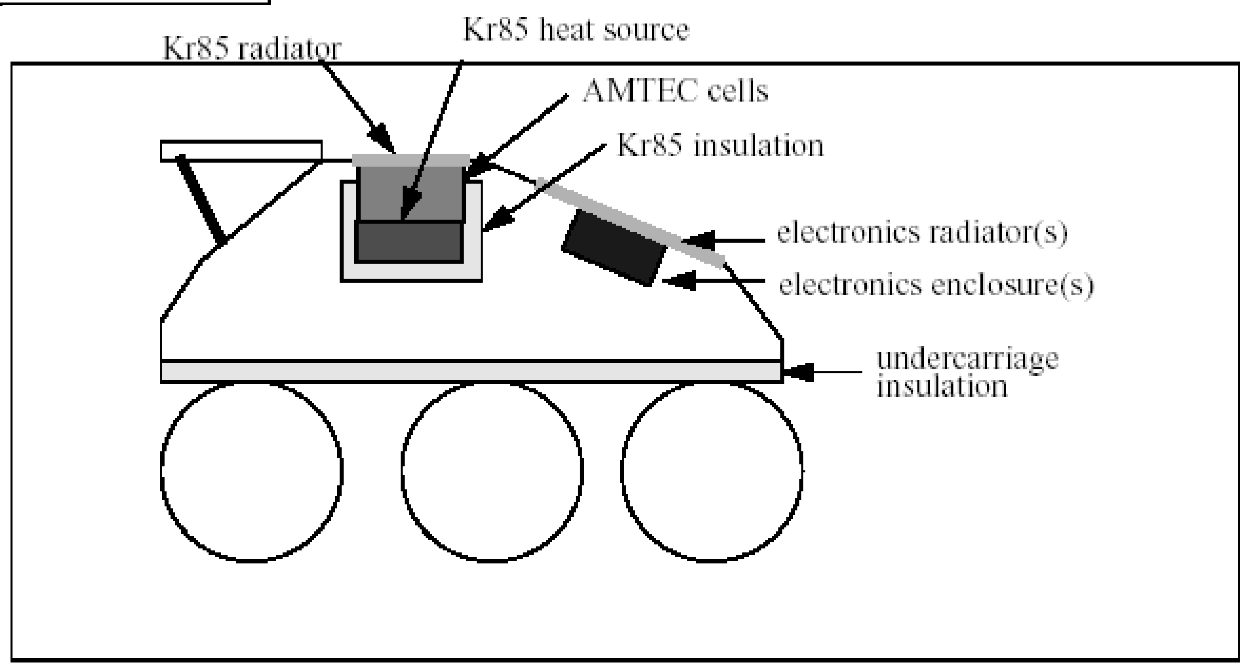
For monitoring the thermal regime aboard the lunokhod there are telemetric temperature sensors which make it possible to obtain routine information on the temperatures of all lunokhod systems during any communication session.

Consulting With Robotics Institute At Carnegie Mellon Resulted In Closed-Up Design With Isotope Heat Sources



Robotic Moon Rover

- Potential Lunar Dust Degradation And Temperature Environment Extremes Would Be Mitigated By Using Closed-Up Isotope Heated Enclosure For CMU "Day-Night" Robotic Rover



Radioisotope Heater And Thermal Control Radiators

Safe Handling Of Radioactive Materials Was Accomplished On Previous Apollo Moon Missions

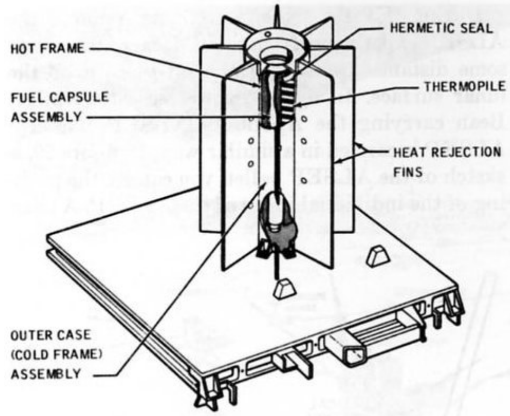


FIGURE 25.—Radioisotope Thermal Generator. This equipment provides all of the power used by the ALSEP. It furnishes continuously about 70 watts. NASA PHOTO S–71–29730.

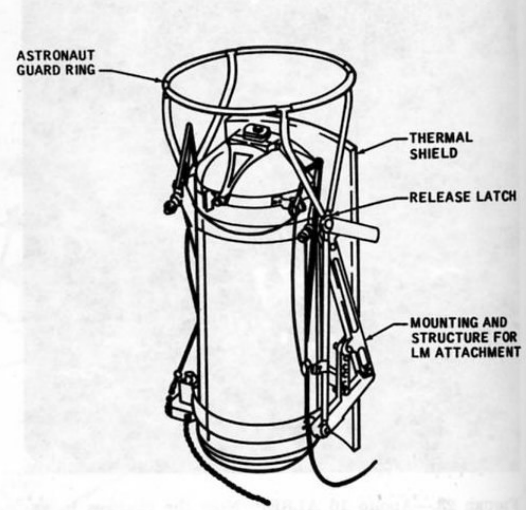


FIGURE 26.—Fuel cask. The fuel, radioactive plutonium, for the RTG is carried to the Moon in this cask, which is mounted outside the LM.

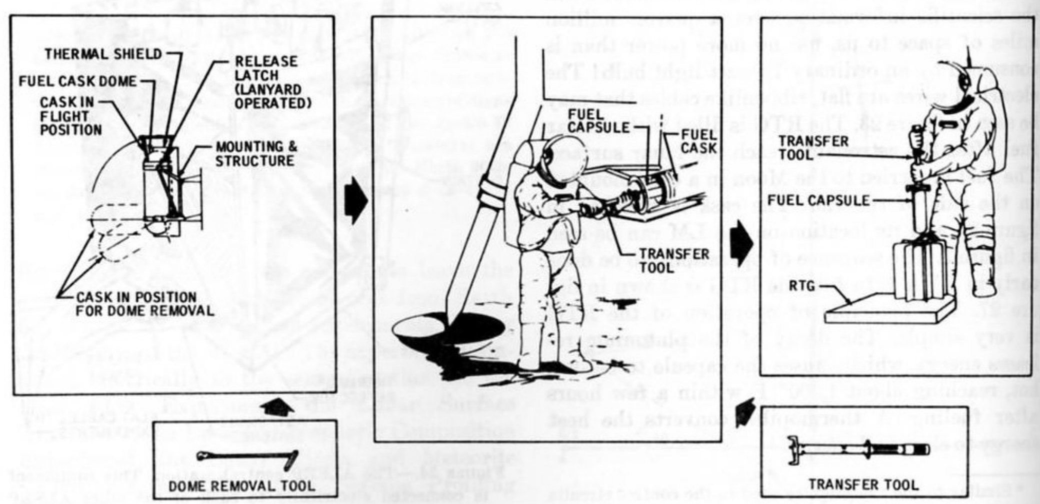


FIGURE 27.—Fueling of RTG. The sequence of operations to be done by one of the astronauts on the Moon to place the capsule of radioactive fuel in the RTG is shown here. The fuel capsule is very hot and so it is handled very carefully. NASA PHOTO S–72–50295.

Nuclear Energy for the Exploration Initiative

Radioisotope Power Systems

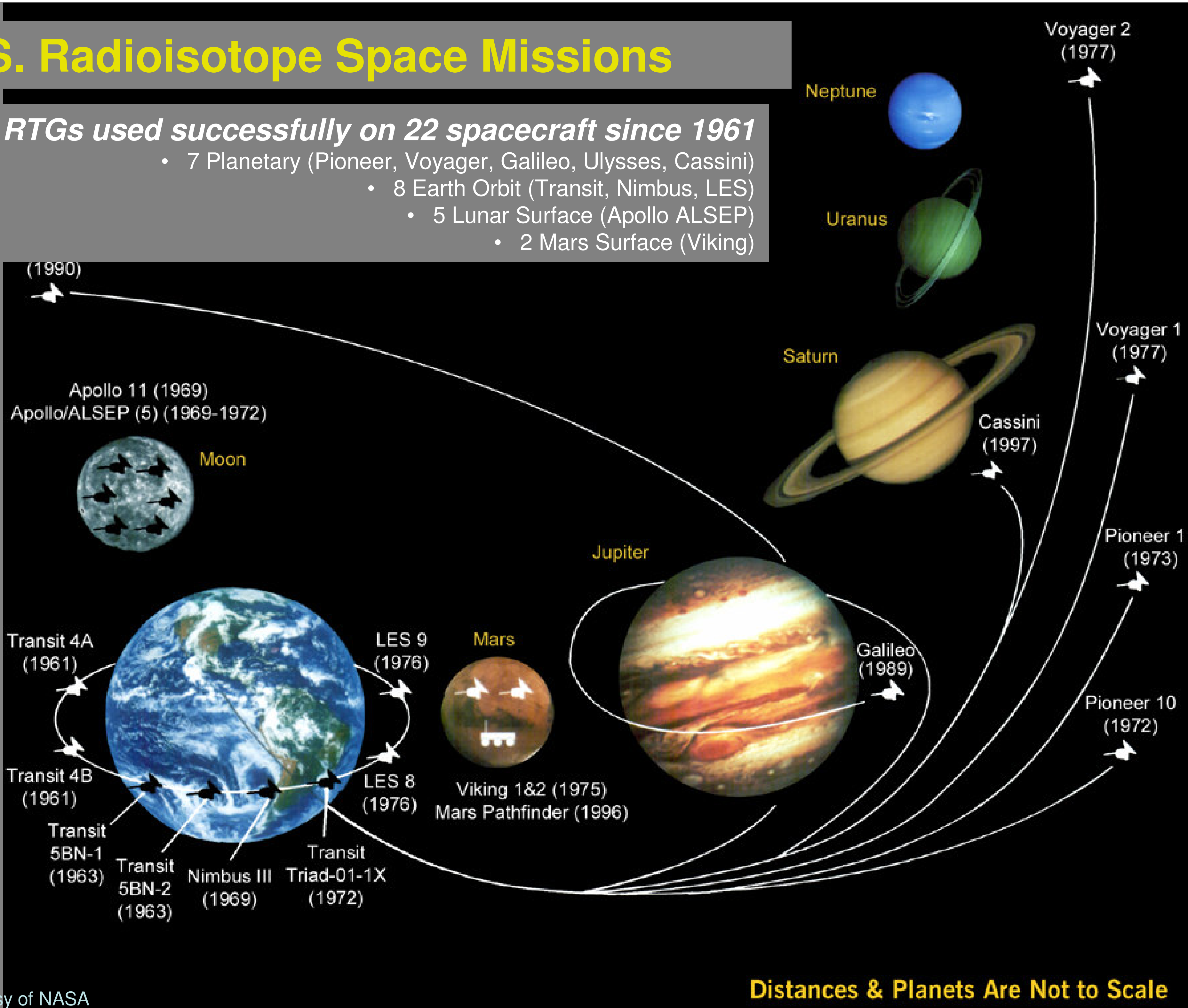
May 30, 2004

Dr. Jaime Reyes, Lockheed

U.S. Radioisotope Space Missions

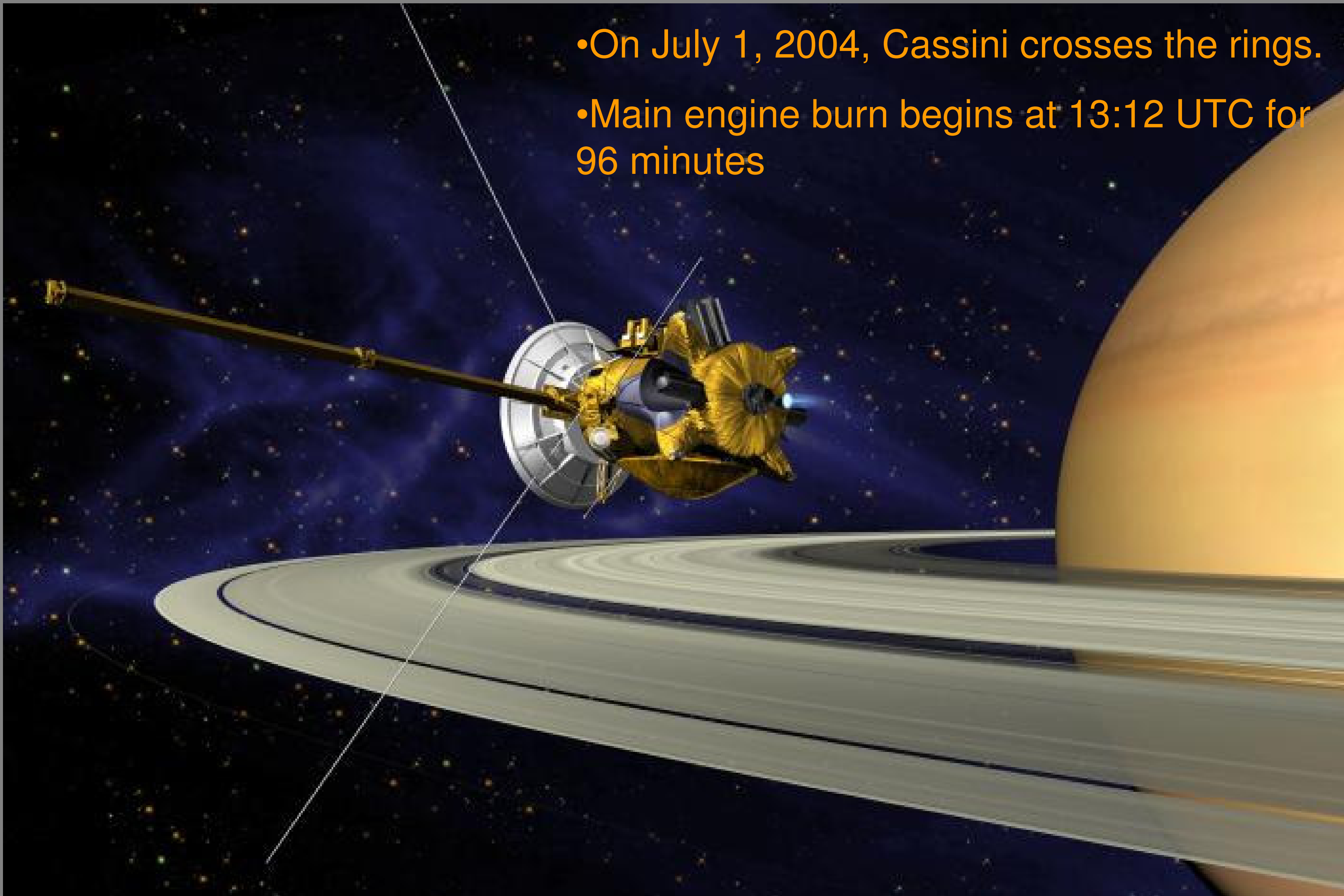
RTGs used successfully on 22 spacecraft since 1961

- 7 Planetary (Pioneer, Voyager, Galileo, Ulysses, Cassini)
- 8 Earth Orbit (Transit, Nimbus, LES)
- 5 Lunar Surface (Apollo ALSEP)
- 2 Mars Surface (Viking)



Courtesy of NASA

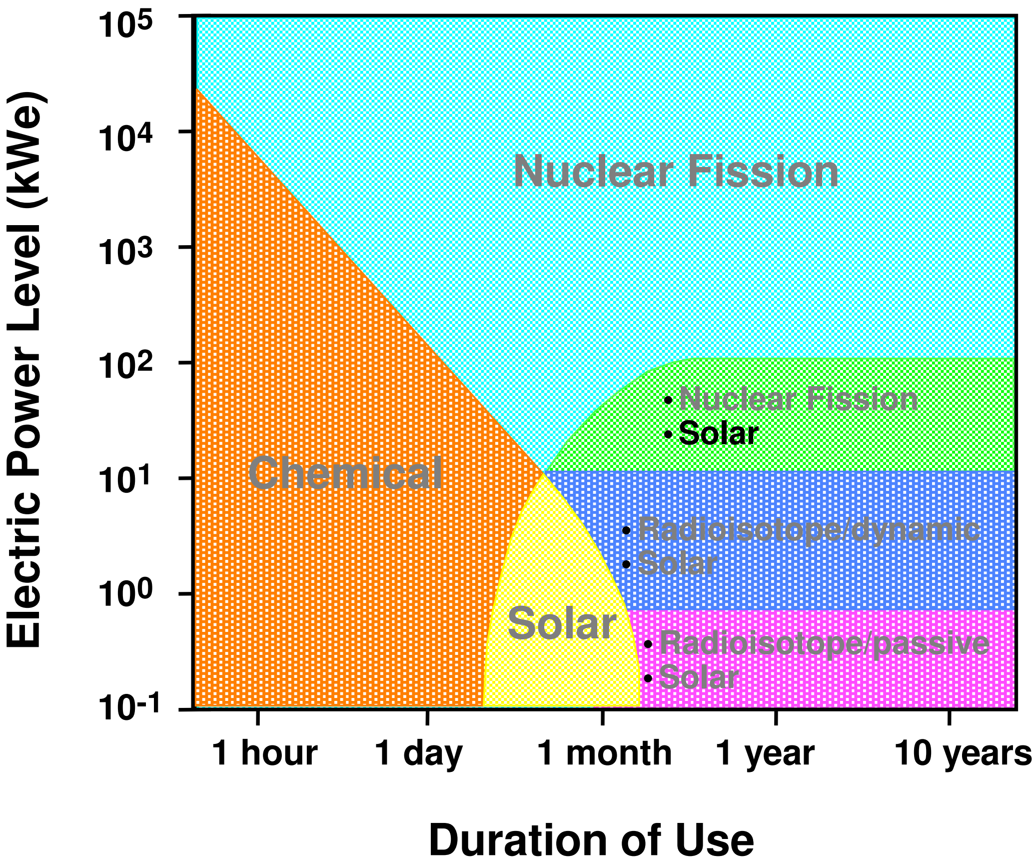
Cassini Saturn Orbit Insertion (SOI)



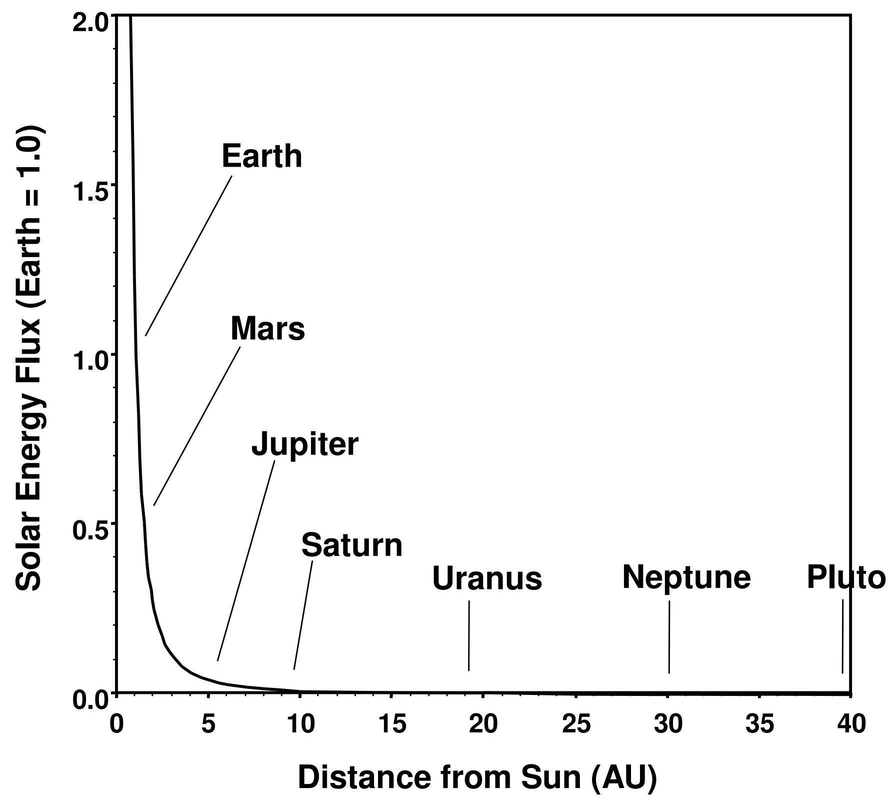
- On July 1, 2004, Cassini crosses the rings.
- Main engine burn begins at 13:12 UTC for 96 minutes

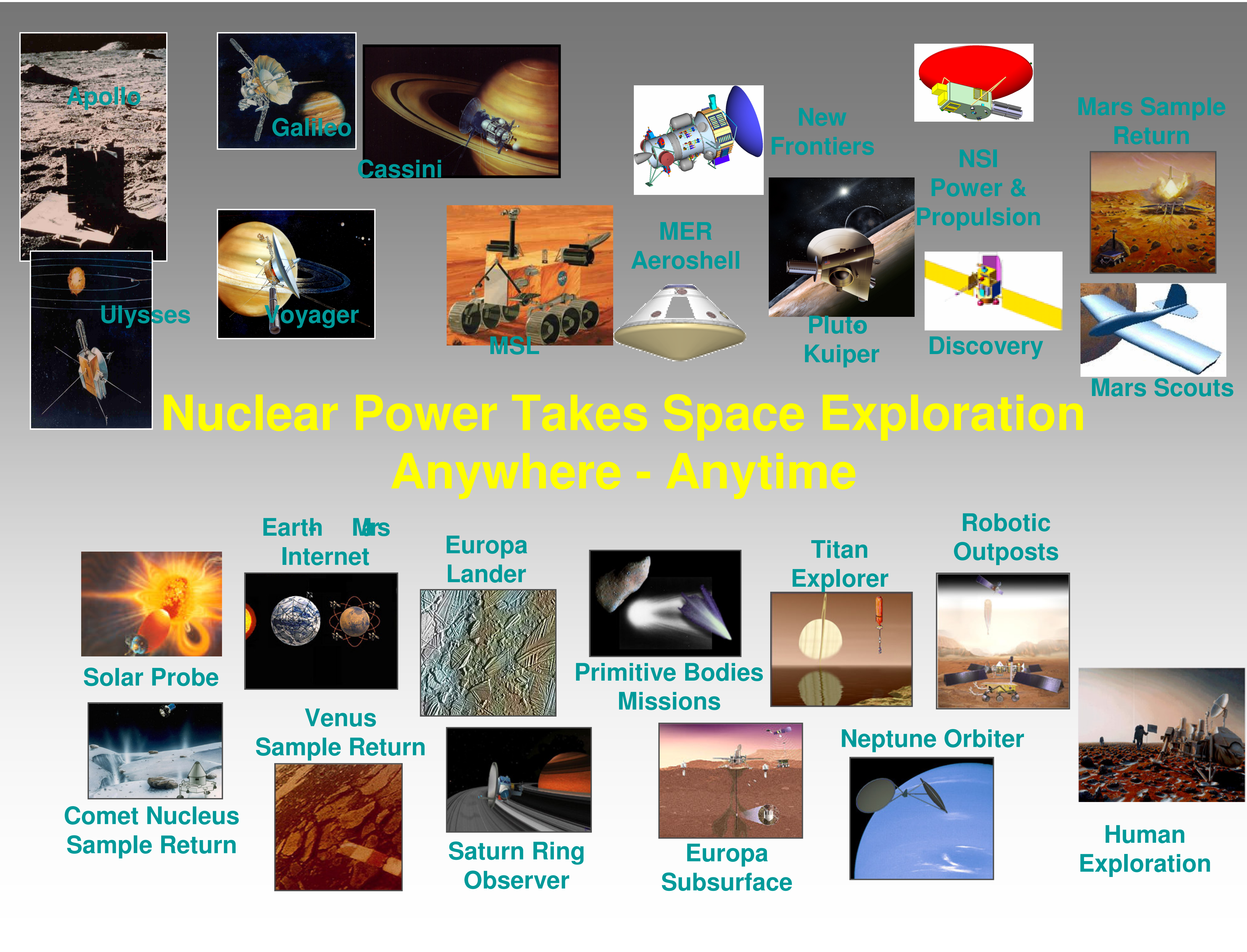
Space Exploration Power Systems

Power Sources Options

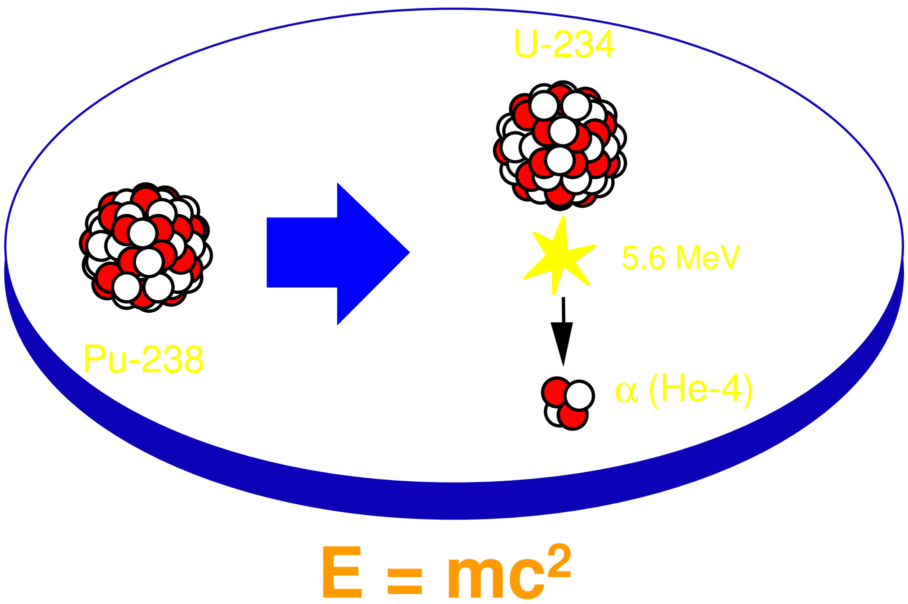


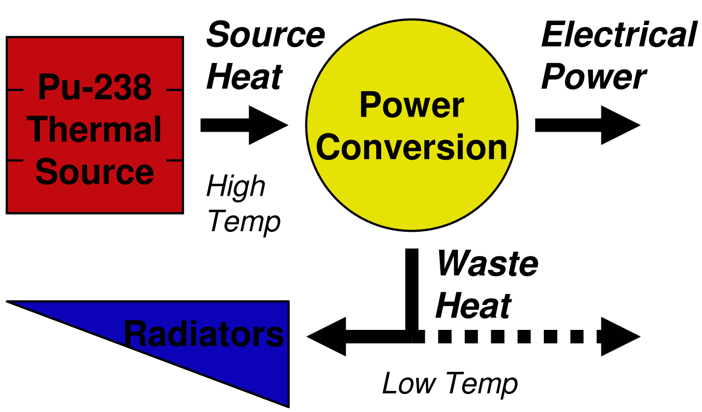
Limits of Solar Power




Apollo
Galileo
Cassini
New Frontiers
NSI Power & Propulsion
Mars Sample Return
Ulysses
Voyager
MSL
MER Aeroshell
Pluto Kuiper
Discovery
Mars Scouts
Nuclear Power Takes Space Exploration
Anywhere - Anytime
Earth Mars
Internet
Europa Lander
Robotic Outposts
Titan Explorer
Solar Probe
Primitive Bodies Missions
Venus Sample Return
Neptune Orbiter
Comet Nucleus Sample Return
Saturn Ring Observer
Europa Subsurface
Human Exploration

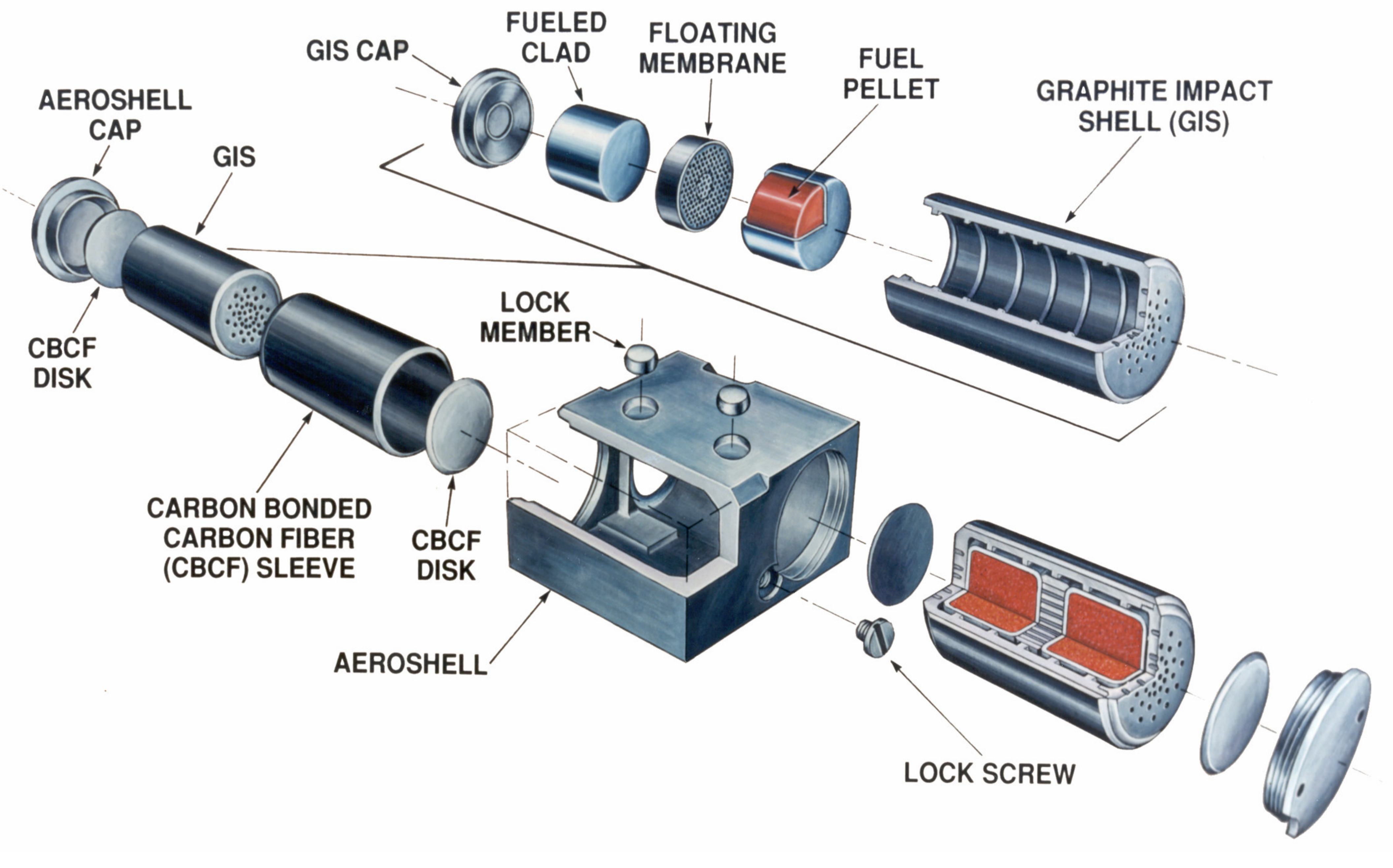
Radioisotope Heat Source





- **Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)**
  - 87.7-year half-life
- **Heat converted to electricity via passive or dynamic processes**
  - Thermoelectric (existing & under development)
  - Stirling (under development)
  - Brayton, TPV, etc. (future candidates)
- **Waste heat rejected through radiators – portion can be used for thermal control of spacecraft subsystems**

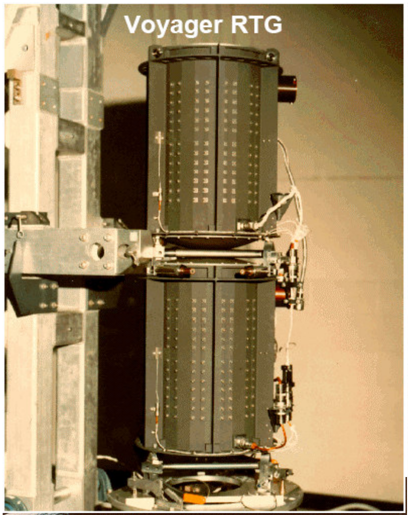
General Purpose Heat Source (GPHS)

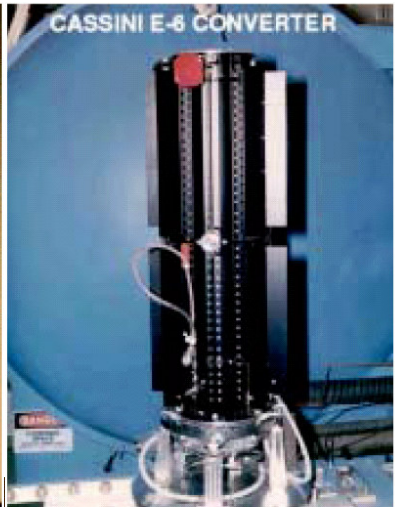


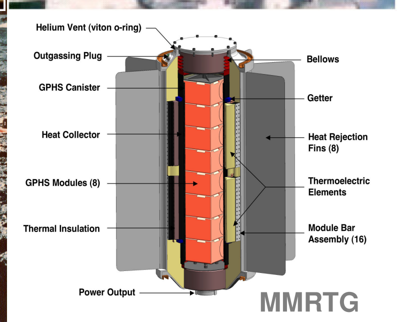
Radioisotope Heater Unit (RHU)

- **Recent uses for thermal control**
  - MER 03 - 16
  - Mars Pathfinder (Sojourner) - 3
  - Cassini - 117
  - Galileo - 120

RPS Power Systems
Past, Present, and Future







SNAP 3, 9, 19, 27

- Transit
- Nimbus
- Pioneer 10 & 11
- Viking 1 & 2
- Apollo 12, 14, 15, 16, 17

MHW-RTG

- LES 8/9
- Voyager 1 & 2

GPHS-RTG

- Galileo
- Ulysses
- Cassini

GPHS-RTG

-Pluto Kuiper Belt Explorer

SRG110/MMRTG

-Mars Science Lab

-Solar Probe

-New Frontiers 2

-Jupiter Polar Orbiter

-South Pole/Aitken Basin Sample Return

-Venus in situ explorer

-Comet Core Sample Return

Small RPS

-Mars Network

-Mars Scouts

Nominal Class

-ISRU

-Lunar/Mars Robotic Stations

-Manned exploration

Nuclear Energy for the Exploration Initiative

Mars Exploration Perspective

Dr. Robert Zubrin, Mars Society

Dr. Zubrin discussed the outlook for nuclear power and propulsion systems for the Mars part of the Space Exploration Initiative

(no charts were provided)

Technology Roadmaps for Advanced Nuclear Concepts
March 11, 2004

Original Presentation by Carl Walz
NASA Program Executive

Synopsis by Tom Kessler
Boeing JIMO Program Office
For ISDC-2004
May 30, 2004

Applications of Nuclear Related Technology

- New scale analogy: JIMO is to piloted interplanetary spacecraft as a small nuclear research submarine (NR-1) is to a Nimitz Class Aircraft Carrier
  - 100's kWe to Multi- Megawatt electric
- In addition, we have two competing concepts for piloted missions
  - Multi-Megawatt Nuclear Electric Propulsion
  - Nuclear Thermal Propulsion
- Regardless of which direction we take, JIMO nuclear technology WILL be used for the following additional applications
  - JIMO nuclear fuel and power conversion technologies have potential for surface power plant for human habitats, ISRU, robotic systems
  - JIMO reactor could be used as an auxiliary power system for piloted mission
  - JIMO power conversion technologies will be the basis for larger power conversion systems for larger NEP systems

Technology Roadmaps for Advanced Nuclear Concepts

Which Way for Piloted Spacecraft?

- First: For this analysis, define a Crew Exploration Vehicle and in-space propulsion element
  - Sized for a piloted round trip to Mars, 365 days desired to minimize astronaut exposure to interplanetary radiation, microgravity
  - Surface stay on Mars ~40 days
  - On orbit assembled
  - 25 MT CEV (habitat and return capsule) payload, no masses dropped
  - 5 MT auxiliary power system for NTP vehicle

- Second: do a parametric analysis of NEP and NTP systems.

Nuclear Electric Propulsion (NEP)

Features

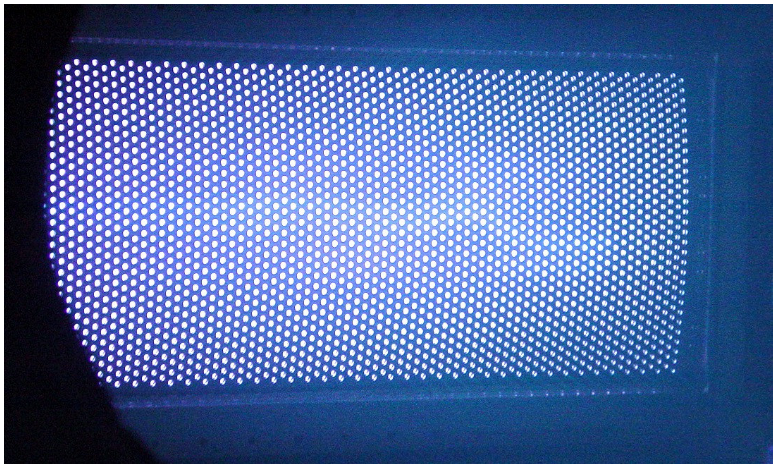
- Long-duration operation (10+ years for robotic missions)
- Low thrust , high efficiency electric engines (high Isp)
- Reactor generates large quantities of thermal energy 500+ kWt)
- Power conversion system converts heat to electricity (100's kWe)

Benefits

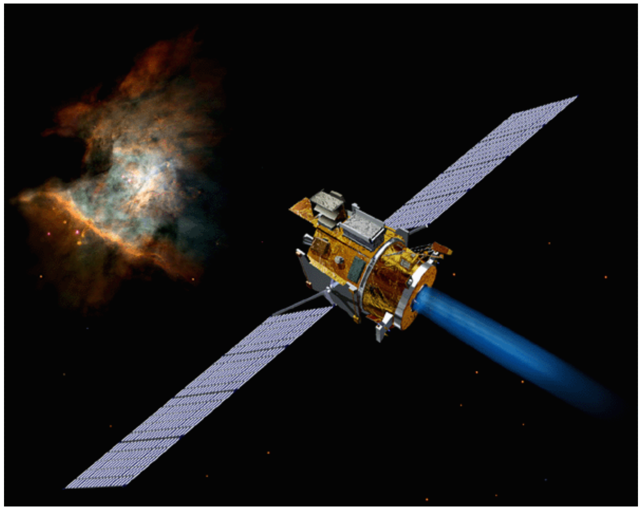
- Relaxes or eliminates launch window (timing) constraints (because few or no gravitational assists required)
- Provides high total velocity change after launch and ability to change course during mission (*vs*. free drift)
- Provides capability to enter into orbit around multiple objects (such as outer planet moons) *vs.* fly-by
- Large amounts of electrical power available for deep space instruments and communications

***History*:**

- Only launched low power reactors as power sources. Totals: US: 1 (1965), Russia: 34 (1970's – 1980's)
- Deep Space 1 demonstrated a capable electric propulsion system in space using solar power. HiPEP is one of many ground based tests and demonstrations of electric propulsion.



HiPEP Ion Engine (25 kW)



Deep Space 1 (2.5 kW)

Nuclear Thermal Propulsion (NTP)

– Nuclear Engine for Rocket Vehicle Applications (NERVA)

FEATURES

- 50 – 250Klbs thrust engines, Isp 825-875 sec, 4.5 hrs total time on NRX-XE for 28 starts
- Very high power reactors generating high temperatures and high thrust
- Turbopumps, LH2 handling, nozzle technology from existing conventional systems are usable for NTP systems

BENEFITS

- Could provide thrust for piloted mission to Mars, Near Earth Asteroids
- Advanced NTP fuels could also enable future NEP systems (synergism between technologies)
- First generation NERVA fuel elements currently exists for initial research and testing to recapture technology

HISTORY

- Ground Tested in 1960’s and 1970’s

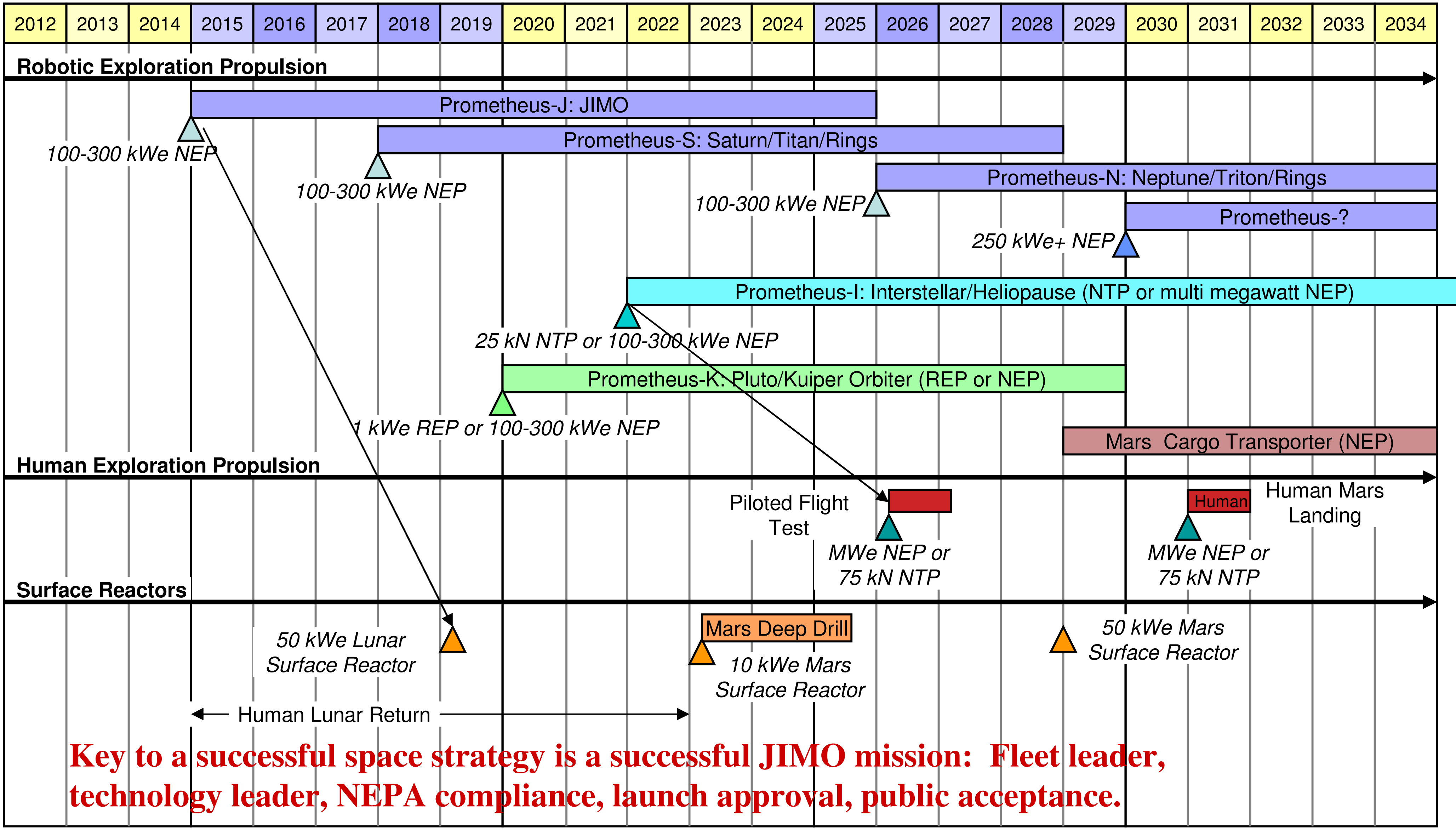
Technology Roadmaps for Advanced Nuclear Concepts

Analysis Summary

Propulsion Mode	Performance Level	Trip Time (days)	Initial Mass Low Earth Orbit (MT)	Comments
Chemical	SSME	480	890	Isp = 460 sec
Current NEP	UN pin fuel	<550	<900	Economy of scale for current SOA
Multi Megawatt NEP	2nd Gen fuel (CERMET)	440	700	2000 K core temp, continuous
Multi Megawatt NEP	3rd Gen fuel (gas core?)	365	400	3rd Gen power conversion,engines
Unknown	4th Gen fuel (TBD)	160	TBD	Possibly fusion?
NTP	Current (Graphite Prismatic)	365	533	Isp ~ 860 sec, 2500 K
NTP	2nd Gen fuel (CERMET)	365	463	Isp ~ 900 sec 2900 K
NTP	2nd Gen fuel (CERMET)	365	366	Isp ~ 980 sec (higher temp system)

Preliminary Project Prometheus Application Roadmap

Potential Applications of Prometheus Technologies in Notional Progression



Key to a successful space strategy is a successful JIMO mission: Fleet leader, technology leader, NEPA compliance, launch approval, public acceptance.

Technology Roadmaps for Advanced Nuclear Concepts

- Back up charts

Enabling Aspects of Space Nuclear Power Systems

- Systems and techniques developed within Project Prometheus for robotic missions will provide:
  - advanced capabilities for scientific exploration,
  - address long term issues for development of nuclear systems,
  - demonstrate operation of fission systems in space,
- Human surface exploration activities will also REQUIRE a new source of power (compact, all-weather, day and night), enabled by JIMO-developed technologies.
  - ample electric power to support a human crew
  - ample electric power to support in-situ resource utilization
- Human exploration vehicles will REQUIRE a new scale of power for propulsion systems.

New vehicle and power system concepts will build on current Project Prometheus technologies AND incorporate these new concepts

PROJECT PROMETHEUS History

- Project Prometheus brings increased electric power and electric propulsion to challenging science and exploration missions in space.
  - The ability to make 10's of kilowatts of electricity based on SP-100 nuclear reactor technology and its nuclear fuel, Uranium Nitride (UN).
  - An important robotic science missions that is uniquely enabled by these technologies.
    - JIMO supports the recommendation from the National Research Council Decadal Survey for a Europa Geophysical Explorer mission as a high priority for a flagship mission in Solar System exploration.
    - JIMO would be the first demonstration of a Nuclear Electric Powered mission for science and exploration.
  - The new Exploration Vision dictates that we look at additional ways to use nuclear power for human and robotic missions, such as nuclear surface power and propulsion systems scaled for human missions.

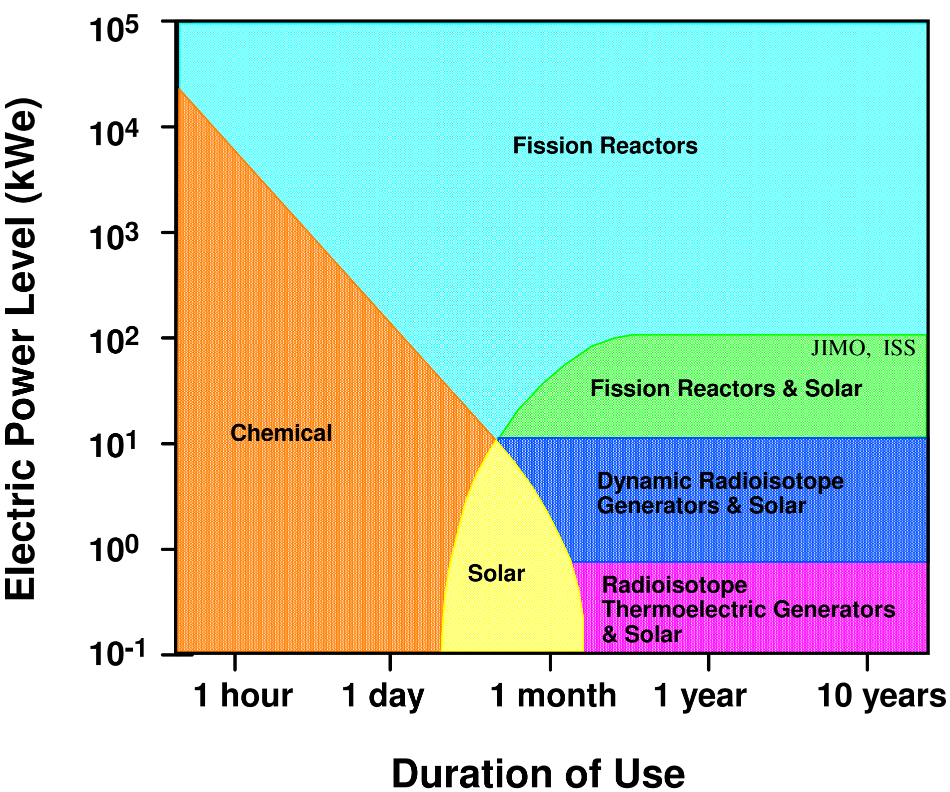
Technology Roadmaps for Advanced Nuclear Concepts

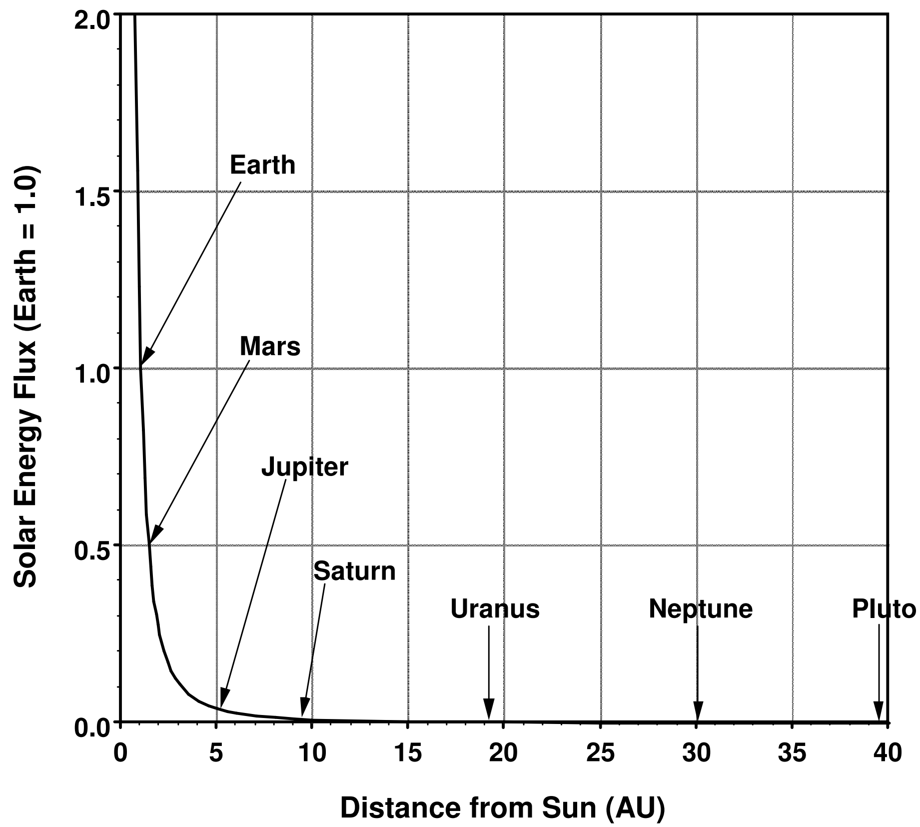
Summary

- Key to successful space nuclear strategy is a successful JIMO mission.
  - Fleet leader for reactor development, regulatory compliance (NEPA), public acceptance, launch approval
- Current investment in nuclear power and propulsion technologies would yield additional capabilities for robotic missions and support of human habitats (surface and en-route) and ISRU.
- With addition of human planetary transportation, a new scale of power and/or propulsion will be required.
  - New investment in nuclear fuels would need to begin now.
    - Cermet fuels for NTP/NEP applications
  - Current investment in nuclear power and propulsion technologies must continue:
    - Recapture and extend NERVA-like technology
    - Electric Propulsion technologies
  - Decision on NTP versus multi-megawatt NEP can be made later.

Enabling Aspects of Space Nuclear Power Systems

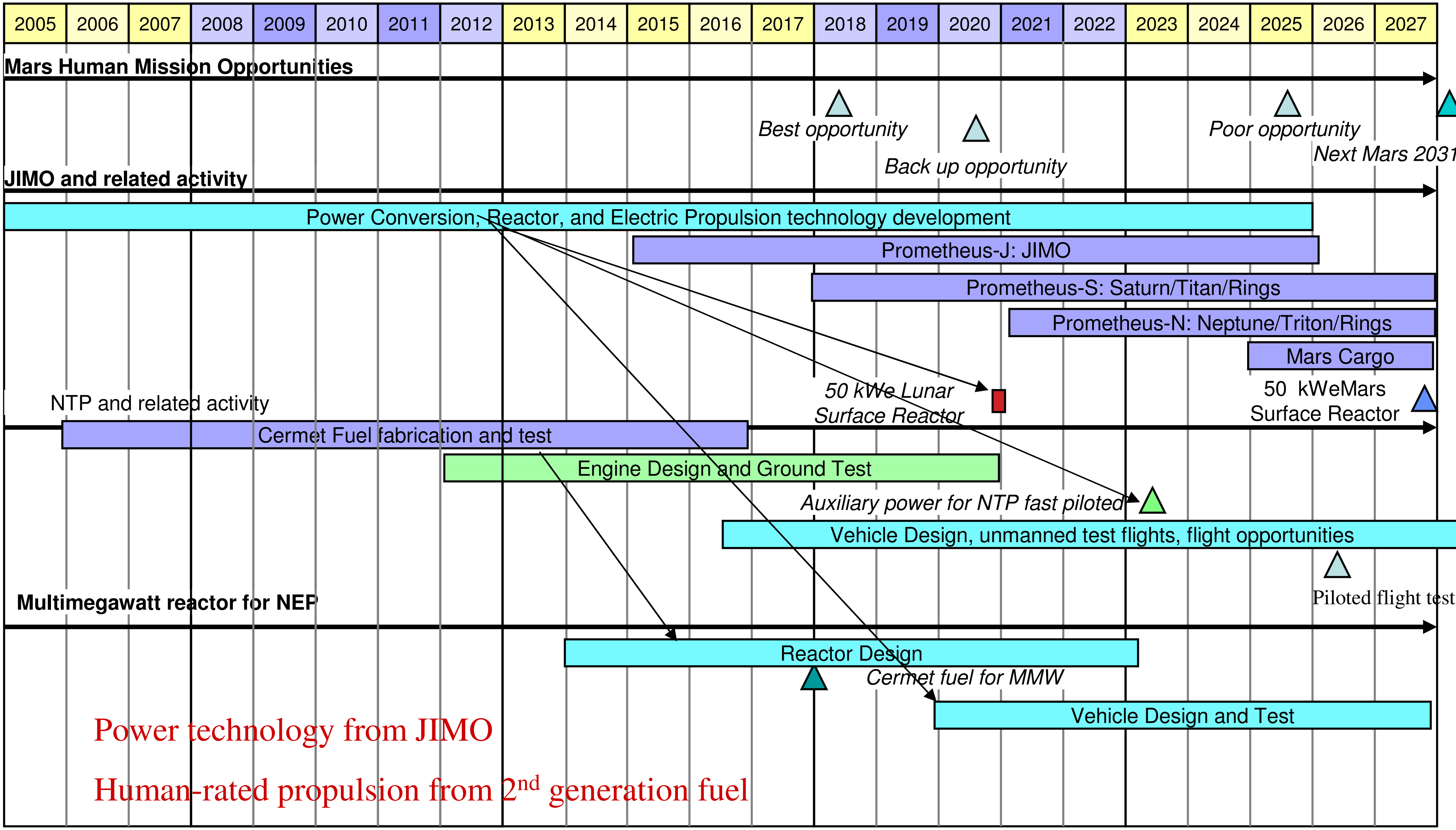
- Operate continuously regardless of orientation or distance from the Sun
  - Night, lunar polar craters, high Martian latitudes
- Operate for long-durations (years to decades) at power levels from milliwatts to megawatts
- Operate in harsh environments (radiation, weather, magnetic)
- Provide long-lived heat source
- Support high (nuclear thermal) or low (electric) thrust propulsion systems and flagship-scale missions





Robotic and Human Flight Opportunities and Technology

Technology Tie-Ins to Project Prometheus Potential Applications



PROJECT PROMETHEUS History

- Project Prometheus initiated in response to identified technical limitations of the current paradigm for Solar System exploration
  - Solar power is not a viable source of power for missions to the outer solar system
  - Electric propulsion requires large amounts of power
  - The use of nuclear power sources greatly improves the reach of missions on planetary surfaces.
  - Chemical propulsion limits maneuverability and destinations
- Initial mission studies, detailed technical analysis, and industry surveys completed in early 2003
- Nuclear Systems Initiative included in President’s FY03 Budget and renamed Project Prometheus in President’s FY04
  - Funding for the first Project Prometheus mission was provided by Congress in FY03 for the Jupiter Icy Moons Orbiter (JIMO) mission
- Support from Administration shows commitment that nuclear power and propulsion and power is an essential addition to future NASA missions and that JIMO is an example of what science can be accomplished with the technologies developed within Project Prometheus

Technology Roadmaps for Advanced Nuclear Concepts

- Another Way to Assess NEP Technology
  - System "alpha" is the measure of specific power in kg/kWe
  - System "alpha" values can represent level of NEP technology.
    - Current JIMO "alpha" between 80 and 100.
      - Could be scaled up to alpha of ~25* for a larger system (.6 empirical scaling factor yields 48 to 60), but just building a bigger core is not the answer, since heat rejection must be considered
    - Competitive human-rated systems (minimizing trip time) need an alpha below 10
    - NEP alpha values rely on simultaneous development of five technologies: reactor, power conversion, power management and distribution, thermal control, and electric thrusters
      - Difficult to predict the pace of technical advancement
    - Higher temperature materials, fuels required
    - *Frisbee, Nuclear Electric Propulsion Mars Cargo Missions, 12 May 1993, Final Briefing

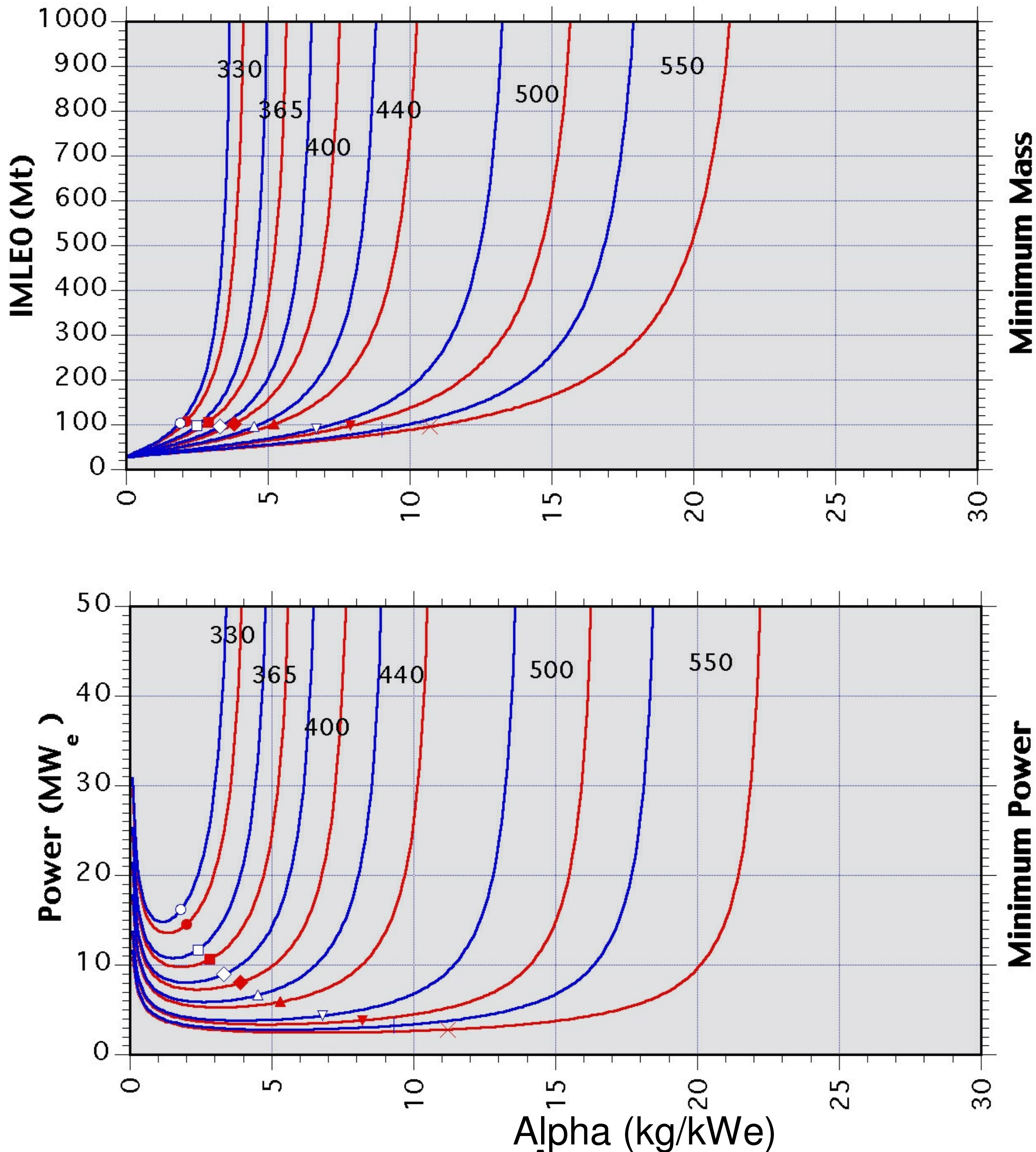
Next Steps

- Requirements Definition
  - Core and Blue Teams have defined Level 0 requirements, will be reviewed next week by Red Team.
  - Code T Requirements Division will determine Level 1 requirements (complete September 04)
- FY06 Budget Formulation ongoing
- JIMO draft RFP released
- High Power Electric Propulsion research grant selection this summer
- Contractor trade studies on surface power and cargo vehicle applications
- In house trade studies in work

NEP Sensitivity to Specific Mass

2018 Short Stay Mission

- IMLEO and Power requirement highly sensitive to specific mass
- 440 day missions require alpha values less than 10
- 365 day missions required alpha values less than 5

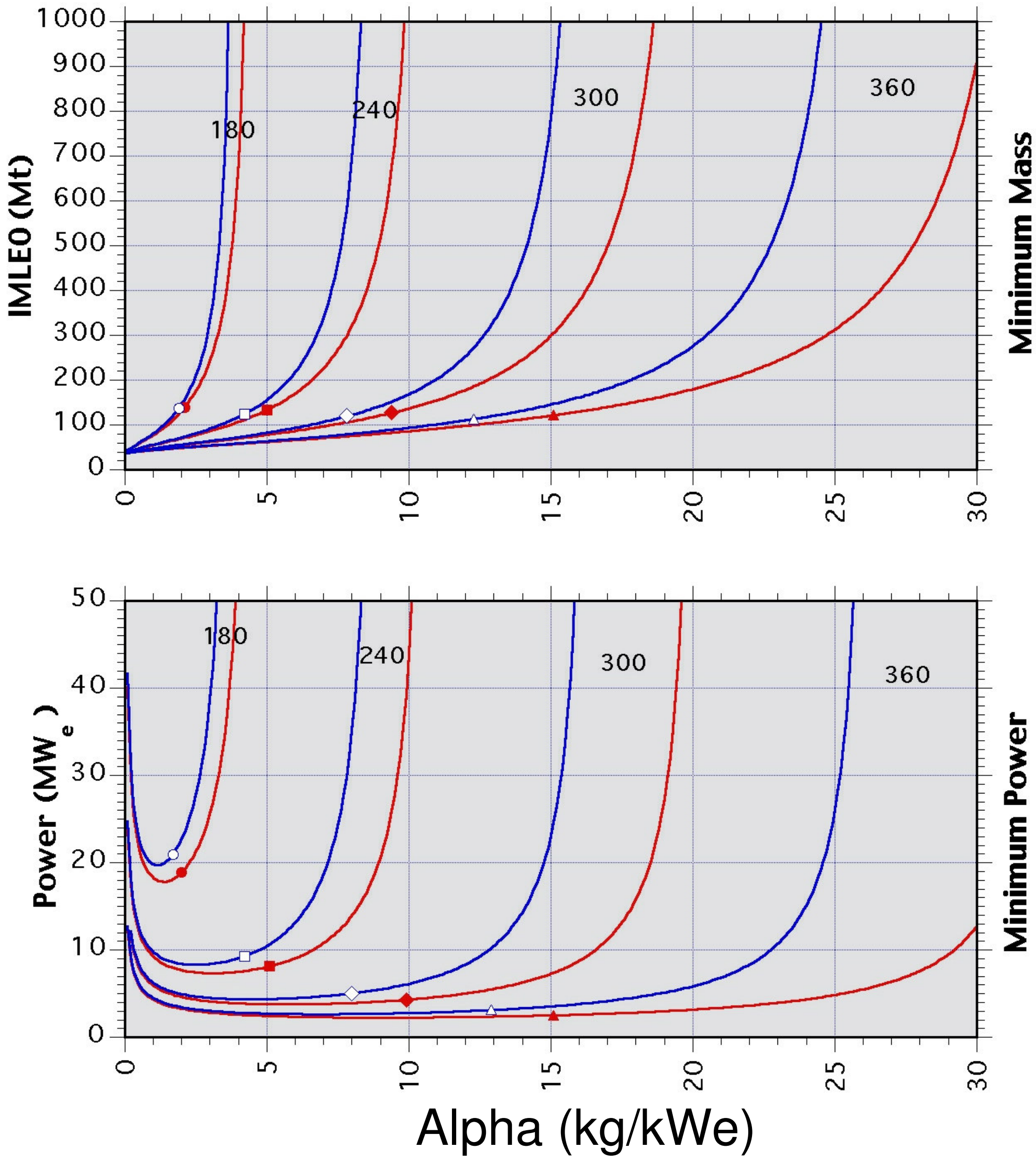


– *Leonard A. Dudzinski, Space Nuclear Power Requirements for Emerging Human Mars Mission Propulsion, presented to Space Technologies International Forum 2001, February 14, 2001

NEP Sensitivity to Specific Mass

2018 Long Stay Mission

- IMLEO and Power requirement highly sensitive to specific mass



– *Leonard A. Dudzinski, Space Nuclear Power Requirements for Emerging Human Mars Mission Propulsion, presented to Space Technologies International Forum 2001, February 14, 2001

NTP Sensitivity Analysis

Groundrules and Assumptions

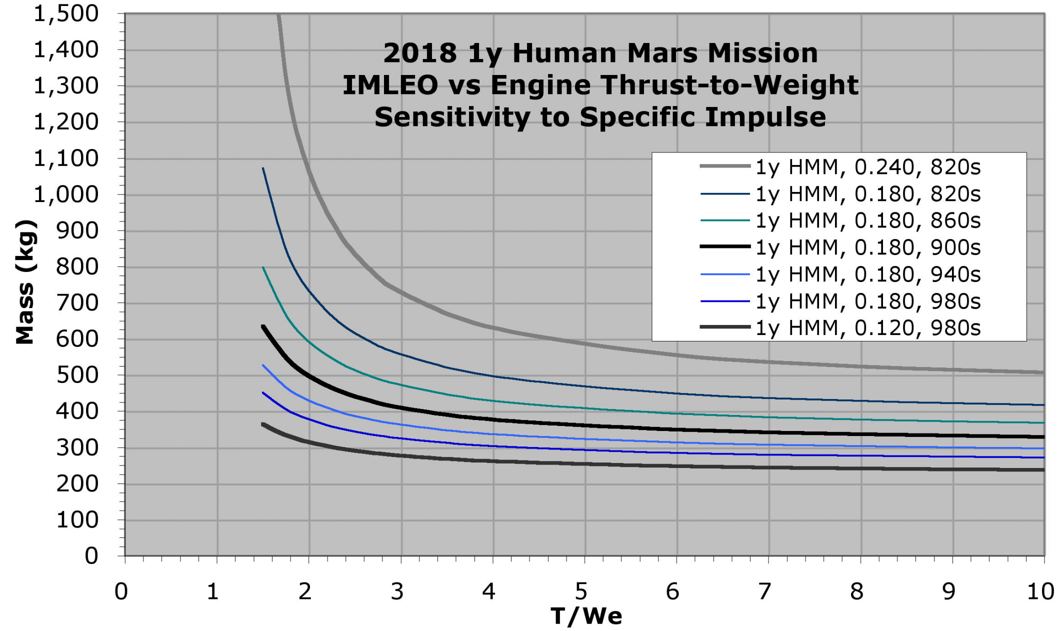
- 2018 Mars transfer opportunity, 1 year round trip
- 40 day Mars stay
- 25 Mg Payload mass includes CEV, consumables, and non-scalable structures
- 250 km altitude by 1 sol Mars staging orbit
- NTP vehicle flys-by Earth at return
- Capsule return for crew at Earth, 13 km/sec entry velocity, 4.7 Mg
- Storable chemical propulsion stage for Earth entry slow-down maneuver of capsule, specific impulse 330 sec
- Storable chemical propulsion for 50 m/sec mid-course maneuvers in-bound and outbound, 100 m/sec arrival maneuvers, specific impulse 330 sec
- NTP for Trans-Mars Injection, Mars Orbit Capture, 250 m/sec Departure Maneuvers, and Trans Earth Injection
- Engine thrust scaled to maintain initial acceleration at .1g and gravity loss of 10% of ideal ΔV

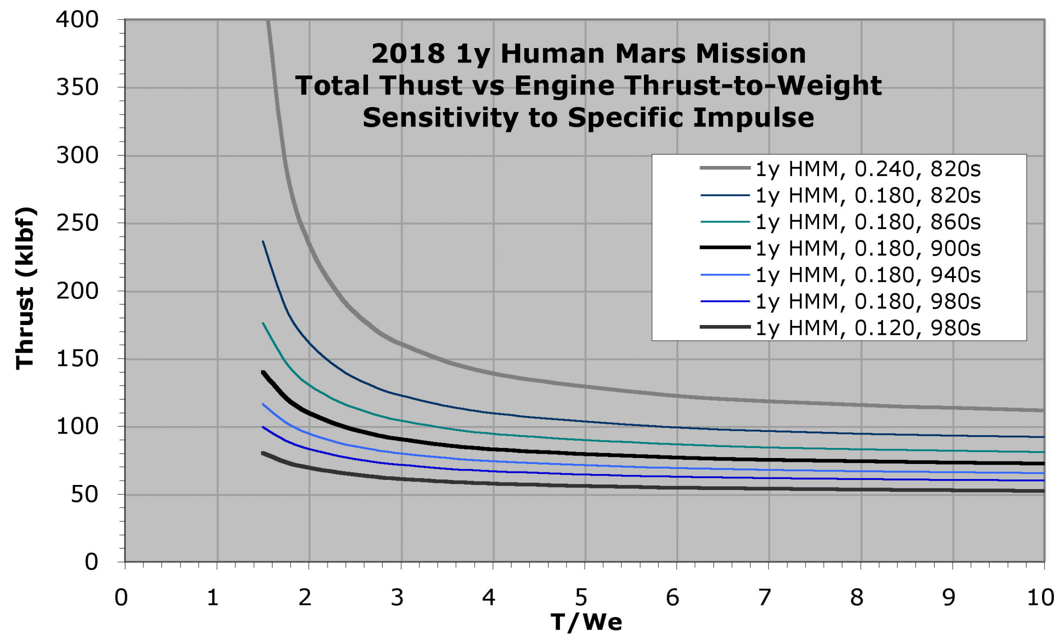
NTP Sensitivity to Specific Impulse

2018 1 year Short Stay Mission

- Baseline case is 900s specific impulse, 18% tankage mass (as a percentage of propellant mass)
  - NERVA technology was approximately 3:1 T/W_e at 880 sec, 75 klb_f
- Performance is highly sensitive to engine thrust-to-weight (T/W_e) below 3:1
- Above 3:1 T/W_e:
  - Performance is acceptable for I_{sp} between 820 and 980 sec
  - Initial Mass In Low Earth orbit (IMLEO) ranges between 250 Mg and 700 Mg
  - Total engine thrust ranges between 50 klb_f and 150 klb_f
- Note: higher T/W_e is easier to achieve at lower I_{sp}

  - *Leonard A. Dudzinski, Human Mars Mission Technology Requirements, internal document, 10 January 2004



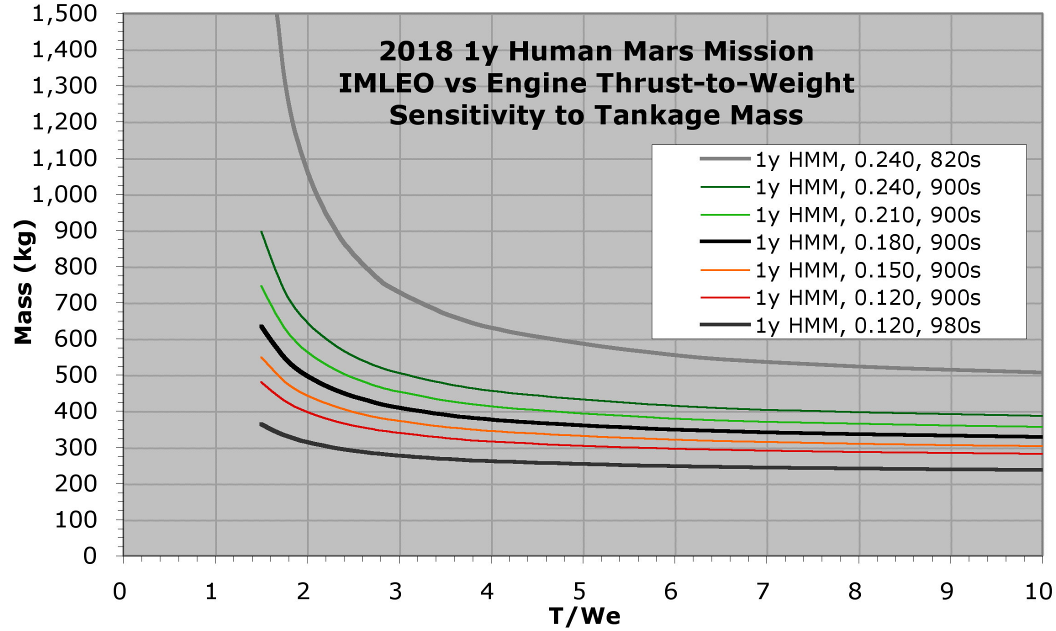


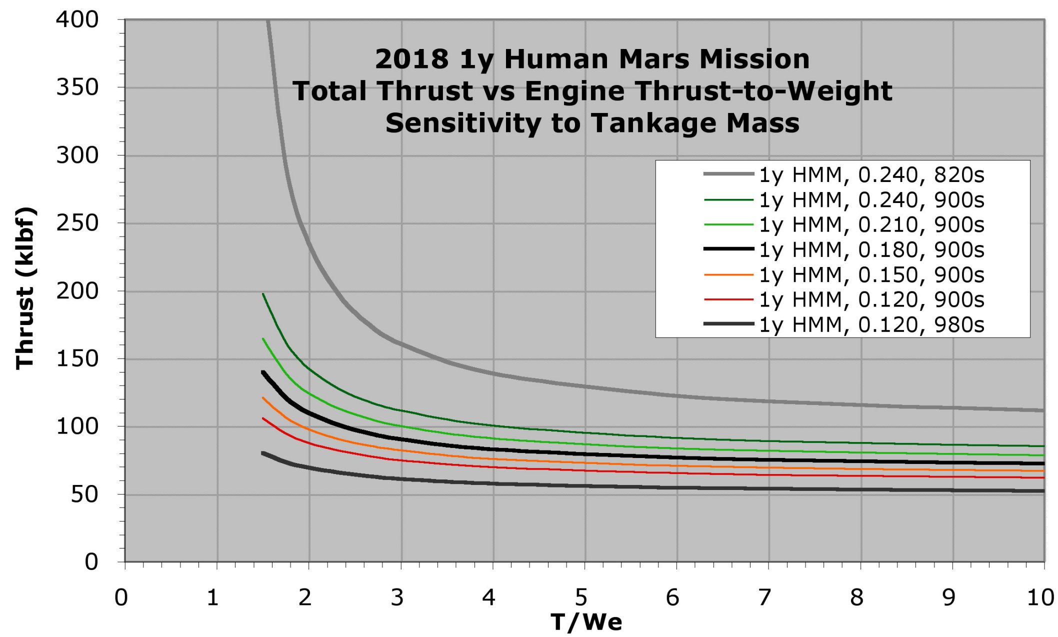
NTP Sensitivity to Tankage Mass

2018 1 year Short Stay Mission

- Baseline case is 900s specific impulse, 18% tankage mass (as a percentage of propellant mass)
  - 18% tankage is conservatively representative of current technology
- Above 3:1 T/W_e performance is acceptable for tankage between 12% and 24% of propellant mass
- Performance in less sensitive to tankage mass than engine thrust-to-weight

  - *Leonard A. Dudzinski, Human Mars Mission Technology Requirements, internal document, 10 January 2004





Technology Roadmaps for Advanced Nuclear Concepts

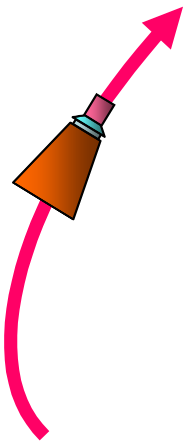
- Chemical to NTP Mission Comparison
  - Opposition Class, 40 day surface stay, no refueling

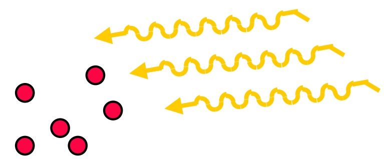
Propulsion	Isp	IMLEO	T/W	Trip time
Chemical	460	890	30-1	480
NTP	900	470	3-1	365

- Note: Chemical propulsion cannot accomplish a 365 day mission.

Leonard A. Dudzinski, Space Nuclear Power Requirements for Emerging Human Mars Mission Propulsion, presented to Space Technologies International Forum 2001, February 14, 2001

Nuclear Propulsion System Design and Operational Safety Approaches and Processes



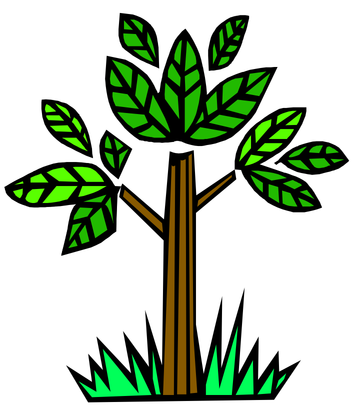


ISDC-2004

Oklahoma City, OK

30 May 2004

Roger X. Lenard



Outline

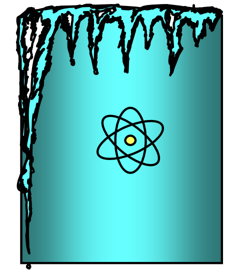
- Historical Snapshot
- Safety Versus Other Considerations
- Reactor Launch and Operational Safety
- Rules, Laws and Treaties
- Some Important Design Requirements
- Environmental and Safety Compliance Processes

Nuclear Power Sources

- US
  - 1 Reactor in 1964, SNAP-10A
  - 44 RTGs (some launch failures most RTGs recovered safely with no isotope release)
  - Largest single RTG launch, Cassini in 1997
  - Numerous RHUs
- Russia (USSR)
  - 38 Reactors on Rorsats
  - Several RTGs
  - 1 Known RTG reentry (not recovered)
  - 2 Known Reactor reentries (Cosmos 954 landed in Canada, cleanup completed)
- New emphasis on nuclear power in NASA

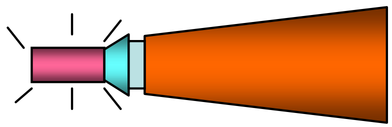
Distinguish Safety vs Other Issues

- **<u>Safety</u>: Protect public, workers, and Earth environment from harm.**

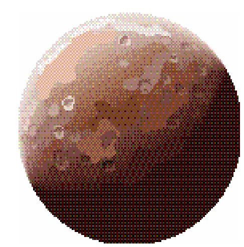


- **<u>Safeguards</u>: Protect special nuclear materials from theft, diversion, loss, or sabotage.**

- **<u>Operational</u>: Provisions for meeting mission objectives.**

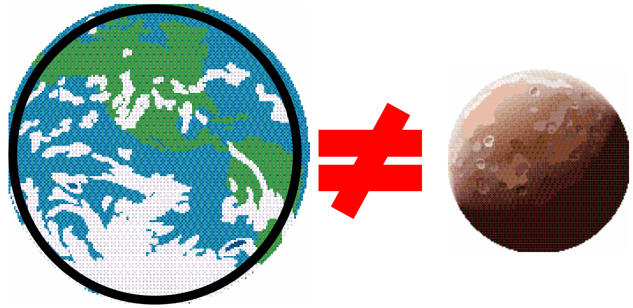


- **<u>Space environment</u>: Protect space assets and future space activities from consequences of space nuclear missions.**



Focus on Space, Not Earth

1. Earth is not Space



Safety approach must focus on *Space*.

Space and Earth reactor conditions very different.

Example	Space	Earth
- Operation in Earth's biosphere	**No**	**Yes**
- Reentry accidents possible	**Yes**	**No**
- Propellant fires/explosions possible	**Yes**	**No**
- Radioactive inventory	**Small**	**Large**
- Inventory Half-Life	**Short**	**Long**

Terrestrial safety considerations may not apply. Example:

- LOCA in LEO, MEO, or HEO may have no safety implications.

- Radioactive leakage may have no safety or biospheric impact, even in LEO.

Pre-Launch, Launch and Ascent Phases

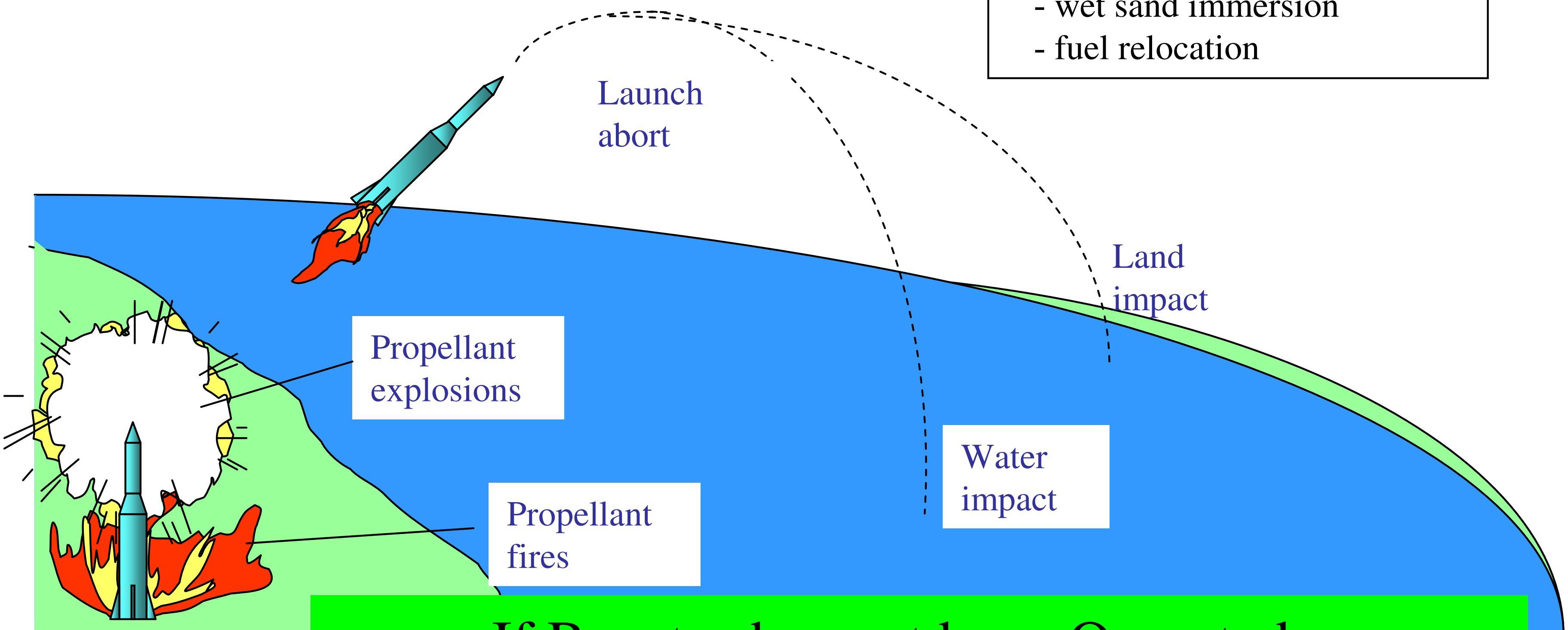
2. Launch & Ascent Issues

Pre-launch/launch issues focus on startup and inadvertent criticality.

- Dispersal of fuel/toxic material

(No startup = cold fuel, low consequences)

- Inadvertent criticality potential
  - compaction
  - immersion, flooding
  - wet sand immersion
  - fuel relocation



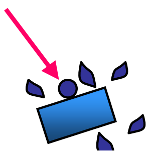
If Reactor has not been Operated a Reactor Launch => Essentially Zero Added Risk

Various In-Orbit Operations and Issues

3. Where are we going, What are we Doing?

HEO operation:
No consequences on Earth

Nuclear propulsion:
•Potential failures in LEO
- Reentry of hot system potentially possible



MEO operation:
Ballistic coefficient change possible,
- Reentry of hot debris unlikely

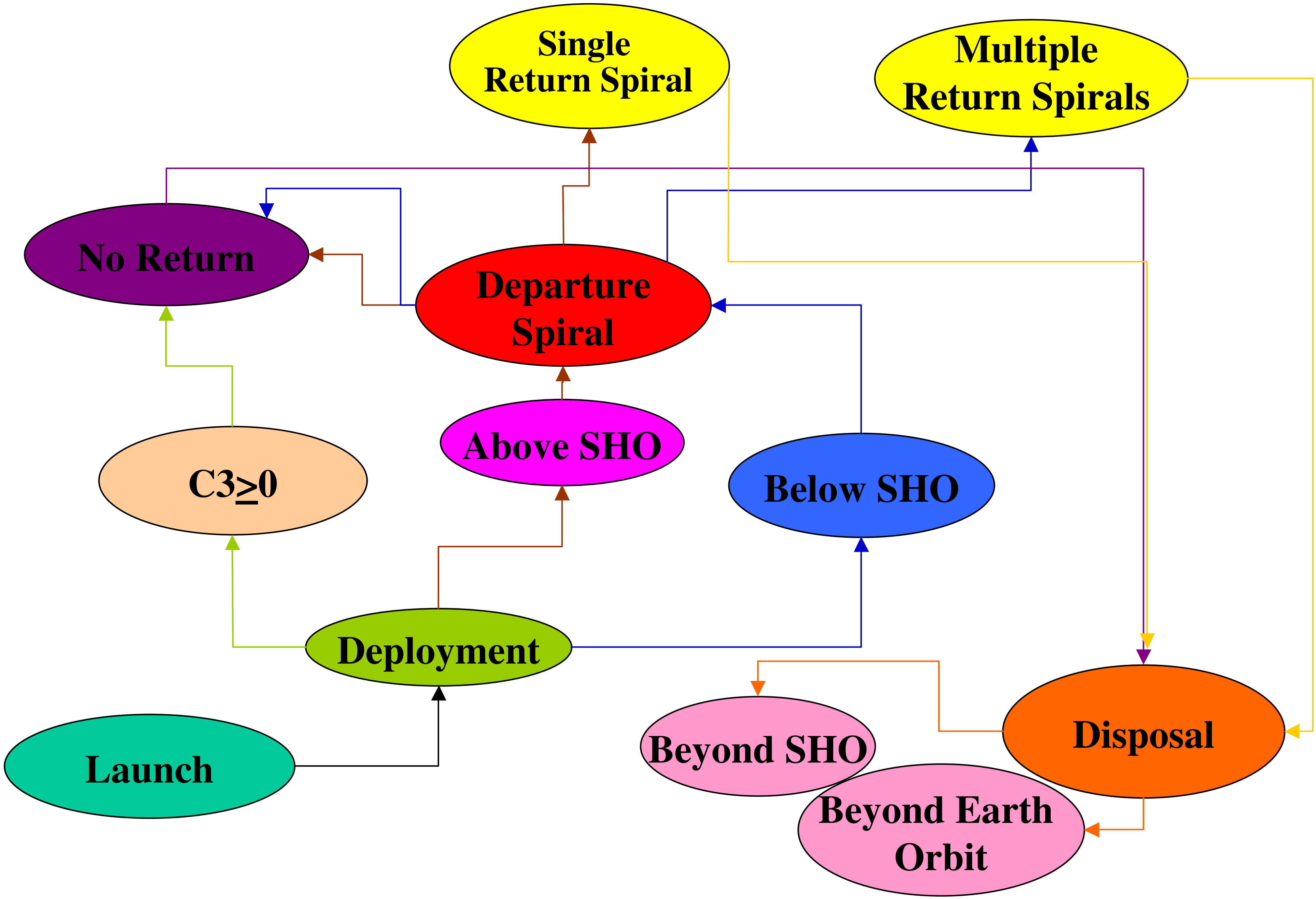
System disruption possible
•Meteor/debris impact
• Internal initiators
(LOCA, LOFA, Transients)

• Potential boost to disposal orbit failure

LEO operation:
Failure to achieve disposal orbit,
-Hot system/debris reentry feasible, make ~ zero probability
-Boost system reliability

If Reentry is Precluded Reactor Operations In earth Orbit => Essentially Zero Added Risk

Operational Modes for Fission Electric Propulsion



Important Reactor Launch and Operations Rules

- The reactor shall not be operated prior to space deployment, except for low-power testing on the ground, from which negligible radioactivity is produced.
- The reactor system shall be designed to remain shut down prior to the system achieving its planned orbit.
- Inadvertent criticality shall be precluded for credible accident conditions.
- Radiological release from the spacecraft during normal operation shall have an insignificant effect on Earth.
- The consequence on Earth of a radiological release from an accident in space shall be insignificant.
- Safe disposal of spent nuclear systems shall be explicitly included in mission planning.
- Planned Earth reentry shall be precluded from mission profiles.
- Both the probability and the consequences of an inadvertent reentry shall be made as low as reasonably achievable.
- For inadvertent reentry through the atmosphere, the reactor shall be essentially intact or shall result in essentially full dispersal of radioactive materials at high altitude.
- The reactor shall remain sub-critical throughout an inadvertent reentry and Earth impact.
- For an Earth impact, radioactivity shall be confined to a local area to limit radiological consequences.

Numerous Laws and Treaties Apply

- 1967 United Nations Treaty on Space Exploration
- For Reactors, Principle 3 Provides Guidance
- Reactors May
  - Operate in Low Earth Orbits if sent to SHOs* afterward
  - In Sufficiently High Orbits*, or
  - Interplanetary Trajectories
- Reactors
  - Use only Highly Enriched Uranium-235 Fuel
  - Become Critical only on Orbit or Beyond
  - Employ design and construction to ensure sub-criticality during all possible (credible) launch events
  - Use highly reliable operational system to ensure disposal
- NSC/PD-25 Guidance (US) (Reactors in orbit no less safe than what we already launch) [Use Cassini as Envelope???]
- National Space Policy (US) Reactors may not be used in Earth Orbit without the permission of the President or his designee

*Present Definition >> Orbit with sufficient life to allow radioactive product decay to "about the level of the actinides"

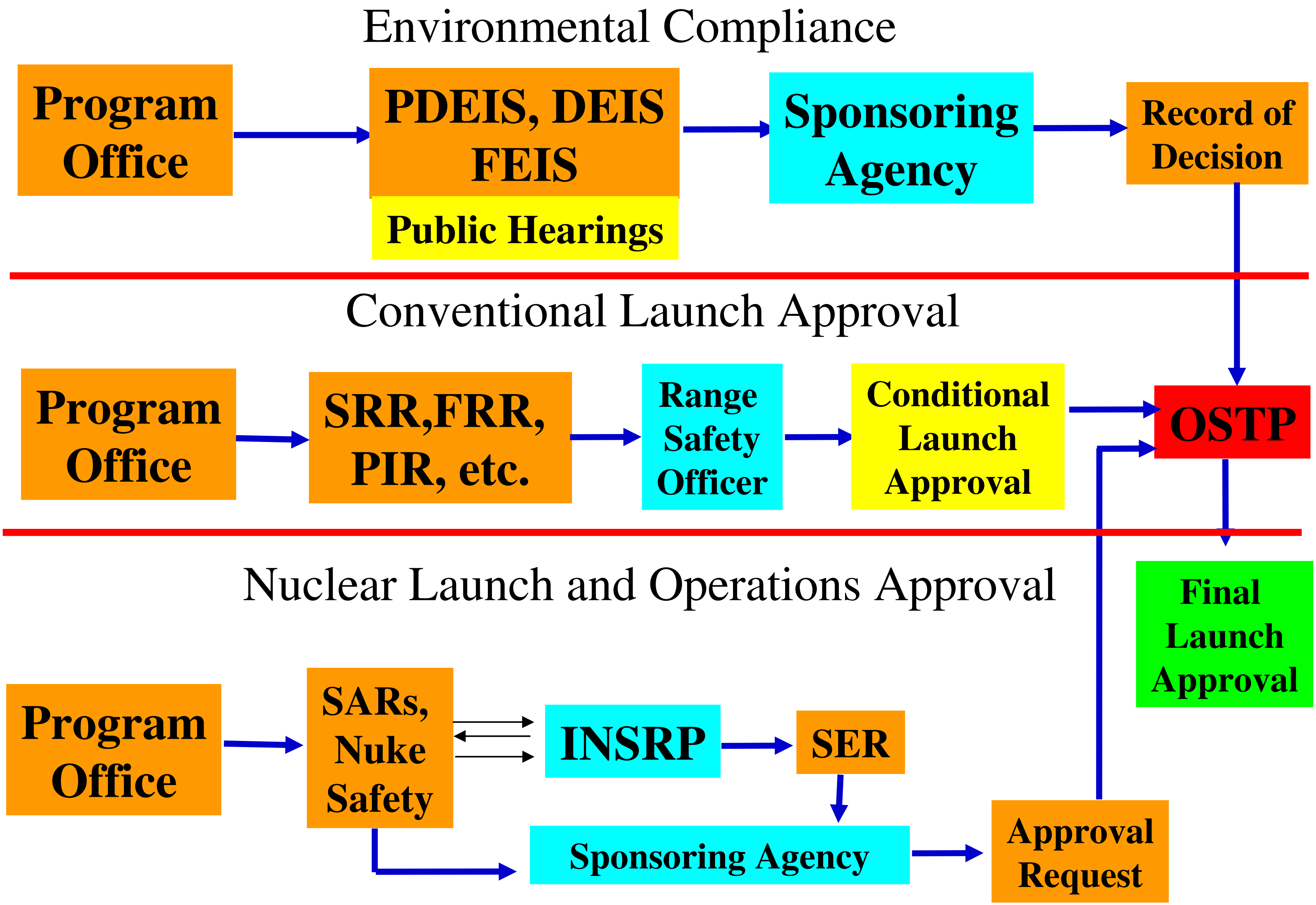
Reactor Requirement: Safety by Design

- Reactor Design Approaches
  - Employ design and construction to ensure sub-criticality during all possible (credible) launch events
    - » Water immersion: Remain sub-critical = design requirement
    - » Wet Sand impact: Remain sub-critical = design requirement
    - » Compaction on hard surface impacts: Remain sub-critical = design requirement
    - » Immersion in other moderating media: Remain sub-critical = design requirement
  - On-orbit operations
    - » Requirement: Minimize fission-product/isotope release, decay heat removal = possible design requirement
    - » Minimize or eliminate contaminants and orbital debris
  - Deep Space operations
    - » No decay-heat removal requirement
  - Operations Within Extra-Terrestrial Celestial Object Gravity Field:
    - » Minimize potential fission-product/isotope releases
  - Consider Safe-Standby Power Production – Stay-alive power

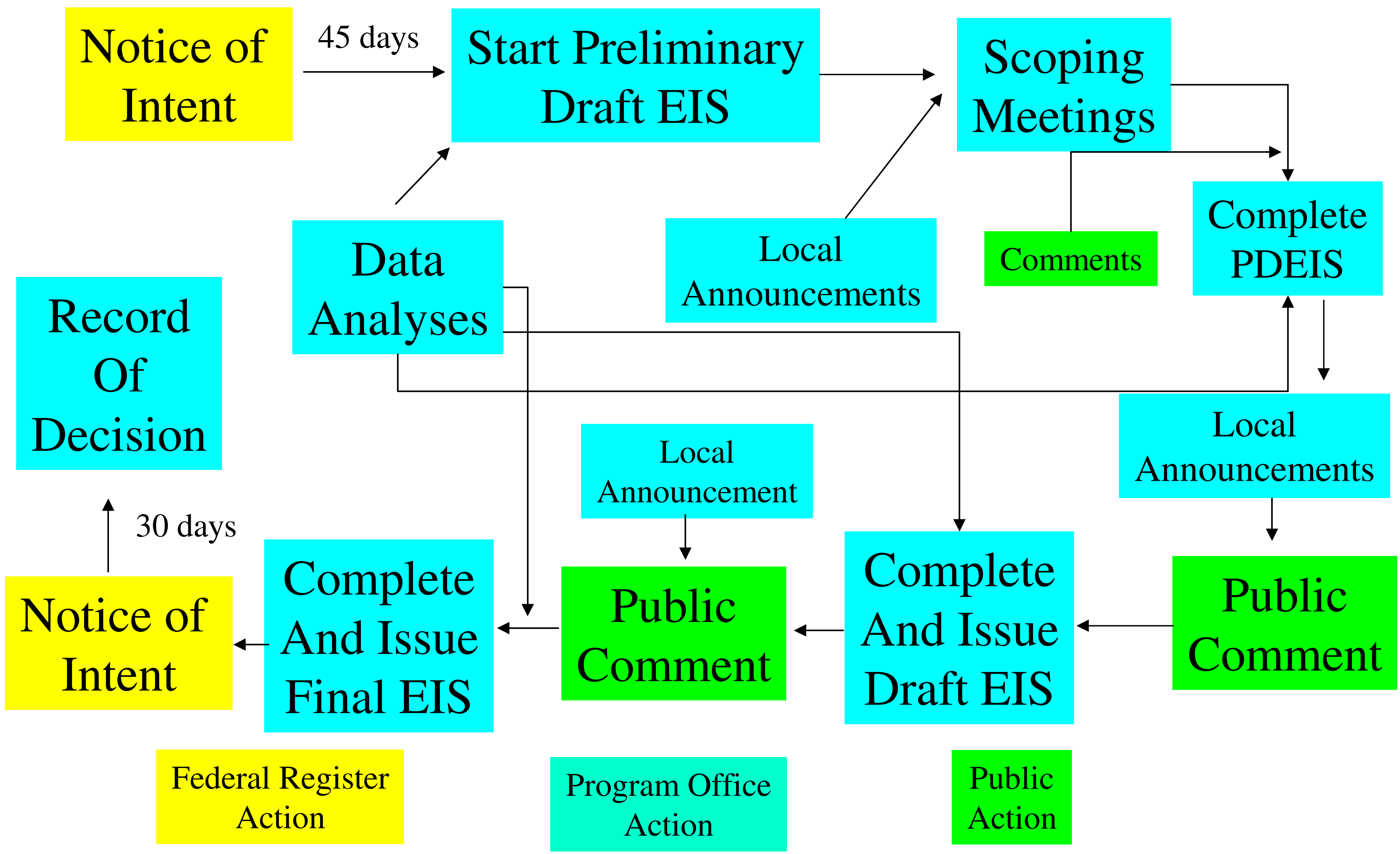
Safety in Design - Continued

- Probably need negative temperature coefficient of reactivity
  - Probably eliminates need for active load-following within reasonable power ranges
  - Not *required* by U.S. safety process, but they hade a dim view of positive power coefficient in Topaz reactors
  - JIMO designs probably possess a small negative temperature coefficient

Current Space Nuclear Systems Launch and Operations Approval Process



Typical EIS Program Flow

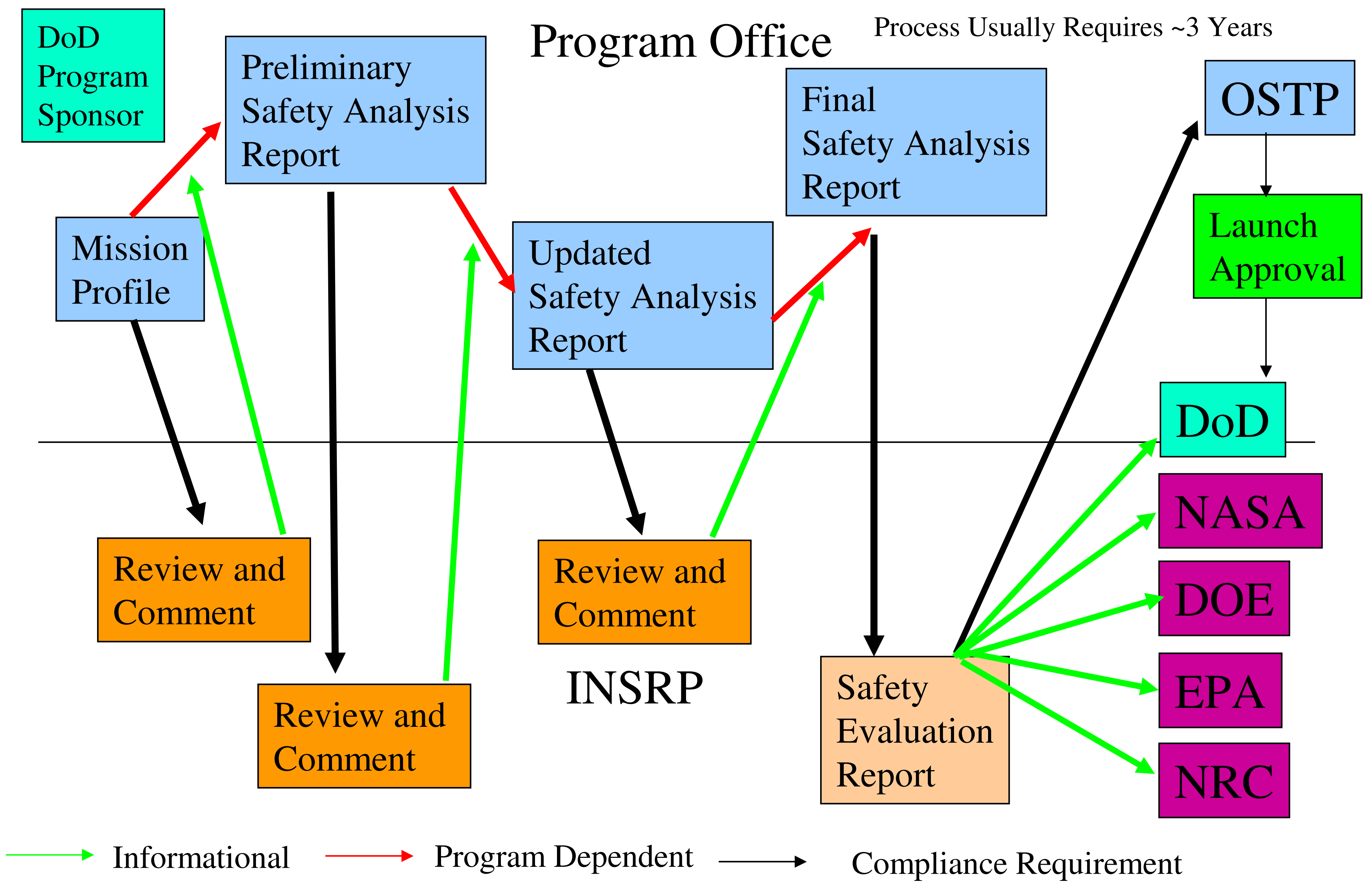


Environmental Impact Statement What is it?

- Performed as a requirement under National Environmental Policy Act of 1969
- Codified in 10 CFR 1021, CEQ Regulations (40 CFR 1500-1508)
- Reactors cited specifically as requiring EIS compliance
- Several choices to pursue
  - Programmatic EIS
  - Program-specific EIS
  - Specific portion of a program

- Programmatic EIS encompasses all aspects of a program
  - Can include various operations, reactors, propulsion types
  - Can include several launch systems
  - Can be employed to build a “tiered” document
  - Typically costs more initially, but can provide savings later
  - If public “interest” groups are unsuccessful in challenging PEIS initially, probability of successful intervention later becomes more difficult – even with very broad application EIS

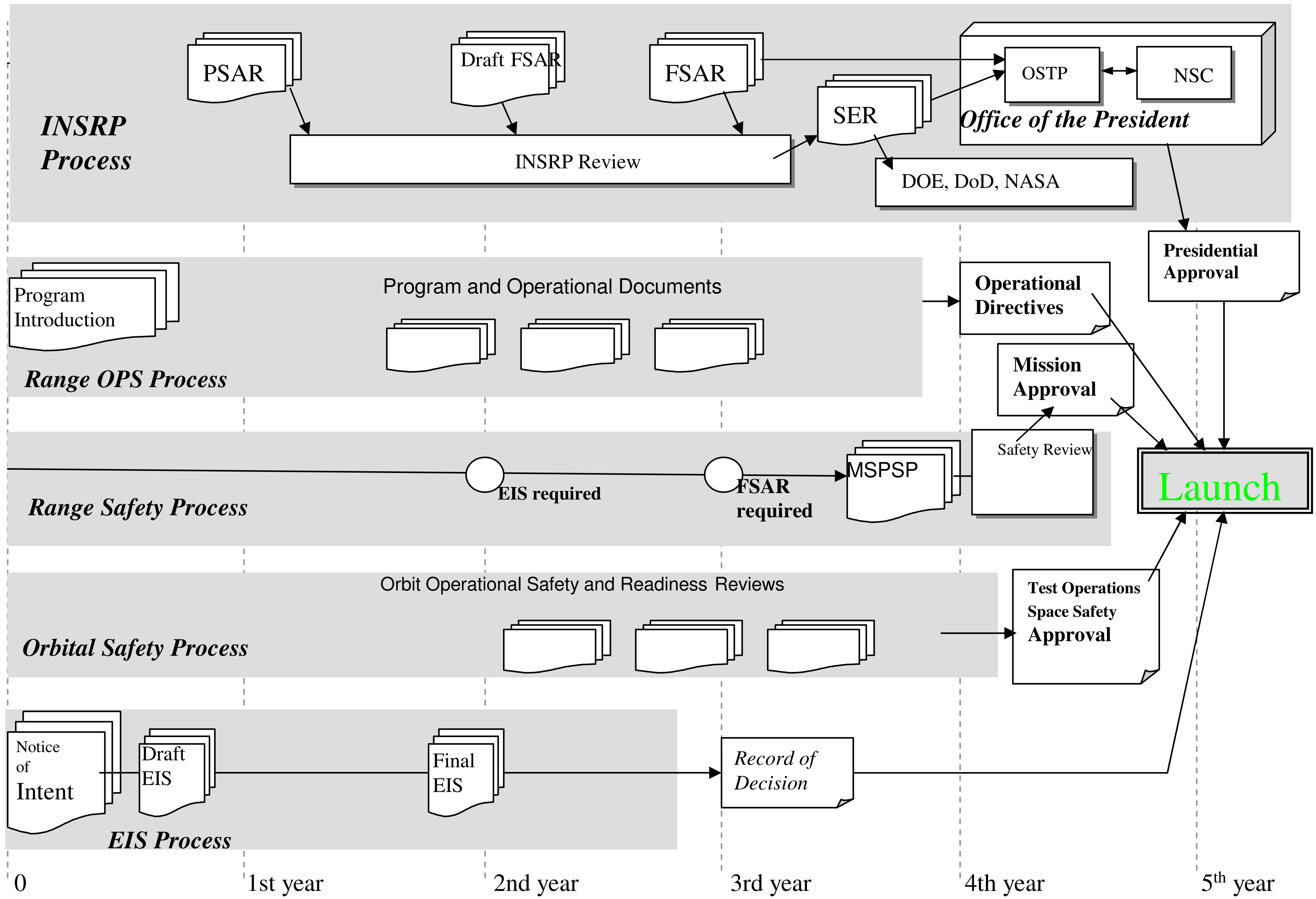
INSRP Process Flow



INSRP – What is it?

- One part of a multi-faceted safety review regulatory procedure necessary for gaining approval to launch
- The INSRP is required by National Security Council/ Presidential Directive – 25 – Requires Presidential Approval to Launch
- The INSRP is an ad hoc group that performs an independent safety review of nuclear materials containing launches
- Four Members, One Advisor
  - DoD
  - NASA
  - DOE
  - EPA
  - NRC - Advisor
- INSRP provides results of independent safety review in for of Safety Evaluation Report (SER) to
  - Sponsoring Agency
  - Supporting Agencies
  - OSTP

INSPRP And EIS Timelines

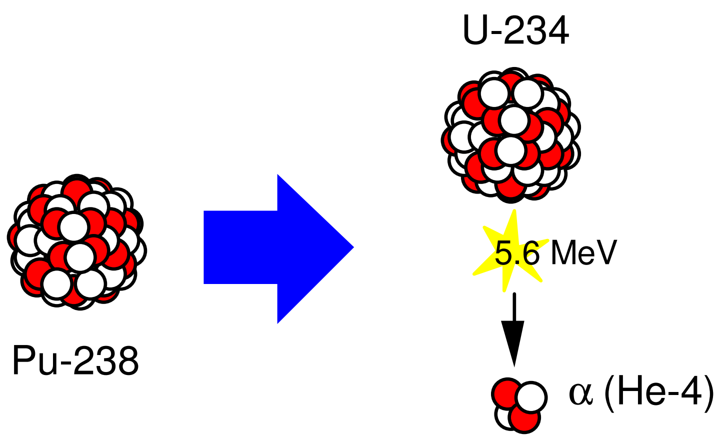


Concluding Remarks

- Reactors can be made both safe and high performance to meet space missions
- Safety must be designed-in, not added later
- An integrated safety program is a must
- All reactor concepts for JIMO can be made to be equally safe
- Processes that have served the RTG nuclear power source effectively are well-suited to reactor systems
- A well executed safety program should result in reactor powered space systems with risk similar to non reactor powered space systems
- Keep in mind that space is a high radiation environment – it's maybe easier to shield from reactor radiation than from the radiation environment around Jupiter

Fission versus Radioisotope Power

Radioisotope Decay

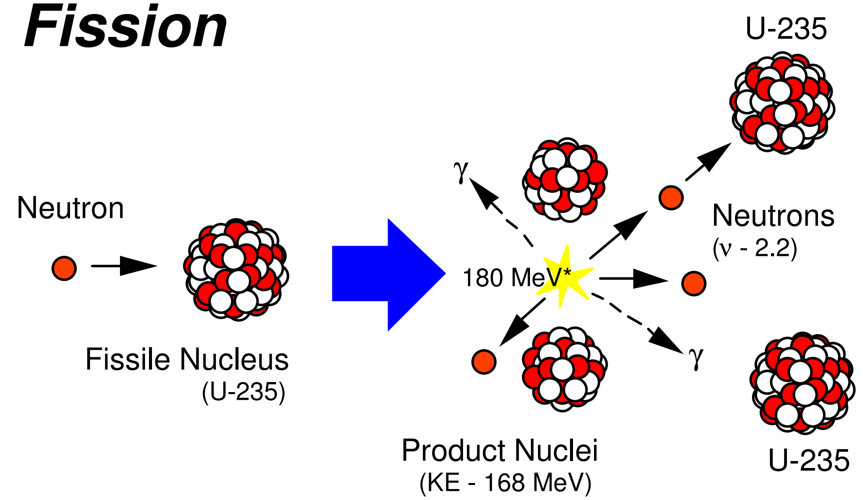


Heat Energy = 0.024 MeV/nucleon (0.558 W/g Pu-238)

Natural decay rate (87.7-year half-life)

- Long history of use on Apollo and space science missions - 44 RTGs and numerous RHUs launched by U.S. past 40 years
- 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.
- Other isotopes: ^{244}Cm, ^{90}Sr

Fission



Heat Energy = 0.851 MeV/nucleon

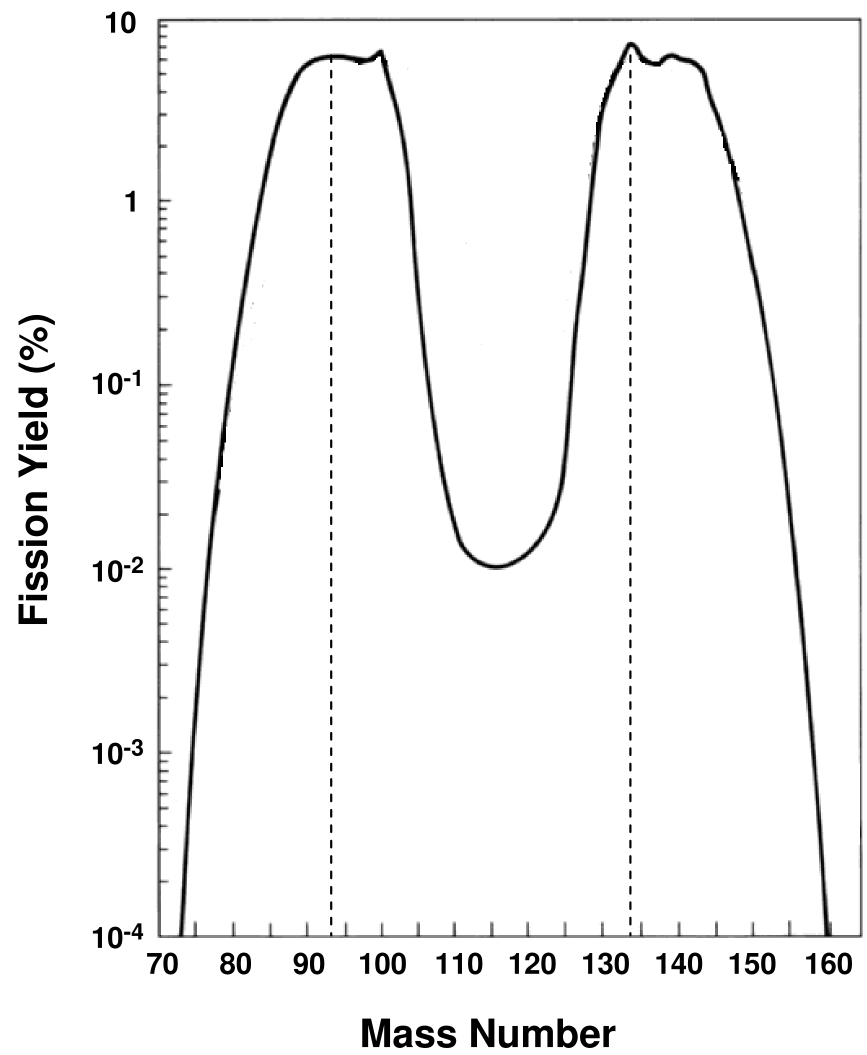
Controllable reaction rate (variable power levels)

- Many U.S. technology programs over last 50 years - only one unit (SNAP-10A) was flown in 1965. *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.

Fission Products

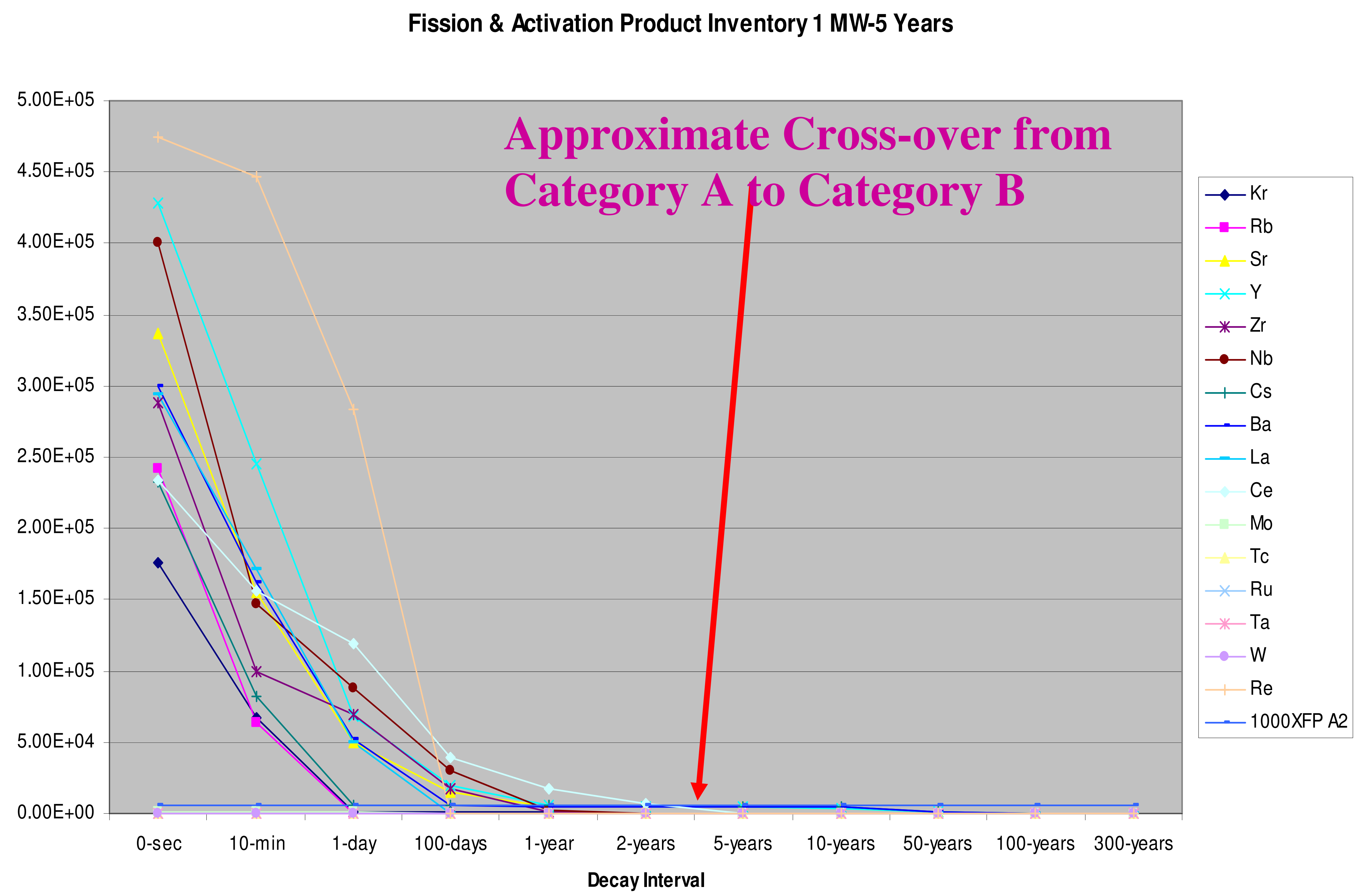
- Large number of fission events yield bimodal distribution of product elements.
- These products are generally neutron-rich isotopes of their stable element configurations.
- They also typically emit beta and gamma particles in radioactive decay chains.
- Most products rapidly decay to stable forms – a few, however, decay at slow rates or decay to daughter products which have long decay times.
- Example fission products of concern:
  - —Strontium-90 (29.1-year half-life)
  - —Cesium-137 (30.2-year half-life)
  - —Isotope amounts decrease by factor of 1,000 after 10 half-lives and 1,000,000 after 20 half-lives.

Product Yields for Thermal Neutron (0.025 eV) Fission of U-235

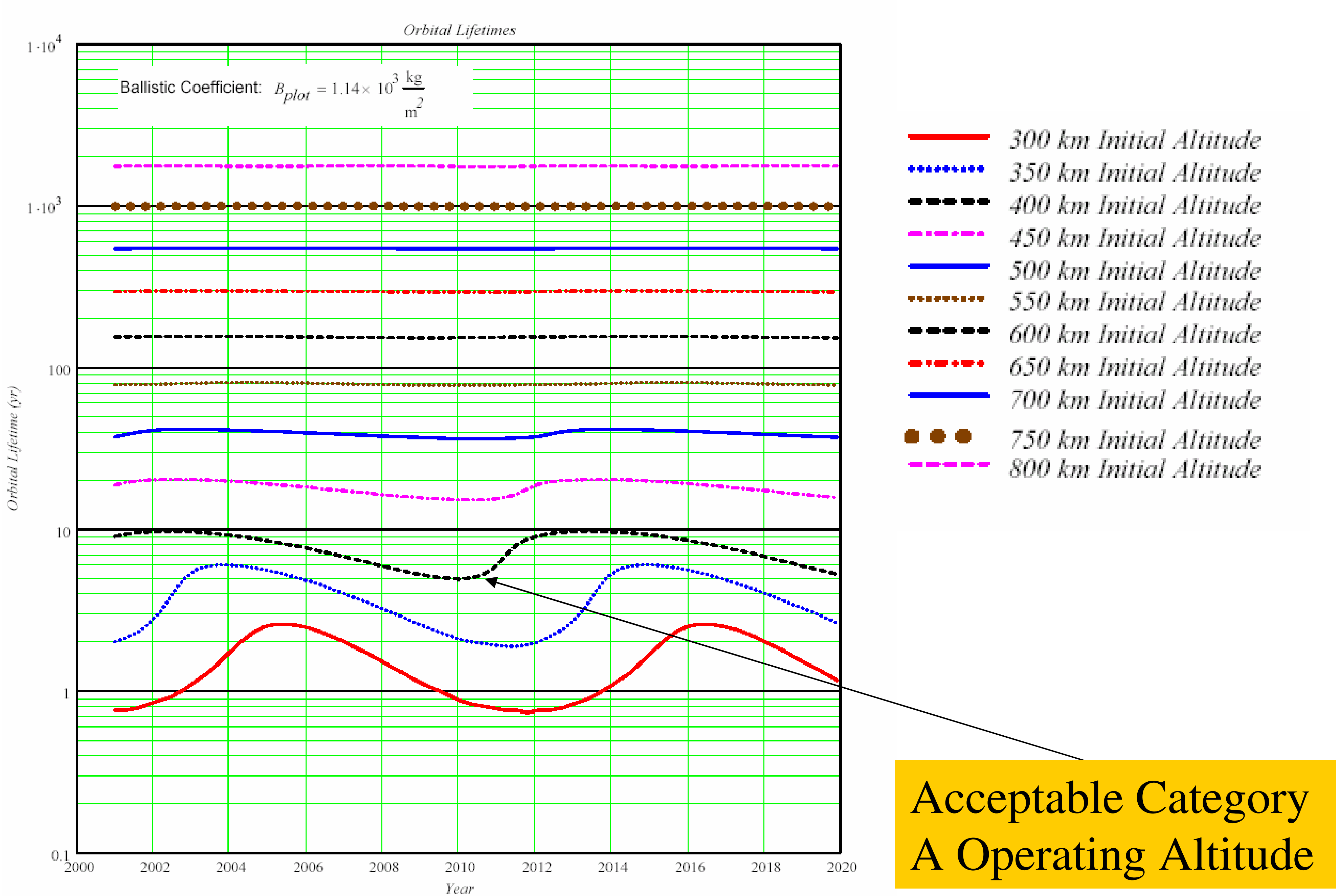


Fission Products Rapidly Decay to Acceptable Levels

For Selected Important Isotopes – Not All Curies are Created Equal



Orbital Lifetime of Reactor/Shield



How Low can You Go – the History

- Russian Rorsats
  - Started at 271-400 km
  - Boosted to 900 km End-of-Life
  - Two Failures (Cosmos 954)
- SNAP-10A
  - 400 miles
  - NEPSTEP 1500 miles (proposed)
- JIMO
  - JPL initial altitude C3>0
  - Lowered to 800 km
  - Raised to 1000 km
  - Spiral out to Earth escape
  - As always – system is mass limited
  - Lower altitude could mean more power and less spiral time, but issue is emotional