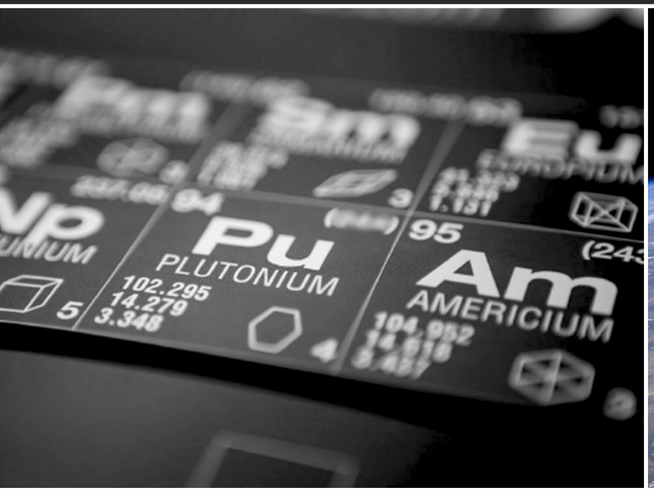
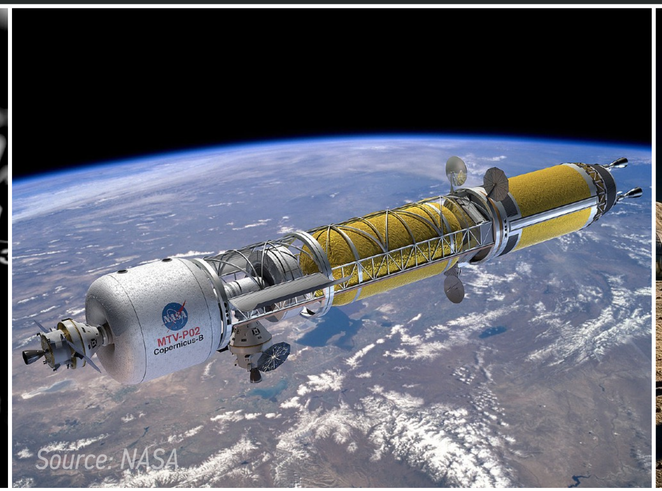
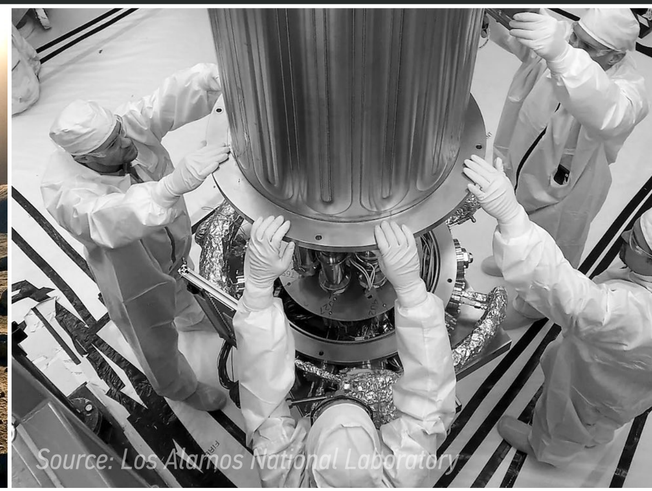






BEYOND THE HORIZON

FISSILE MATERIALS IN AN EXPANDING NUCLEAR WORLD

Alexander Glaser

Program on Science and Global Security
Princeton University

Review Conference of the Treaty on the Non-Proliferation of Nuclear Weapons

United Nations, New York, May 15, 2026

Revision 0.2

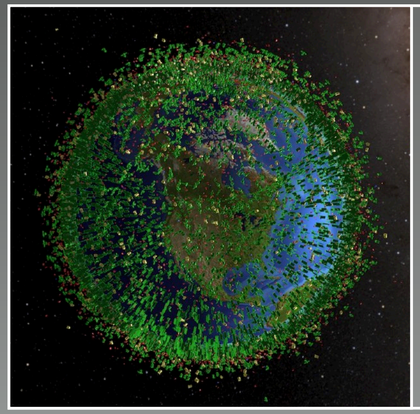
SPACE x NUCLEAR

BACKGROUND

THE NEW RACE TO SPACE

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

Many new players are entering the field — and they now also include 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

Permanent human presence on the Moon: Possibility of declaring (temporary) keep-out zones

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)

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)

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)

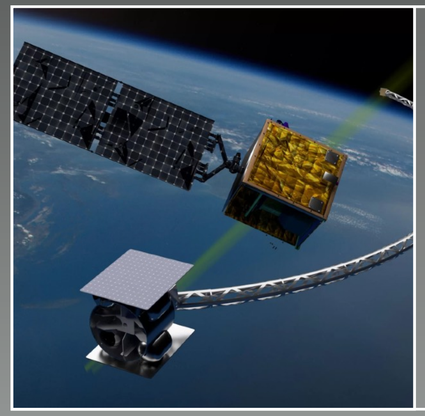
Source: iaea.org (top) and nasa.gov (bottom)

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

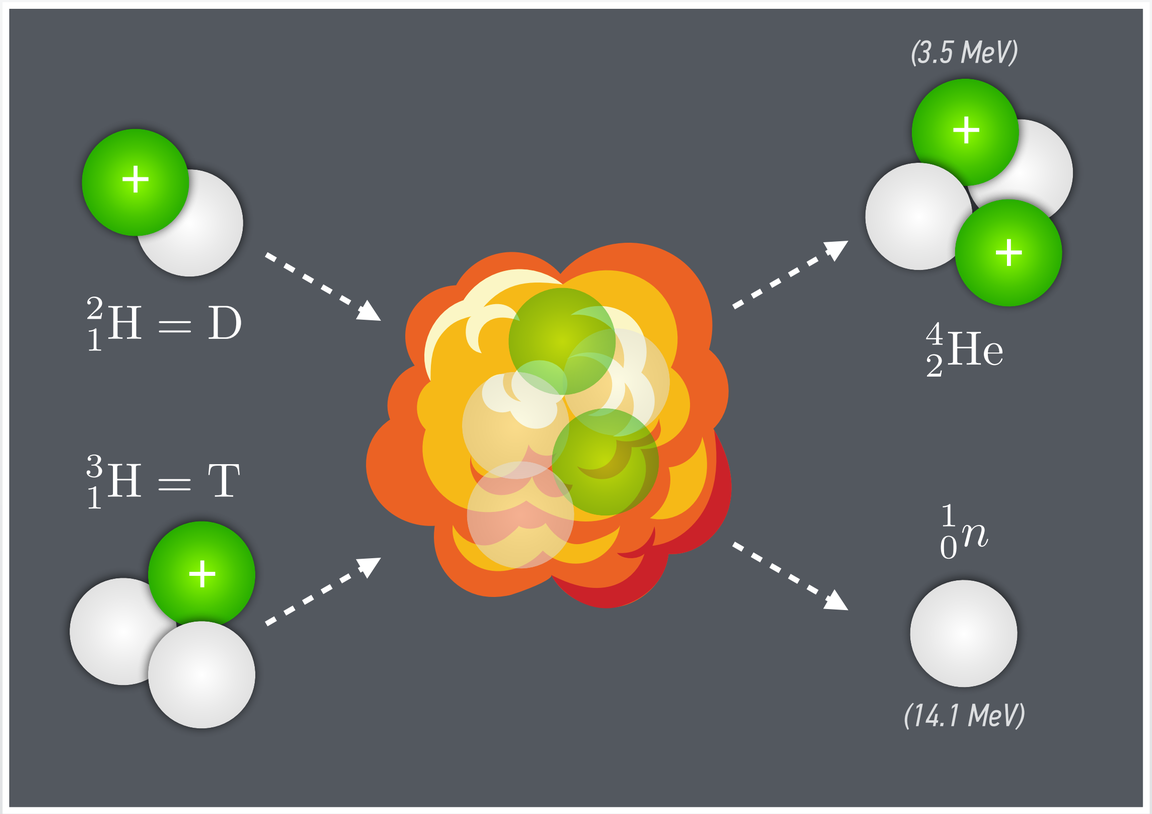
Pre-launch (and perhaps post-launch) inspections could provide confidence in the civilian nature of planned missions involving fission power or other nuclear systems

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

NUCLEAR FUSION

NUCLEAR FUSION

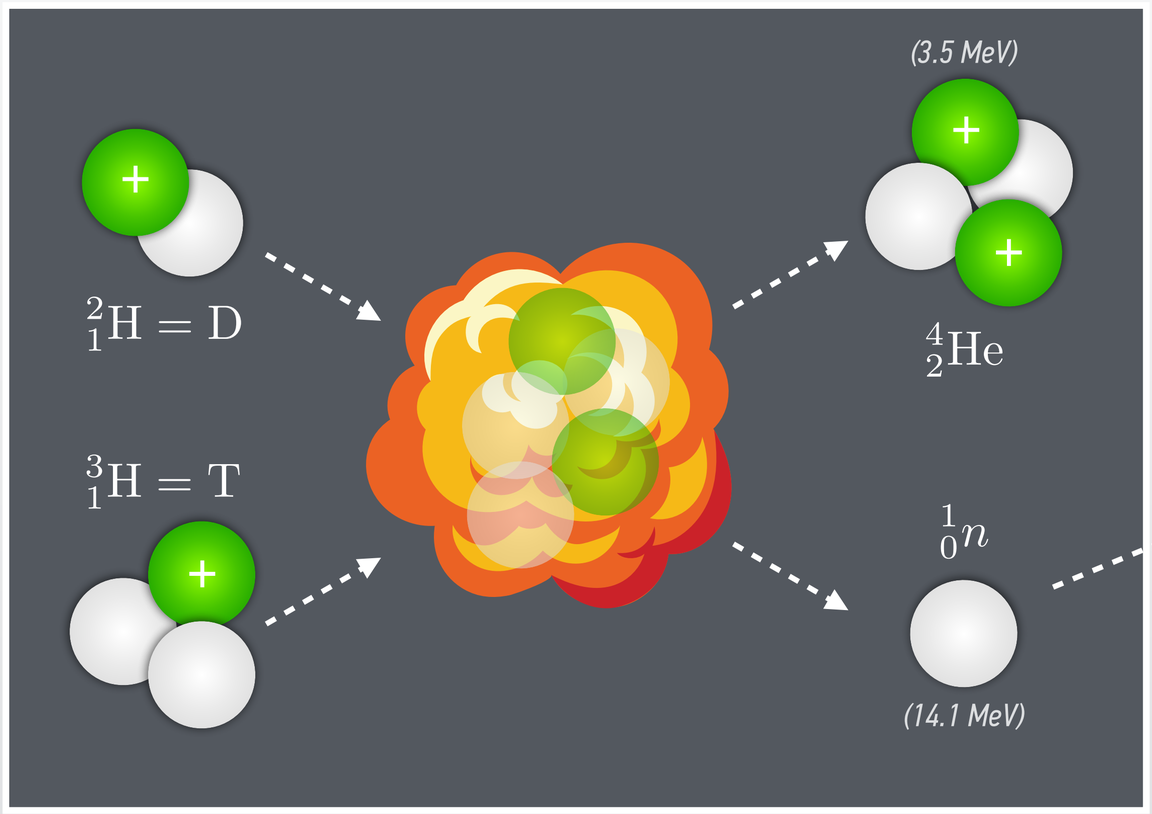
OF DEUTERIUM AND TRITIUM



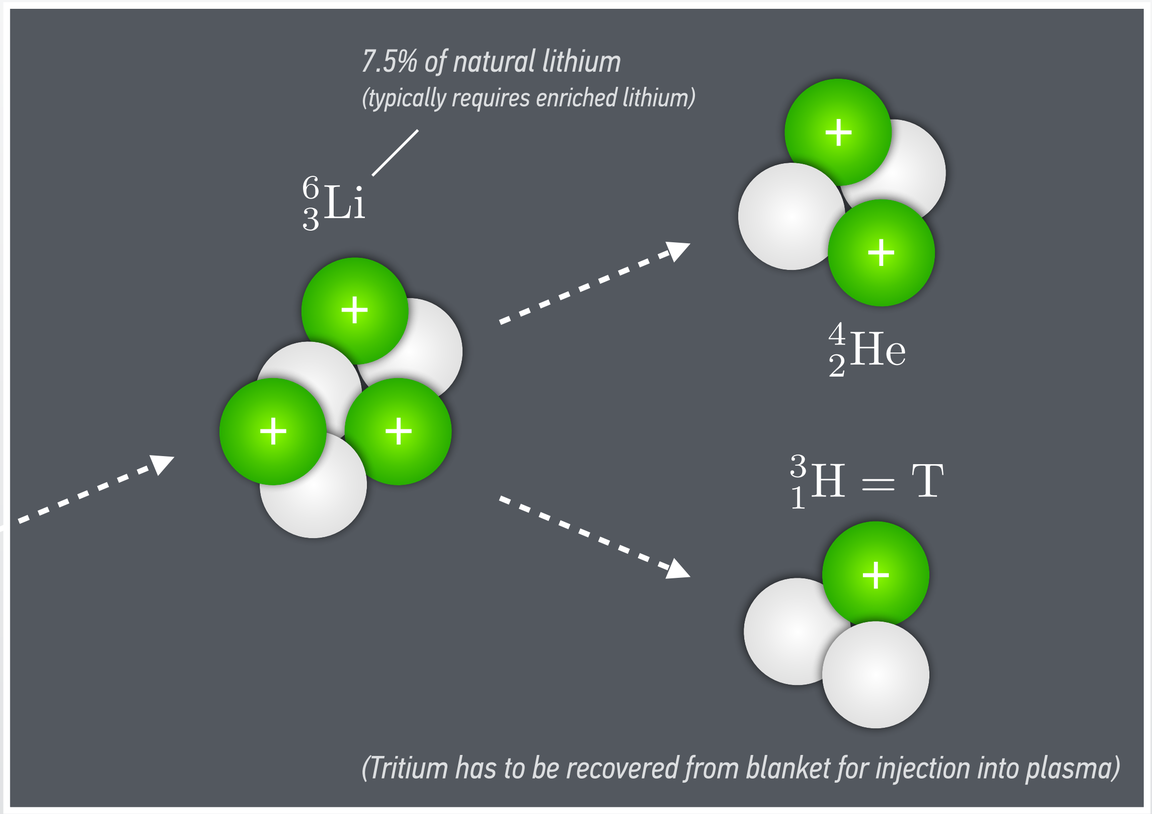
DT fusion reaction in plasma

NUCLEAR FUSION

OF DEUTERIUM AND TRITIUM



DT fusion reaction in plasma



Tritium breeding in blanket

International Thermonuclear Experimental Reactor (ITER), under construction near Cadarache, France — currently 3–5 times over budget
Source: iter.org

NUCLEAR FUSION IN 2026

For many decades, largely a government-led effort, but fusion R&D is increasingly conducted by startups and/or involves public-private partnerships

- At least 45 companies are seeking to commercialize fusion energy
- More than $7 billion in funding
- More than 1,000 scientists and engineers recruited per year

Most concepts pursued for energy applications are based on magnetic confinement fusion and rely on the DT fusion reaction

$$D + T \longrightarrow {}^{4}He + n + 17.6\ \mathrm{MeV}$$

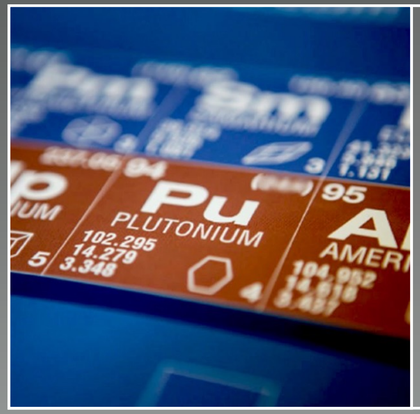
The Global Fusion Industry in 2025, Fusion Companies Survey by the Fusion Industry Association, Fusion Industry Association, 2025

FISSILE MATERIAL PRODUCTION POTENTIAL

OF NUCLEAR FUSION REACTORS

FUSION REACTORS AS NEUTRON-RICH ENVIRONMENTS

Standard operation of a fusion reactor does not involve nuclear materials, which offers significant nonproliferation benefits compared to nuclear fission reactors; the presence of intense neutron fluxes provides an environment, however, that could be used for covert production of fissile materials



HOW MUCH FISSILE MATERIAL COULD POSSIBLY BE PRODUCED?

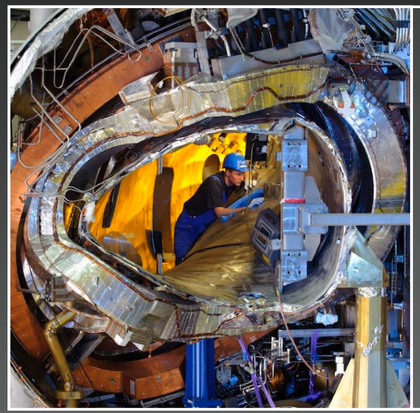
Previous analyses have shown that a commercial-scale reactor with a fusion power of 1500 MW (600–750 MWe) could be used to make on the order of 10 kg of Pu-239 or U-233 per week

A. Glaser and R. J. Goldston, Proliferation Risks of Fusion Energy: Clandestine Production, Covert Production, and Breakout, Nuclear Fusion, 52 (4), 2012

Source: iter.org (top)

ADDRESSING DUAL-USE ASPECTS OF FUSION

A PROACTIVE APPROACH



FUSION TECHNOLOGY

Consider (and prioritize) system configurations and materials that make military use difficult, especially with regard to fissile material production (and tritium diversion)

Design reactors and other test facilities with inspections and verifiability in mind

POLICY & REGULATION FOR NUCLEAR FUSION

Acknowledge that nuclear fusion reactors are reactors — and can raise security concerns

Involve, at an early stage, the International Atomic Energy Agency on how to monitor fusion reactors

Source: Max Planck Institute for Plasma Physics (top) and iaea.org (bottom)

Earthset captured through the Orion spacecraft window, April 6, 2026
www.nasa.gov/image-detail/art002e009288/