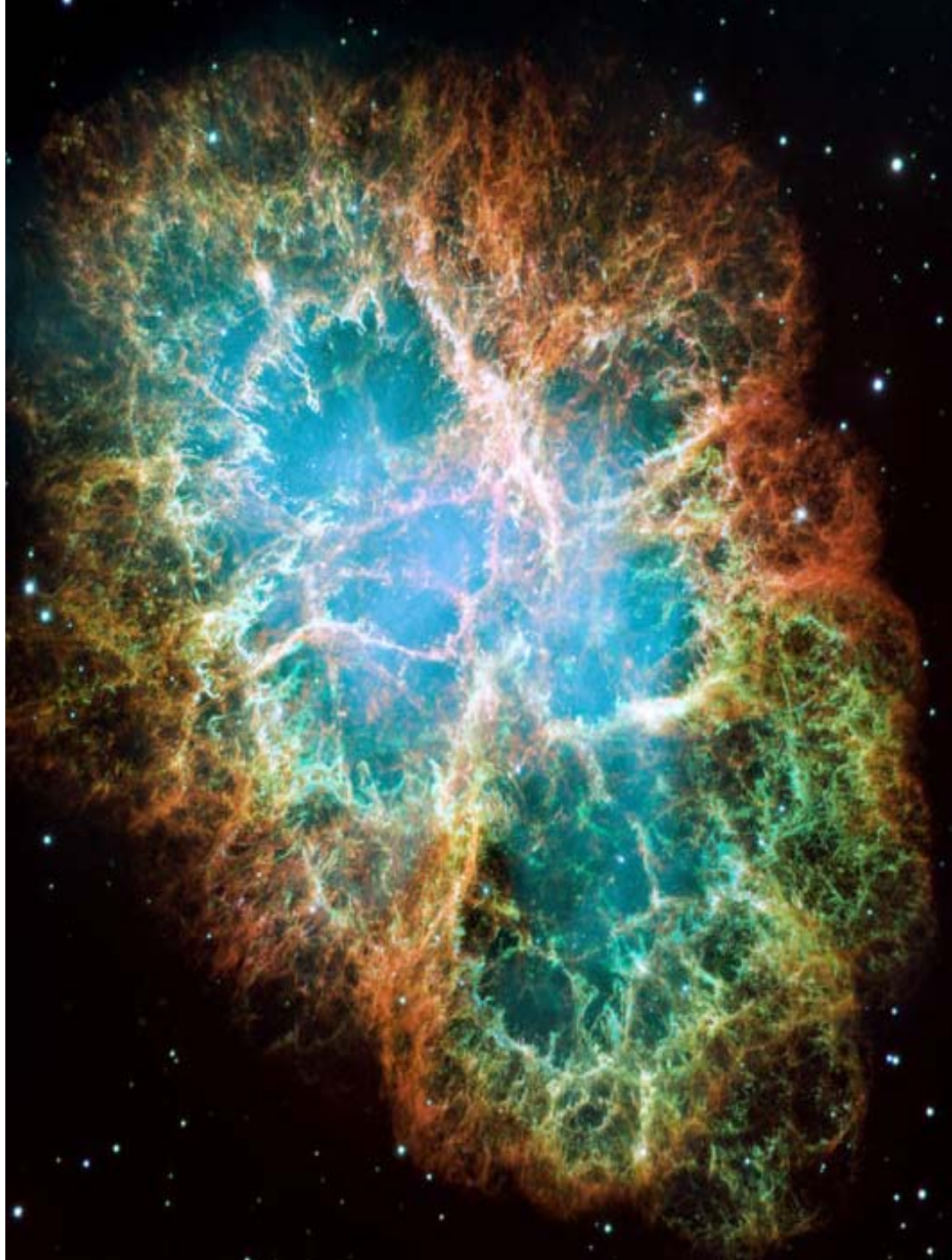
Aim High!

Thorium energy cheaper than from coal.

Walk away safe.

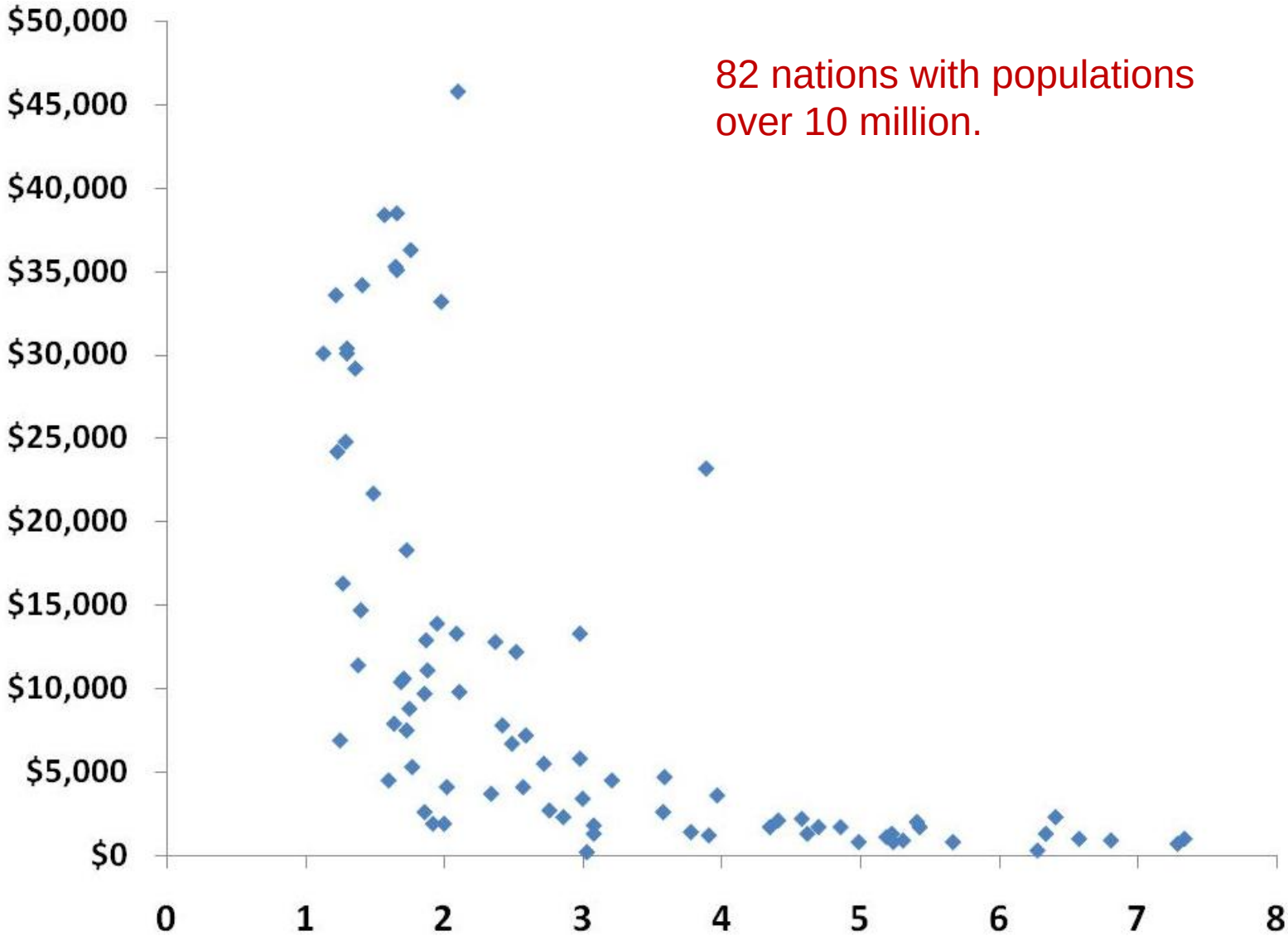
robert.hargraves@gmail.com



Global environmental problems mount.

Prosperity stabilizes population.

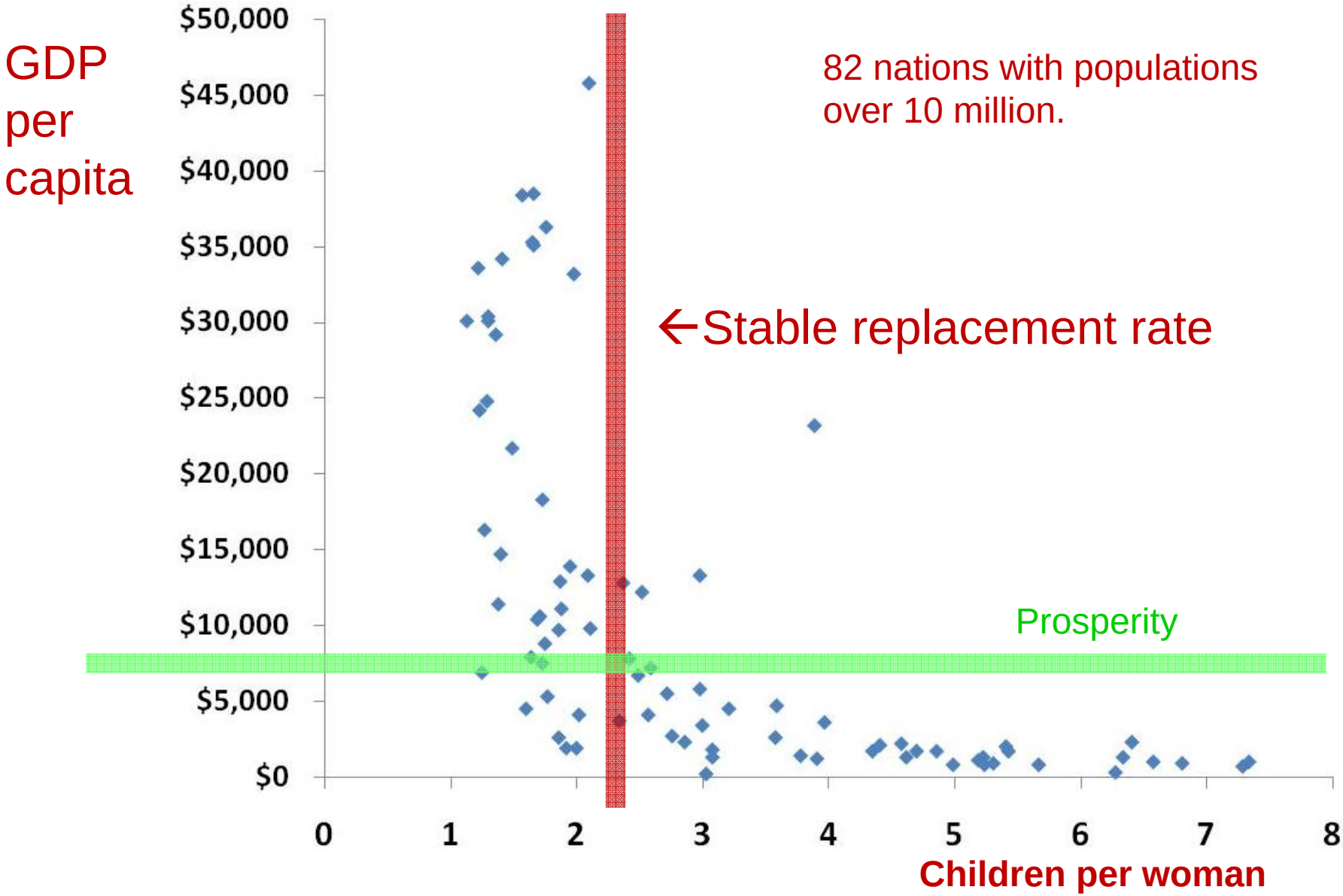
GDP per capita



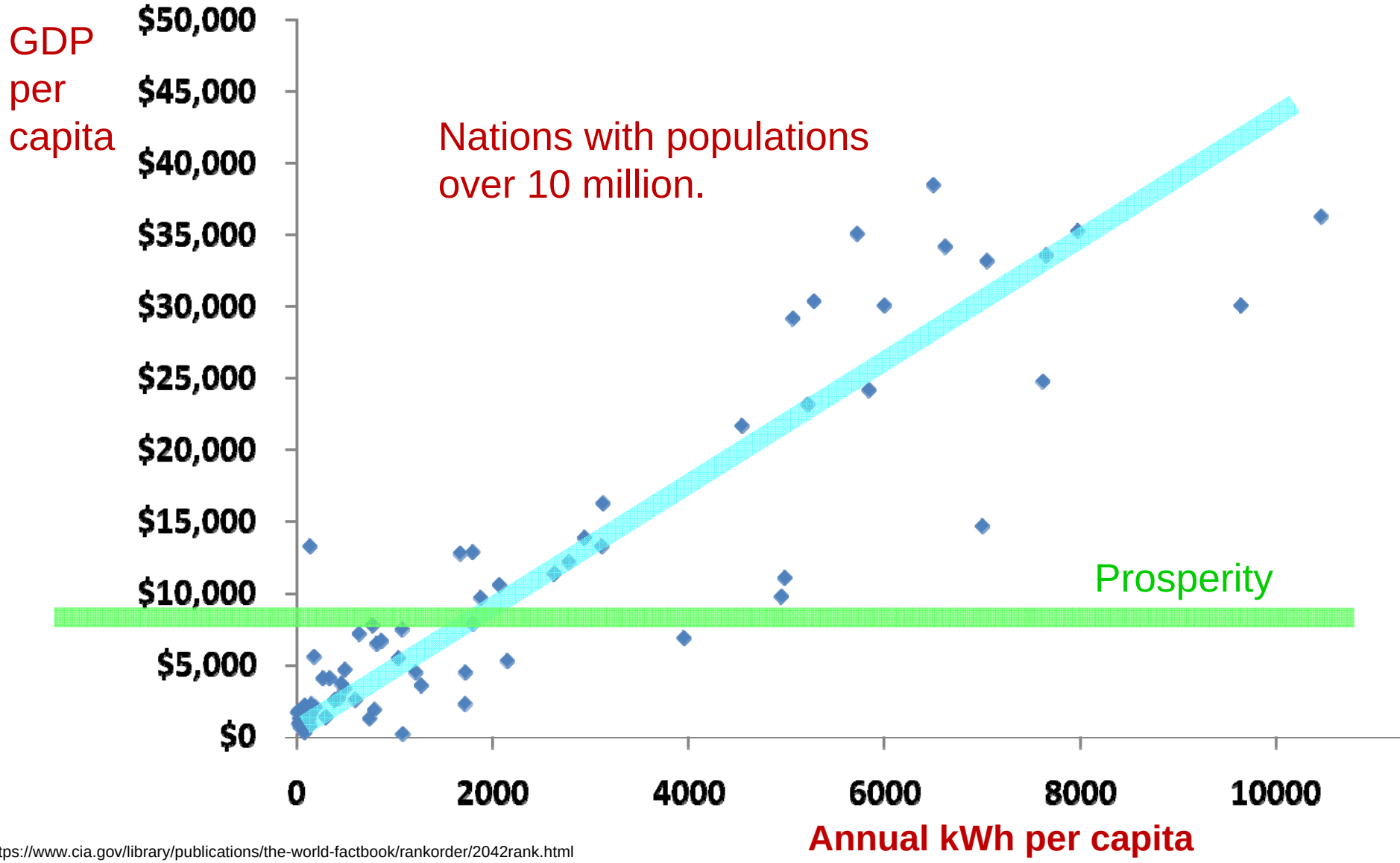
82 nations with populations over 10 million.

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

Prosperity stabilizes population.

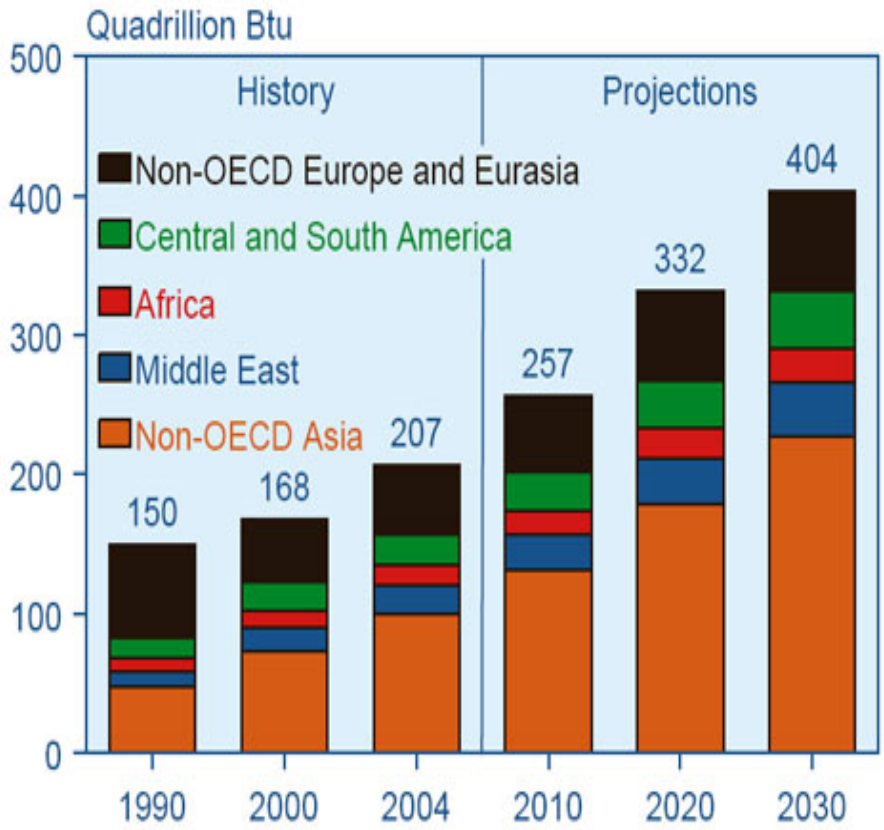


Prosperity depends on energy.

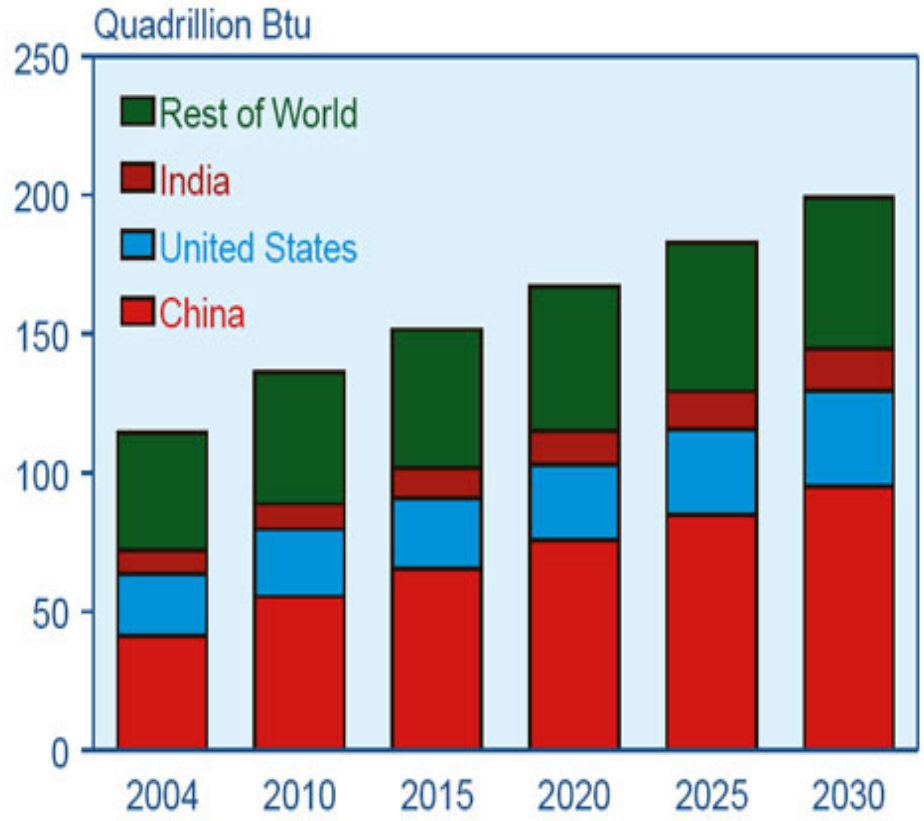


https://www.cia.gov/library/publications/the-world-factbook/rankorder/2042rank.html

Energy and coal use is growing rapidly in developing nations.



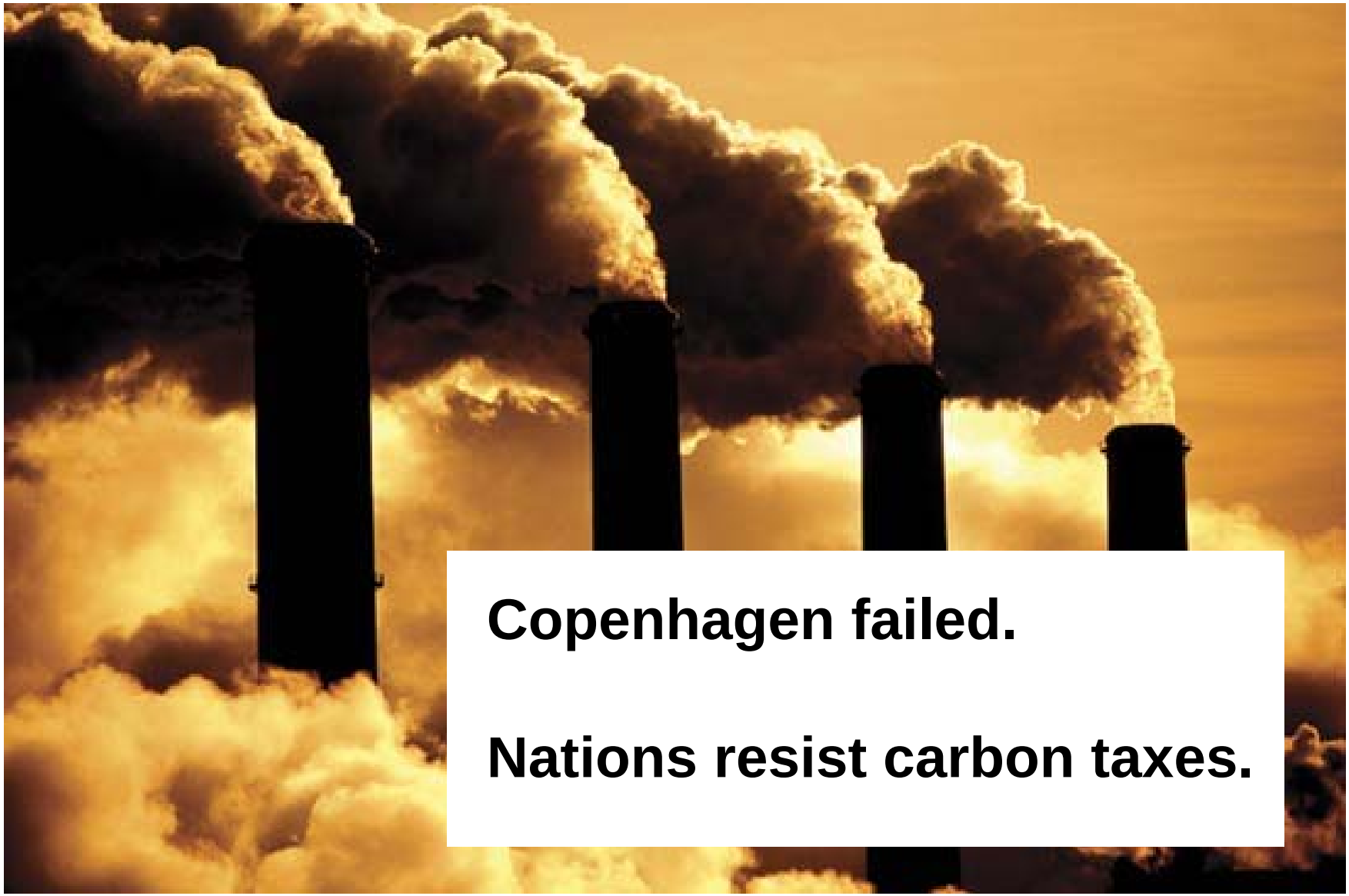
Non-OECD energy use



World coal use

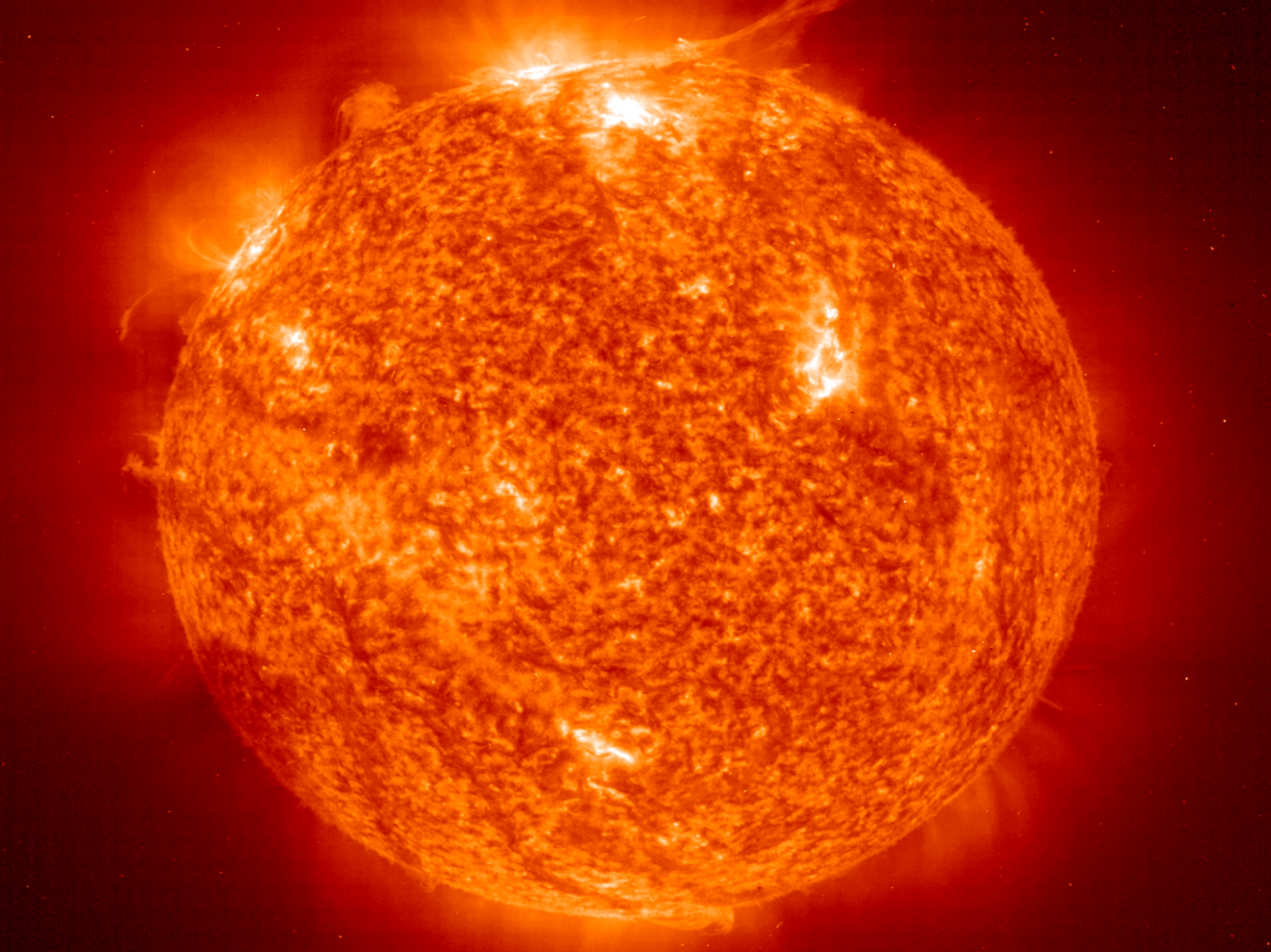
http://www.eia.doe.gov/oiaf/ieo/world.html

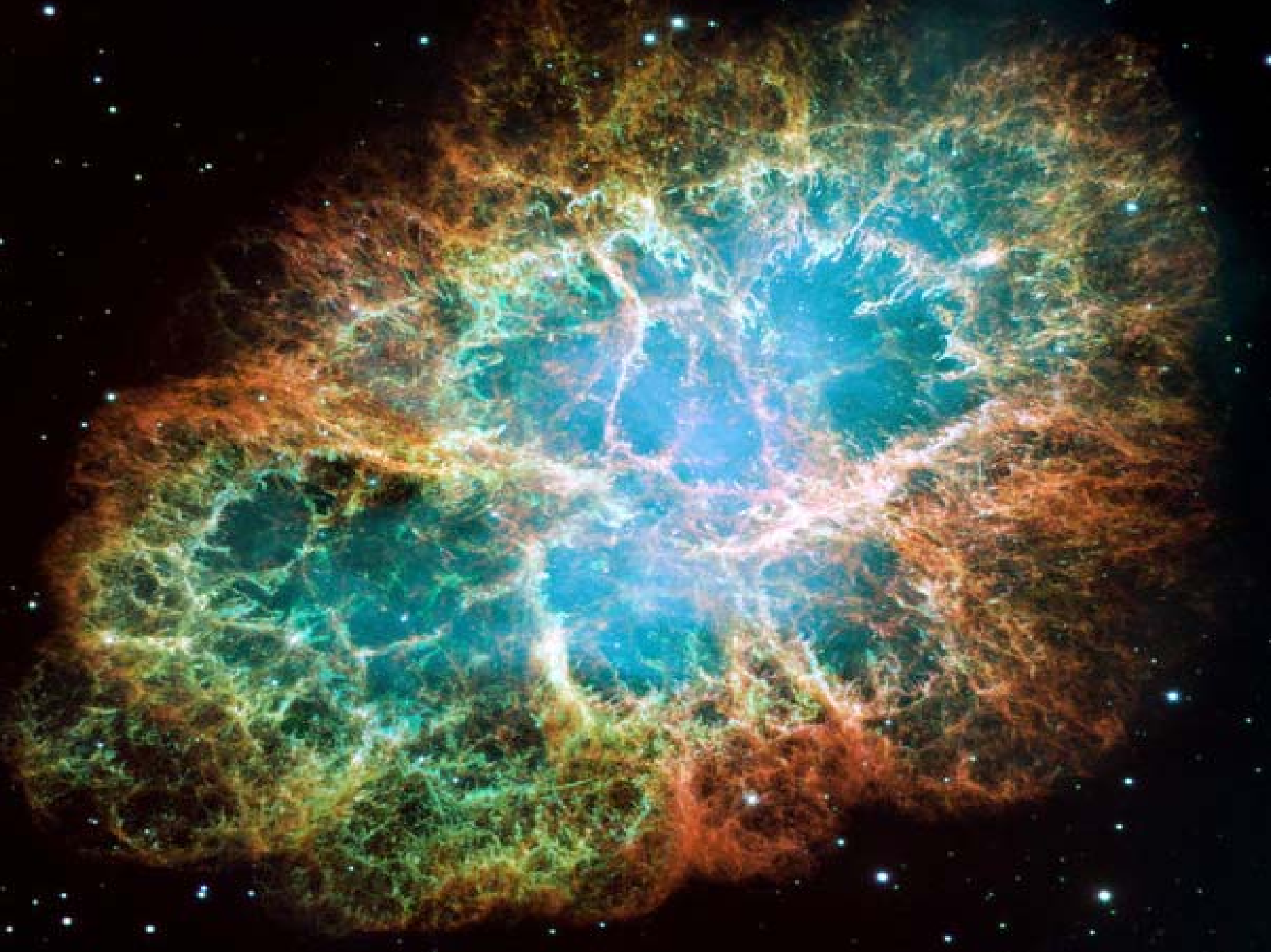
We need energy cheaper than from coal.



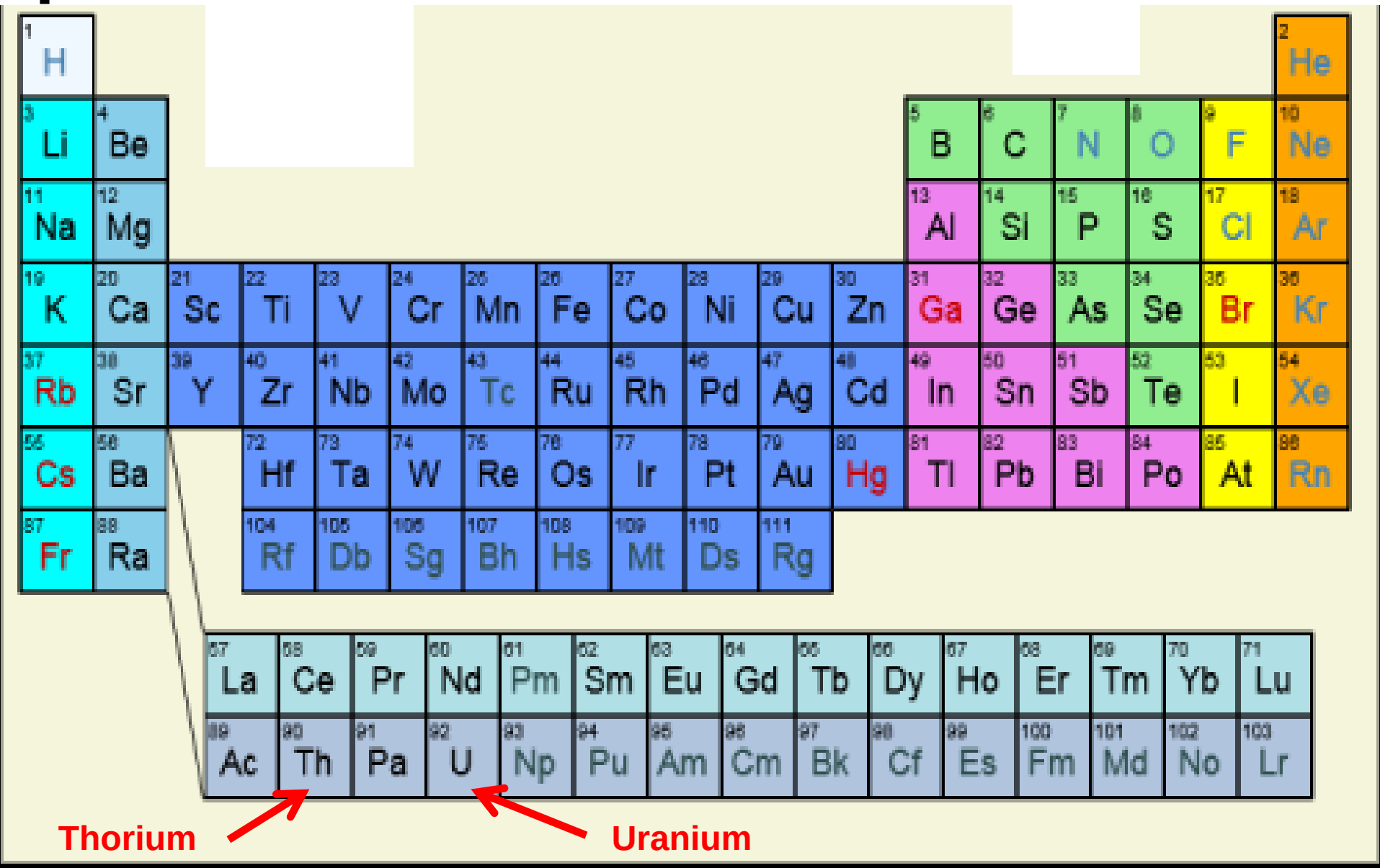
Copenhagen failed.

Nations resist carbon taxes.



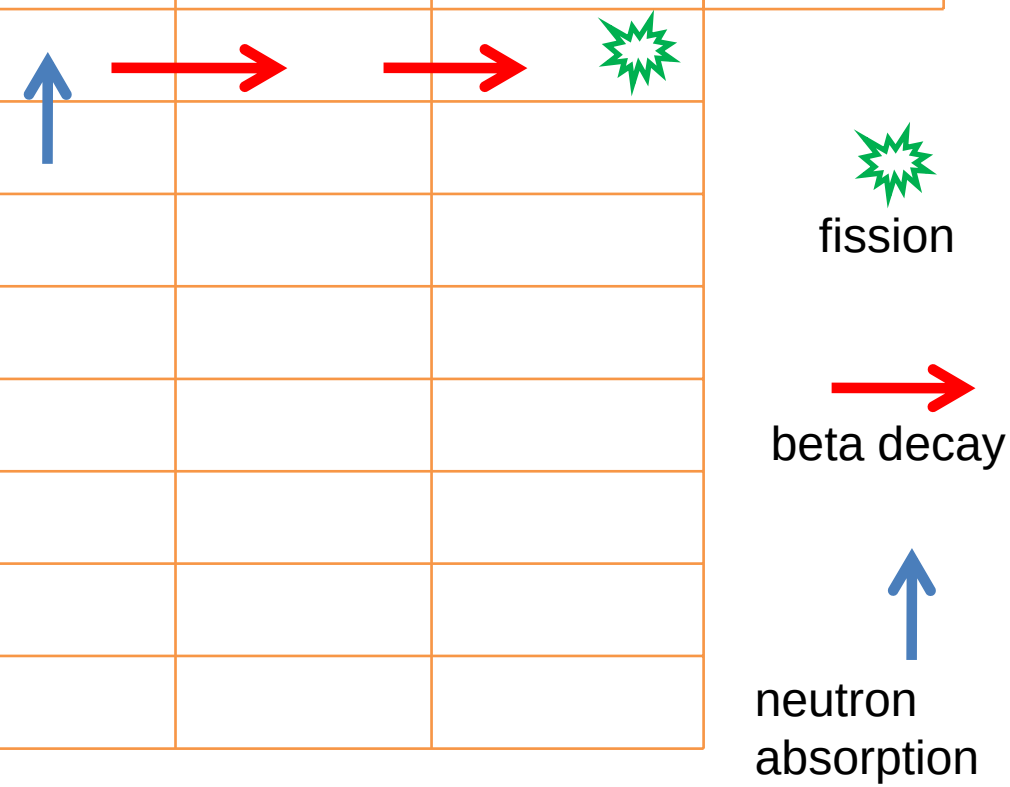


A supernova made the elements of the periodic table.



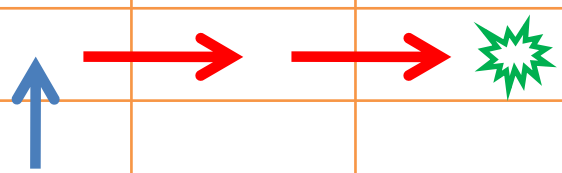
Uranium-238 neutron absorption makes fissionable plutonium-239.

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



Thorium-232 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						

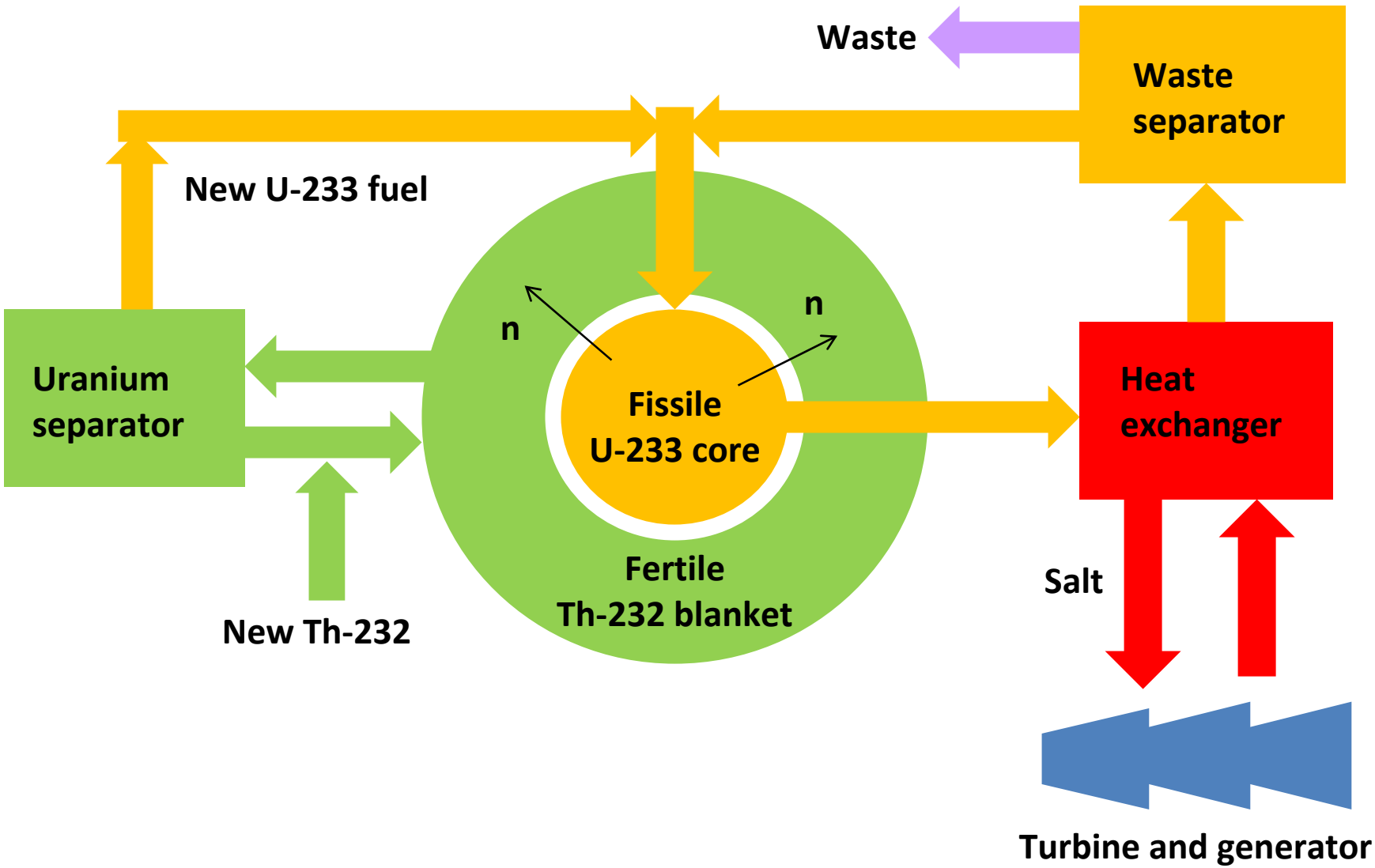


fission

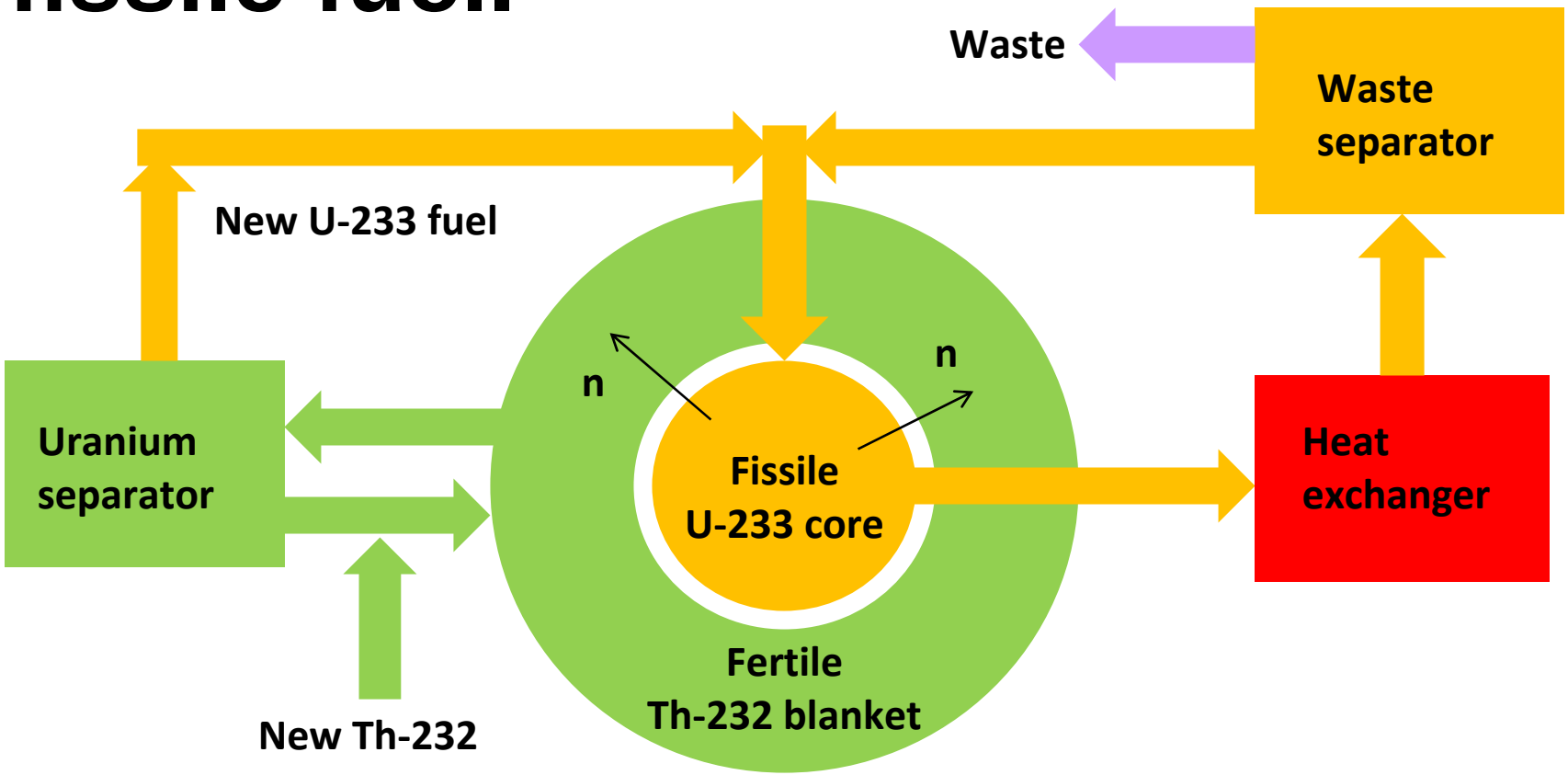
beta decay

neutron absorption

A Liquid Fluoride Thorium Reactor (LFTR) makes thorium into uranium.

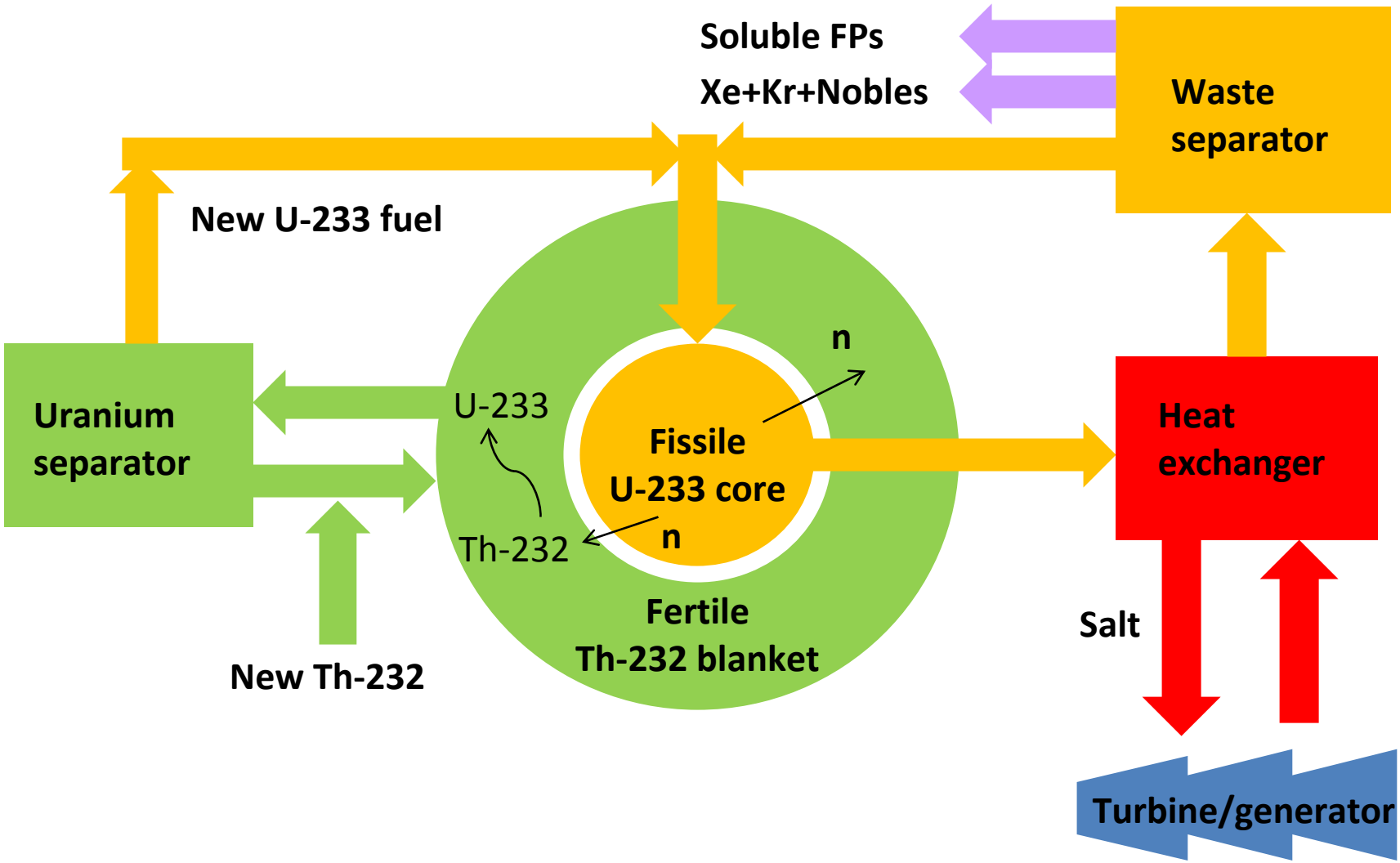


Start up LFTR by priming it with a fissile fuel.

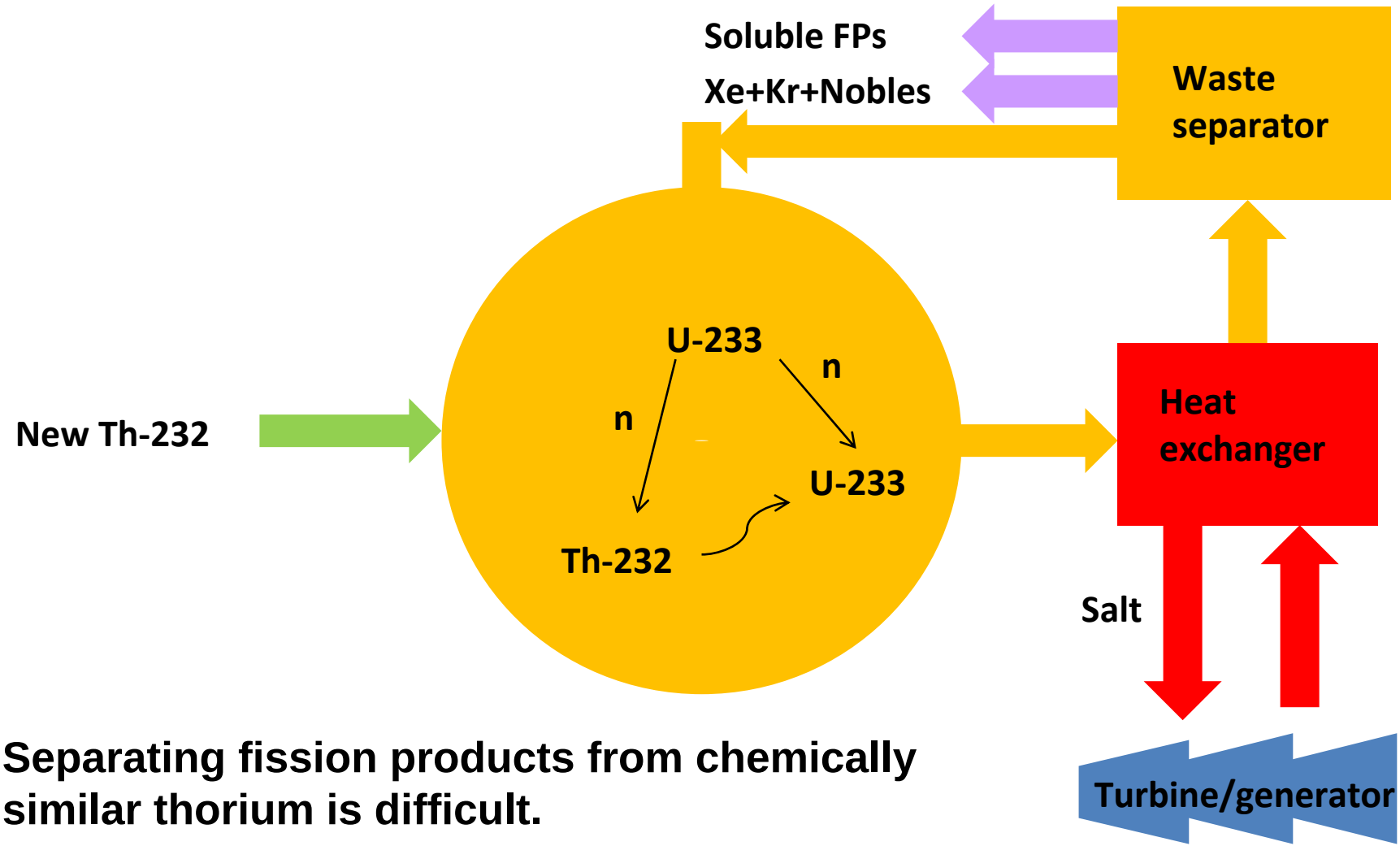


- The US government has 500 kg of U-233.
- Prime with U-235, or Pu from spent LWR fuel.

The two-fluid LFTR is one of several molten salt reactor designs.



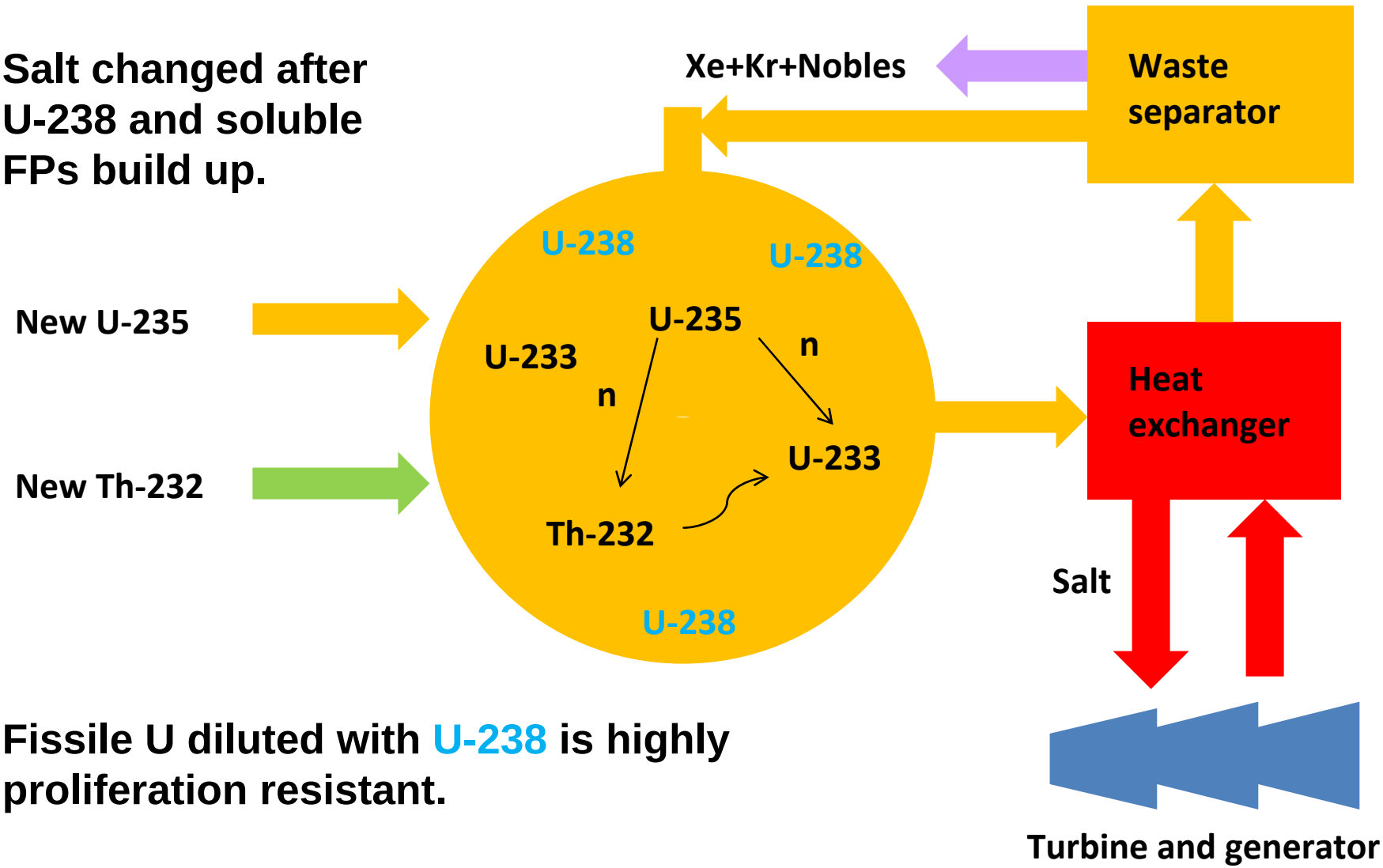
A single fluid thorium reactor makes U-233 within the fissioning core.



Separating fission products from chemically similar thorium is difficult.

Denatured thorium molten salt reactor needs both Th-232 and U-235 feeds.

Salt changed after U-238 and soluble FPs build up.

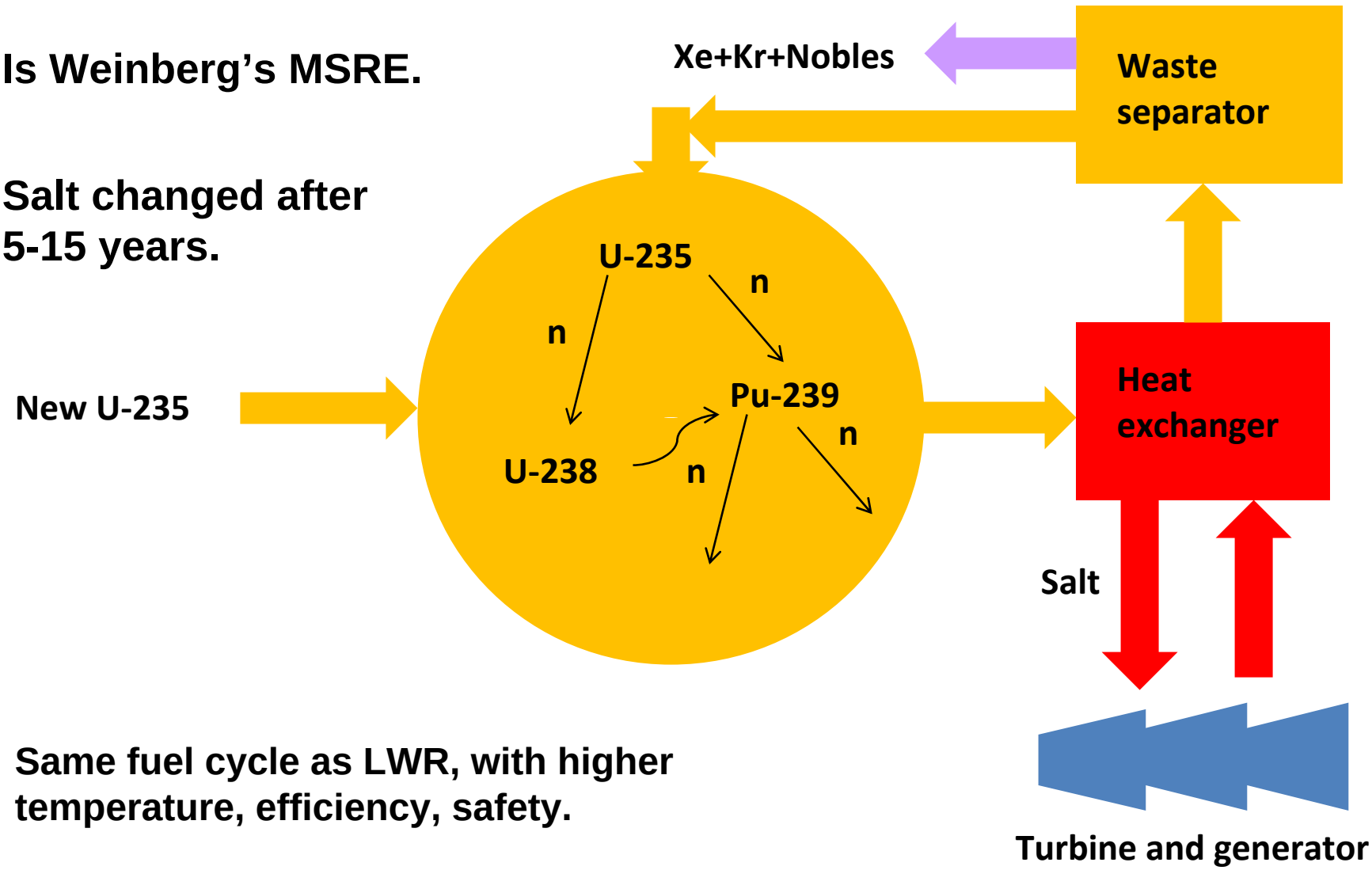


Fissile U diluted with U-238 is highly proliferation resistant.

A uranium molten salt reactor fissions its U-235 and some Pu-239.

Is Weinberg's MSRE.

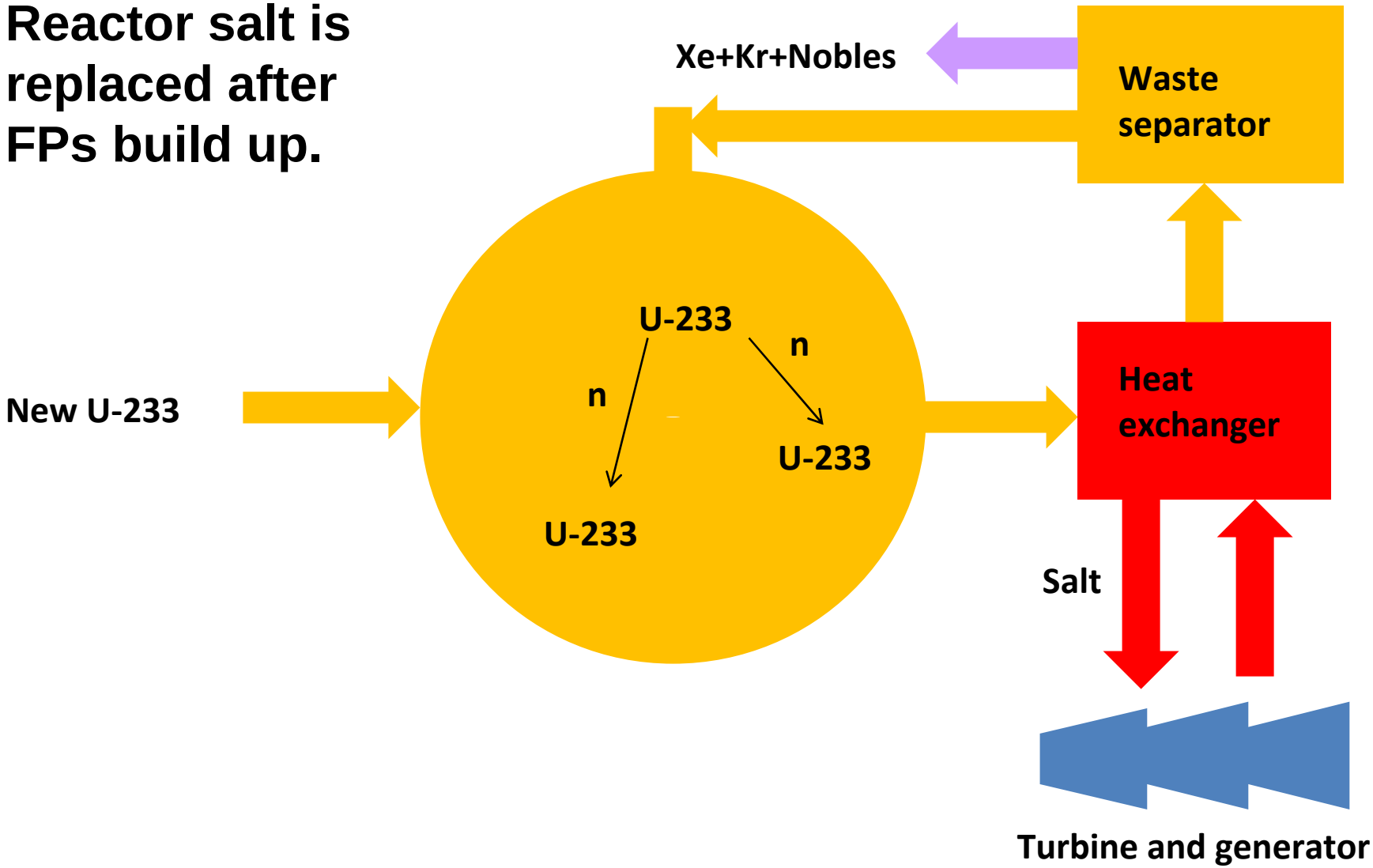
Salt changed after 5-15 years.



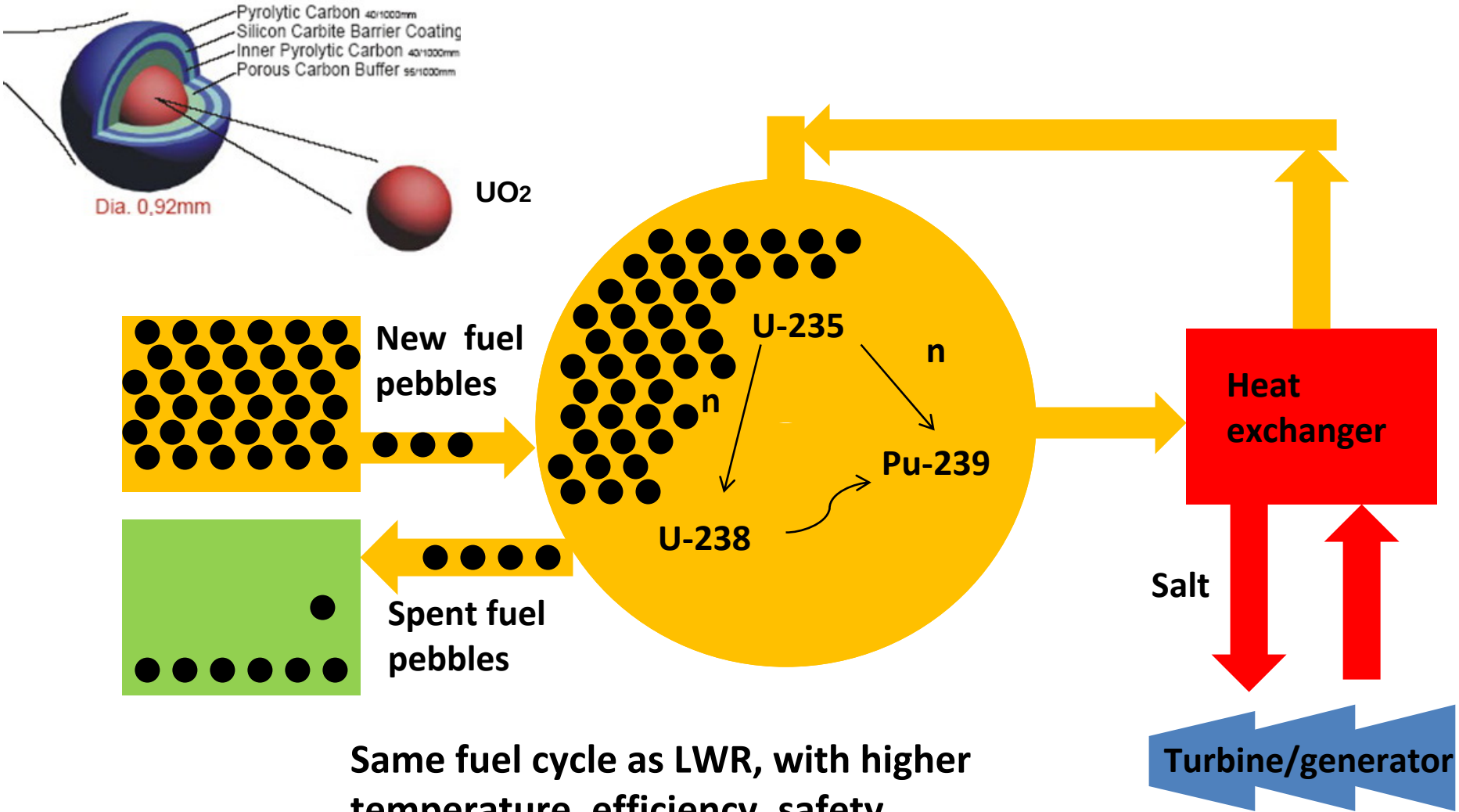
Same fuel cycle as LWR, with higher temperature, efficiency, safety.

Fuji molten salt reactors import uranium from a central Th-232/U-233 factory.

Reactor salt is replaced after FPs build up.

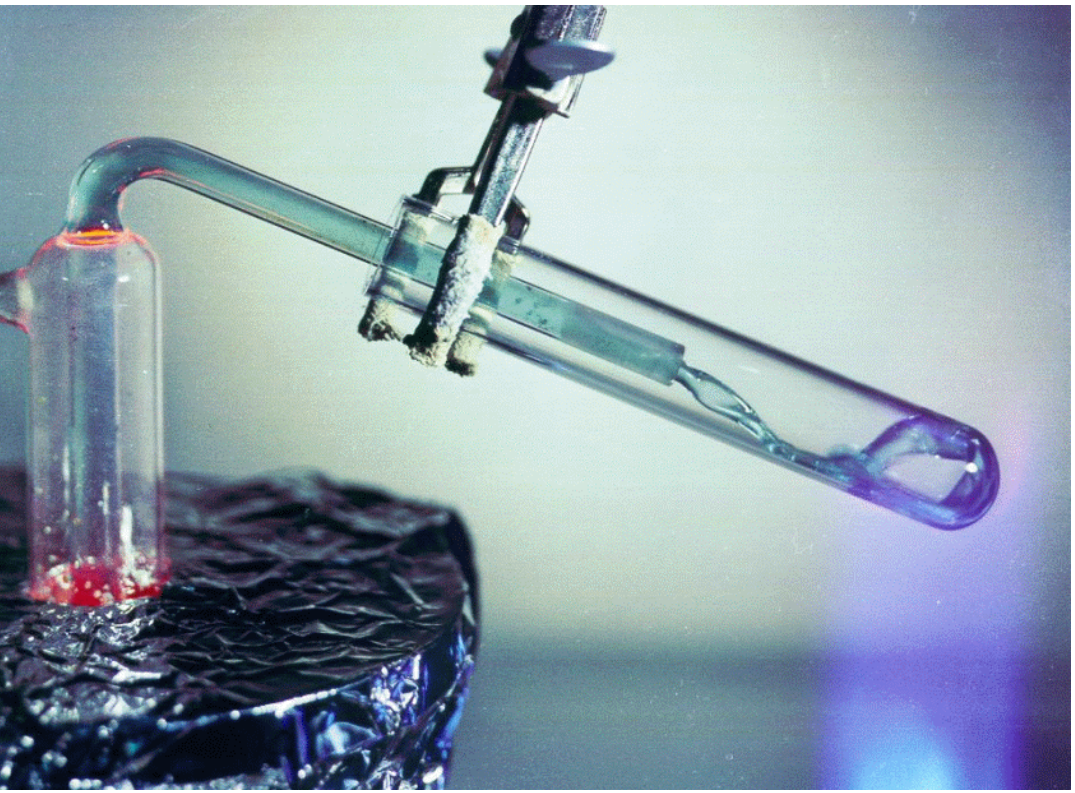


A fluoride-salt cooled reactor contains fission products within 3 ceramic layers, in pebbles.



Same fuel cycle as LWR, with higher temperature, efficiency, safety.

LFTR fuel is dissolved in liquid.



Key technology -- liquid fuel form!

Molten fluoride salt mix: LiF and BeF_2

Excellent heat transfer

Continuous chemical processing

Atmospheric pressure

Room temp solid

Thorium fuel is compact and inexpensive.

440,000 tons in US: USGS

$300,000 per ton

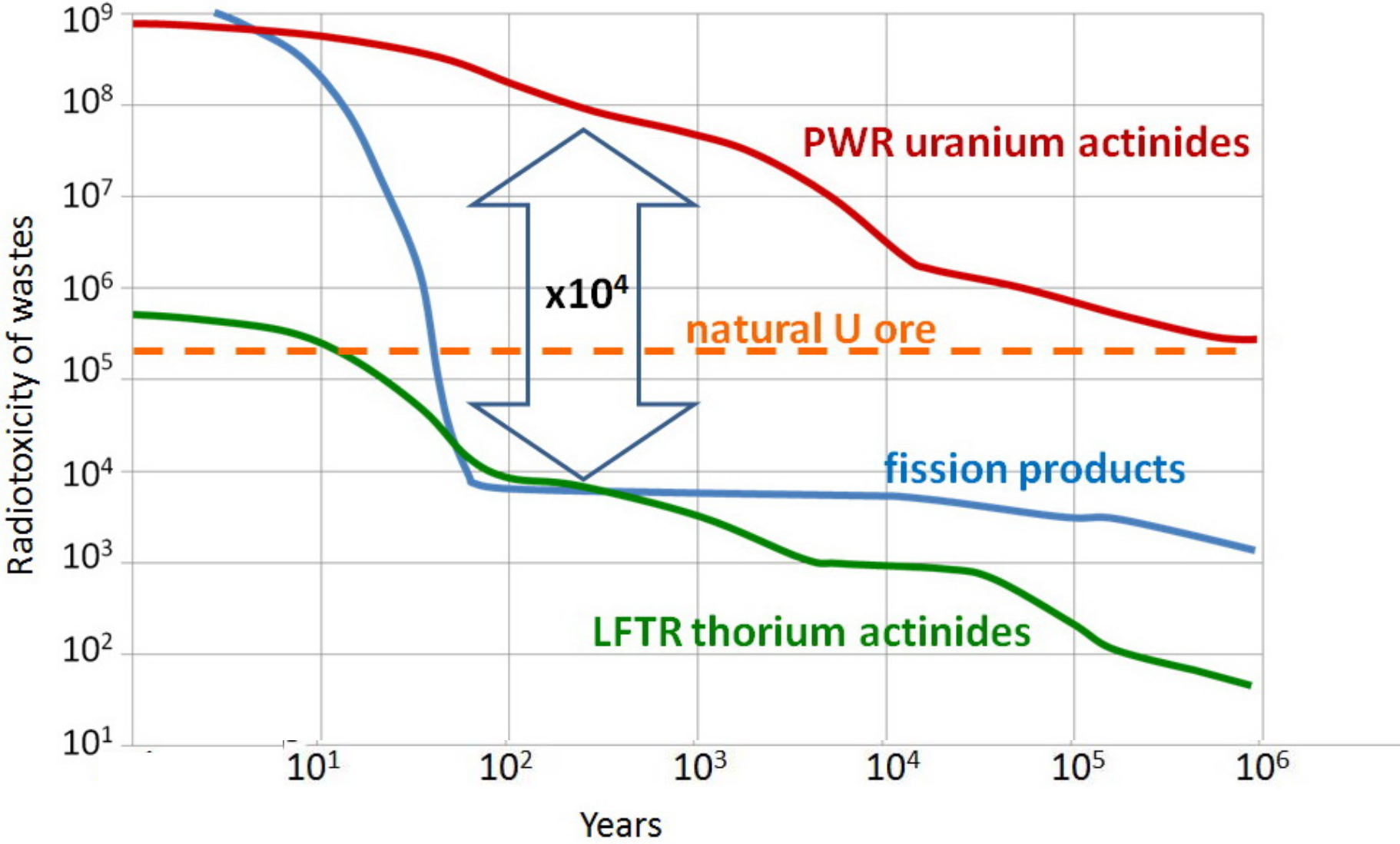
500 tons, entire US, 1 year

1 ton, 1 city, 1 year

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

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

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



LFTR is walk-away safe.

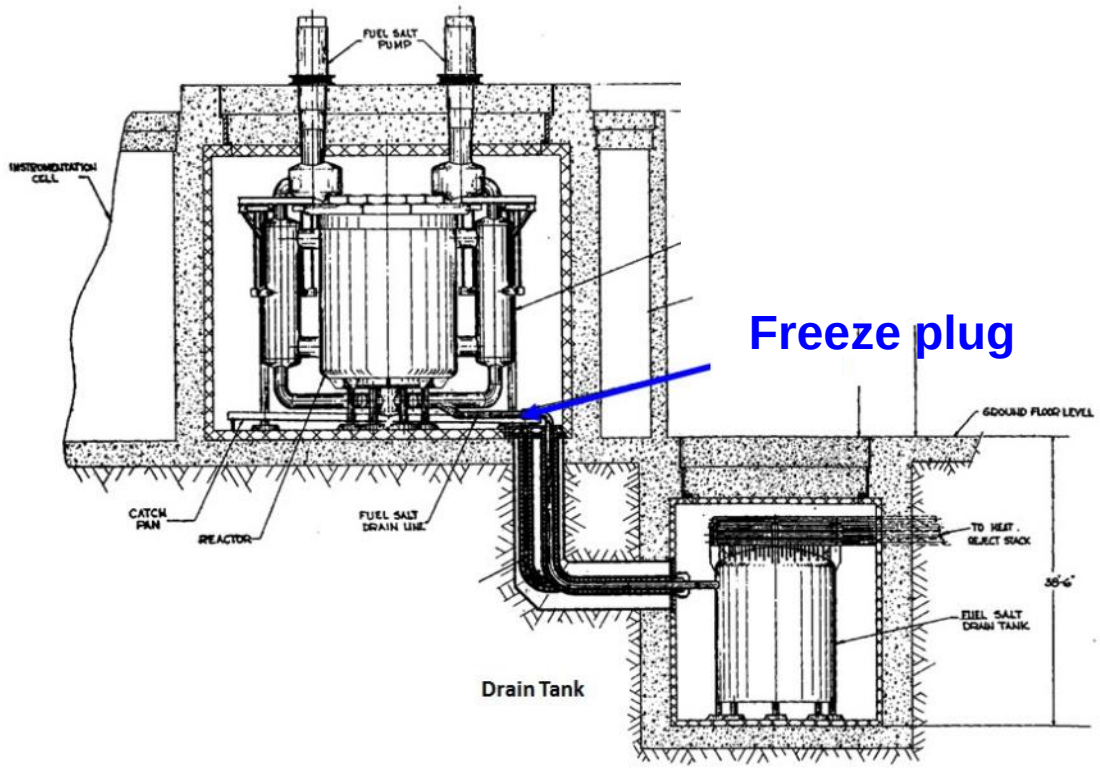
Stable reactivity.

Fuel already melted.

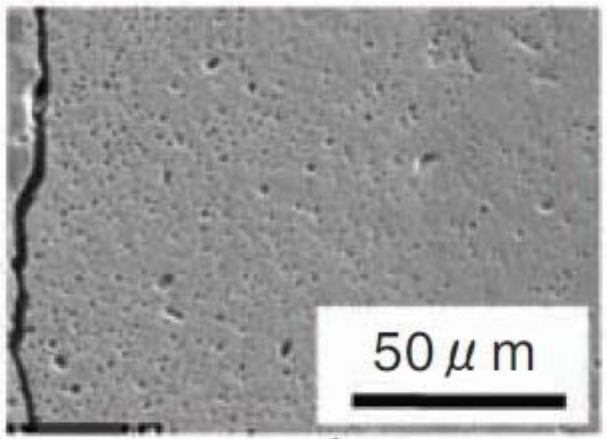
Atmospheric pressure.

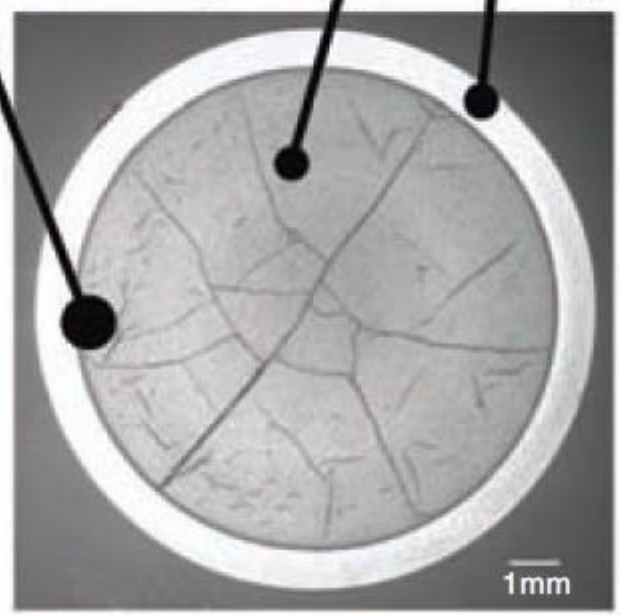
Melting freeze plug dumps salt to tank.

Salt from rupture or leak will solidify.



Radiation, fission products, and heat damage solid fuel.



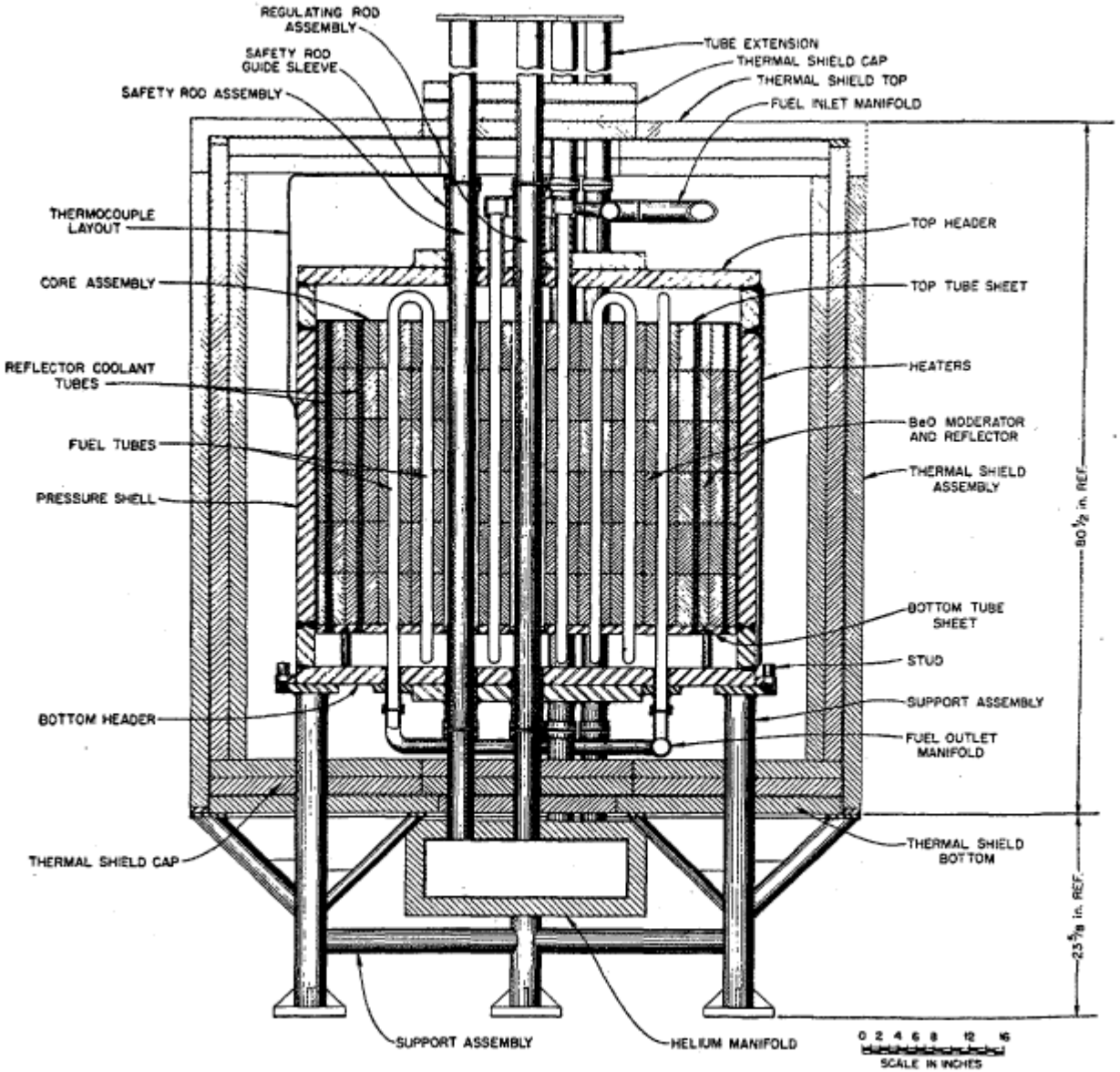


A cross section of fuel rod

Fuel rod

Zirconium cladding must contain fuel and fission products for centuries.

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



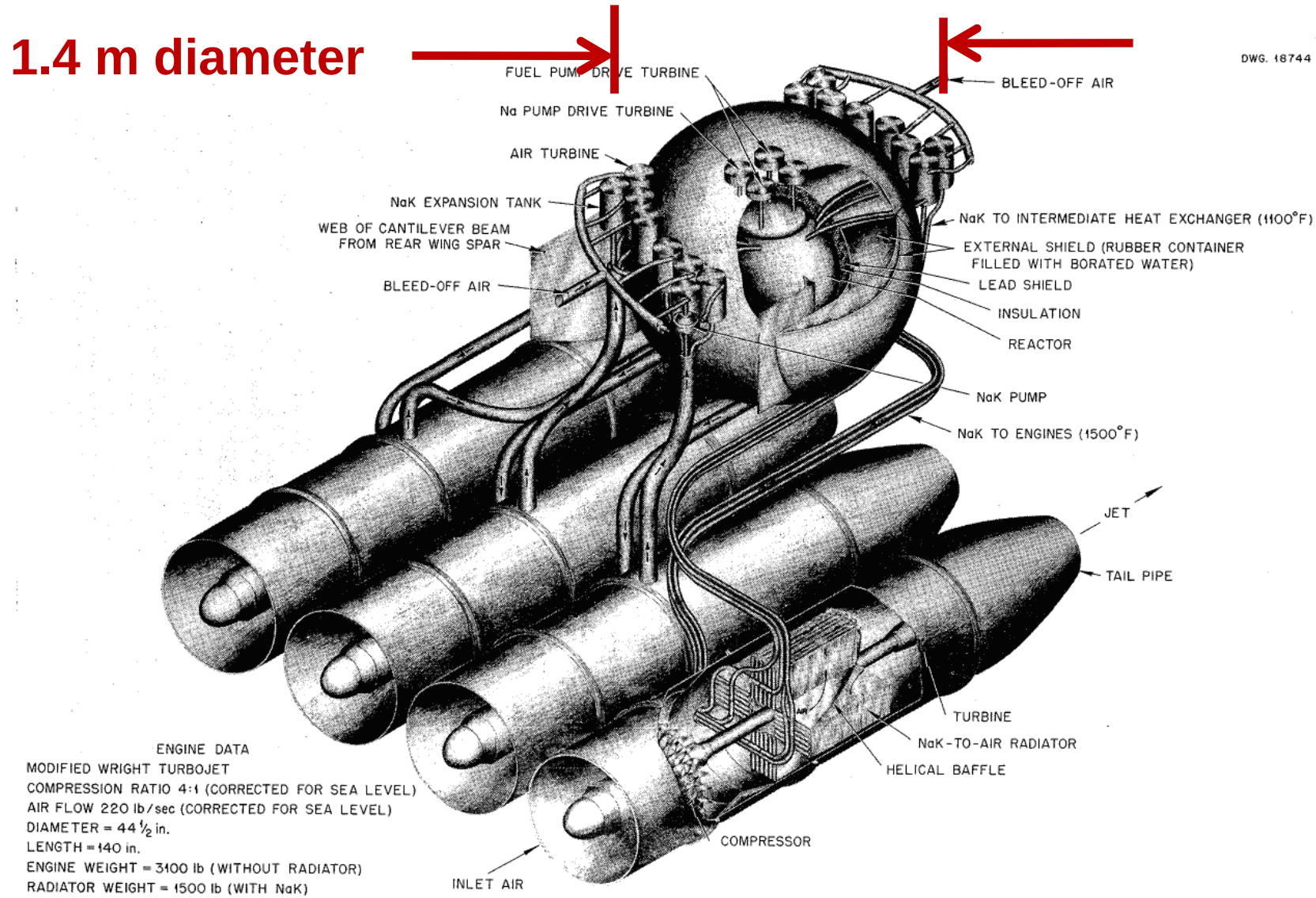
860 C

Red hot!

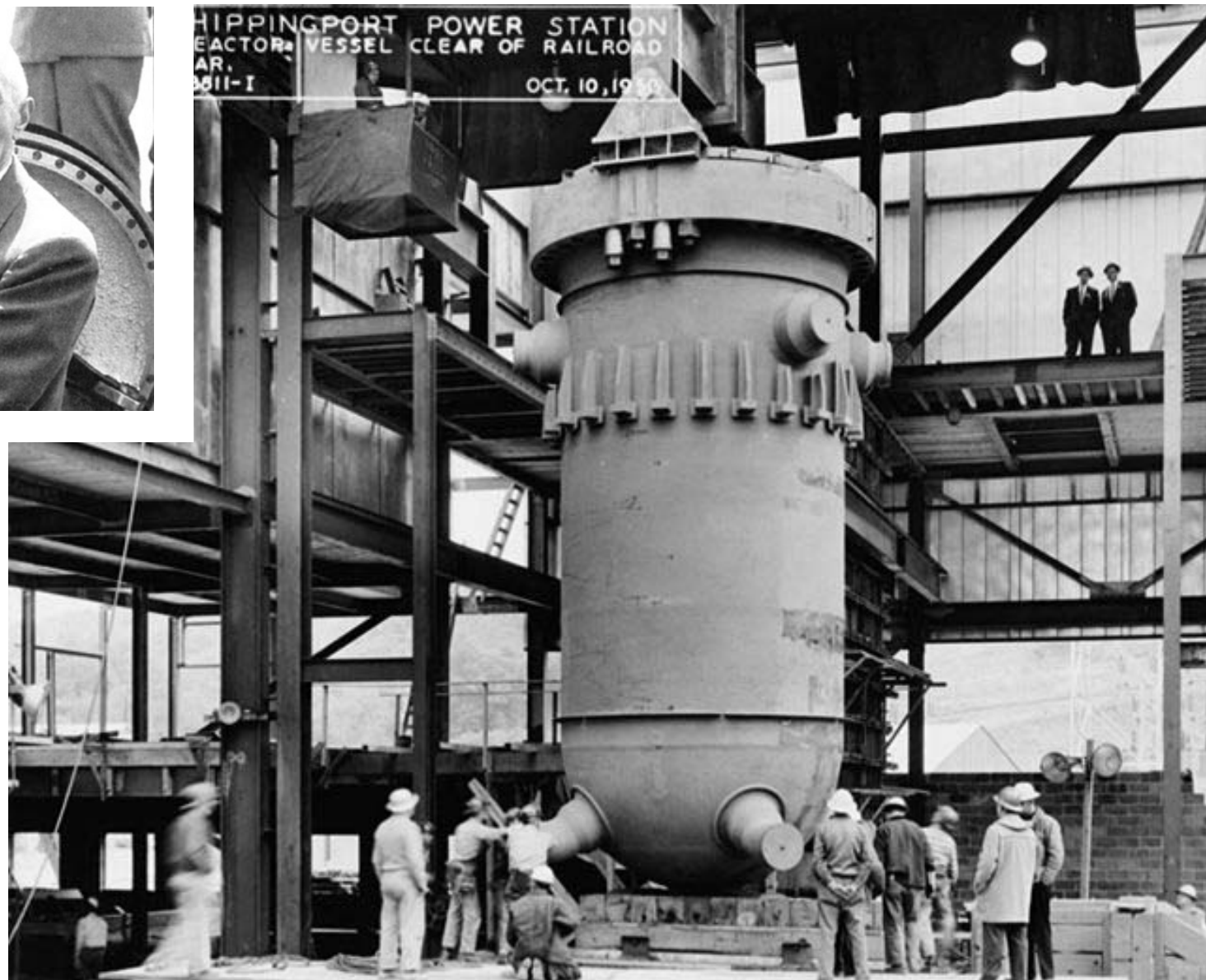
100 hours

2.5 MW

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



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

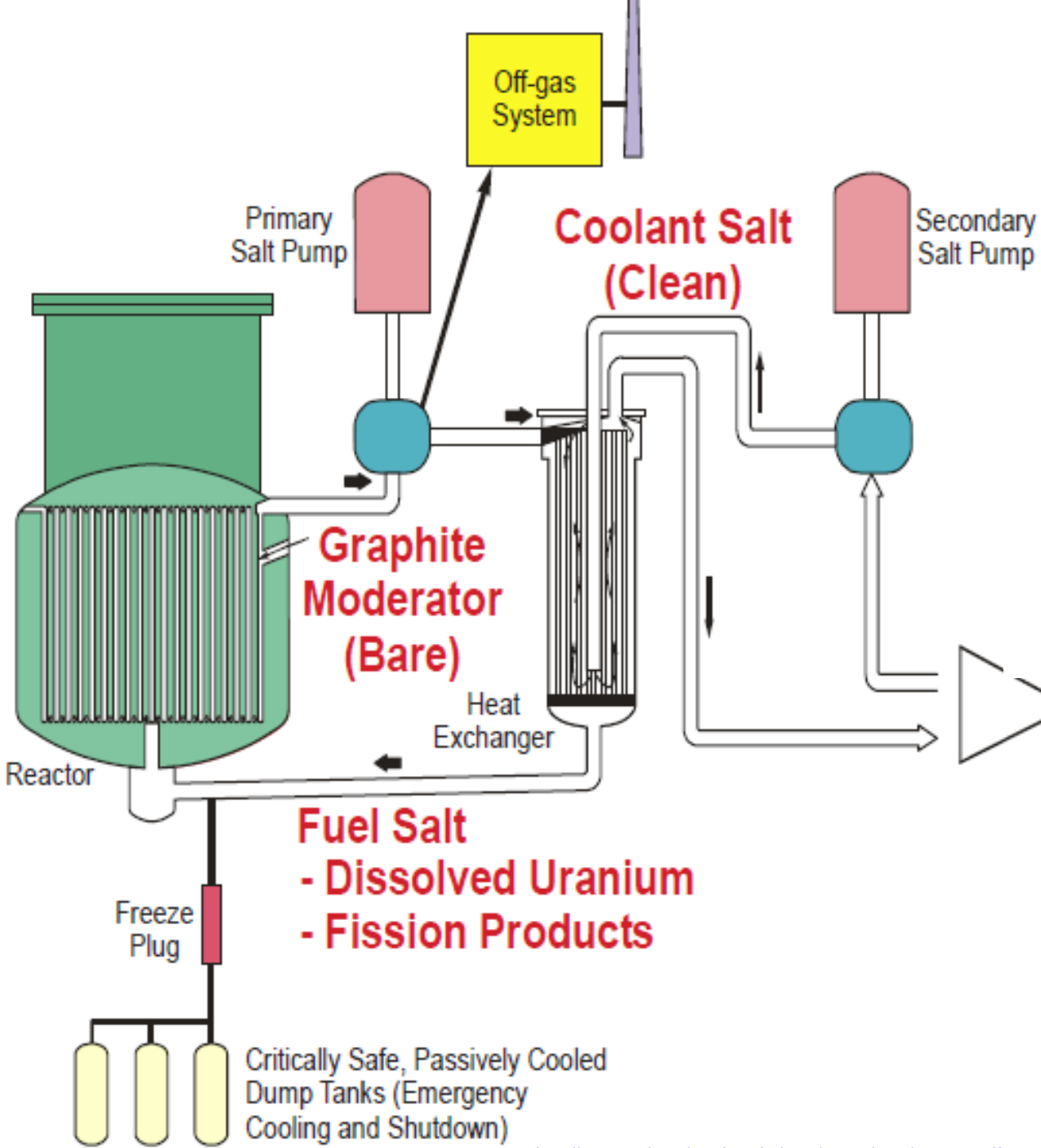


The Molten Salt Reactor Experiment ran from1965 to 1969.

Salt flowed through channels in this graphite core.

The Molten Salt Reactor Experiment succeeded.

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



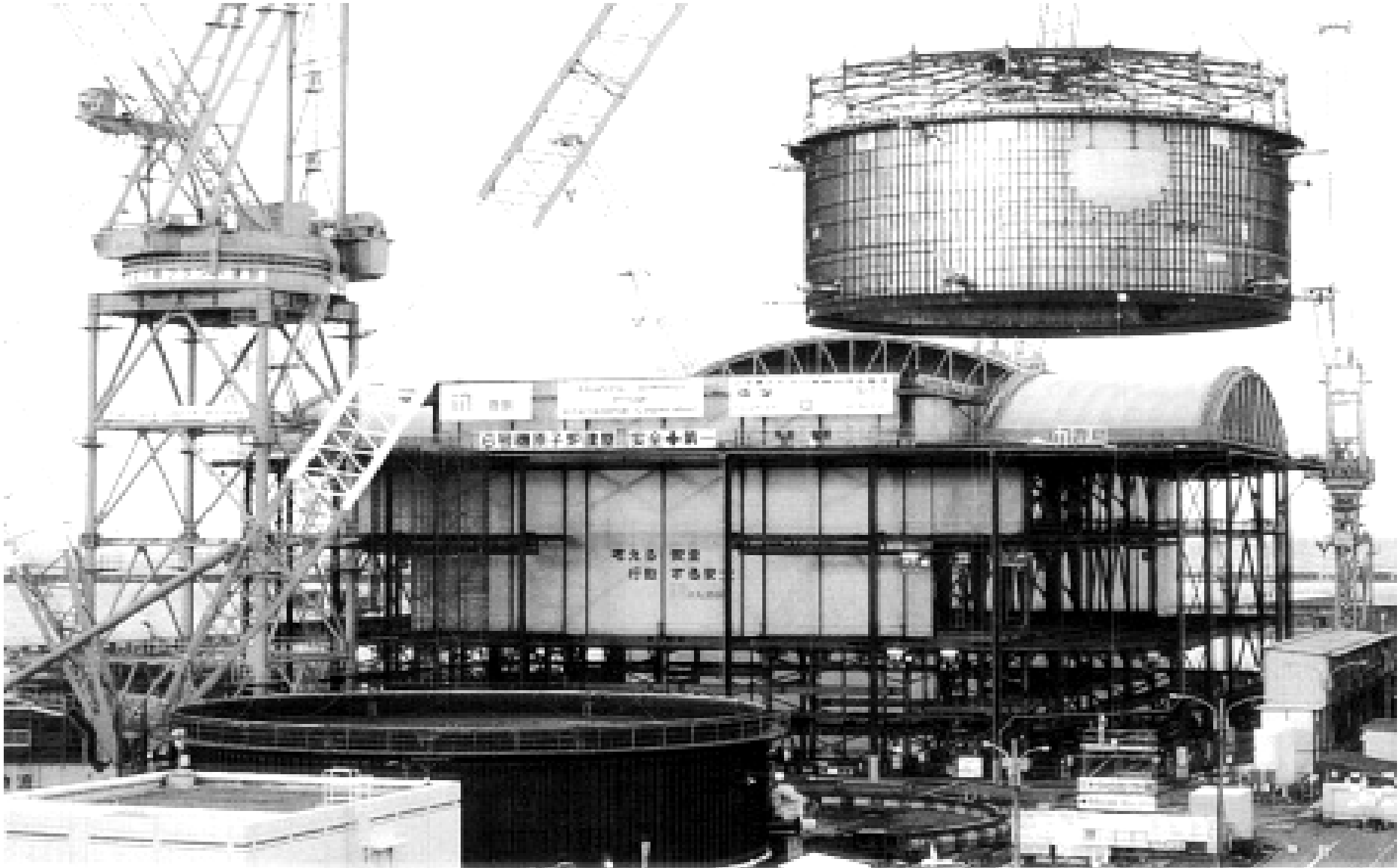
http://www.ornl.gov/~webworks/cppr/y2006/pres/124659.pdf

Why can LFTR energy be cheaper than from coal?

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

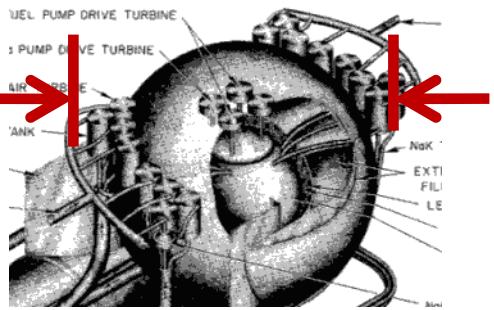
Estimate	Year	$/watt	2009 $/watt
Sargent & Lundy	1962	0.650	4.64
Sargent & Lundy ORNL TM-1060	1965	0.148	1.01
ORNL-3996	1966	0.243	1.62
Engel et al, ORNL TM7207	1978	0.653	2.16
Moir	2000	1.580	1.98

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



The Westinghouse AP-1000 is massively larger than LFTR.

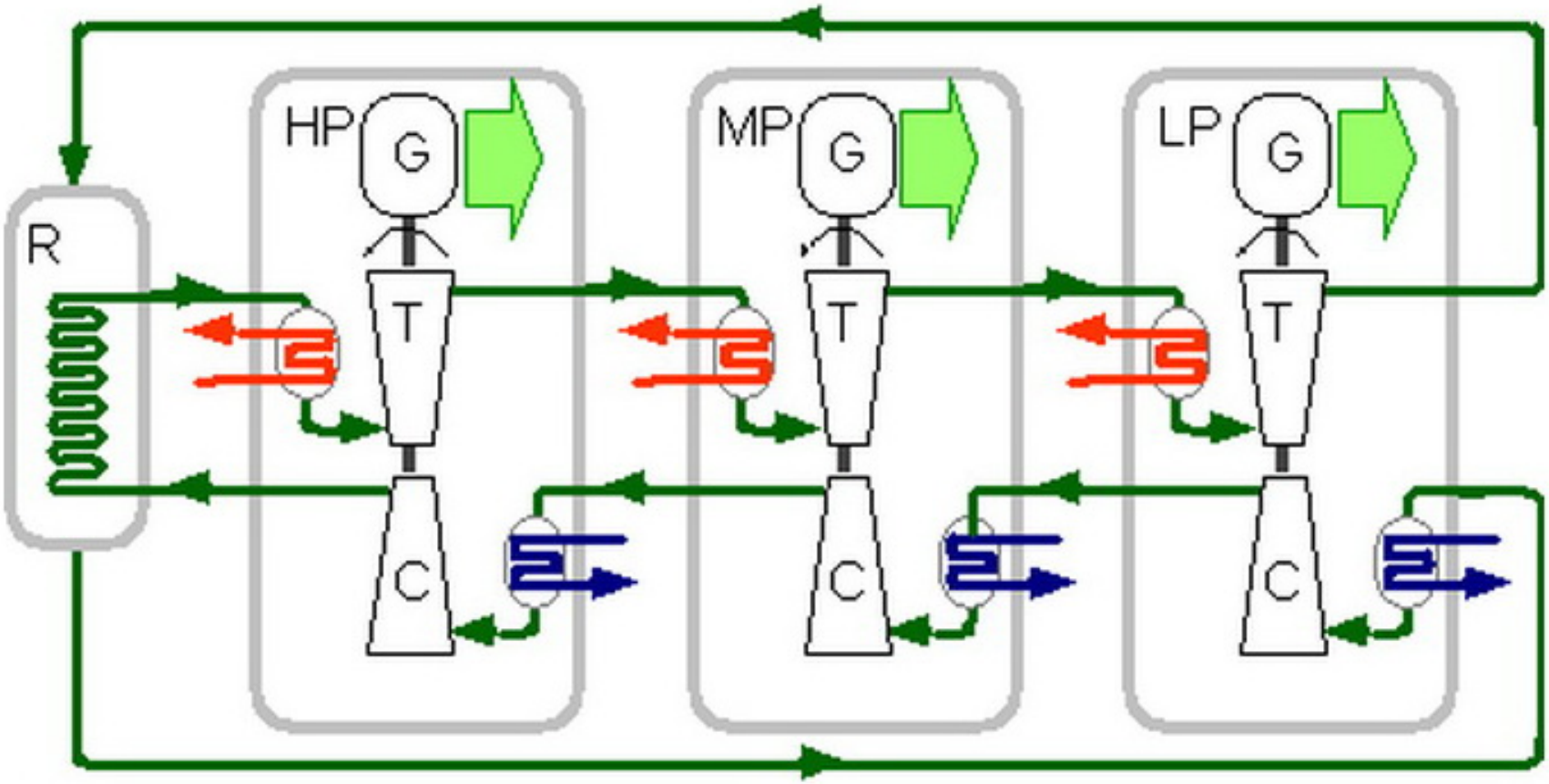
1.4 m



1.4 m

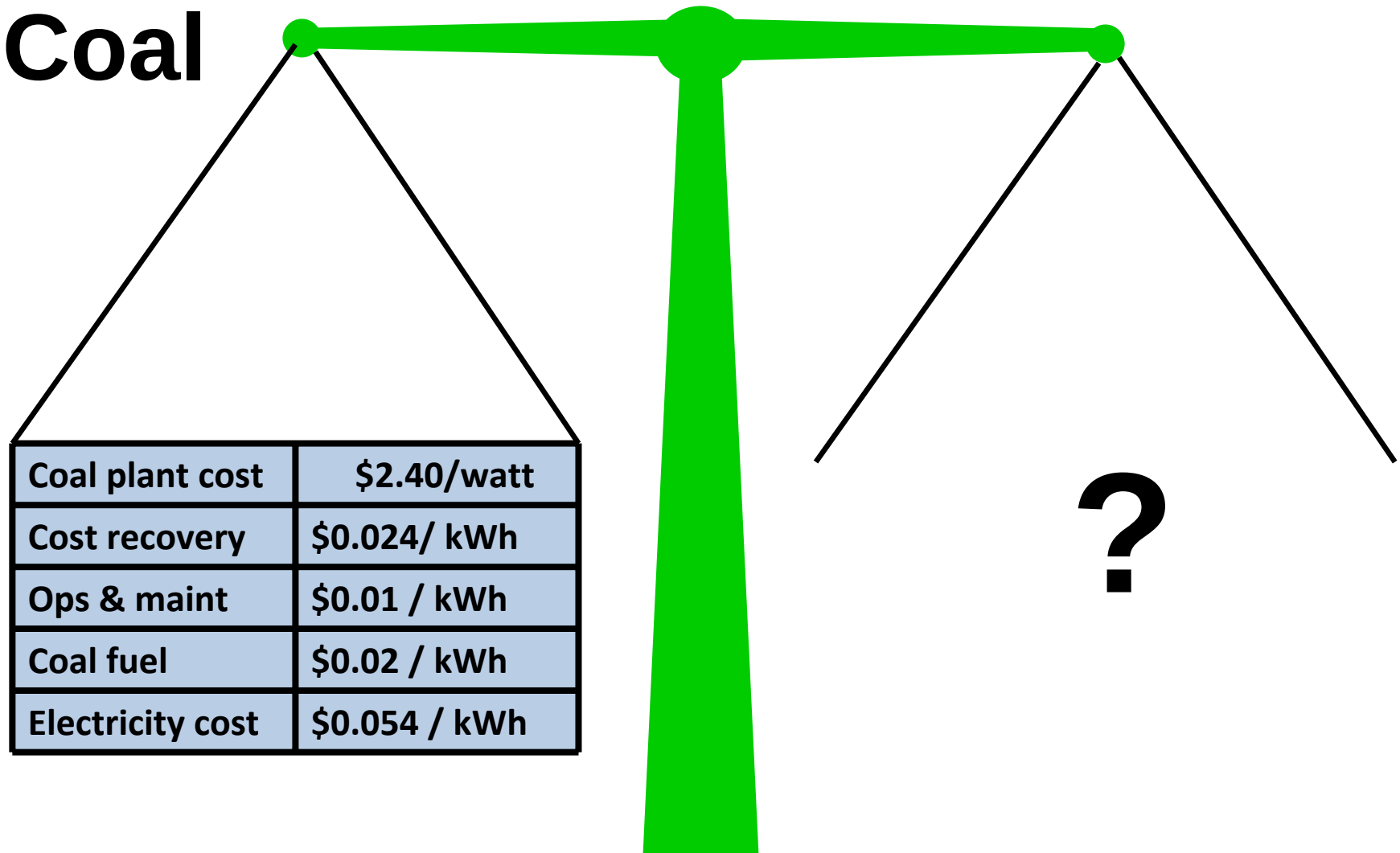
AP-1000
Samen, China

Compact closed cycle Brayton turbine raises power conversion efficiency.



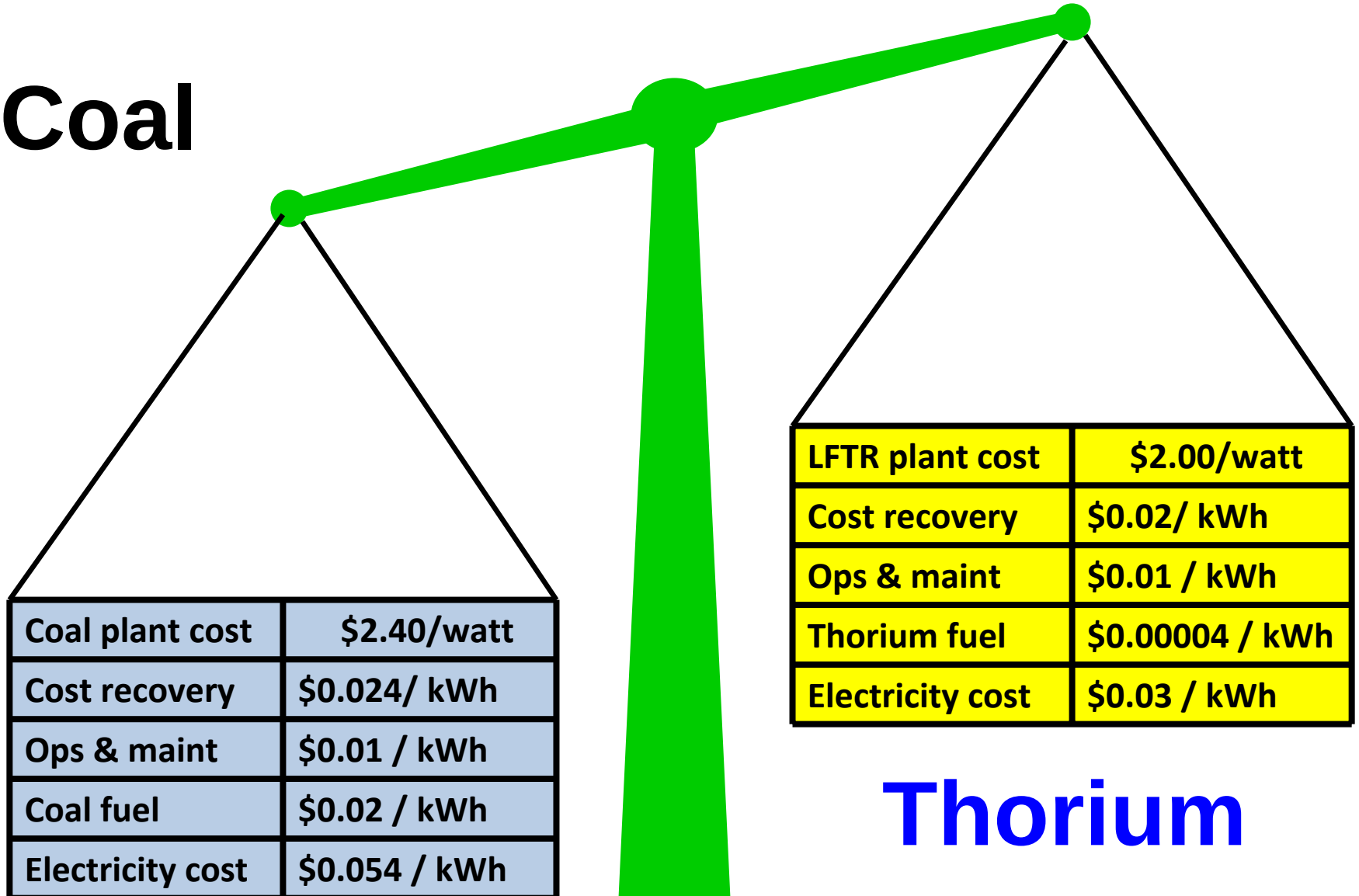
Halving rejected heat enables air cooling.

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!

Develop a small modular reactor.

Small LFTR modules can be transported by trucks.

100 megawatt, $200 million
-- cheaper than coal

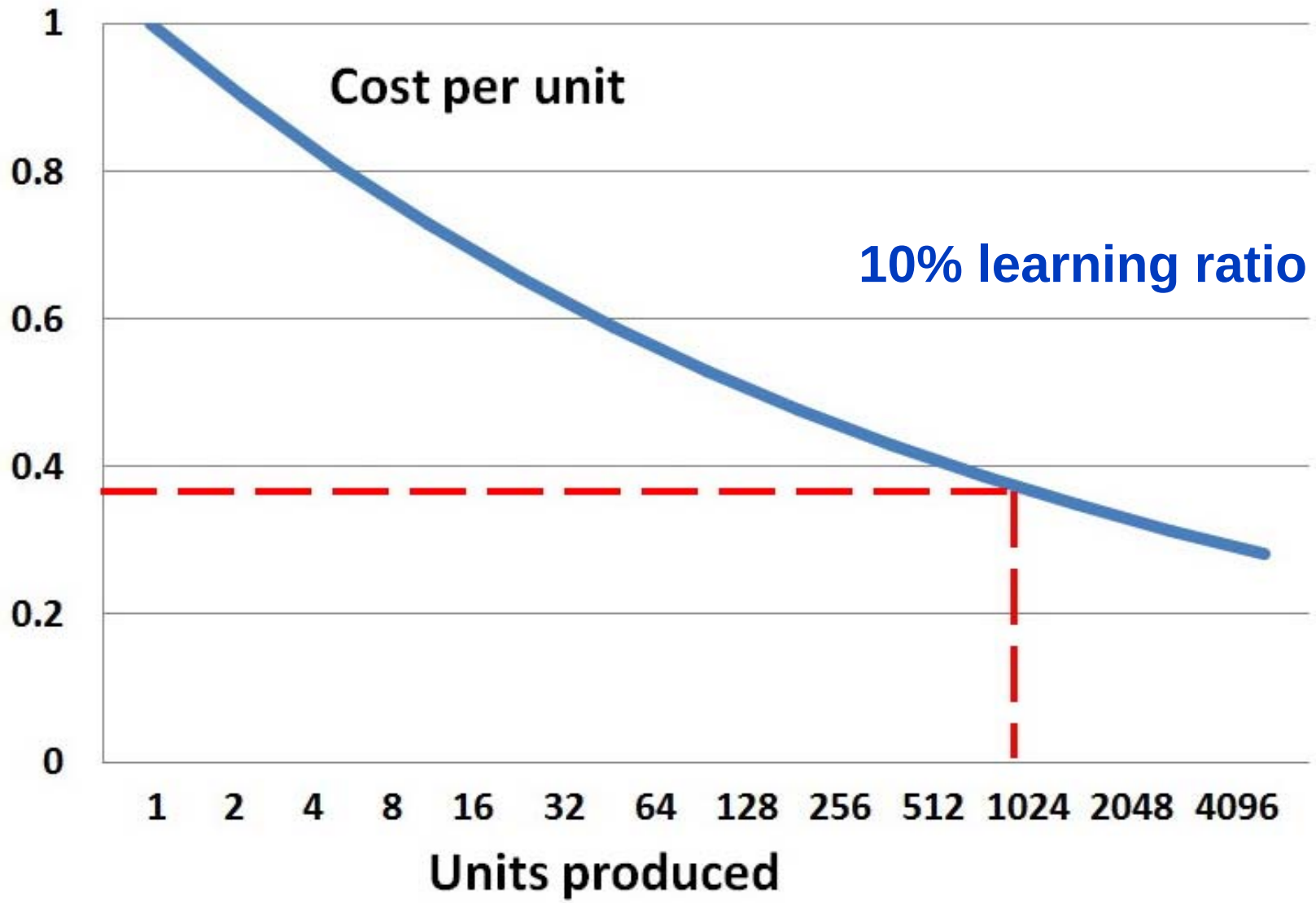
Affordable to developing nations

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

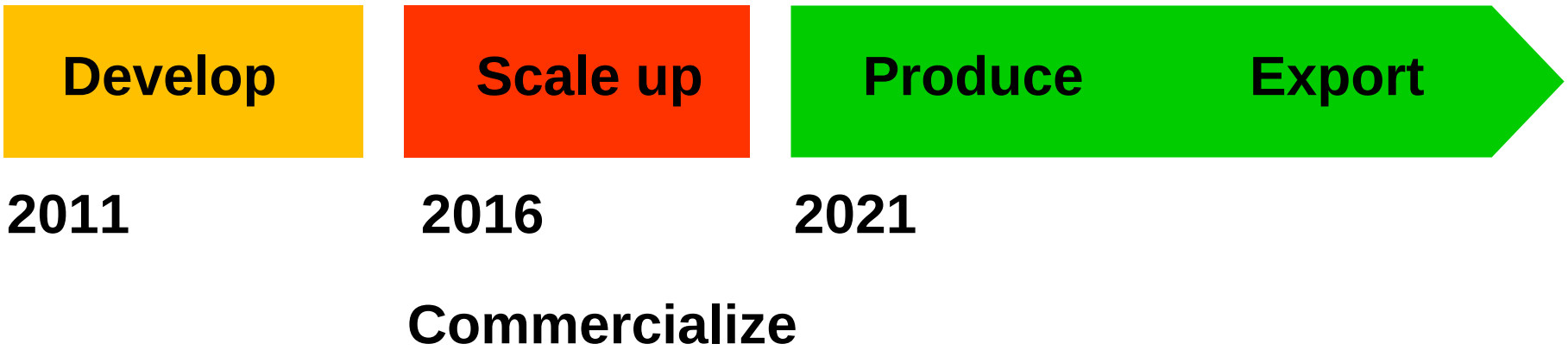
Multi-module power stations
-- incremental growth and cost
-- replace plants at existing sites

Boeing makes one $200 million aircraft per day.

The learning curve reduces costs.



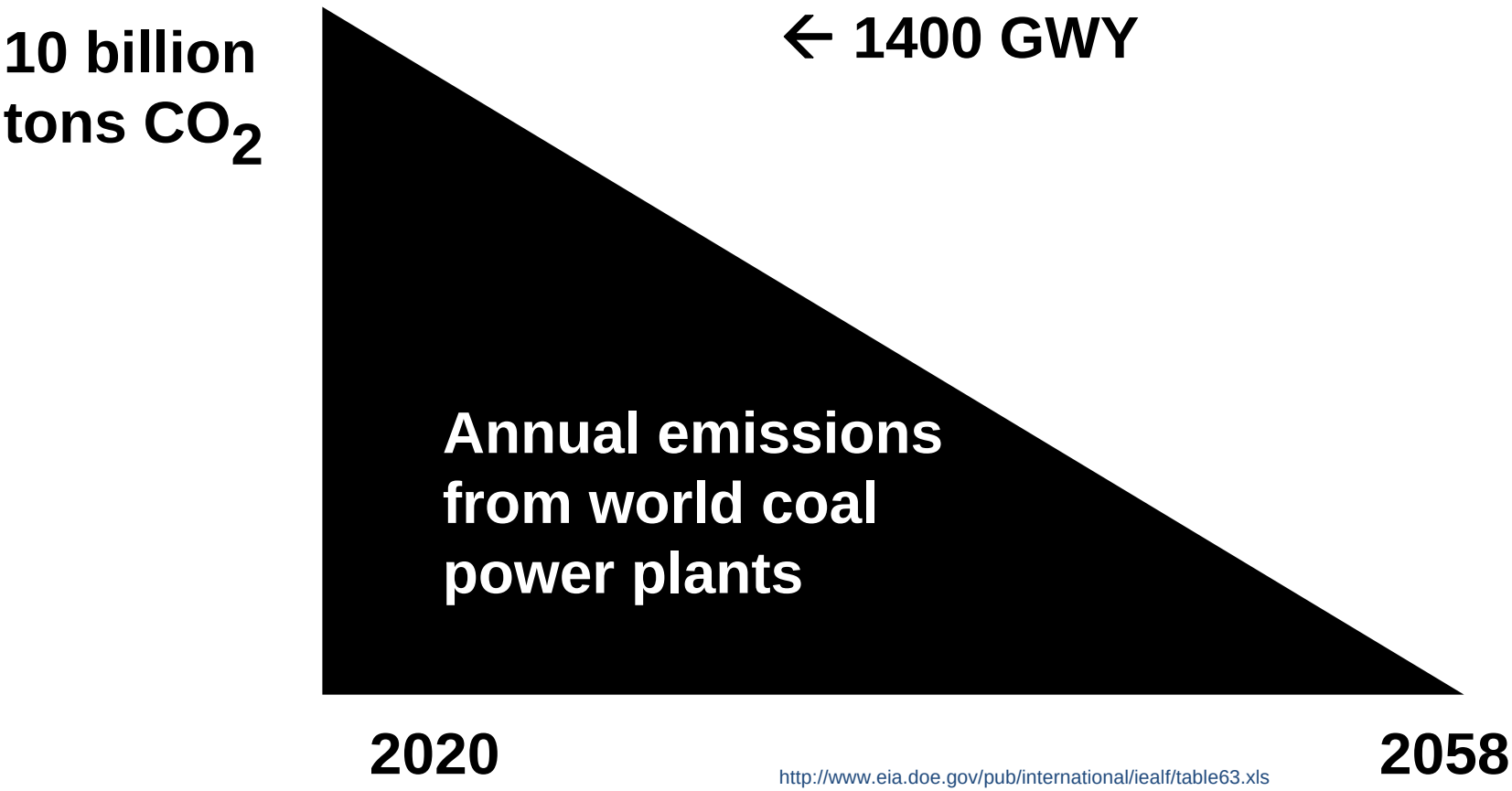
One-a-day production of 100 MW LFTRs can be a $70 billion industry.



Aim High!

Check global warming.

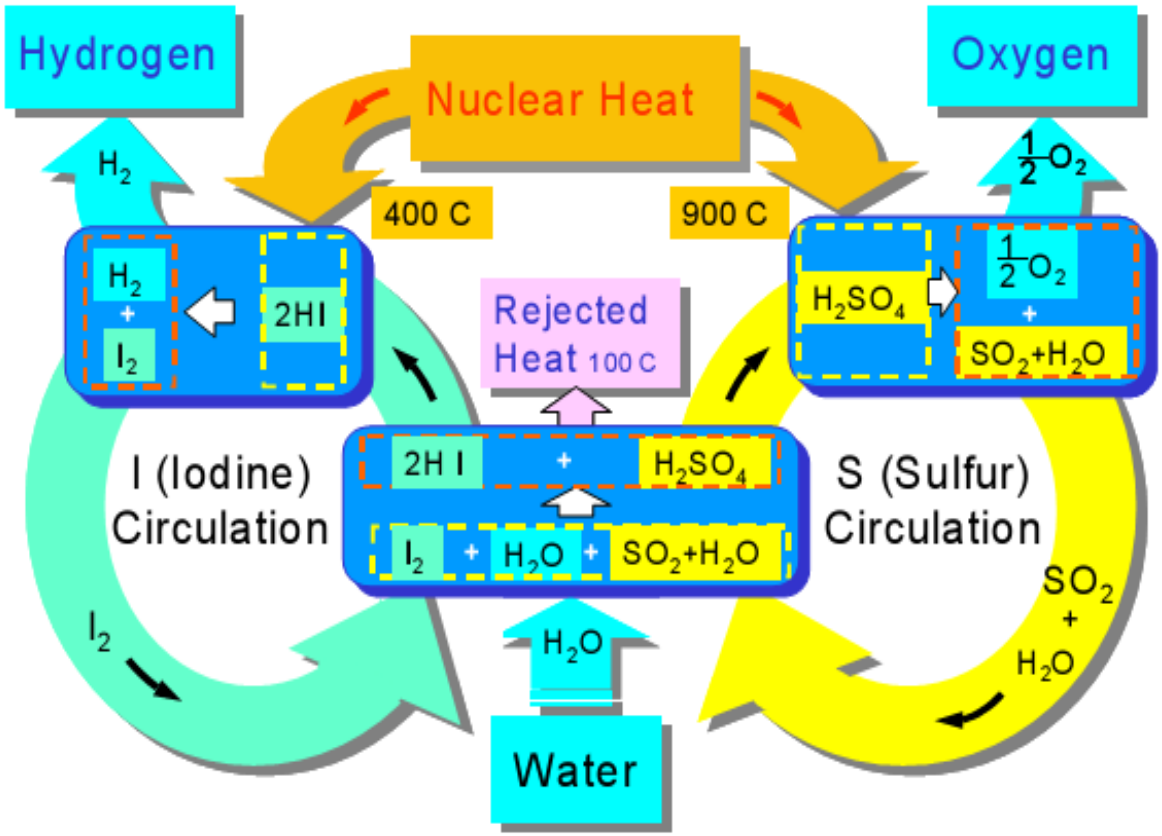
Install one 100 MW LFTR each day, worldwide, to replace all coal power.



Aim High!

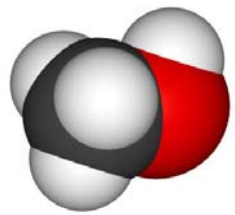
Synthesize fuel from H_2.

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

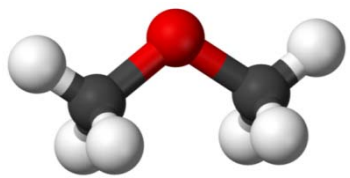


Ammonia

CO2 + 3 H2 → CH3OH + H2O



Methanol for gasoline



Dimethyl ether for diesel

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

Aim High! Cut US oil imports.

Dissociate H_2 and synthesize fuel

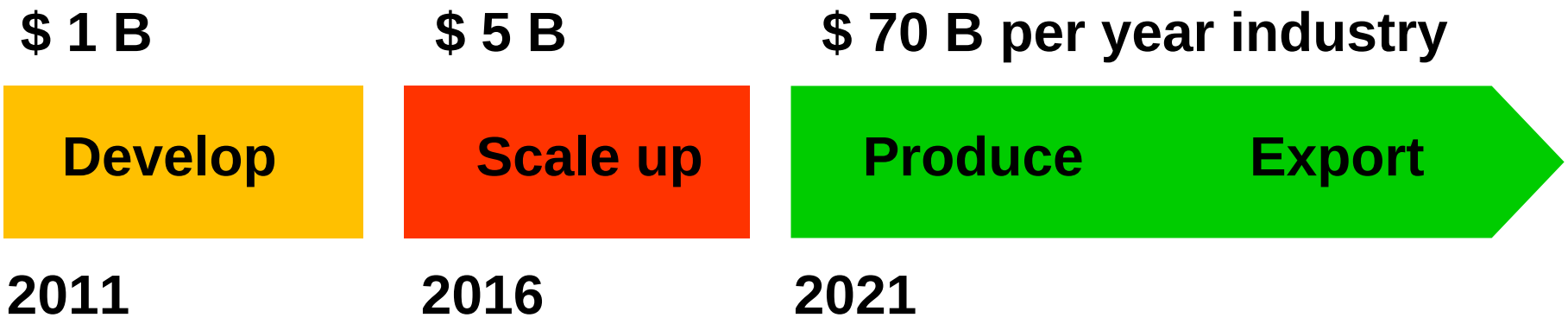
(@ 50% x 50% efficiency).

200 MW_{th} LFTR and plant makes 250,000 bbl/year.

(@ one a day)

http://www.eia.doe.gov/pub/international/iealf/table63.xls

Aim High!



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

Avoid carbon taxes.

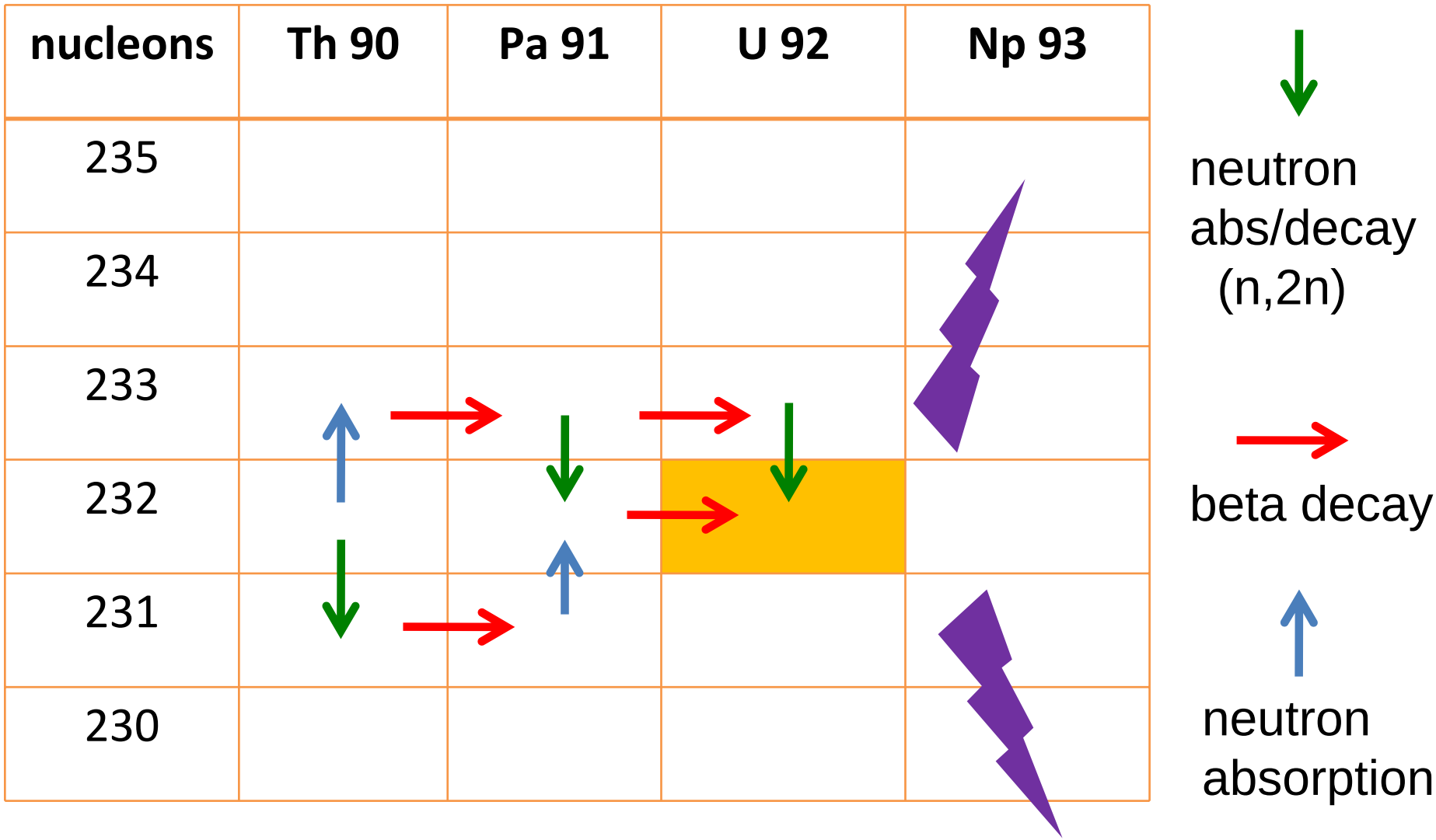
Improve world prosperity, and check overpopulation.

Reduce radiotoxic waste; consume world fissile stocks.

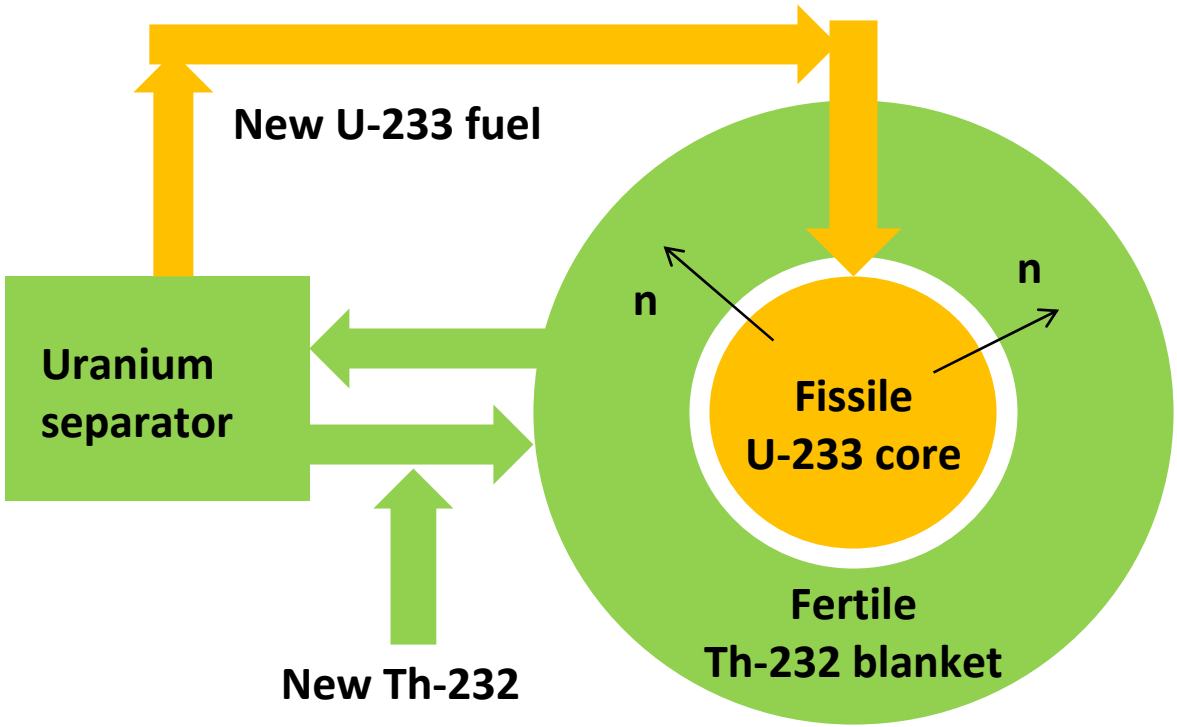
Use inexhaustible thorium fuel, available in all nations.

Walk-away safe.

By-product U-232's decay chain emits gamma rays hazardous to bomb builders.



Uranium from a commercial LFTR will not be used for weapons.



Breeds only as much U-233 as it consumes.

Removing any will stop the LFTR.

U-232 contamination will be 0.13%.

A 5 kg sphere of it radiates 4,200 mrem/hr at 1 meter.

After 72 hours of exposure a weapons worker will likely die.

India, Pakistan, and North Korea demonstrated far less technically challenging and costly paths.

Renewable energy wrecks the environment, says one scientist.

Jesse E. Ausubel

- Director, Program for the Human Environment, Rockefeller University.
- Program Director, Alfred P Sloan Foundation.
- Former Director of Studies, Carnegie Commission on Science, Technology, and Government.

http://phe.rockefeller.edu/jesse/index.html

Flooding the entire province of Ontario behind a 60 m dam would provide 80% of the power of Canada's existing nuclear electric plants.

Displacing a single nuclear power plant with biomass would require 1,000 square miles of prime Iowa farm land.

Wind farms on 300 square miles of land could displace a 1 GW nuclear plant.

60 square miles of photovoltaic cells could generate 1 GW.

Powering New York City would require a wind farm the size of Connecticut.

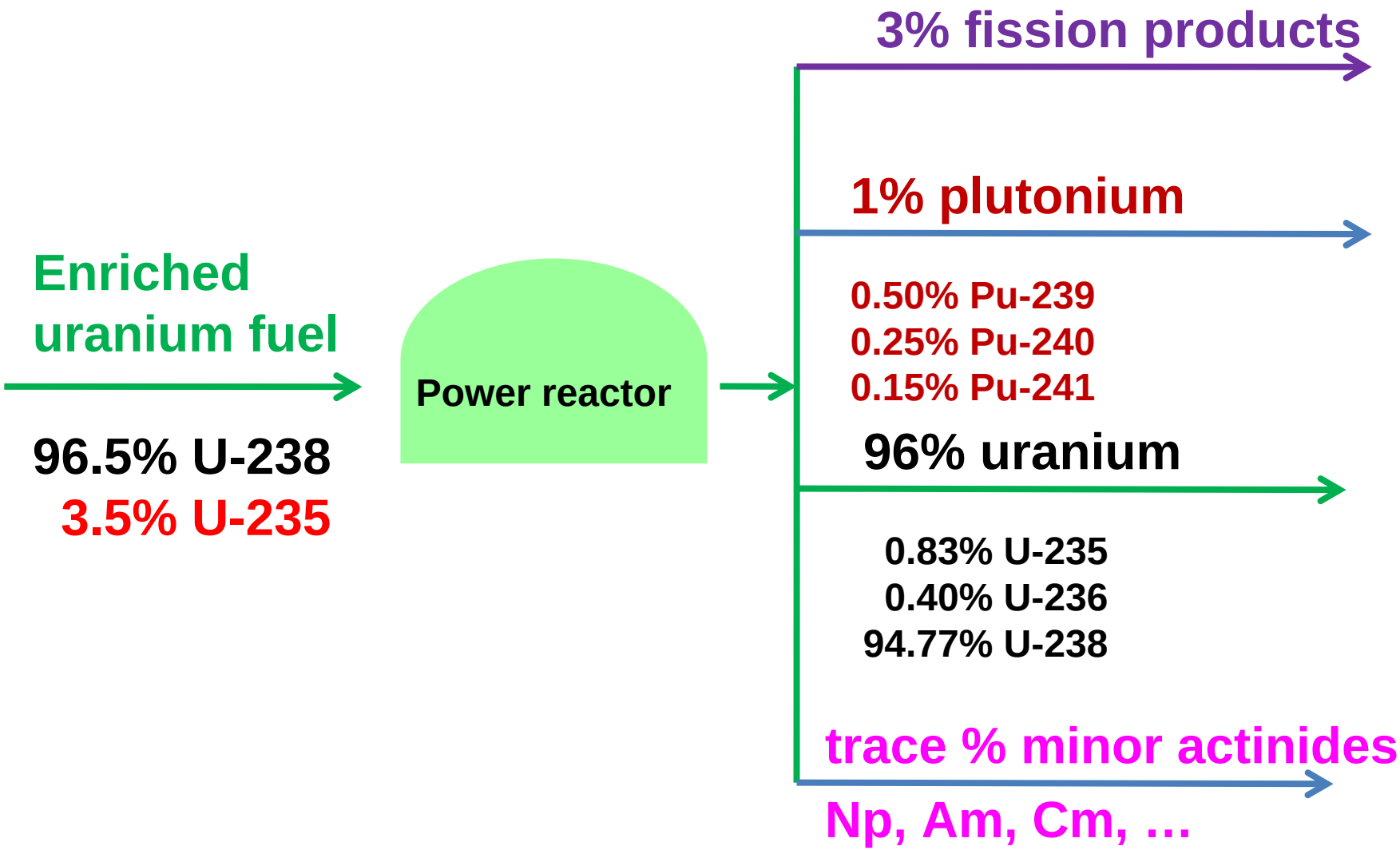
Nuclear power was kindest to the human environment in 1969-1996.

Energy Chain	Accidents with > 4 fatalities	Fatalities	Fatalities per GW-year
Coal	185	8,100	0.35
Oil	330	14,000	0.38
Natural Gas	85	1,500	0.08
LPG	75	2,500	2.9
Hydro	10	5,100	0.9
Nuclear	1	28	0.0085

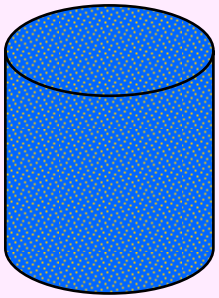
htpp://gabe.web.psi.ch/pdfs/PSI_**Report**/ENSAD98.pdf

Paul Scherrer Institut, November 1998, Severe Accidents in the Energy Sector

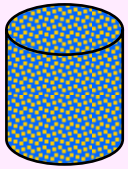
Spent fuel still contains 97% of its potential energy.



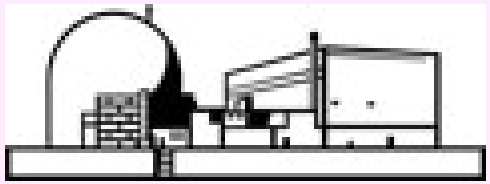
Aim High! Mine < 1% of the ore; bury < 1% of the waste.



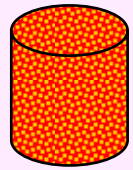
250 t uranium containing 1.75 t U-235



35 t of enriched uranium (1.15 t U-235)

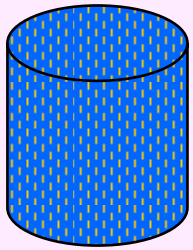


U-235 is burned; some Pu-239 is formed and burned.



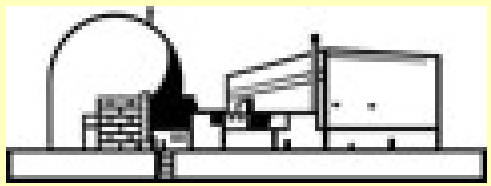
35 t of spent fuel stored containing:

33.4 t U-238
0.3 t U-235
1.0 t fission products
0.3 t Pu



215 t of depleted U-238 (0.6 t U-235)

1 t thorium

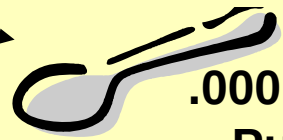


Fluoride reactor converts Th-232 to U-233 and burns it.

1 t fission products

In 10 yrs, 83% FP stable.

17% FP stored ~300 years.



.0001 t Pu