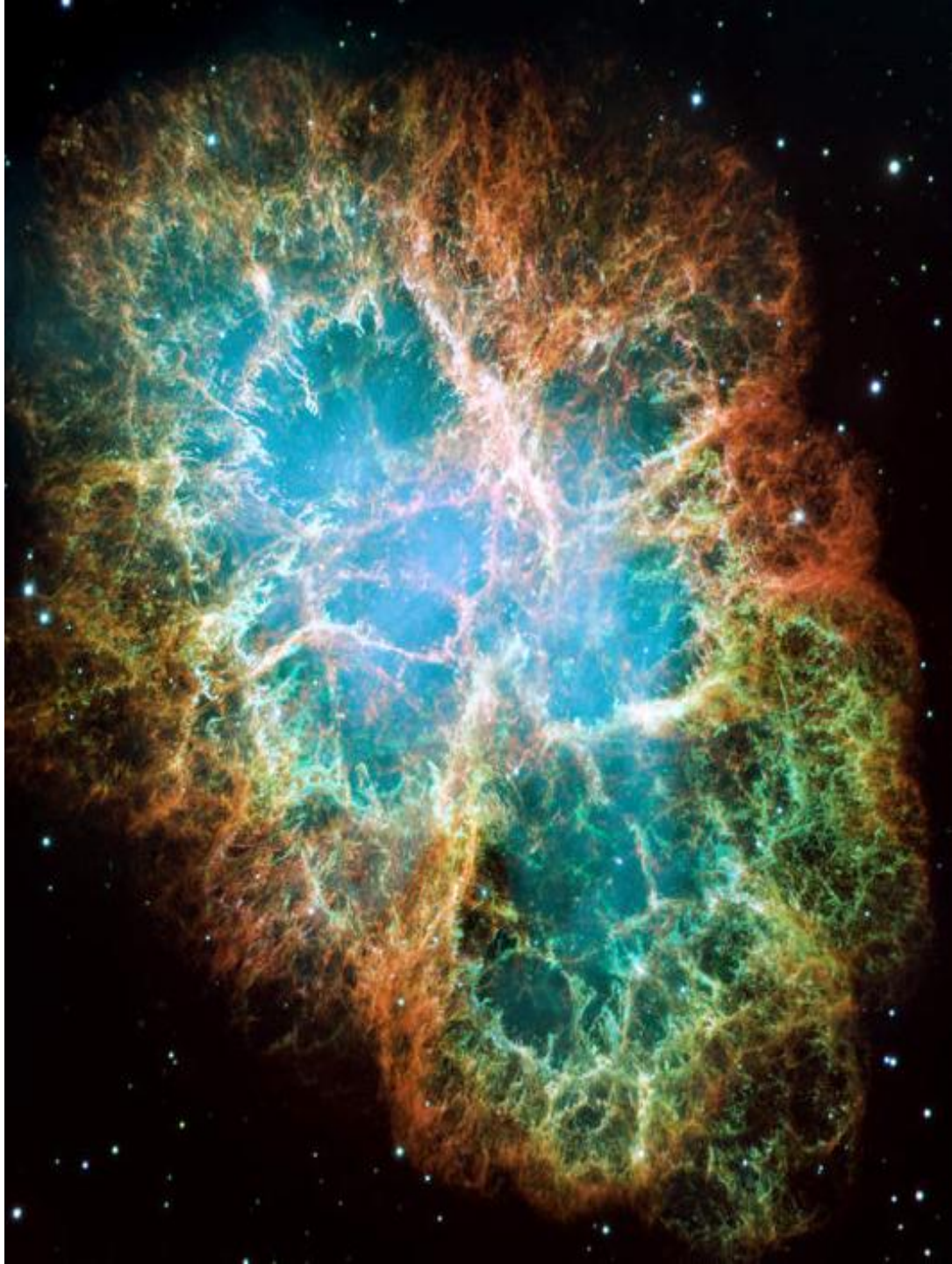
Aim High!

Thorium energy cheaper than from coal



Presented By

Cavan Stone
Dartmouth College
Cavan.Stone@Dartmouth.edu

Special Thanks to Robert Hargarves

The Aim High! presentation has been given at Dartmouth ILEAD, Thayer School of Engineering, Brown University, Amherst College, Columbia Earth Institute, American Nuclear Society, the Royal Institution of Great Britain, and many private audiences.

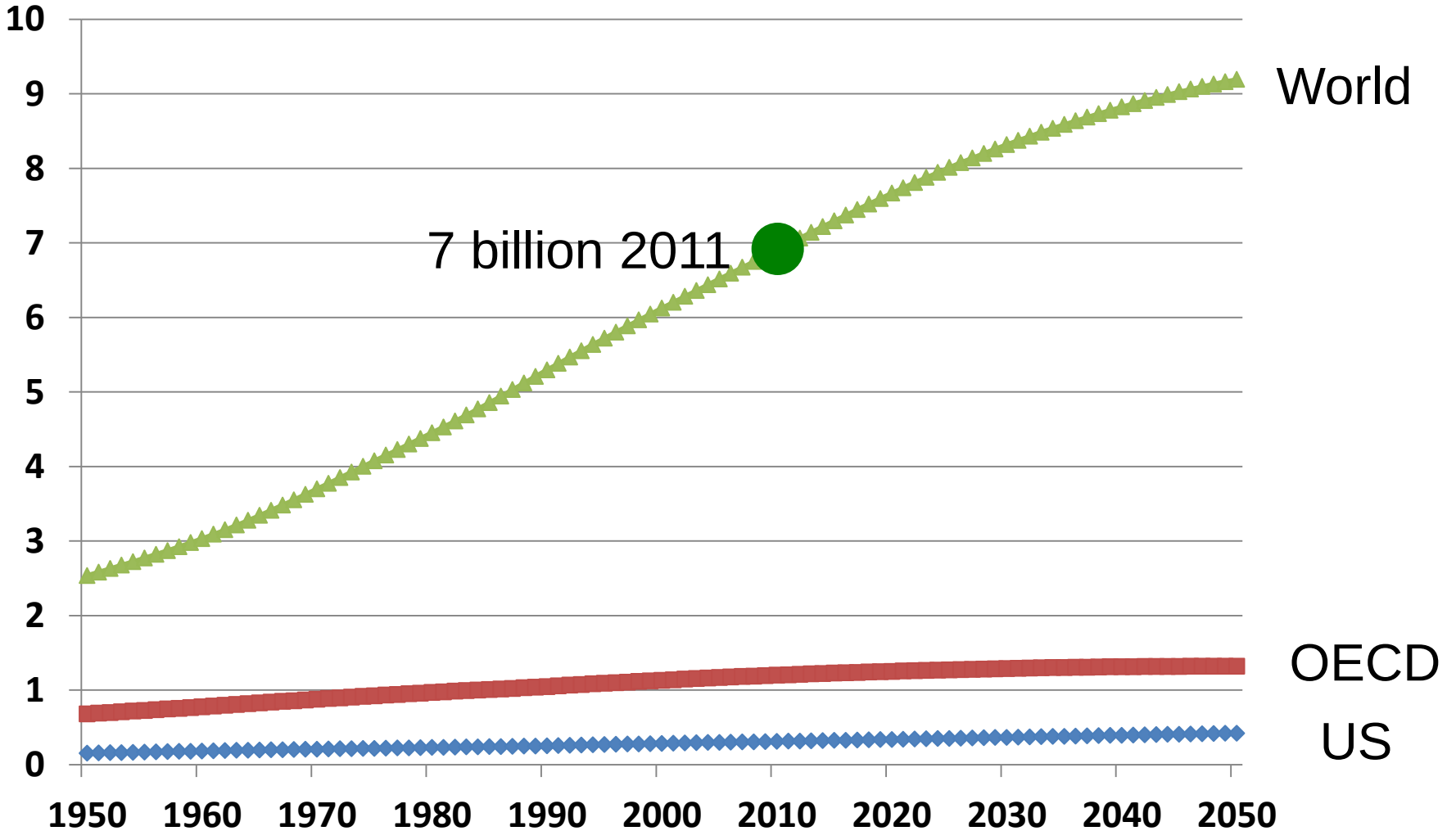
Internet Search Keywords: Aim High Thorium

https://sites.google.com/site/rethinkingnuclearpower/aimhigh

Robert Hargraves
Hanover NH
robert.hargraves@gmail.com

Global environmental problems mount.

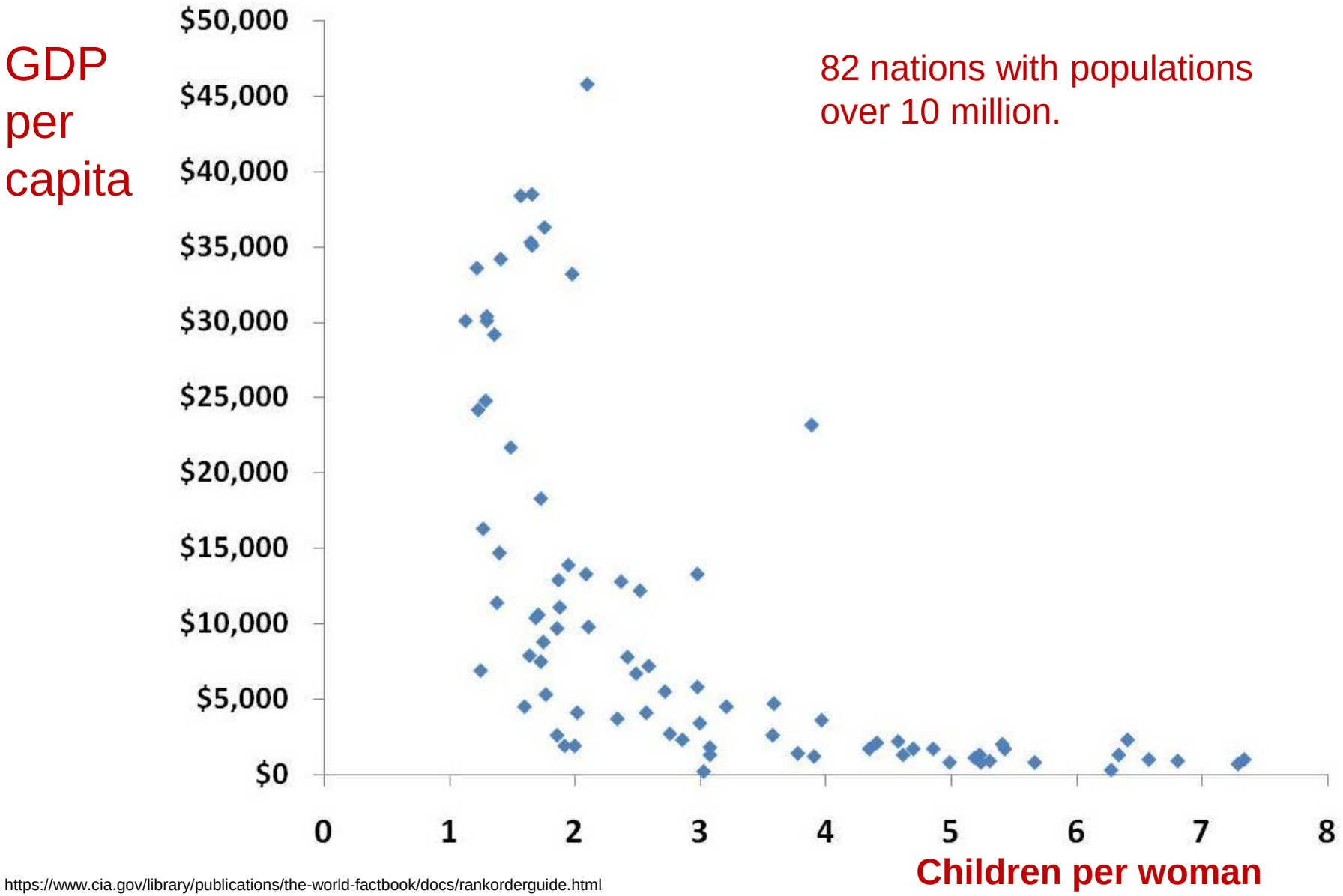
Population is Growing in Developing Nations



http://caliban.sourceoecd.org/vl=1260748/cl=17/nw=1/rpsv/factbook/010101.htm

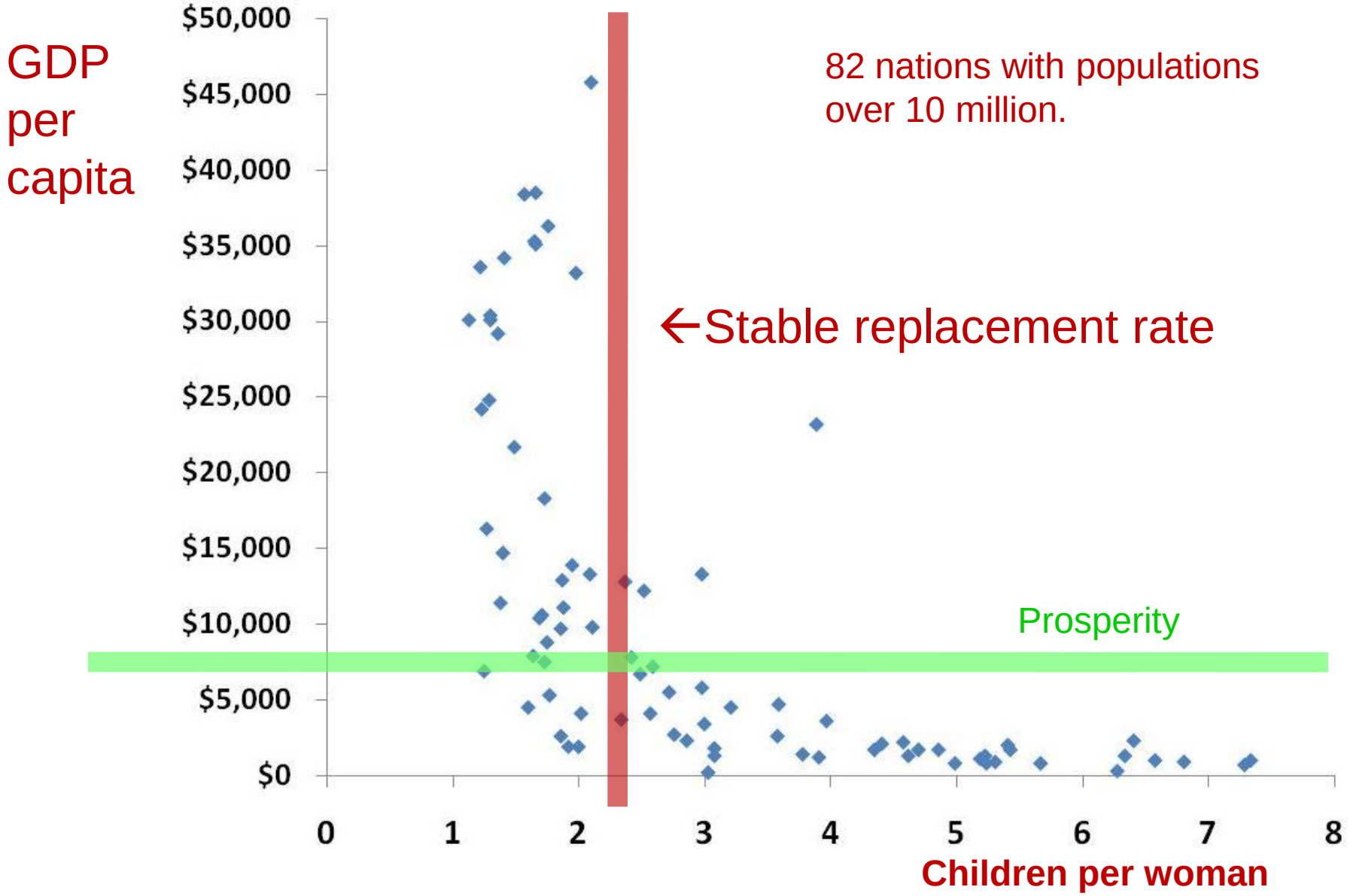
http://www.oecd.org/dataoecd/13/38/16587241.pdf

Prosperity stabilizes population.

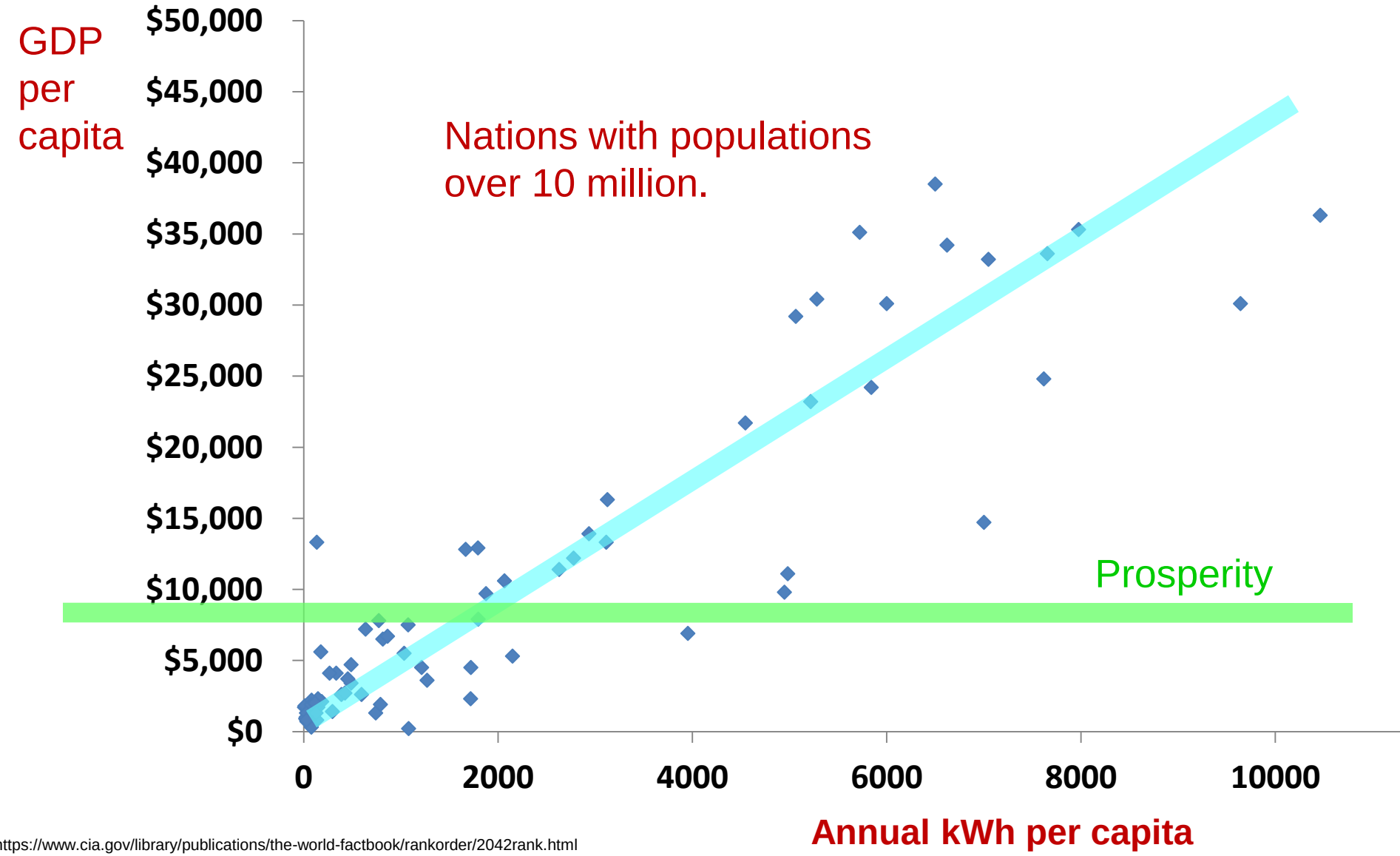


https://www.cia.gov/library/publications/the-world-factbook/docs/rankorderguide.html

Prosperity stabilizes population.



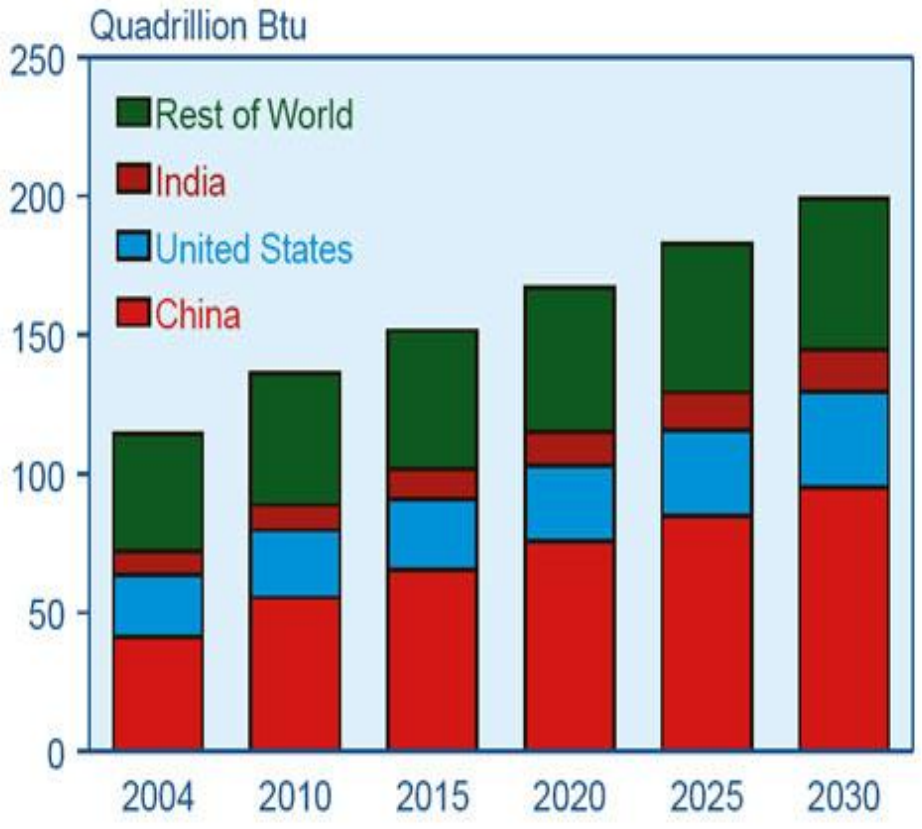
Prosperity depends on energy.



https://www.cia.gov/library/publications/the-world-factbook/rankorder/2042rank.html

Energy and coal use is growing rapidly in developing nations.

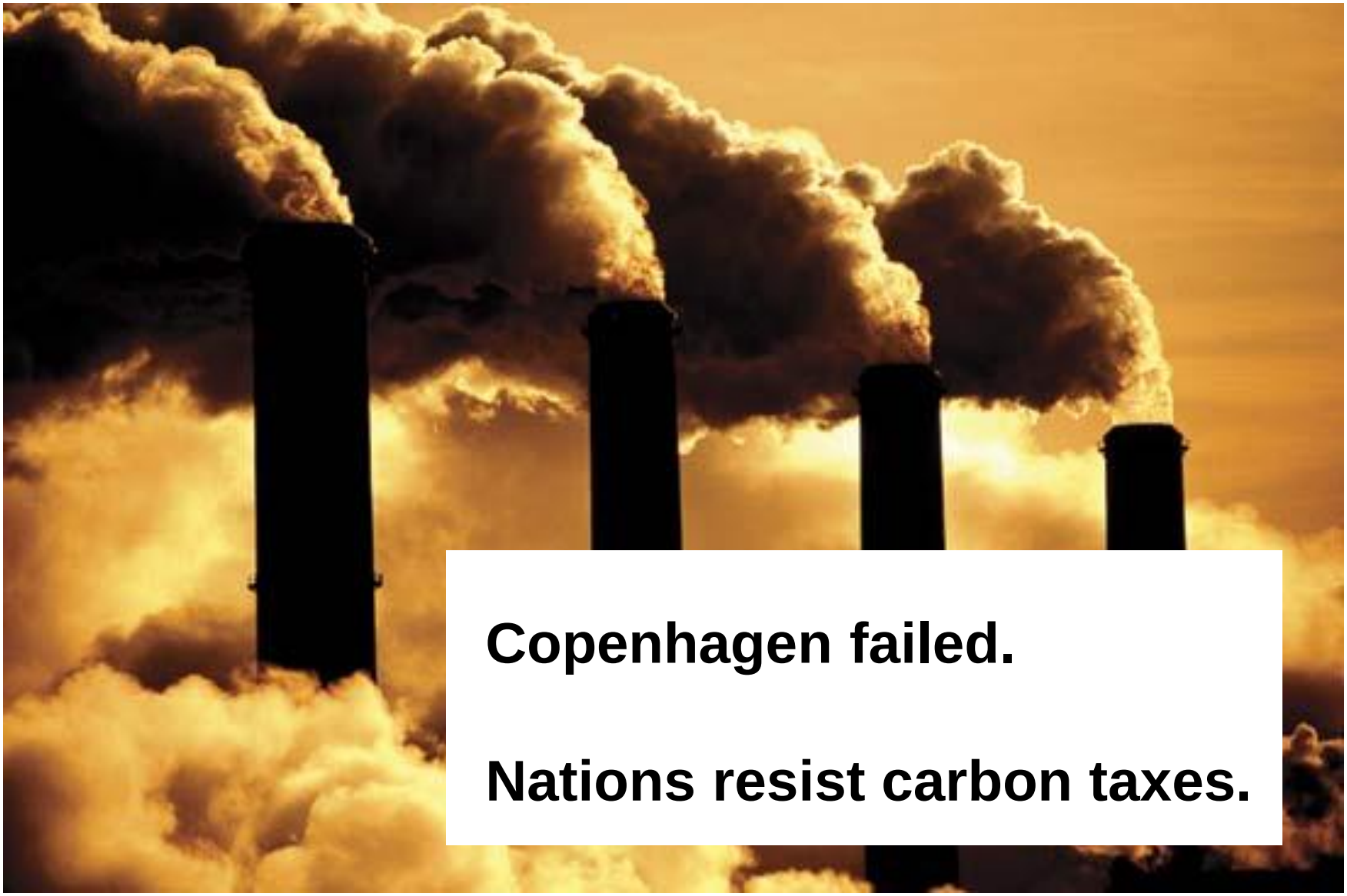
Non-OECD energy use



World coal use

http://www.eia.doe.gov/oiaf/ieo/world.html

We need energy cheaper than from coal.

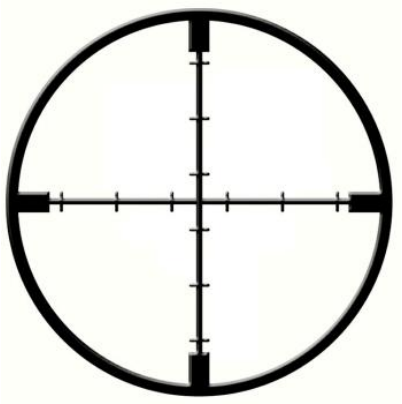


Copenhagen failed.

Nations resist carbon taxes.

Aim High!

Set aggressive goals.



Develop a new energy source that

1. produces electricity cheaper than from coal,

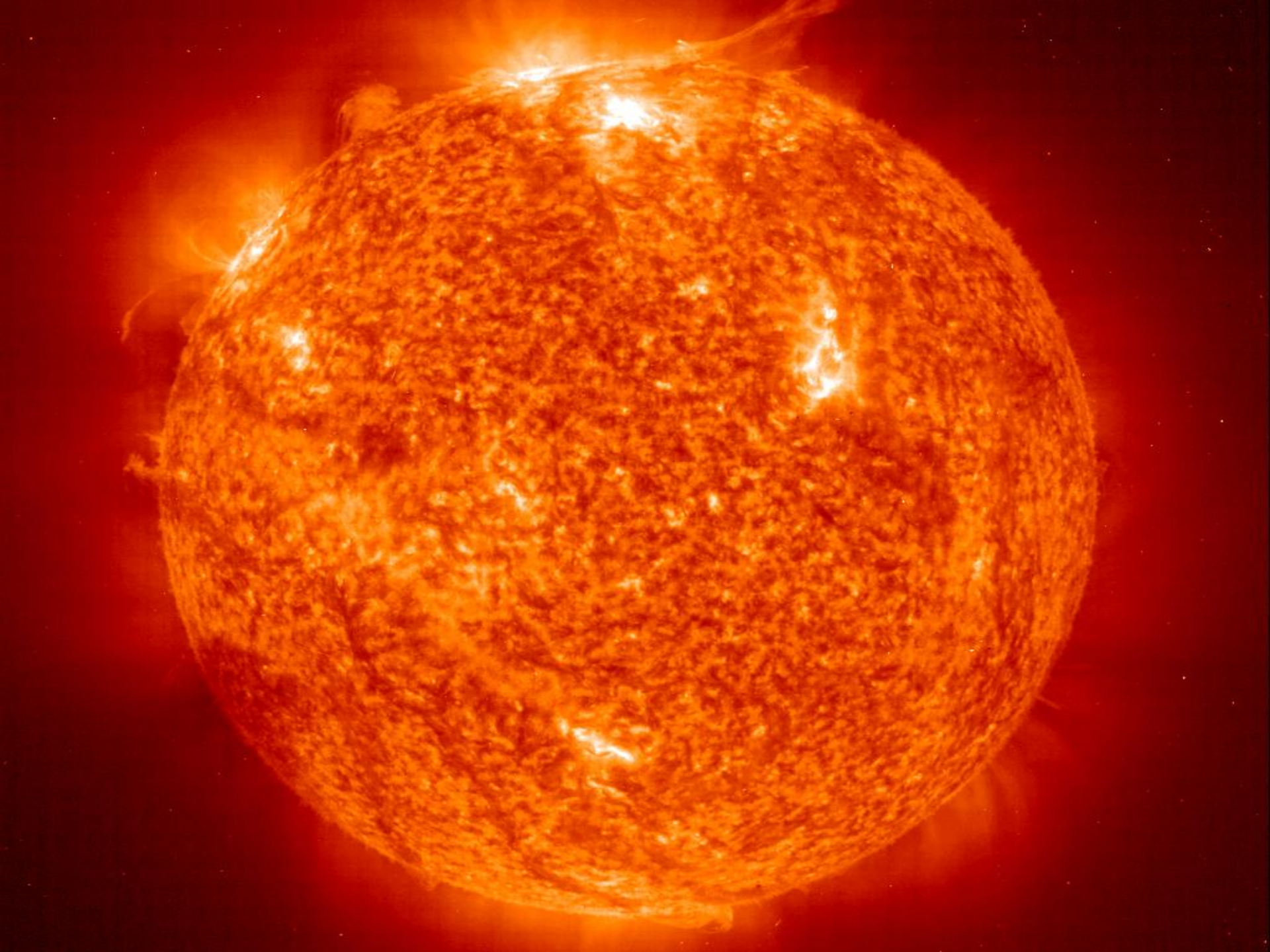
2. synthesizes vehicle fuel,

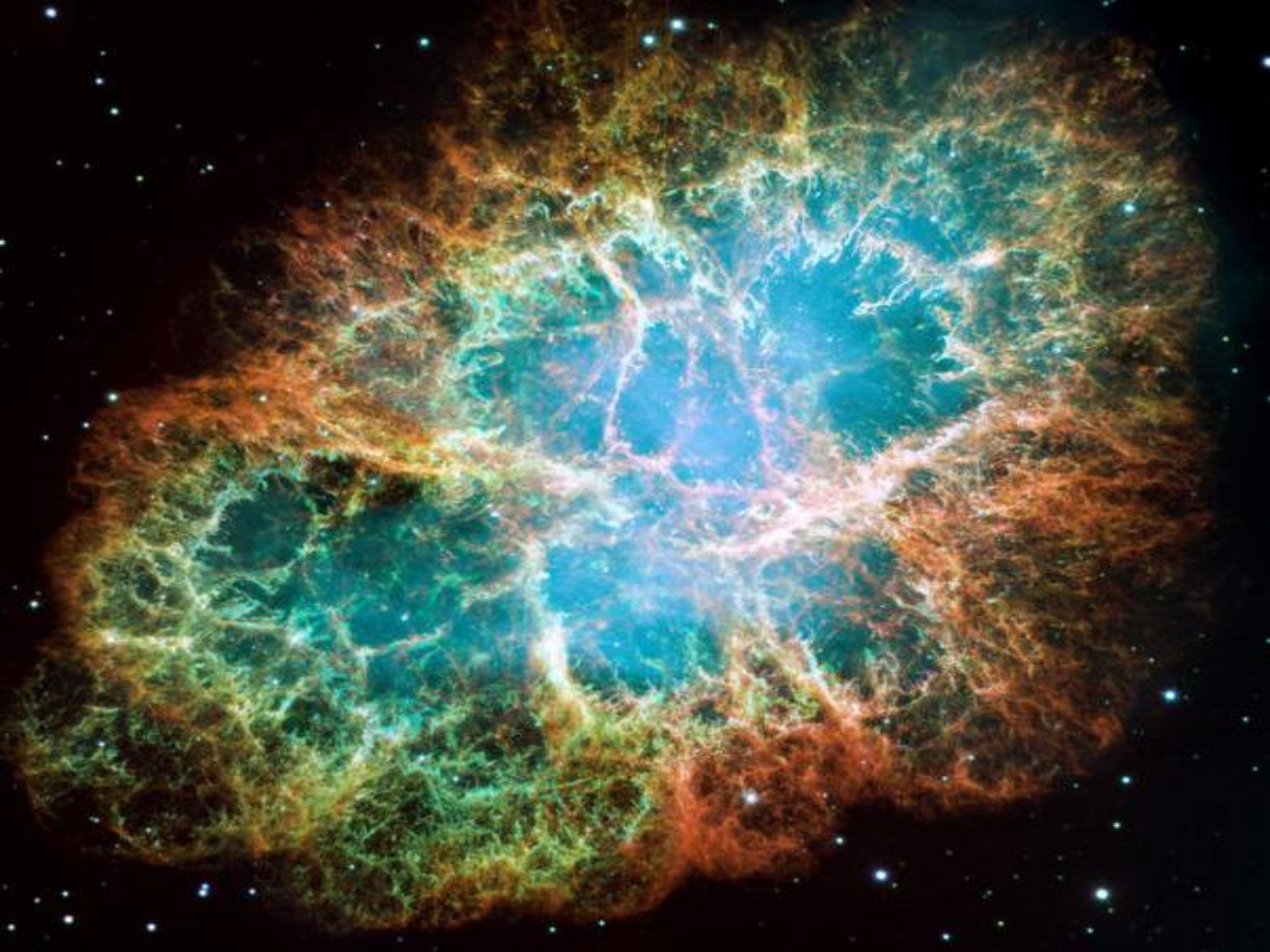
3. is inexhaustible,

4. reduces waste, and

5. is affordable to developing nations.

Develop | **Scale up** | **Produce** | **Export**





We have 3 possible nuclear fuels

nucleons	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95
241						
240						
239						
238						
237						
236						
235						
234						
233						
232						

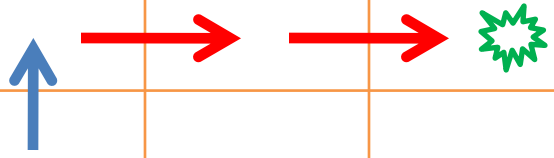
fission

beta decay

neutron absorption

Thorium-233 neutron absorption makes fissionable uranium-233.

nucleons	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95
241						
240						
239						
238						
237						
236						
235						
234						
233						
232						

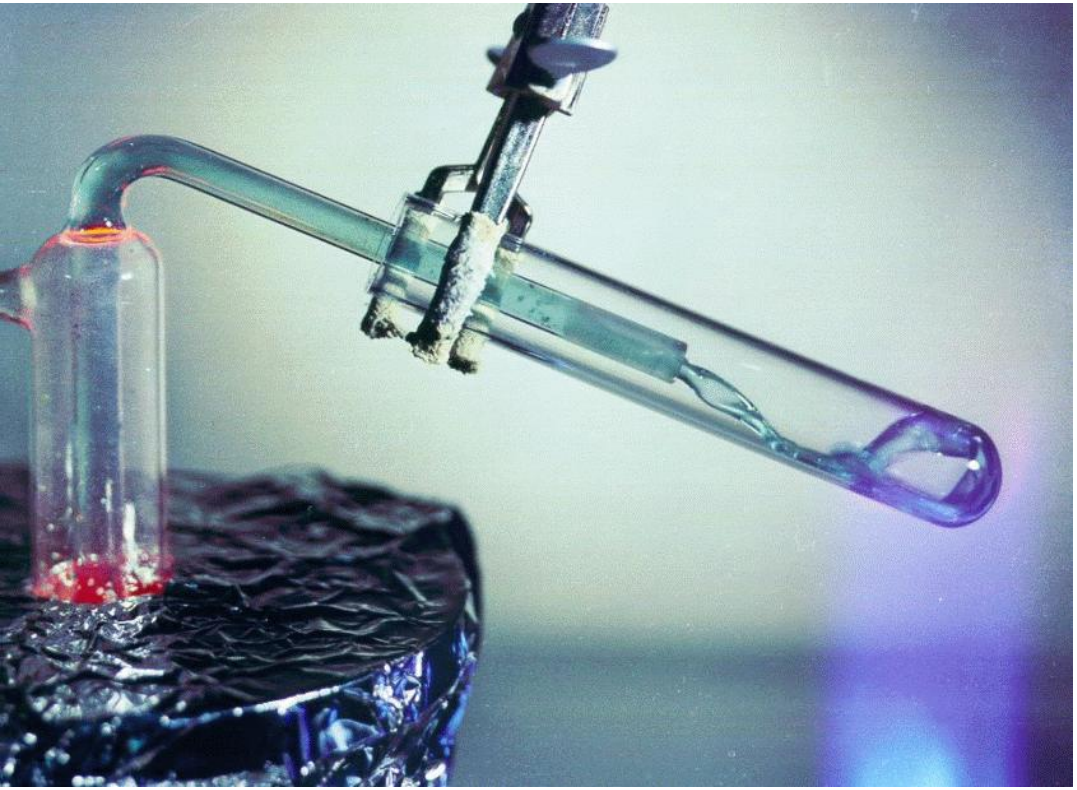


fission

beta decay

neutron absorption

LFTR = Th breeder reactor + liquid Fuel



Molten fluoride salt mix: LiF and BeF_2

Excellent heat transfer

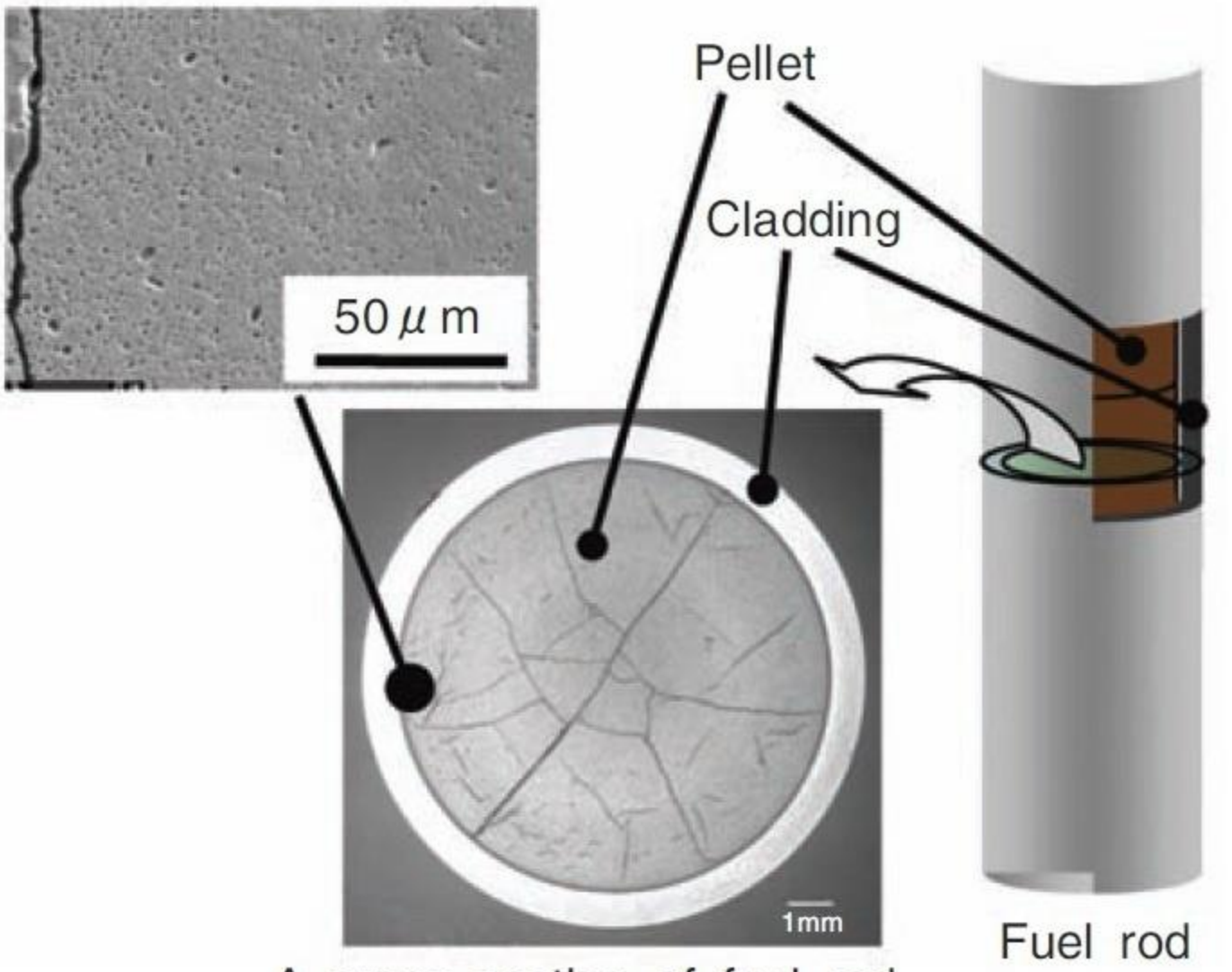
Continuous chemical processing

Atmospheric pressure

Room temp solid

Key technology -- liquid fuel form!

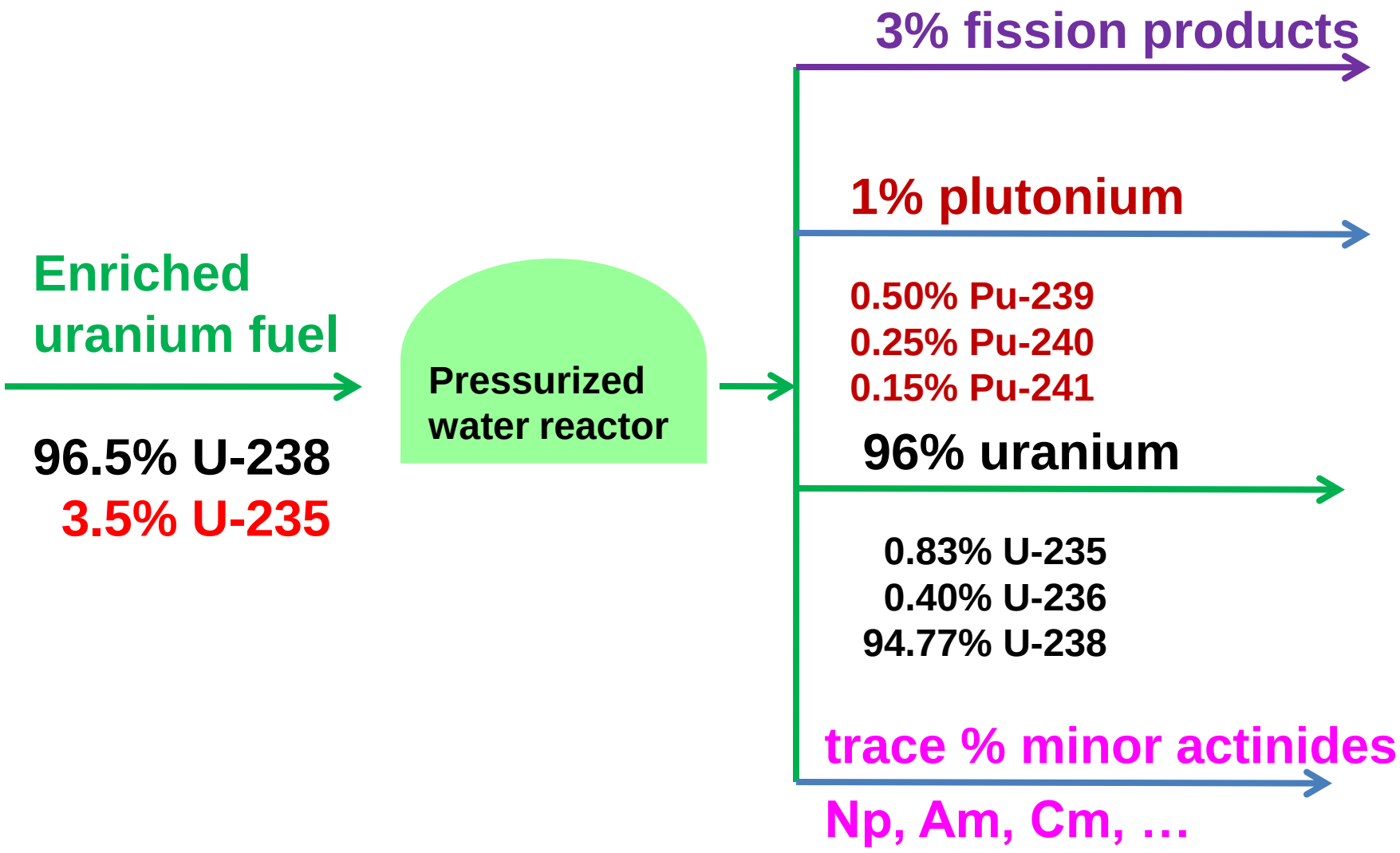
Radiation, fission products, and heat damage solid fuel.



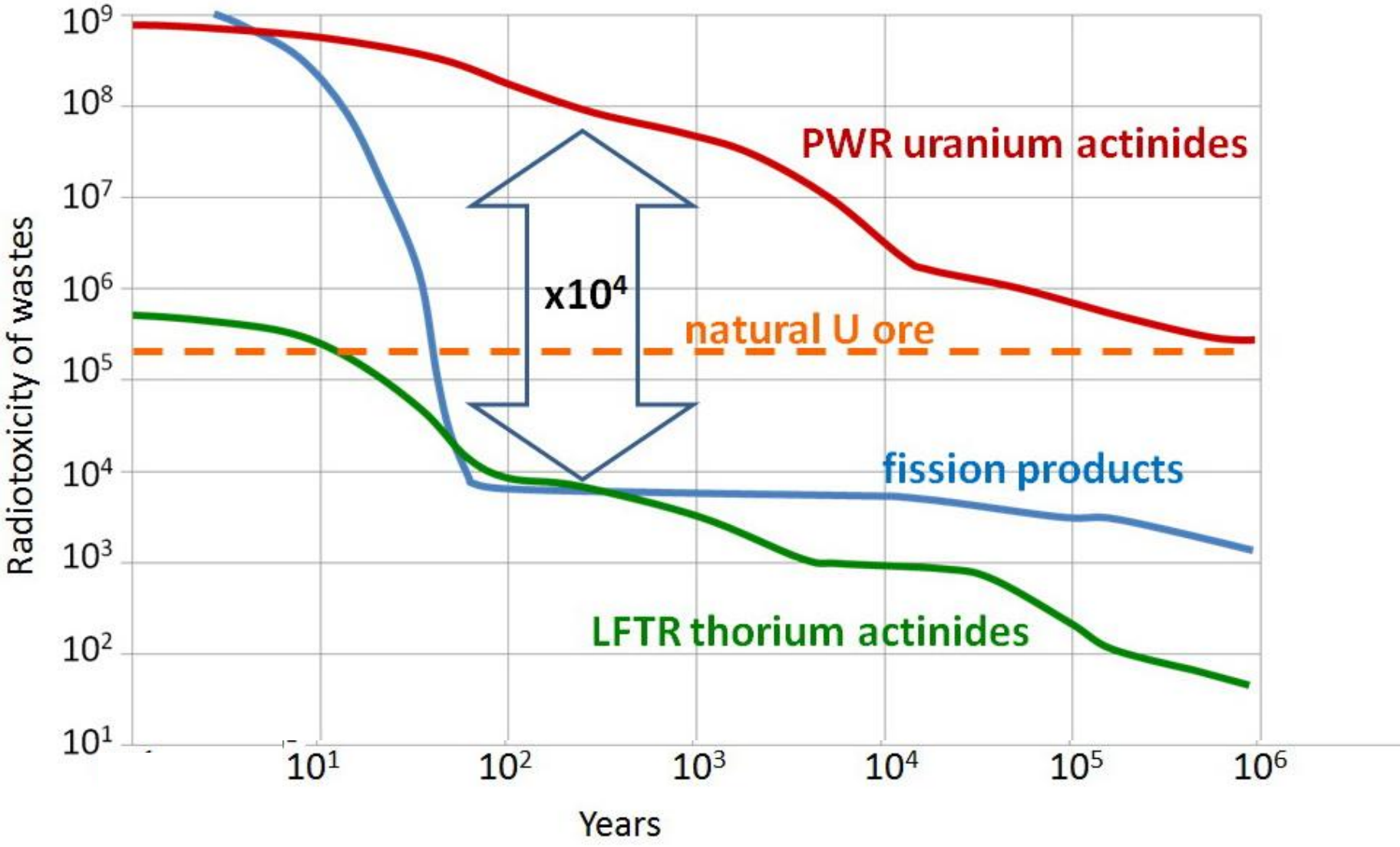
A cross section of fuel rod

Zirconium cladding must contain fuel and fission products for centuries.

Solid fuel reactors use only 3% of the potential energy.



LFTR produces < 1% of the long-lived radiotoxic waste of today's reactors.



LFTR is walk-away safe.

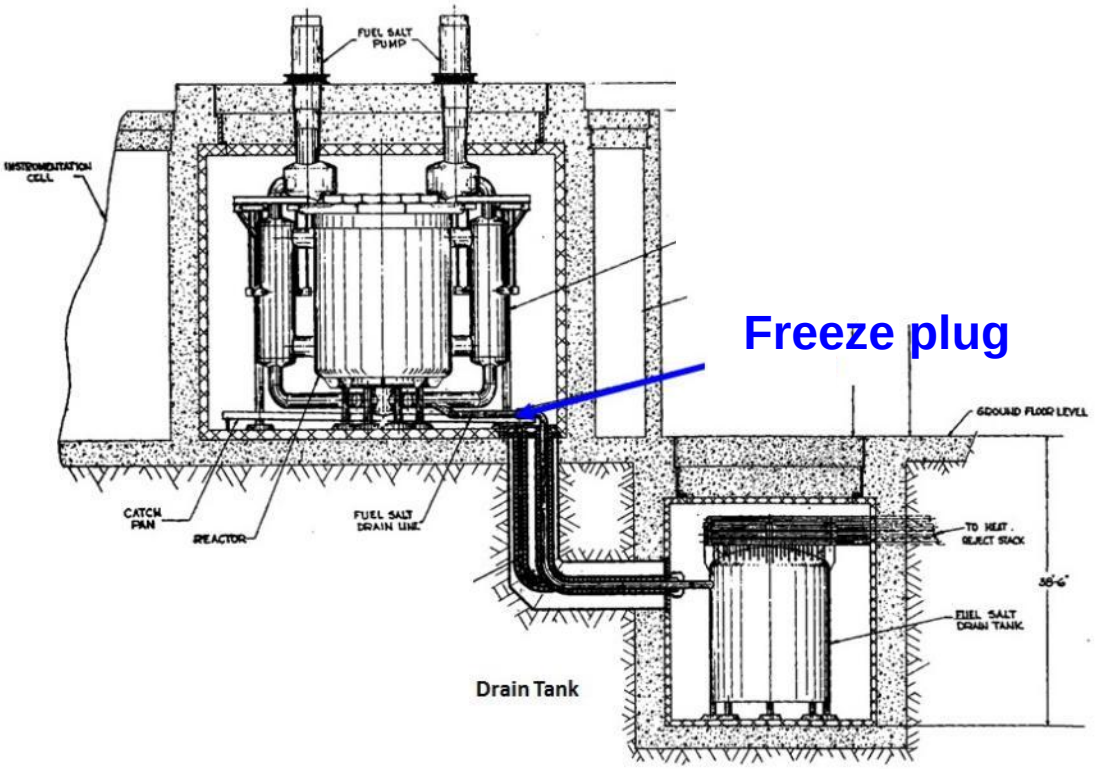
Stable reactivity.

Fuel already melted.

Atmospheric pressure.

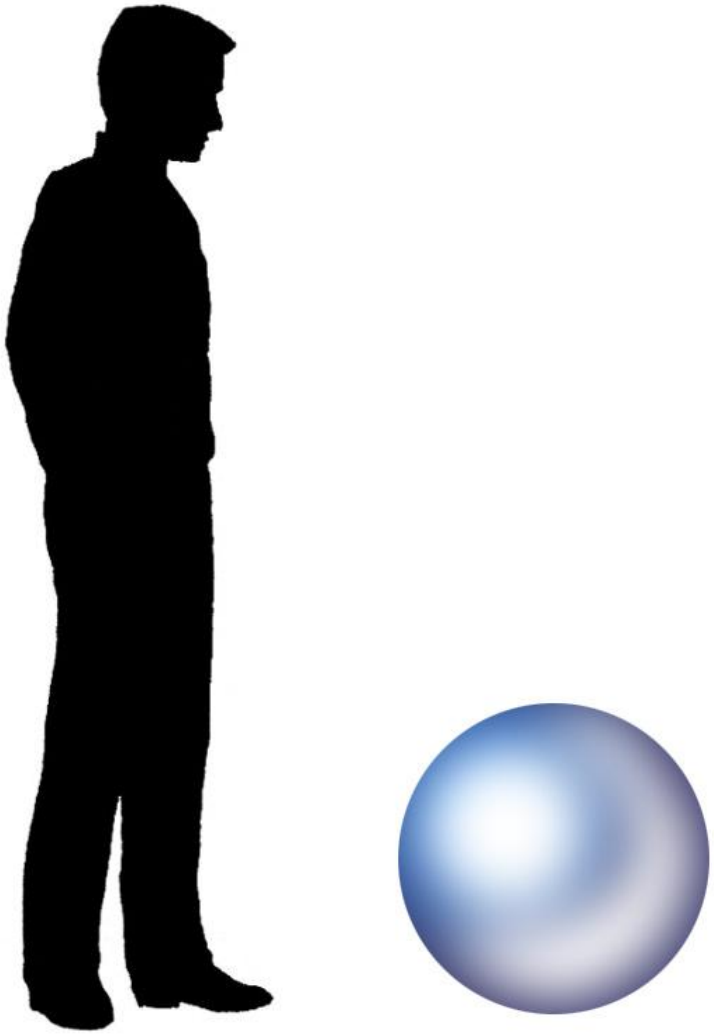
Melting freeze plug dumps salt to tank.

Salt from rupture or leak will solidify.



Passive cooling dump tank.

Thorium fuel is plentiful, compact, and inexpensive.



440,000 tons in US (USGS)

$300,000 per ton

500 tons, entire US, 1 year

1 ton, 1 city, 1 year

← dense, silvery, ½ m, 1 ton thorium sphere

http://minerals.usgs.gov/minerals/pubs/commodity/thorium/690798.pdf

One Lemhi Pass claim has enough thorium for 1,000 years.

Thorium Energy, Inc. claims 1,800,000 tons of thorium ore.

500 tons of thorium can supply all US annual electricity.

The US has 3,200 tons stored in the Nevada desert.

http://www.thoriumenergy.com/index.php?option=com_content&task=view&id=17&Itemid=33

http://www.energyfromthorium.com/ppt/ThoriumBriefSep2008.ppt

Oak Ridge developed and tested LFTR technology

Develop

Physicists
Eugene Wigner
Alvin Weinberg

Chemists
Ray Briant
Ed Bettis
Vince Calkins

Fluoride salts at temperatures to 1000ºC.

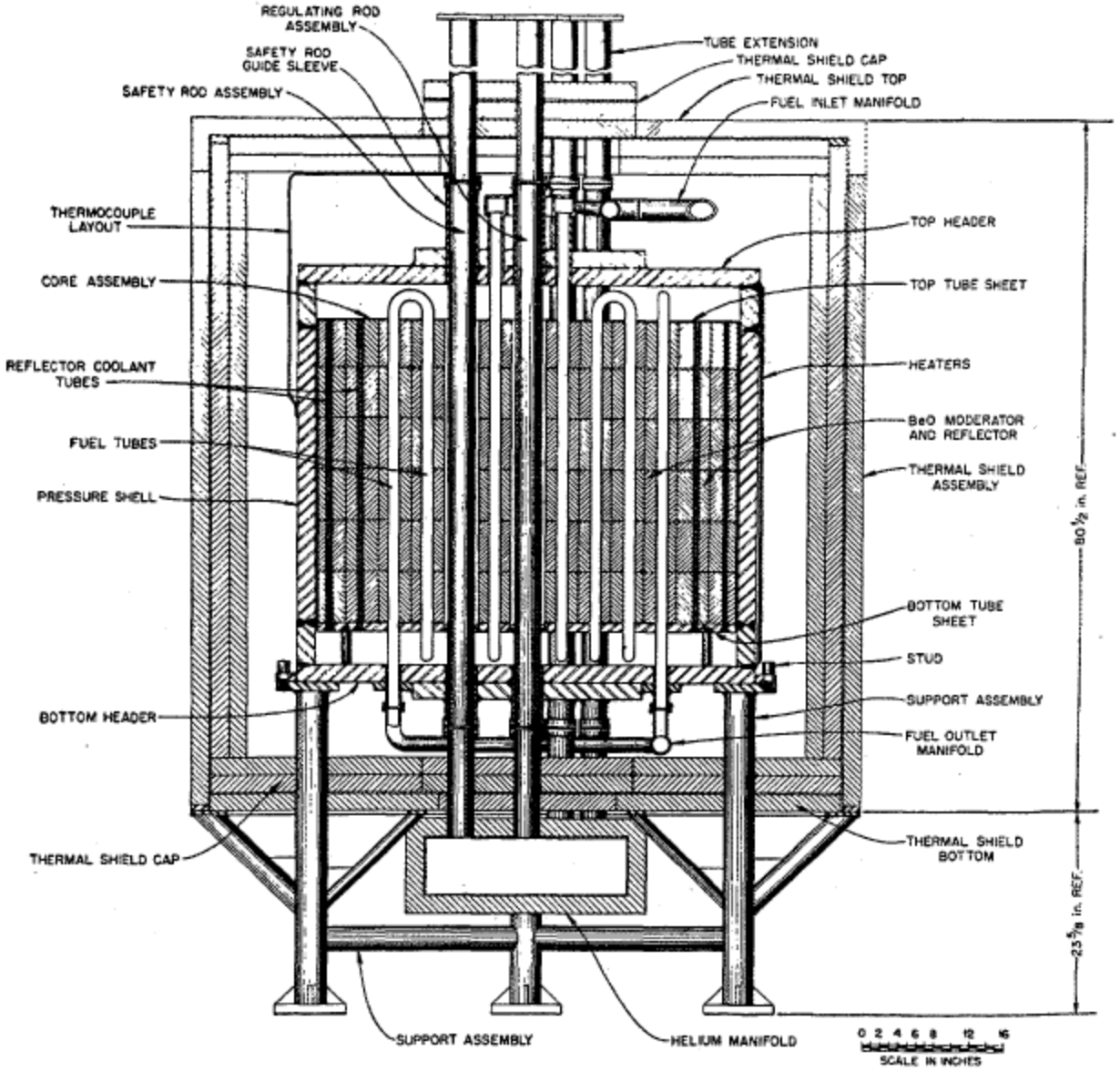
Fission products: krypton, rubidium, strontium, yttrium, zirconium, molybdenum, technetium, ruthenium, rhodium, palladium, cadmium, indium, tin, antimony, tellurium, iodine, xenon, caesium, barium, lanthanum, cerium, neodymium, promethium, samarium.

Neutron irradiation.

The aqueous homogeneous reactor at Oak Ridge generated 140 kW in 1953.

Richard Engel adds 300 g of uranium in 500 ml of heavy water to generate electric power for two months.

Weinberg and Oak Ridge developed the first molten salt nuclear reactor in 1954.



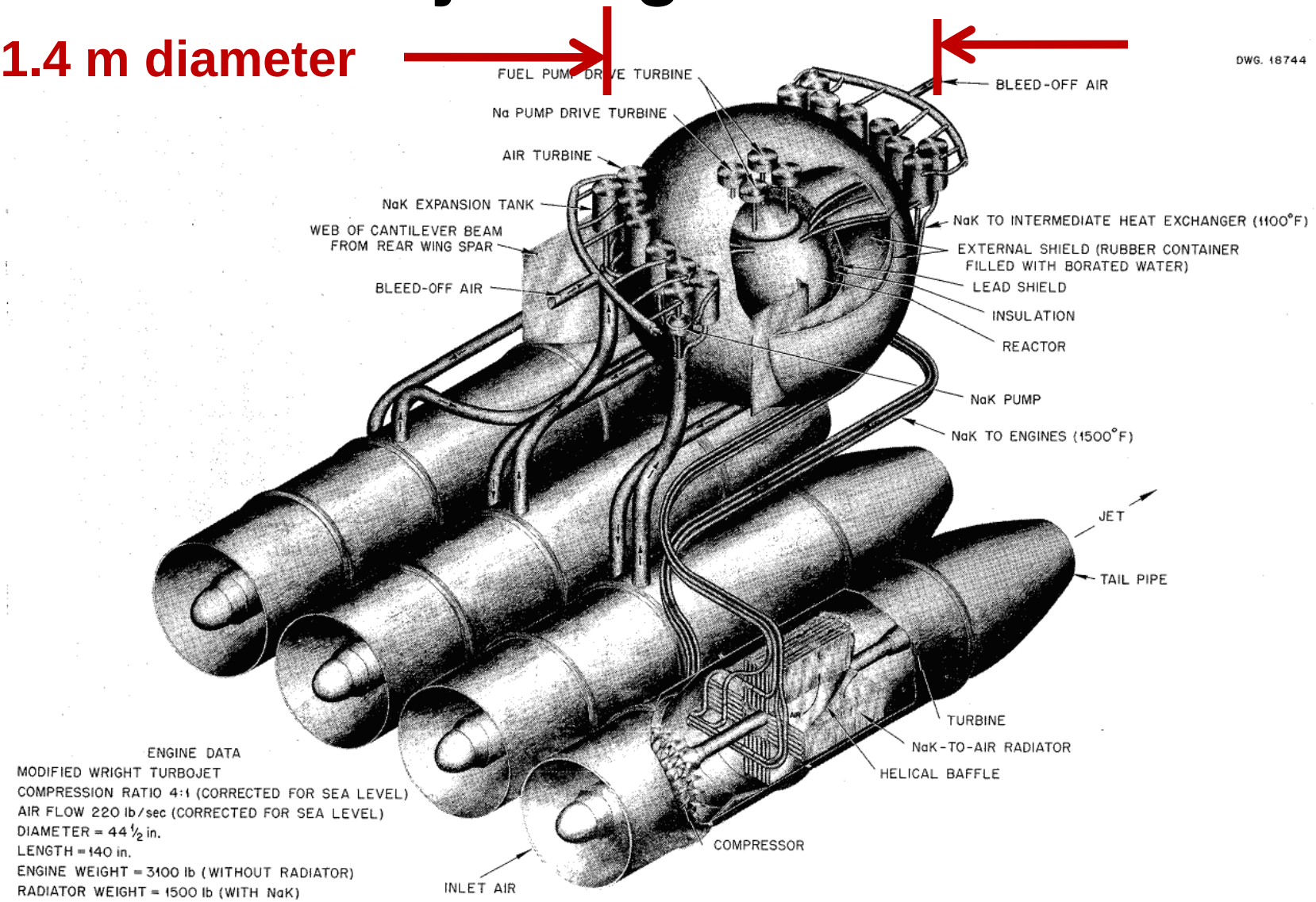
860 C

Red hot!

100 hours

2.5 MW

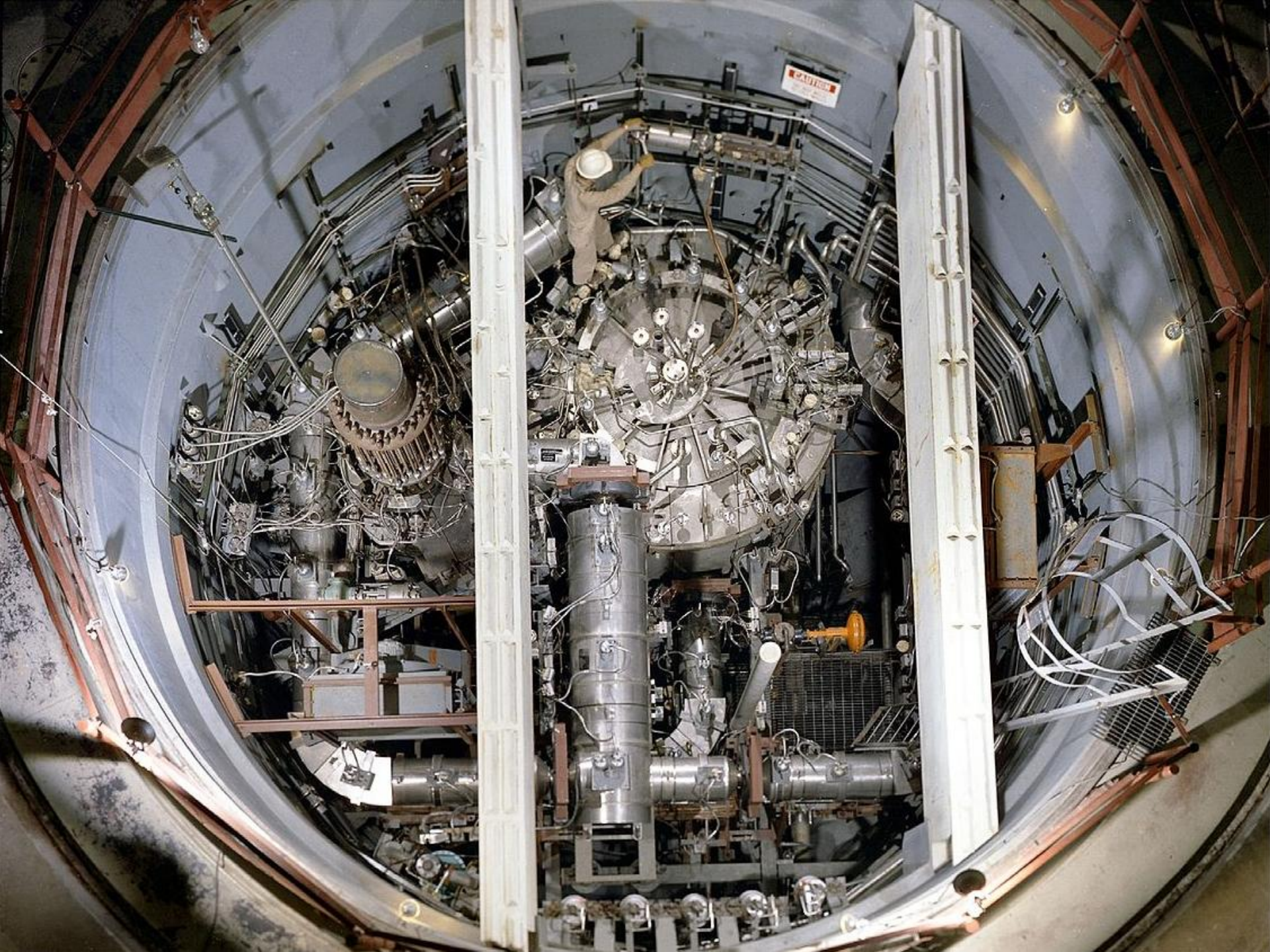
The *Fireball* reactor made heat to power jet engines.

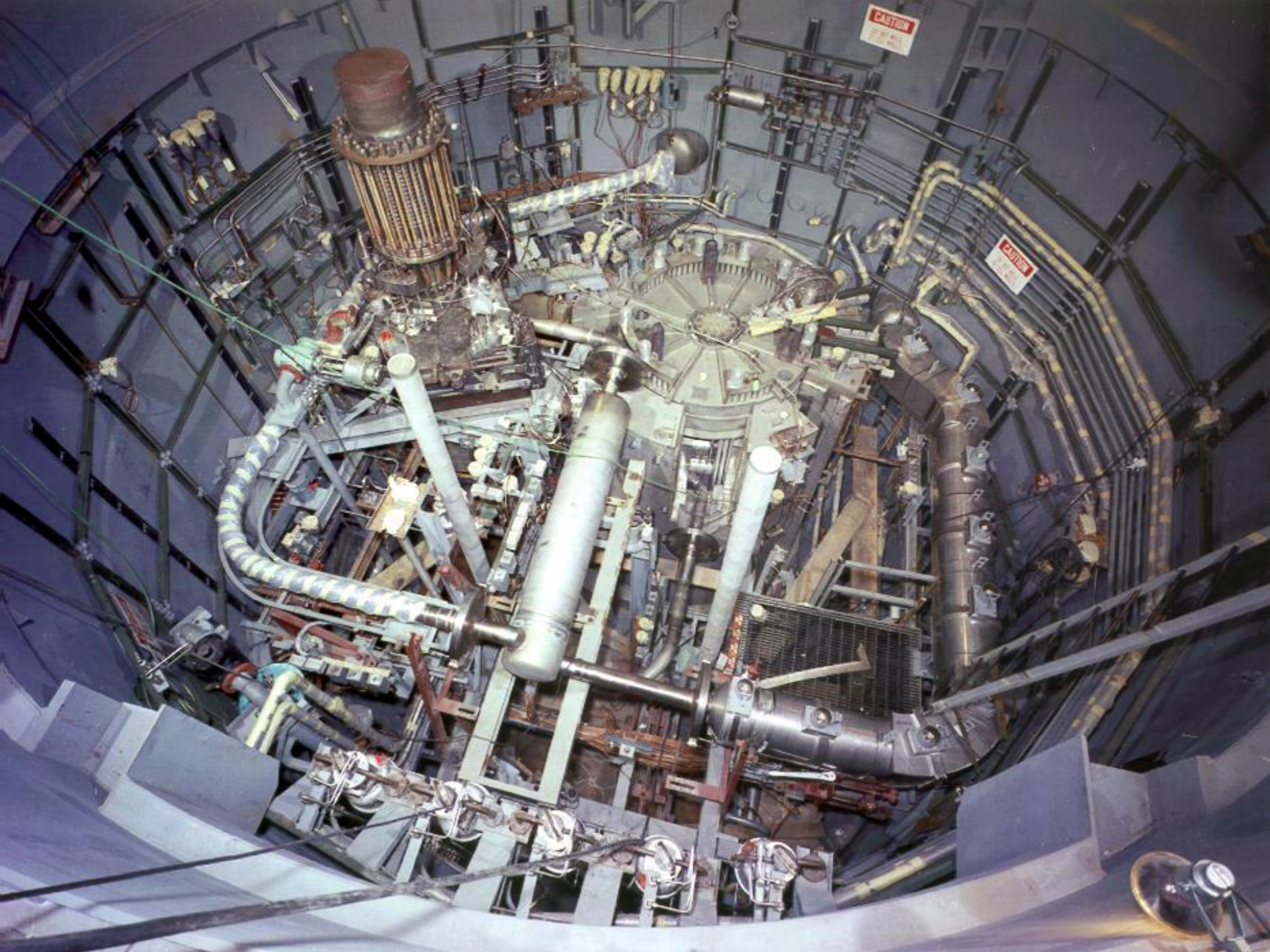


Rickover's drive, Nautilus submarine, and Shippingport power plant ➔100 US PWRs.

The Molten Salt Reactor Experiment ran from 1965 to 1969.

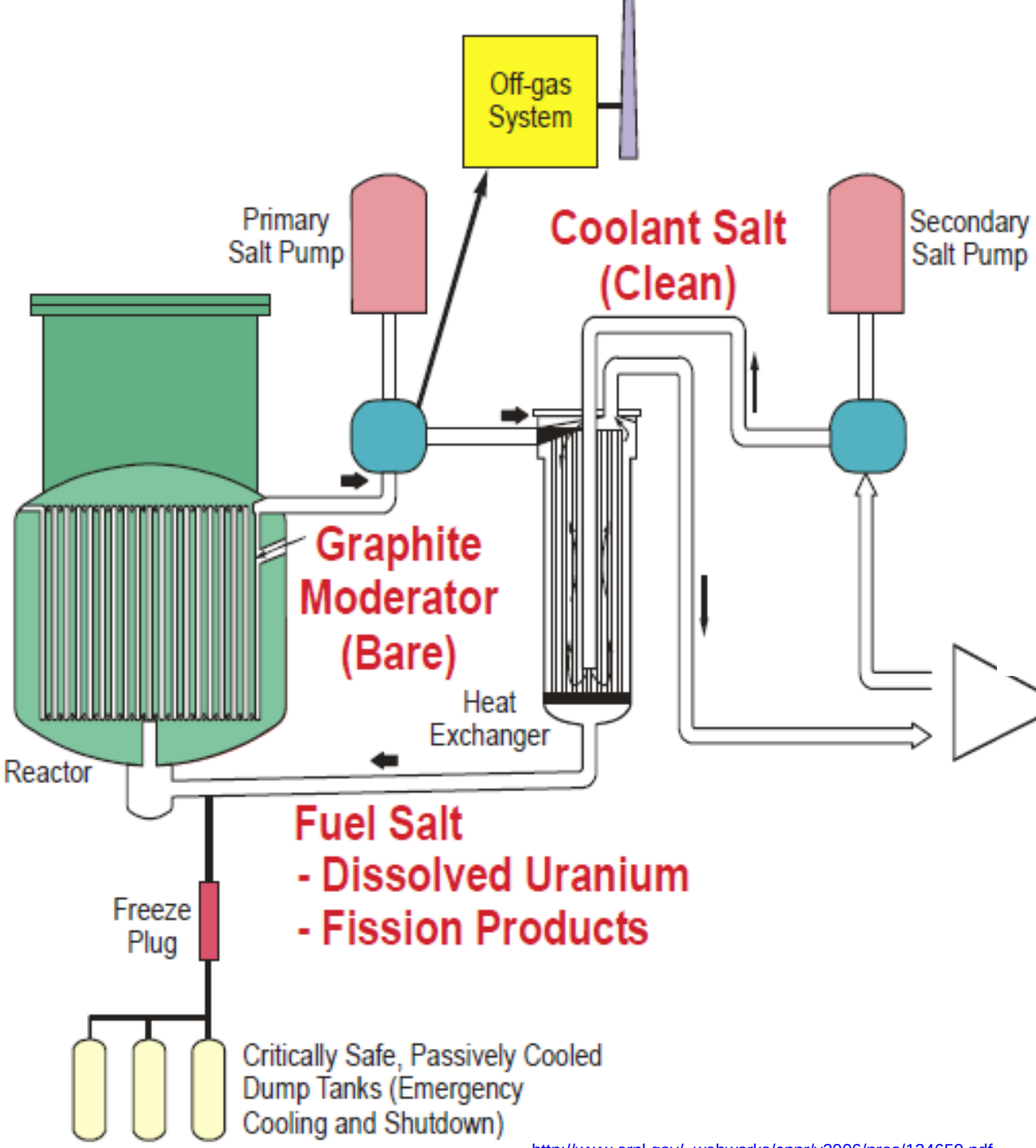
Salt flowed through channels in this graphite core.




CAUTION
CAUTION

The Molten Salt Reactor Experiment succeeded.

Hastelloy
Xe off-gas
Graphite
Pumps
Fluorination
Dump tanks
U-233
17,655 hours



http://www.ornl.gov/~webworks/cppr/y2006/pres/124659.pdf

Development is nascent.

$ 1 B

Develop

2011

LFTR technology is disruptive to the nuclear industry.

US makes small grants to UCB, MIT..

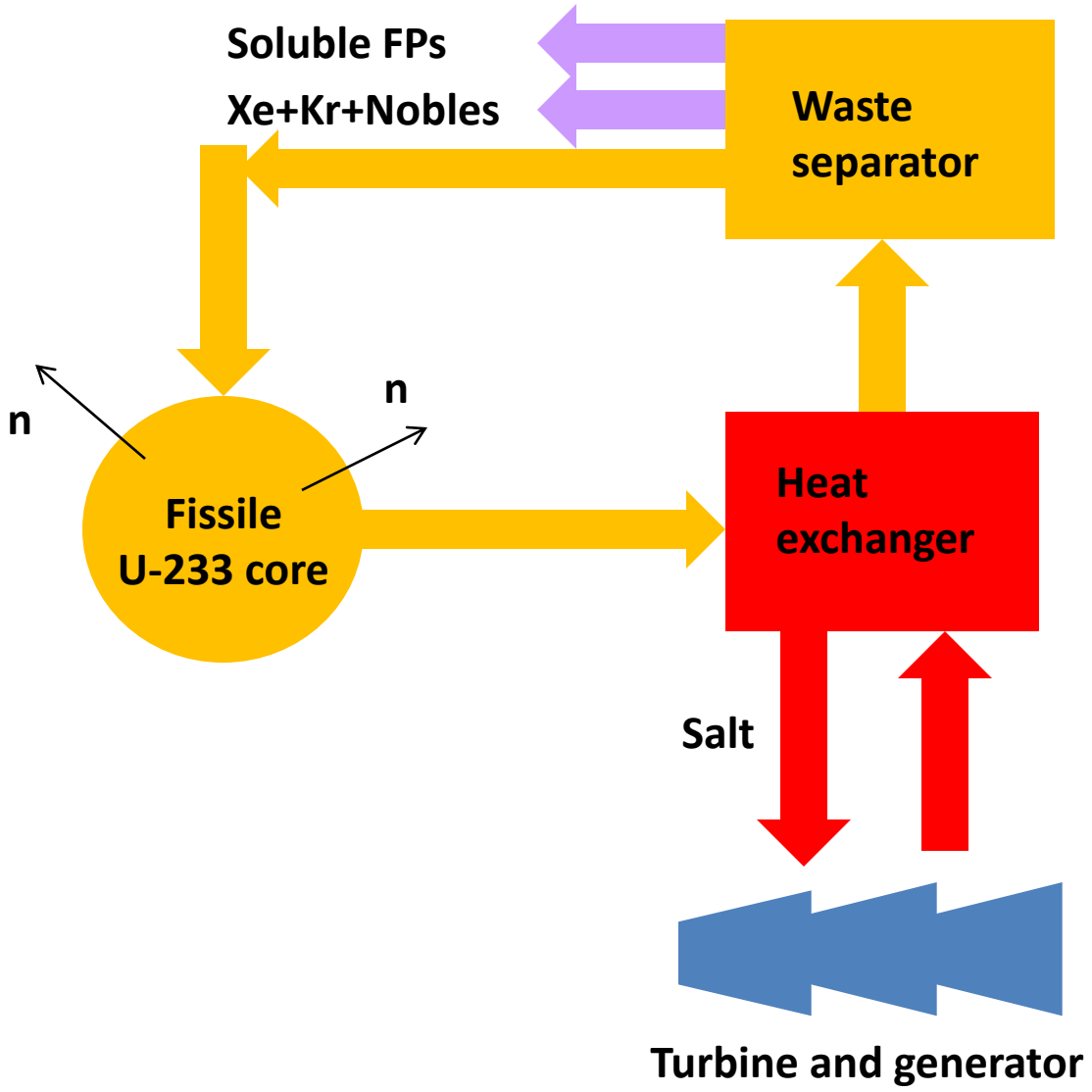
R&D papers published in France, Japan, Canada, …

Ventures seeking money in US, Japan, South Africa.

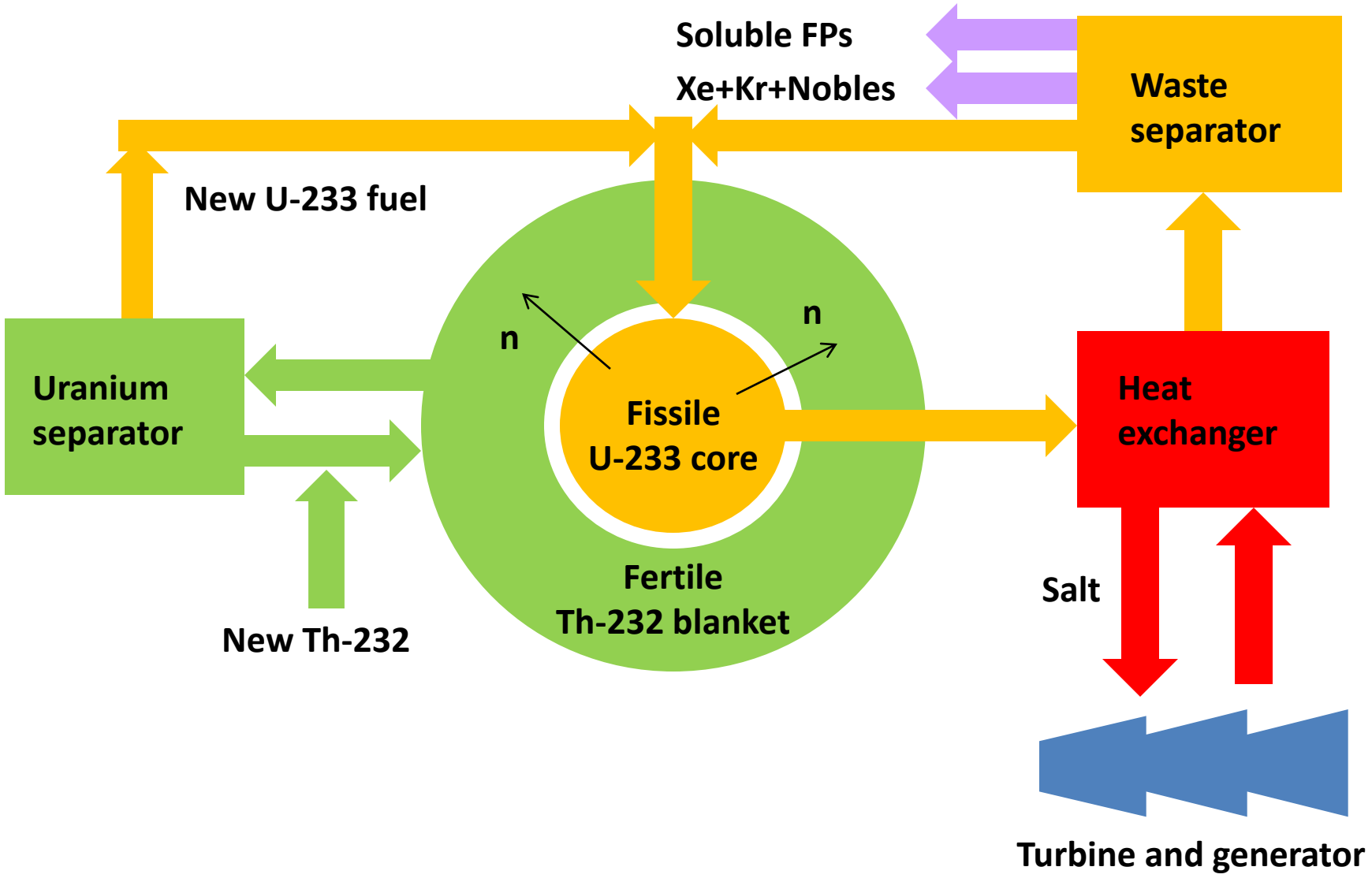
China announces LFTR project! (Jan 2011)

***Energy from Thorium* volunteers contribute.**

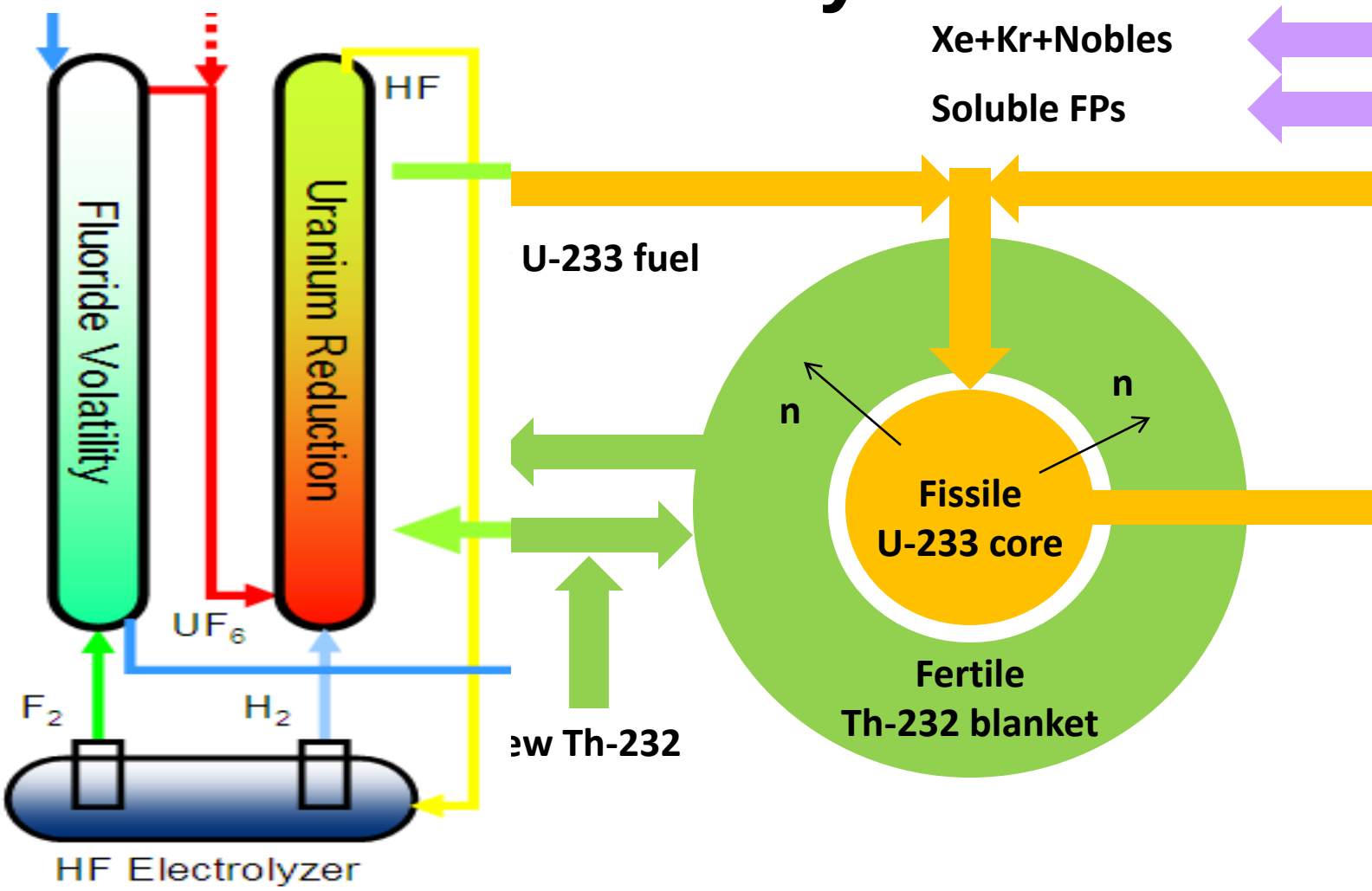
Start with what Oak Ridge Tested



Add the breeding blanket

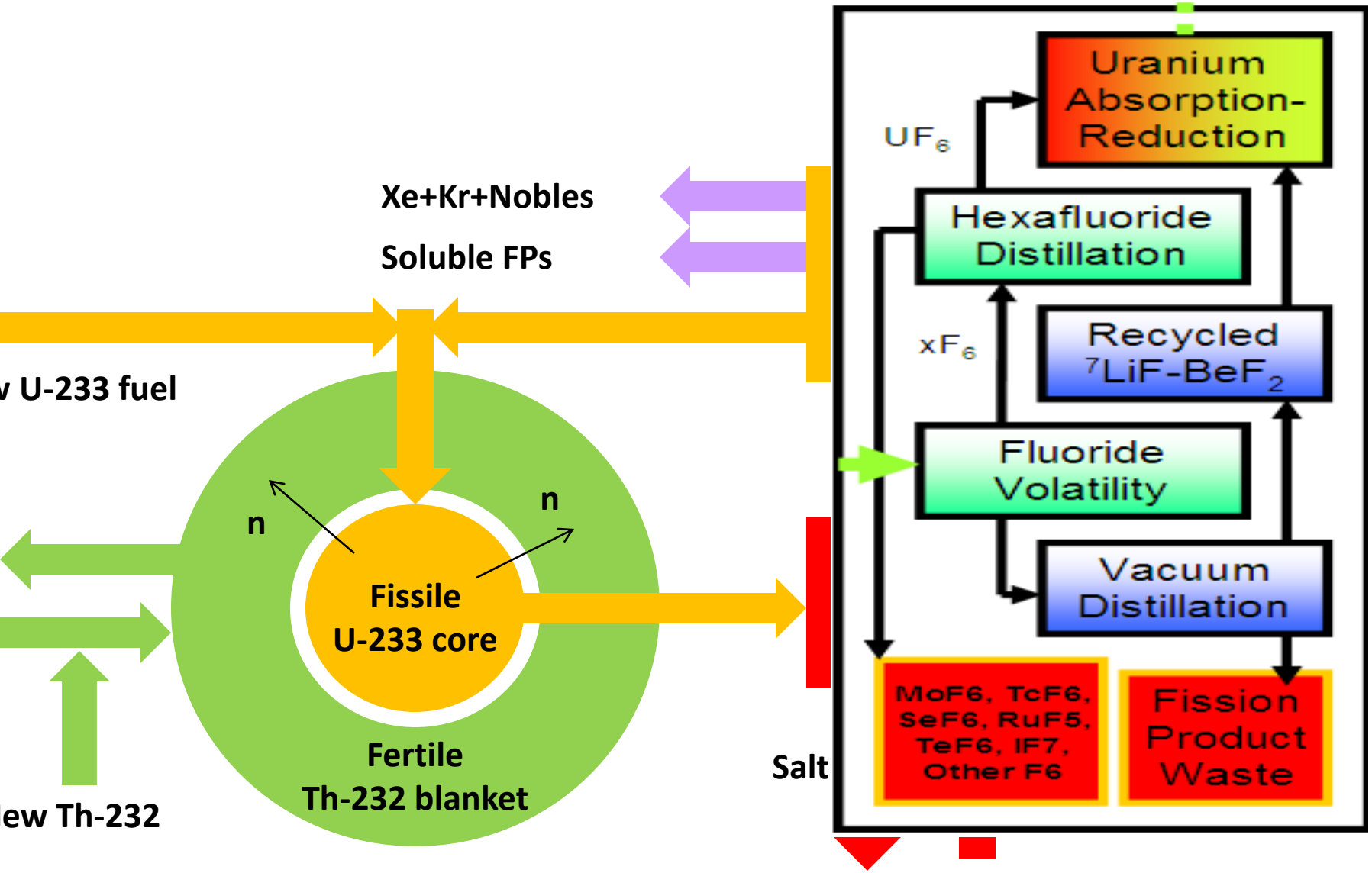


Separate U-233 from Th-232 by fluoride volatility.

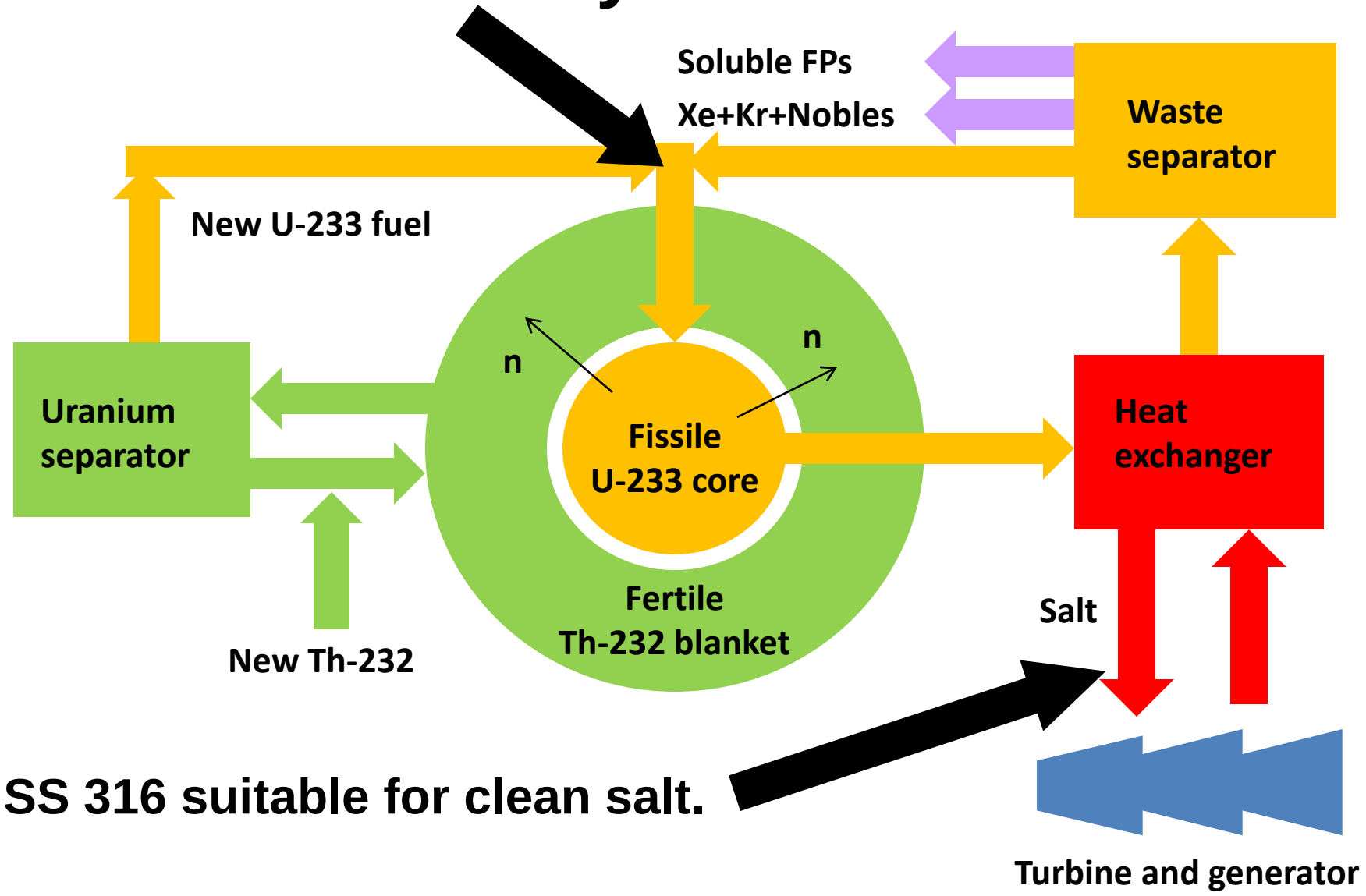


Internal continuous recycling of blanket salt

Remove the various fission products

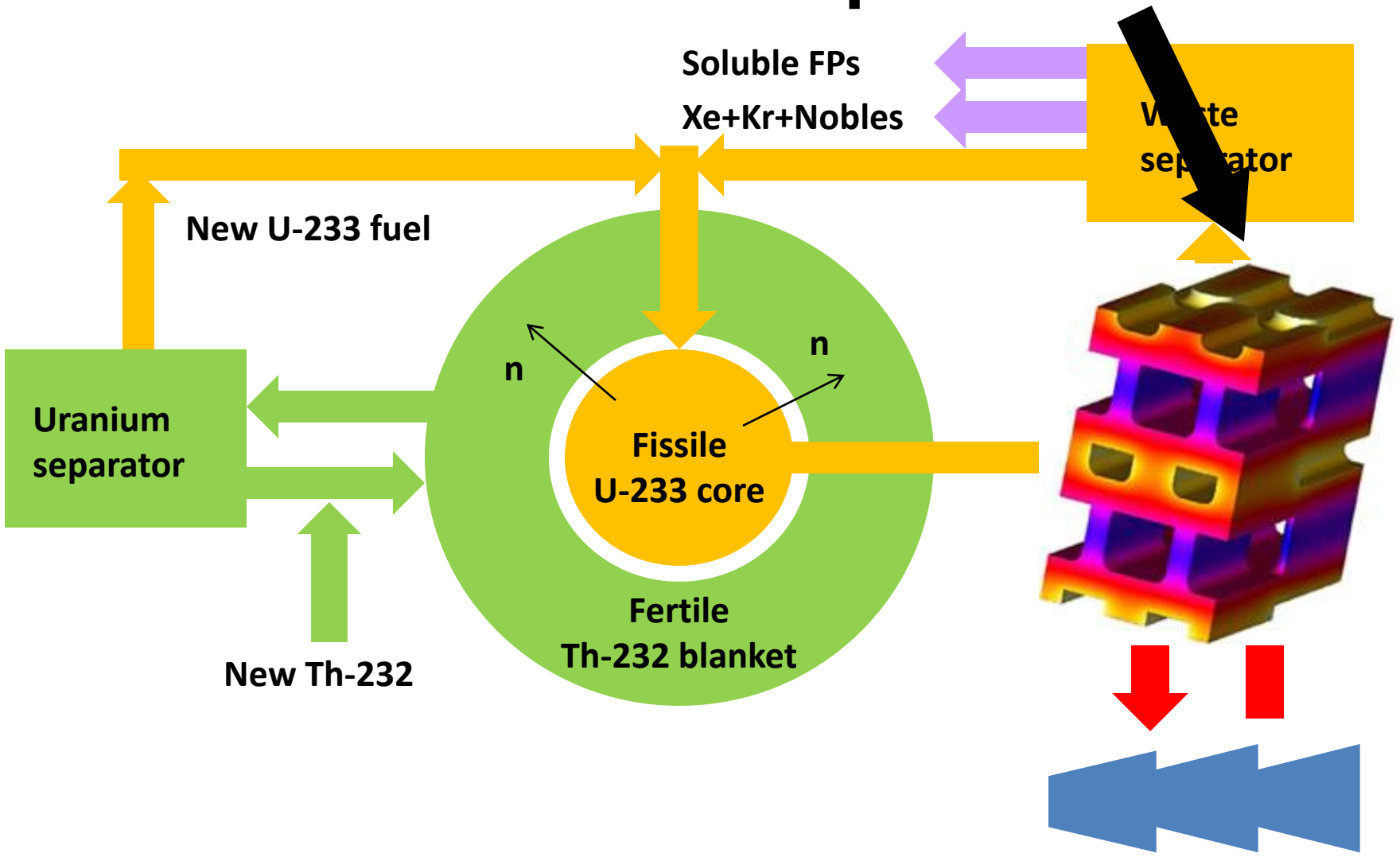


Removing fission products controls Hastelloy-N Corrosion



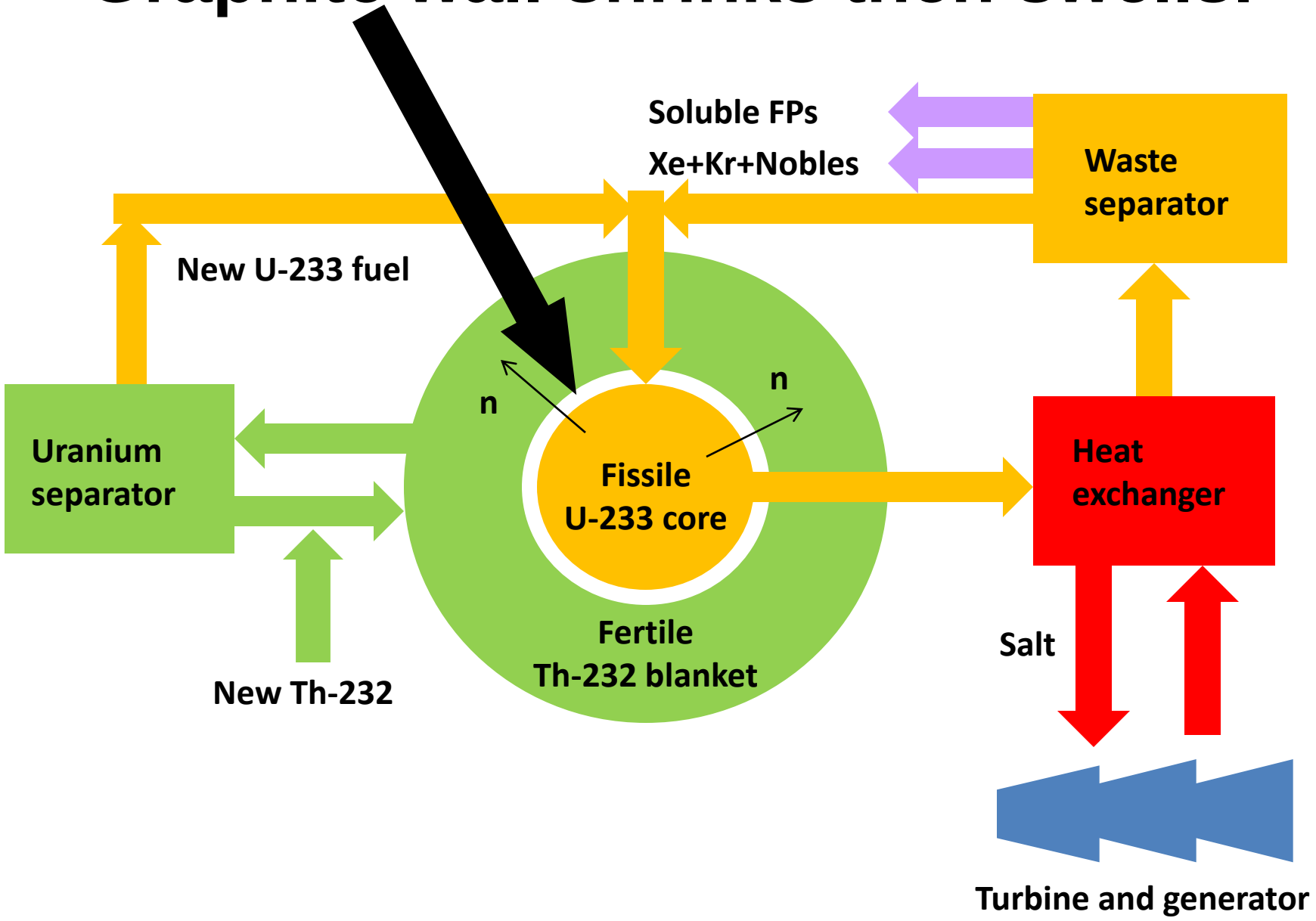
SS 316 suitable for clean salt.

Use silicon carbide composites for future 1000ºC temperatures.

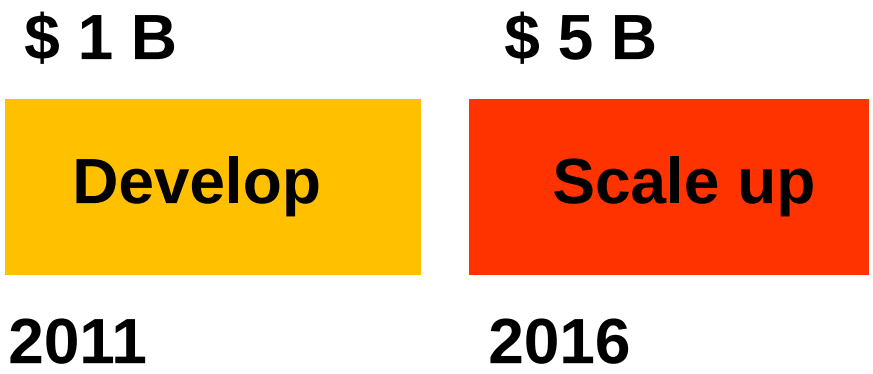


William Corwin, INL, ORNL

Graphite wall shrinks then swells.



Scale up to commercial models and develop applications



Aim High! Use air cooling.

A typical 1 GW coal or nuclear plant heats 600,000 gal/min of water, or evaporates 20,000 gal/min.

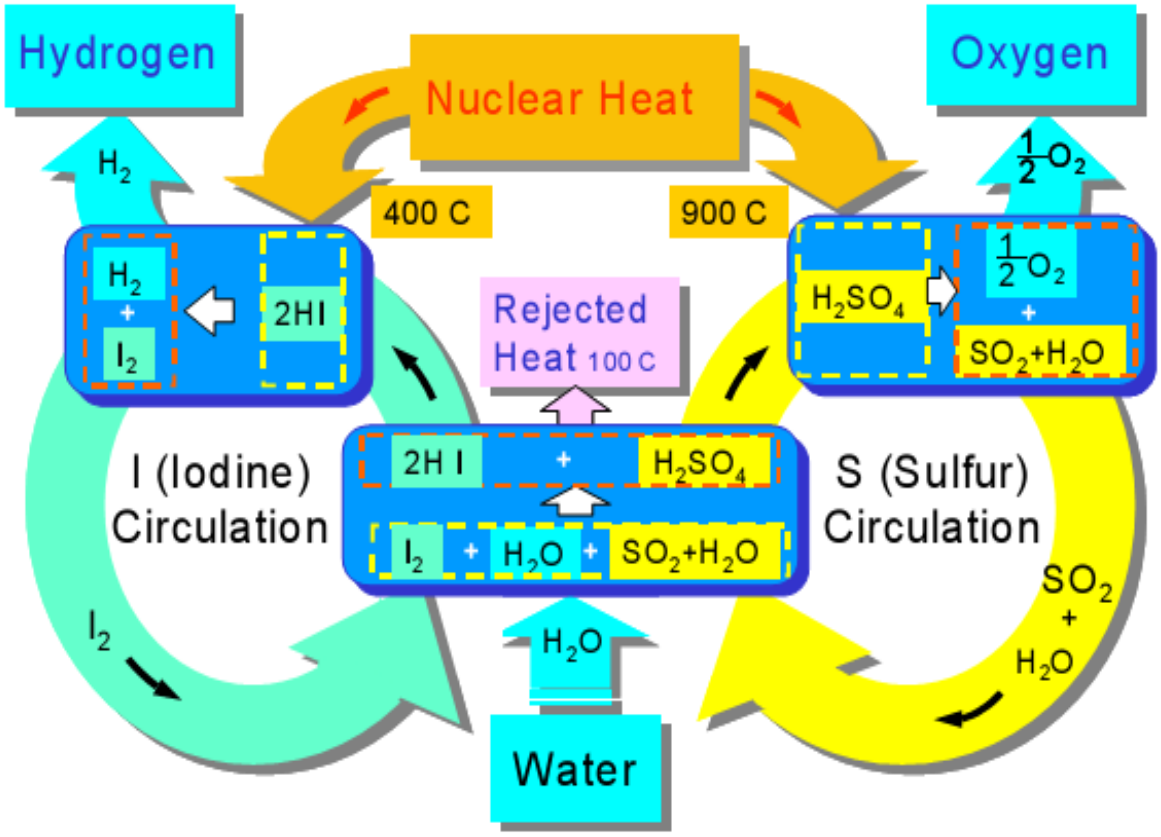
High temperature LFTR halves heat loss.

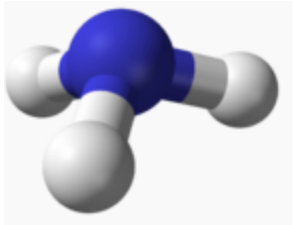
Air cooling is needed where water is in short supply.

Aim High!

Synthesize fuel from H_2.

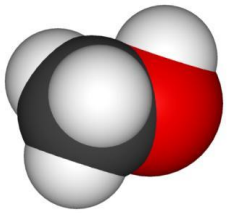
Dissociate water with sulfur-iodine or copper-chlorine cycle.



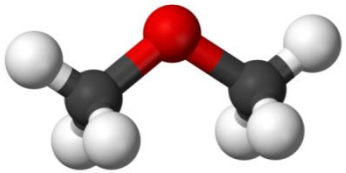


Ammonia

CO2 + 3 H2 → CH3OH + H2O



Methanol for gasoline



Dimethyl ether for diesel

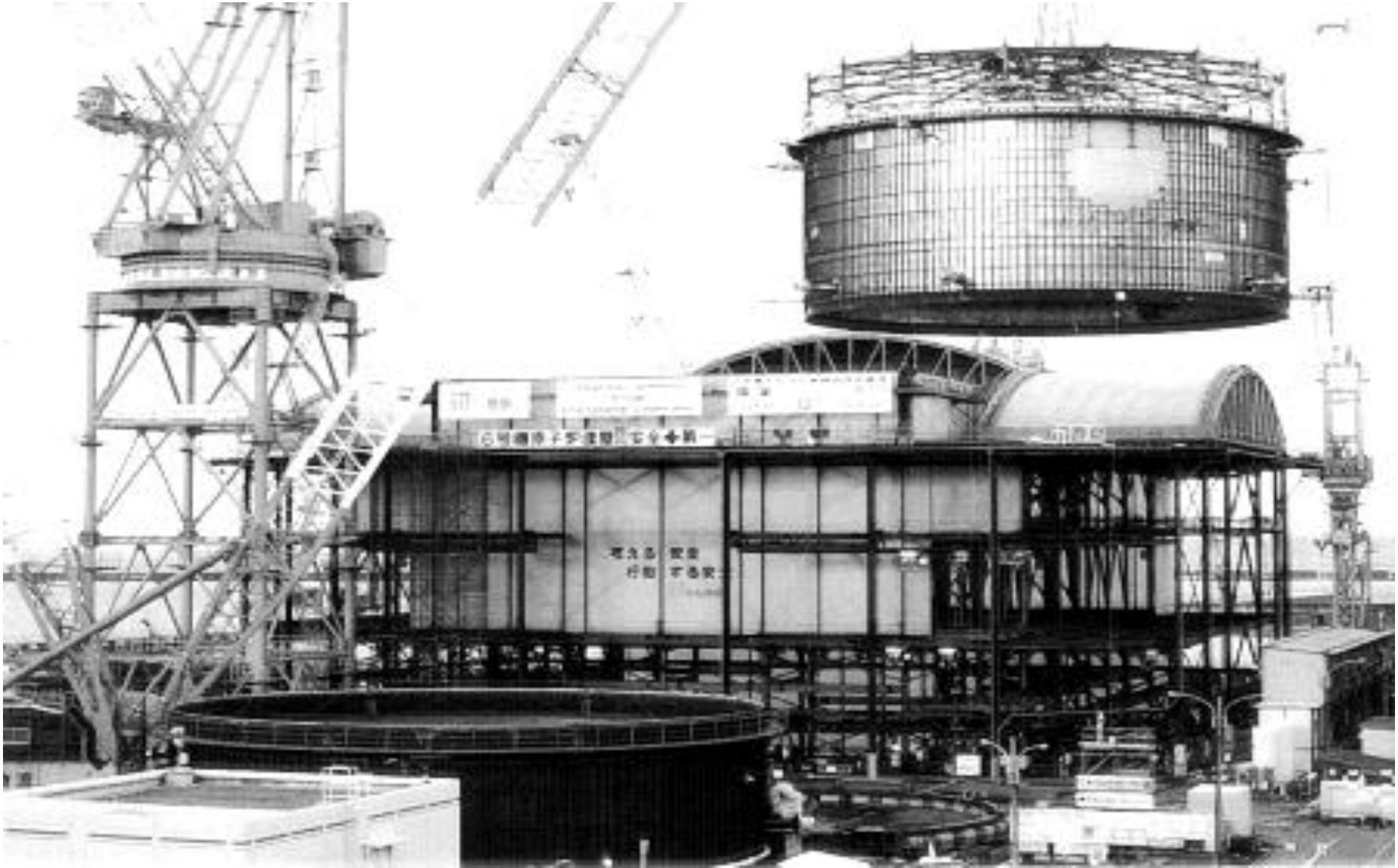
http://wwwtest.iri.tudelft.nl/~klooster/reports/hydro_slides_2003.pdf

Why can LFTR energy be cheaper than from coal?

The median of five cost estimates for molten salt reactors is < $2/watt.

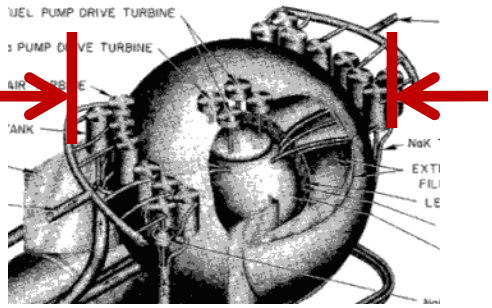
Estimate	Year	$/watt	2009 $/watt
Sargent & Lundy	1962	0.650	4.64
Sargent & Lundy ORNL TM-1060	1965	0.148	1.01
ORNL-3996	1966	0.243	1.62
Engel et al, ORNL TM7207	1978	0.653	2.16
Moir	2000	1.580	1.98

LFTR needs no costly 160-atmosphere pressure vessel and containment dome



The Westinghouse AP-1000 is massively larger than LFTR.

1.4 m

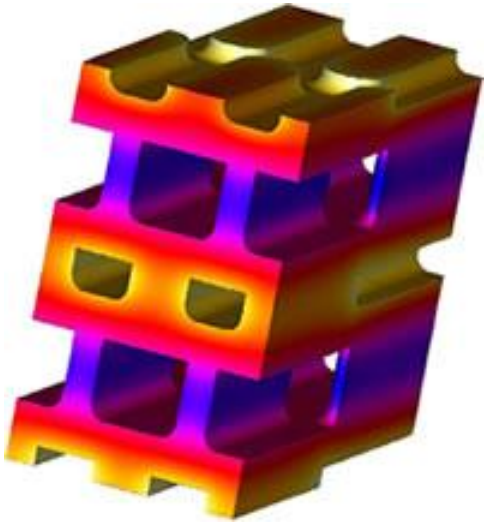


1.4 m

AP-1000
Samen, China

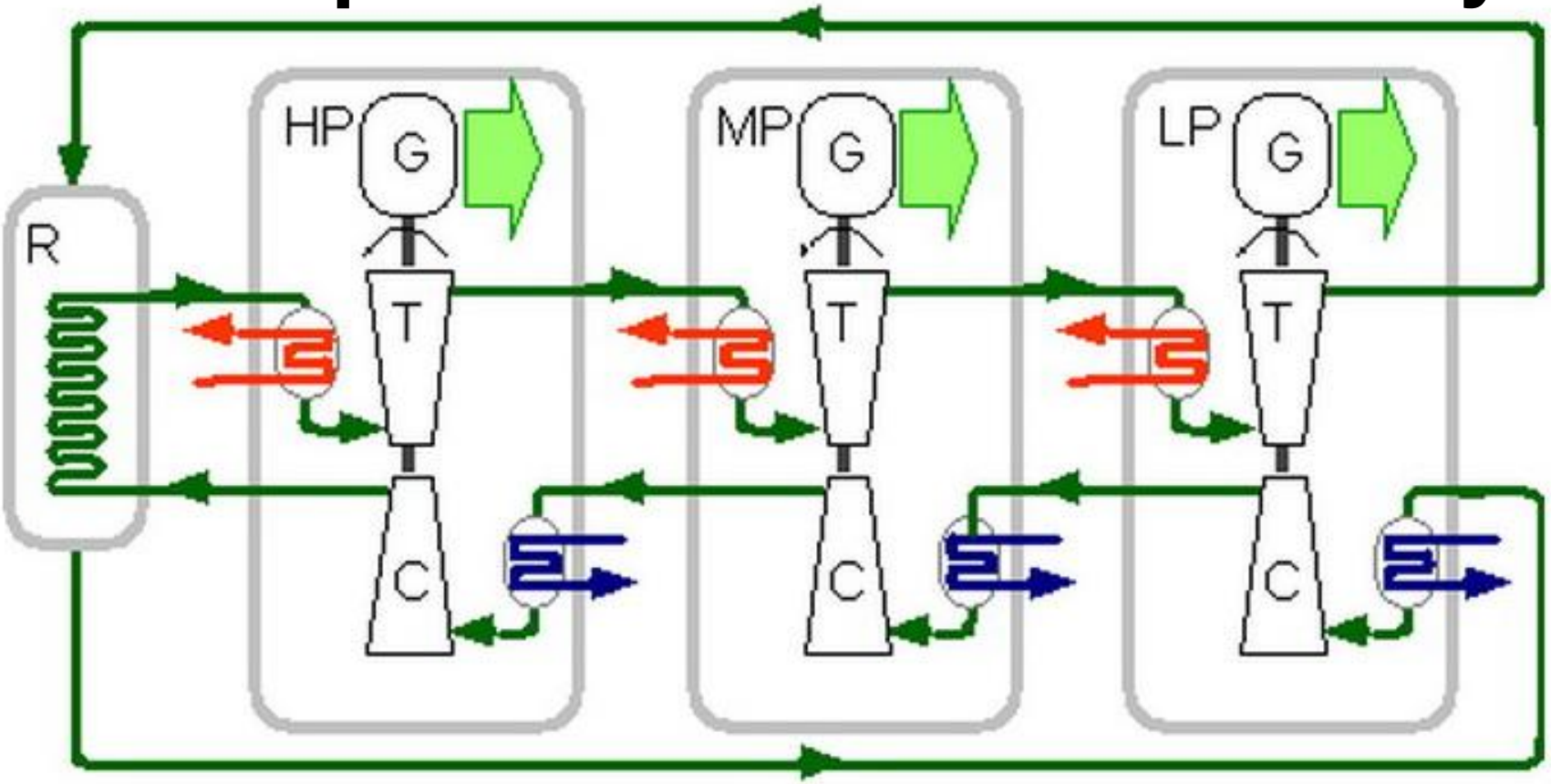
High thermal energy efficiencies keep LFTR compact at low cost.

High thermal capacity heat exchange fluid



Carbon composite high temperature heat exchanger

Compact closed cycle Brayton turbine raises power conversion efficiency.



Halving rejected heat enables air cooling.

Aim High!

Develop a small modular reactor.

Small LFTR modules can be transported by trucks.

100 megawatt, $200 million
-- cheaper than coal

Affordable to developing nations

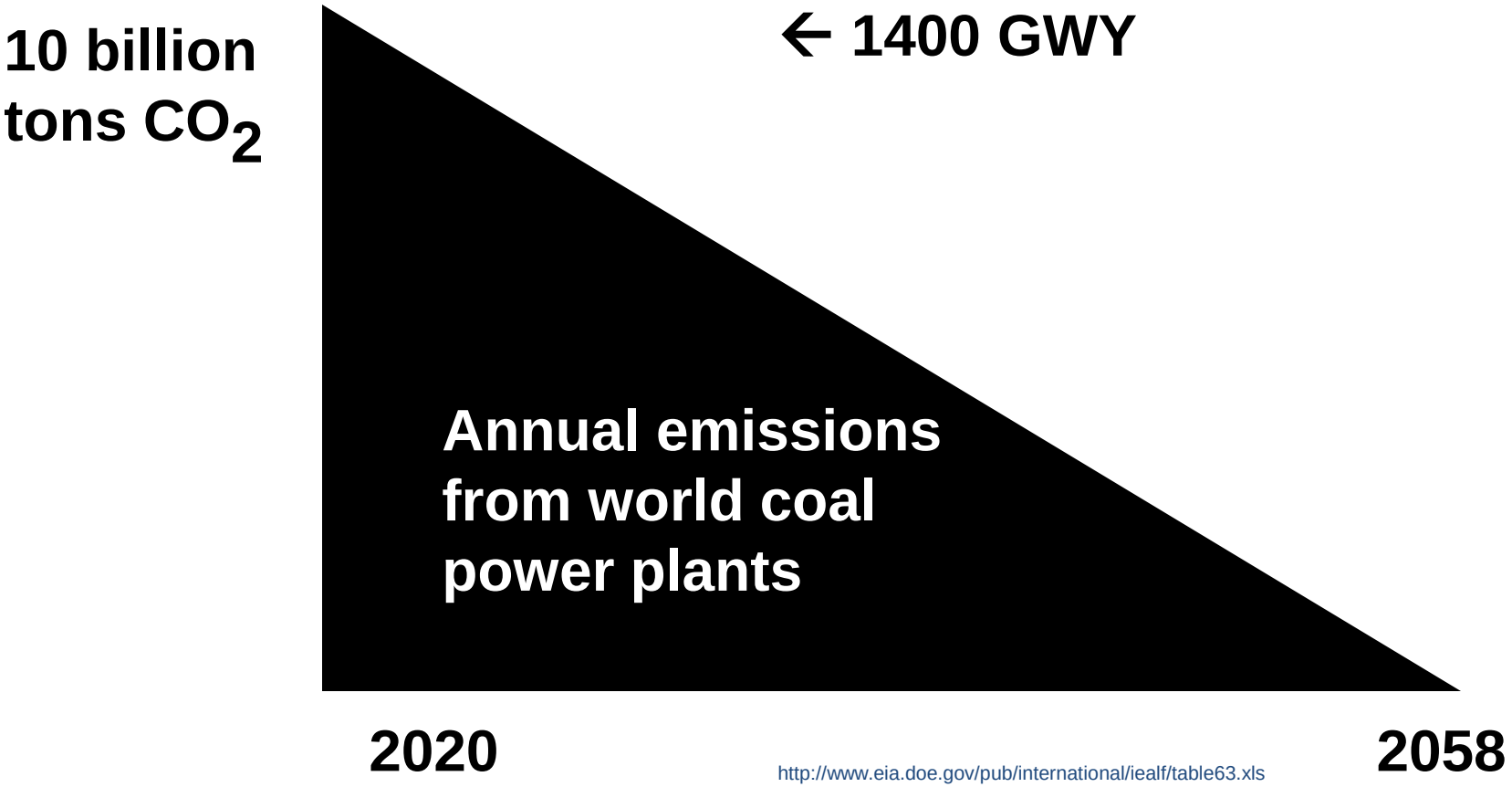
Single modules
-- suited for small cities
-- short transmission lines

Multi-module power stations
-- incremental growth and cost
-- replace plants at existing sites

Aim High!

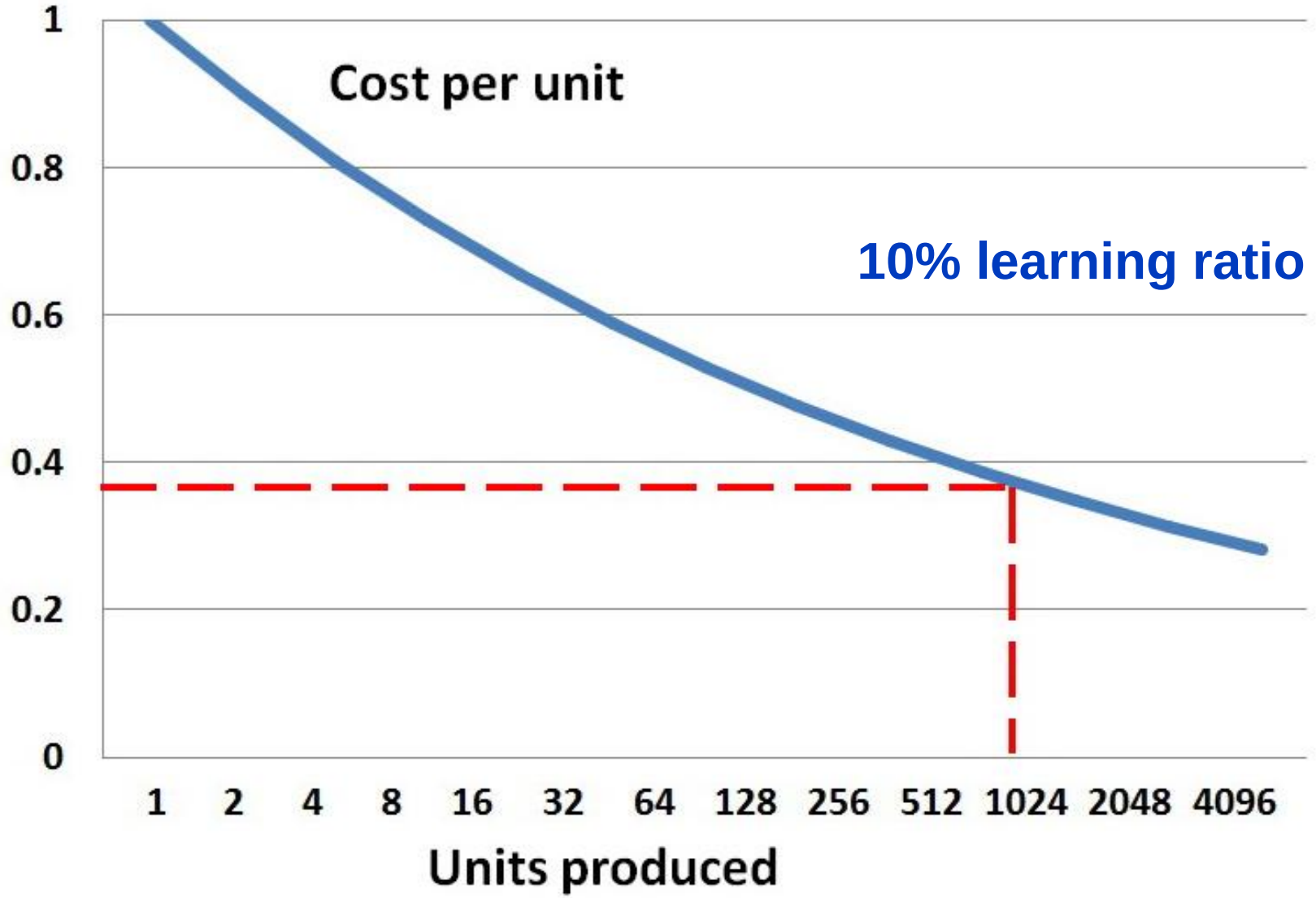
Check global warming.

Install one 100 MW LFTR each day, worldwide, to replace all coal power.

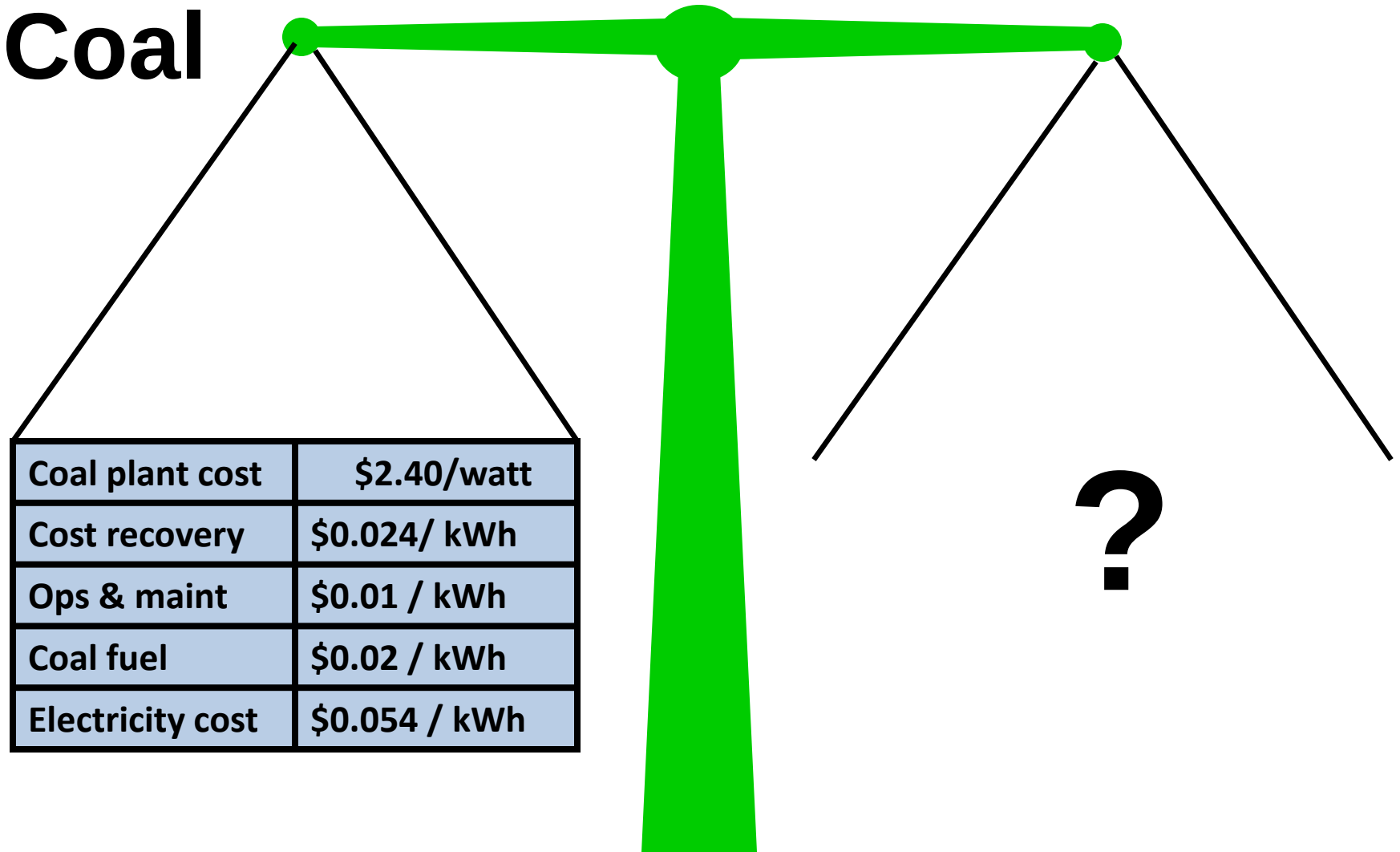


Boeing makes one $200 million aircraft per day.

The learning curve reduces costs.

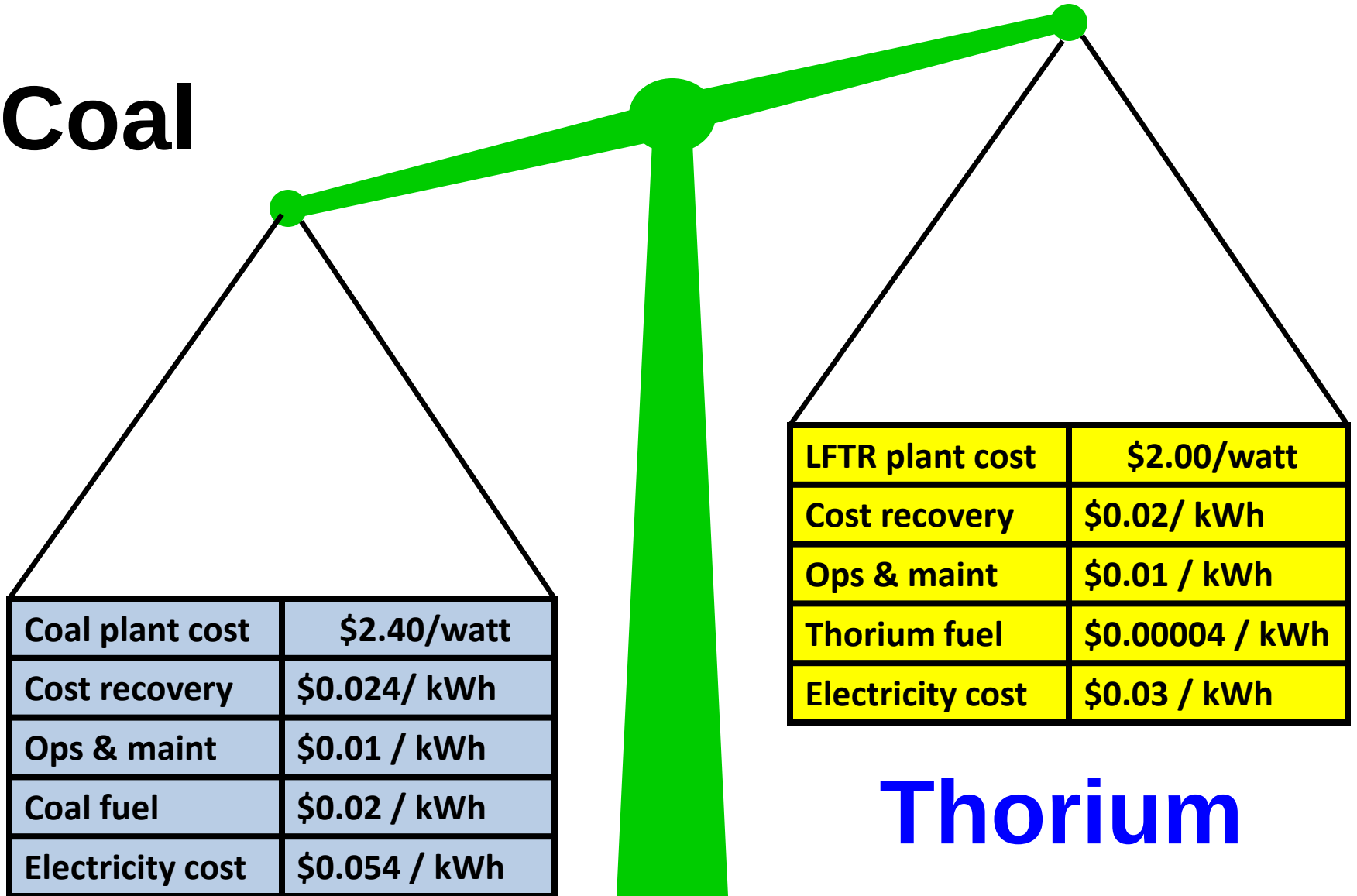


LFTR can undersell coal.

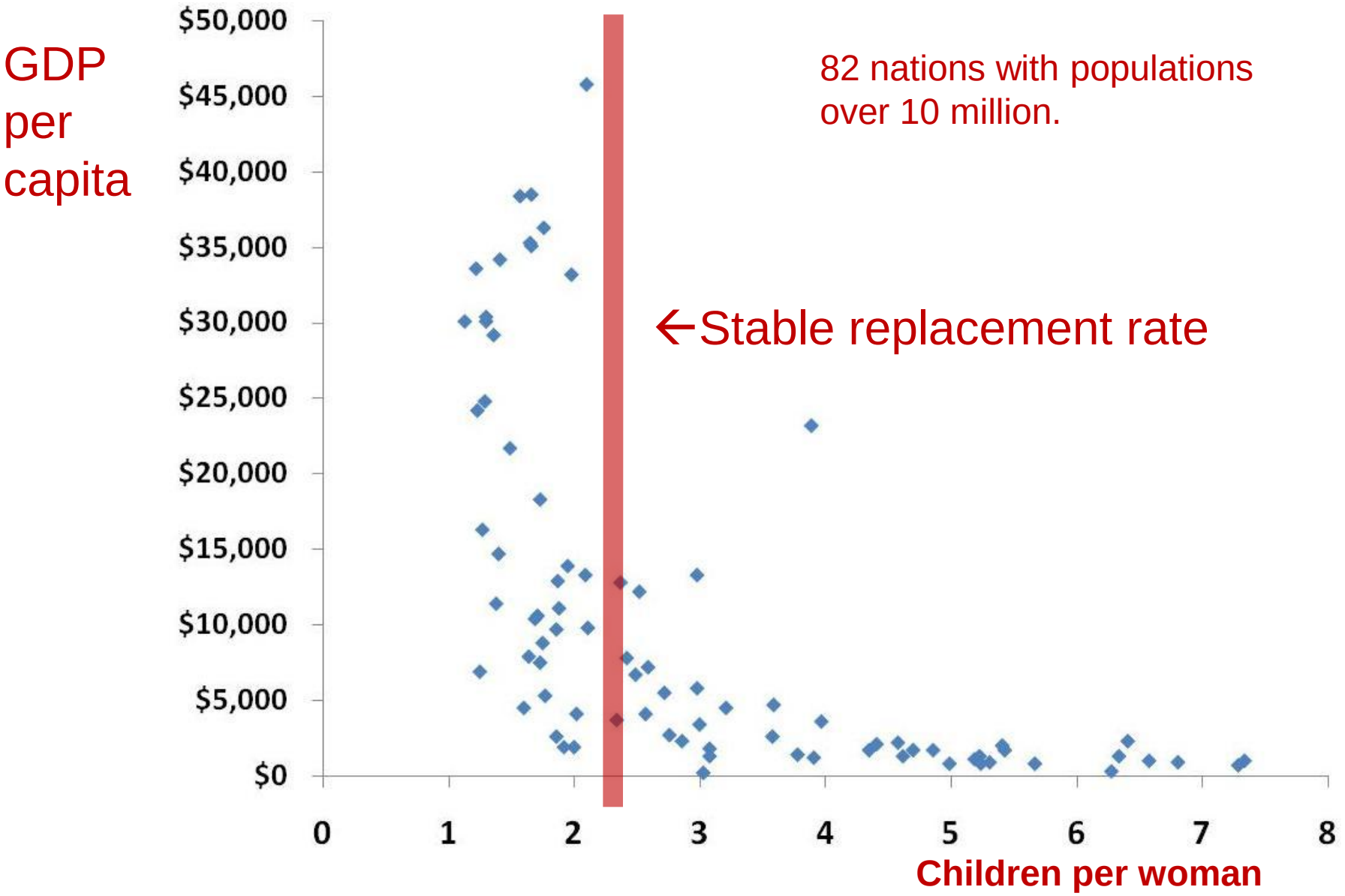


Coal plant cost	$2.40/watt
Cost recovery	$0.024/ kWh
Ops & maint	$0.01 / kWh
Coal fuel	$0.02 / kWh
Electricity cost	$0.054 / kWh

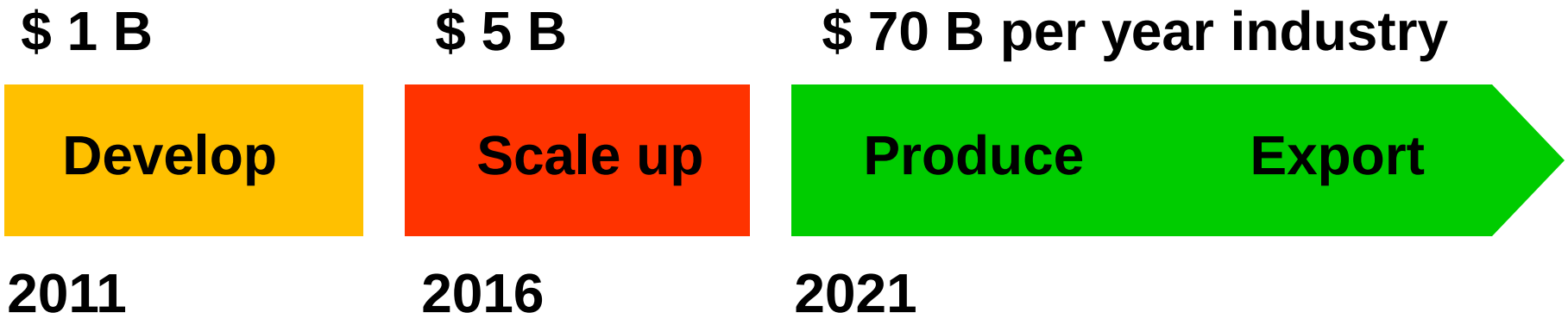
LFTR can undersell coal.



Aim High! Stabilize world population.



Aim High!



Cut 10 billion tons/year CO_2 emissions to zero by 2058.

Avoid carbon taxes.

Improve world prosperity, and check overpopulation.

Reduce radiotoxic waste; consume world fissile stocks.

Use inexhaustible thorium fuel, available in all nations.

Walk-away safe.