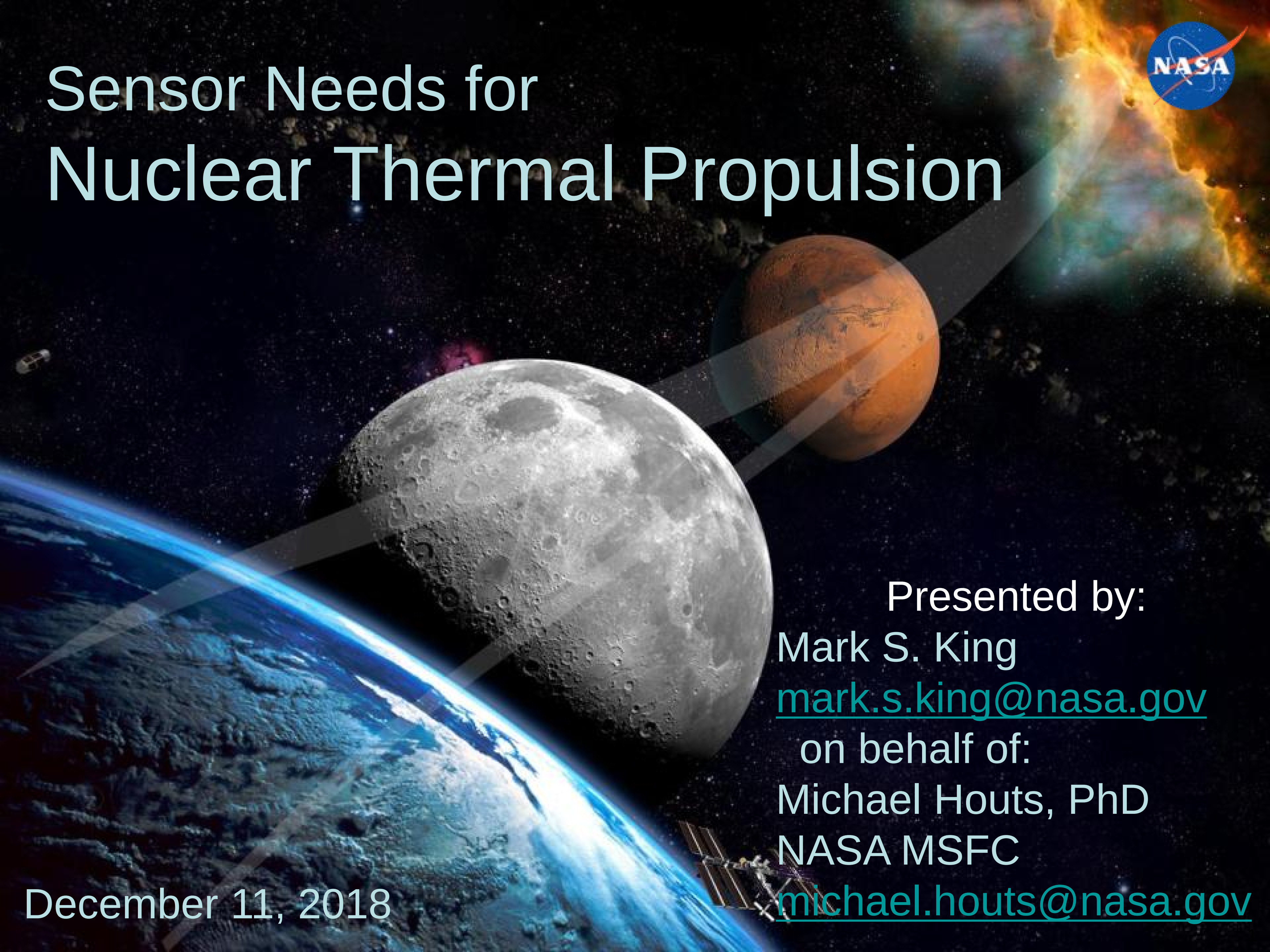


Sensor Needs for Nuclear Thermal Propulsion

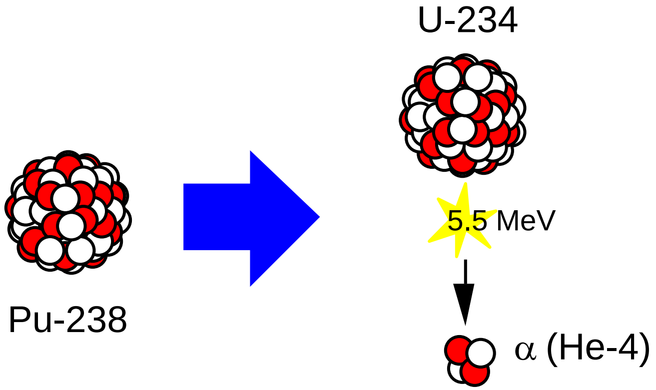
Presented by:
Mark S. King
mark.s.king@nasa.gov
on behalf of:
Michael Houts, PhD
NASA MSFC
michael.houts@nasa.gov

December 11, 2018

Why Nuclear Thermal Propulsion?

- For human Mars missions, first generation NTP can reduce crew time away from earth from >900 days to <500 days while still allowing ample time for surface exploration
  - Reduce crew exposure to space radiation, microgravity, other hazards
- First generation NTP can enable abort modes not available with other architectures
  - Potential to return to earth anytime within 3 months of earth departure burn, also to return immediately upon arrival at Mars
- First generation NTP is a stepping stone to fission power systems and highly advanced nuclear propulsion systems that could further improve crew safety and architectural robustness

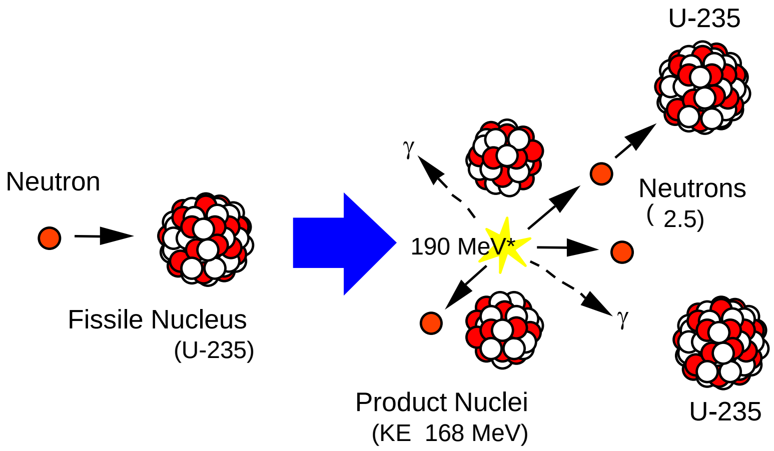
Basics of Nuclear Systems



Heat Energy = 0.023 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 hundreds of RHUs launched by U.S. since the 1960s
- Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)
- Used for both thermal management and electricity production



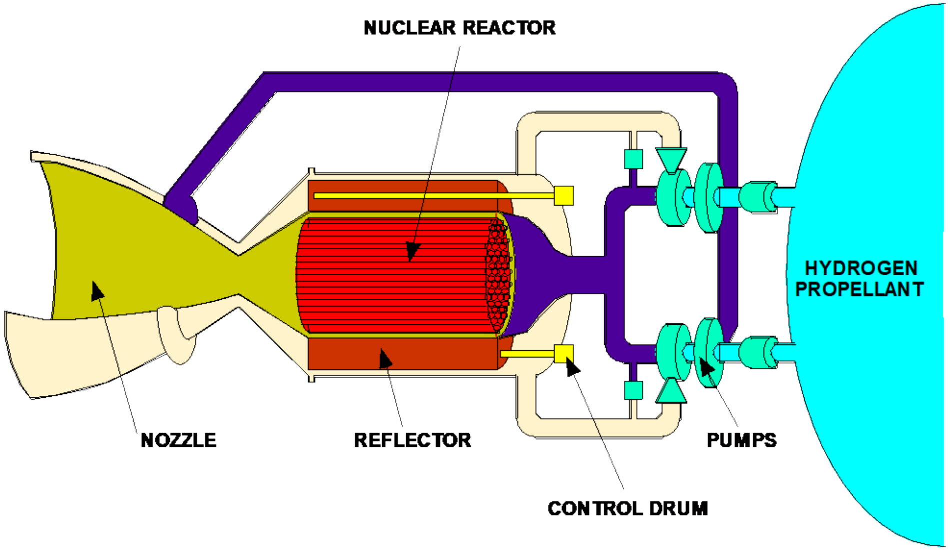
Heat Energy = 0.851 MeV/nucleon

Controllable reaction rate (variable power levels)

- Used terrestrially for over 70 years
  - Fissioning 1 kg of uranium yields as much energy as burning 2,700,000 kg of coal
- One US space reactor (SNAP-10A) flown (1965)
  - Former U.S.S.R. flew 33 space reactors
- Heat produced from neutron-induced splitting of a nucleus (e.g. U-235)
  - At steady-state, 1 of the 2 to 3 neutrons released in the reaction causes a subsequent fission in a “chain reaction” process
- Heat converted to electricity, or used directly to heat a propellant

How Might Initial NTP Systems Work?

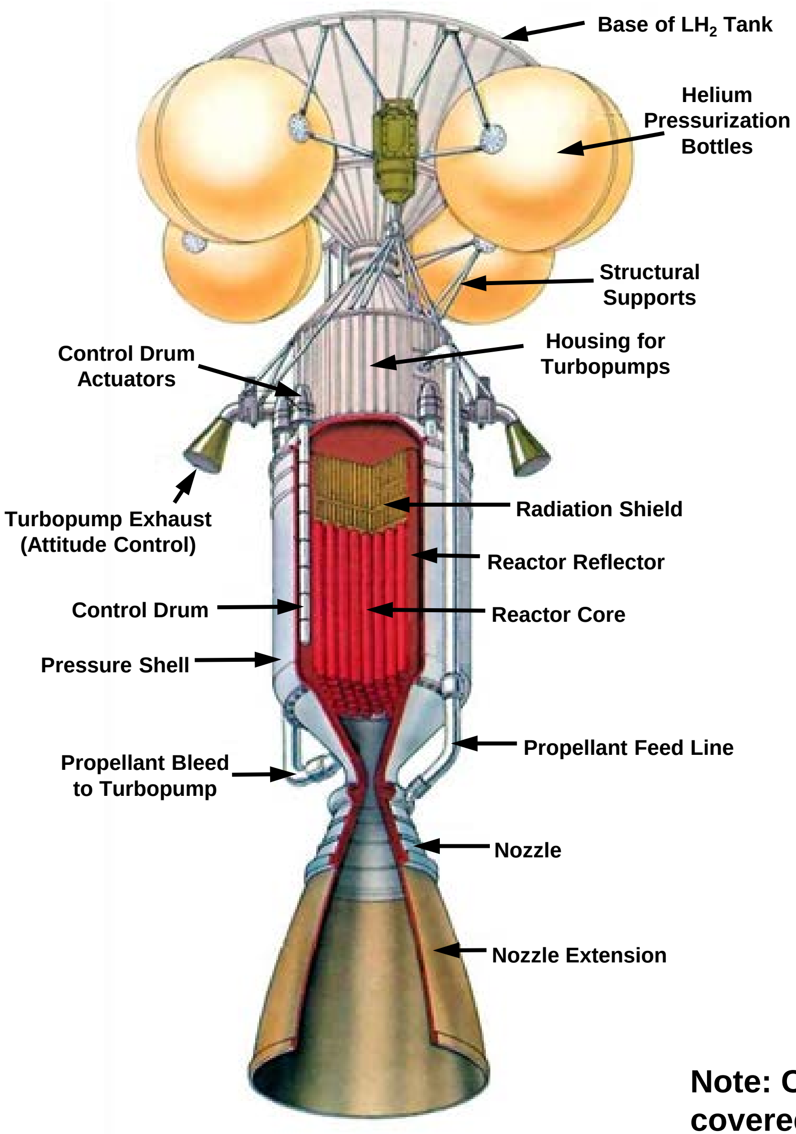
- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor: 100,000 N ≈ 450 $\mathrm{MW_{th}}$ at 900 sec. (100,000 N ≈ 22,500 lbf)
- Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K) for solid core, much higher for liquid or gas core
- NTP-derived systems could be used for high power / high performance production of electricity

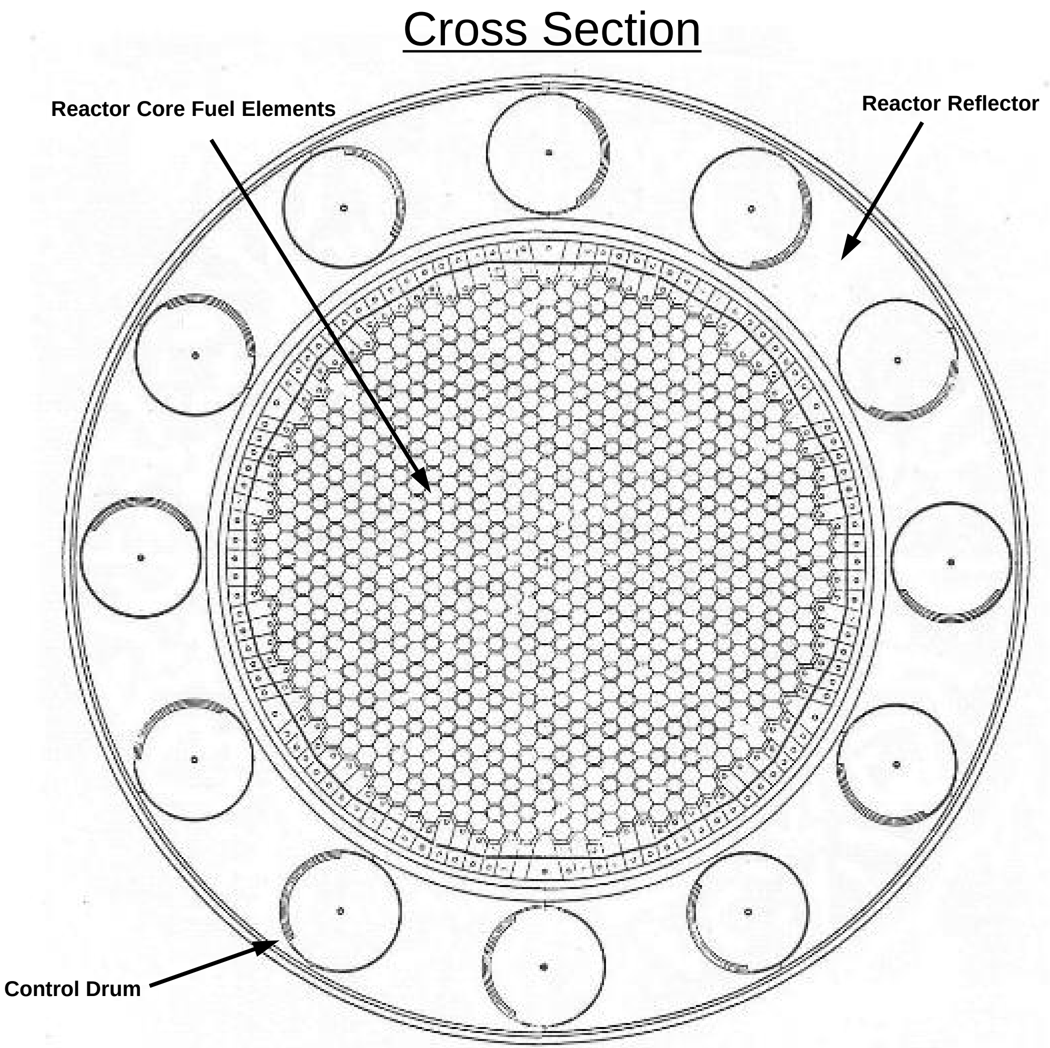


Major Elements of a Nuclear Thermal Rocket

NERVA Nuclear Thermal Rocket Prototype

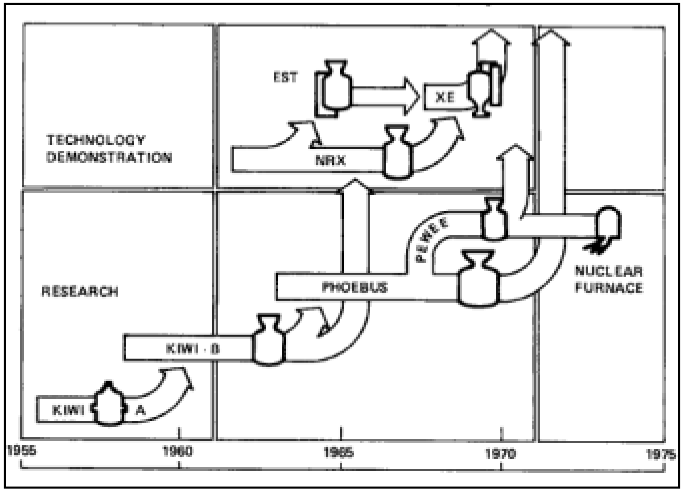
How Might Initial NTP Systems Work?

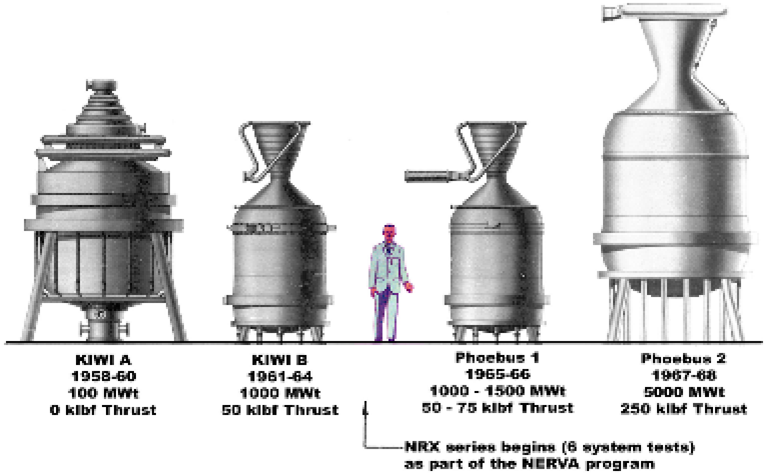


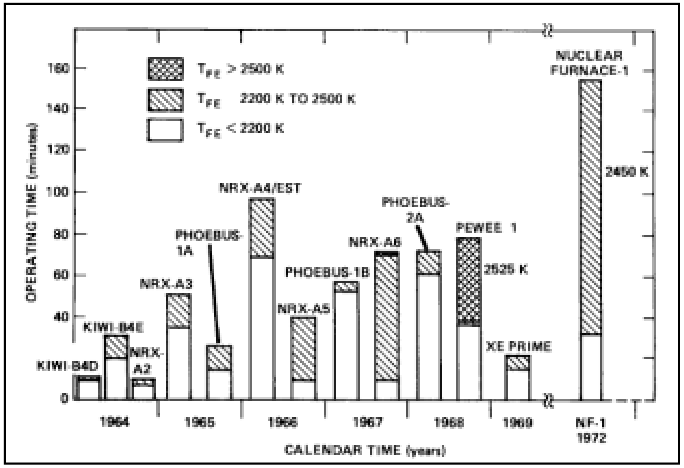


Note: Control drums rotate to control reactivity. Portion of circumference covered with neutron absorber and remainder is reflector.

20 NTP Engines Designed, Built, and Tested During the Rover/NERVA Program (1955-1973)







Typical Sensor Usage in the NERVA Program

Challenges in Reactor Instrumentation

NERVA reactor ~10X power density of power reactor, much greater fuel temperatures. Example sensor types:

Vibration Transducers

- o 0 – 500 Hz, 10 g
- o Neutron flux ~ 10^{17} n/cm^2 caused damage

Pressure Transducers

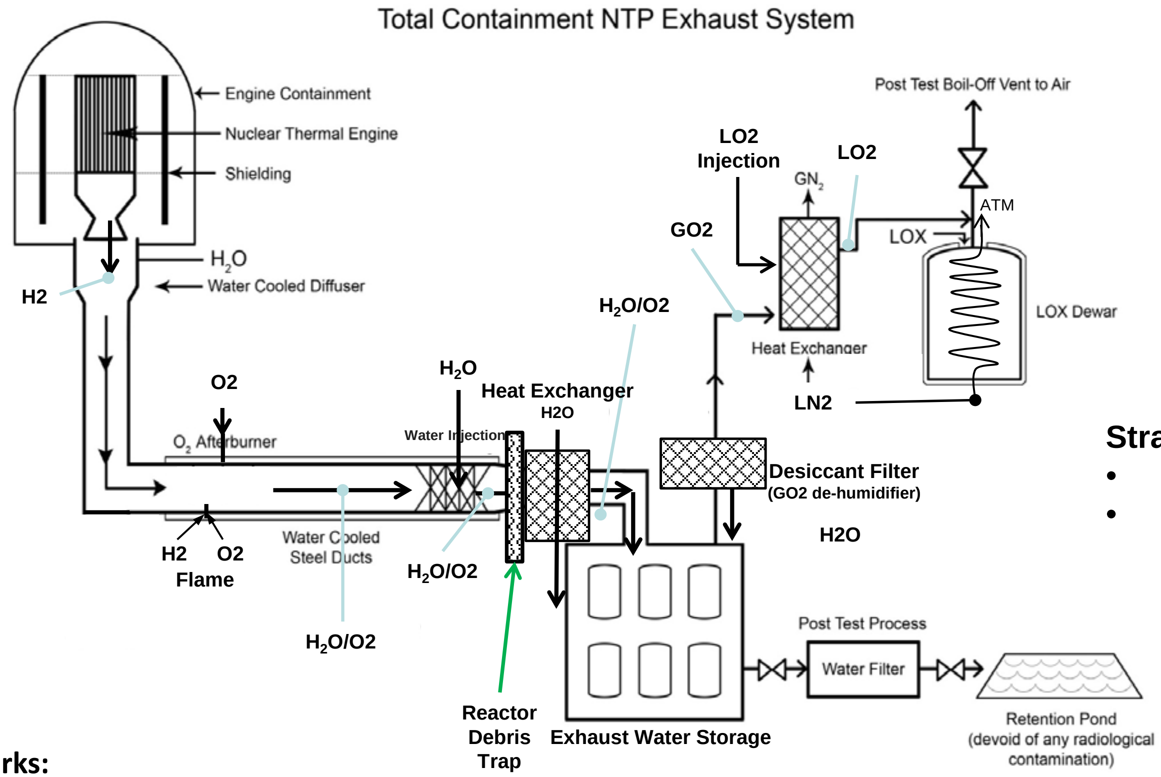
- o <5 Hz, 0-1000 Hz freq response
- o 400 deg F operating temp.
- o 3-4 watts/gram gamma heating caused failures. Moved to 0.5 W/g location.

High Temperature Thermocouples (reactor core)

- o Design goal: 4,500 deg F, +/- 50 deg, usable life of one hour
- o Obtained: 4,020 deg F, +/- 150 deg F for < 1 hour (sheath life limit)

Melick et al., IEEE Transactions on NS, Vol 13, Issue 1, Feb 1966

NTP Ground Testing
Exhaust Capture Concept



Strategy:
- Fully Contain engine exhaust
- Slowly drain containment vessels after test

How it works:

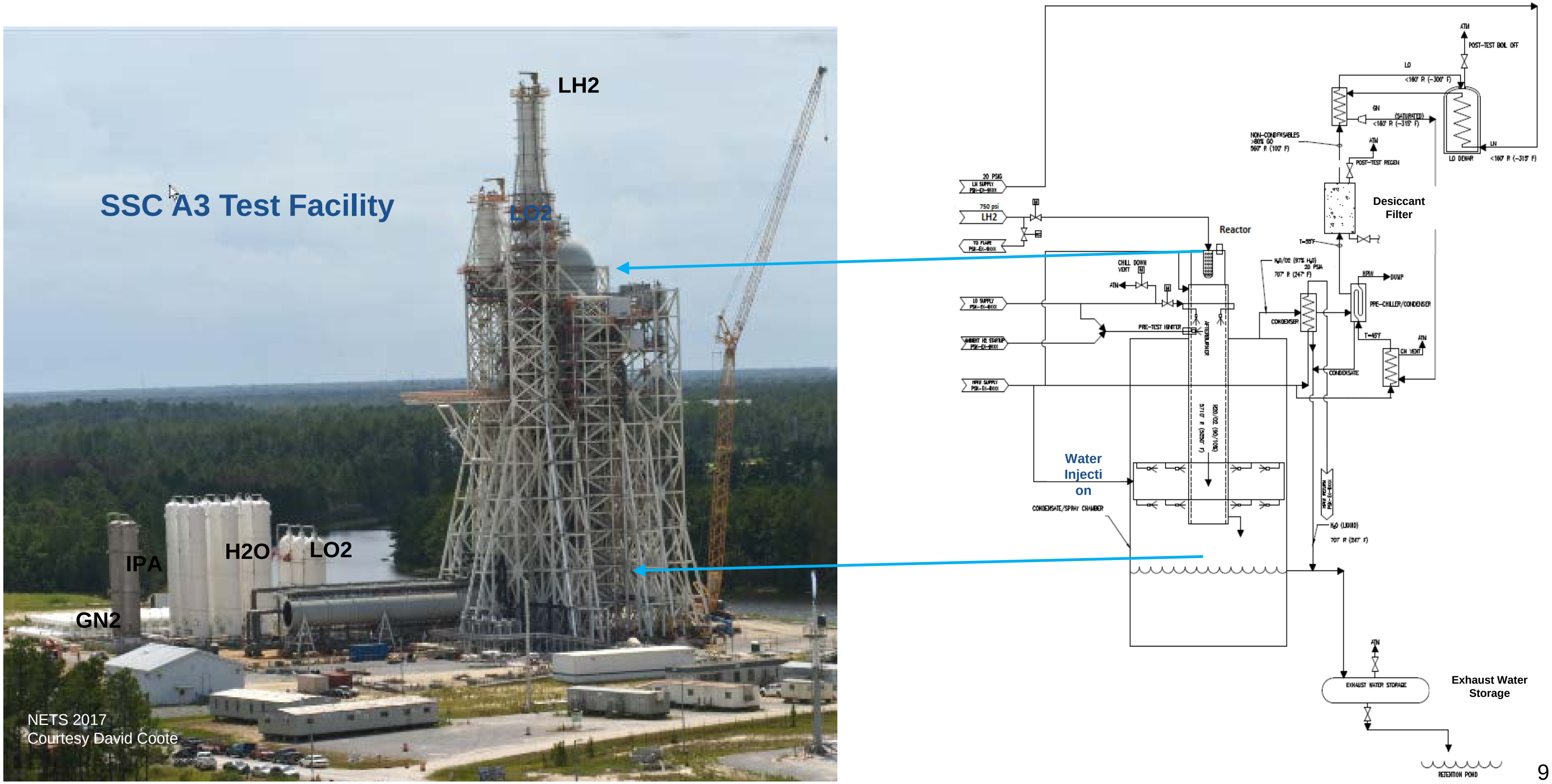
- Hot hydrogen exhaust from the NTP engine flows through a water cooled diffuser that transitions the flow from supersonic to subsonic to enable stable burning with injected LO_2
  - Products include steam, excess O_2 and potentially, a small fraction of noble gases (e.g., xenon and krypton)
- Water spray and heat exchanger dissipates heat from steam/O_2/noble gas mixture to lower the temperature and condense steam
- Water tank farm collects H_20 and any radioactive particulates potentially present in flow.
  - Drainage is filtered post test.
- Heat exchanger-cools residual gases to LN_2 temperatures (freezes and collects noble gases) and condenses O_2.
  - LOX Dewar stores LO_2, to be drained post test via boil-off

NTP Ground Test Exhaust Capture Concept

Conceptual System Design Layout

One Potential Option: Stennis Space Center’s (SSC’s) A3 Test Stand

- Most of the infrastructure required by ground test facility (including exhaust capture) is already in place:
  - Tower, test cell, propellant, HPIW & data and controls infrastructure, the Test Control Center, electric power, etc.
  - Major modifications, procurements, and construction work will be required and are captured in the ROM estimate.



NETS 2017
Courtesy David Coote

Sensor Needs for the Ground Test Complex

Instrumentation needs are standard pressures and temperatures with the following exceptions:

Hydrogen monitoring

- In the exhaust duct
- Current technology is expensive, not real-time

Radiation monitoring

- New requirement!

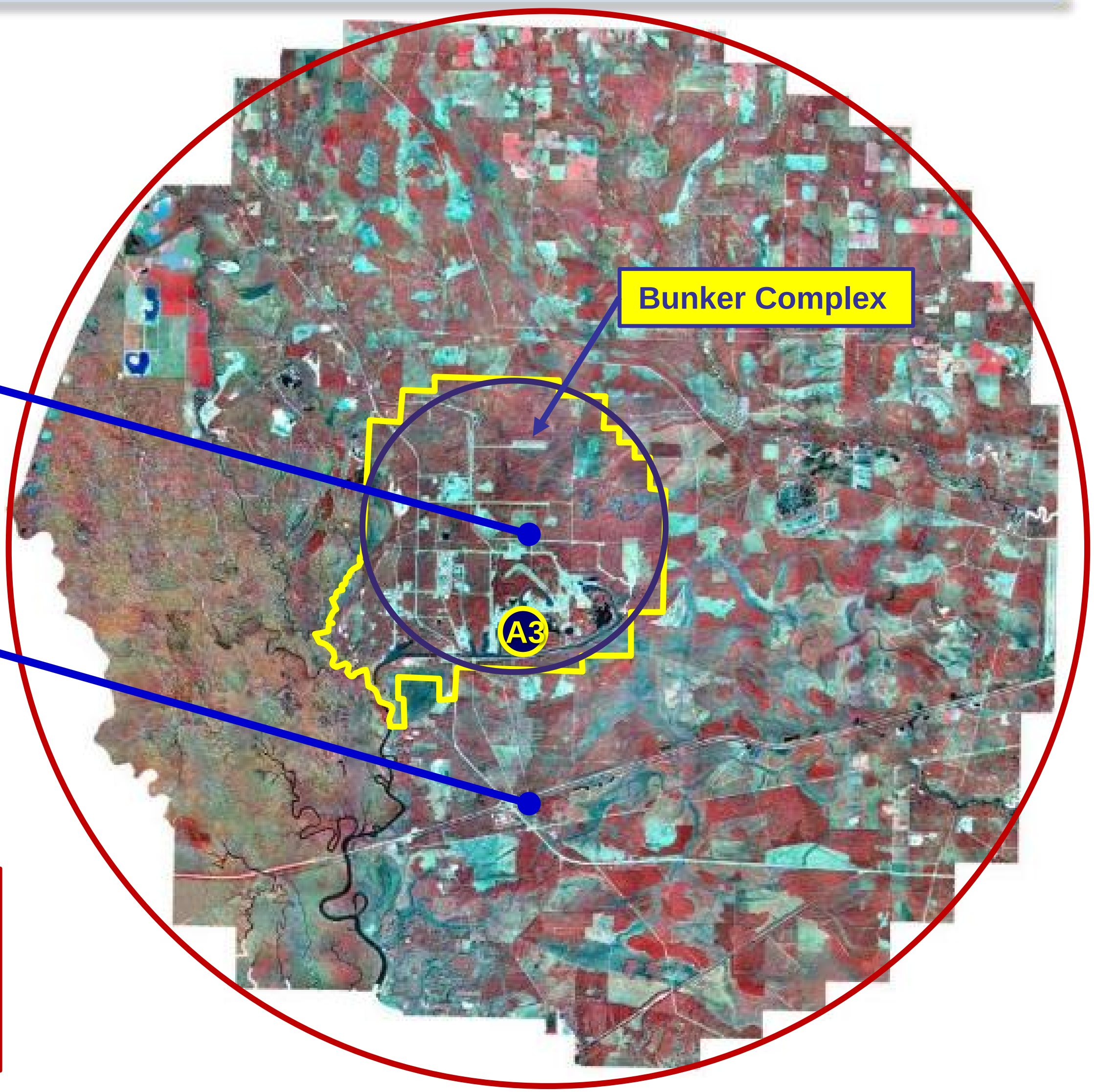
Other

- Real-time health monitoring
- Plume diagnostics (current laser system is not real-time)

Per conversation with SSC Test Manager David Coote on 11/20/18

SSC's Acoustic Buffer Zone

Illustration of Comparable NRC-Designated Planning Zones



13,800 Acre
Fee Area/"Exclusion Area"
(20 mi²)

"Fee Area" Avg. Radius ~ 2.5 mi

125,000 Acre
Buffer Zone/"Low-Population Zone"
(195 mi²)

"Buffer Zone" Avg. Radius ~ 7.9 mi

- **Slidell, LA**
- **Population ~ 27,000**
- **PCD from A3 ~ 8 miles**

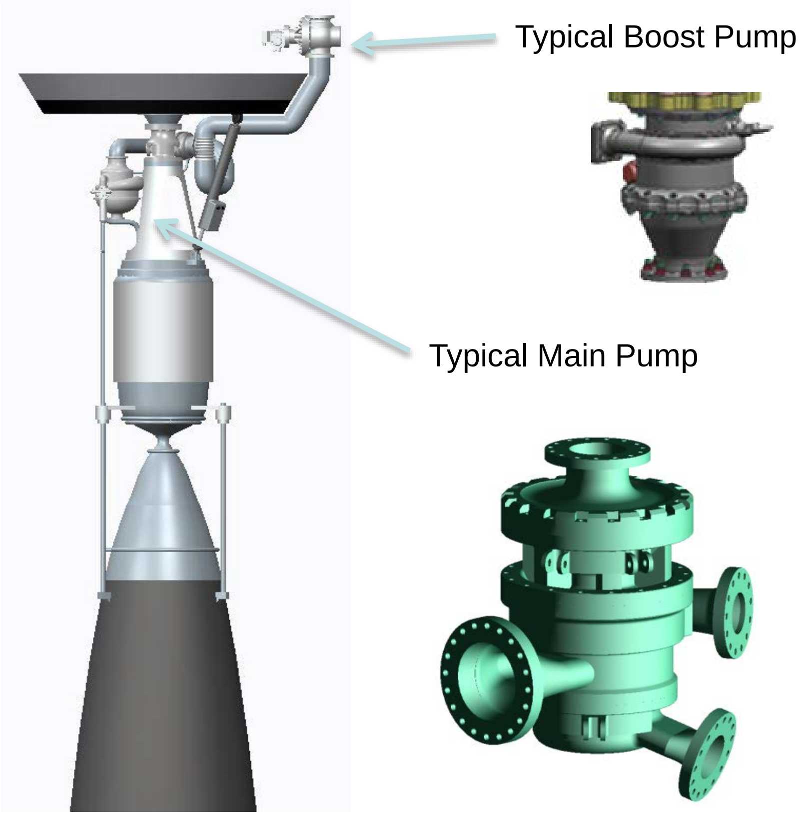
  => LPZ < 6 miles

PCD (Population Center Distance ~8 miles) > 1.333 x LPZ ~ 1.333 x 6 miles ~ 8.0 miles

Ref.: NRC Regulatory Guide 4.7

Boost Pumps Condition the Propellant

- Autogenous pressurization may not be able to maintain steady state pressure of the tank
  - Analysis indicates a drop of ~12 psia during longest burn
  - Boost pump brings propellant back up to turbopump inlet conditions
  - Allows some saturated vapor to exit from the main propellant tank (risk mitigation to nucleate boiling)
- Investigating electric or hydraulic options
  - May have relatively small impact to system mass
  - May add additional approach to engine control



Introduction of a boost pump prior to main turbo pump allows for a wider range of propellant outlet conditions from the propellant tank.

Can NTP systems using Low-Enriched Uranium (LEU) be Developed?

- Directly reduce cost through savings related to safeguards and security
- Indirectly (and more significantly) reduced cost through enabling use of an optimal development approach and team
- Consistent with ongoing programs to convert operational Highly Enriched Uranium (HEU) systems to LEU
- Consistent with US policy. “The United States is committed to eliminating the use of HEU in all civilian applications, including in the production of medical radioisotopes, because of its direct significance for potential use in nuclear weapons, acts of nuclear terrorism, or other malevolent purposes.” (2012 White House “Fact Sheet”)

Initial LEU Conceptual Designs Very Promising

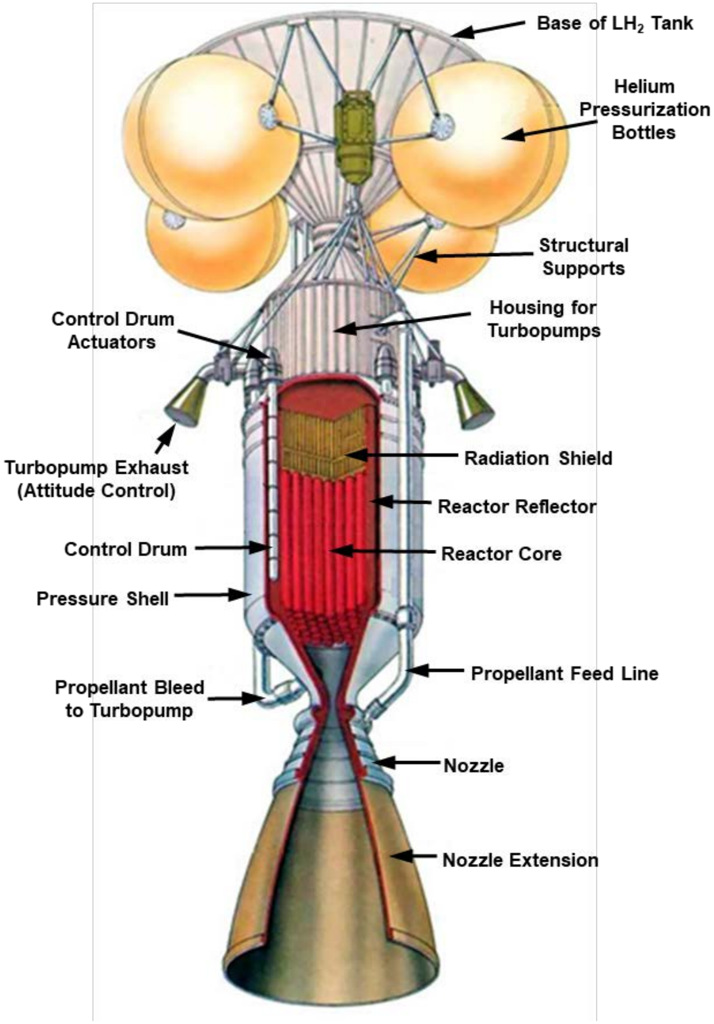
LEU Fission System Considerations

- Greatly reduced safeguards considerations if LEU is used. US encourages use of LEU in nuclear programs around the world.
- No uniquely hazardous materials in fission systems prior to operation. LEU toxicity comparable to depleted uranium. Depleted uranium used in shielding for industrial radiography cameras, trim weights in aircraft (up to 1500 kg in Boeing 747-100), sailboat keels, ammunition, armor plating, etc. Beryllium used in most modern spacecraft. James Webb telescope contains ~300 lbs of beryllium.
- Primary potential hazard from space fission systems is inadvertent criticality while personnel are in very close proximity (i.e. ground processing). Highly affected radius is < 10 m. System design and procedures for precluding inadvertent criticality during ground processing can be made independent of launch vehicle specifics.
- For criticality (with significant fissions) to occur during a launch failure the system must remain geometrically intact while safety mechanisms are simultaneously removed.

Sensor Needs for Engine System Design

Instrumentation is needed for engine control and health monitoring:

- High thermal temperatures and vibration levels
- Nuclear radiation composed of neutron fluxes and gamma rays
- Non-invasive sensor designs for:
  - o Neutron flux (outside reactor)
  - o Chamber temperature
  - o Operating pressure
  - o LH2 propellant flow rates

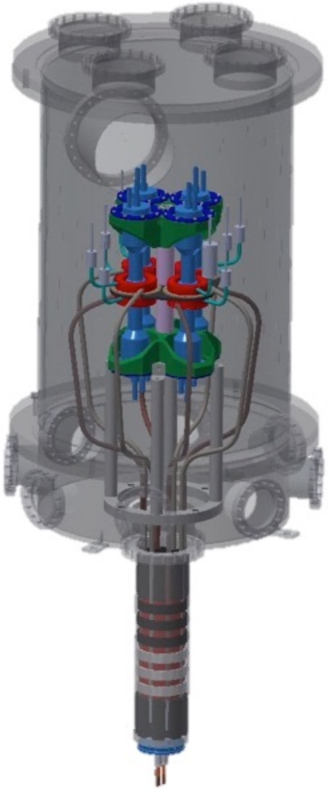


DRAFT SBIR “Nuclear Thermal Propulsion” Subtopic: Release ~January 2019

Fission Has Tremendous Growth Potential

- The first flight of a modern space fission system will be a tremendous first step towards the development and utilization of highly advanced space fission systems (analogous to DC-3 helping enable SR-71)
- Advanced fission systems include potential options for liquid, gas, or plasma core reactors (very high performance)
- Advanced NTP systems could potentially use any volatile as propellant
  - Move asteroids or Kuiper Belt objects using volatiles from the object as propellant?
  - Combination of NTP and gravity assists to relocate objects anywhere in solar system?
  - Refueling depots? Terraforming?

What is Kilopower?



- Small and simple approach for long-duration, sun-independent electric power for space or extra-terrestrial surfaces
  - Produces from 1 to 10 kilowatts, continuously for 10 years or more
  - Weighs about 400 kg at 1 kW or 1500 kg at 10 kW, for complete system
  - Uses solid, cast uranium-235 reactor core, about the size of a paper towel roll
  - Transfers reactor heat with passive sodium heat pipes
  - Converts heat to electricity with high efficiency Stirling engines
  - Leverages current DOE fuel production processes and abundant material supply from dismantled nuclear weapons
  - Launches as a radiologically benign, non-operating (cold) payload

- Represents NASA's first attempt at building and testing a REAL space reactor since the 1960s SNAP Program

2013 R&D 100

Chart courtesy Lee Mason, NASA GRC

Nuclear Test Assembly

Chart courtesy Lee Mason, NASA GRC

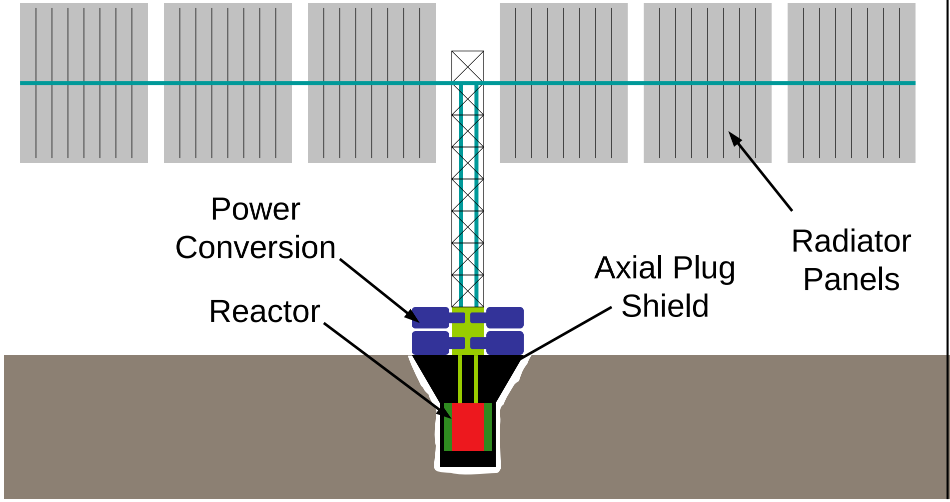
Design Configuration & Shielding

The Emplaced option uses regolith shielding to reduce mass and permit near outpost siting. The Landed option reduces the reliance on crew and equipment for installation.

Ref.

Emplaced Configuration

Off-Loaded from Lander
Below-Grade, Axial Shield
Augmented by Lunar Regolith
<5 rem/yr at 100 m (360°)
Boom Deployed Radiator
400 V Power Transmission



Option

Landed Configuration

Dedicated Lander
Above-Grade, Shaped 4-Pi Shield
<5 rem/yr at 1 km (Habitat Area)
<50 rem/yr at 1 km (Non-Habitat)
Boom Deployed Radiator
2 kV Power Transmission

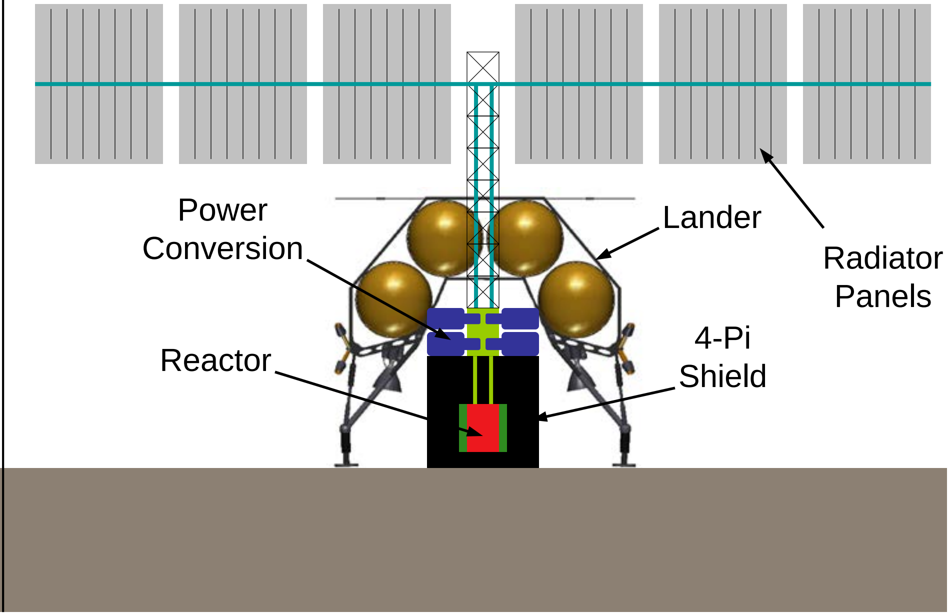


Chart courtesy Lee Mason, NASA GRC

Shielding Comparison

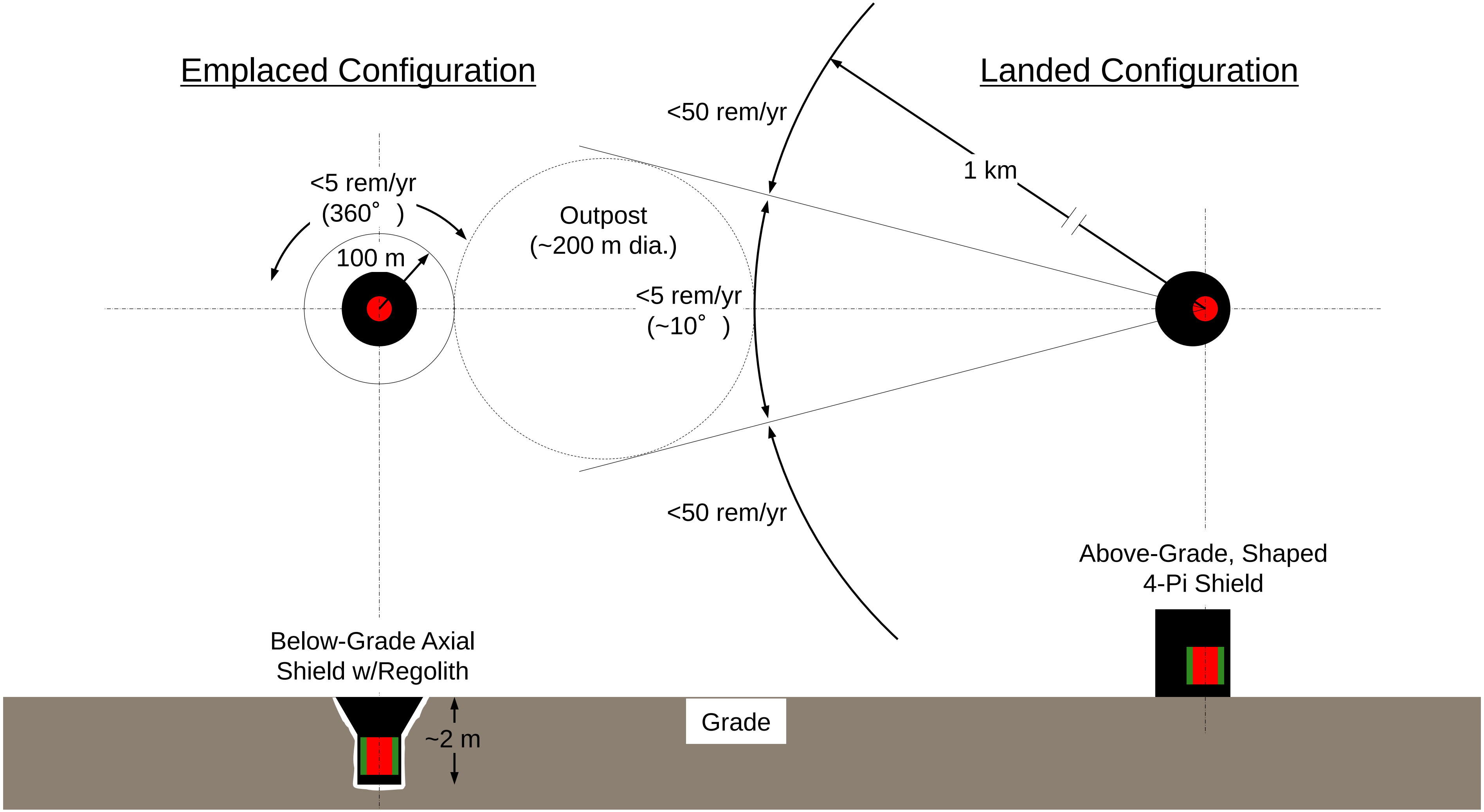
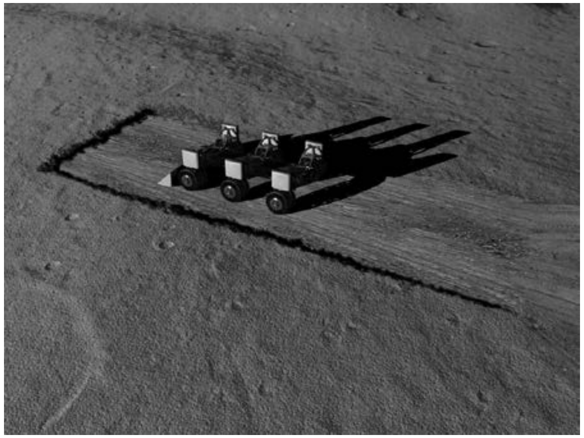


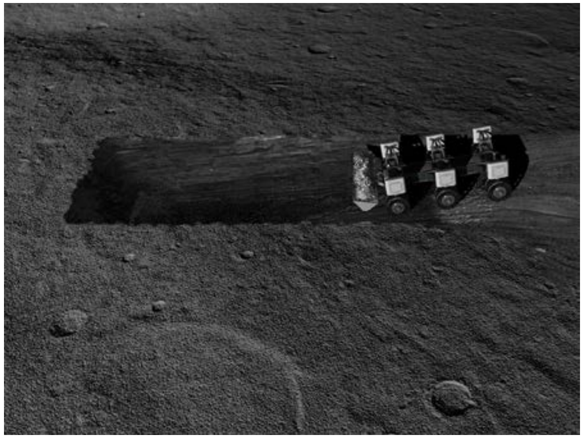
Chart courtesy Lee Mason, NASA GRC

Fission Surface Power System Installation

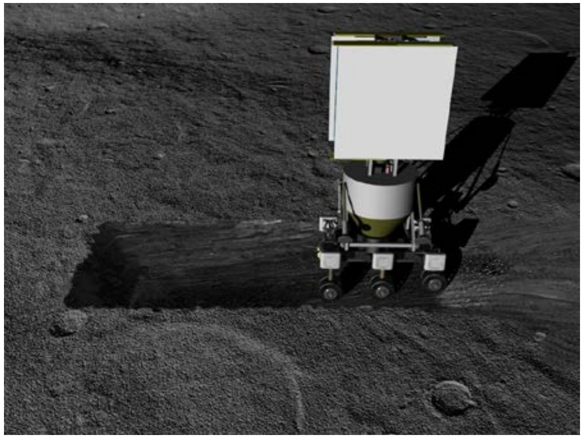
(Lunar Architecture Team)



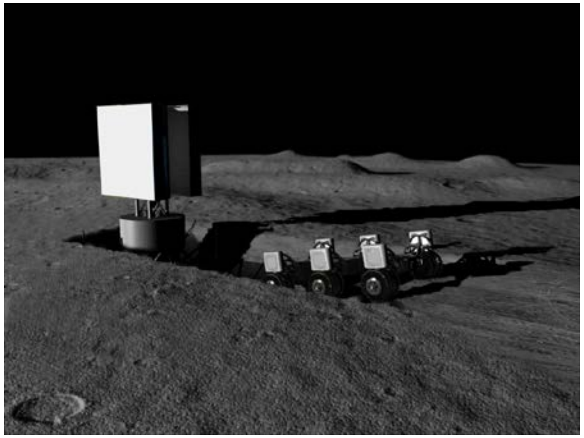
1. Site Selection



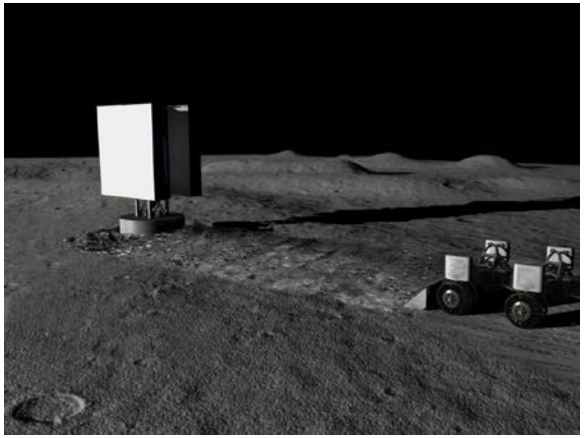
2. Excavation



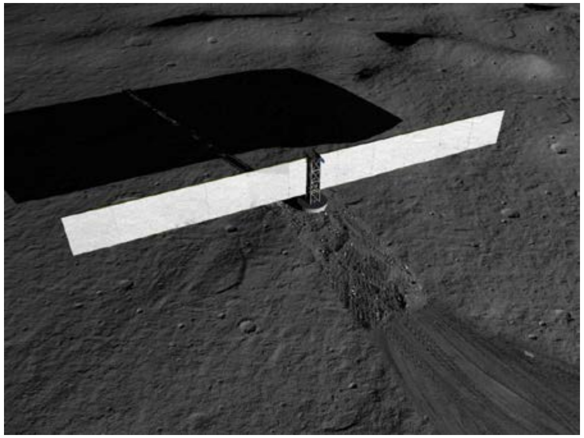
3. Delivery



4. Emplacement



5. Back-filling



6. Startup

Chart courtesy Lee Mason, NASA GRC

Conclusions

- Space fission power and propulsion systems are game changing technologies for space exploration.
- First generation NTP systems could provide significant benefits to sustained human Mars exploration and other missions.
  - Potential for Earth-Mars transit times of 120 days; 540 day total Mars mission times; reduced crew health effects from cosmic radiation and exposure to microgravity; robust Mars architectures including abort capability.
  - Faster response times, improved capability, and reduced cost for cis-lunar operations. NTP derivatives could enable very high power systems on lunar surface (ISRU) and in space.
- Advanced space fission power and propulsion systems could enable extremely ambitious space exploration and development.

- New sensor technology will be needed for ground test and flight systems!

Nuclear Thermal Propulsion (NTP)

STMD (GCD) Nuclear Thermal Propulsion Video

https://www.youtube.com/watch?feature=youtu.be&v=miy2mbs2zAQ&app=desktop

Backup

Space Technology Mission Directorate (STMD)
Game Changing Development (GCD) Program
Nuclear Thermal Propulsion (NTP) Project Overview

Project Manager: Sonny Mitchell, NASA MSFC

Project Objective:

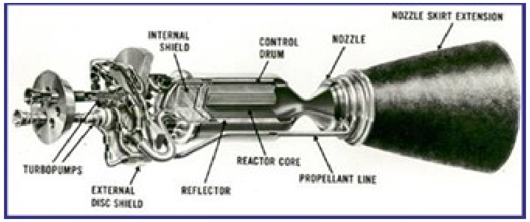
Determine the feasibility and affordability of a Low Enriched Uranium (LEU)-based NTP engine with solid cost and schedule confidence

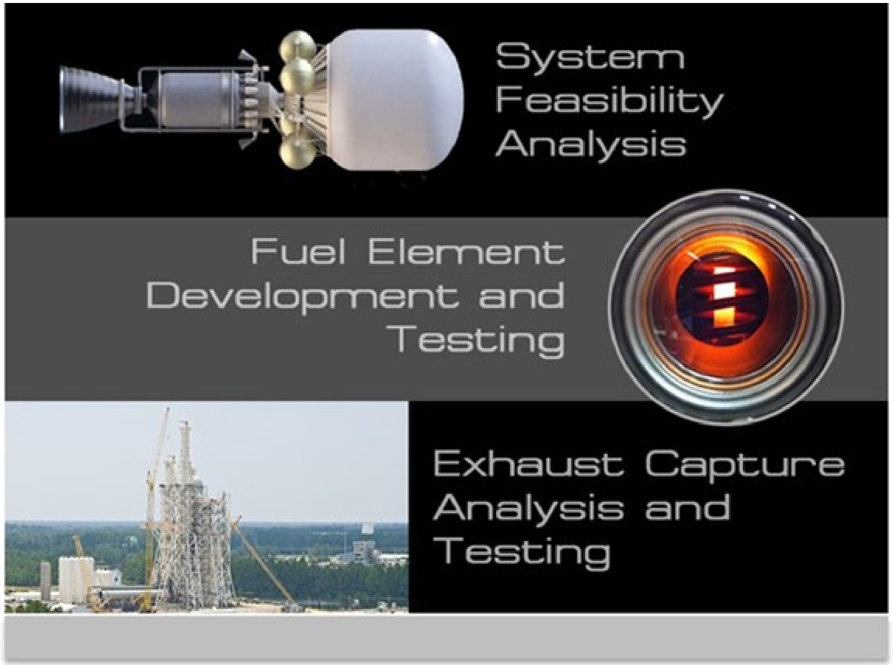
Approach:

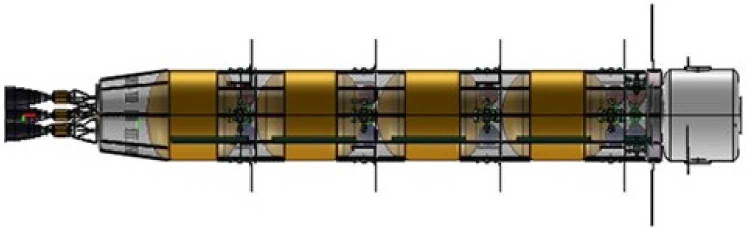
- Evaluate the implications of using LEU fuel on NTP engine design
- Fuel element, reactor, and engine conceptual designs and feasibility analyses
- Mature critical technologies associated with LEU fuel element materials & manufacturing
- Develop an exhaust capture method to facilitate ground testing
- Develop relevant cryogenic propellant management technologies

Roles and Responsibilities

- **MSFC**: PM, SE & Analysis Lead, Cryo ConOps Lead, FE Testing
- **GRC**: Cryocooler Testing, Cryo ConOps Support, Sys. Analysis Support
- **SSC**: Rocket Exhaust Capture System Subscale (RECSS)
- **KSC**: Ground Processing ConOps / Propellant Densification
- **Aerojet Rocketdyne**: LEU Engine Analysis
- **AMA:** Engine Cost Lead
- **Aerospace:** Engine Cost Independent Review
- **BWXT:** Fuel Element (FE) / Reactor Design/Fabrication
- **DOE:** FE / Reactor Design and Fabrication Support







CFEET Segment Test

- Completed successful test of the first fuel element (FE) specimen, C0, in the MSFC Compact Fuel Element Environmental Tester (CFEET) on 8/9/18
  - C0 specimen was a pathfinder for FE fabrication techniques
  - C0 was a 0.75 inch hexagonal “can” with solid laser-welded end caps filled with a surrogate powder
  - Reached the specimen target temperature of 2200K with a hold time of 20 minutes.
  - Next test of the specimen is planned to reach a temperature of 2400K