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MacroVoices 2024 Holiday Special

Advanced Nuclear Technologies for Energy Transition

Joint presentation by Thomas-Jam Pedersen and Erik Townsend

Episode 2 of 2:

Nuclear Fuels and Fuel Cycles for Energy Transition

FOURTH TURNING
CAPITAL MANAGEMENT, LLC

Topics for this episode…

- Nuclear Fuels for Energy Transition-scale Nuclear Buildout
  - Uranium isn’t enough!
- Why the fuel supply chain challenges are even more daunting than the engineering challenges when you consider 24x scale nuclear build-out
- Deep dive on Uranium-based Nuclear Fuels
  - LEU, HALEU, TRISO, MOX, etc.
- Uranium-233 and Thorium
- Weapons Proliferation & Spent Fuel Waste Management

Thinking at *Scale*...

Few Nuclear engineers & scientists have analyzed **truly large-scale** nuclear energy deployment

What would it take to replace *all* the energy we presently derive from Coal, Oil, and Gas with Nuclear?

When you think at scale...

Suddenly the **Fuel Supply Chain** becomes the more important challenge/issue than the features of the reactor design

In the opinion of Erik & Thomas-Jam...

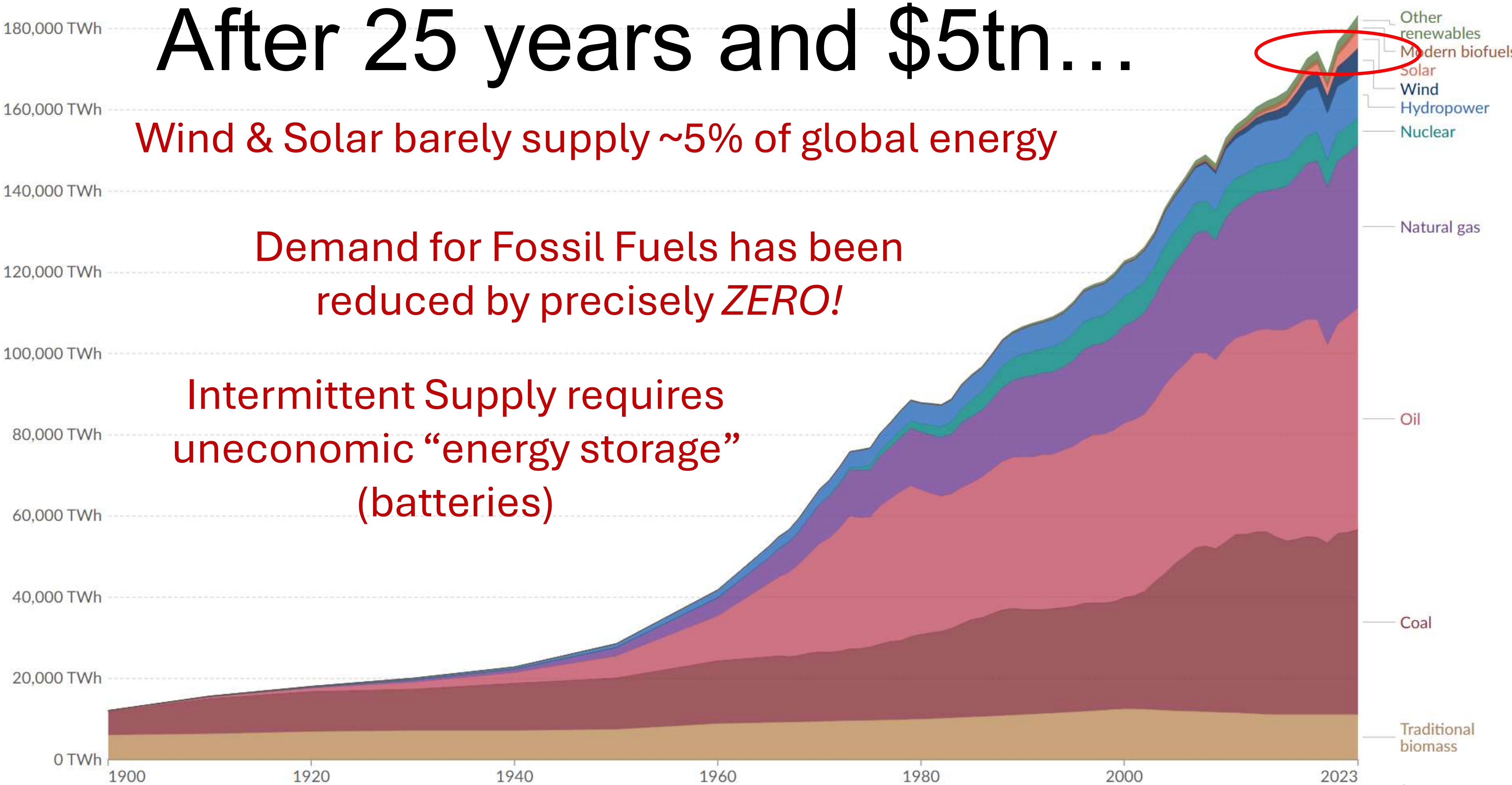
Thorium rather than Uranium is the only fuel that truly scales to meet the needs of global energy transition

After 25 years and $5tn…

Wind & Solar barely supply ~5% of global energy

Demand for Fossil Fuels has been reduced by precisely *ZERO!*

Intermittent Supply requires uneconomic “energy storage” (batteries)



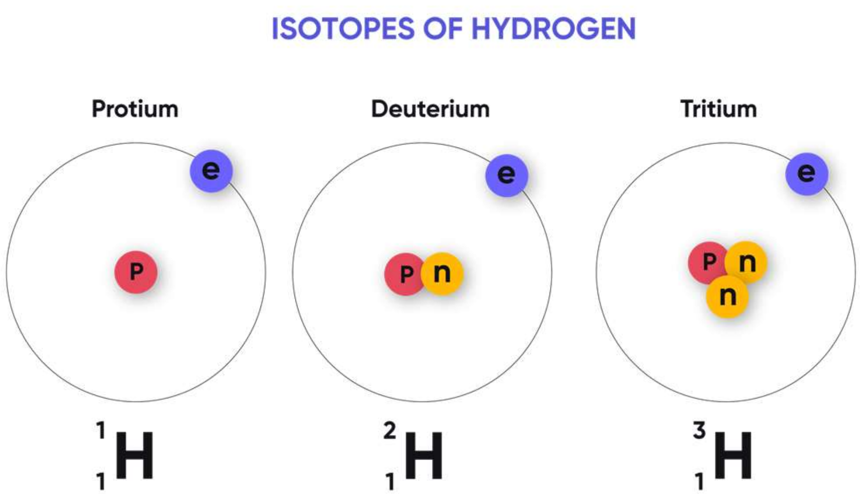
*When making electric cars, most people assume the engineering is the hard part. But getting the **manufacturing** right is actually the hardest and most important part.*

--Elon Musk

*When contemplating nuclear energy transition, most people focus on the reactor designs. The **fuel cycles** and supply chain challenges are actually far more important, and very few people have really thought them through at scale.*

--Erik Townsend

Atoms, Elements, and Isotopes



Atoms were once thought to be the smallest unit of matter.

Elements are atoms with a specific number of <u>protons</u> in the nucleus. Hydrogen=1 proton, Helium=2, Lithium=3. Beryllium=4, Uranium=92, etc.

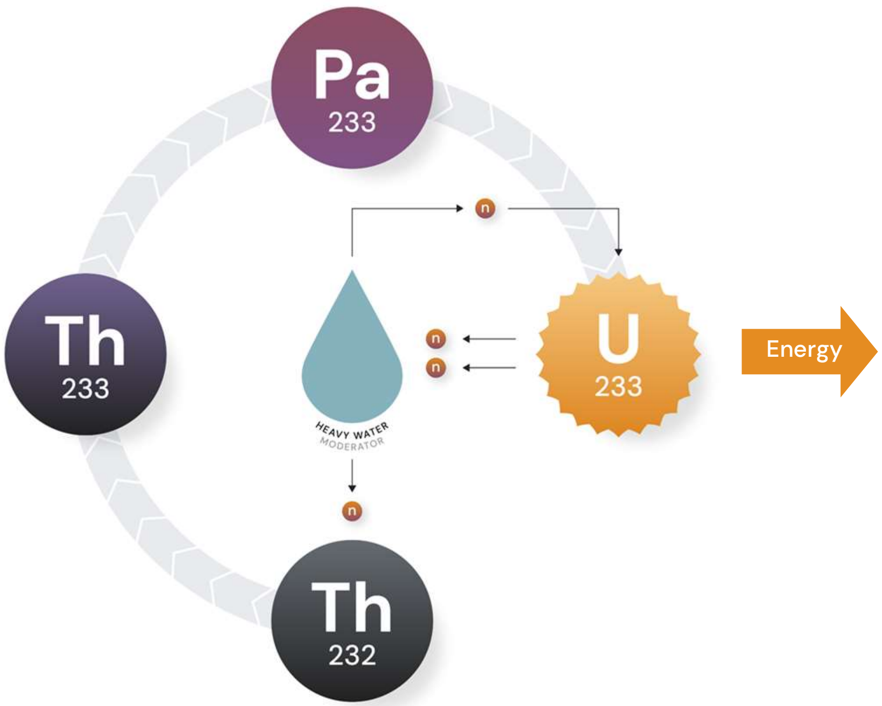
Isotopes are variants of elements, determined by the number of <u>neutrons</u> in the nucleus. Examples of isotopes are Hydrogen-1, Hydrogen-2, Uranium-235, Uranium-238, etc.

There are only THREE Fissile Nuclear Fuels

Fissile Isotope	Source	Method of Production
Uranium-235	Occurs in nature, but only in small quantities. Only 0.72% of natural uranium is U-235.	Must be "enriched" from 0.72% to at least 3% to be useful as fuel in most conventional reactor designs. Centrifuge enrichment is the most common method in use today. Laser enrichment is the "hot new idea".
Plutonium-239	Man-made element; can only be produced by *transmutating* **Uranium-238** in a nuclear reactor. Plutonium is incredibly toxic and challenging to handle.	A small amount Pu-239 is produced in conventional reactors (about 3% of the U-238 present transforms into Pu-239 as a by-product of the nuclear fission chain reaction). "Fast neutron reactors" are designed to transform a much higher percentage of the U-238 into Pu-239.
Uranium-233	Man-made isotope of Uranium; does not occur in nature. Made by transmutating **Thorium-232** in a nuclear reactor.	Thorium-232 is placed in a ***breeding blanket*** encircling a nuclear reactor. The neutrons escaping the reactor core transmutate the Thorium-232 into Protactinium-233 which then decays naturally into **fissile** Uranium-233 in about 30 days on average.

Thorium

Fuel cycle



1 kg of thorium gives you 22 GWh of thermal energy

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6 o'clock: Natural thorium will convert to Th-233, when hit by a slow neutron, which then quickly convert, through radioactive decay to Pa-233 at 12 o'clock.

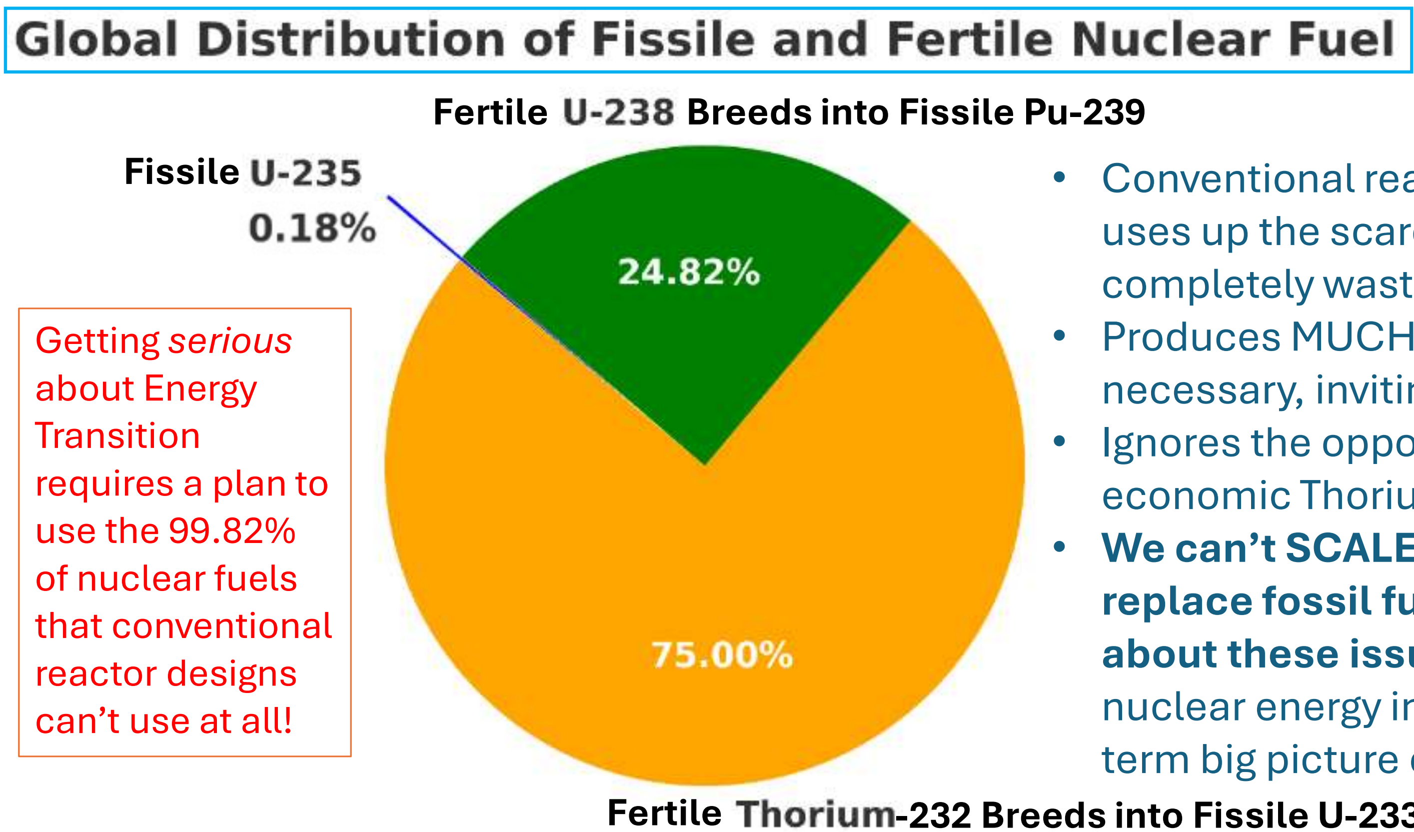
Pa-233 converts to U-233 through radioactive decay with a 30 days half life.

U-233 is not found in nature, but it is the best nuclear fuel you can get.

When you hit U-233 with a slow neutron it fissions with a high probability and give off 2.35 neutrons on average, which make a chain reaction possible.

Copenhagen Atomics will use heavy water as the moderator.

Using up scarce U-235 as fuel is crazy!



Getting *serious* about Energy Transition requires a plan to use the 99.82% of nuclear fuels that conventional reactor designs can't use at all!

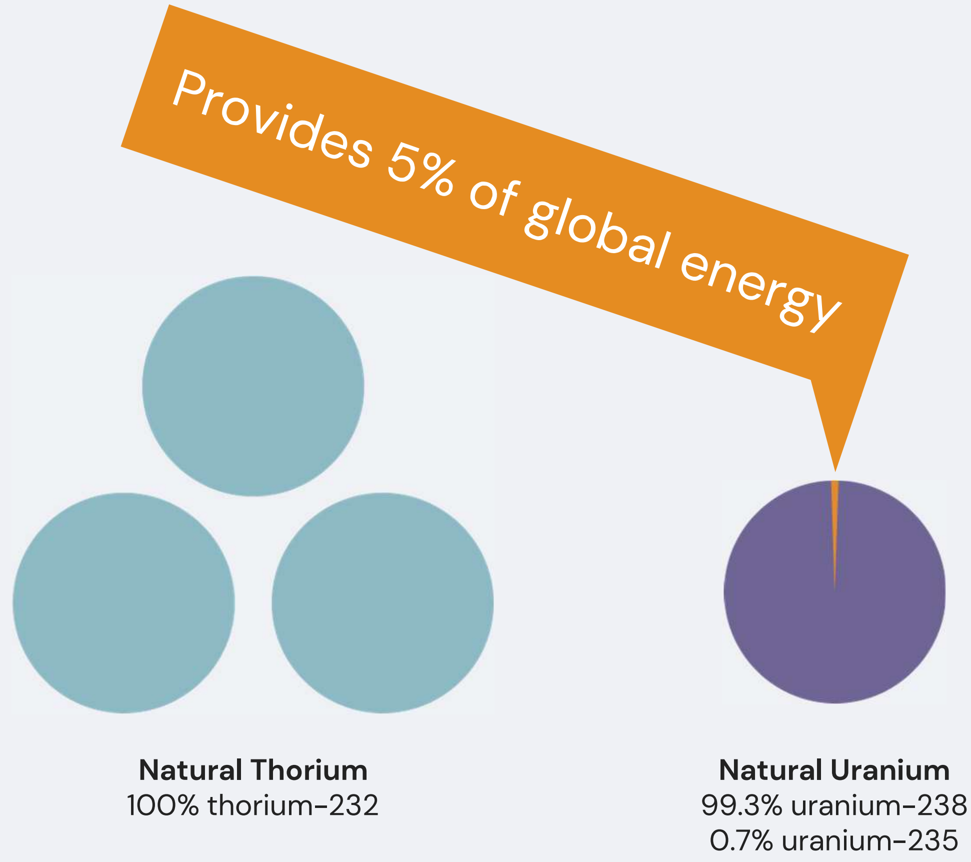
- Conventional reactor "once-thru" fuel cycle uses up the scarce U-235 as its sole fuel while completely wasting almost all the U-238
- Produces MUCH more spent fuel waste than necessary, inviting anti-nuclear opposition
- Ignores the opportunity to use the much more economic Thorium/U-233 fuel cycle
- **We can't SCALE nuclear energy to fully replace fossil fuels until we start thinking about these issues.** Almost nobody in the nuclear energy industry thinks about the long-term big picture of fissile/fertile fuel supply.

We will never run out

Thorium is more abundant than uranium

Classic nuclear uses U235 and we may run out of it in 200 years time. Therefore it is not considered a renewable energy source.

However thorium can make a breeder reactor and we will run out of materials to build wind and solar before we run out of thorium and the materials needed to build Copenhagen Atomics power plants. Therefore CA reactors are considered über-renewable energy.



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NO ENRICHMENT REQUIRED

NO WEAPONS PROLIFERATION RISK

90
Th
Thorium
232.04

PRIMARY FUEL

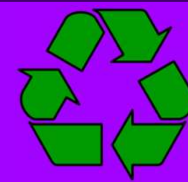
5% U-235 | 95% U-238

235 92 U

92 U Uranium 238.03

LOW ENRICHED URANIUM

OR



RECYCLED SPENT NUCLEAR FUEL WASTE

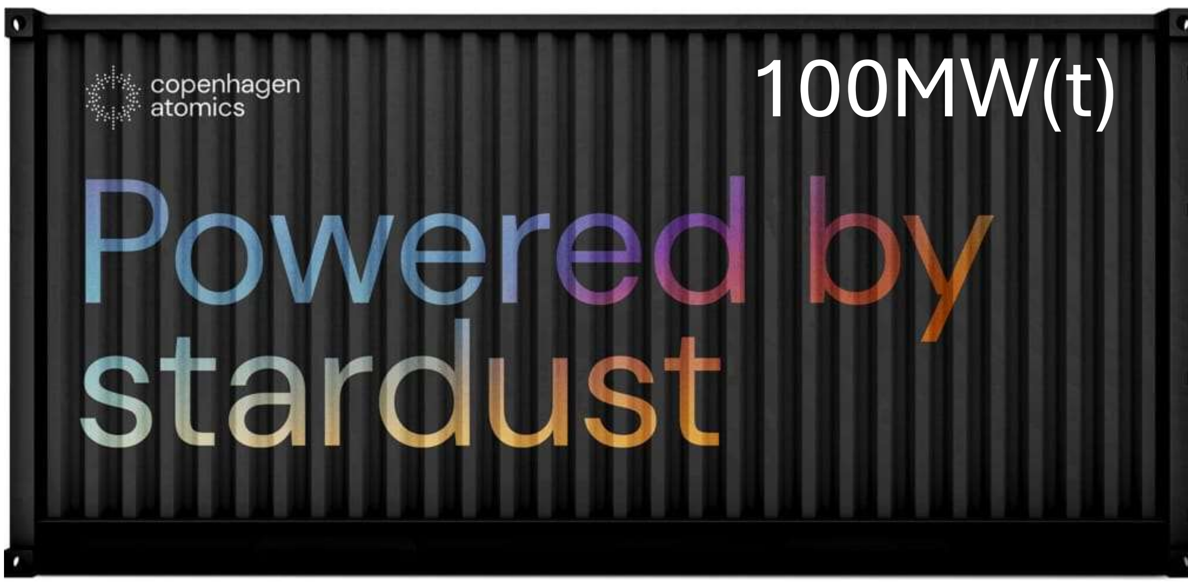
JUST ONE INITIAL LOAD REQUIRED

“KICK-STARTER” FUEL

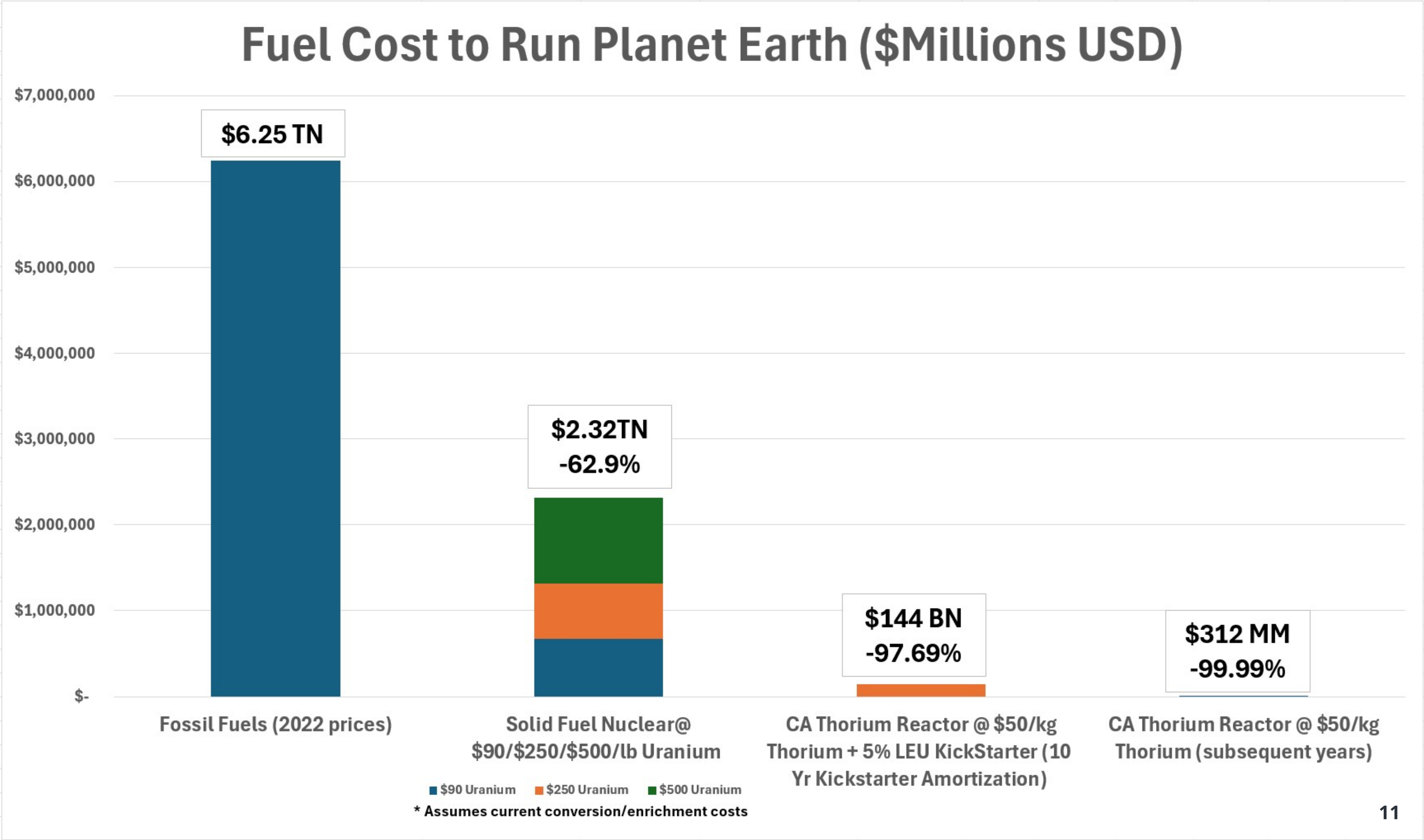
36<u>kg</u> of Thorium per year!

Cost: $1,800

Normalized to AP1000 3,400MW(t) $61.2k vs $194mm = ~3,170x, or a -99.97% fuel cost reduction!

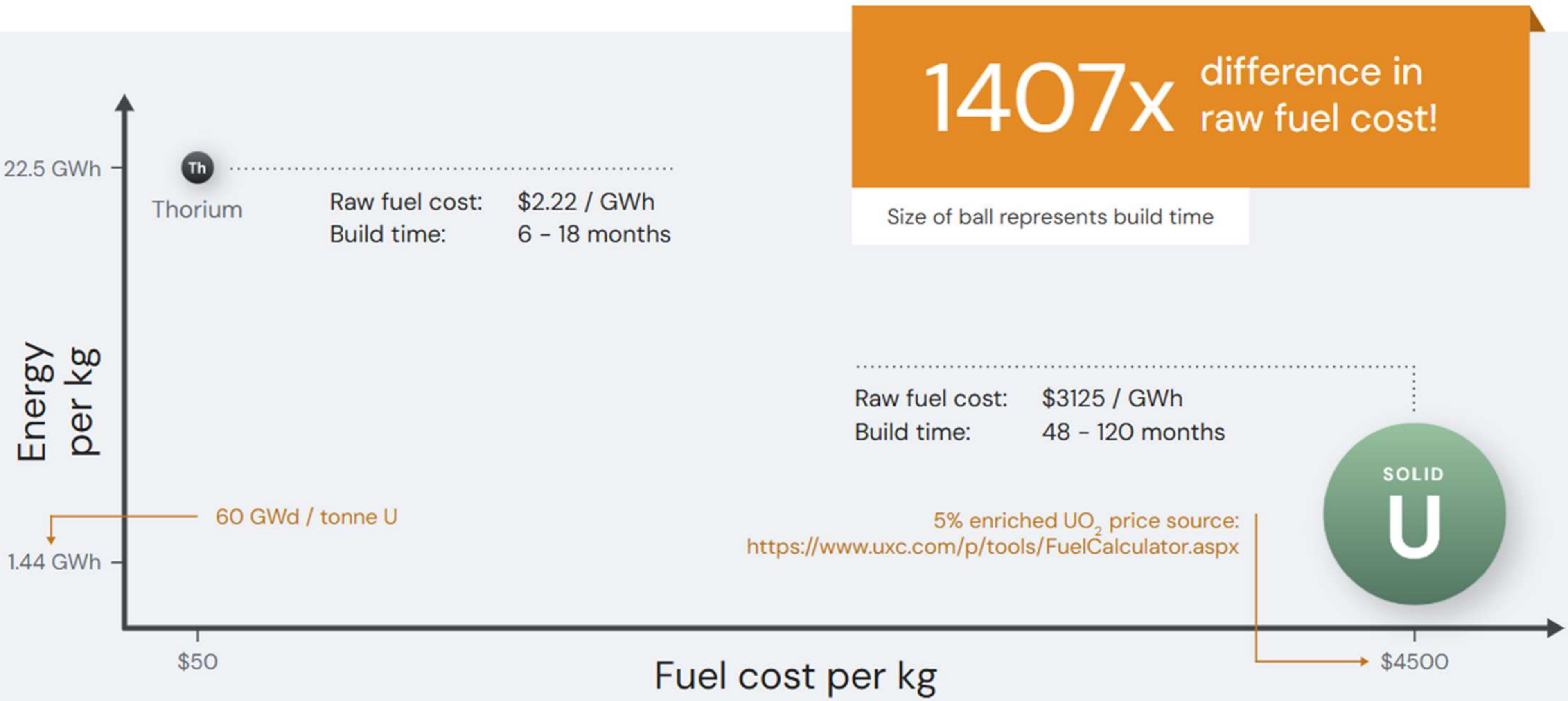


131,000 metric tons COAL per year (20km railway train) ~$19mm USD


Fuel Cost to Run Planet Earth ($Millions USD)
$7,000,000
$6,000,000
$5,000,000
$4,000,000
$3,000,000
$2,000,000
$1,000,000
$-
$6.25 TN
$2.32TN
-62.9%
$144 BN
-97.69%
$312 MM
-99.99%
Fossil Fuels (2022 prices)
Solid Fuel Nuclear@ $90/$250/$500/lb Uranium
CA Thorium Reactor @ $50/kg Thorium + 5% LEU KickStarter (10 Yr Kickstarter Amortization)
CA Thorium Reactor @ $50/kg Thorium (subsequent years)
$90 Uranium
$250 Uranium
$500 Uranium
* Assumes current conversion/enrichment costs

Uranium solid fuel reactors vs CA thorium breeder reactor

Fuel cost, energy per kg & build time



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Cost & Time

Plant size: 1 GWe in europe or usa

	Coal	Gas	Classic Nuclear (CLEAN ENERGY)	CA thorium breeder (CLEAN ENERGY)
Electricity cost	$30 – 60 / MWh	$60 – 100 / MWh	$60 – 100 / MWh	$20 – 40 / MWh
Raw fuel cost / year	$400 million	$600 million	$100 million	$50.000 – 300.000
OPEX / year	$50 million	$50 million	$100 million	$50 million
CAPEX & Build time	$2 billion ~2 years	$1 billion ~1 year	~$10 billion 4–15 years	$2 billion 1 year

BILLION $

YEARS

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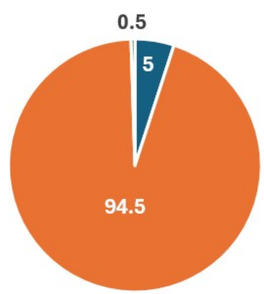
Uranium Fuels & Supply Chain Challenges

5% Enriched LEU Reactor Fuel for PWR



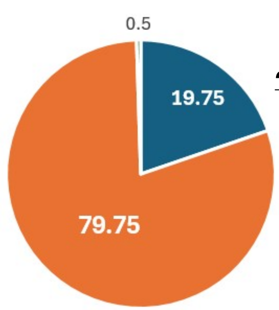
~$3,500/kg

■ U-235 5% ■ U-238 94.5% ■ Zirconium (Cladding) 0.5%

"HALEU" Fast Reactor Fuel

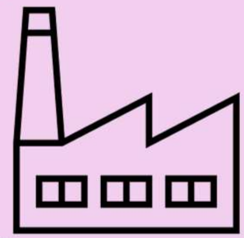
With HALEU & fast neutrons, a much lower % of the U238 is perceived to be wasted.

But what about the tailings?



~$25,000/kg

■ U-235 19.75% ■ U-238 79.75% ■ Zirconium (Cladding) 0.5%



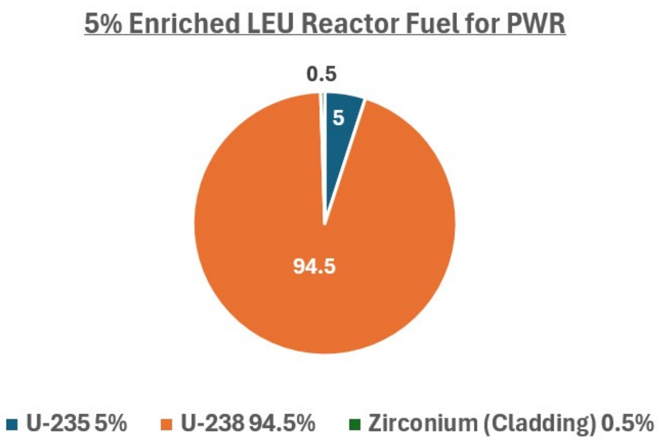
Conversion & Enrichment

- We already have a shortage of conversion & enrichment facilities in the West
- Recent geopolitical escalation with Russia just made the problem much worse
- Some analysts question whether we can achieve "Triple-Nuclear" due to insufficient enrichment capacity
- HALEU requires *far* more SWUs, and demand is expected to explode due to prominence of fast sodium reactor designs in the present nuclear renaissance
- Meanwhile, almost nobody noticed that the Thorium fuel cycle doesn't require any enrichment!
- Approx cost of an 5mm SWU enrichment facility in USA is $3bn+ (Source: ChatGPT 4o)

Meltdown-Proof Nuclear Fuels

- **TRISO**
  - The fuel "pebbles" in a "pebble bed" high-temperature, gas cooled reactor
  - Each TRISO pebble is effectively a miniature containment system in case of accident
    - Melt-downs impossible
  - Primary downside is higher cost ($35,000/kg+) relative to other fuel systems
- **Flouride and Chloride** Fuels for liquid-fueled Molten Salt Reactors
  - You can remove fission products online and offline
  - You can refuel online and offline
  - You can breed more fuel than you consume
  - Liquid fuels are less expensive than TRISO
  - You can reuse Li7 or BeF
  - Easy to dump the salt and avoid criticality and enable passive decay heat remoal
  - Salt has a strong negative temperature coefficient and self balance power & temperature

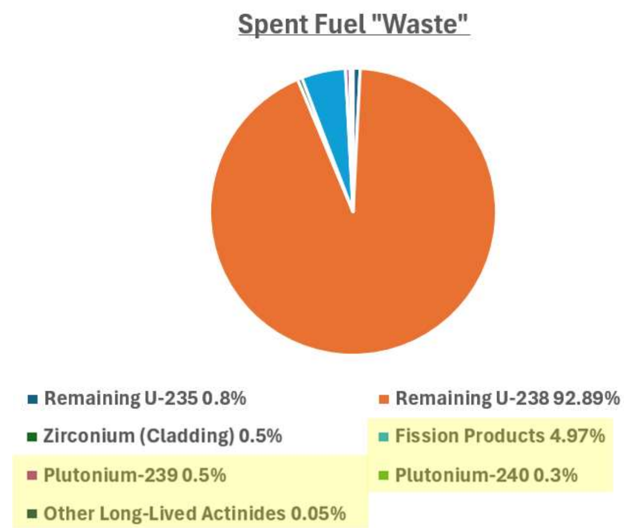
Spent Fuel Waste Reprocessing

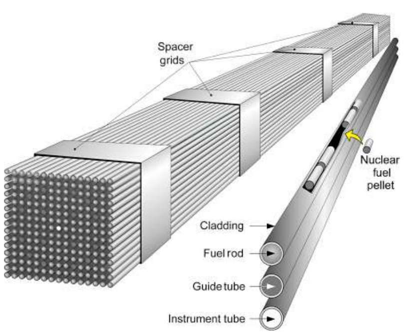


Westinghouse AP1000 Nuclear Power Station

1,117 MW(e) Generation Capacity
Requires cooling water source (river/ocean)

CAPEX Data from Vogtle, GA:
Original Cost Est. ~$7.5bn per reactor
Actual cost ~$15bn per reactor
(= $13,428/kw)



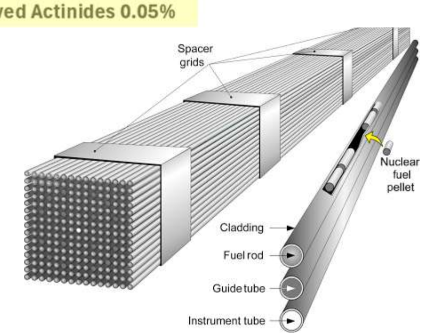


AP1000 5% LEU Fuel Bundle
(~$4,000 USD/kg)

80,000 kg Fuel Load (~$320mm)

Yields ~396-420MWh Electricity per kg (5% LEU)

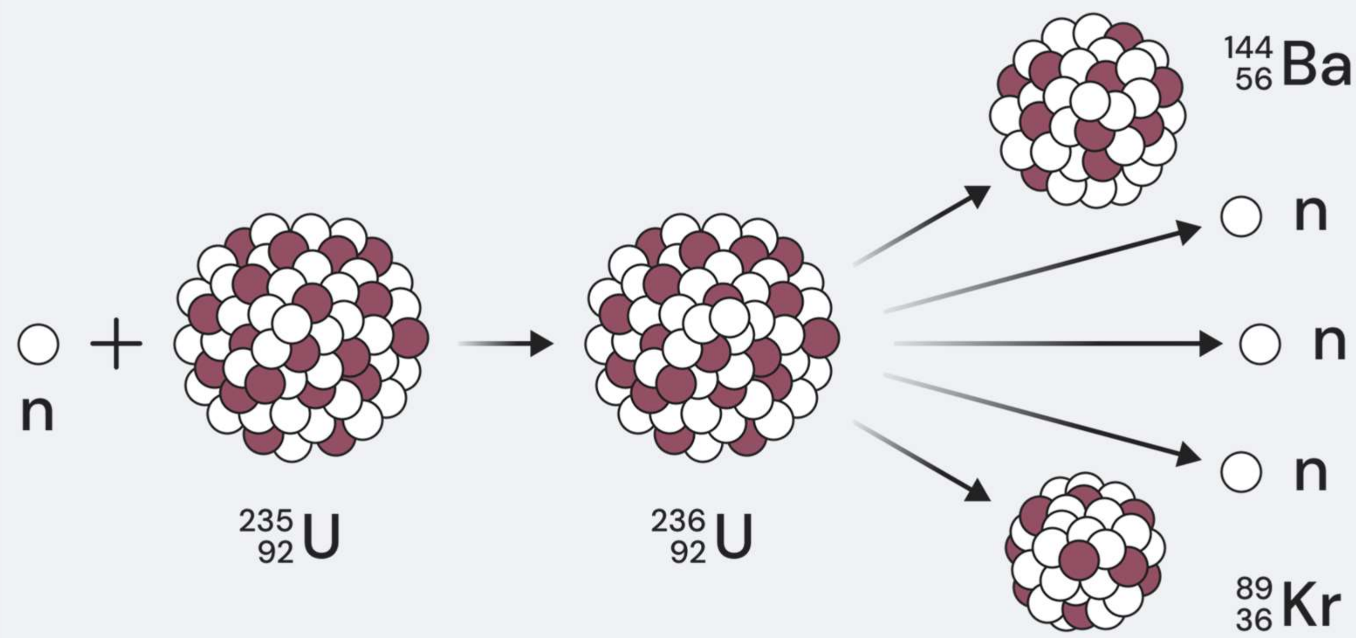
80,000 kg "Waste"



AP1000 Spent Fuel "Waste" Bundle
<5% Of the Energy it contains has been consumed!

Fission event

Neutron economy & fission products



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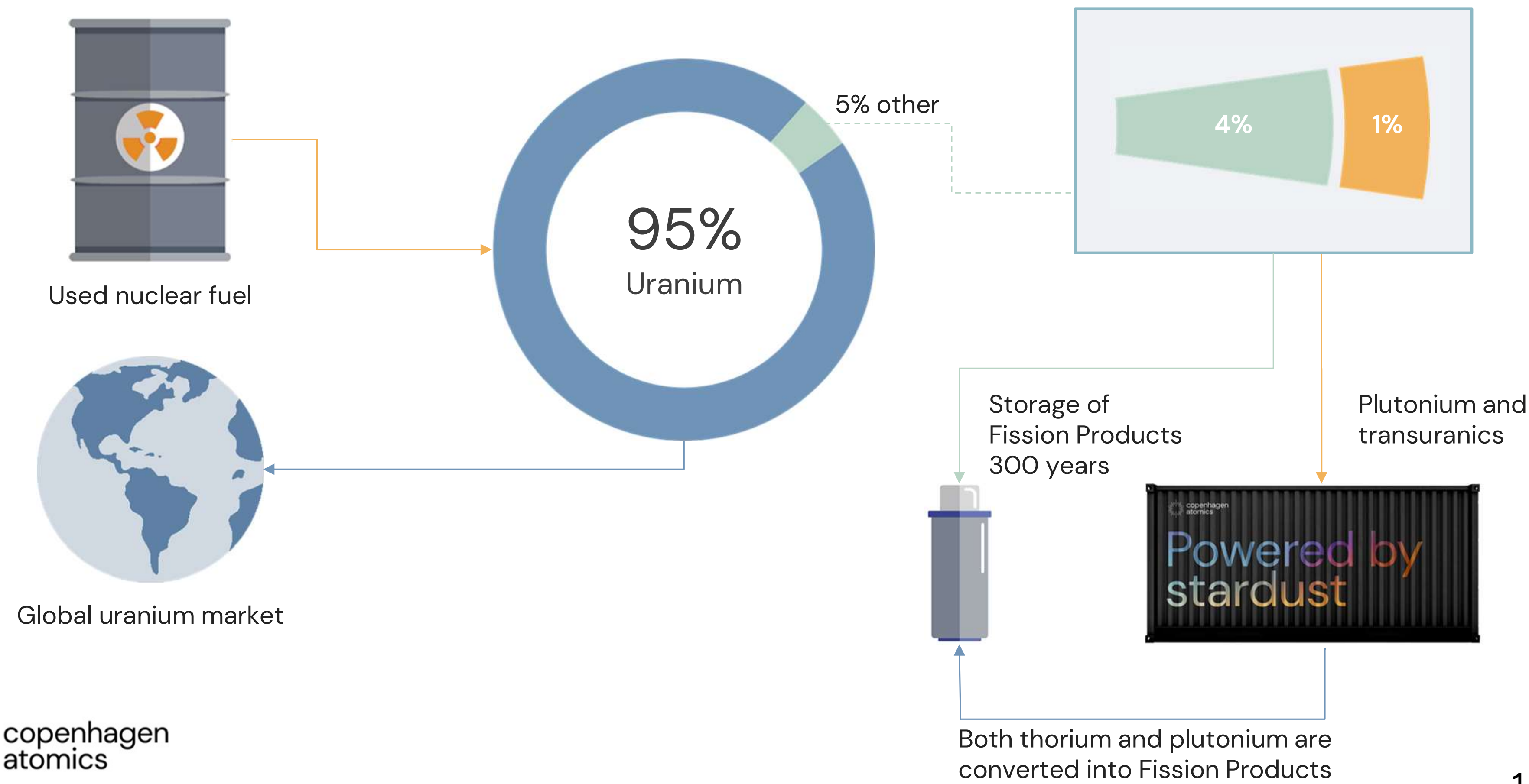
Recycling
Used nuclear fuel



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Nuclear Fuels from Reprocessed Waste

MOX

(Mixed Oxide = Uranium + Plutonium)

Combines 3% - 10% Plutonium recovered from spent fuel waste reprocessing with

Diluted with U-238 (depleted uranium) to mitigate proliferation risks

Can be used as drop-in replacement for LEU in some reactor designs

Is this really the best use for this valuable plutonium fuel?

Plutonium Kickstarter Fuel (for Thorium MSRs)

CA Design uses reactor grade plutonium from spent fuel reprocessing as kickstarter fuel for Thorium-fueled reactor.

Eliminates the longest-lived waste from existence while eliminating the need to use LEU to kickstart a large fleet of Thorium reactors

This is **<u>not allowed</u>** under current rules!

But Reprocessing is "Borderline Illegal" Globally!

It all started in 1946 with Acheson-Lillenthal

Then eventually, the Nuclear Non-Profileration Treaty

The only reason France has been able to recycle its spent fuel waste for decades with great success is that Charles de Gaulle had the good sense *not* to sign the NPT in 1968.

France eventually signed the NPT in 1992, but only after first establishing itself as a Nuclear Weapons state, thus exempting it from reprocessing restrictions

Today, the U.S. Gov't is preventing reprocessing globally

Section 123 of the Atomic Energy Act of 1954 is the mechanism USA uses to bully other countries *not* to act responsibly and recycle their spent fuel waste.

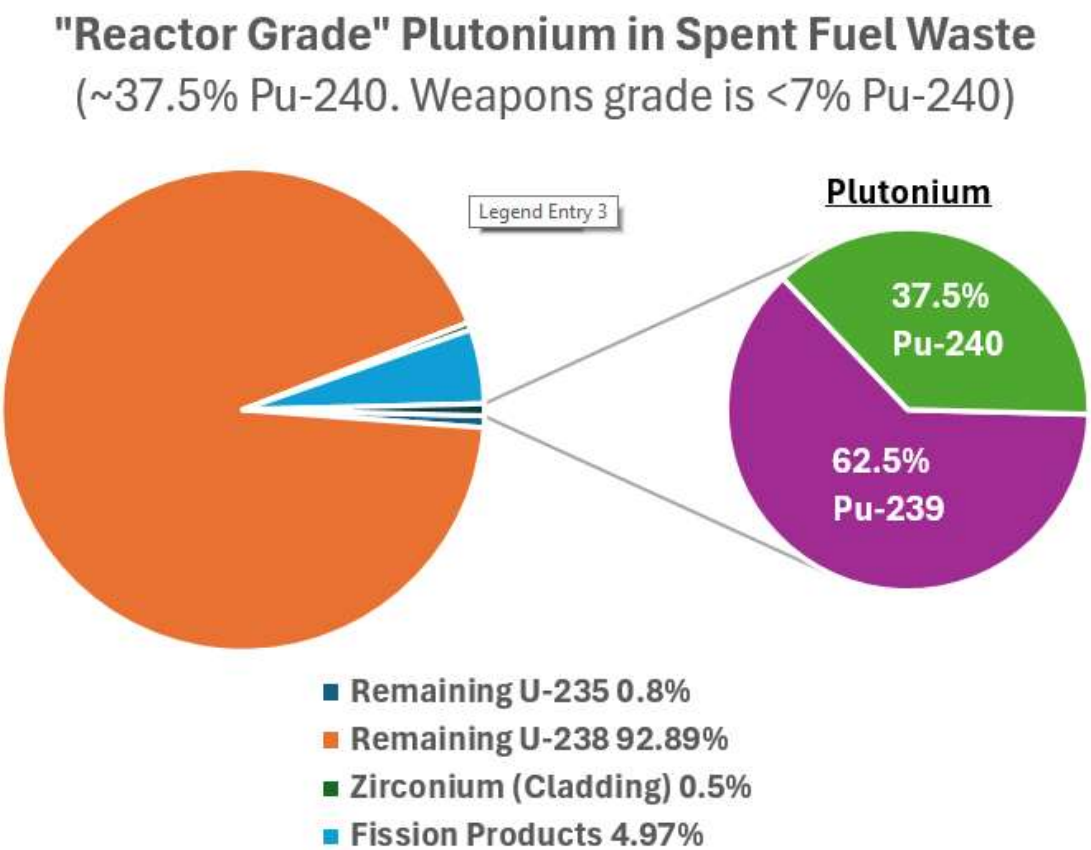
We can't get serious about Energy Transition until Section 123 is reformed.

What they're worried about is bad guys getting the Plutonium out of the waste and making a bomb from it

But that argument doesn't make any sense! The following several pages will explain why.

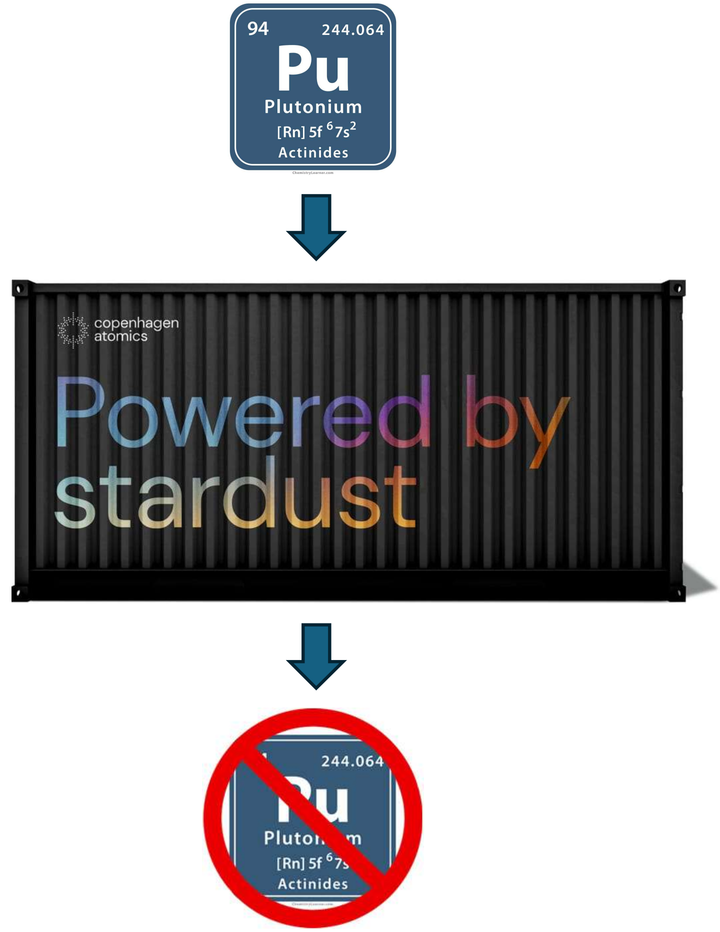
Erik’s Elevator Risk Analogy

Reactor Grade Plutonium



- Spent fuel waste contains ~1% Plutonium
- Weapons grade requires <7% Pu-240
- Separating Pu-239 from Pu-240 is incredibly hard!
- If bad guys wanted weapons grade Pu239, there's a much easier and well-known way they could make it ("Roasting")

Which is better?



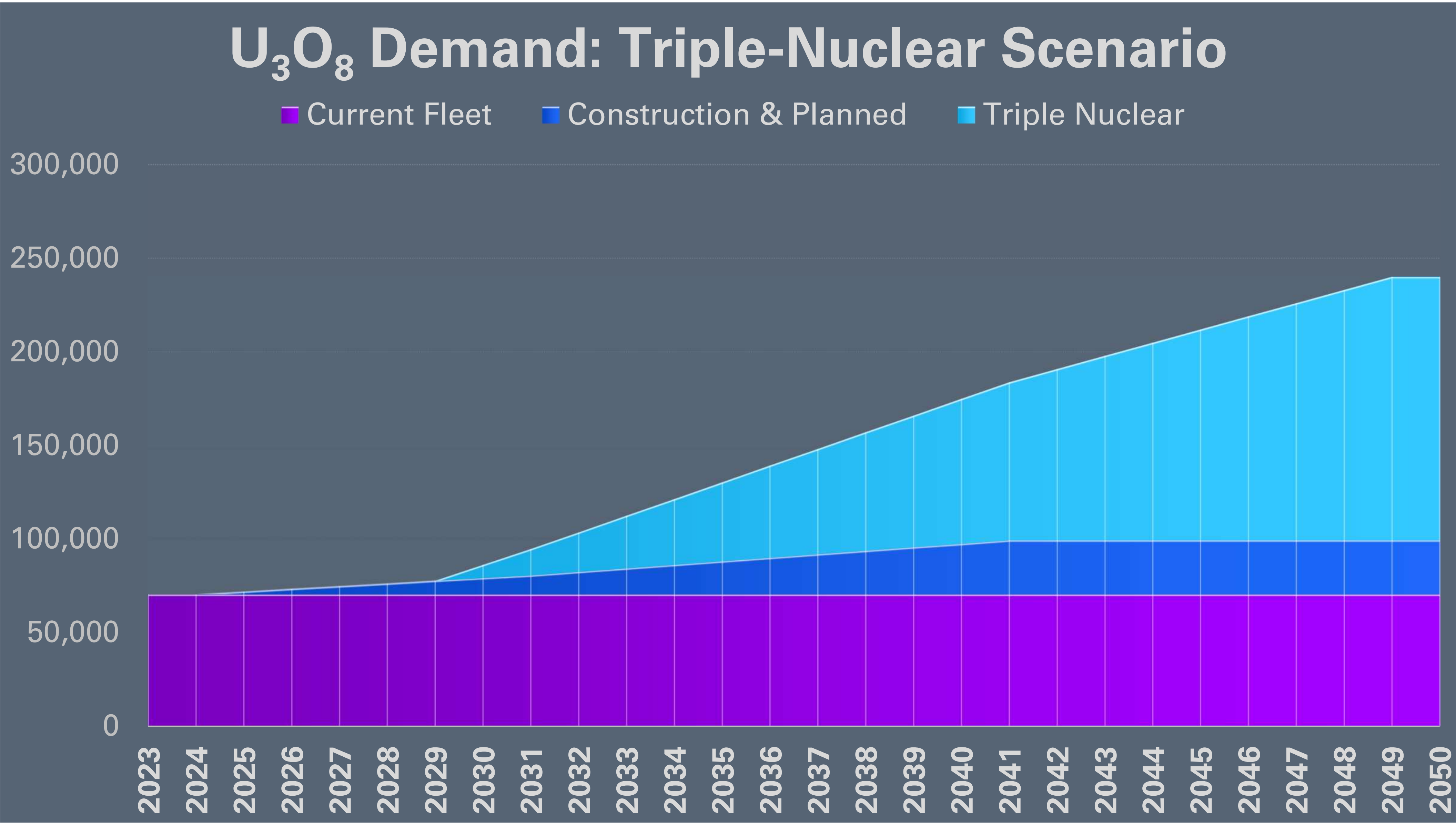
Option 1: Leave the Plutonium in the waste where it could be stolen or repurposed

Option 2: Burn the Plutonium up as kickstarter fuel so it *no longer exists* and can't possibly be misused.

Challenges to Scaling Nuclear Energy to Fully Replace Fossil Fuels

"TRIPLE-NUCLEAR" PLEDGE

- Build another ~742GW using Conventional reactors by 2050
- Approximate cost US$3.7tn - $11.2tn
- Build time ~ 5 – 10 yrs
- Electricity more expensive than coal or gas
- Supply ~11% of global energy



U_3O_8 Demand: Triple-Nuclear Scenario
Current Fleet
Construction & Planned
Triple Nuclear
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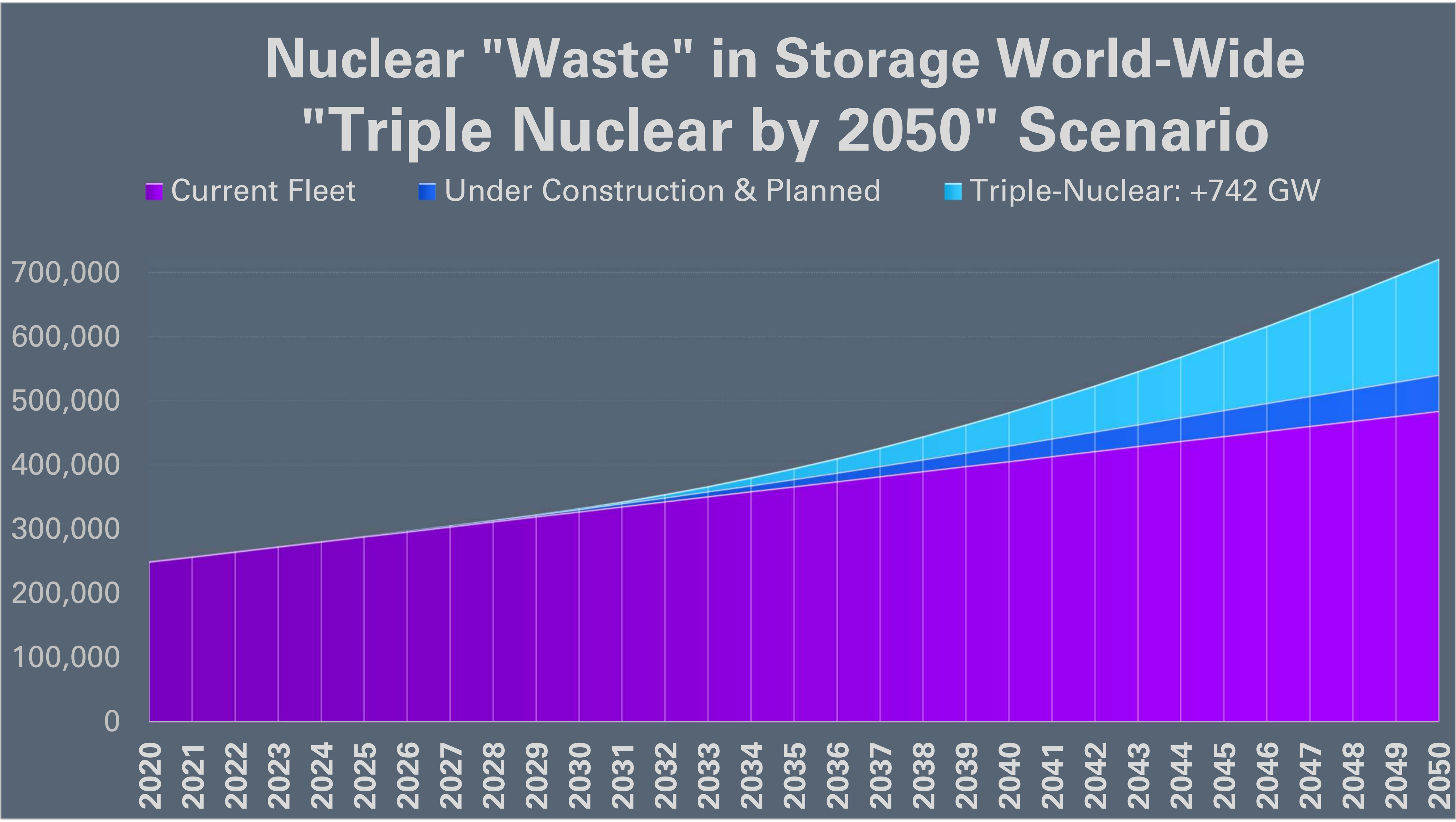
Nuclear "Waste" in Storage World-Wide
"Triple Nuclear by 2050" Scenario
Current Fleet
Under Construction & Planned
Triple-Nuclear: +742 GW
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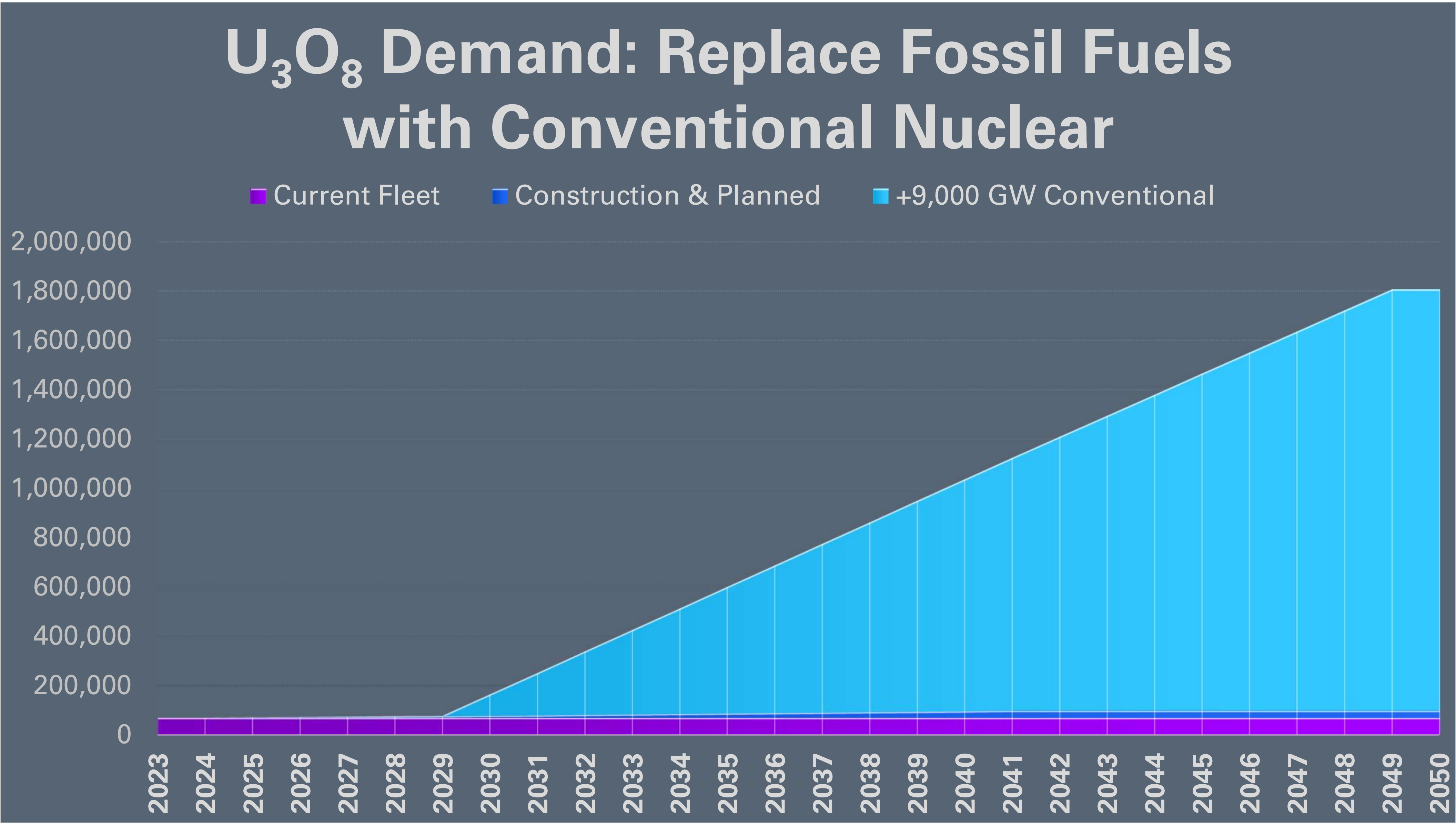
REPLACE ALL FOSSIL FUEL ENERGY

- Probably impossible…
- Build another 9,000 GW of **conventional** reactors (!)
    - 24x, not 3x current fleet
- Approx cost US$45tn - $135tn
- Build time ????
- Electricity much more expensive than fossil fuels or renewables
- Supply ~85% of global energy



U3O8 Demand: Replace Fossil Fuels with Conventional Nuclear
Current Fleet
Construction & Planned
+9,000 GW Conventional
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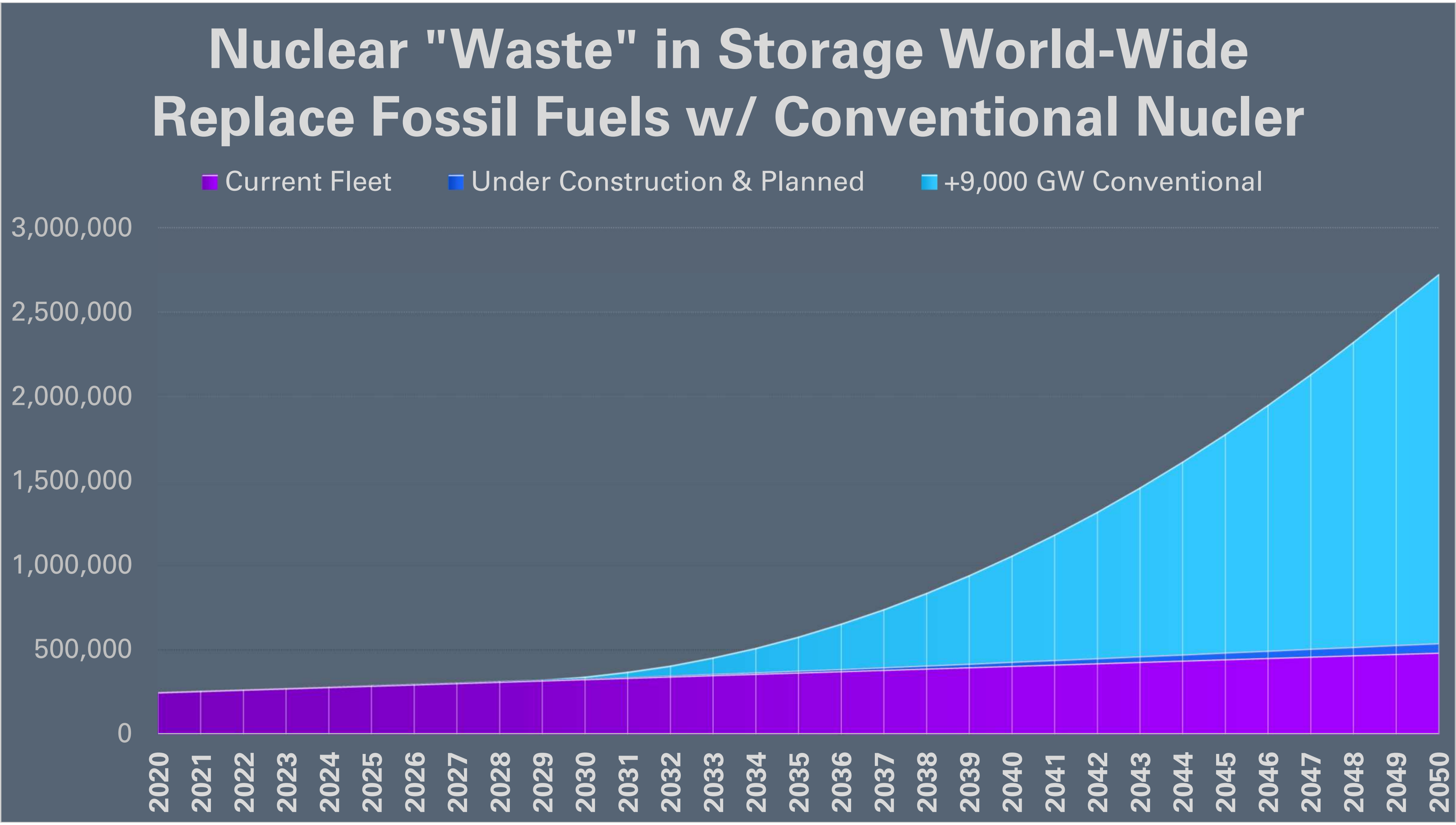
Nuclear "Waste" in Storage World-Wide
Replace Fossil Fuels w/ Conventional Nucler
Current Fleet
Under Construction & Planned
+9,000 GW Conventional
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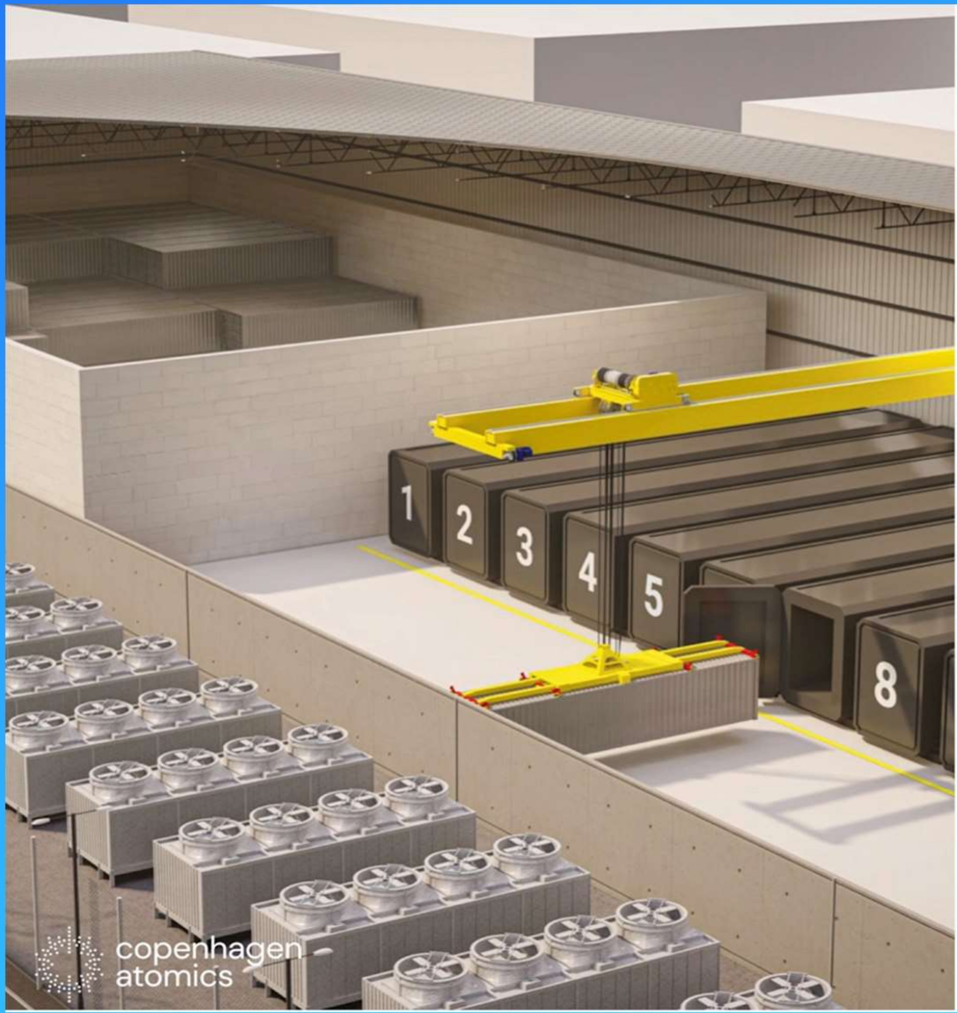
WE NEED A COMPLETELY DIFFERENT APPROACH!



Technology

The energy source of the future - A metal from the Periodic Table

Th 90

Thorium

A single ball of thorium metal can supply you with all the energy you need your entire life.

$100

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ERIK'S ENERGY TRANSITION VISION

1 Embrace "Triple-Nuclear" initiative!

Tripling nuclear using *conventional* technology will increase Uranium demand by 140k MT and triple nuclear waste to 750k+ MT by 2050

2 Re-process ALL Nuclear Waste in storage worldwide.

Yields 2,500 mt plutonium, kick-starts first 12,500 MSRs = 1,250GW(t) + 1,170 =117 GW/yr

3 Mass-produce 9,000 GW modular power plants based on Thorium MSRs (24x)

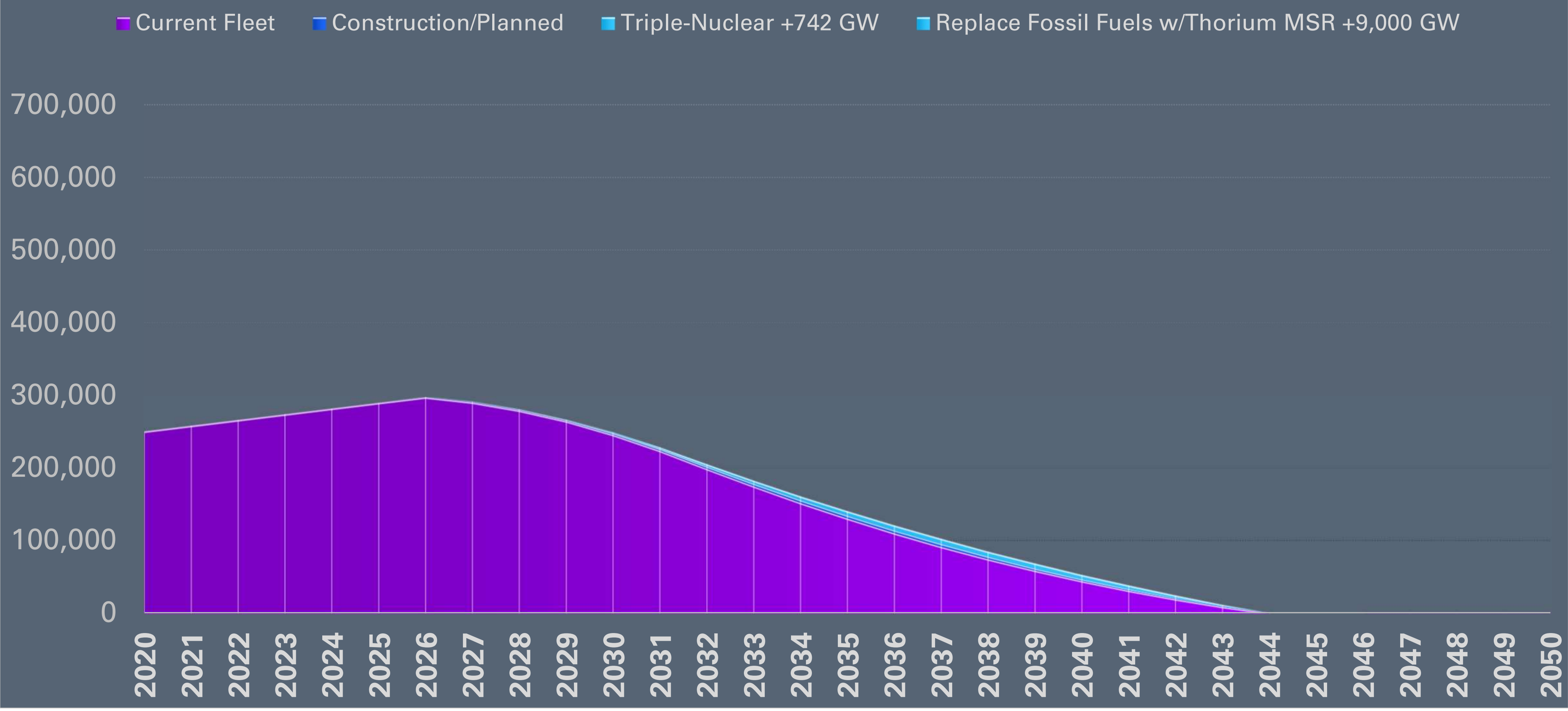
Fully replace ALL fossil fuels!

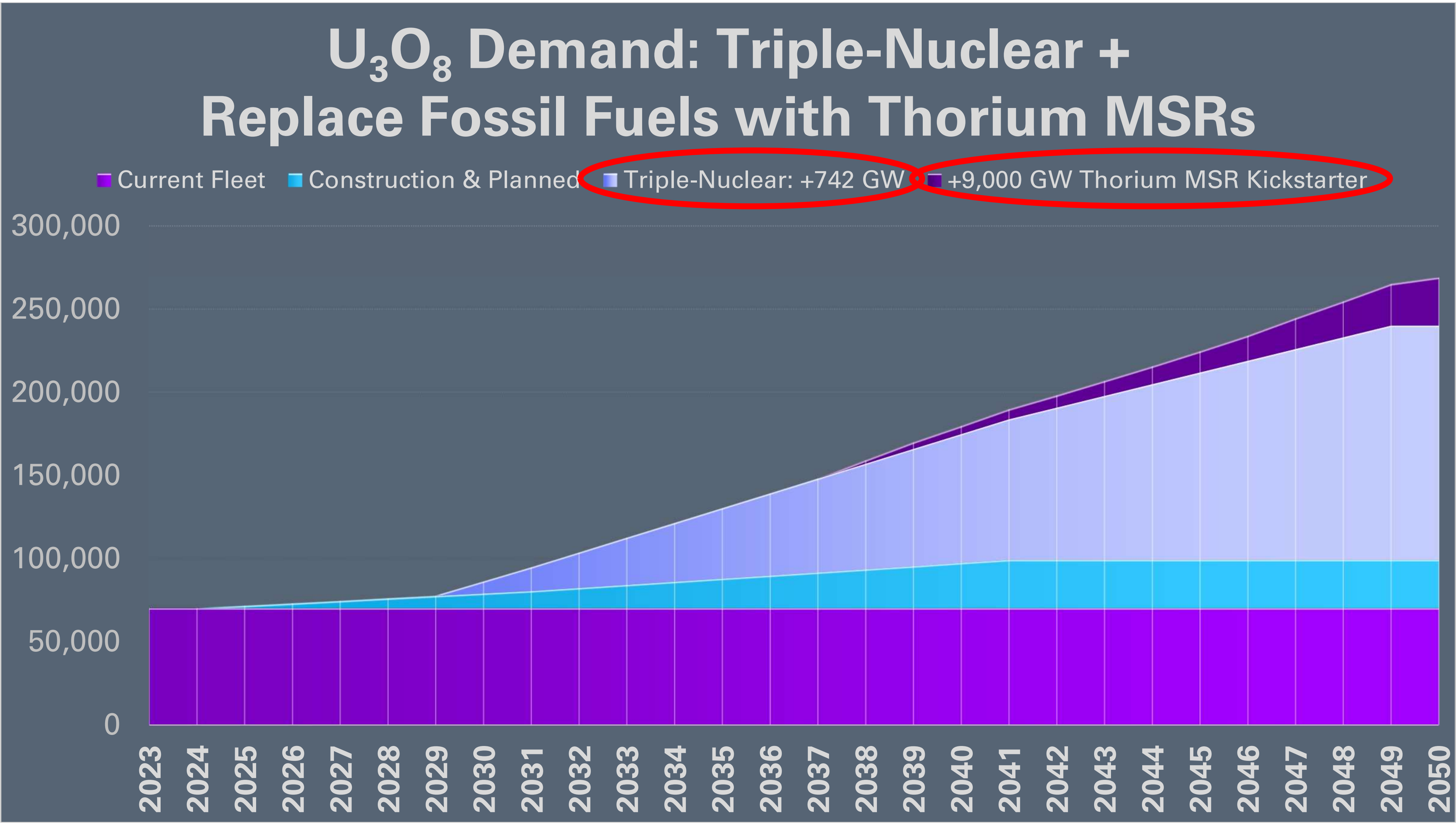
1 Reactor *per hour* 24/7/365 for 20 years!

Costs $4.5tn - $6.75tn

ZERO risk of melt-down or hydrogen explosions

Nuclear "Waste" in Storage World-Wide
Replace Fossil Fuels w/ Thorium MSRs





U3O8 Demand: Triple-Nuclear +
Replace Fossil Fuels with Thorium MSRs
Current Fleet
Construction & Planned
Triple-Nuclear: +742 GW
+9,000 GW Thorium MSR Kickstarter
300,000
250,000
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Thorium Molten Salt Reactor =  ?

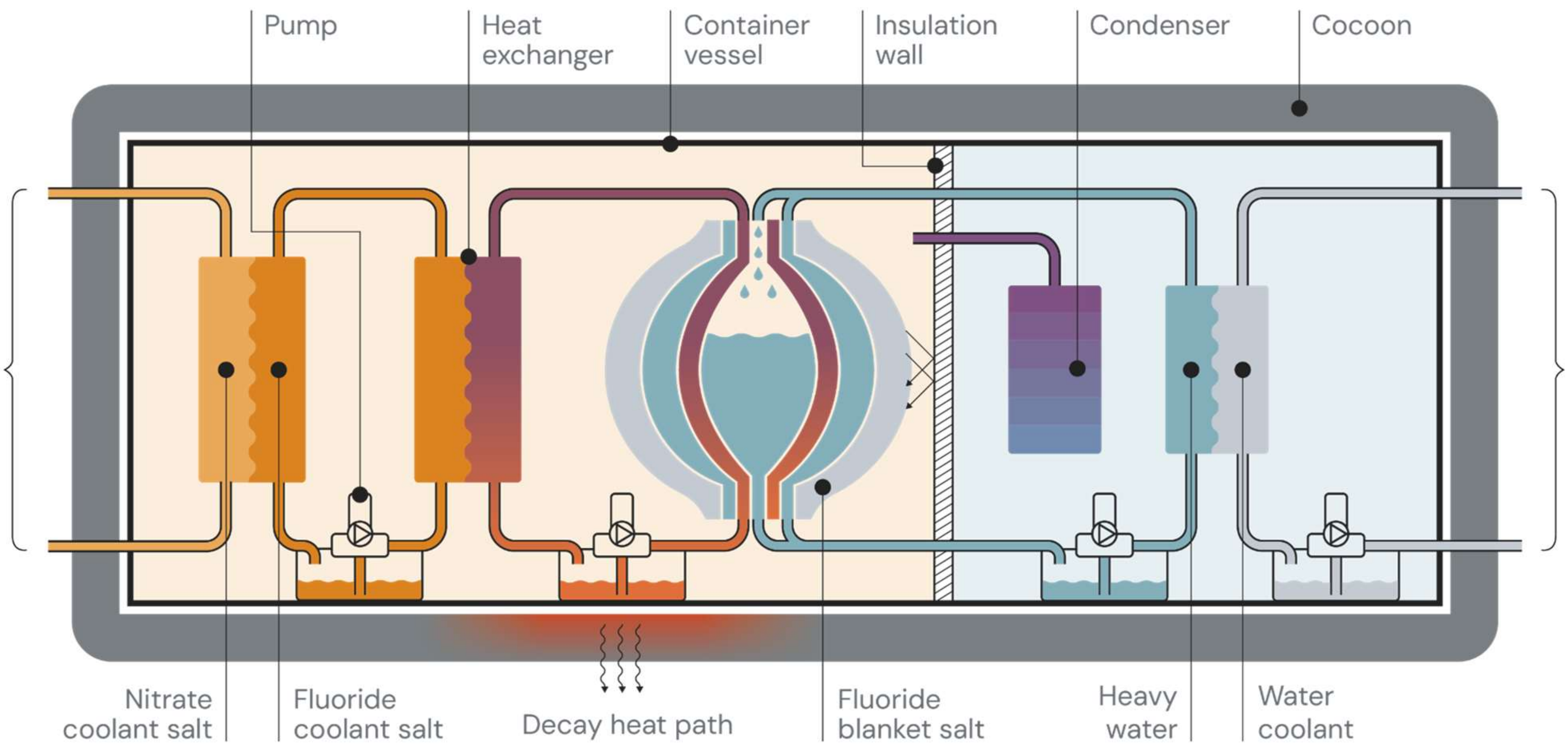
Why Erik & Thomas-Jam agree the best “workhorse reactor to do the bulk of the work for energy transition” should be a Thorium liquid-fueled molten salt reactor:

- One economic design that can be **mass-produced** in very large qty. on a factory assembly line
- The “**iPhone of nuclear reactors**”
- Suitable for both **electricity generation** and **process heat**.

The Onion Core®

The Onion Core®

Loops and containment



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The Onion Core®

Cross-section view

- Unpressurized room temperature heavy water moderator
- Double barrier and insulation between salt and heavy water
- segments made from metal or composite material
- Below 2% neutron leakage
- Reactivity control using heavy water level adjustment

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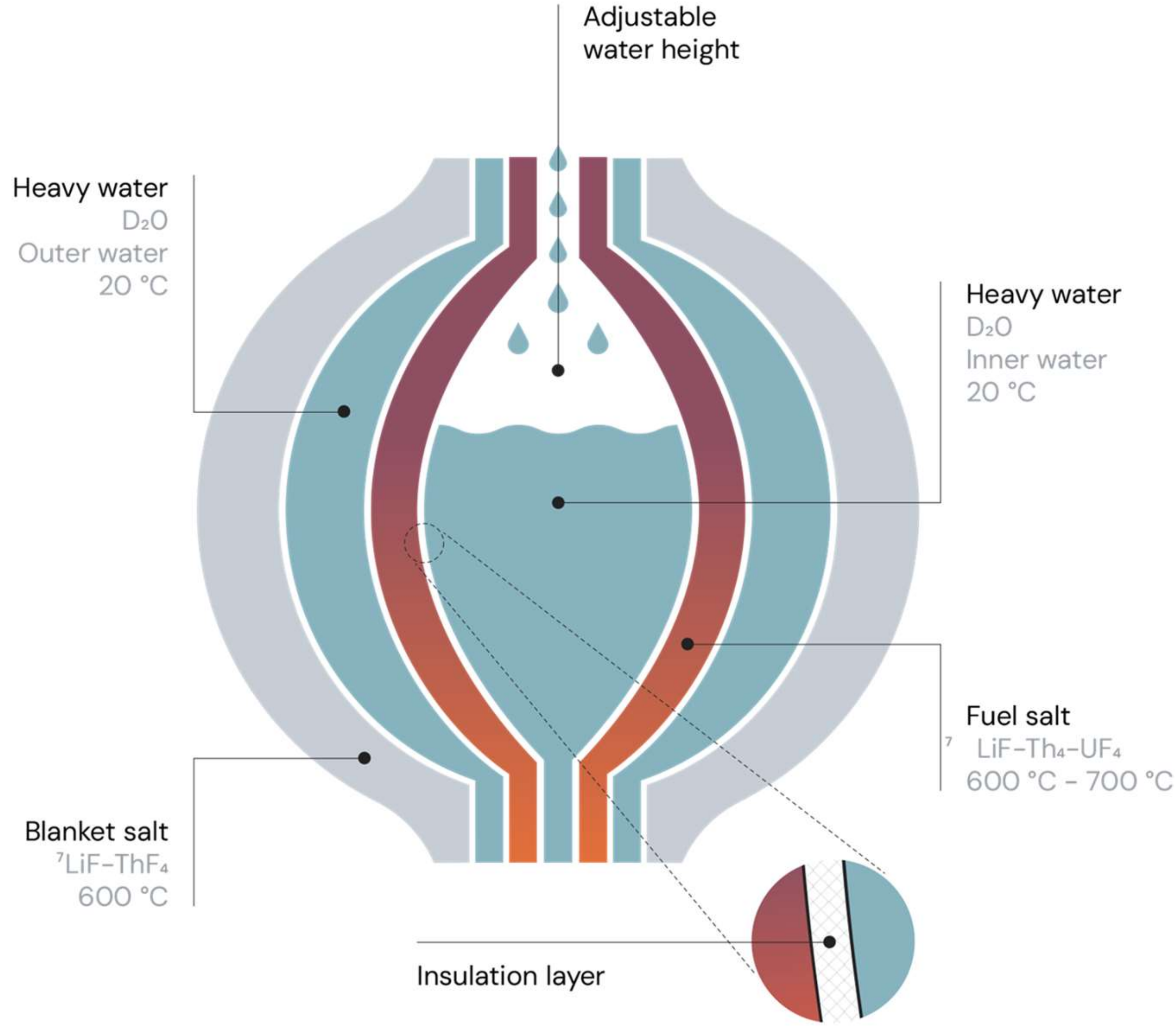
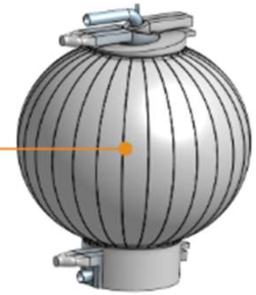
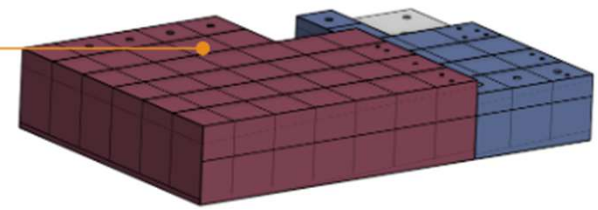


Cost split of FOAK reactor

Reactor container without salts & water

Core	€2 – 5 million
Box	€300k ± 10%
Tanks and pipes	€400k ± 10%
Heat exchanger	€350k ± 10%
Electro + sensors	€500k ± 20%
Pumps	€550k ± 20%
Total	**€4 ~ 8 million**





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Current Capital Raise:

- Copenhagen Atomics is currently in an active ~€50M capital raise
  - Participation is limited to Institutional and Accredited Investors
    - Minimum investment is € 100,000
- Qualified investors should contact CFO Mike Christiansen
  Invest@copenhagenatomics.com

The goal

Mass manufacturing thorium reactors

100 MW heat = 42 MW electric

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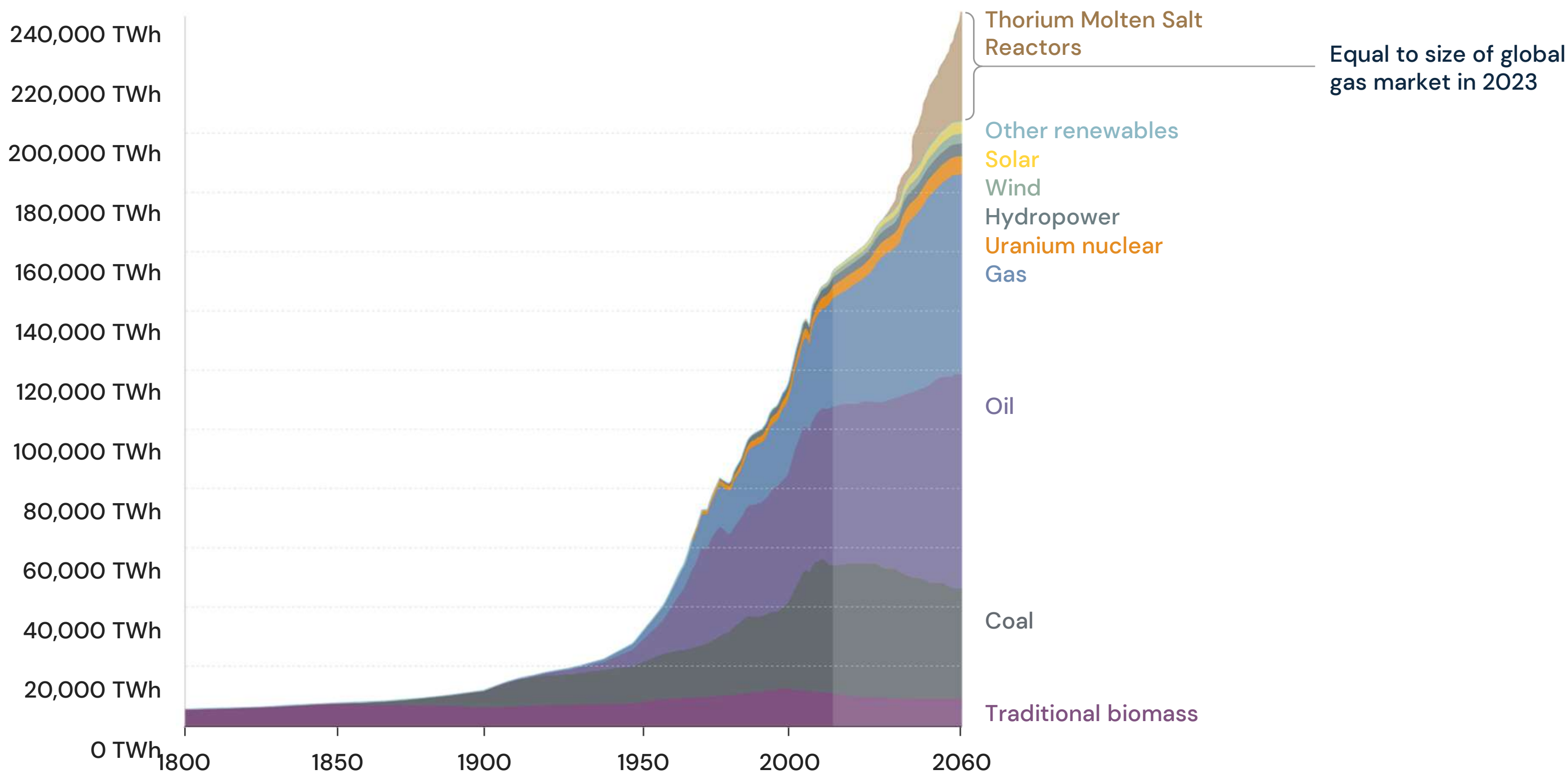
Global primary energy consumption

1800-2060



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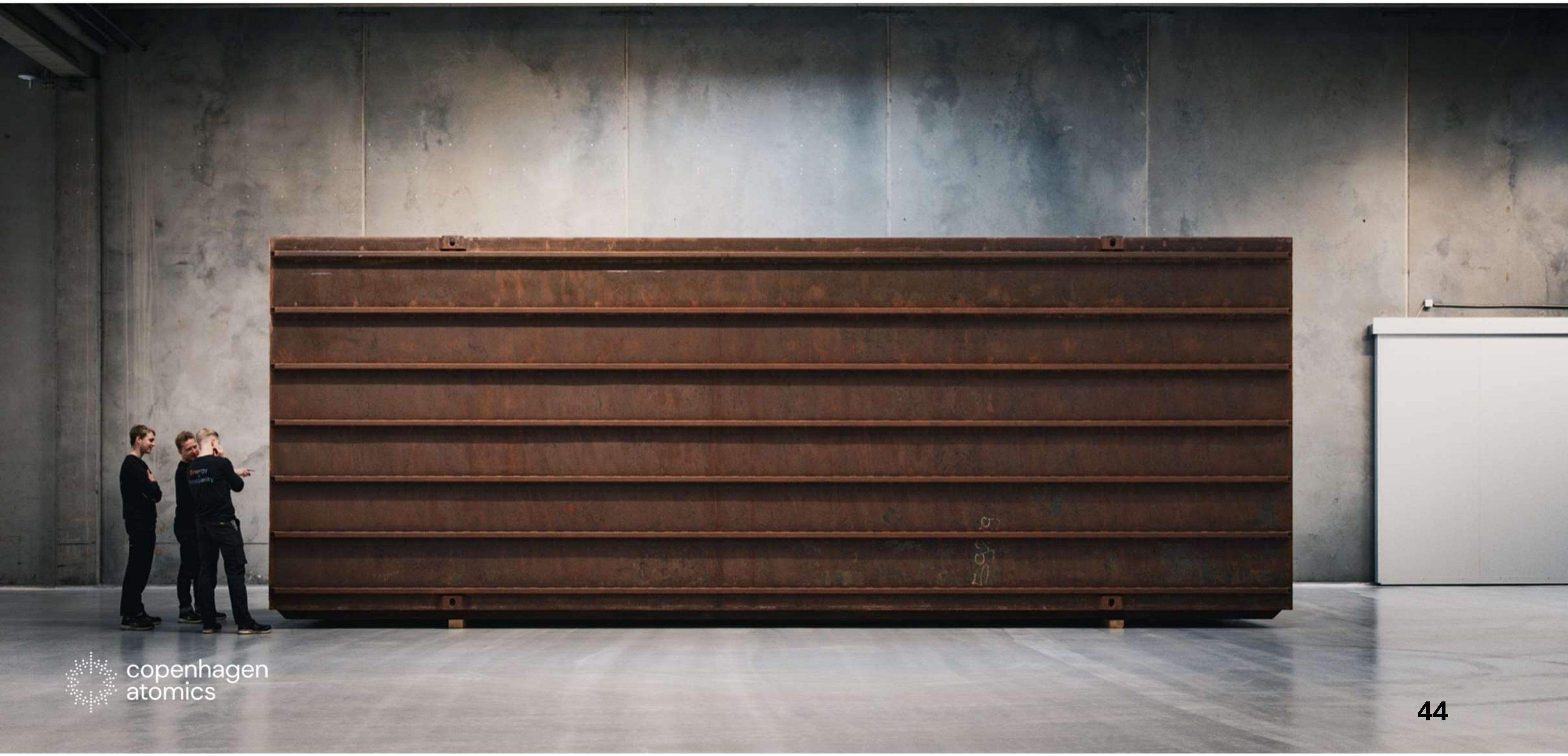
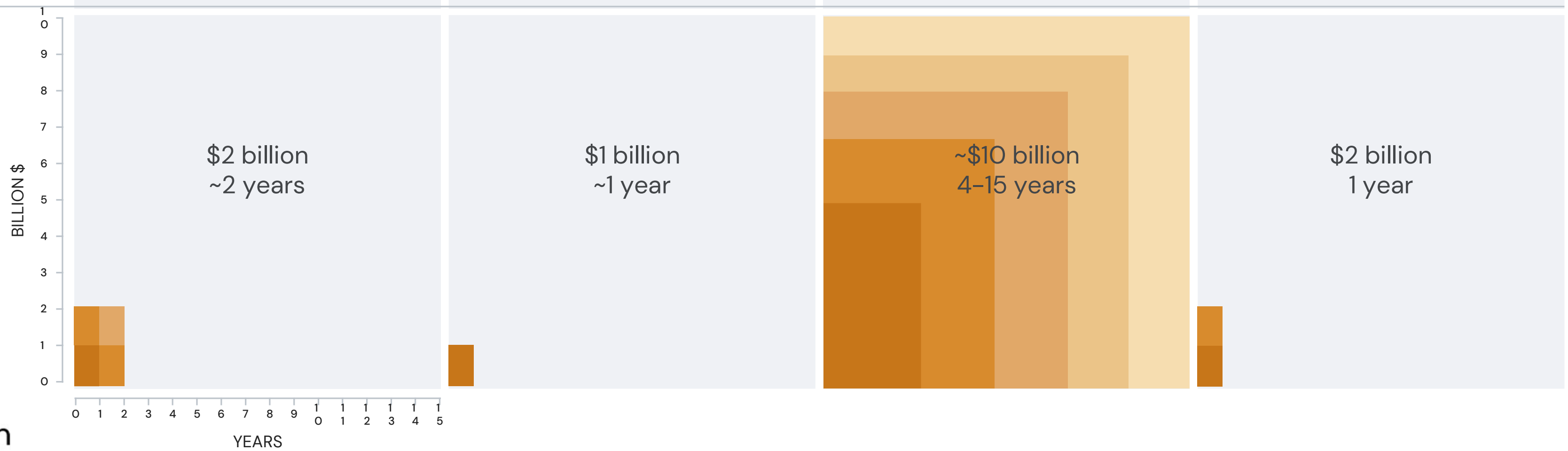
Non-fission prototype



Cost & Time

Plant size: 1 GWe in europe or usa

	Coal	Gas	Classic Nuclear (CLEAN ENERGY)	CA thorium breeder (CLEAN ENERGY)
Electricity cost	\$30 – 60 / MWh	\$60 – 100 / MWh	\$60 – 100 / MWh	\$20 – 40 / MWh
Raw fuel cost / year	\$400 million	\$600 million	\$100 million	\$50.000 – 300.000
OPEX / year	\$50 million	\$50 million	\$100 million	\$50 million
CAPEX & Build time	\$2 billion ~2 years	\$1 billion ~1 year	~\$10 billion 4–15 years	\$2 billion 1 year



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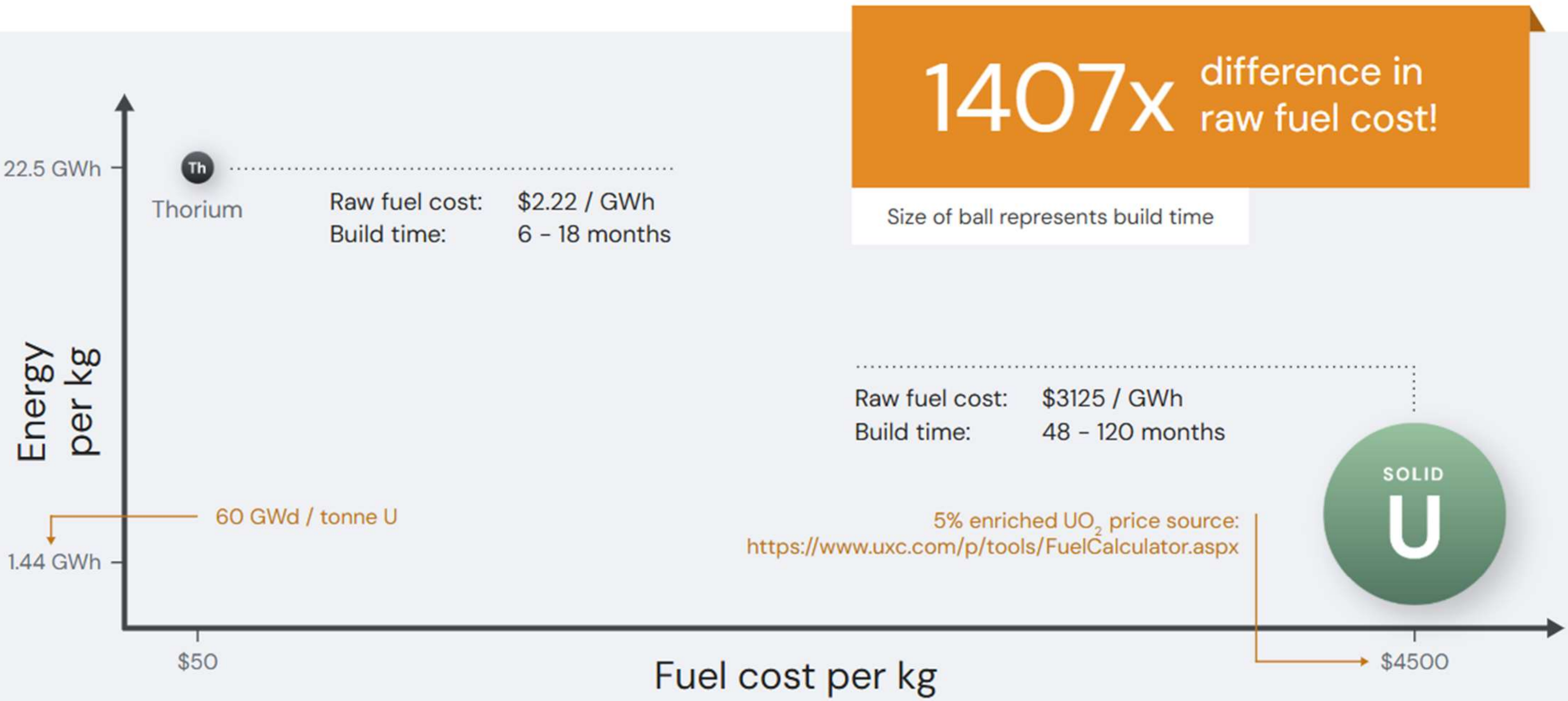
Uranium solid fuel reactors vs CA thorium breeder reactor

Fuel cost, energy per kg & build time



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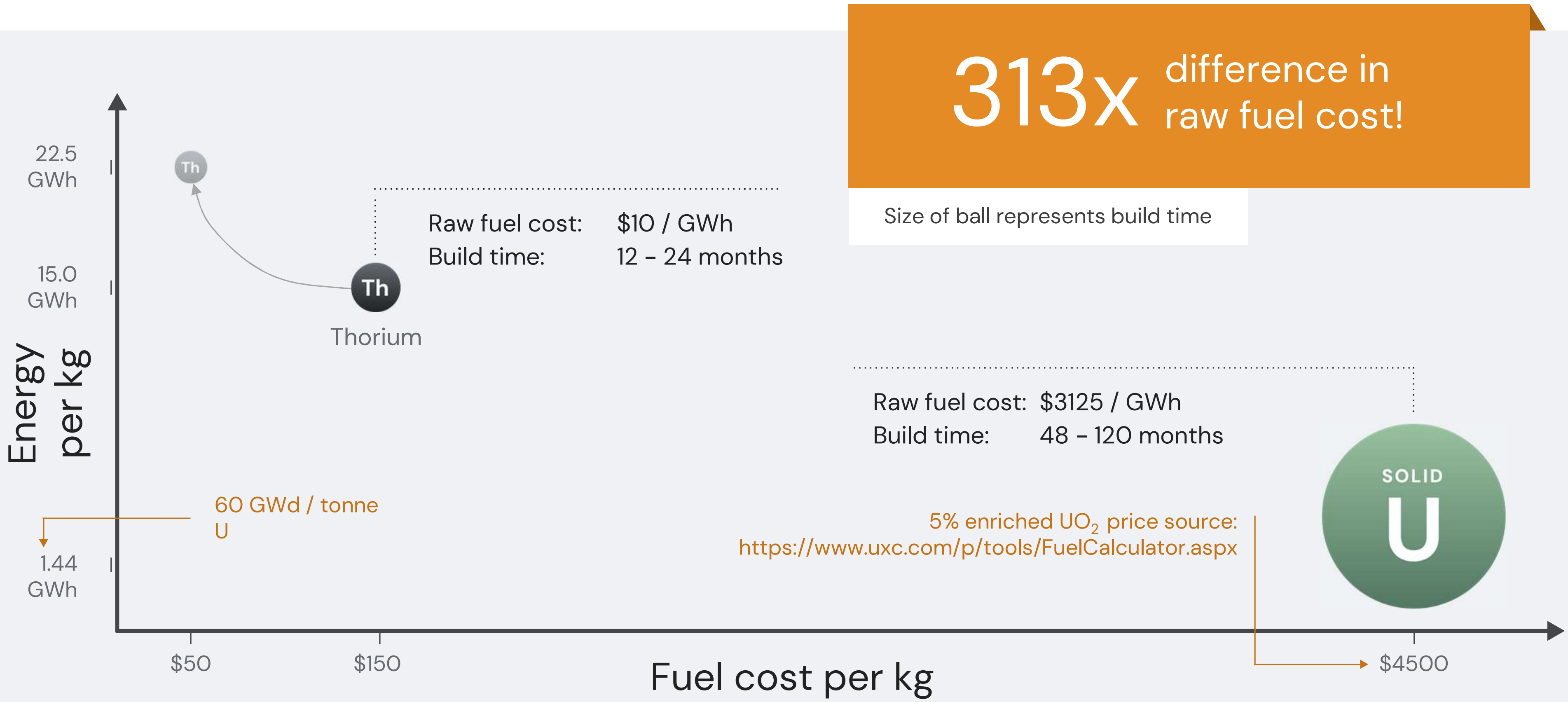
Uranium solid fuel reactors vs CA thorium reactor

Fuel cost, energy per kg & build time



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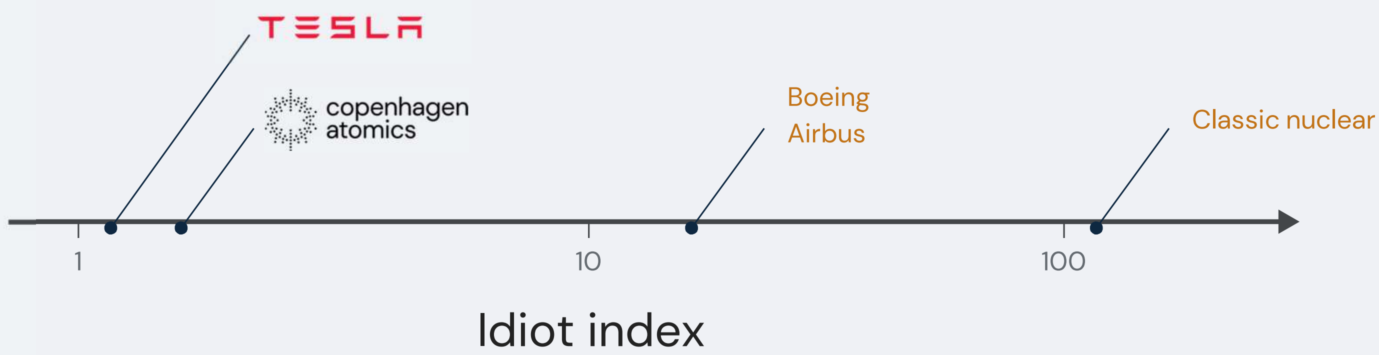
Idiot index

Product price / material cost



Milestones towards
a 1MW & 30MWd test reactor

2023	2024	2025	2025	2026	2027
Water Prototype	FLiNaK Prototype	Fertile Salt Production FLiTh & FLiU	Fertile Prototype	LEU Subcritical Prototype	LEU Test Reactor
Completed	Completed	Upcoming	Upcoming	Upcoming	Upcoming
€20 M	€+10 M	€+10 M	€+40 M	€+80 M	€+80 M

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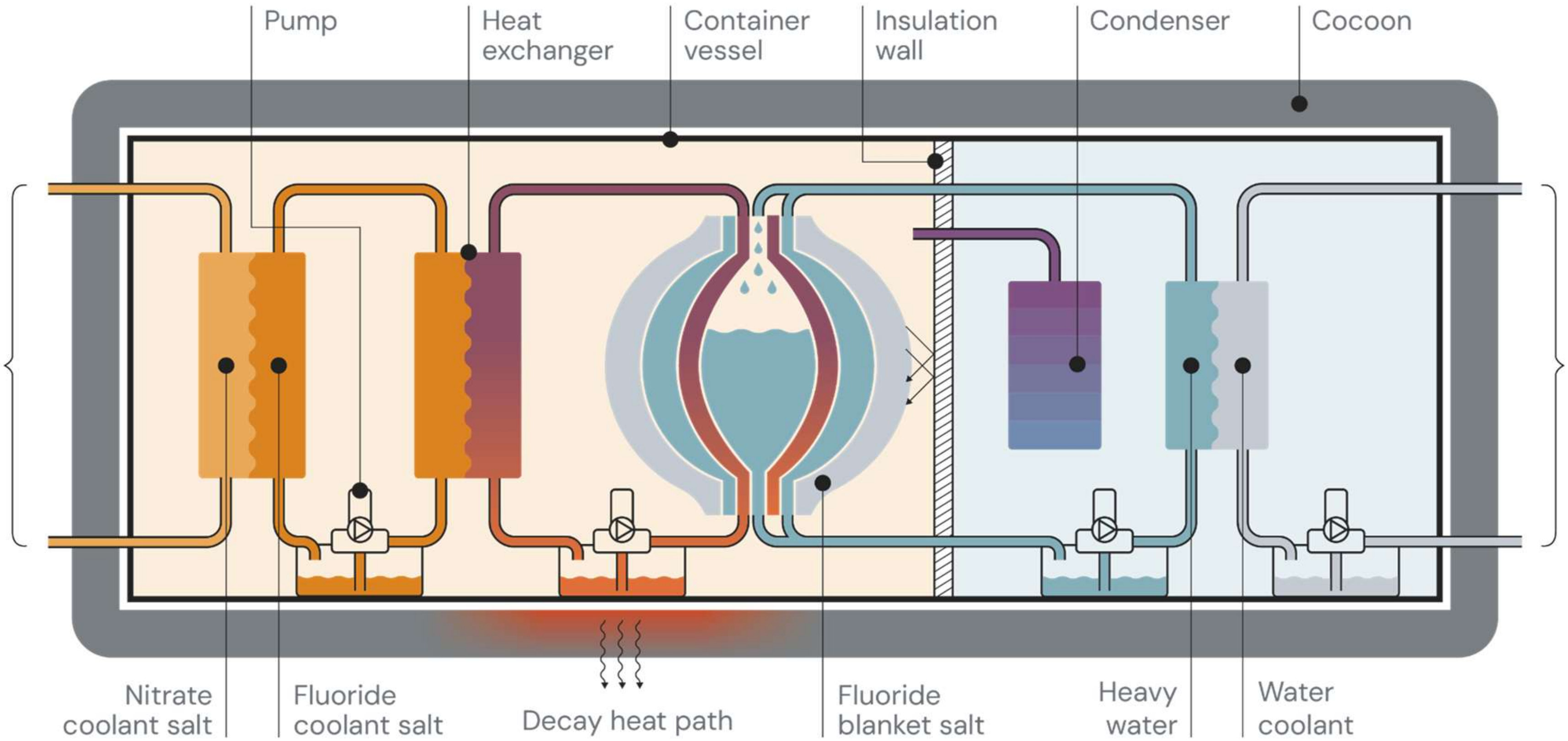
The Onion Core®

Loops and containment



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The Onion Core®

Cross-section view

- Unpressurized room temperature heavy water moderator
- Double barrier and insulation between salt and heavy water
- segments made from metal or composite material
- Below 2% neutron leakage
- Reactivity control using heavy water level adjustment

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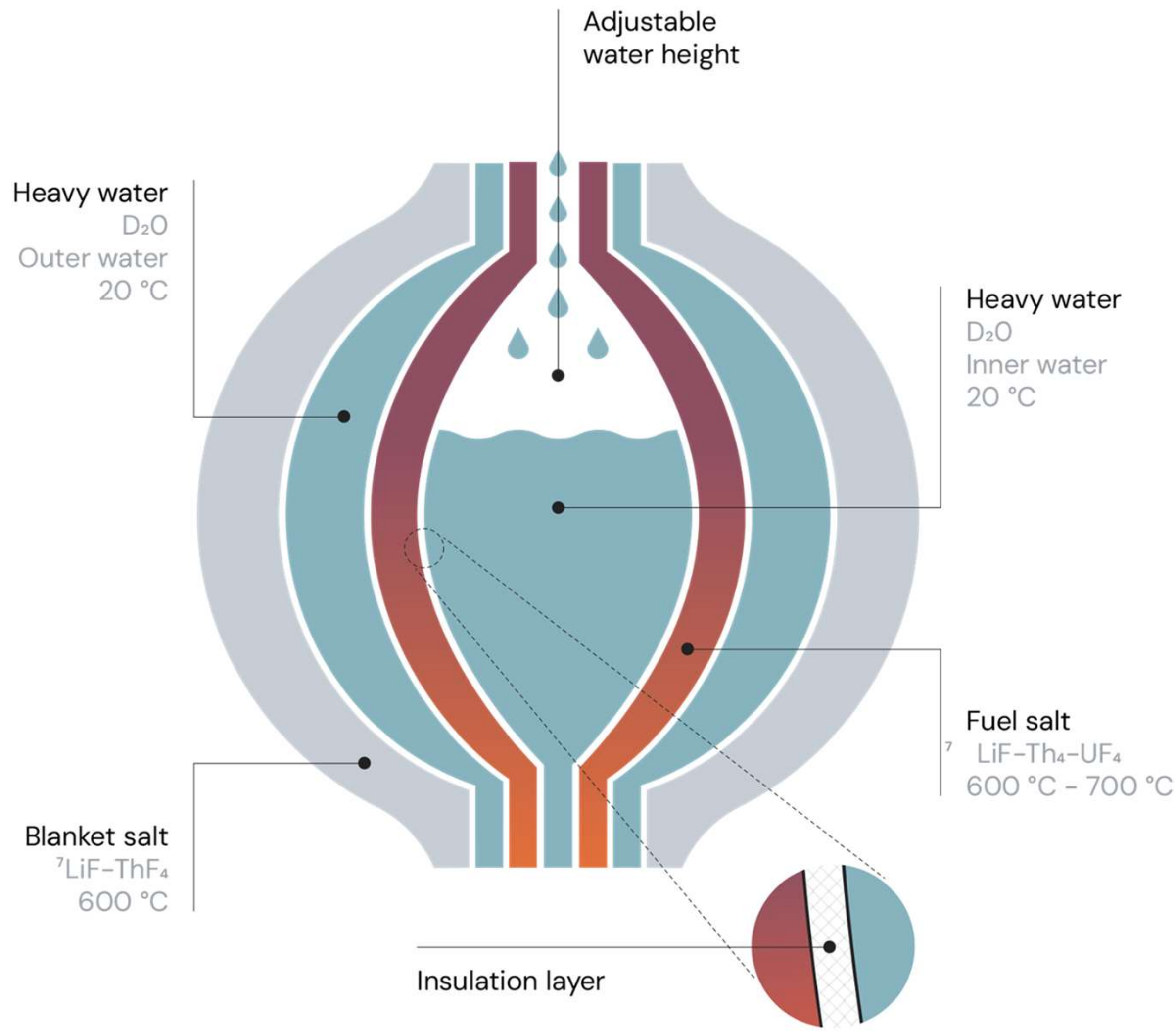


PSI

52

1 MW test reactor

Run for 30 days (30 MWday)

COPENHAGEN ATOMICS

2025
Order fuel &
metal parts

2026
Assemble
and test

2026
Disassemble and
load on 25 trucks

COPENHAGEN ATOMICS

2028
Drive back to
Copenhagen and setup
again

2026 / 2027
Setup and test
at new site

2027
Cool down radioactively
and disassemble

TEST STIE ABROAD

Our team is actively engaging in dialogue with international key players in the industry.

From left to right

Thomas Steenberg
CEO
M.sc. Chemical Engineering
& Ph.D. material science

Peter Szabo
Board member
M.Sc. Chemical Engineering
& Ph.D. Flow of non-Newtonian fluids

Thomas Jam Pedersen
Chairman of the Board, COO
M.Sc. Electrical Engineering
& software & mathematical modelling

Aslak Stubsgaard
CTO
M.sc. Theoretical Physics

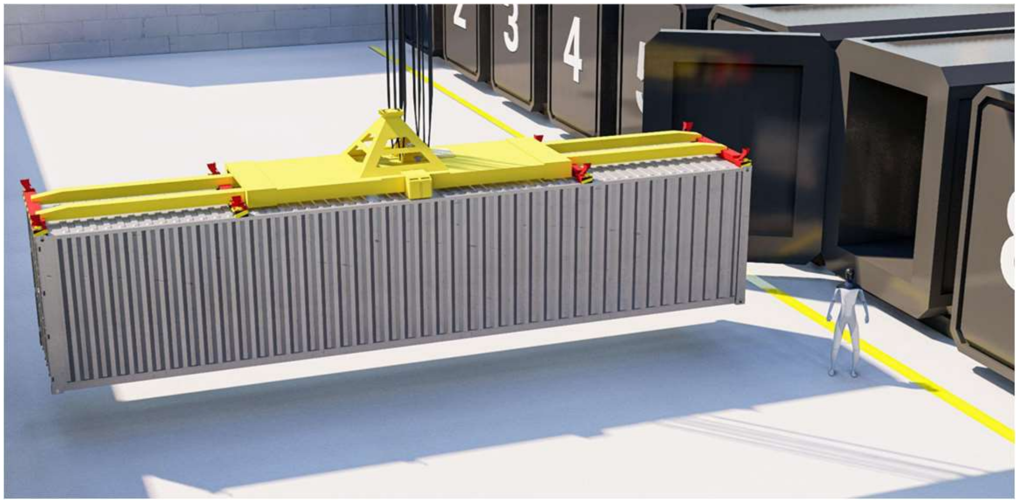
Bonus Slides

We won't have time to get to every slide in the deck on this podcast

But we've included several more photos and drawings to give investors a sense of the company's vision and progress

Visualisation of a 1 GW power plant

A conceptual visualization of a 1GW Power plant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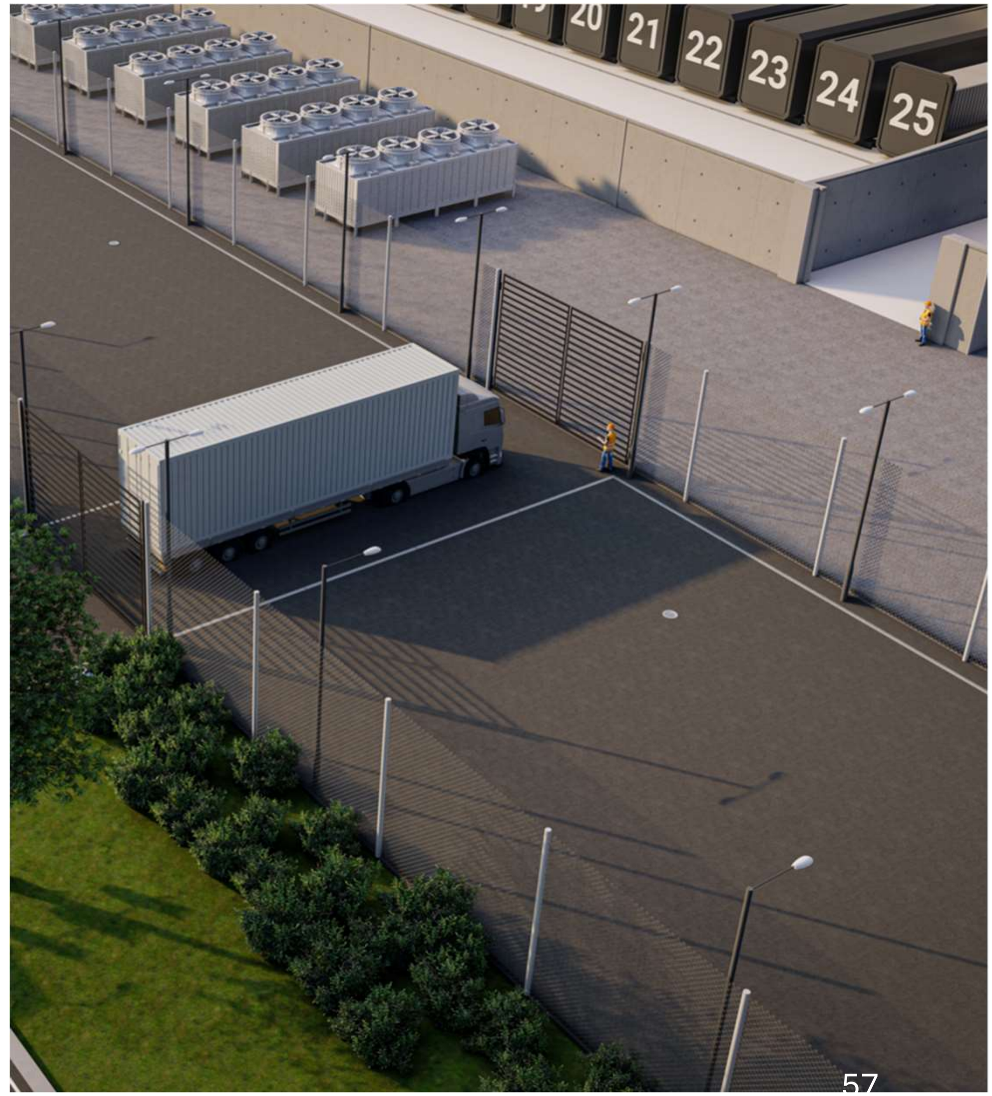
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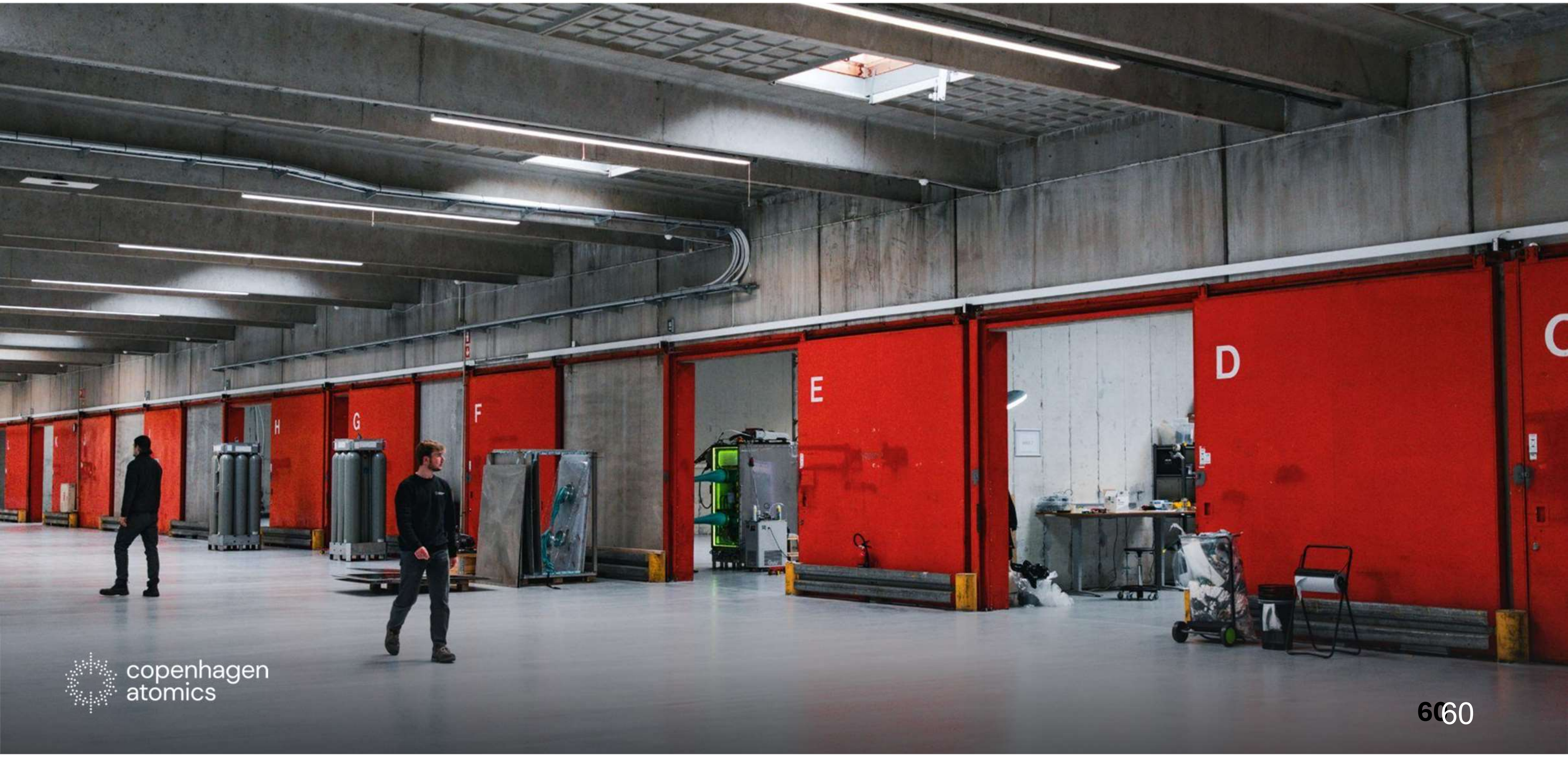
Inside Copenhagen Atomics' new facility



60

Pumps

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Loops

Specs

Pump
Valve
Flow meter
Pressure sensor
Salt leak sensor

1000h warranty

Upcoming

Online salt chemistry monitoring

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Worlds largest molten salt test facility

65

Neutron cross-sections

for fission of uranium & plutonium

Copenhagen Atomics want to run our reactors in thermal spectrum, making Pu239 the perfect kick starter fuel.

1 barn = 10^{-28} m^2
1 MeV = 1.6 x 10^{-13}J

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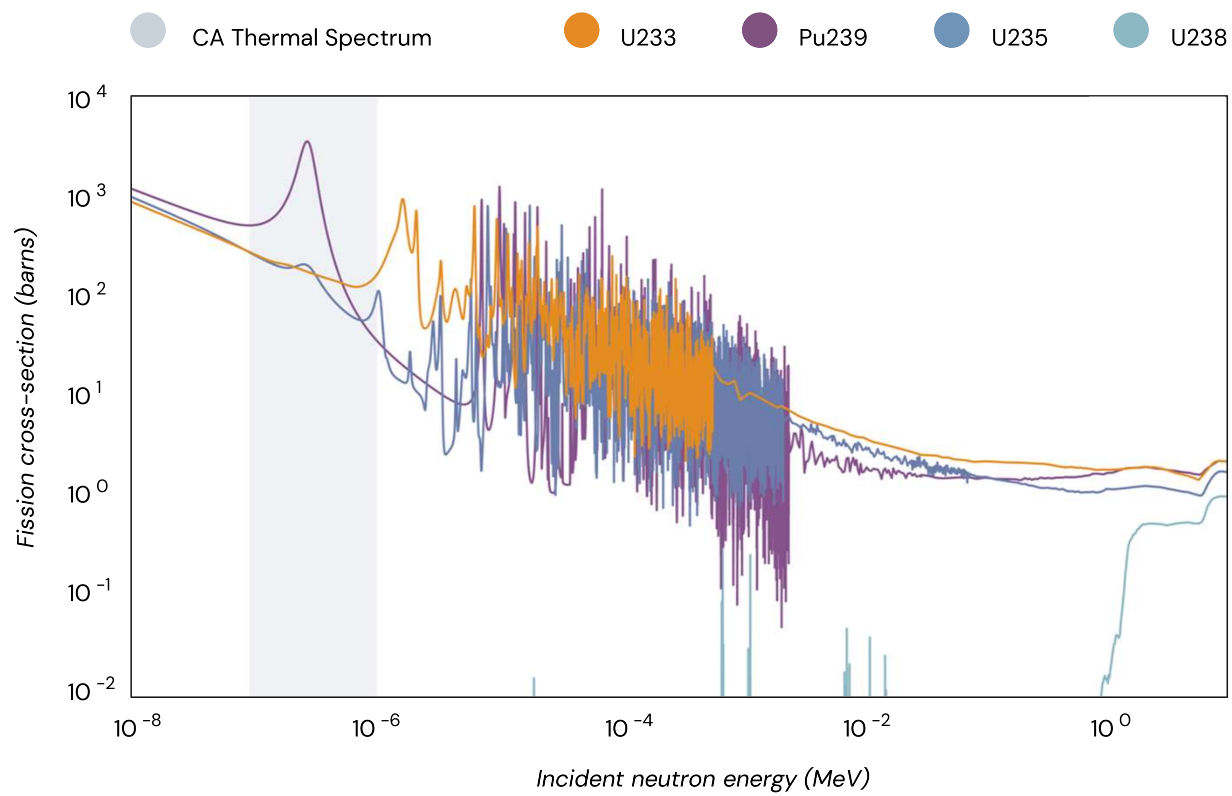
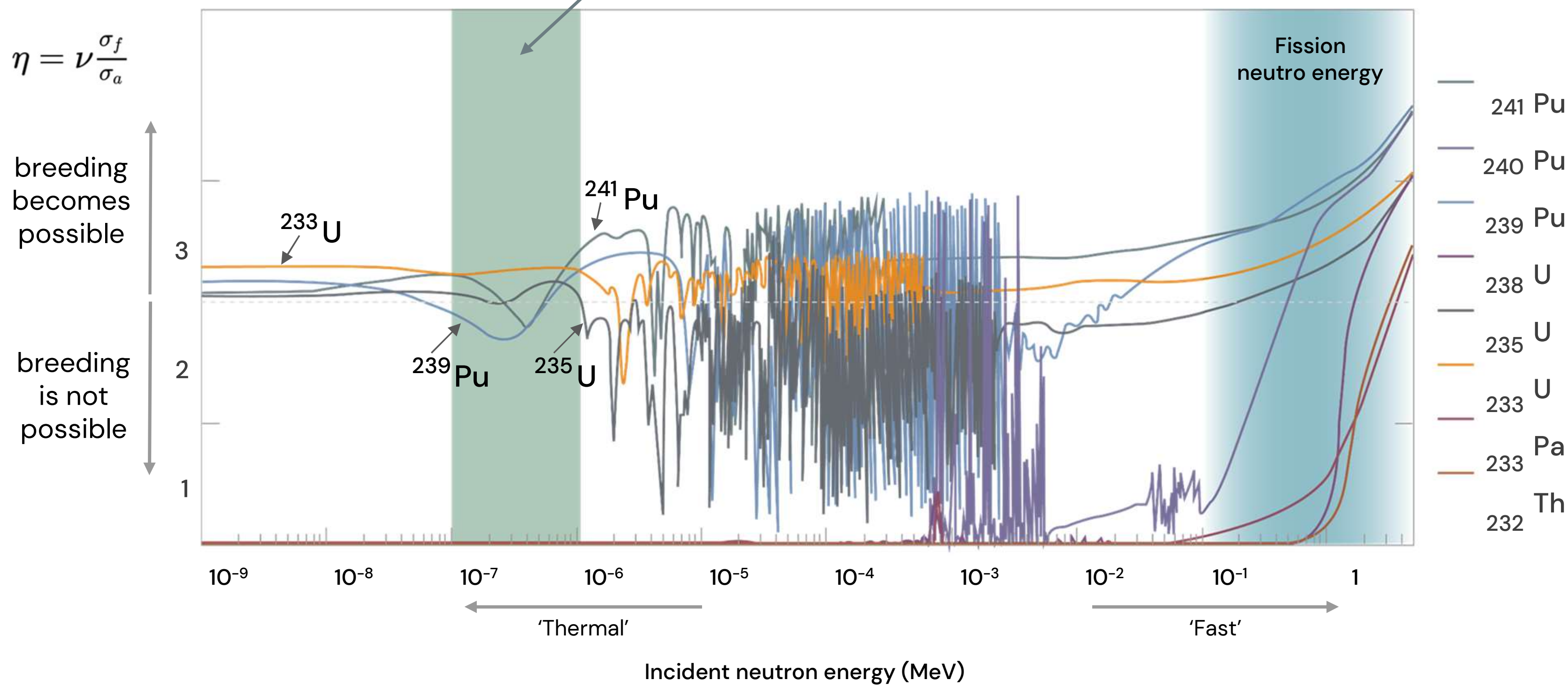


Sources: *OECD/NEA 1989. Plutonium fuel - an assessment. Taube 1974. Plutonium - a general survey.*

Free neutrons

from fission of important isotopes



This is why thorium is the **ONLY** fuel in the world, which allow a breeder reactor in thermal spectrum.

Sources: Reproduction factors based on interpolations, and data from ENDF/B-VII. 1 and smoothing.

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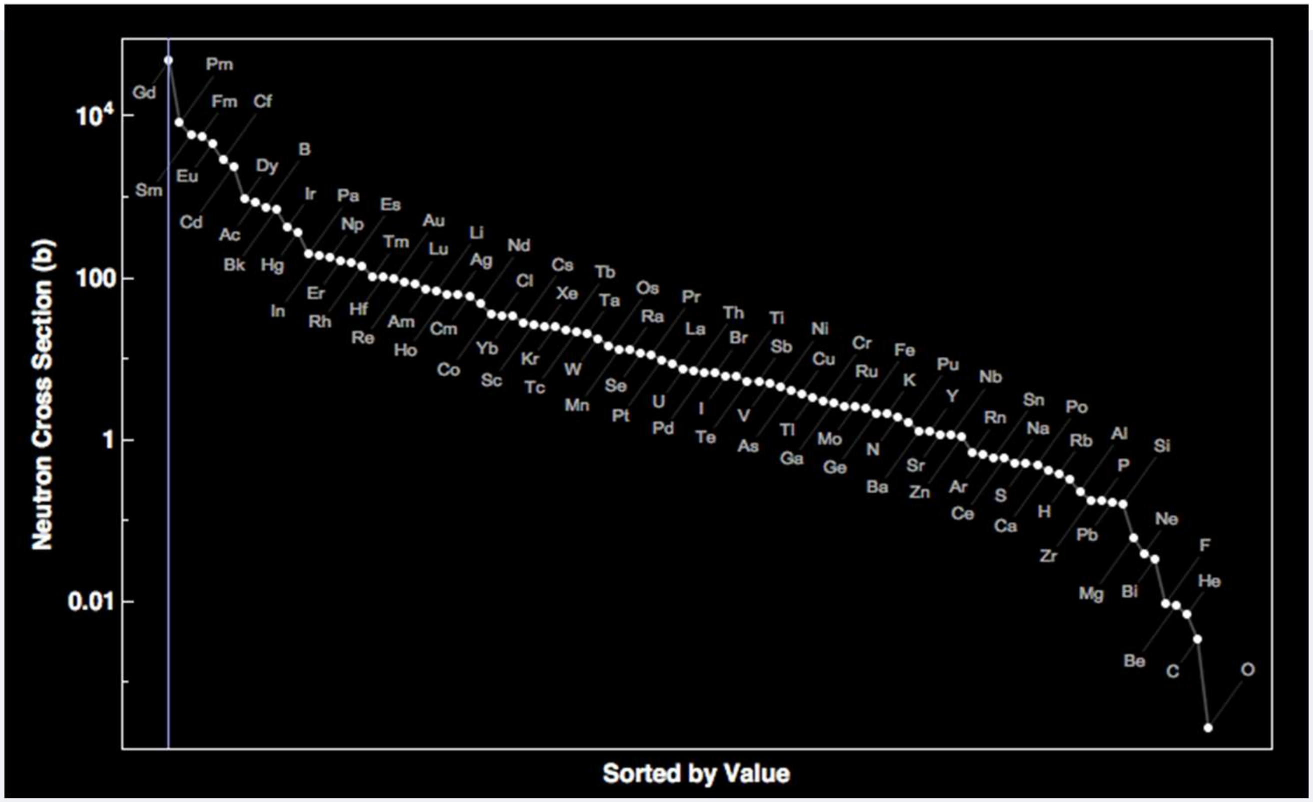
Low neutron capture cross section in thermal spectrum



Essential for a breeding ratio > 1

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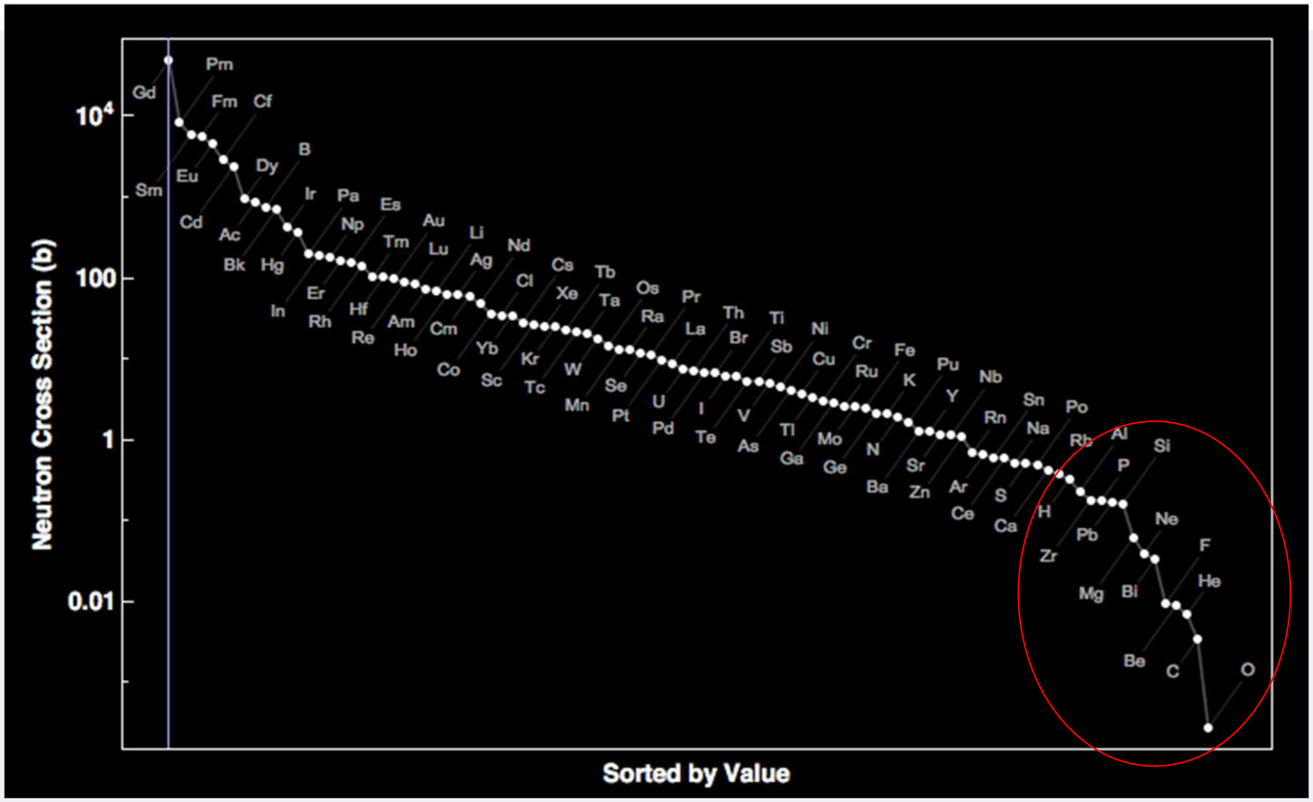
Neutron capture cross section in thermal spectrum



Essential for a breeding ratio > 1