X energy

Space Reactors

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Director of Engineering, Xe-Mobile

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X-energy was Created to Change the World

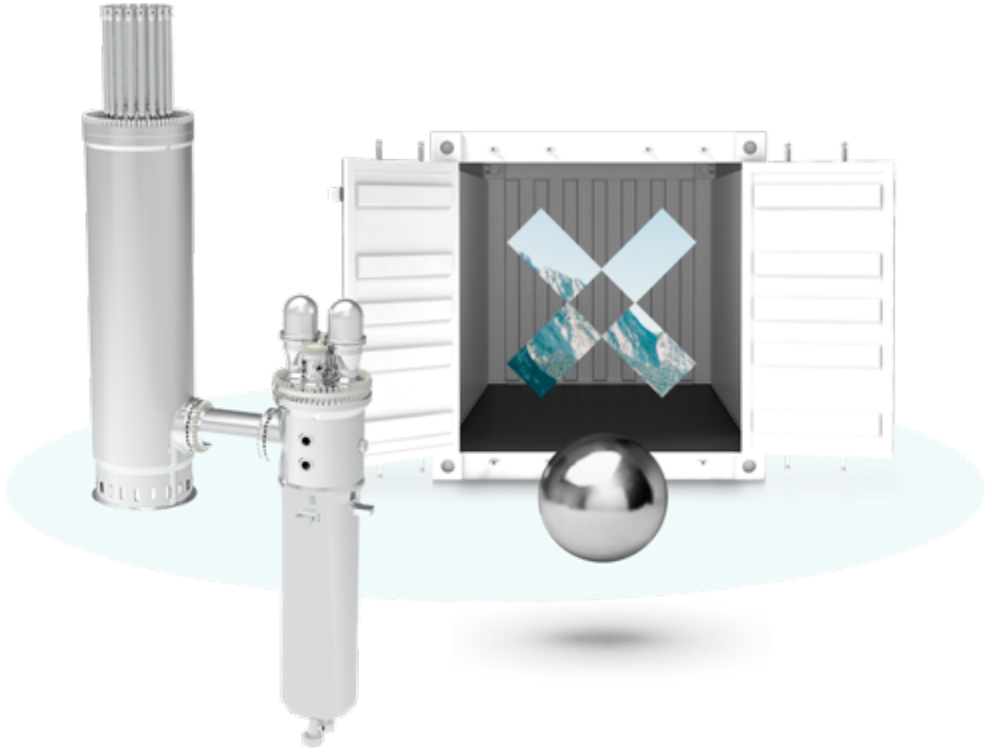
Dr. Kam Ghaffarian, Founder and Executive Chairman

"President Kennedy once said that we are in a space race and my work with NASA reflects the progress he had hoped for.

Today, I believe we are in an energy race. Providing clean energy across the world is my vision for X-energy and I believe that clean, safe, reliable nuclear energy is necessary to making this possible."

- Dr. Kam Ghaffarian is a globally recognized technology visionary across energy, space and information technology.
- Created and grew Stinger Ghaffarian Technologies (SGT), Inc. to $650 million in annual revenue and 2,400 employees. SGT was ranked as the U.S. National Aeronautics and Space Administration's second largest engineering services company prior to being acquired by KBRwyle, subsidiary of KBR, Inc.
- Founded X-energy in 2009 to address innovation in critical energy solutions. X-energy was awarded ~$60M from DOE to focus on an advanced nuclear reactor and TRISO fuel.
- Began Intuitive Machines in 2016 to leverage NASA technologies for commercial space and terrestrial applications. Intuitive Machines won its first Commercial Lunar Lander Contract from NASA in 2018 with first landing scheduled for 2021.
- Began Axiom Space in 2017 to develop the first commercial space station, to be launched by 2021.

We design & build reactors and the fuel that powers them



Reactor: Xe-100

We're focused on Gen-IV High-Temperature Gas-cooled Reactors (HTGR) as the technology of choice, with advantages in sustainability, economics, reliability and safety.

Reactor: Xe-Mobile

To address the need for ground, sea and air transportable small power production. We've developed reactor concepts with potential civilian government, remote community and critical infrastructure applications.

Fuel: TRISO-X

Our reactors use tri-structural isotropic (TRISO) particle fuel, developed and improved over 60 years. We manufacture our own proprietary version (TRISO-X) to ensure supply and quality control.

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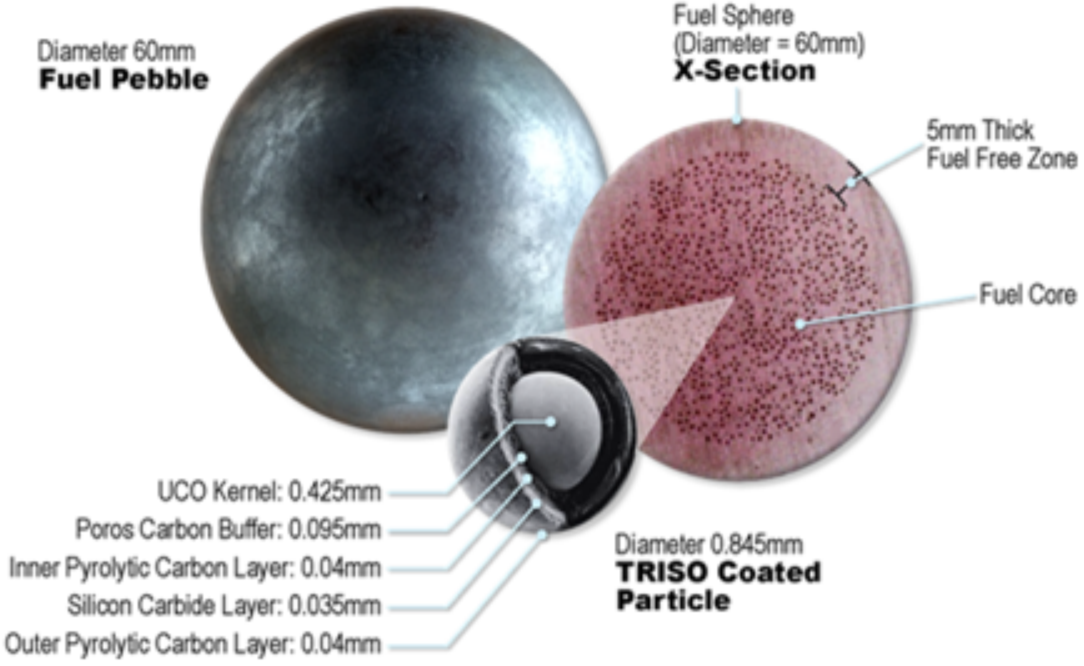
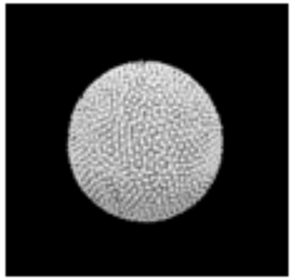
TRISO-X Fuel Production

TRISO Coated Particle Fuel is the Key to Safety

- Each TRISO particle forms a miniature containment vessel that retains radionuclides at the source for full spectrum of off-nominal events
- Demonstrated ability to withstand extremely high temperatures for extended periods (1800 °C for 300+ hours) without fuel failure
- High level of maturity due to >$250M investment by DOE in design and qualification and characterization of the TRISO fuel
- World's only active TRISO fuel fabrication facility.




Prototype pebble mold

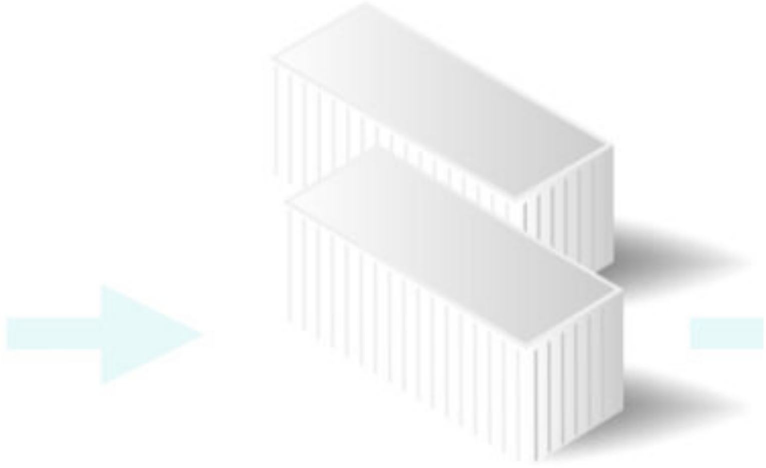

Innovative visualization of particles in pebble

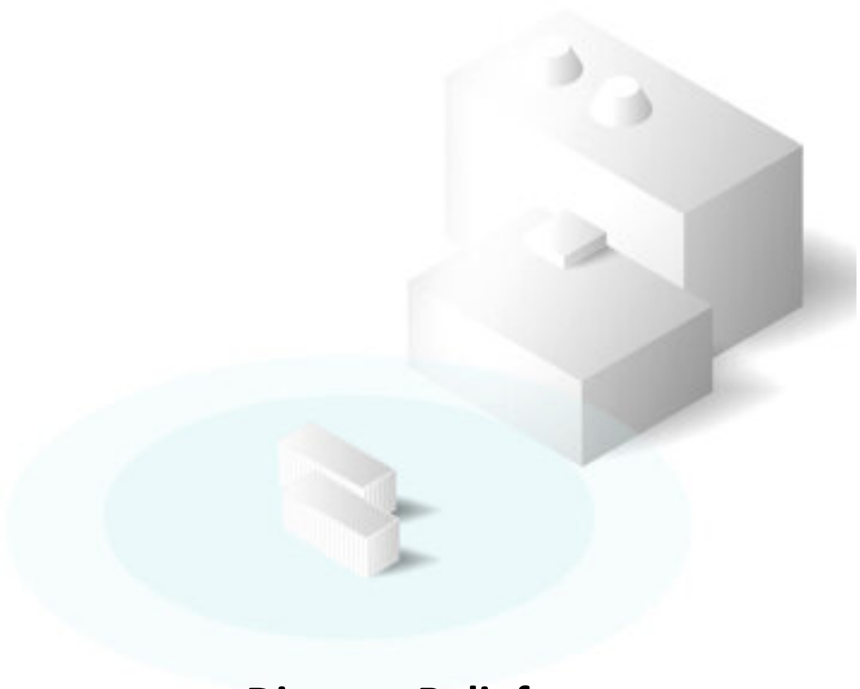

First fuel form pebbles produced at ORNL, Fall 2018

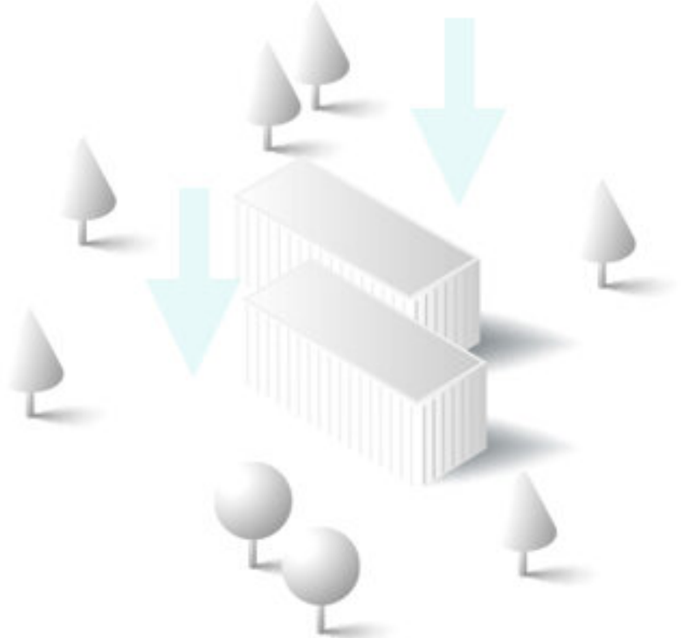

DOE's Dr. Rita Baranwal tours TRISO-X Pilot Lab

Fuel is an integral part of the HTGR safety basis and economics

Novel Applications of Microreactors







Defense & forward bases

As the US Military prepares for "near-peer" adversaries of the future, highly portable power with a high energy density will be a game-changing technology.

Highly Portable Power

Disaster Relief

The ability to transport flexible electricity solutions that do not require fueling for months or years provides critical infrastructure to get railroads, water purification facilities, and hospitals powered again – within one week.

Be powered again – within one week

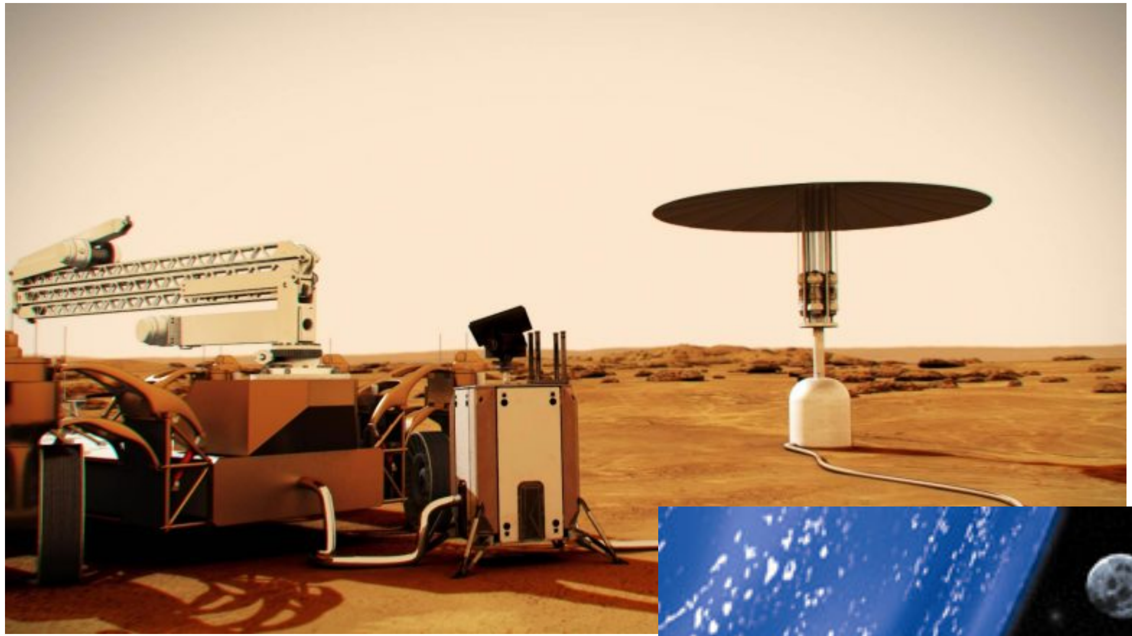
Remote Communities

Arid, Island and Alaskan/Canadian communities often use government-subsidized petroleum fuel deliveries to maintain their power. If their deliveries are disrupted, the impact can be significant.

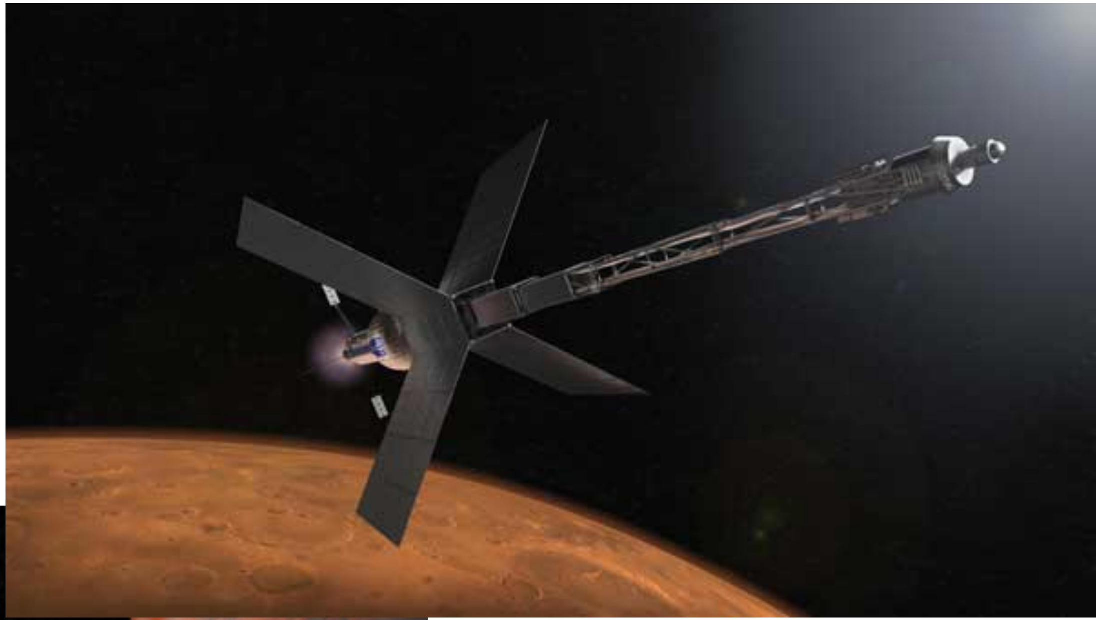
Maintain Power

Space Nuclear Applications

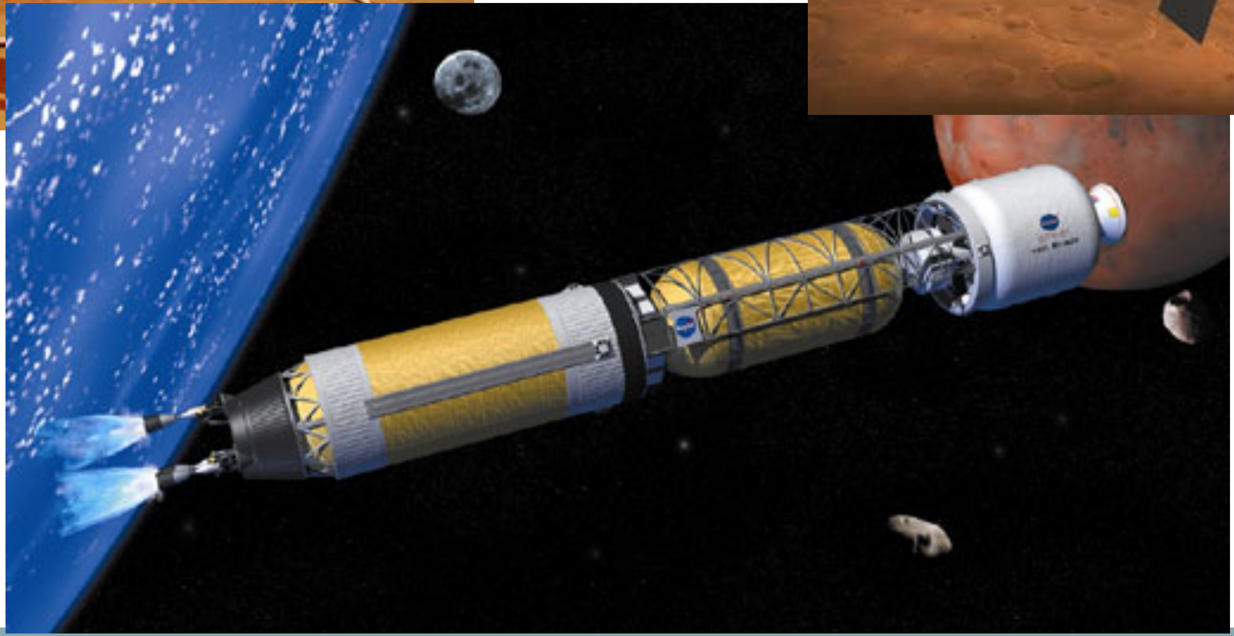
Fission Surface Power System



Nuclear Electric Propulsion



Nuclear Thermal Propulsion

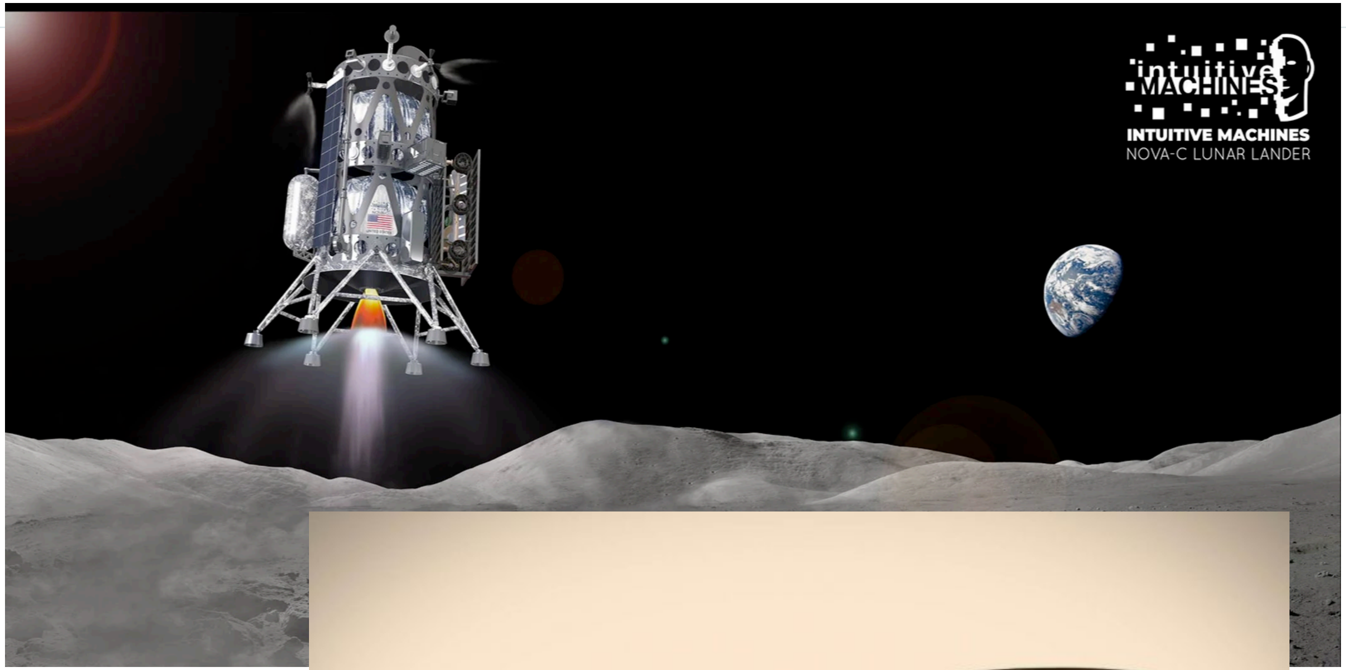


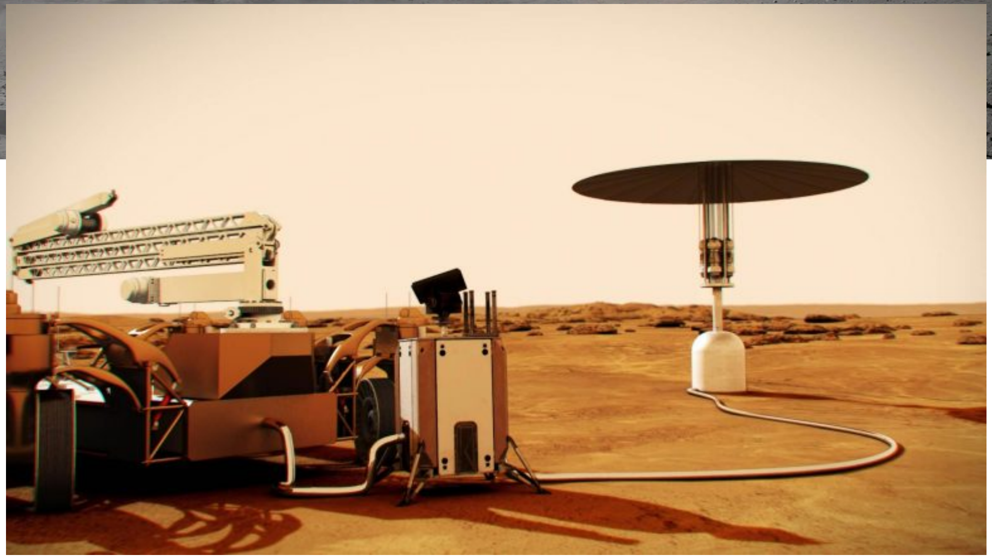
Images: NASA

Fission Surface Power Systems

Sustained Power for Sustained Human Presence on the Moon, then Mars

- NASA with Battelle Energy Alliance (INL) has issued a draft Request for Proposals
- >10 kWe and 10-year autonomous operation with control and monitoring from Earth
- Desire for HA-LEU fuel <19.75% ^{235}U
- <3500 kg integrated power plant mass
  - Reactor
  - Shielding
  - Power conversion
  - Heat rejection
  - Control and communication
- Entire system dimensions 3.5 x 3.5 x 6 m for transport
- Structural loads for launch, landing
- Fault tolerant
- ***Launch ready by 2026***





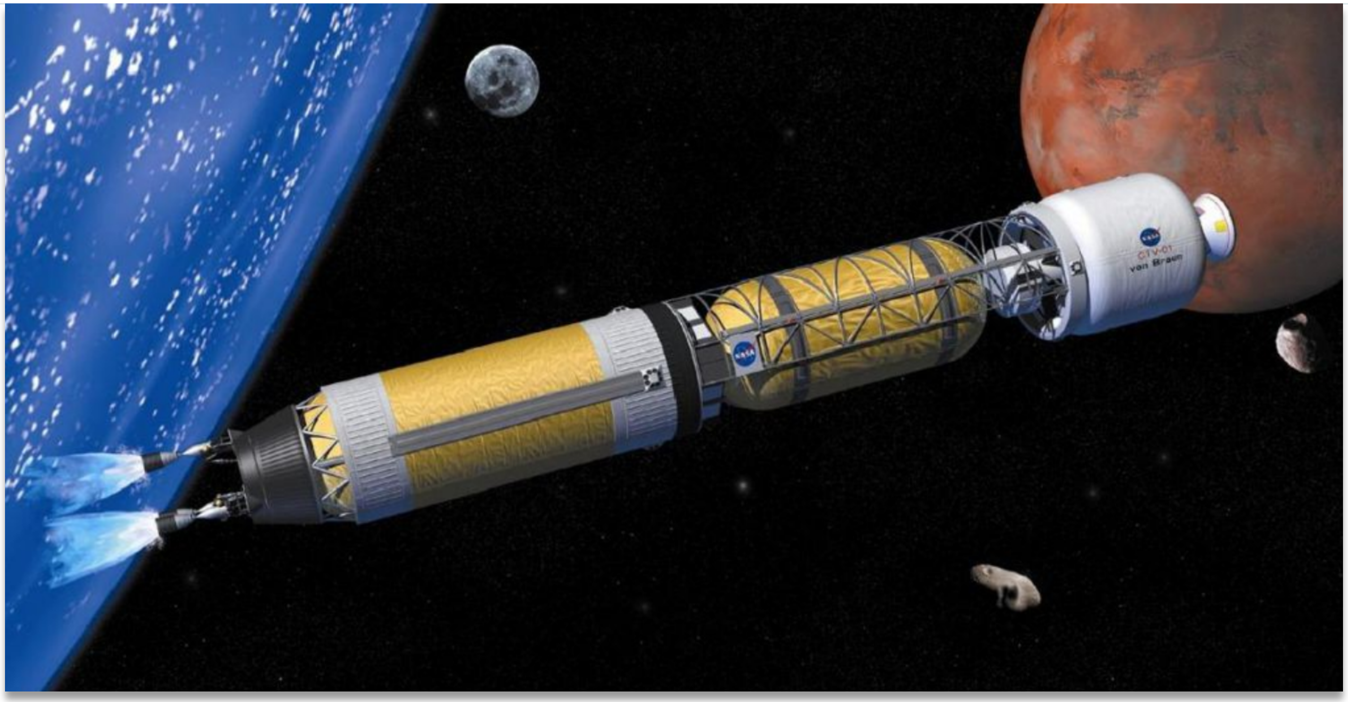
Our family companies are landing on the Moon.

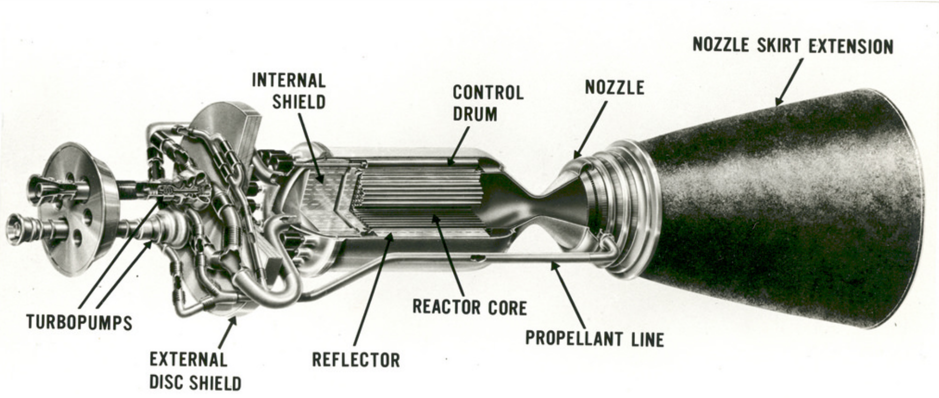
Nuclear Thermal Propulsion

100s of MW Burst Systems for Manned Missions to Mars

- NASA with Battelle Energy Alliance (INL) has issued a draft Request for Proposals
- HA-LEU <20% ^{235}U
- Hydrogen propellent
- I_{sp} of 900 sec, extensible to 1000 sec
- 12,500 lbf thrust, scalable to 25,000 lbf
- Requires temperatures approaching 3000 K
- Total system mass of 2500–3500 kg
  - Reactor and all components
  - Pressure vessel
- Operation
  - Continuous thrust 2–5 hrs
  - ≥ 5 startup/shutdown
- Engine interface
- Test plan for unfueled and fueled reactor

- Numerous studies performed by industry teams over the past 2 years



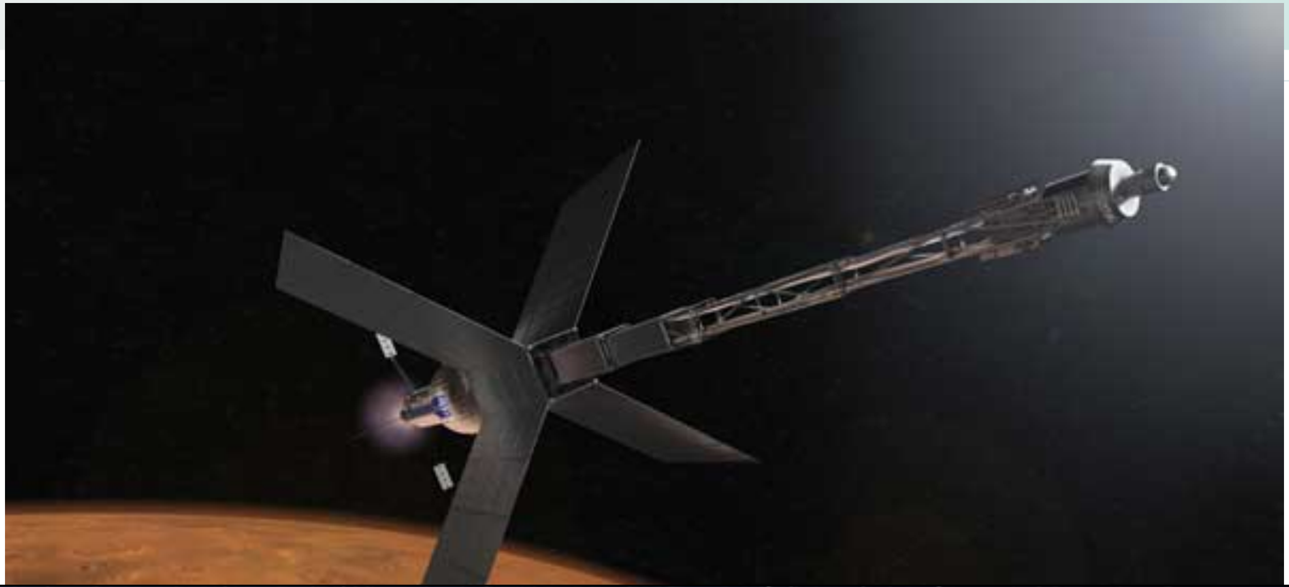


1960s Nuclear Engine for Rocket Vehicle Application (NERVA)

Nuclear Electric Propulsion

MW Level Electrical Power Systems for Sustained Thrust to Mars

- NASA currently hosting Technical Interchange Meetings
- Late 2030s flight target
- Reactor temperature >1200 K to reduce size of heat rejection radiator
- > 20,000 hrs operation
- ≥ 2 MWe
- Integrated with power conversion system



Space Nuclear Propulsion

Summary of Space Brayton Development Efforts

- Highest demonstrated per unit power level was 11 kW_e

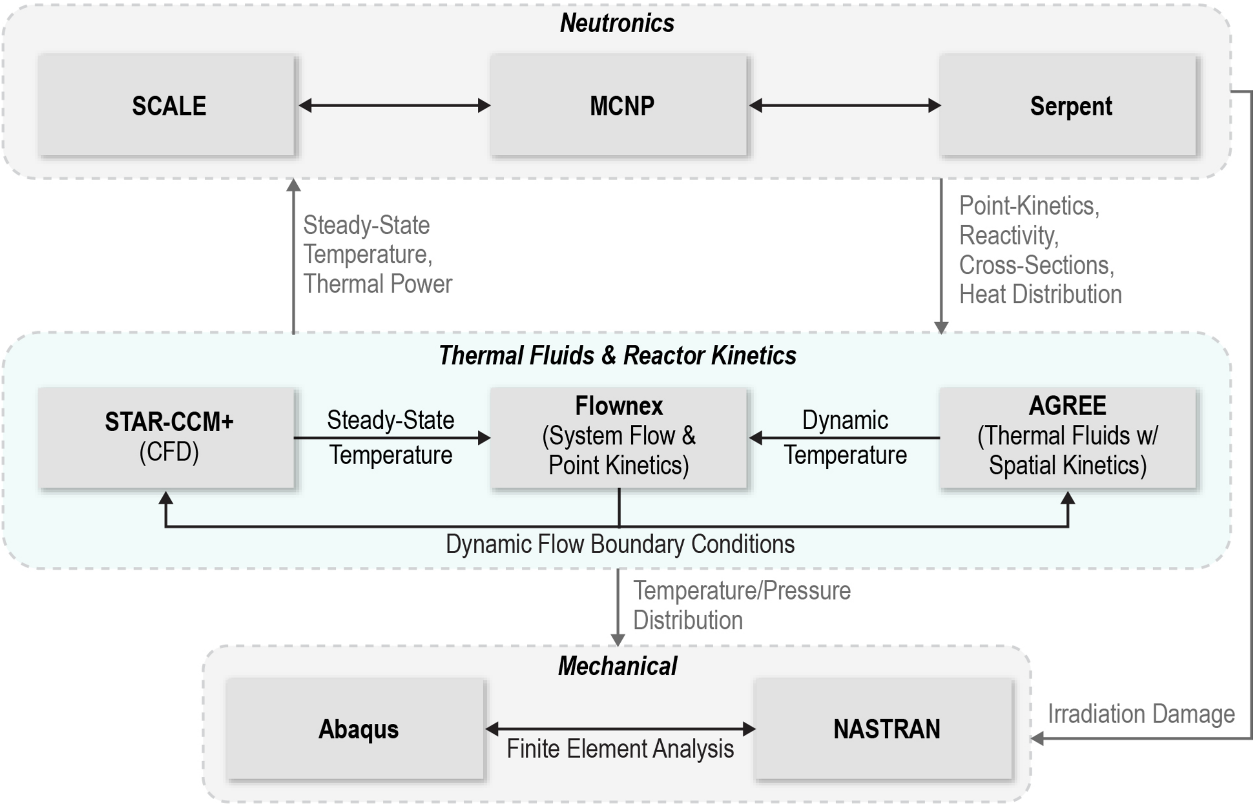
Years	Project	Power	Convertor	State Achieved
1960s	BRU Development	10 kWe	BRU	Hardware testing – 38K hrs on single unit (50K hrs total on 4 units)
1970s	BIPS	2 kWe	Mini-BRU	Hardware testing – 1,000 hrs
1980s	SSF	25 kWe	SD Power Module	Design
1980s	SP-100	20 to 500 kWe	Various Brayton Designs	Design
1990s	SDGTD	2 kWe	Mini-BRU	Hardware testing – 800 hrs
1990s	SD Mir	2 kWe	Mini-BRU flight version	Flight cancelled
2000s	Prometheus	200 kWe	JIMO-Brayton (dual 100 kWe units)	Design
2008	FSP	22 kWe	Dual Capstone (dual 11 kWe units)	Hardware testing
2010s	FSP	12 kWe	FSP Brayton	Conceptual Design
2010s	RPS	100 We	Turbo-Brayton	Hardware Assembly
2017	RPS	337 We	Turbo-Brayton	Hardware Assembly in progress

Executive Actions and Appropriations

- **Promoting Small Modular Reactors for National Defense and Space Exploration (**Executive Order 13972, January 2021)
  - Demonstration of Commercial Reactors to Enhance Energy Flexibility at a Defense Installation
  - Defense Capabilities
  - Space Exploration
  - Domestic Fuel Supply
  - Common Technology Roadmap
- **Launch of Spacecraft Containing Space Nuclear Systems (**National Security Presidential Memorandum-20, August 2017)
  - Safety prescribed in terms of Total Effective Dose to population

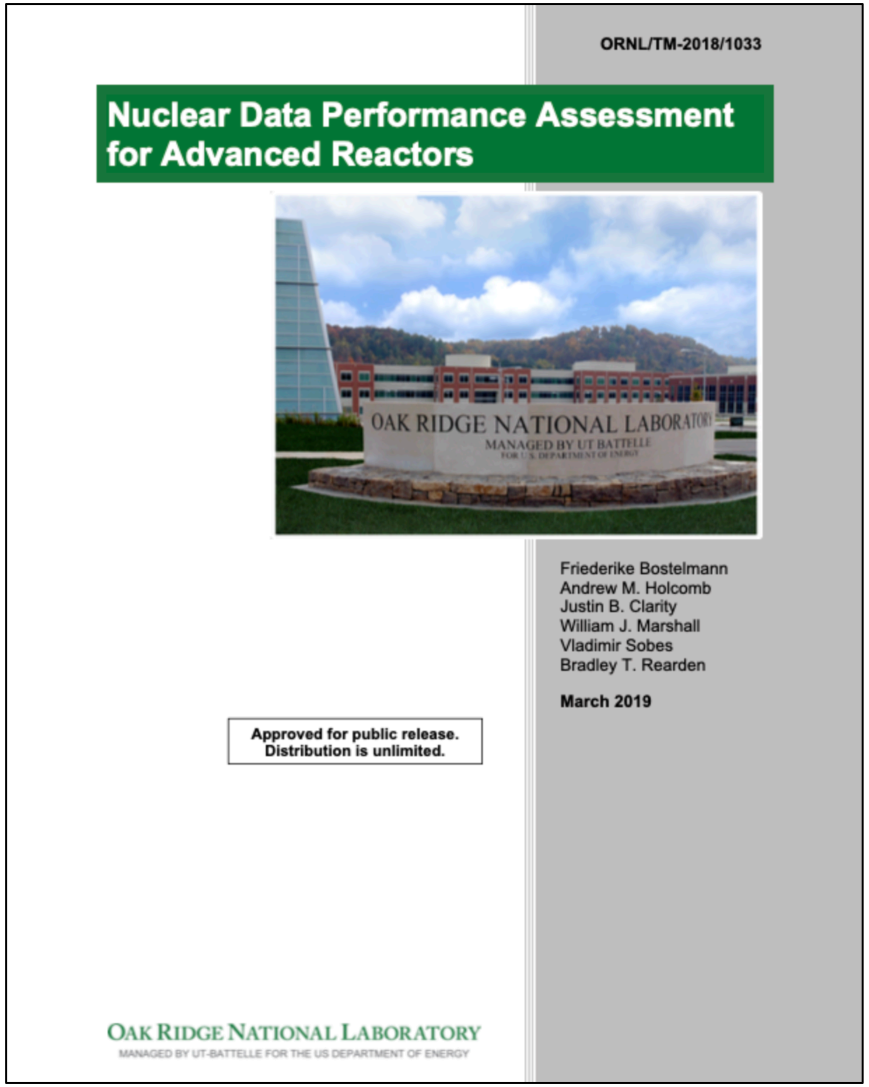
- **DOE-NE** Advanced Reactor Demonstration Program ~$200M/yr, operational reactors and technology maturation by 2027-2030s
  - Xe-100 320 MWe 4-unit plant, $1.6B
- **DOD** Mobile Microreactor $70M FY21, demonstration unit in 2024
- **DARPA** – "Demonstration Rocket for Agile Cislunar Operations" program, or DRACO - $21M FY21
- **NASA NTP** ~$100M FY21
- **NASA FSP** – Launch ready 10 kWe, 10-year lifetime, 3500 kg power plant by 2026
- **NASA NEP** – Studies resuming in 2021

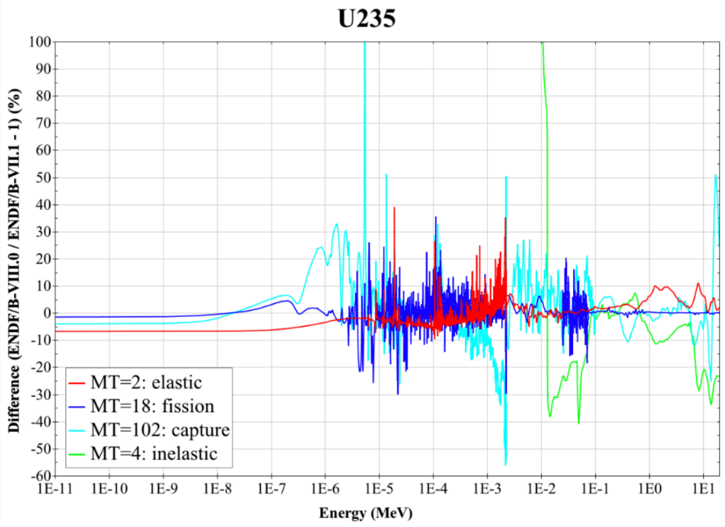
Nuclear data provide a foundation for performance and safety analysis

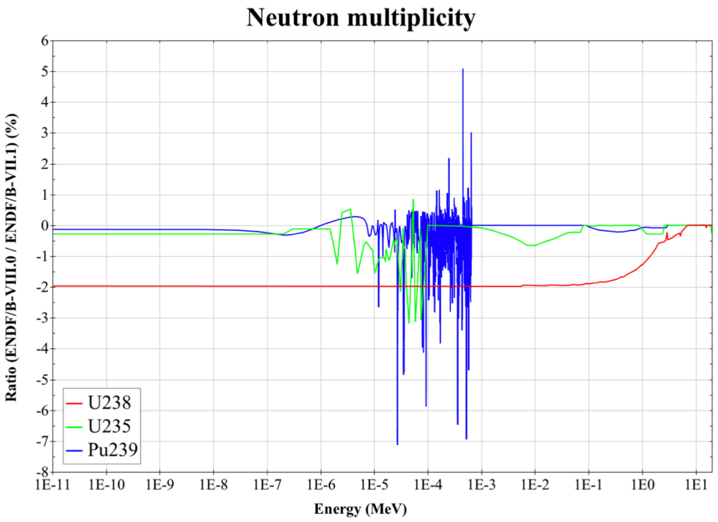


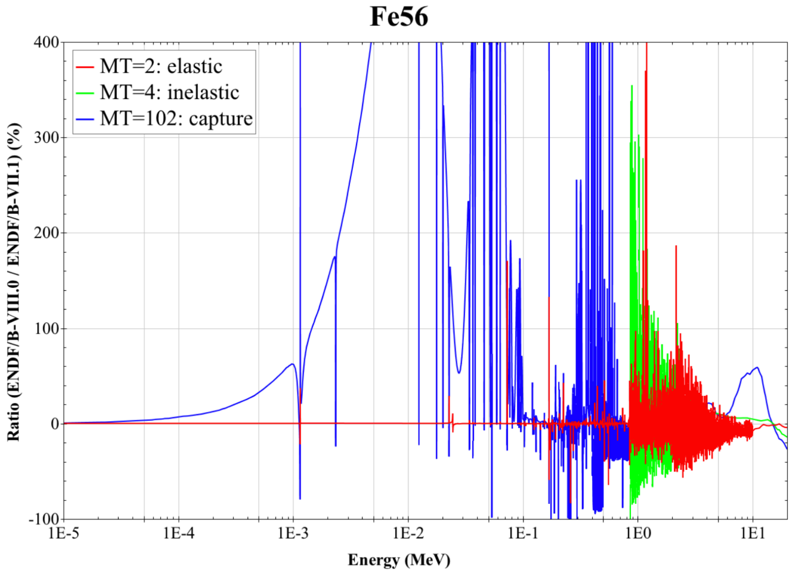
Analysis	Tool/Model	Analysis Type	Outcome
Core neutronics	SCALE/ KENO/ORIGEN	Steady-state Monte Carlo neutron transport and transmutation	Power Profiles, Core life, Burnable poison design, Temperature and control element reactivity
Cross section generation	Serpent	Steady-state Monte Carlo neutron transport	Generated few-group cross sections for AGREE-Xe and verified reactivity results from SCALE and MCNP
Photon/Neutron Transport	MCNP	Steady-state Monte Carlo neutron and photon transport	Ex-core heating rates
Reactor Thermo-fluid Analysis	StarCCM+	High fidelity heat conduction and thermo-fluid dynamic behavior	Spatially resolved temperatures and coolant flow rates
Coupled neutronic-thermal fluid analysis	AGREE-Xe	Steady-state and time-dependent neutron diffusion/heat conduction/ subchannel fluid behavior	Peak and average temperatures of structures during transient scenarios
Plant Dynamics	Flownex	Steady-state and time-dependent analysis of plant-wide behavior	Plant/Reactor response to perturbations and fault conditions. Startup, shutdown, and critical power maneuvers
Shielding	SCALE/ MAVRIC/ ORIGEN	Steady-state neutron and gamma transport, activation, decay	Ex-vessel dose and activation rates
Structural Dynamics	NASTRAN	Dynamic Finite Element Analysis	Static-equivalent accelerations to be used for stress analysis, Load Isolation System evaluation
Mechanical and thermal stress	Abaqus	Steady-state Finite Element Analysis	FEA-calculated stresses, to be compared against material allowables to determine if the parts meet design requirements
Instrumentation & Controls	PSCAD	Simulation of electric power conversion	Power Balance of EPCS with a notional load bank at steady state response of system to various load transients, including abnormal loads and fault conditions
Hazards Analysis (Fire, chemical, mechanical, electrical, etc.)		Identification of hazards associated with assembly, transport, and disassembly operations	Design requirements for hazard mitigation systems (e.g., Fire Detection and Suppression)

Concerns with changes in ENDF/V-III.0 without consideration for reactor applications









Validated Nuclear Data Needs

- **Small and precise reactors require optimized power and lifetime predictions**
  - Power distribution
  - Reactivity control and shutdown margin
  - Fission product inventories
- **Close proximity to public and need for low mass solutions require precise source term and shielding data**
  - Prompt neutrons and gammas from fission
  - Gamma emissions from fission product decay
  - Neutron capture data
  - Material activation and decay
  - Neutron and gamma attenuation
- **Thermal scattering law data**
  - Advanced moderators/reflectors are needed for small HA-LEU cores
  - YH_x is of interest for lower temperature applications
  - NTP systems approach 3000 K for fuel and structural materials with H_2 as internal propellant
- **Irradiation damage assessment is needed for wide range of materials**
  - Damage cross sections should be included in ENDF libraries