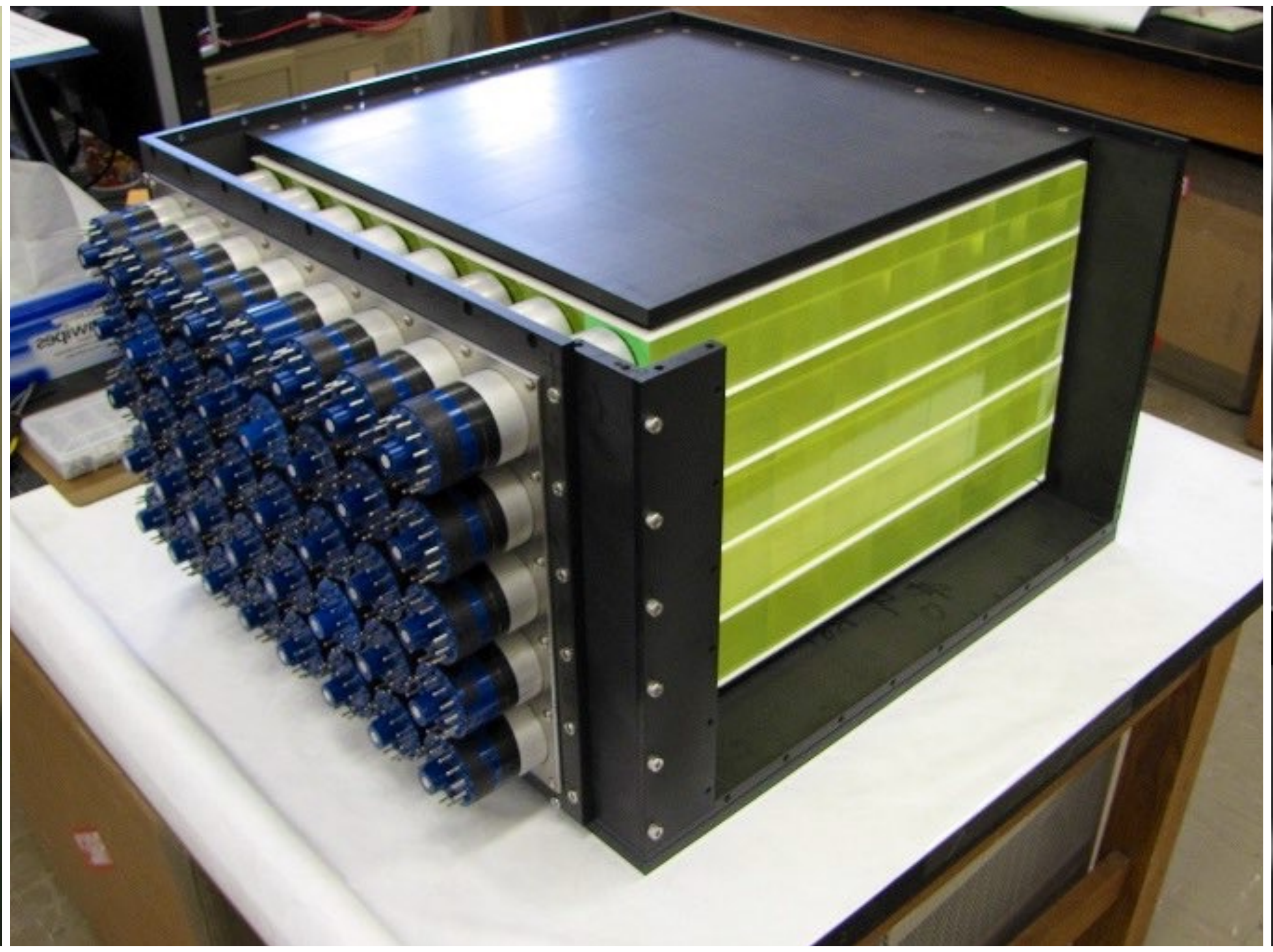
Source: Universal Pictures



DETECTABILITY OF COVERT FISSILE MATERIAL PRODUCTION IN NUCLEAR FUSION REACTORS VIA ANTINEUTRINO EMISSIONS

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Revision 3

BACKGROUND

NUCLEAR FUSION IN 2025

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:

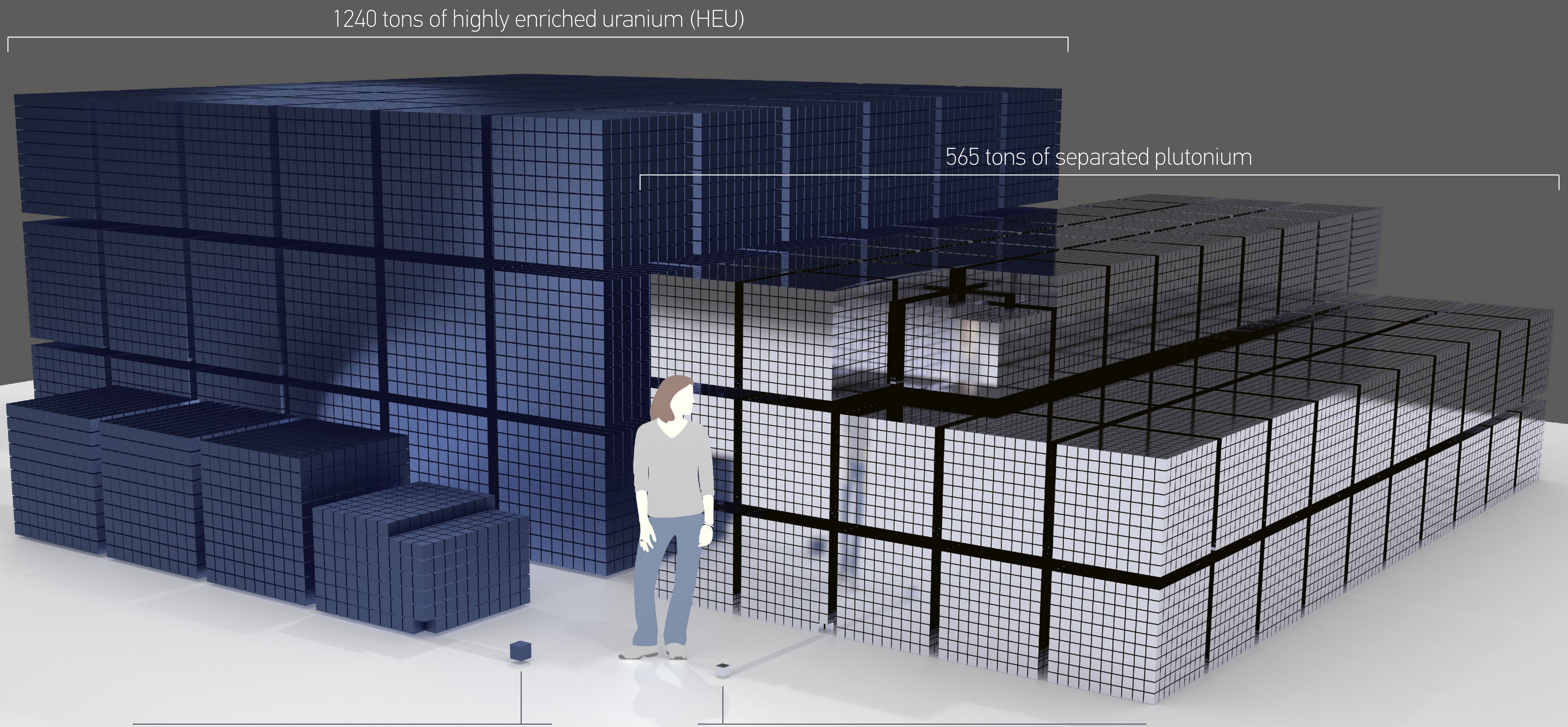
$$D + T \longrightarrow {}^4He + n + 17.6\ \mathrm{MeV}$$

In-situ tritium breeding, primarily via: $n + {}^6Li \longrightarrow {}^4He + T + 4.8\ \mathrm{MeV}$

The Global Fusion Industry in 2024, Fusion Companies Survey by the Fusion Industry Association, Fusion Industry Association, 2024

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

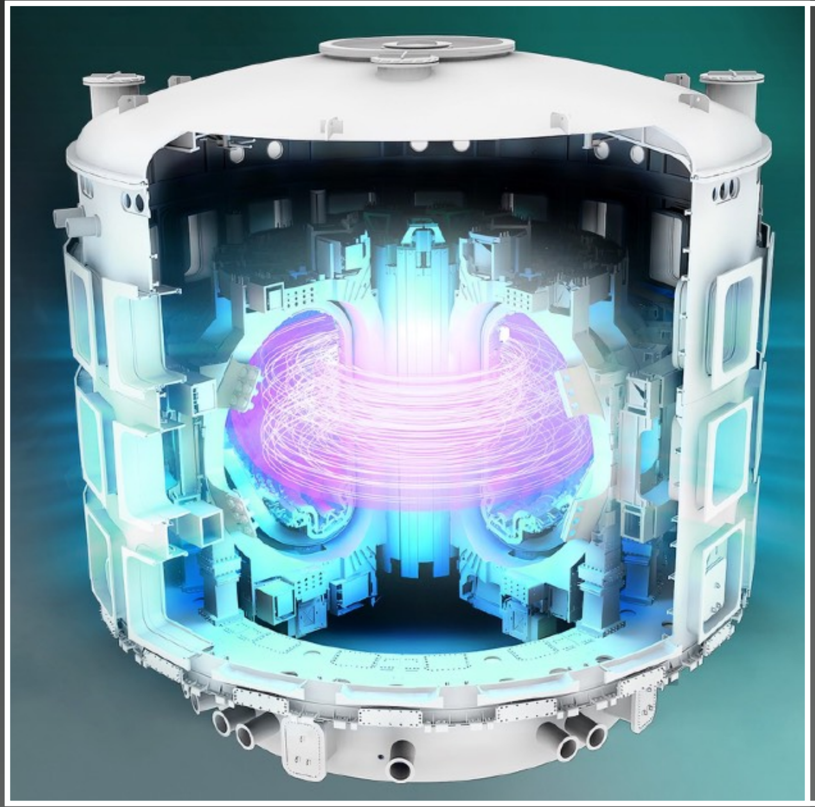


Each block corresponds to 12 kg of HEU, the amount necessary to make a fission bomb; about 100,000 bombs-worth total

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

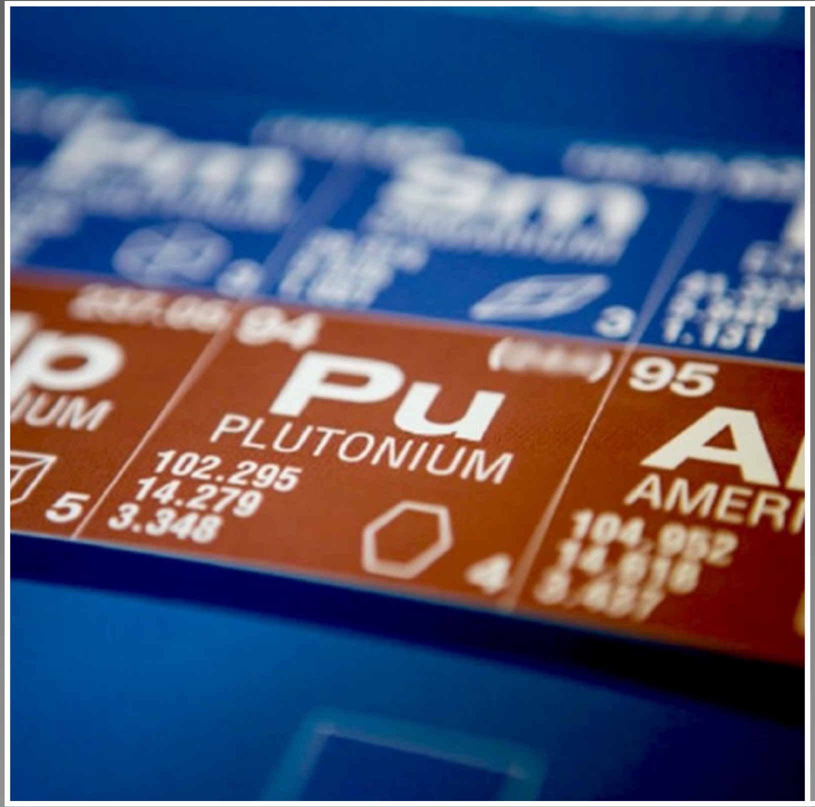
FISSILE MATERIAL PRODUCTION POTENTIAL

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)

Are there robust & non-intrusive ways to confirm the absence of fissile material production in a nuclear fusion reactor?

(How about antineutrinos?)

METHODS & RESULTS

We consider two types of blankets:

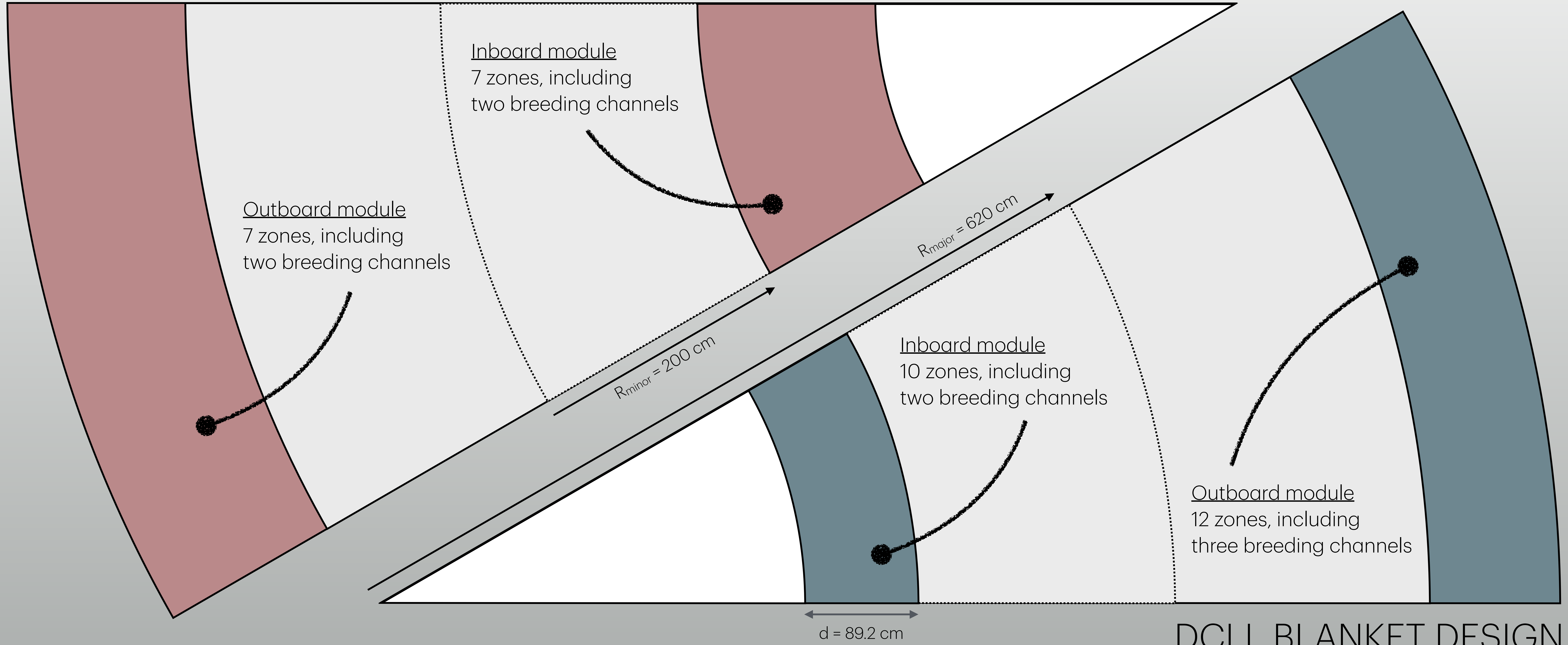
- Molten salt (LiF-BeF2 or FLiBe) design
- Dual-coolant lead-lithium (DCLL) design

The main purpose of the blanket is to extract heat and to enable the production of tritium via neutron capture in lithium

Illustration of a Tokamak machine
Source: iter.org

BLANKET DESIGN OF THE REFERENCE REACTOR

FLIBE BLANKET DESIGN



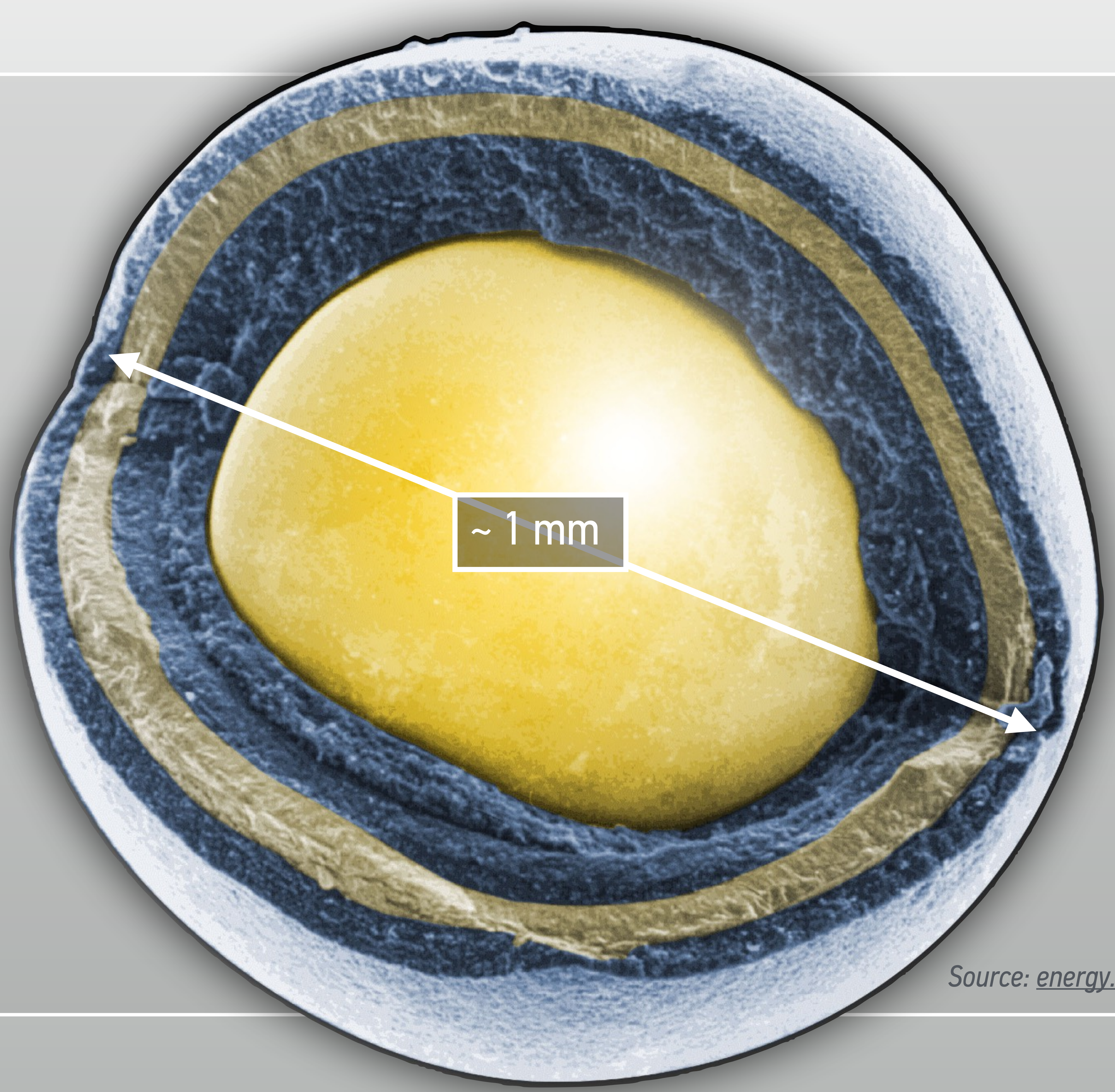
DCLL BLANKET DESIGN

HOW TO INTRODUCE THE FERTILE MATERIAL?

We consider the small amounts of fertile material (uranium-238 or thorium-232) into the breeding channels of the blanket in the form of simplified (millimeter-sized) TRISO particles

The particles would have to be tailored for suspension in the carrier material; they could be mechanically removed after exposure

Alternatively, the fertile material could be dissolved in the carrier material, but this would require chemical processing for extraction of the product

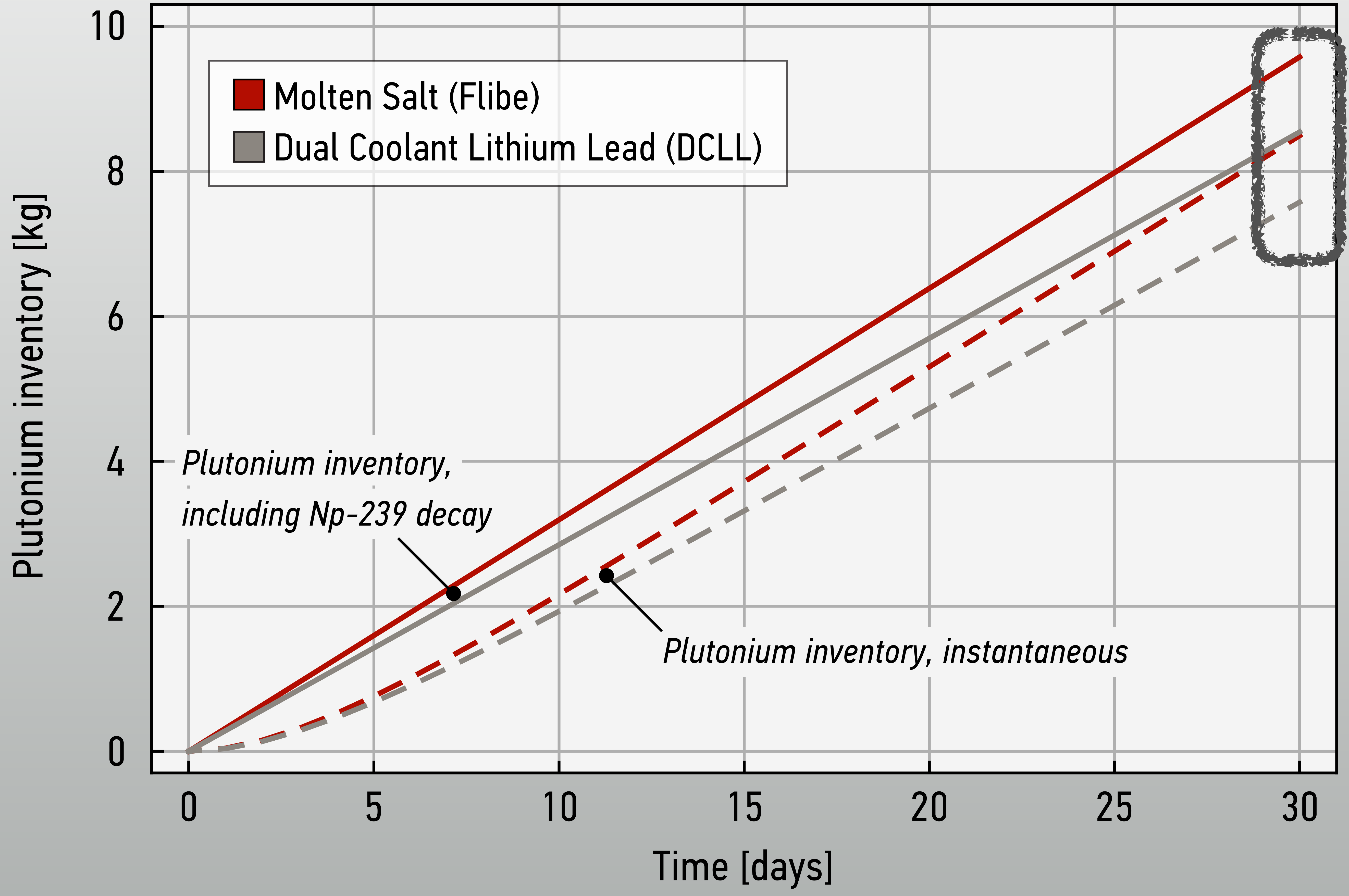


Source: energy.gov

For a concept of a fusion-fission hybrid system using suspended TRISO particles, see:
Y. Wu et al., Conceptual Design of the Fusion-driven Subcritical System FDS-I, Fusion Engineering and Design, 81, February 2006, doi.org/10.1016/j.fusengdes.2005.10.015

PLUTONIUM BUILDUP IN THE BLANKET

(1500 MW OF FUSION POWER; 25 TRISO PARTICLES/CC IN BREEDING CHANNELS)



In the reference scenario, about one significant quantity of plutonium builds up in one month

Depending on the blanket type, 60-85 MW of fission power are generated throughout the process

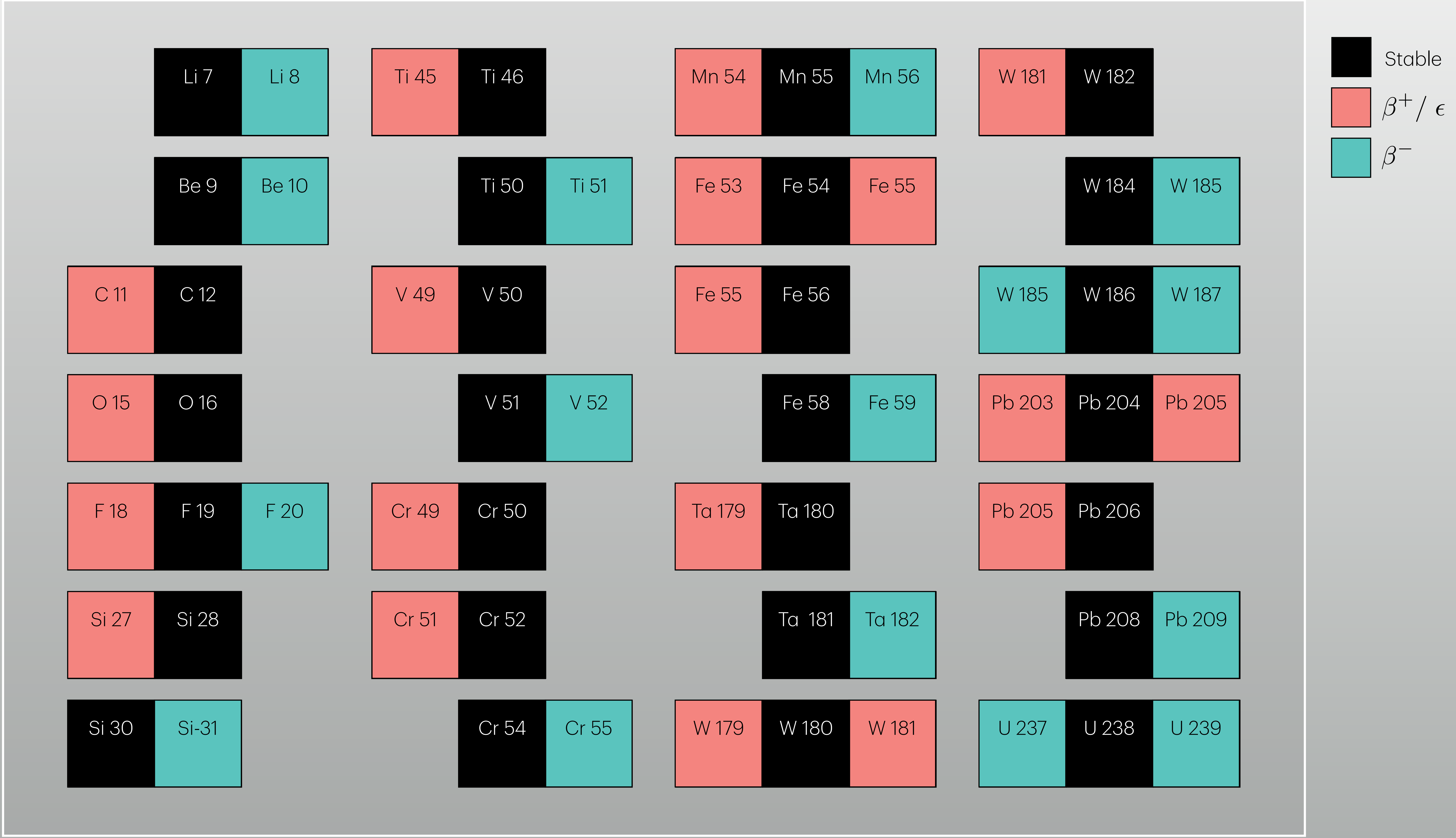
Note that more aggressive production scenarios could deliver 8–10 kilograms of plutonium per week

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

A. Glaser, R. J. Goldston, P. Huber, Detectability of Covert Fissile Material Production in Nuclear Fusion Reactors via Antineutrino Emissions, August 2025, arxiv.org/abs/2508.16358

Illustration of a Tokamak machine
Source: iter.org

ACTIVATION PRODUCTS TRACKED & MODELED



NEUTRINO & ANTINEUTRINO EMISSIONS

(1500 MW OF FUSION POWER; ~ 5.3 x 10^{20} NEUTRONS PER SECOND FROM PLASMA)

FLIBE BLANKET DESIGN

Isotope	Decay	Q [MeV]	A_{30} [Bq]	A_{360} [Bq]	
W-181	ϵ	0.205	6.97E+18	3.83E+19	
W-185	β^-	0.431	5.31E+18	2.11E+19	
W-179	ϵ	1.062	1.41E+19	1.40E+19	
F-18	β^+	0.634	1.27E+19	1.27E+19	
W-187	β^-	1.313	6.36E+18	6.32E+18	
Cr-51	ϵ	0.752	2.61E+18	4.93E+18	
F-20	β^-	7.024	3.28E+18	3.28E+18	←
V-49	ϵ	0.602	2.52E+16	2.19E+17	
Li-8	β^-	16.004	1.64E+17	1.64E+17	←
Cr-49	β^+	1.608	7.81E+16	7.81E+16	
Ti-45	β^+	1.040	1.25E+16	1.25E+16	
Fe-55	ϵ	0.231	1.06E+15	1.13E+16	
Ti-51	β^-	2.470	6.64E+15	6.64E+15	←
Cr-55	β^-	2.602	5.96E+15	5.95E+15	←
Ta-182	β^-	1.816	6.64E+14	3.54E+15	←
Mn-56	β^-	3.695	2.11E+15	2.11E+15	←

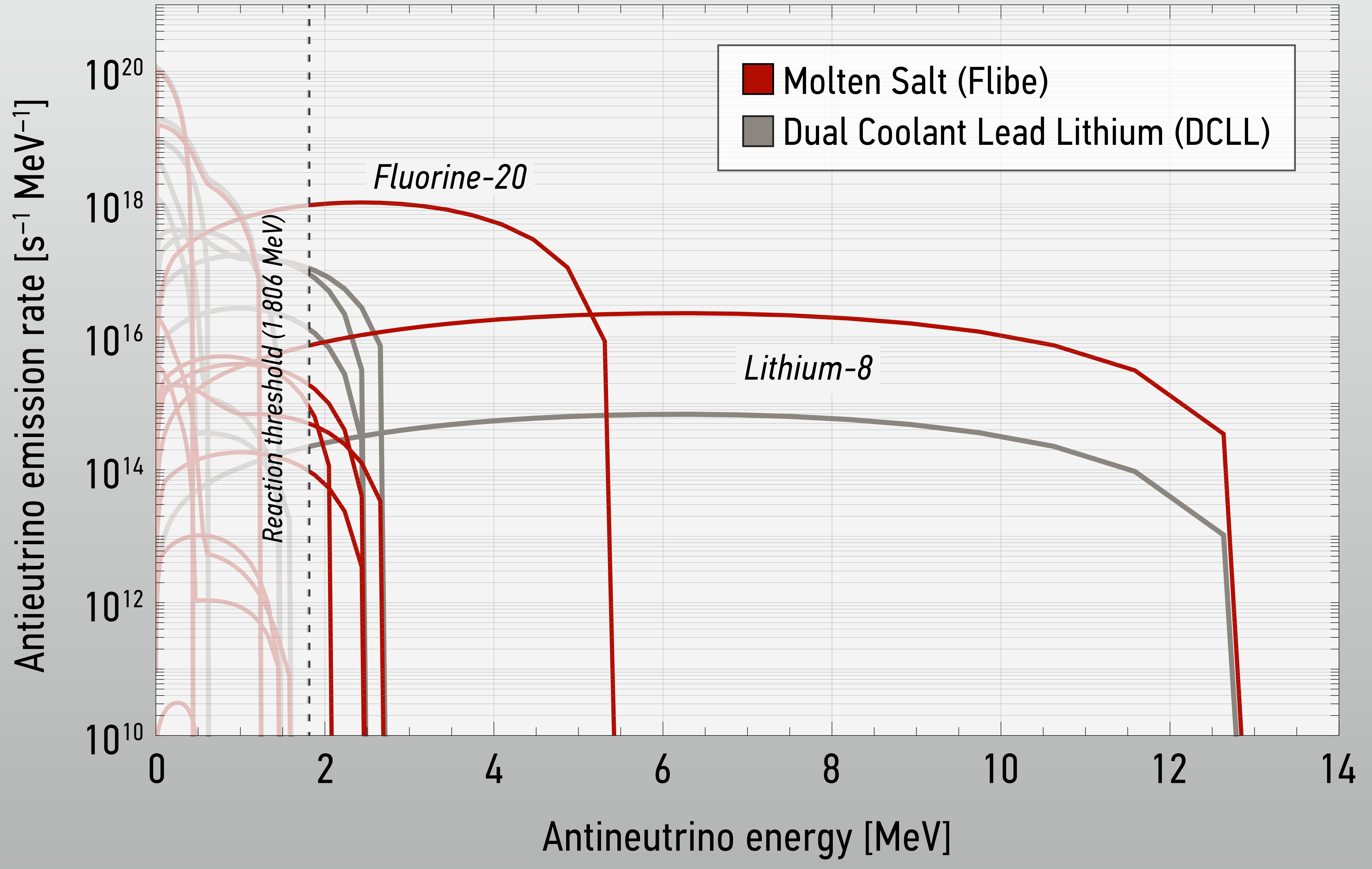
DCLL BLANKET DESIGN

Isotope	Decay	Q [MeV]	A_{30} [Bq]	A_{360} [Bq]	
Pb-203	ϵ	0.975	1.09E+20	1.09E+20	
W-181	ϵ	0.205	4.67E+18	2.57E+19	
Fe-55	ϵ	0.231	2.30E+18	2.47E+19	
W-185	β^-	0.431	5.75E+18	2.28E+19	
W-179	ϵ	1.062	1.40E+19	1.39E+19	
W-187	β^-	1.313	7.81E+18	7.77E+18	
Pb-209	β^-	0.644	2.95E+18	2.95E+18	
Cr-51	ϵ	0.752	1.02E+18	1.94E+18	
Ta-182	β^-	1.816	1.48E+17	7.89E+17	←
Mn-56	β^-	3.695	4.59E+17	4.59E+17	←
Fe-53	β^+	2.721	3.74E+17	3.73E+17	
Si-31	β^-	1.492	3.50E+17	3.50E+17	
V-52	β^-	3.976	2.63E+17	2.63E+17	←
Fe-59	β^-	1.565	8.20E+16	2.19E+17	
Mn-54	ϵ	1.377	7.57E+15	6.46E+16	
Cr-55	β^-	2.602	4.12E+16	4.11E+16	←

A. Glaser, R. J. Goldston, P. Huber, Detectability of Covert Fissile Material Production in Nuclear Fusion Reactors via Antineutrino Emissions, August 2025, arxiv.org/abs/2508.16358

ANTINEUTRINO EMISSIONS FROM REACTOR BLANKET

(1500 MW OF FUSION POWER)

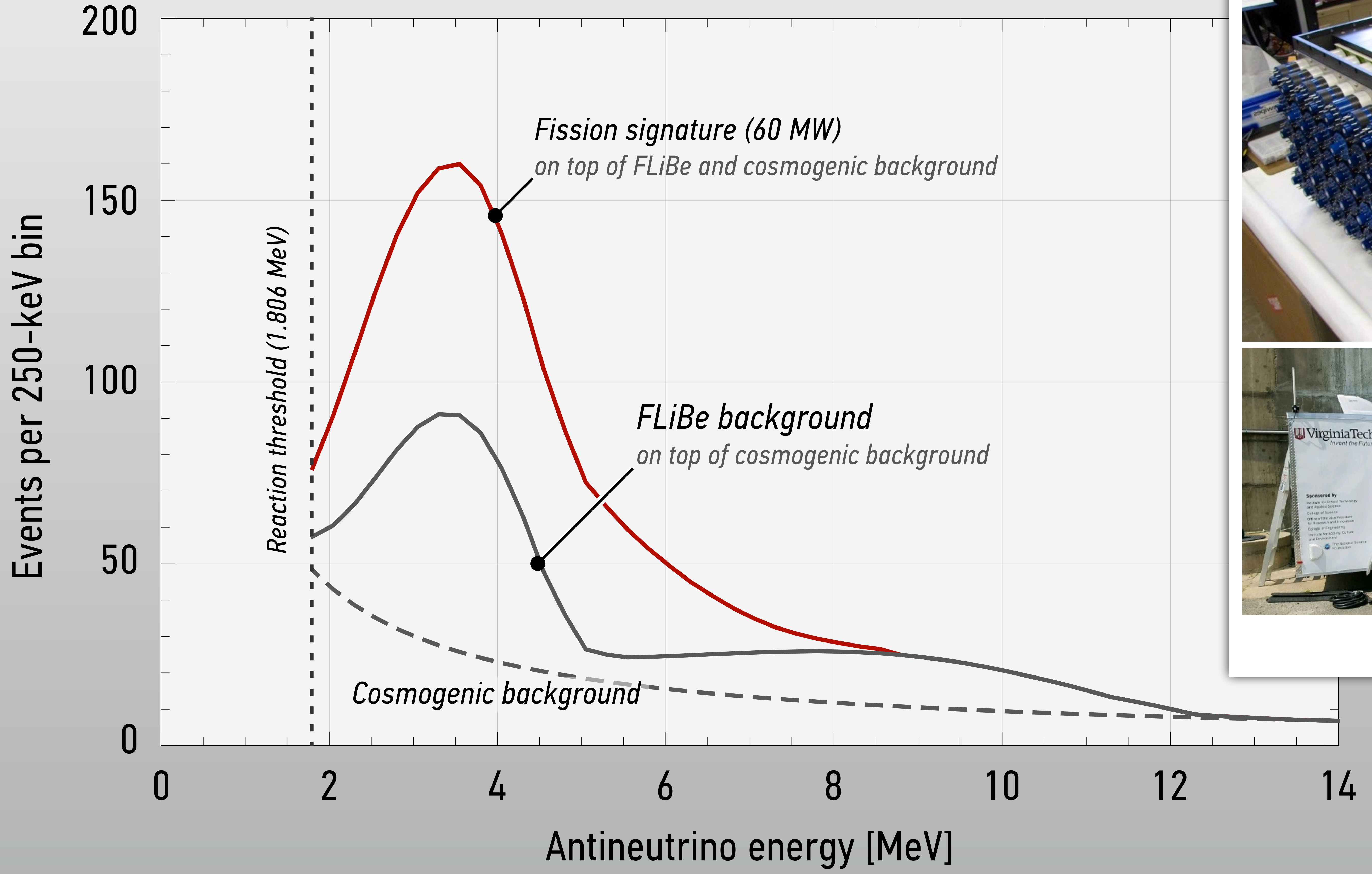


Antineutrino spectra calculated with CONFLUX software package

A. Glaser, R. J. Goldston, P. Huber, Detectability of Covert Fissile Material Production in Nuclear Fusion Reactors via Antineutrino Emissions, August 2025, arxiv.org/abs/2508.16358

ANTINEUTRINO EVENT SPECTRUM

COLLECTED OVER THIRTY DAYS IN A ONE-TON (MINICHANDLER-TYPE) ANTINEUTRINO DETECTOR

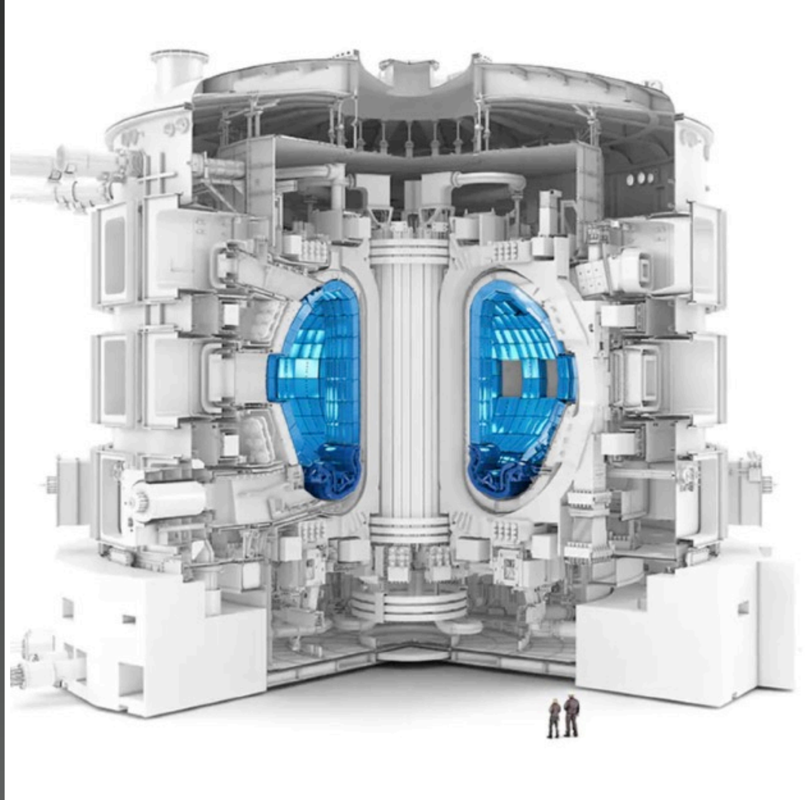


cnp.phys.vt.edu/chandler

A. Haghighat, P. Huber, et. al., Observation of Reactor Antineutrinos with a Rapidly Deployable Surface-Level Detector, Physical Review Applied, 13, 2020

A. Glaser, R. J. Goldston, P. Huber, Detectability of Covert Fissile Material Production in Nuclear Fusion Reactors via Antineutrino Emissions, August 2025, arxiv.org/abs/2508.16358

KEY FINDINGS AND OUTLOOK



KEY FINDINGS

Even a modestly-sized antineutrino detector should be able to detect the presence of fertile material during operation in a reliable and timely manner; the production of one significant quantity (8 kg) of plutonium in one month provides a strong and easily detectable signature

NEXT STEPS AND OUTLOOK

Further work is required to optimize such a detector system

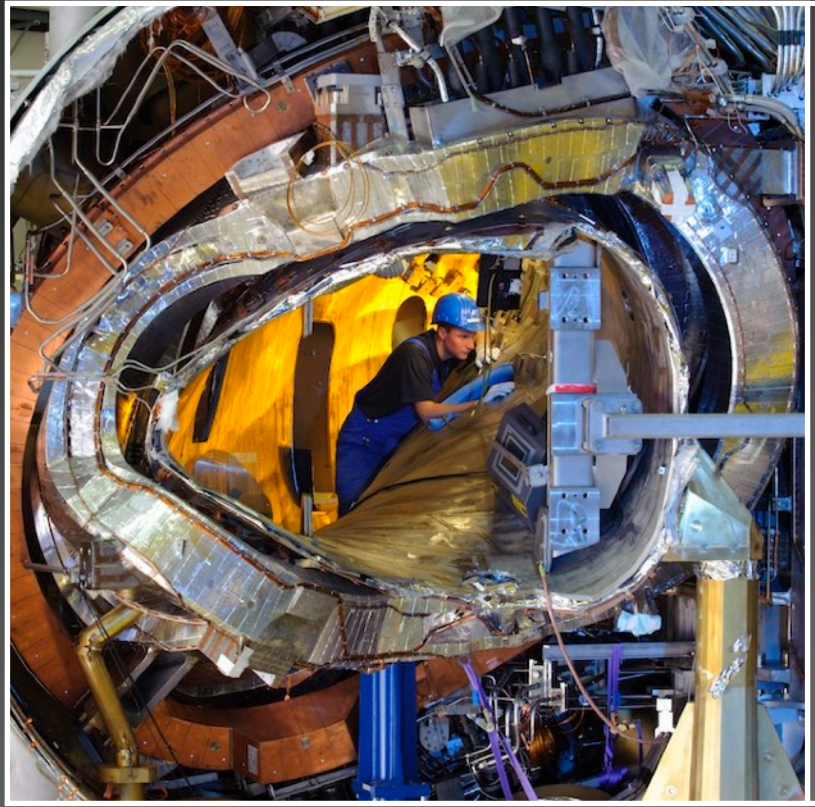
A wider range of blanket designs should be studied

Additional covert production scenarios could also consider thorium (weaker fission signature)

Source: fusionforenergy.europa.eu (top) and bnl.gov (bottom)

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 can raise security (and safety) 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)