Summary of Atoms for Space: Nuclear Systems for Space Exploration IAEA Webinar February 2022

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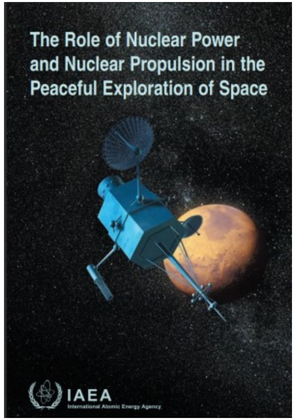
IAEA's work in this area



2005

Joint United Nations/ IAEA Technical Workshop on the Objectives, Scope and General Attributes of a Potential Technical Safety Standard for Nuclear Power Sources in Outer Space

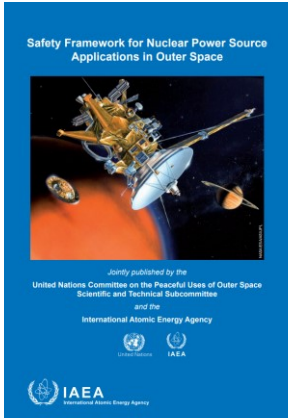
20-22 February 2006

The technical workshop on the objectives, scope and general attributes of a potential technical safety standard for nuclear power sources in outer space is organized jointly by the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space and the International Atomic Energy Agency (IAEA) in accordance with paragraph 16 of General Assembly resolution 60/99 of 8 December 2005.

Over the past years, formal and informal discussions within the Working Group on the Use of Nuclear Power Sources in Outer Space of the Subcommittee, and between the Working Group and representatives of IAEA, have led to the conclusion that further work on any of the potential options for cooperating with IAEA in developing technical safety standards for nuclear power sources in outer space (NPS) would be assisted significantly by holding a joint workshop. The joint workshop would facilitate an exchange of views between the Working Group and IAEA on the objective, scope and general attributes of a potential safety framework for NPS. Such an exchange would improve mutual understanding of the respective roles and methods of working of IAEA and the Committee and assist in examining the main issues that would arise in carrying out such a joint exercise successfully.

The main objectives of the Workshop are: a) to enhance the proposed outline of objectives, scope and attributes for an international technically based framework of goals and recommendations for the safety of planned and currently foreseeable NPS applications in outer space; and b) to enhance the definition of potential implementation options for establishing an international technically based framework of goals and recommendations for the safety of planned and currently foreseeable NPS applications in outer space.

2006



2009

2022

Two-day webinar focusing on three nuclear systems followed by 500+ participants

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- **Nuclear Propulsion Systems**
  - **Nuclear Thermal Propulsion**
  - **Nuclear Electric Propulsion**
  - **Plasma based Propulsion**
  - **Direct Fusion Drive**
- **Nuclear Power Systems**
  - **Radioisotope Thermoelectric Generators**
  - **Radioisotope heater Units**
  - **Fusion (PFRC)**
- **Nuclear Surface Power Systems**
  - **Fission**
  - **Fusion**

- The **purpose** of the webinar was to present the status of development of these systems and outline some prospects in this area
- **505 participants** attended (out of 546 registrations) from 66 Member States

Presentations, abstracts and **recordings** are available at

https://www.iaea.org/topics/nuclear-technology-and-applications/webinars/atoms-for-space-nuclear-systems-for-space-exploration

6 Talks / 2 days

Agenda

Day 1

1. Progress towards space nuclear power objectives | *Mr Vivek Lall (**General Atomics Global Corporation**)*
2. Developing the VASIMR® Engine Historical Perspective, Present Status and Future Plans | *Mr Franklin R. Chang Díaz (**Ad Astra Rocket Company**)*
3. Application of Space Nuclear Power Sources in Moon and Deep Space Exploration Missions in China | *Mr Hui Du (**Beijing Institute of Spacecraft System Engineering**)*

Day 2

4. Promises and Challenges of Nuclear Propulsion for Space Travel | *Mr William J Emrich (**NASA**)*
5. Fusion Propulsion and Power for Advanced Space Missions | *Ms Stephanie Thomas (**Princeton Satellite Systems**)*
6. NASA Investments in Space Nuclear Fission Technology | *Mr Anthony Calomino (**NASA**)*

Key Messages

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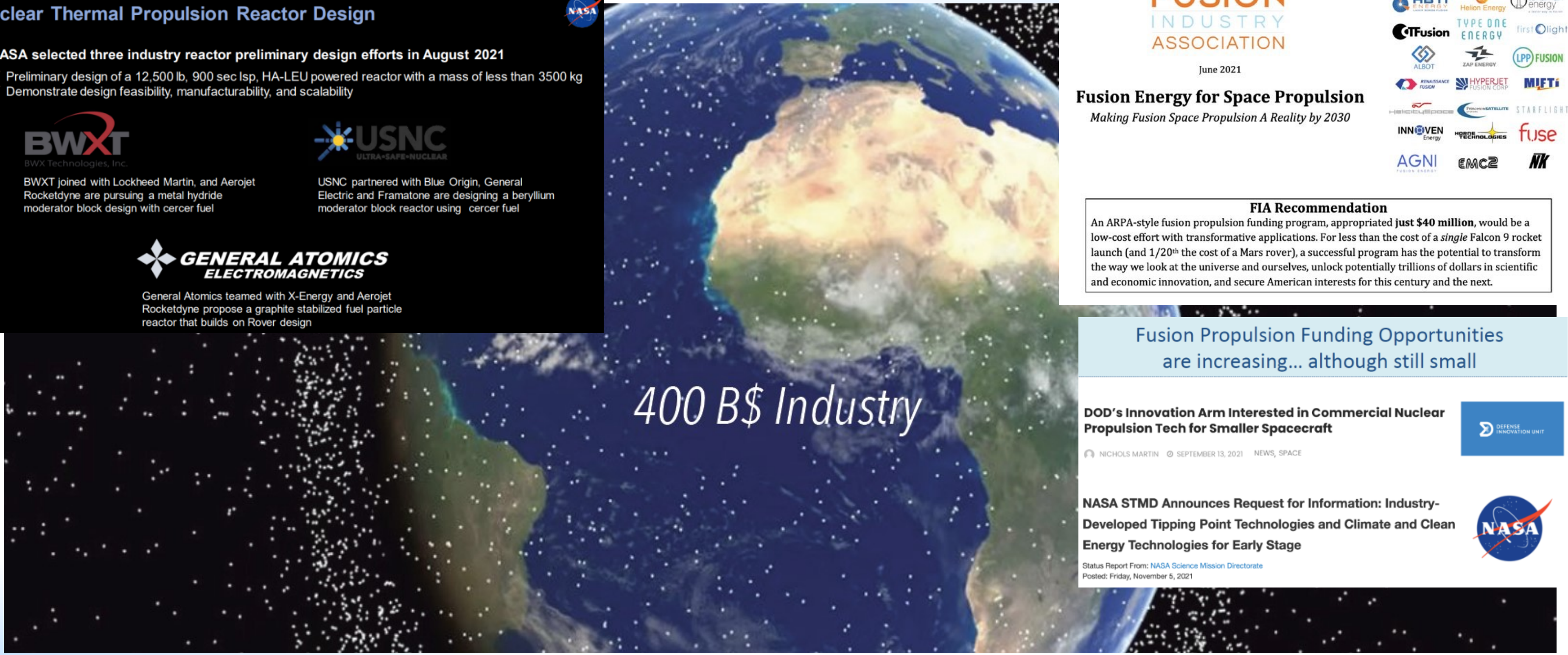
- A transportation paradigm shift is needed to enable humans to truly become a space faring specie
- Nuclear enables higher energy systems that operate continuously in extreme environments
- Nuclear propulsion systems can enable robust exploration to Mars and beyond and is crucial for fast deep space crewed interplanetary missions
- For surface exploration missions, space nuclear power system is a very promising choice
- For missions that need high electric power output, such as manned Mars mission and space ferries, fission or fusion reactor-based power system can be a very competitive choice
- Promising research and development is ongoing and was discussed – nuclear thermal propulsion, nuclear electric propulsion, plasma-based propulsion and direct fusion drive

A rapidly emerging space market



Nuclear Thermal Propulsion Reactor Design

NASA selected three industry reactor preliminary design efforts in August 2021

- ✓ Preliminary design of a 12,500 lb, 900 sec Isp, HA-LEU powered reactor with a mass of less than 3500 kg
- ✓ Demonstrate design feasibility, manufacturability, and scalability

BWXT joined with Lockheed Martin, and Aerojet Rocketdyne are pursuing a metal hydride moderator block design with cercer fuel

USNC partnered with Blue Origin, General Electric and Framatone are designing a beryllium moderator block reactor using cercer fuel

General Atomics teamed with X-Energy and Aerojet Rocketdyne propose a graphite stabilized fuel particle reactor that builds on Rover design

FUSION INDUSTRY ASSOCIATION

June 2021

Fusion Energy for Space Propulsion

Making Fusion Space Propulsion A Reality by 2030

FIA Recommendation

An ARPA-style fusion propulsion funding program, appropriated **just $40 million**, would be a low-cost effort with transformative applications. For less than the cost of a *single* Falcon 9 rocket launch (and 1/20th the cost of a Mars rover), a successful program has the potential to transform the way we look at the universe and ourselves, unlock potentially trillions of dollars in scientific and economic innovation, and secure American interests for this century and the next.

Fusion Propulsion Funding Opportunities are increasing... although still small

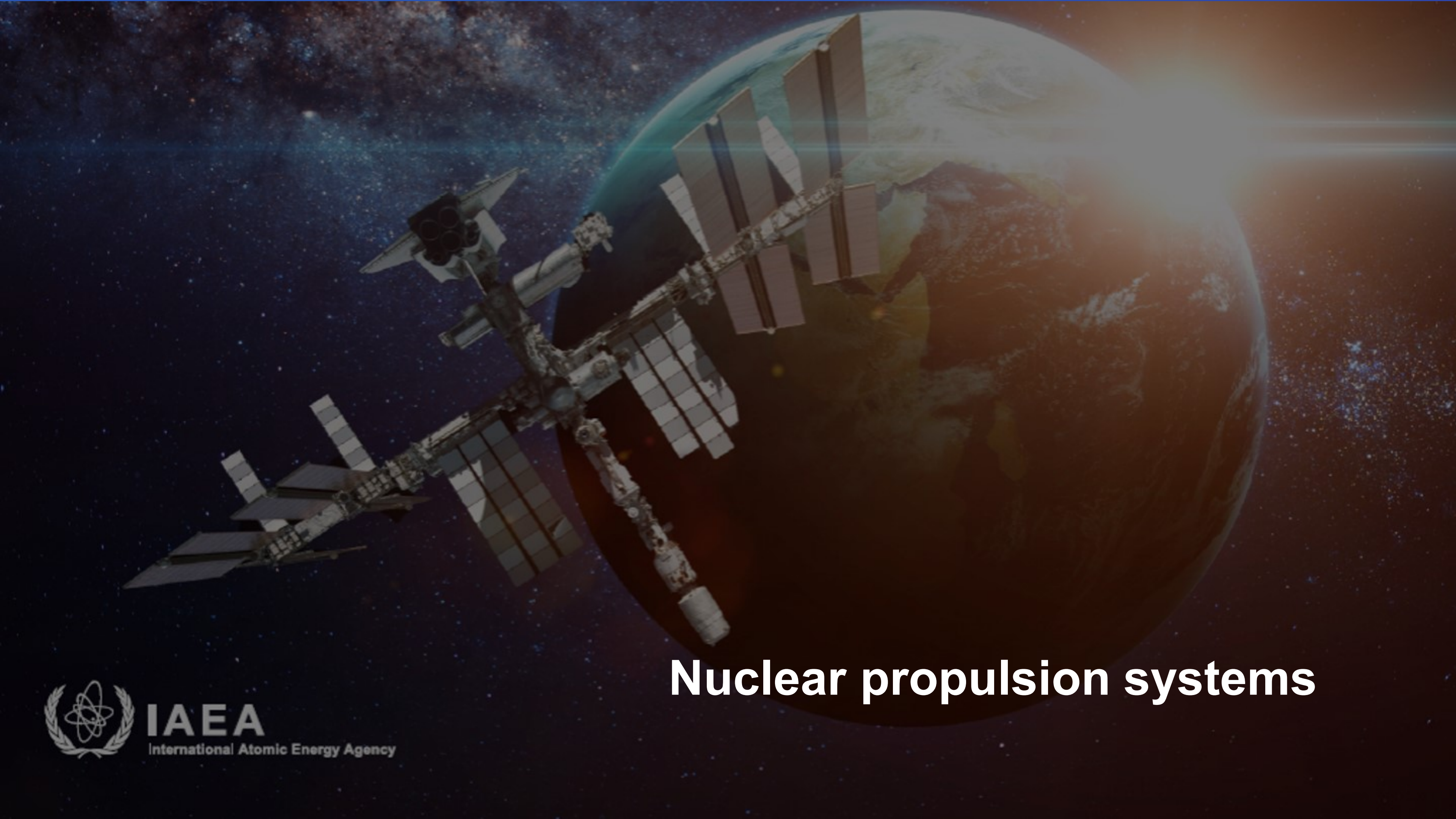
DOD's Innovation Arm Interested in Commercial Nuclear Propulsion Tech for Smaller Spacecraft

NICHOLS MARTIN SEPTEMBER 13, 2021 NEWS, SPACE

NASA STMD Announces Request for Information: Industry-Developed Tipping Point Technologies and Climate and Clean Energy Technologies for Early Stage

Status Report From: NASA Science Mission Directorate
Posted: Friday, November 5, 2021

Adapted from, **Chang Díaz, F., Ad Astra Rocket Company**, *Developing the VASIMR® Engine Historical Perspective, Present Status and Future Plans,* **Thomas, S., Princeton Satellite Systems**, *Fusion Propulsion and Power for Advanced Space Missions*, and **Calomino, A.**,**NASA,** *NASA Investments in Space Nuclear Fission Technology*
(IAEA Webinar Atoms for Space: Nuclear Systems for Space Exploration, 15-16 February 2022)



Nuclear propulsion systems

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Nuclear electric propulsion

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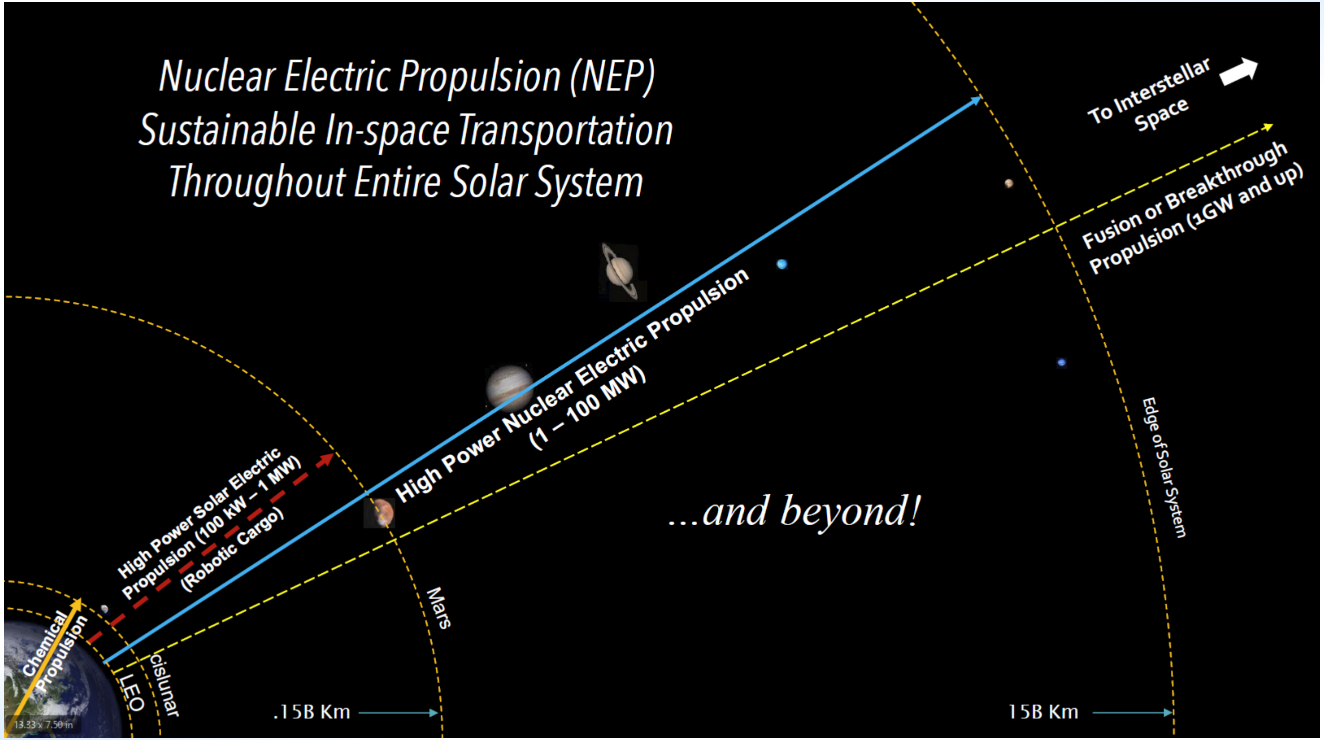
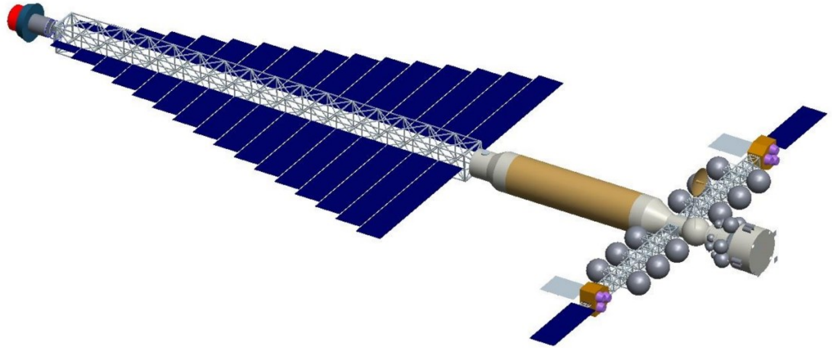


- Nuclear power of at least 1 MWe, mass/power ratio (kg/kWe) substantially lower than the current state-of-the-art, Isp > 2000 s
- Key technologies include nuclear fuel design & manufacturing, thermal-to-electric power conversion, large deployable composite radiators, high-power electric thrusters

Adapted from, **Chang Díaz, F., Ad Astra Rocket Company**, *Developing the VASIMR® Engine Historical Perspective, Present Status and Future Plans,* and **Lall, V., General Atomics Global Corporation**, Progress Towards Space Nuclear Power Objectives (IAEA Webinar Atoms for Space: Nuclear Systems for Space Exploration, 15-16 February 2022)

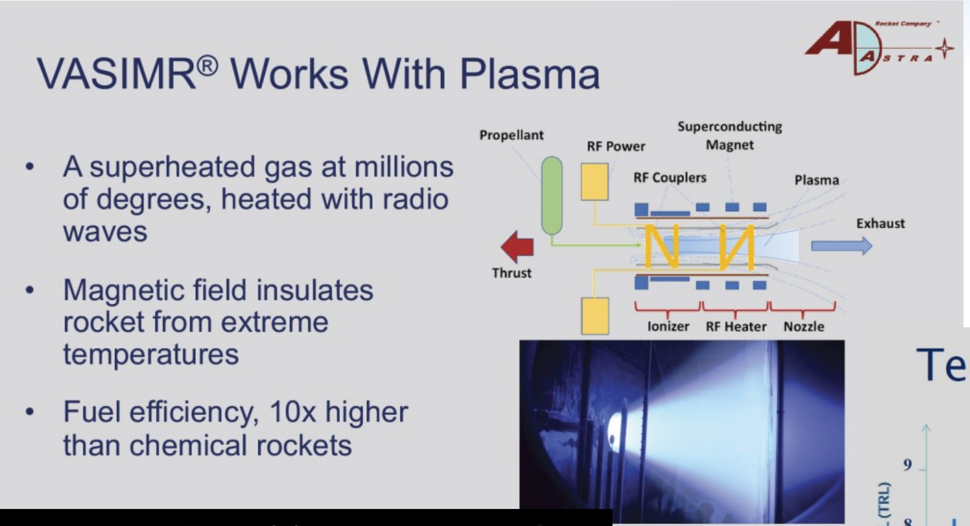
(NEP) Manned Mars exploration

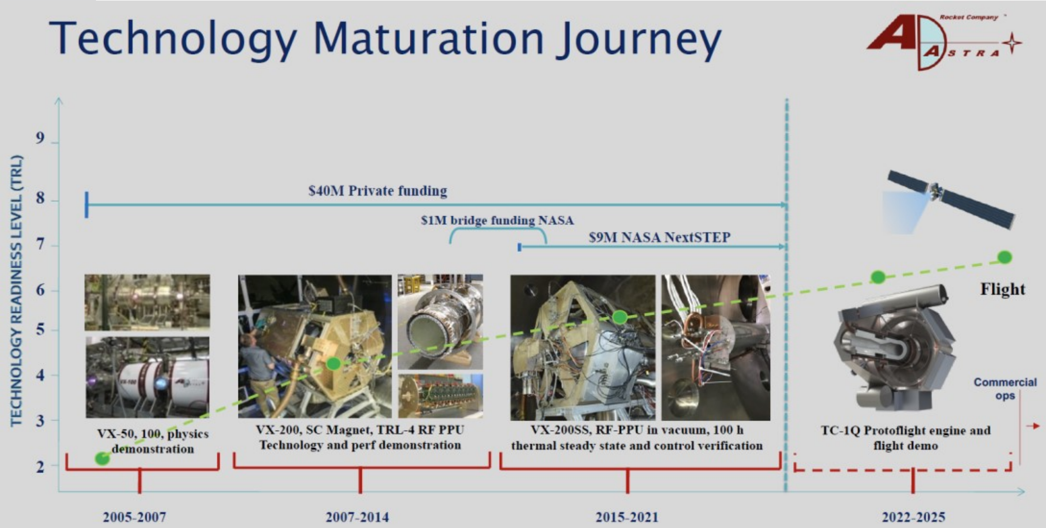
- China Academy of Space Technology (CAST) conducted a conceptual study on nuclear-powered manned Mars exploration mission in 2015
- 511 day round trip, 4 astronauts, 30 day stay on the Mars surface.
- Envisioned to be launched in 2033.
- Fission reactor based electric power system: 10MWe.
- High thrust electrical propulsion systems to be used



Adapted from **Du, H., Beijing Institute of Spacecraft System Engineering**, Application of Space Nuclear Power Sources in Moon and Deep Space Exploration Missions in China (IAEA Webinar Atoms for Space: Nuclear Systems for Space Exploration, 15-16 February 2022).

(NEP) Plasma rocket - VASIMR





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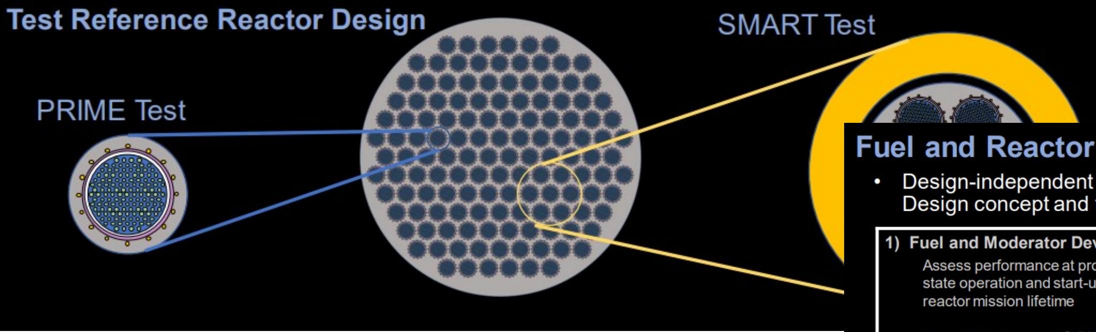
Nuclear thermal propulsion

Nuclear reactor provides high propellant efficiency (900 sec Isp) high thrust (25,000 lb)

NTP technology maturation plan considerations

- Multi 100-megawatt, high-assay, low enriched uranium reactor
- Extreme temperature HA-LEU reactor designs
- Reactor fuel, materials, and manufacturing
- Integrated engine design, build and demonstration

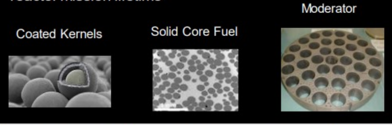


Fuel and Reactor Maturation Testing

- Design-independent reactor risks identified and addressed with government Test Reference Design concept and test assessments capabilities

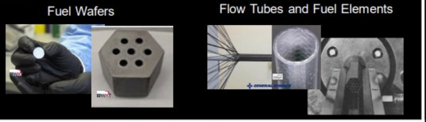
1) Fuel and Moderator Development

Assess performance at prototypic conditions during steady--state operation and start-up transient characterized to satisfy reactor mission lifetime



2) Manufacturing Demonstration

Demonstrate new manufacturing processes proposed to enable a reactor through fabrication of representative design elements

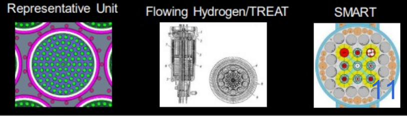


3) Nominal and Off-nominal Reactor Operation

Demonstrate the engineering functionality of representative design elements through combined thermal and nuclear loads testing to increase confidence

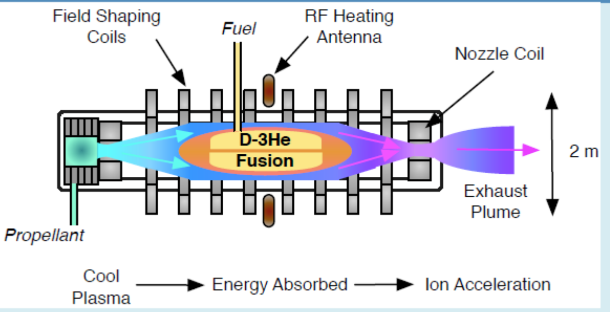
4) New Test Methods and Facilities

Modify existing facilities to enhance prototypical test capabilities and identify new, high-value test facilities that may be needed to reduce design risks



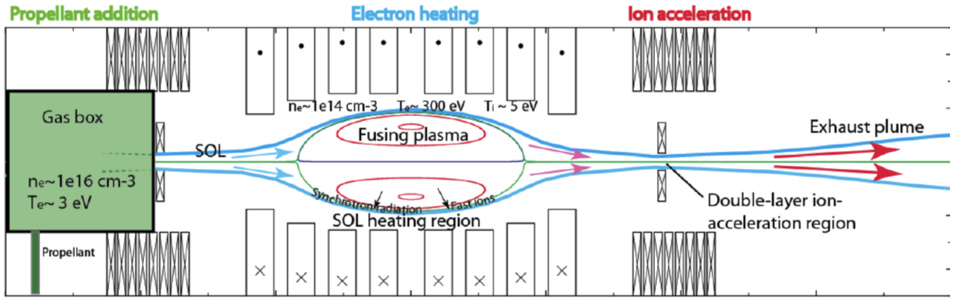
Direct Fusion Drive

DFD: Direct Fusion Drive

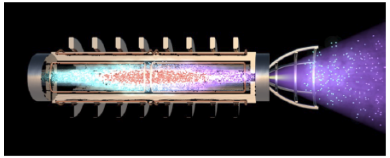


- PFRC with an open end
- SOL flow rate adjusted to produce desired thrust and specific impulse
- "thrust augmentation"
- *Power* **AND** *Propulsion* in one device

Linear Configurations: **Natural Jet for Thrust**

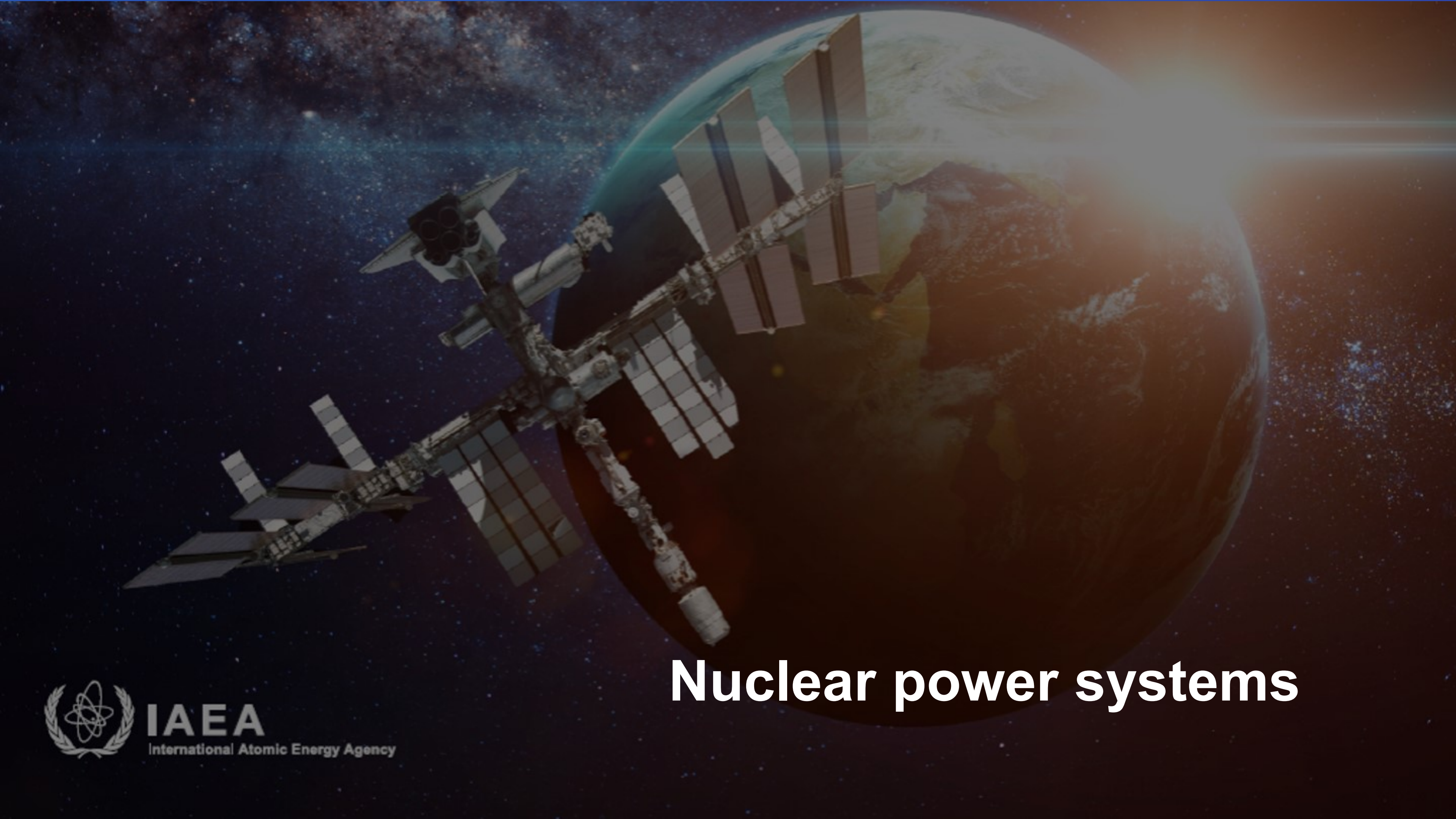


PFRC-2 Configuration (Cohen)



The fusion energy must be transferred to a propellant and directed out a nozzle with maximum efficiency.

Adapted from, **Thomas, S., Princeton Satellite Systems**, *Fusion Propulsion and Power for Advanced Space Missions*, (IAEA Webinar Atoms for Space: Nuclear Systems for Space Exploration, 15-16 February 2022).


Nuclear power systems
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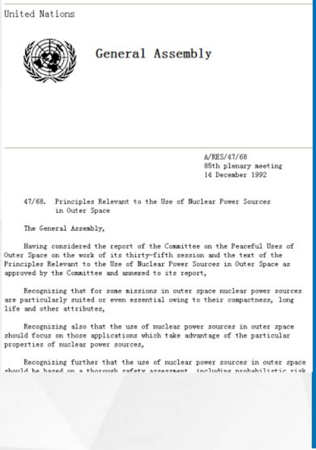
Nuclear Power Systems

- China presented on use of nuclear power systems for space programme
  - Chang’e-3 (2013) was the first space mission of China that applied space nuclear power sources – used RHUs
  - The Chang’e-4 (2018) lander and rover, made the humankind’s first soft landing on the far side of the moon – used RTGs and RHUs
- Applied:
  - Principles Relevant to the Use of Nuclear Power Sources in Outer Space
  - Guidance contained in Safety Framework for Nuclear Power Source applications in Outer Space
- Jupiter Flyby
  - Flyby Jupiter and further planets
  - RTG are needed for the mission
- Solar system boundary exploration
  - Option 1: RTG powered spacecraft with less scientific payloads.
  - Option 2: fission reactor powered spacecraft with more scientific payloads



United Nations

General Assembly

A/RES/47/68
85th plenary meeting
14 December 1992

47/68. Principles Relevant to the Use of Nuclear Power Sources in Outer Space

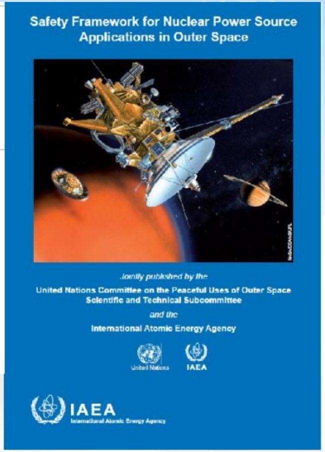
The General Assembly,

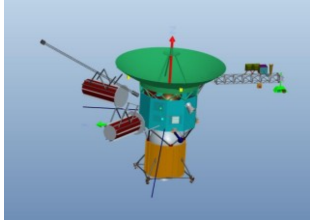
Having considered the report of the Committee on the Peaceful Uses of Outer Space on the work of its thirty-fifth session and the text of the Principles Relevant to the Use of Nuclear Power Sources in Outer Space as approved by the Committee and annexed to its report,

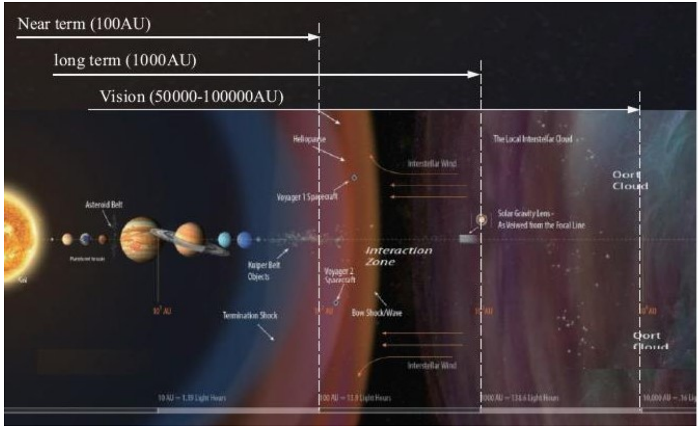
Recognizing that for some missions in outer space nuclear power sources are particularly suited or even essential owing to their compactness, long life and other attributes,

Recognizing also that the use of nuclear power sources in outer space should focus on those applications which take advantage of the particular properties of nuclear power sources,

Recognizing further that the use of nuclear power sources in outer space



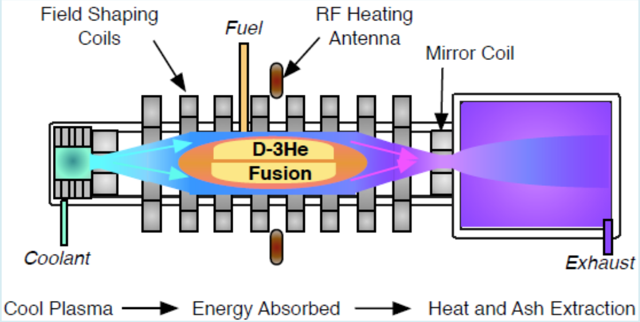




Adapted from **Du, H., Beijing Institute of Spacecraft System Engineering**, Application of Space Nuclear Power Sources in Moon and Deep Space Exploration Missions in China
(IAEA Webinar Atoms for Space: Nuclear Systems for Space Exploration, 15-16 February 2022).

Fusion: Princeton Field-Reversed Configuration

PFRC: Princeton Field-Reversed Configuration



- Compact toroid configuration
- RF heating
- FRC "in a mirror"
- SOL flow removes fusion exhaust
- 1-10 MW

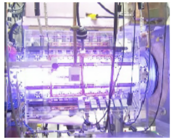
Path to PFRC Fusion Plant

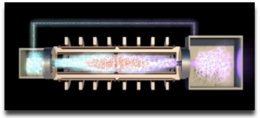
COMPLETED:
Heated electrons with RMF_o in PFRC-1
$2M

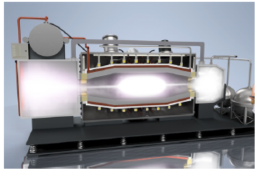
IN PROGRESS for June 2022:
Heat ions in PFRC-2
$6M

DESIGN UNDERWAY for PFRC-3 in 2023:
Fully superconducting, fusion-relevant temps
$50M

PLAN for 2030:
D-^{3}He fusion in PFRC-4, net electric power
$150M





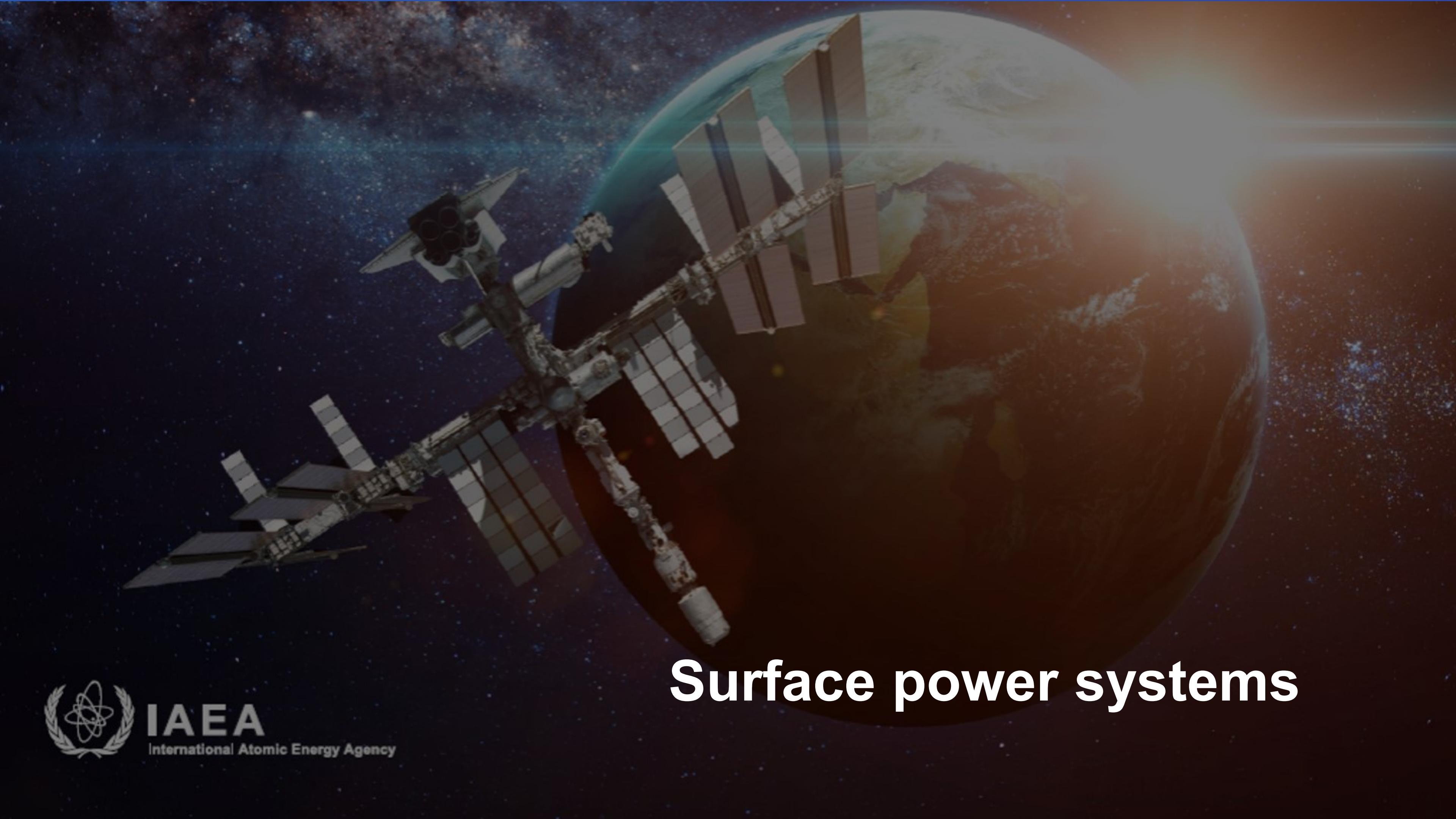


Proof of concept merits private investment

Value inflection from proof of principle

Low-cost, low-radioactivity fusion reactors

Adapted from, **Thomas, S., Princeton Satellite Systems**, *Fusion Propulsion and Power for Advanced Space Missions,* (IAEA Webinar Atoms for Space: Nuclear Systems for Space Exploration, 15-16 February 2022).



Surface power systems

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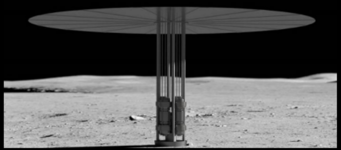
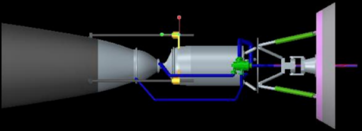
Nuclear Surface Power

Space Nuclear Fission Technology Portfolio



- **Fission surface power**
  - Enable sustained, long-duration lunar operations
  - Establish an evolvable system for the Moon and Mars



- **Space nuclear propulsion**
  - Advance a fast transit, in-space, nuclear propulsion capability
  - Evaluating nuclear thermal and electric propulsion options

NASA's priority is surface fission power for lunar operations

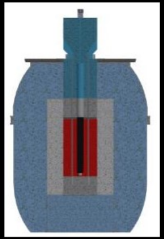
NASA and DOE are working together to develop low-enriched uranium solutions

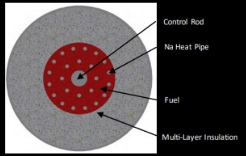
FSP: Two Recommended Reactor Concepts

All DOE reactor configurations studied were deemed feasible, however they all carry varying levels of technical risk

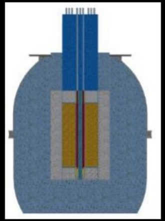
High Enriched Uranium (HEU)-Fast

- Lowest mass for the 40 kWe case
- Reactor operation and performance simple and straight forward
- Needs DOE facilities for processing and fabricating core
- Reduced test infrastructure support
- Increased security and launch safety management

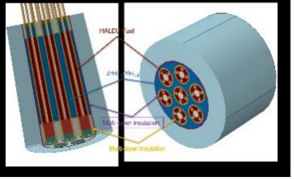




High Assay Low Enriched Uranium (HALEU)-Segmented



- System mass increase < 20%
- Requires more development effort than the Fast configurations
- Potential alignment with ongoing commercial and DoD initiatives
- Expanded test infrastructure support
- Compatible with many fuel forms, including TRISO



	HEU-Fast (kg)	HALEU-ZrH (kg)
Core	240-310	280-410
Core + Shield	900-1100	900-1200

Adapted from **Calomino, A.**,**NASA,** *NASA Investments in Space Nuclear Fission Technology*
(IAEA Webinar Atoms for Space: Nuclear Systems for Space Exploration, 15-16 February 2022)

Challenges

- **Technical challenges**
  - Long life: usually more than 10 years, or even 30 years
  - Thermo-electric conversion: high conversion rate, reliable
  - Heat dissipation: especially difficult for fission reactor powered missions. Need very large dissipation area
  - Technology readiness level: new technologies are not ready yet
- **Safety challenges**
  - Dedicated regulations are needed (vs ground-based nuclear systems)
  - Safety design and tests are very important
- **Financial challenges**
  - Pu238 is quite expensive
  - Development of space qualified RTG and fission reactor power systems is also very costly

Adapted from **Du, H., Beijing Institute of Spacecraft System Engineering**, Application of Space Nuclear Power Sources in Moon and Deep Space Exploration Missions in China
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Conclusions

- Nuclear space technology has advanced in recent years, and new concepts are being researched and developed.
- NASA's priority focus is on designing, building and demonstrating a low enriched uranium fission surface power system that has broad applications for the lunar surface initiative as well as for NASA eventual mission to Mars with humans, scalable to power levels above 100 kWe, and has the potential to advance NEP system needs.
- Direct fusion driven (DFD) propulsion could be advantageous because it offers a path to routine crewed missions to Mars, crewed missions to the outer planets, and deep space high speed robotic missions, with reduced trip times, increased payloads, and high available power. A few kilograms of (deuterium and Helium-3) fuel could power a spacecraft for ten years.
- Safety of space nuclear power source applications is paramount. The Joint Expert Group work and the Safety Framework widely referenced during the webinar.
- A dedicated workshop on NPS applications in outer space would be timely and useful for reviewing and discussing the multitude of concepts under development, which could not be fully covered in the 2-day (4 hours total) webinar.

Webinar Links

- Agenda with presentation abstracts
- Webinar Recording Day 1
- Webinar Recording Day 2

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Thank you!