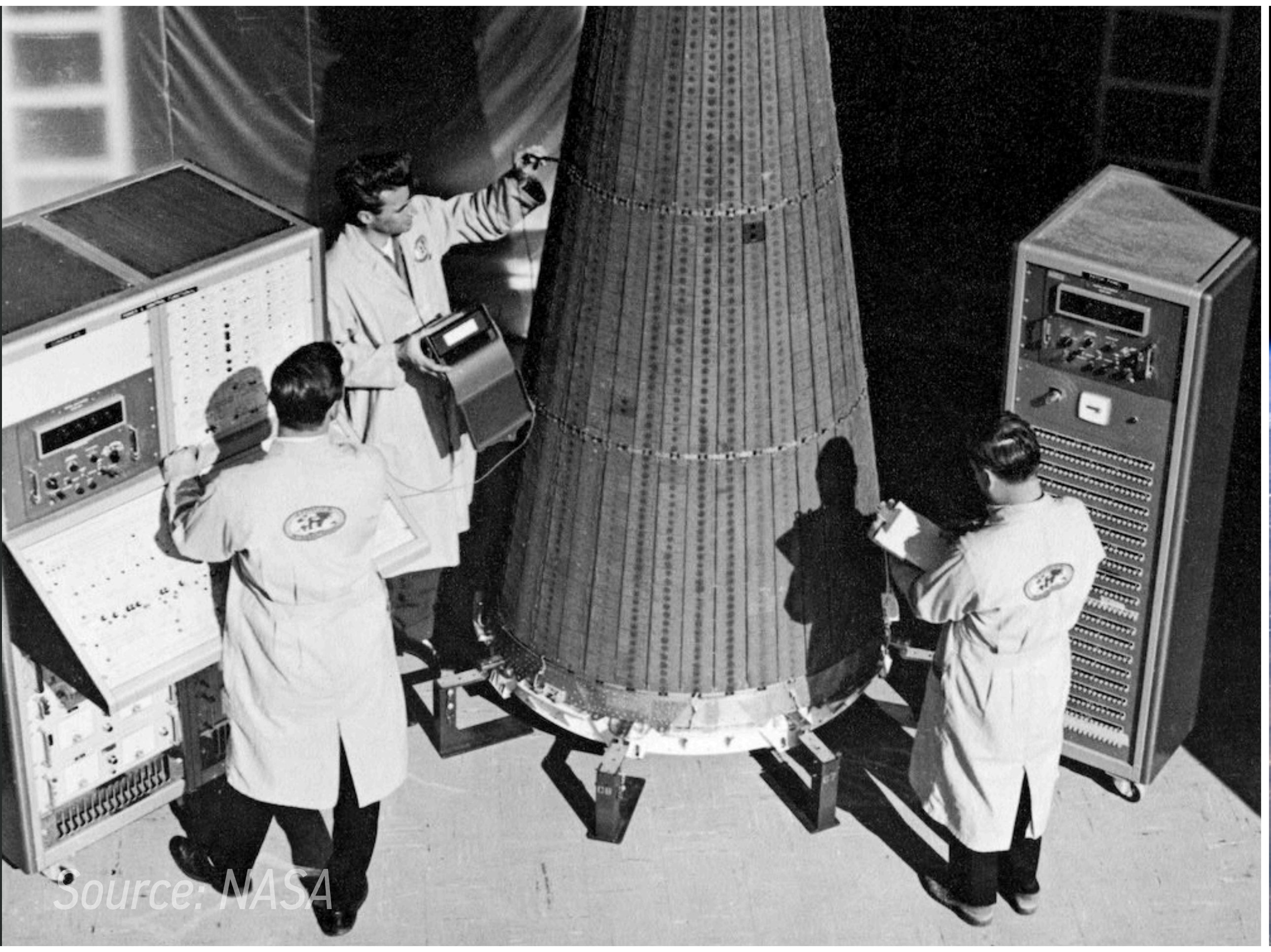

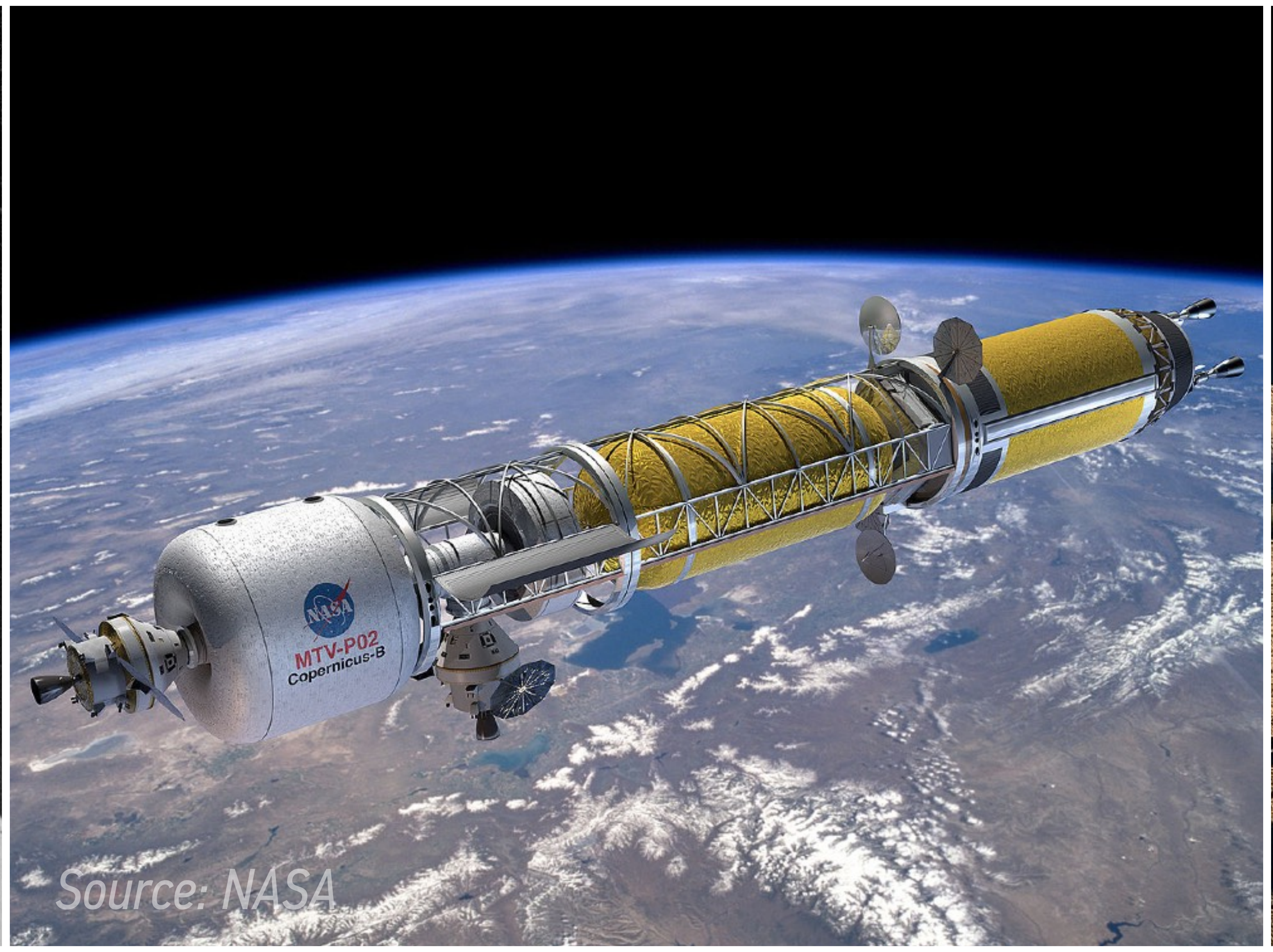

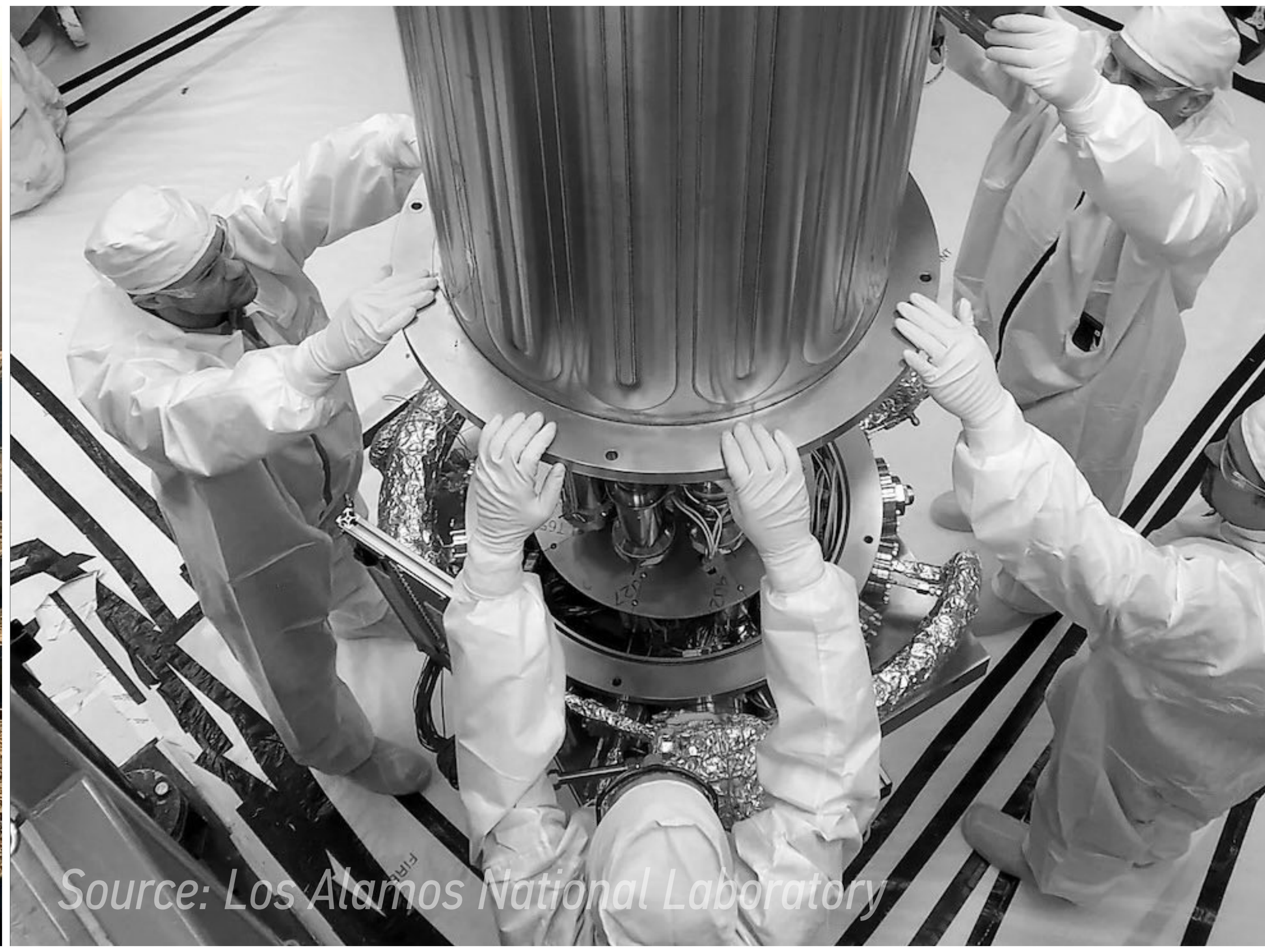

NUCLEAR ENERGY IN SPACE

LESSONS FROM AND FOR EARTH

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Program on Science and Global Security
Princeton University

Meeting of the G8 Nuclear Safety and Security Group (NSSG)

Ottawa, Canada (presented virtually), October 16, 2025

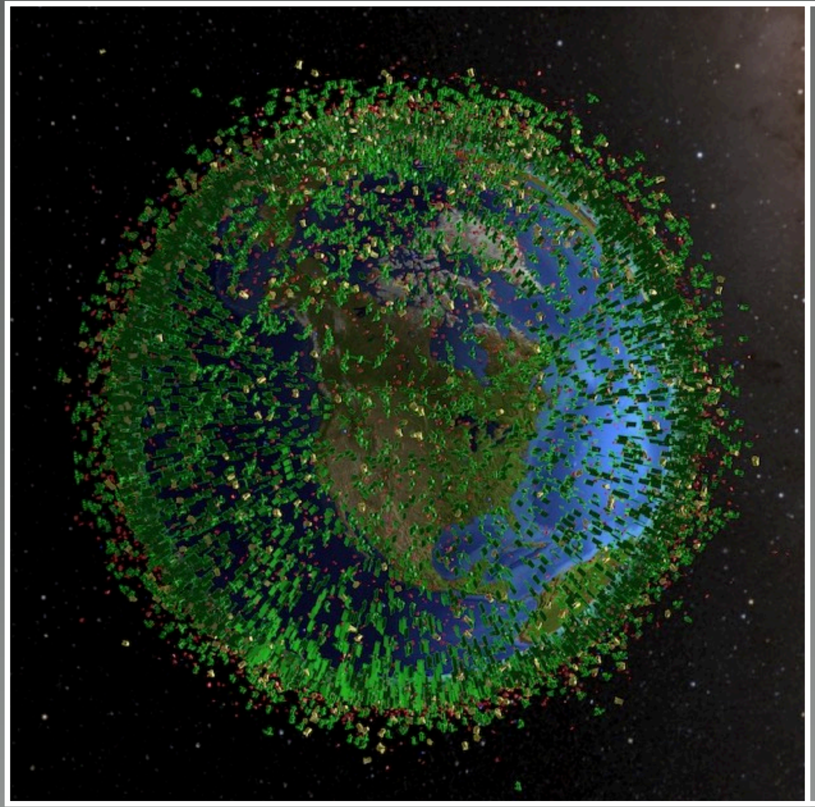
Revision 1

BACKGROUND

THE NEW RACE TO SPACE

The last decade has seen a dramatic increase in human activities in space

Dominated by the United States, and to a lesser extent by China and Russia, others are quickly entering the field — now also including companies and even private individuals



FIRST MOVER ADVANTAGE — WILL THE WINNER TAKE IT ALL?

Space is increasingly seen as a competitive, congested, and contested environment, where the “winner” might take it all — including the ability to declare (temporary) keep-out zones on celestial bodies

Artemis Program led by the United States; International Lunar Research Station (ILRS) led by China and Russia

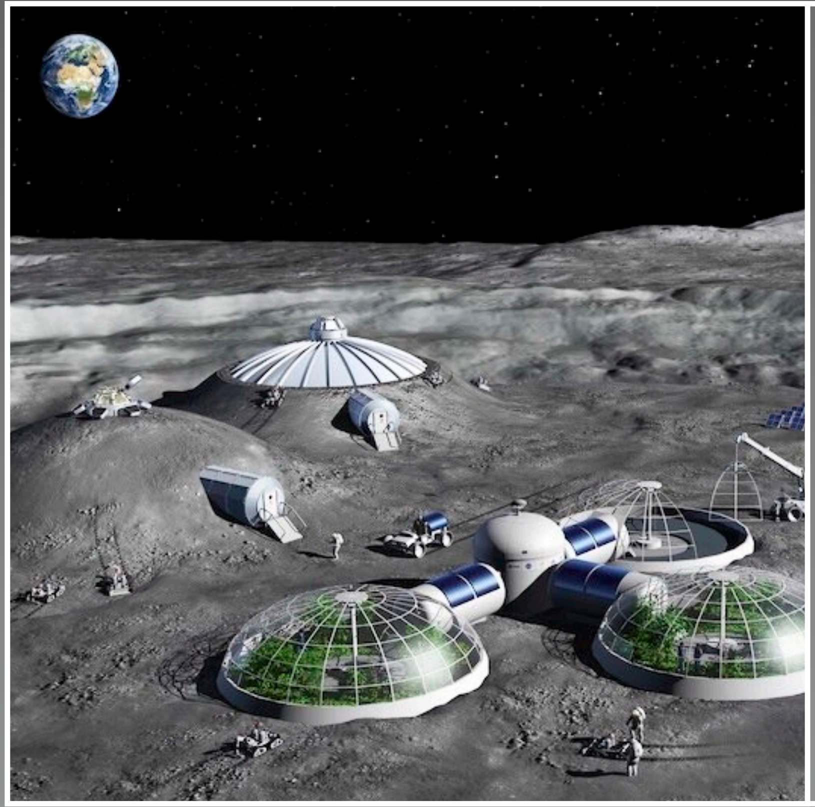
Source: SpaceX (top) and leolabs.space (bottom)

DO WE NEED NUCLEAR POWER IN SPACE?

NUCLEAR RESTRAINT IN OUTER SPACE

"The use of nuclear power sources in outer space shall be restricted to those space missions that cannot be operated by non-nuclear energy sources in a reasonable way."

Principles Relevant to the Use of Nuclear Power Sources in Outer Space, RES 47/68, United Nations, December 14, 1992



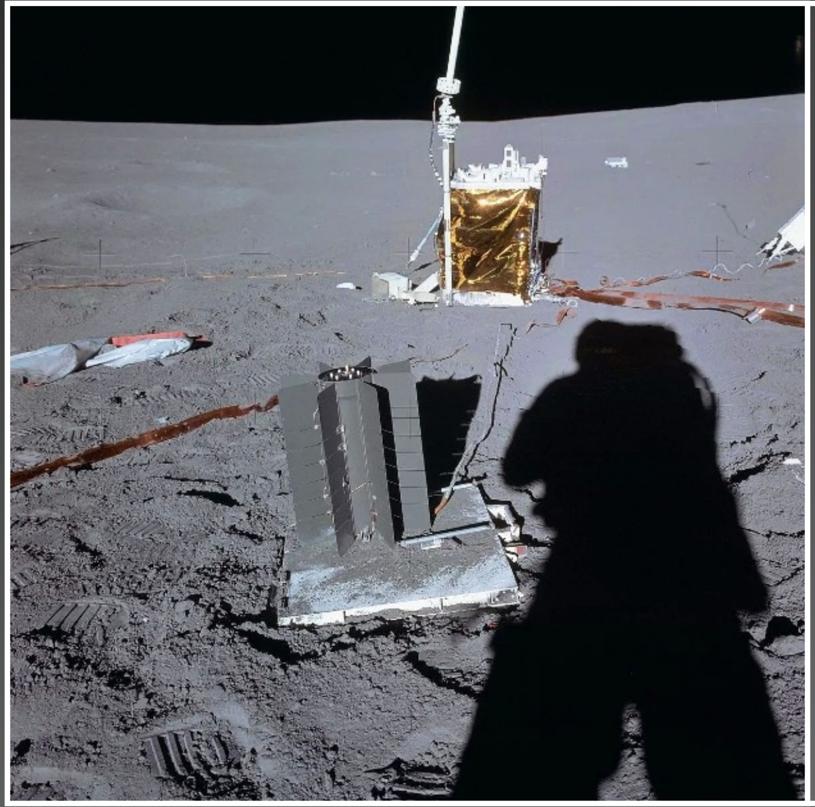
"YES" … IF ONE ACCEPTS SOME PREMISES OF HUMAN SPACE EXPLORATION

- Lunar outposts, permanent human presence on the Moon
- Nuclear propulsion for deep-space missions, especially crewed missions to Mars
- Nuclear power sources in Earth orbit for high-power (military) applications

Source: nasa.gov (top) and esa.int (bottom)

NUCLEAR POWER ON THE MOON

AND ON OTHER CELESTIAL BODIES



SO FAR, NO EXPERIENCE WITH NUCLEAR (FISSION) REACTORS

Some experience with radioisotope thermoelectric generators (RTG)

Power generated by radioactive decay, typically plutonium-238; SNAP-27 (1250 W thermal, 75 W electric)

Current U.S. plan: Deploy nuclear reactor before 2030 — but no demand for power on the Moon

TECHNICAL CHALLENGES FOR LONG-TERM OPERATION OF NUCLEAR REACTORS

- Unattended operation in an extreme environment (–130 °C at night; +120 °C in daylight)
- Long-term safety of nuclear reactors, especially when exposed on lunar surface
- Unresolved governance challenges; including with regard to nuclear waste storage and disposal

Source: NASA (top) and GenAI (bottom)

Three Things

Keeping Earth in focus

Keeping civilian and military applications separate

Ensuring the future of the Outer Space Treaty

KEEPING EARTH IN FOCUS

PERCEIVED URGENCY COULD COMPROMISE BEST PRACTICES & POLICIES … ON EARTH !

Many spacefaring nations might eventually develop and deploy nuclear systems in space

Nuclear power in space has potentially significant consequences for nuclear energy policy on Earth

Need for standards and best practices, especially with regard to safety and liability for accidents

AFFECTING THE SUPPLY CHAIN FOR SPACE NUCLEAR SYSTEMS

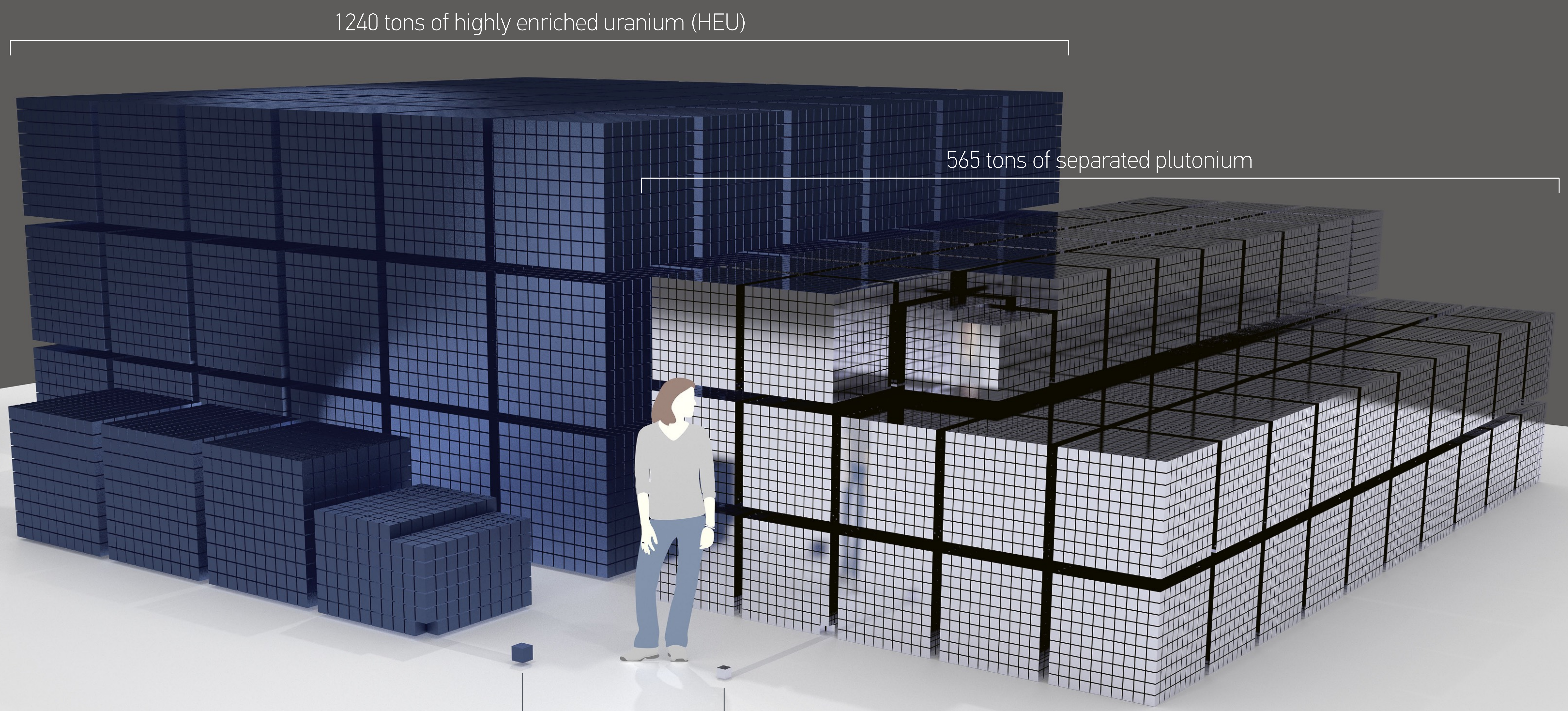
Strong incentive to use fuels with high enrichments, i.e., HALEU or HEU (20–90% enriched in U-235)

National security considerations (often associated with space activities) could encourage additional countries to pursue sensitive domestic nuclear capabilities — rather than relying on suppliers

Source: nasa.gov (top) and U.S. Department of Energy (bottom)

Graphic/concept by Alex Wellerstein and Tamara Patton
Inventory estimates from fissilematerials.org
Status as of beginning of 2024

There is enough nuclear explosive material in the world to make over 200,000 nuclear weapons



Each block corresponds to 12 kg of HEU, the amount necessary to make a fission bomb; about 100,000 bombs-worth total

Each block corresponds to 4 kg of plutonium, the amount necessary to make a fission bomb; about 140,000 bombs-worth total

KEEPING CIVILIAN & MILITARY APPLICATIONS SEPARATE

DEMONSTRATED ON EARTH — EVEN MORE IMPORTANT IN SPACE

SEPARATING CIVILIAN AND MILITARY NUCLEAR POWER ON EARTH

The United States has pioneered the concept, adopted both domestically and internationally

For example, multi-decade effort to convert research reactors to low-enriched fuel

Leading by example has significantly strengthened the nuclear nonproliferation regime of the NPT

MANAGING DUAL-USE ASPECTS OF SPACE ACTIVITIES

Space has been militarized from the outset, but the Moon can only be explored for peaceful purposes

NASA shall "encourage dual-use civil and defense operational architectures for deployed [fission surface power] systems in coordination with interagency partners" (NASA Directive, July 31, 2025)

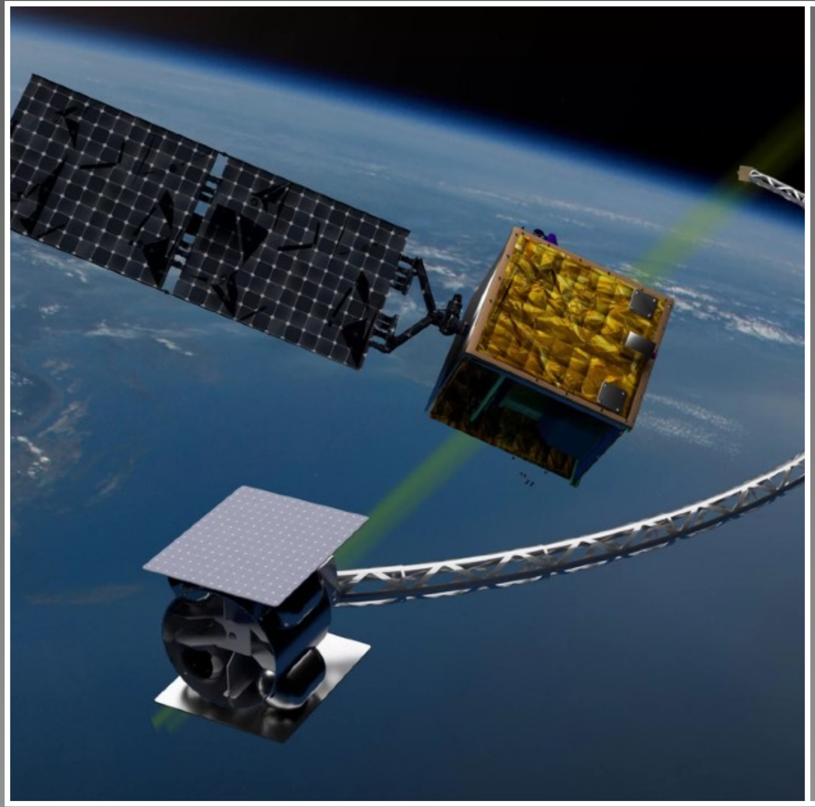
Source: iaea.org (top) and nasa.gov (bottom)

ENSURING THE FUTURE OF THE OUTER SPACE TREATY

WITH MORE TRANSPARENCY AND NON-INTRUSIVE VERIFICATION

NUCLEAR PAYLOADS AND THE NEED FOR MORE TRANSPARENCY

Space launches that include nuclear payloads (for power generation or propulsion) could further increase geopolitical tensions, especially when there are concerns about the peaceful nature of these missions and compliance with the Outer Space Treaty



STRENGTHENING THE 1967 OUTER SPACE TREATY

New technical developments could (finally) allow for verification of the Outer Space Treaty

Pre-launch or post-launch inspections could provide confidence in the civilian nature of planned missions involving fission power or other nuclear systems

Source: esa.int (top) and thinkorbital.com (bottom)

CONCLUDING REMARKS

UPHOLDING THE VISION OF "EARTH-CENTERED" SPACE PROGRAMS

Technologies are often seen as a means to solve humanity's problems — but they can't

First and foremost, space exploration ought to help ensure a sustainable future for humanity on Earth

See also: Daniel Deudney, Dark Skies, 2020

THE NEED FOR INTERNATIONAL COLLABORATION AND COORINDATION

International coordination would be particularly important at the space-nuclear nexus

Possibly unique and important role for those spacefaring nations that prioritize civilian space missions to develop and support new multilateral initiatives

Source: nasa.gov (top) and United Nations (bottom)

Photo: NASA (Apollo 8, Dec. 1968)