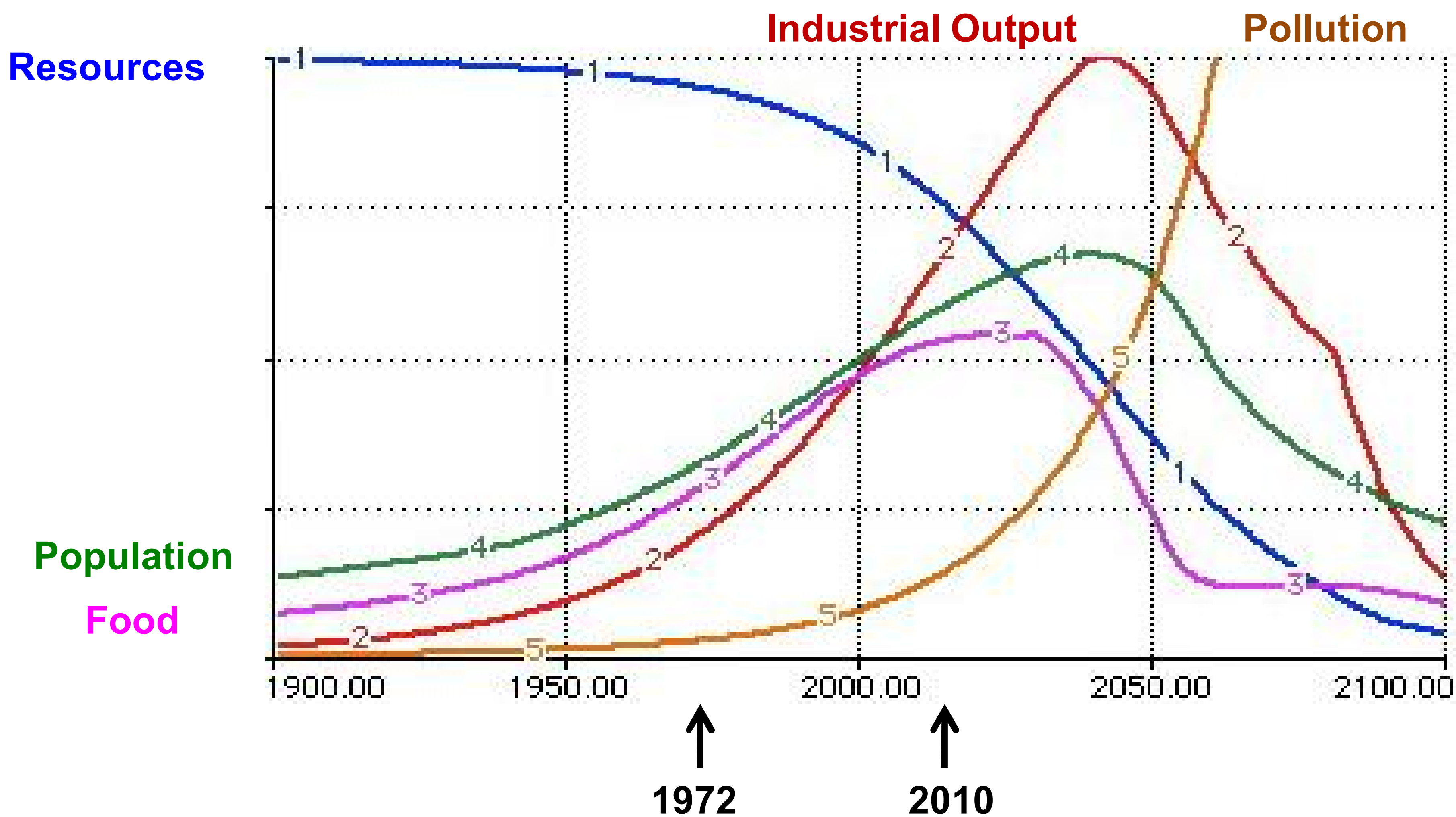
Aim High!

1. Limits to growth
2. Thorium
3. History
4. Aim High
5. Energy cheaper than from coal

robert.hargraves@gmail.com

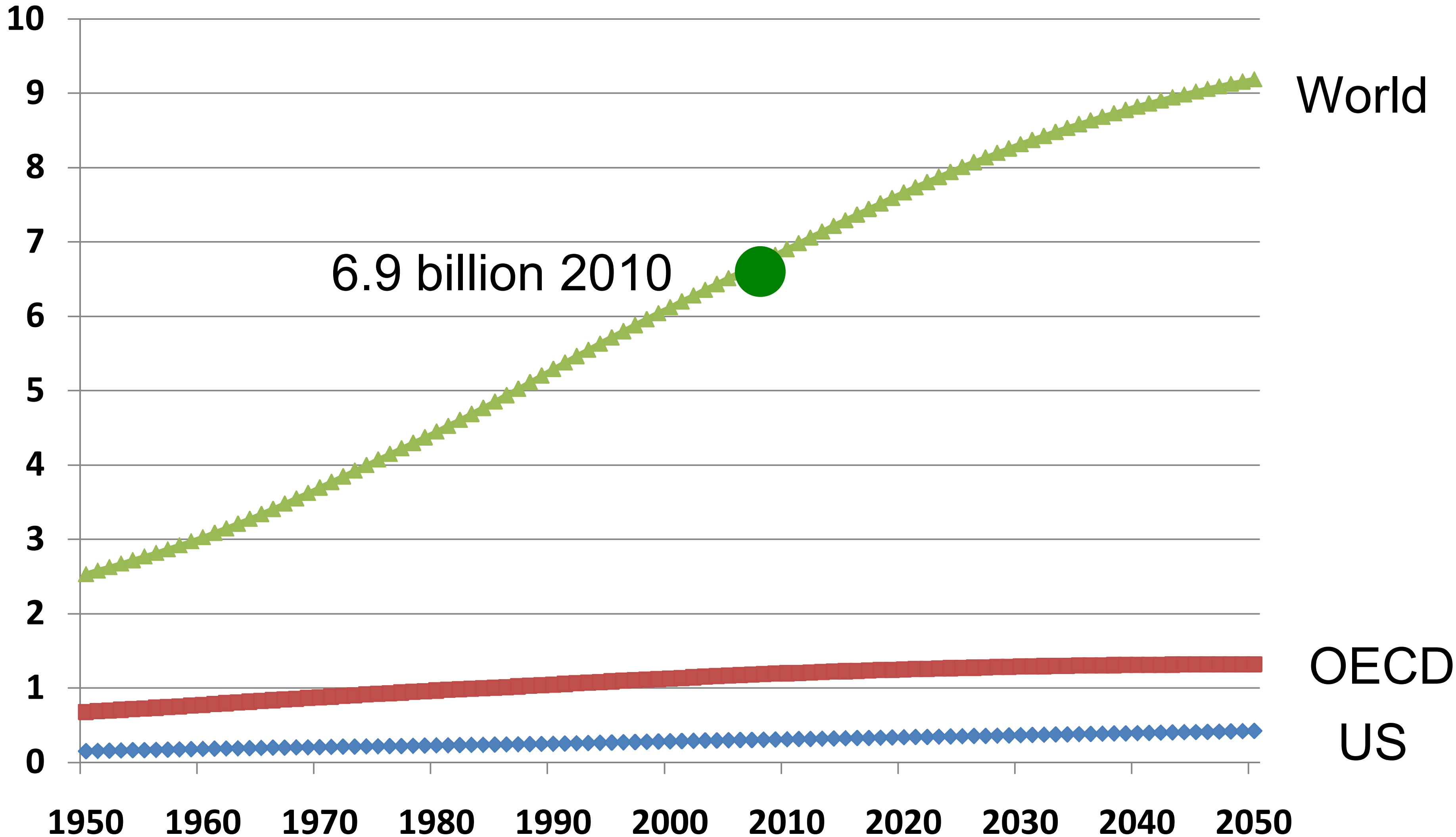
Global environmental problems mount.

Dennis Meadows’ *Limits to Growth* showed effects of finite resources.



http://www.aspoitalia.net/images/stories/aspo5presentations/Meadows_ASPO5.pdf

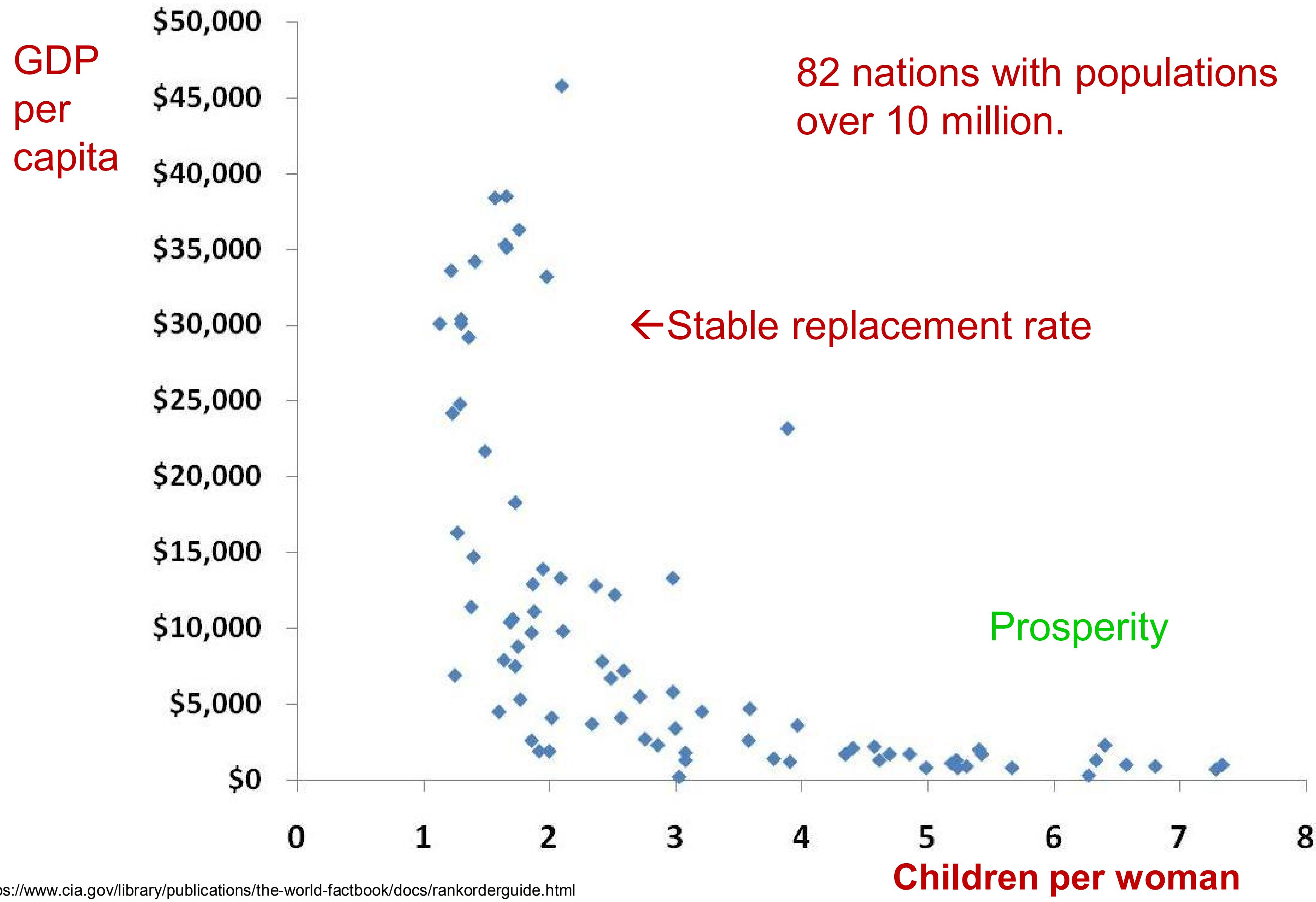
Population is stable in developed nations.



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

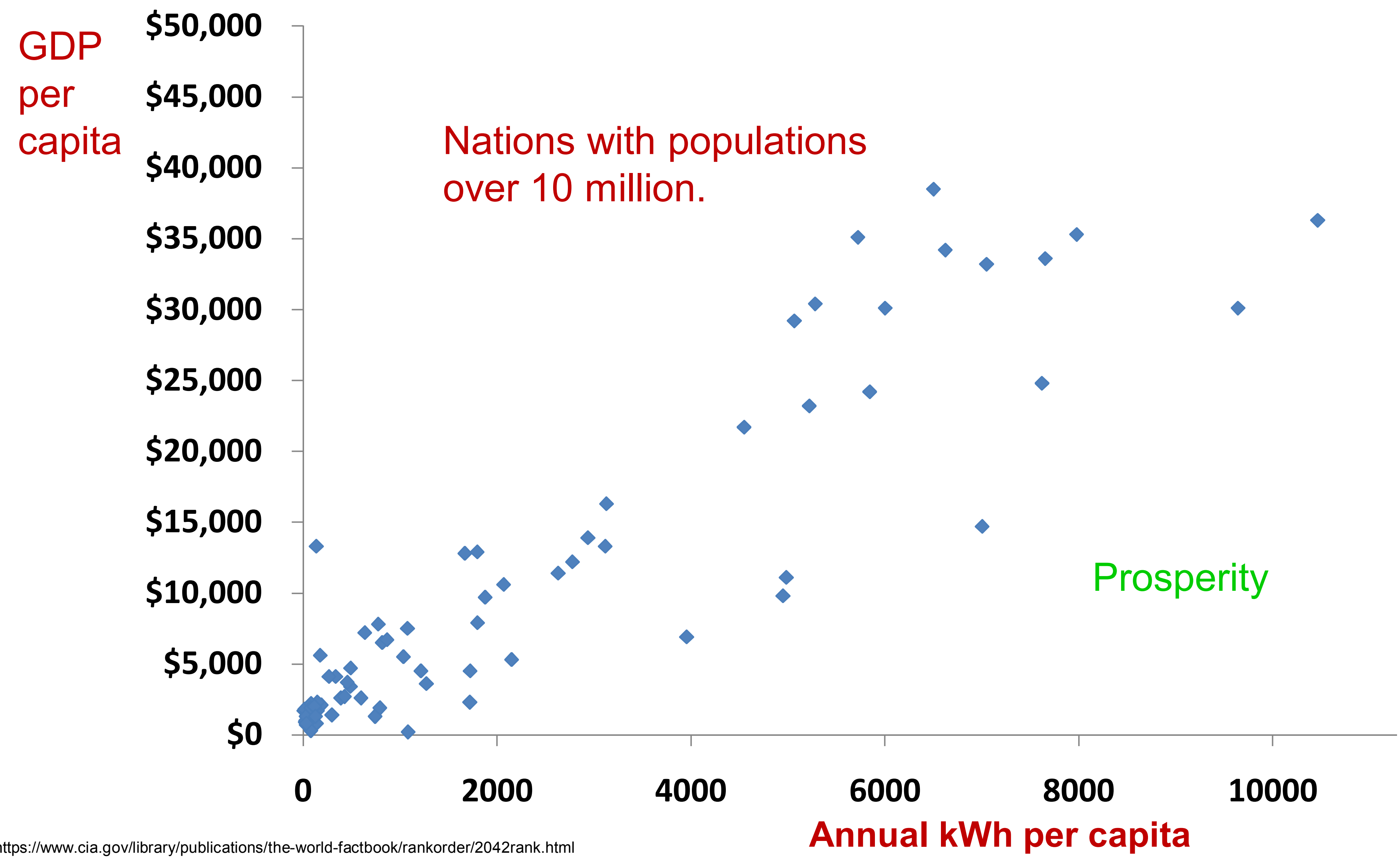
http://www.oecd.org/dataoecd/13/38/16587241.pdf

Prosperity stabilizes population.



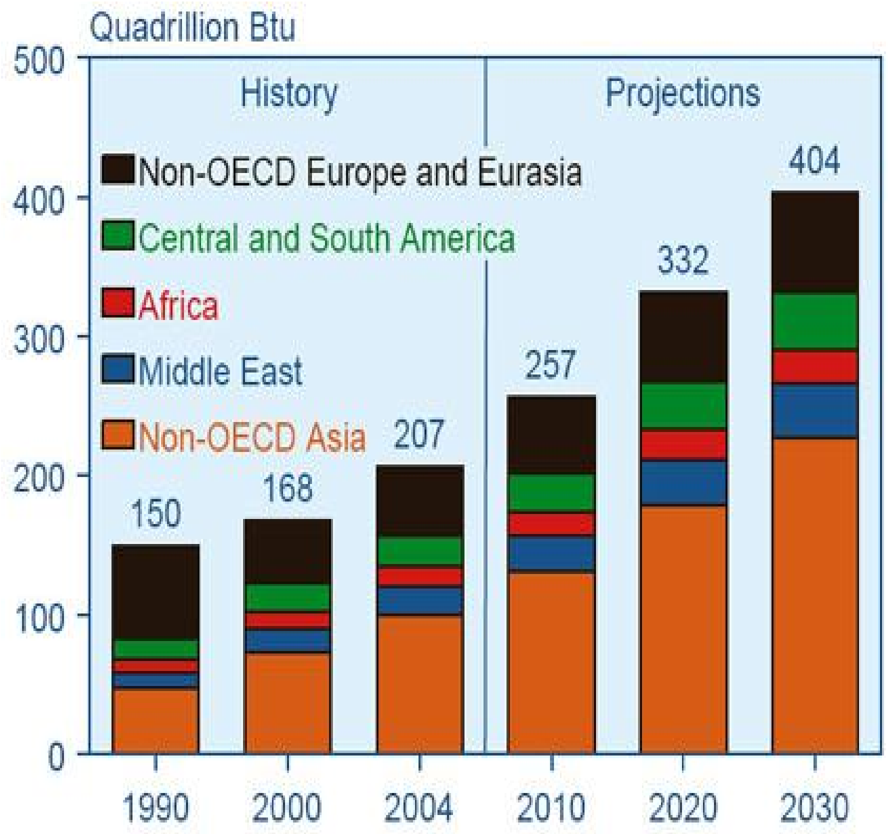
https://www.cia.gov/library/publications/the-world-factbook/docs/rankorderguide.html

Prosperity depends on energy.

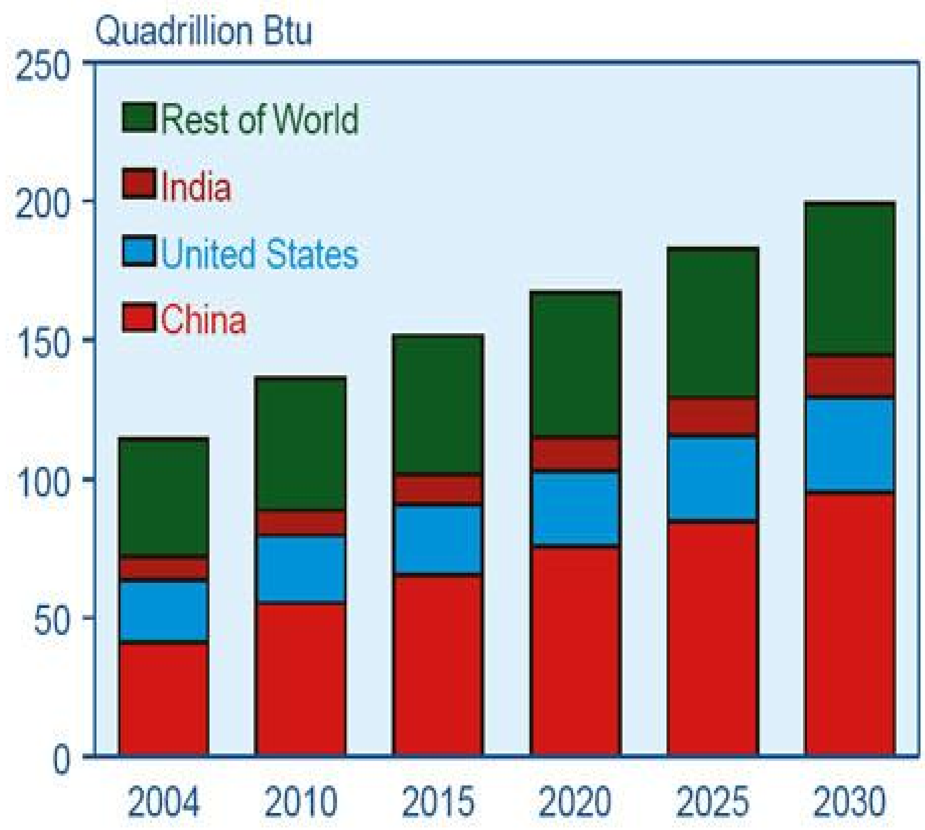


https://www.cia.gov/library/publications/the-world-factbook/rankorder/2042rank.html

Energy and coal use is growing rapidly in developing nations.



Non-OECD energy use



World coal use

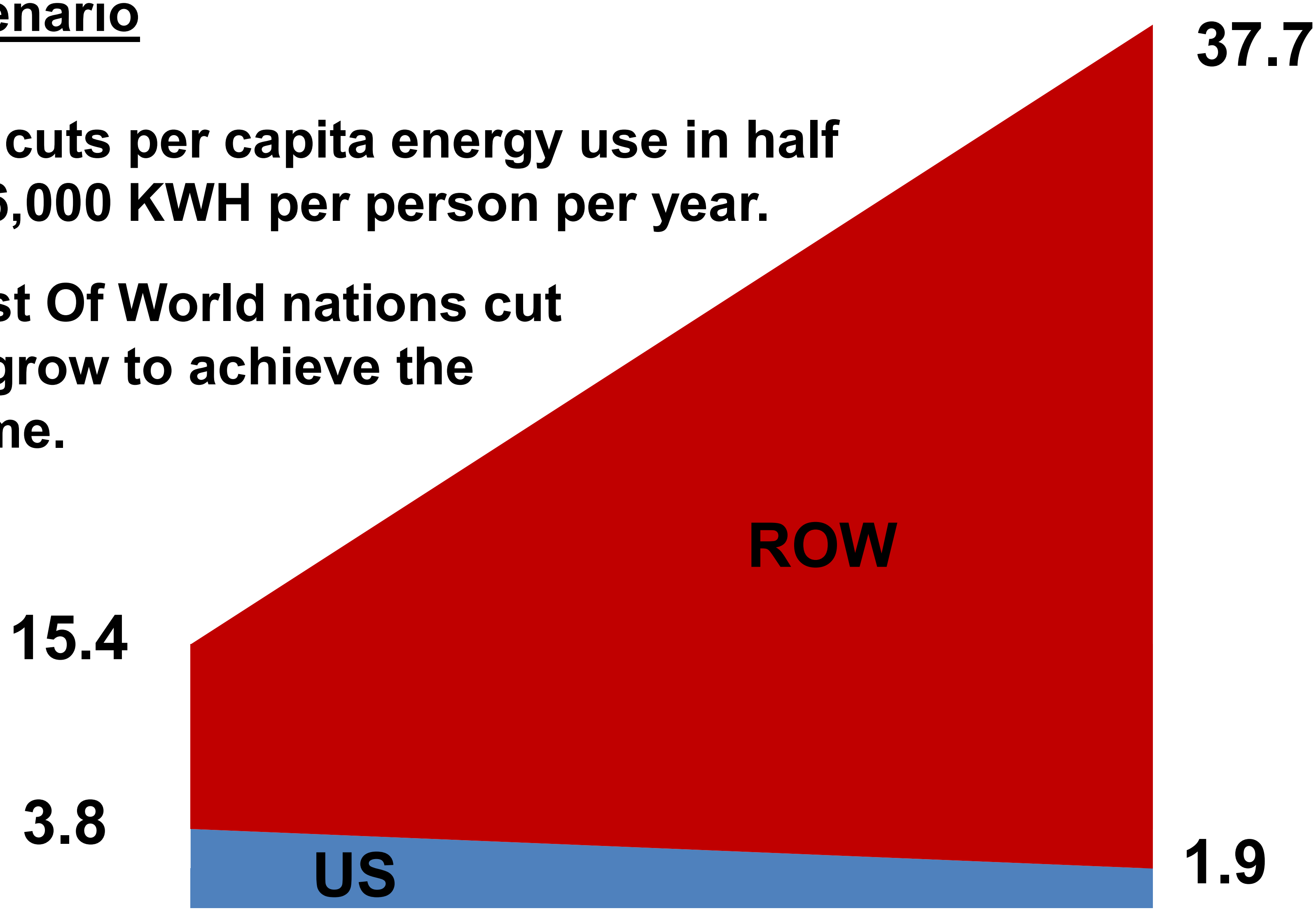
http://www.eia.doe.gov/oiaf/ieo/world.html

Conservation won't stop the growth.

Scenario

US cuts per capita energy use in half to 6,000 KWH per person per year.

Rest Of World nations cut or grow to achieve the same.



Units are 10^{15} watt hours per year

Technology policy lies at the core of the climate change challenge.

Prof. Jeffrey Sachs
Economist, Columbia University
Director of The Earth Institute

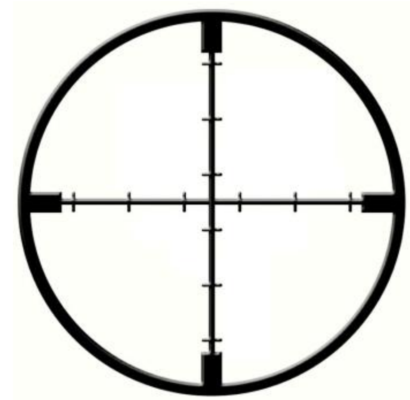
http://www.sciam.com/article.cfm?id=technological-keys-to-climate-protection-extended

"If we try to restrain emissions without a fundamentally new set of technologies, we will end up stifling economic growth, including the development prospects for billions of people.

"We will need much more than a price on carbon.

"…technologies developed in the rich world will need to be adopted rapidly in poorer countries.

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.

Thorium is a plentiful fuel.

Thorium, discovered in Norway in 1828, is named after Thor, the Norse god of thunder and lightning.

Idaho's Lemhi Pass has enough thorium to power the US for a millennium.

Thorium is not fissionable.
How can thorium be a fuel?

http://en.wikipedia.org/wiki/Thorium

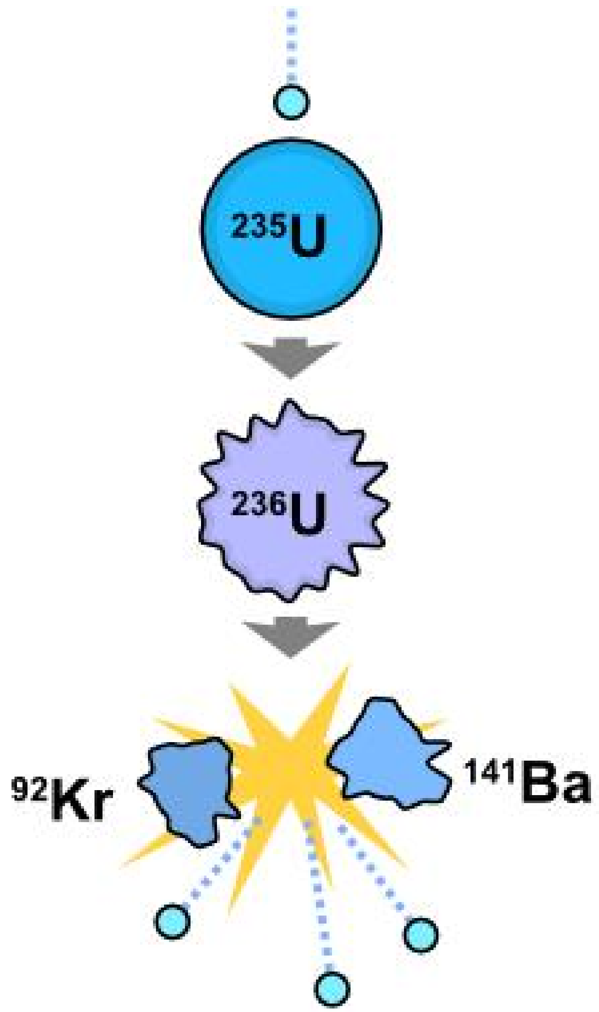
U-233, U-235, and Pu-239 are three possible reactor fission fuels.

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

Natural

fission

Uranium-235 fissions to krypton and barium releasing energy.



http://en.wikipedia.org/wiki/Nuclear_fission

The total mass of the resulting

barium-141
krypton-92
neutrons (3)

is less than the mass of the U-235 + neutron,

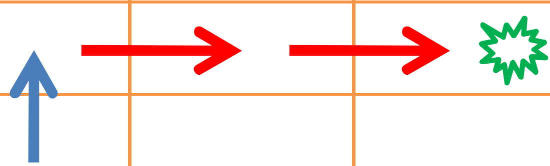
immediately releasing 166 MeV of energy.

Uranium-238 neutron absorption makes fissionable plutonium-239.

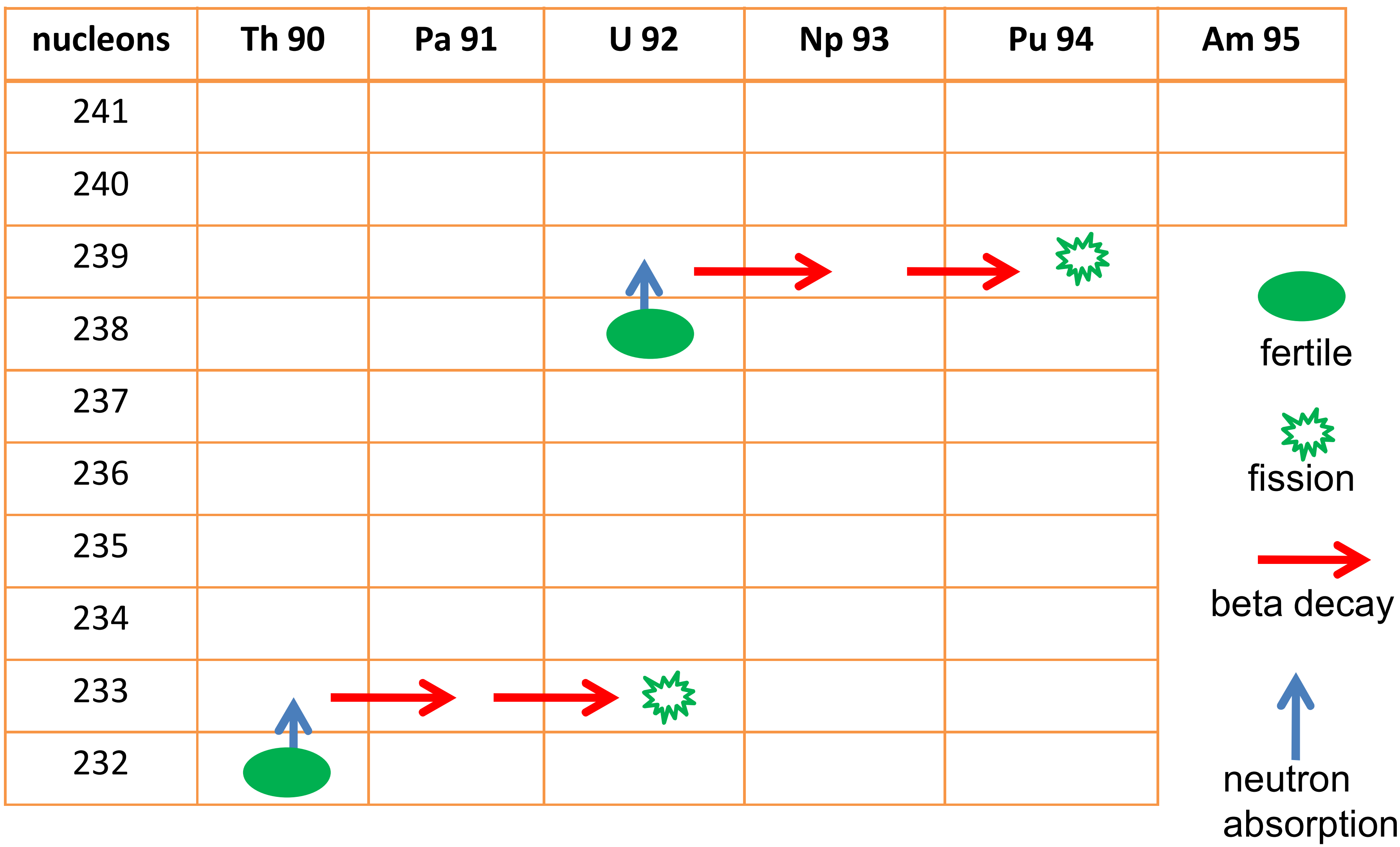
nucleons	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95
241						
240						
239						
238						
237						
236						
235						
234						
233						
232						

Thorium-232 neutron absorption makes fissionable uranium-233.

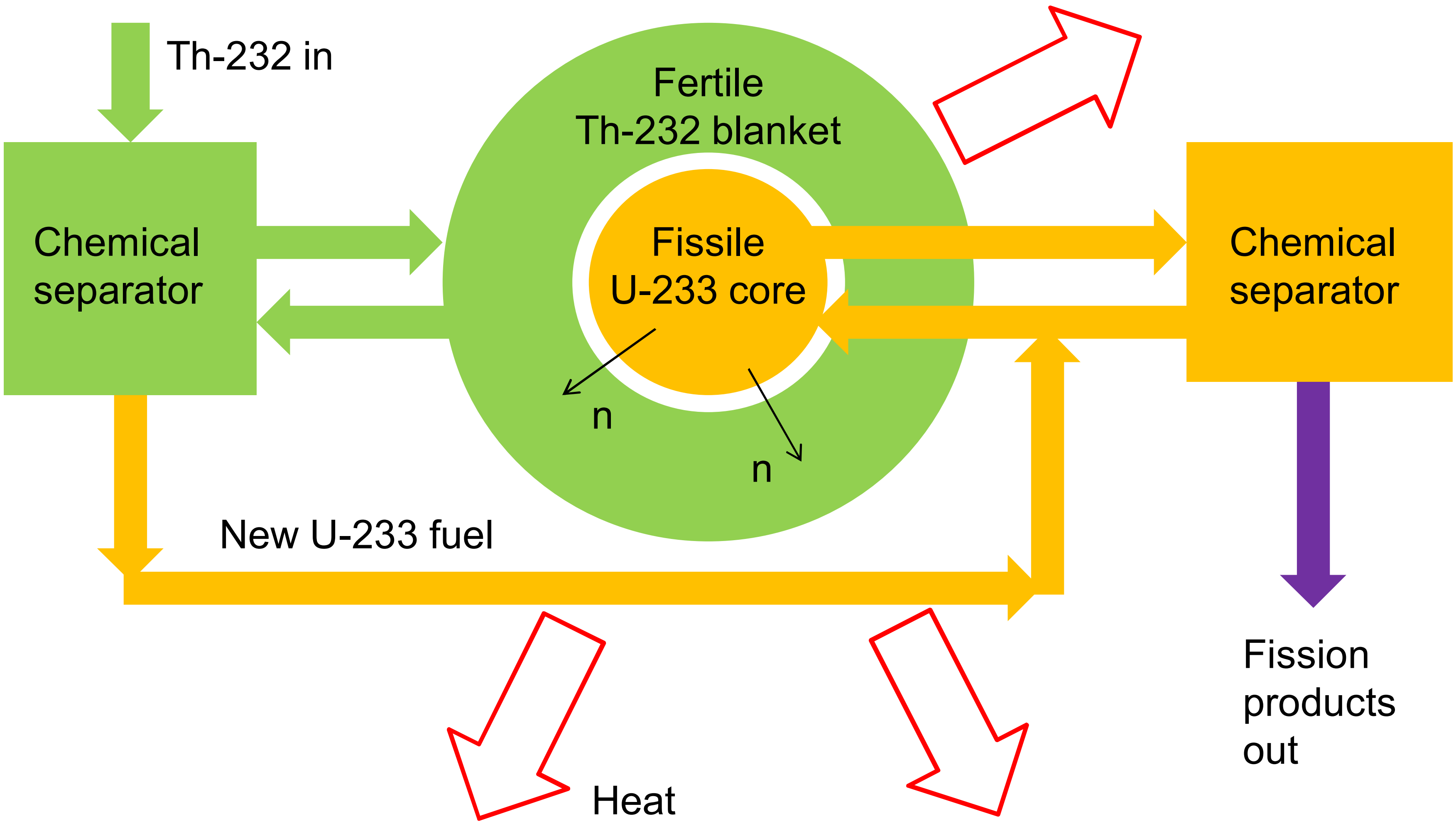
nucleons	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95
241						
240						
239						
238						
237						
236						
235						
234						
233						
232						



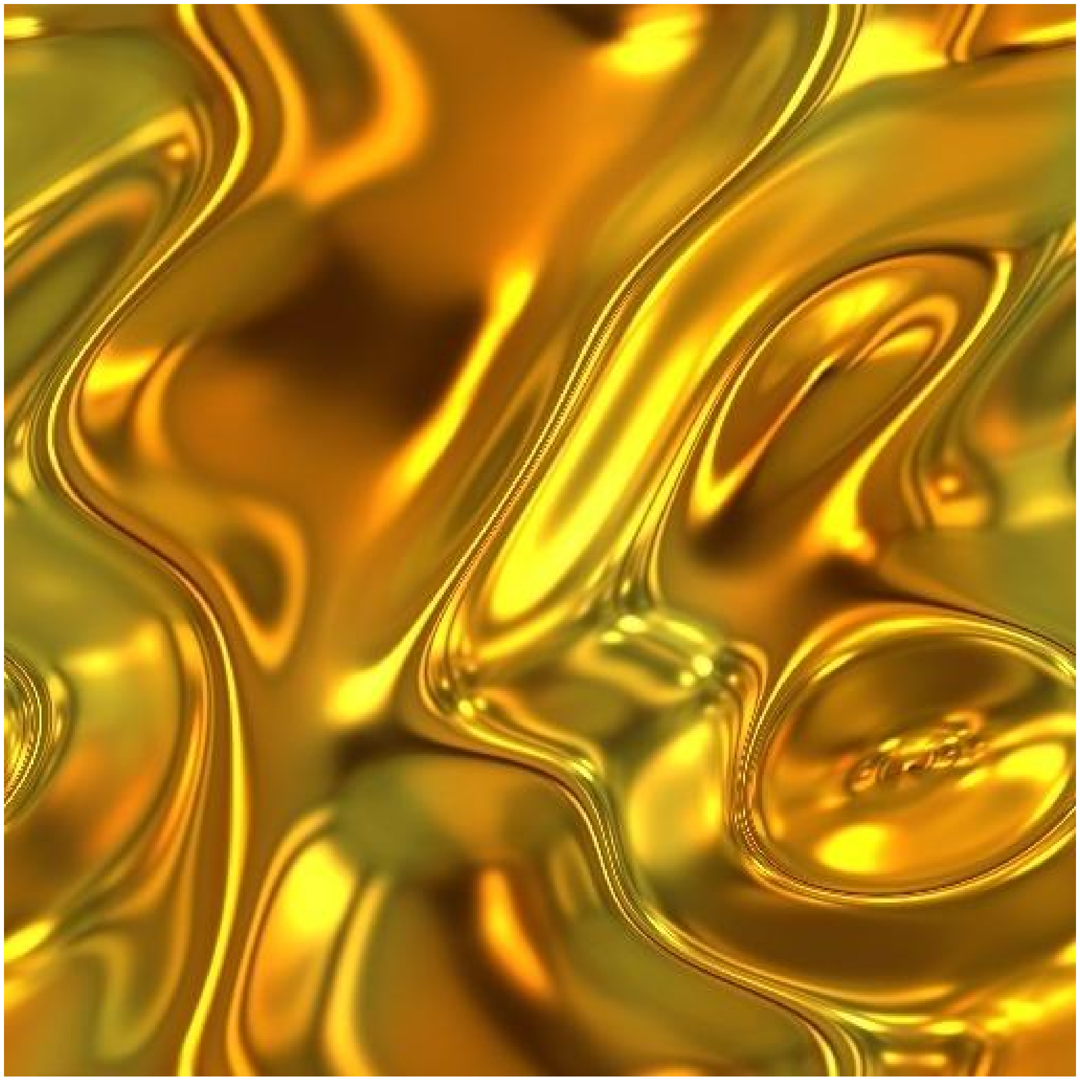
U-238 and Th-232 are called fertile because they make fissionable fuel.



In a thorium reactor the Th-232 blanket becomes the U-233 core.



Liquid Fluoride Thorium Reactor fuel is dissolved in liquid.



Molten fluoride salt mix: LiF and BeF_2

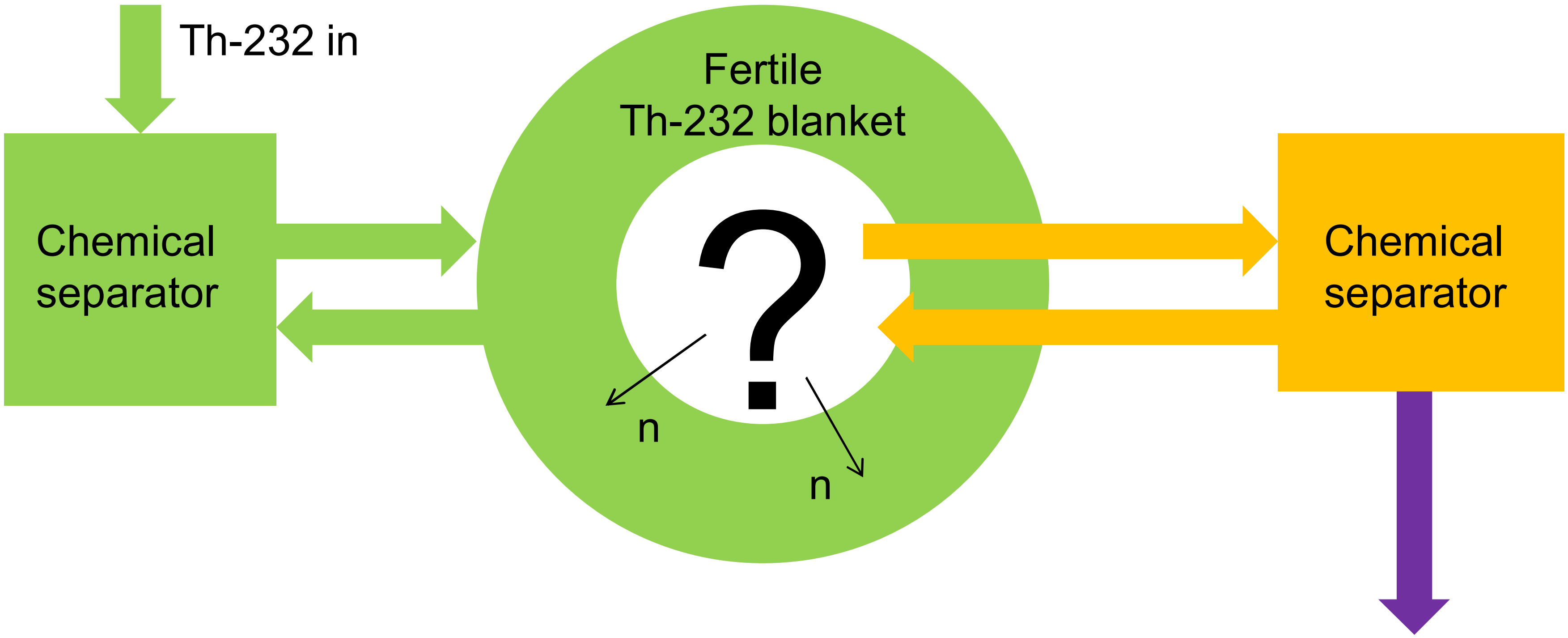
Excellent heat transfer

Continuous chemical processing

Atmospheric pressure

Room temp solid

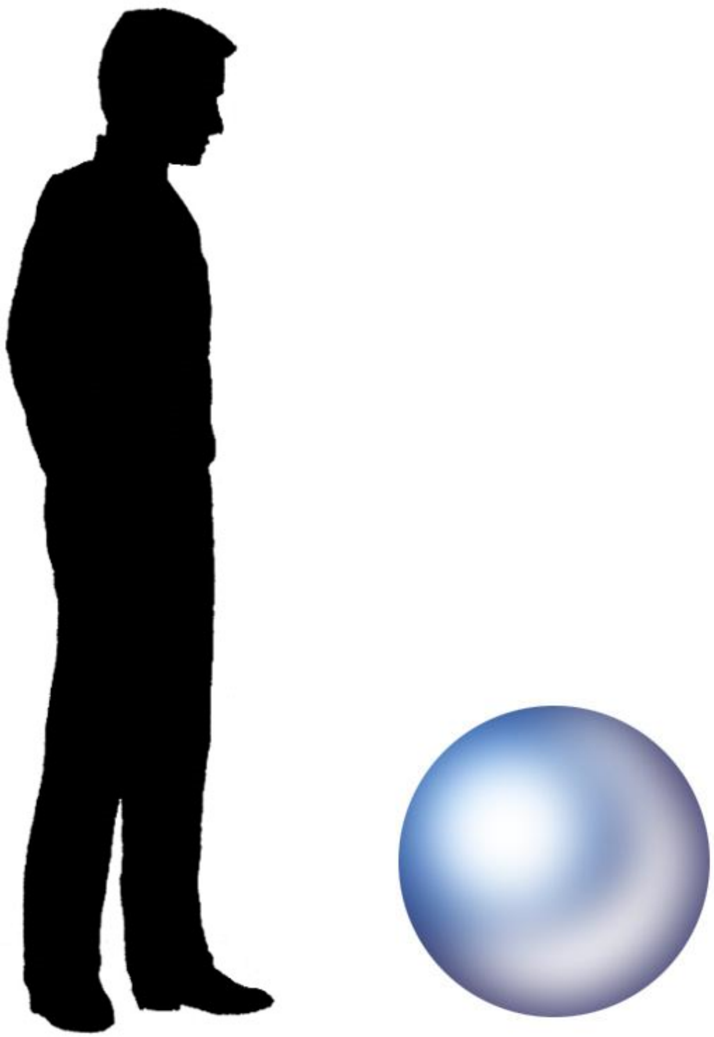
Start up the LFTR by priming it with a fissile fuel.



The US government has 500 kg of U-233.

Prime with U-235, or Pu from spent LWR fuel.

Thorium fuel is plentiful, compact, and inexpensive.



3,752 tons in US storage

$300,000 per ton

500 tons, entire US, 1 year

1 ton, 1 Boston, 1 year

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

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

Lemhi Pass has enough thorium to power the US for millennia.

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

Aim High!

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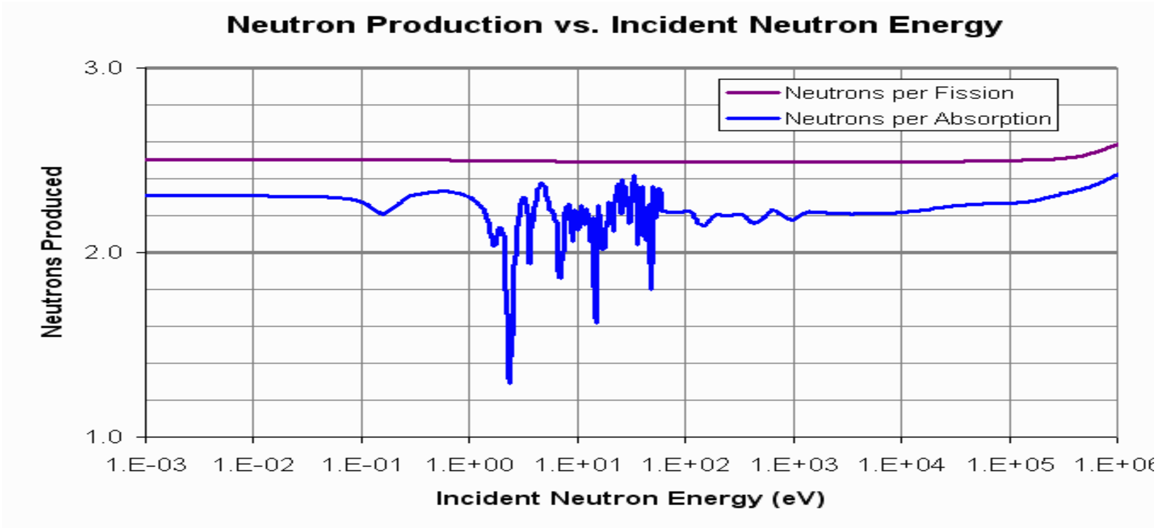
3. History

If LFTR is so good, why do we use Uranium PWRs ?

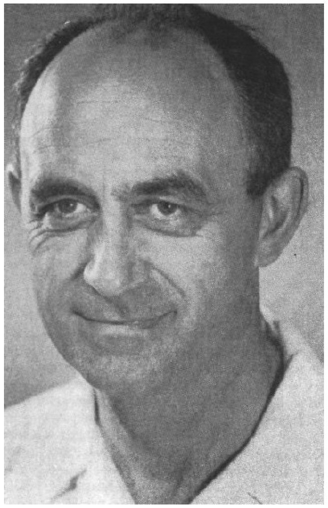
Two Nobel laureates conceived two reactors. One made more fuel and weapons faster.

Eugene Wigner

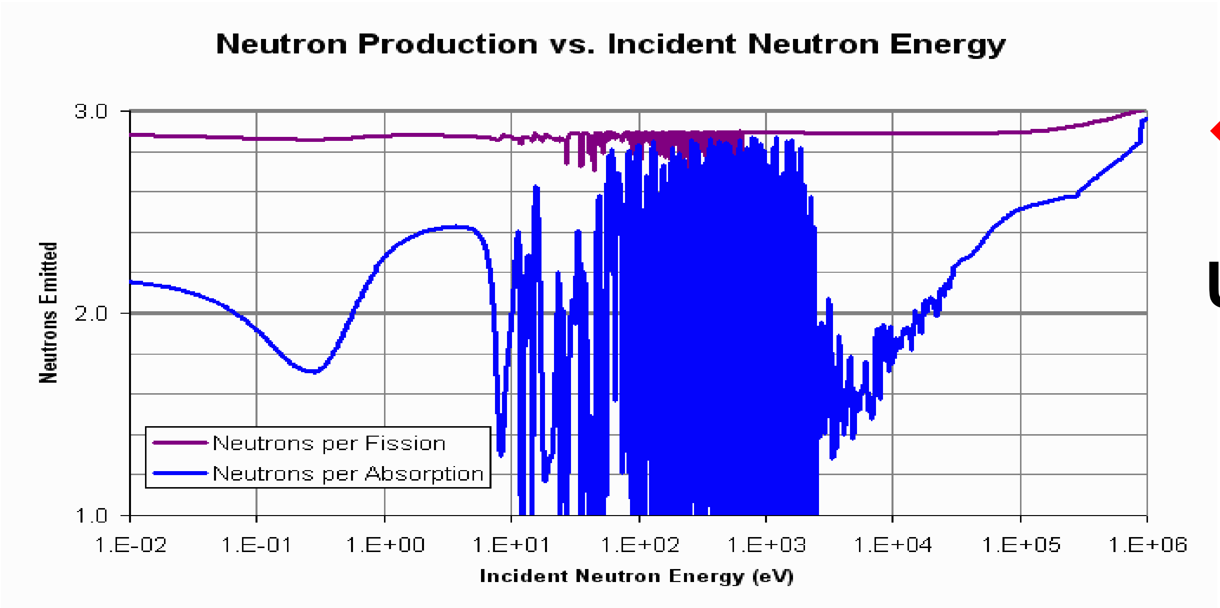


←2.5

Th→U



Enrico Fermi



←2.9

U→Pu

Weinberg proposed the PWR to Rickover's team for naval propulsion.

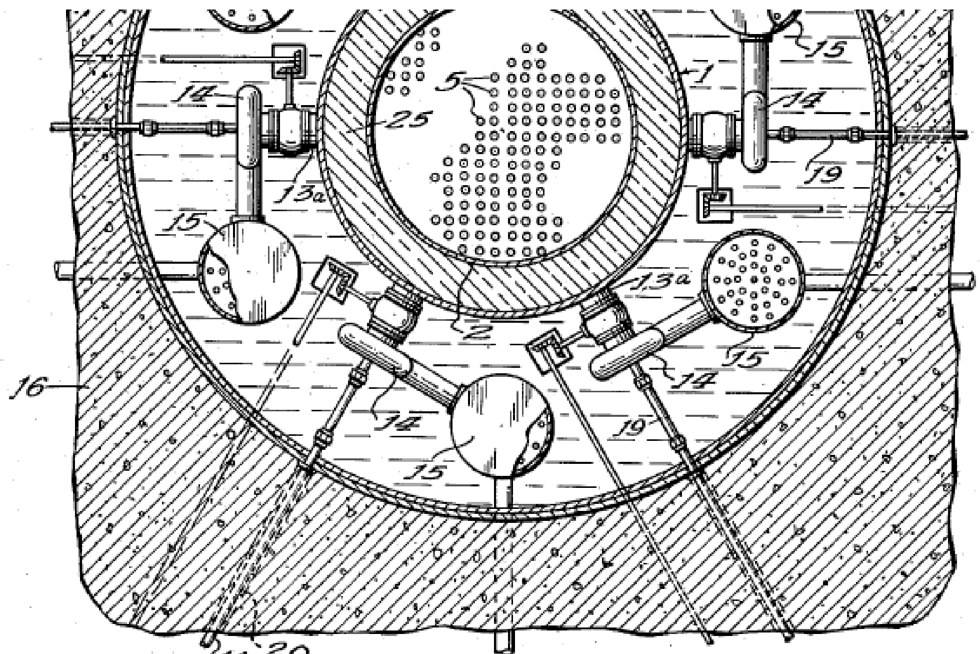


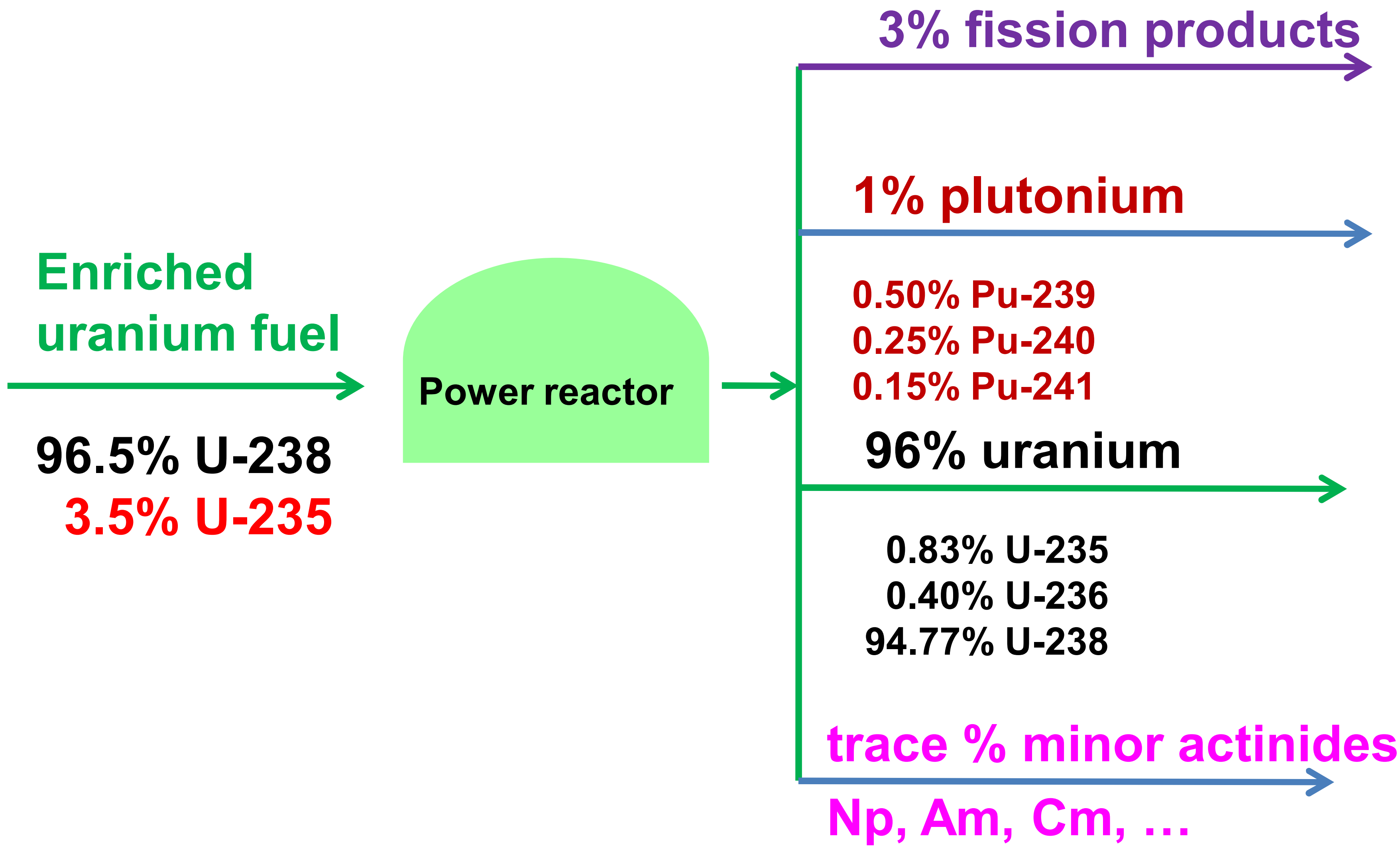
FIG. 3.

Witnesses:
Herbert E. Metcalf
William J. Ruano

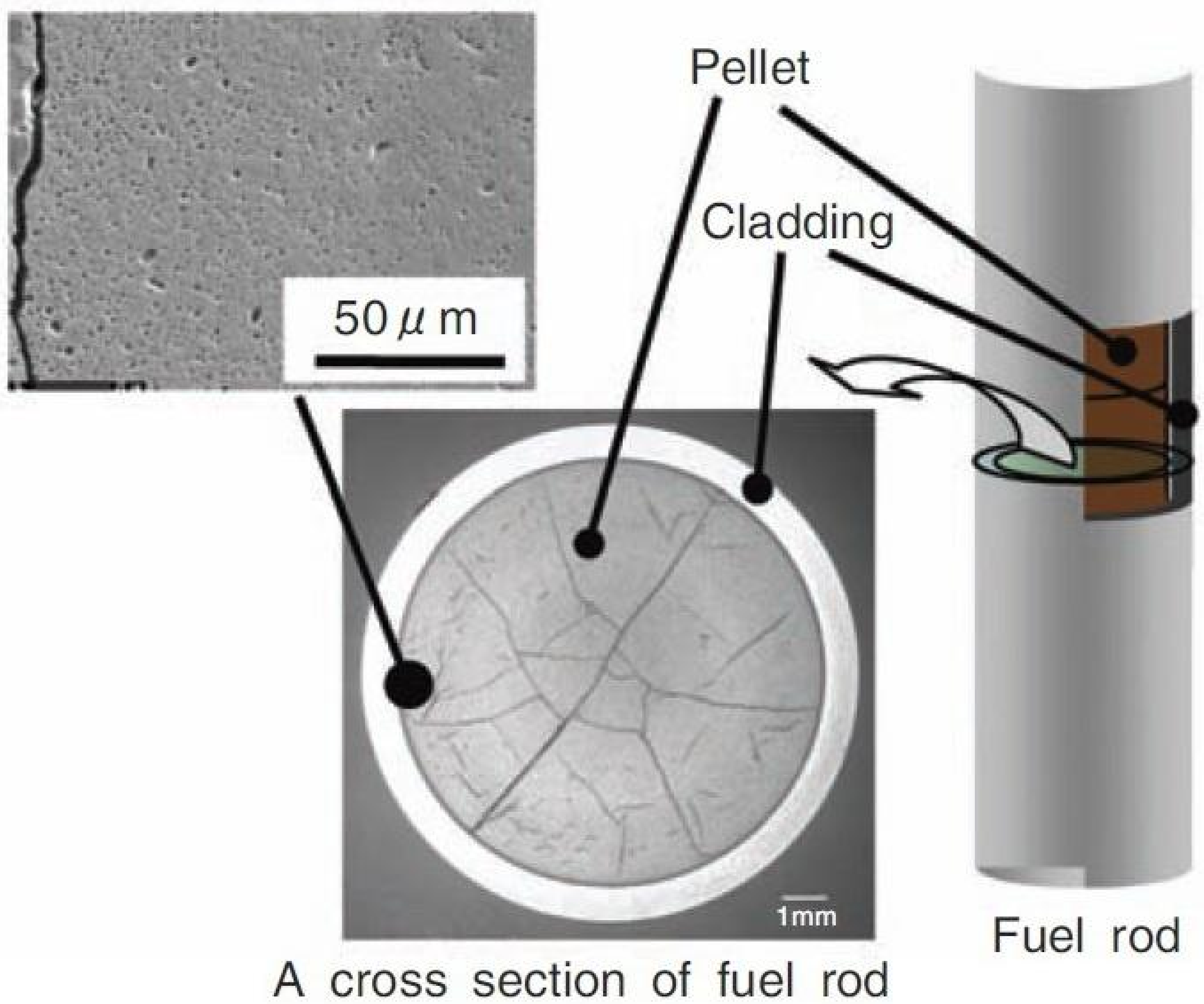
Inventors:
Eugene P. Wigner
Leo A. Ohlinger
Gale J. Young
Alvin M. Weinberg
By: Robert A. [signature]
Attorney

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

Spent fuel still contains 97% of its potential energy.

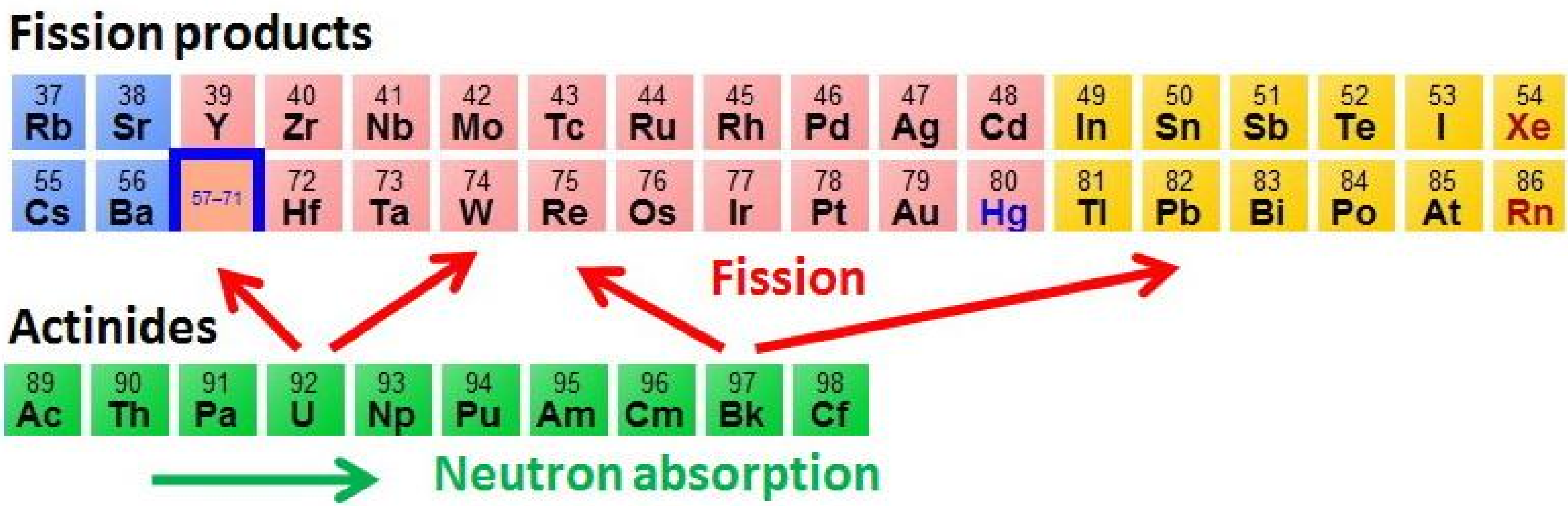


Radiation, fission products, and heat damage solid fuel.

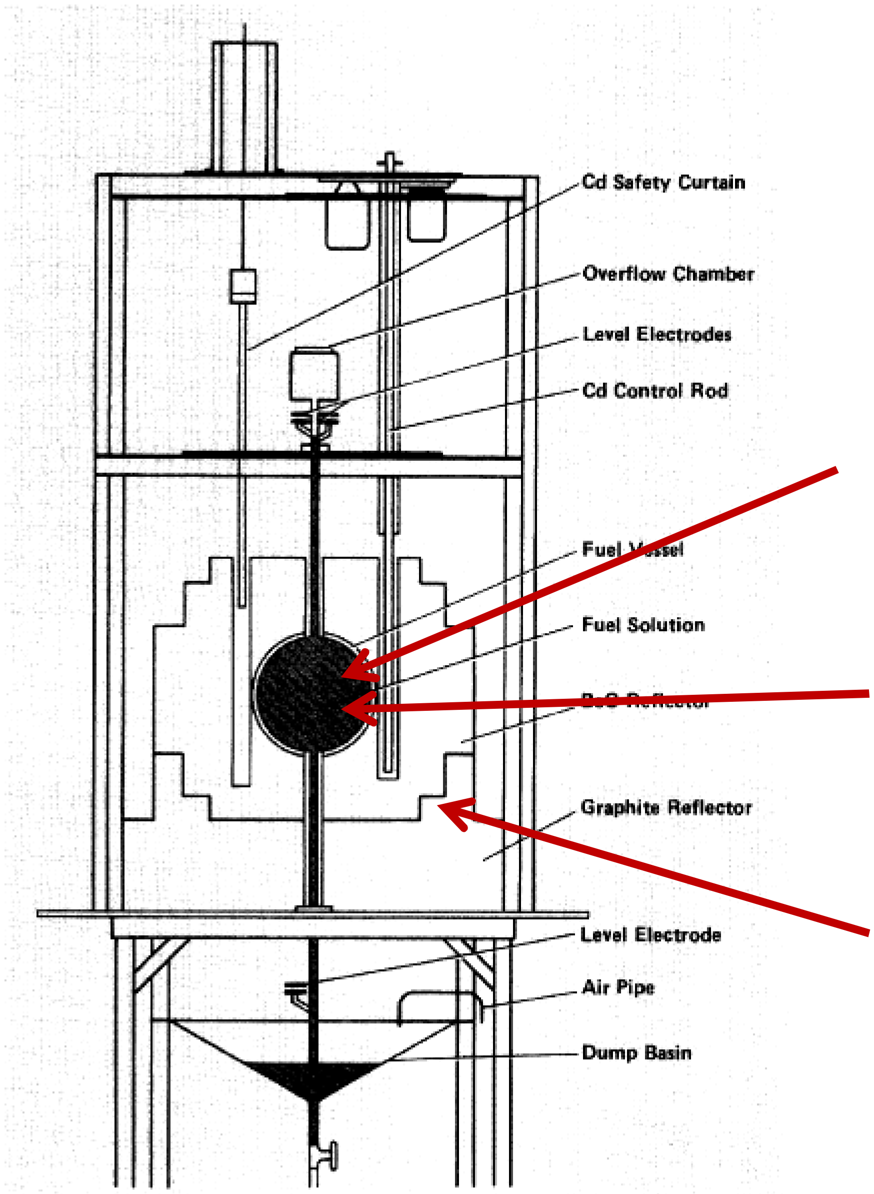


Zirconium cladding must contain fuel for centuries.

Actinides fission or absorb neutrons to form new actinides, which ....



Fermi's 1944 first fluid reactor measured U-235 critical mass.



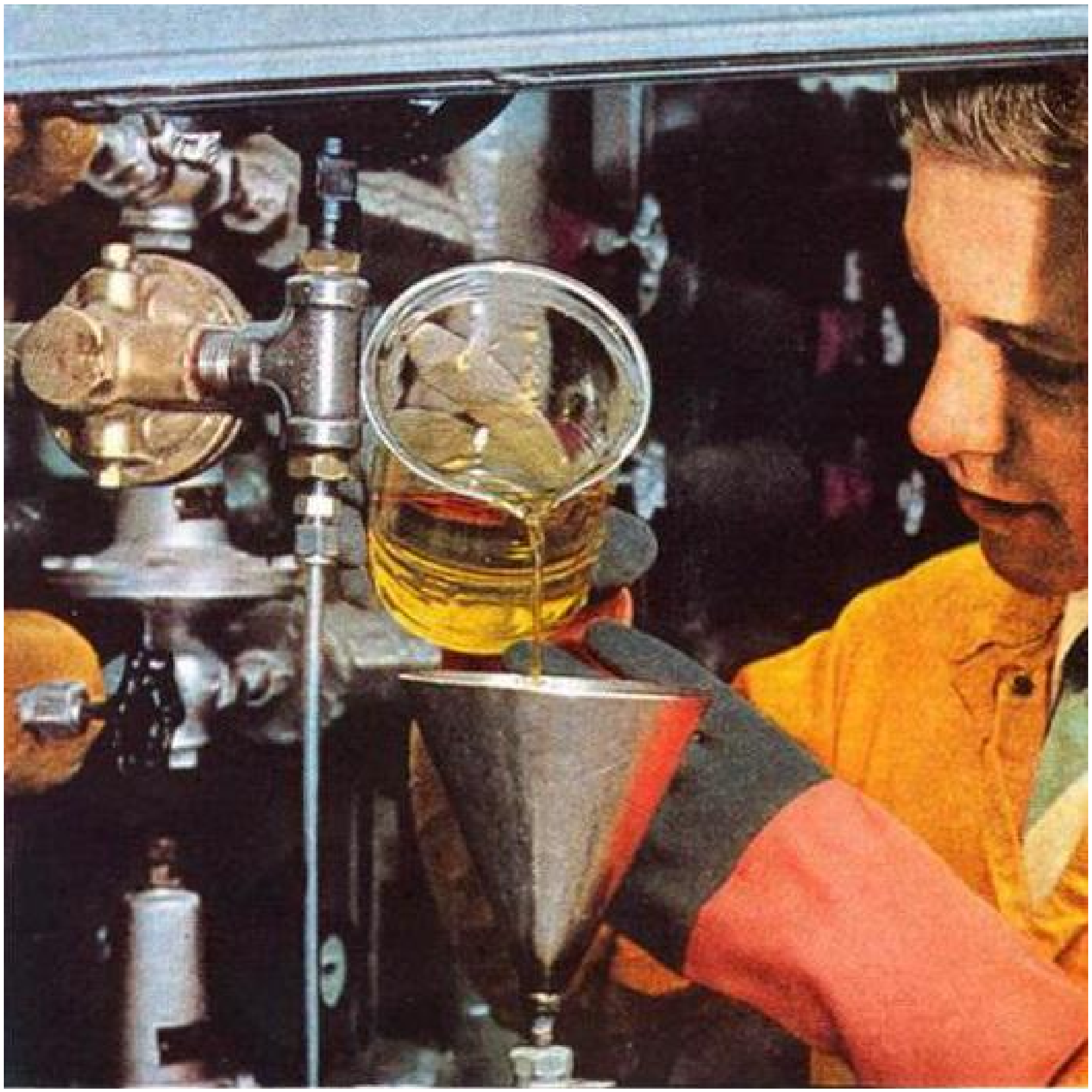
uranyl sulfate in water

all the world's U-235 !

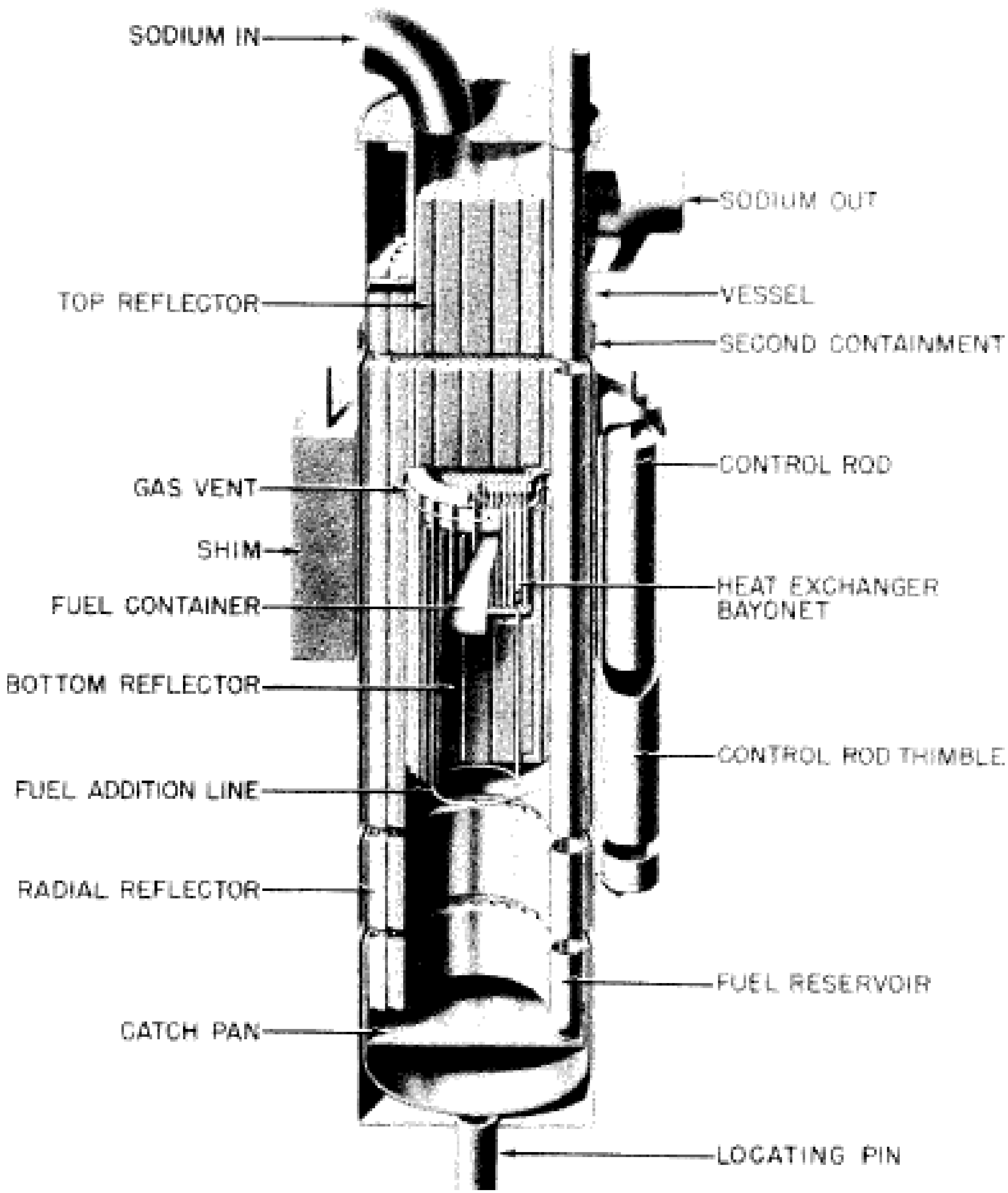
beryllium oxide neutron reflector

http://www.fas.org/sgp/othergov/doe/lanl/pubs/00416628.pdf

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.



LAMPRE

Los Alamos Molten Plutonium Reactor Experiment

1961-1963

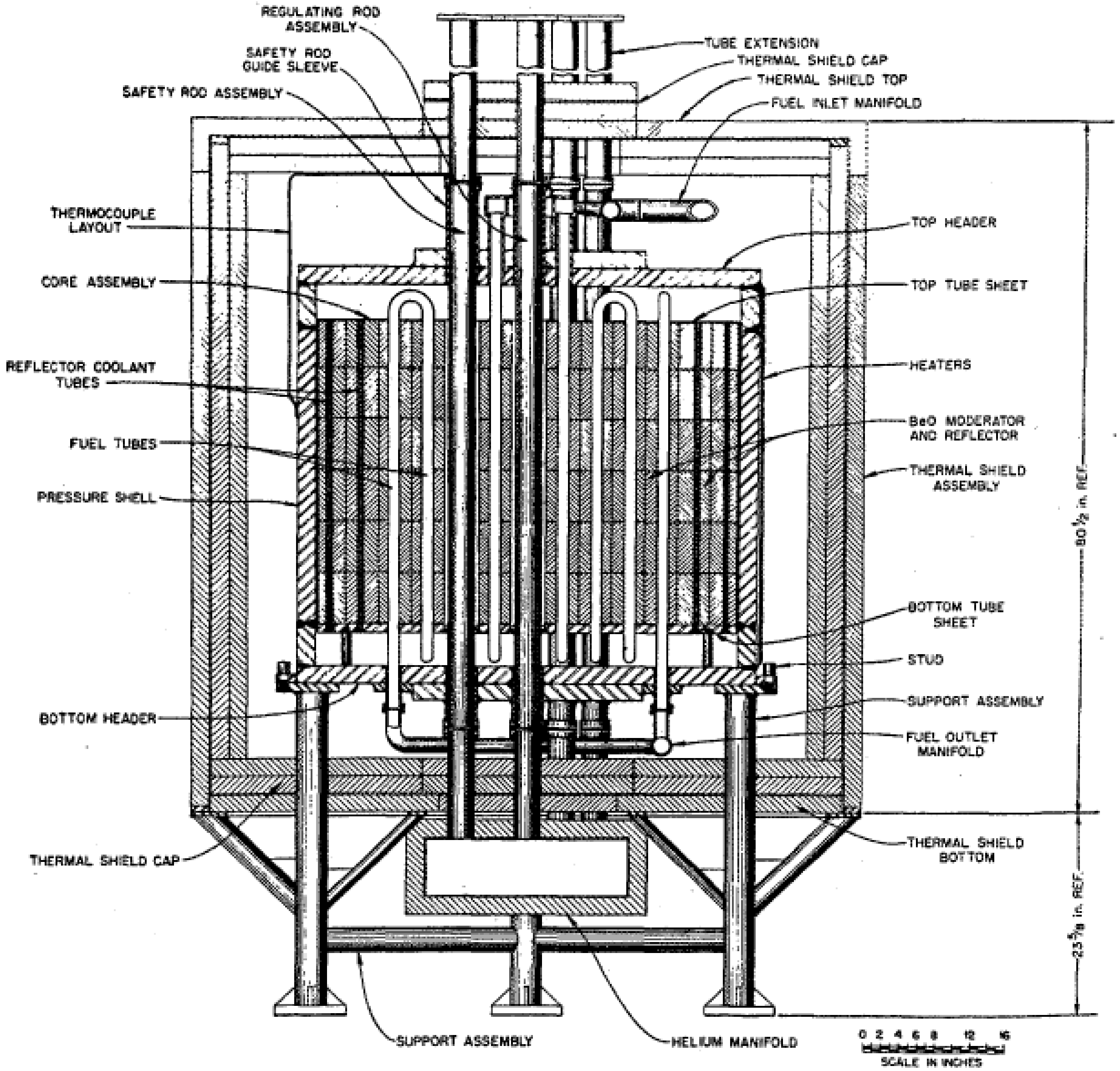
molten iron and plutonium fuel

liquid sodium cooled

J J Went developed a 1 MW suspension test reactor in 1974.

A homogeneous slurry of uranium particles was suspended in heavy water.

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



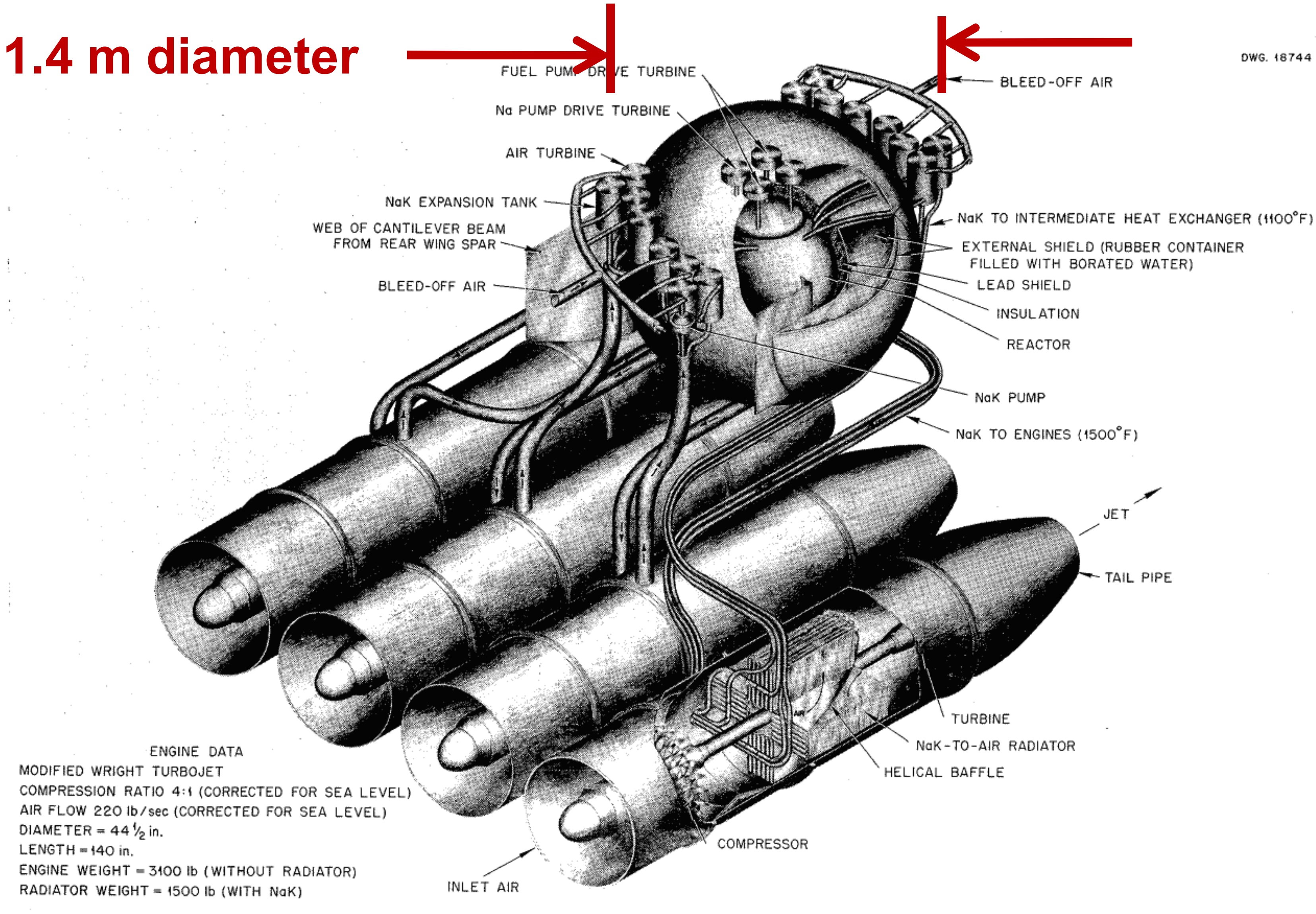
860 C

Red hot!

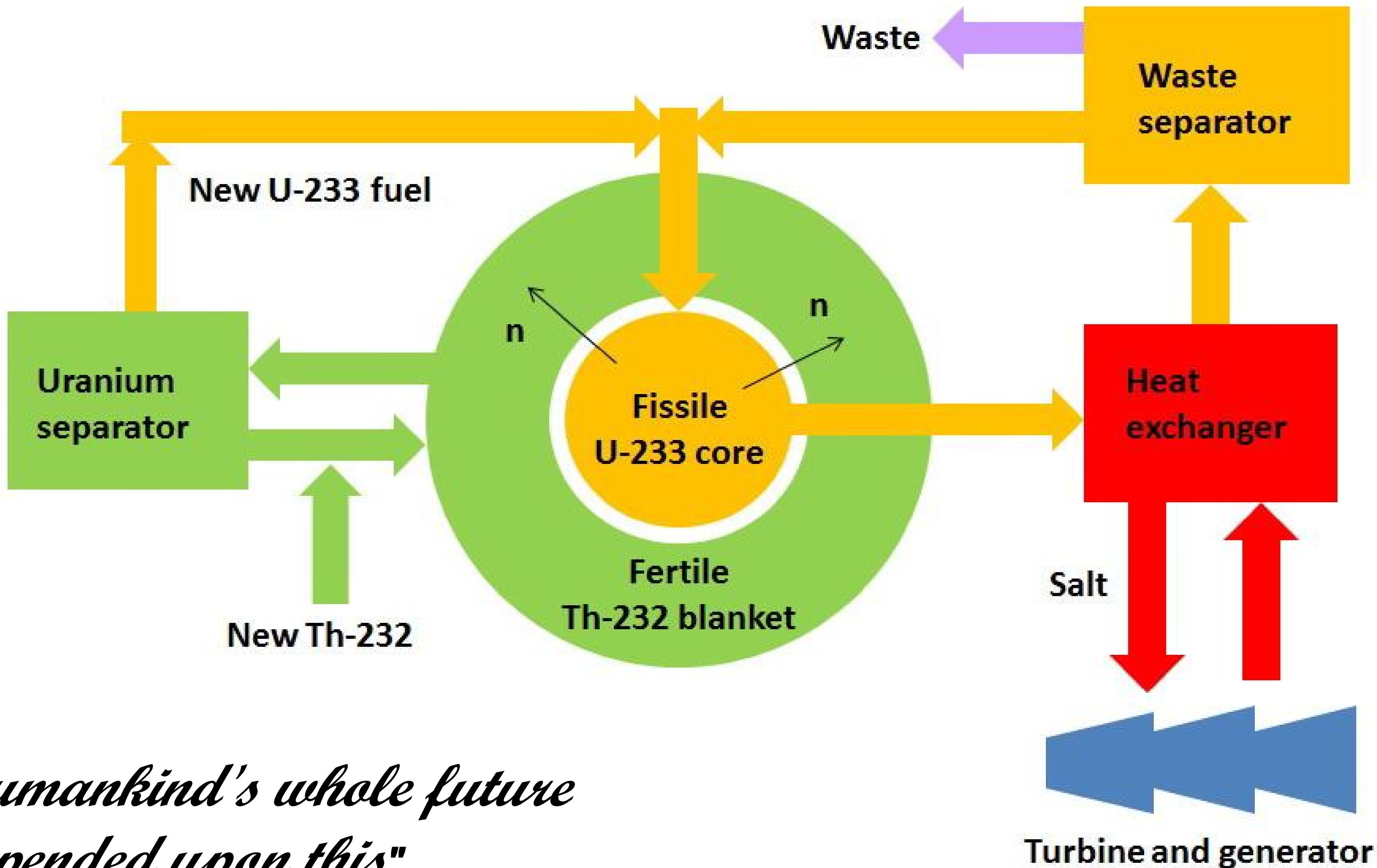
100 hours

2.5 MW

NaK metal would transfer 200 MW thermal power to jet engines.



Weinberg had envisioned LFTR ever since the 1943 Wigner design.



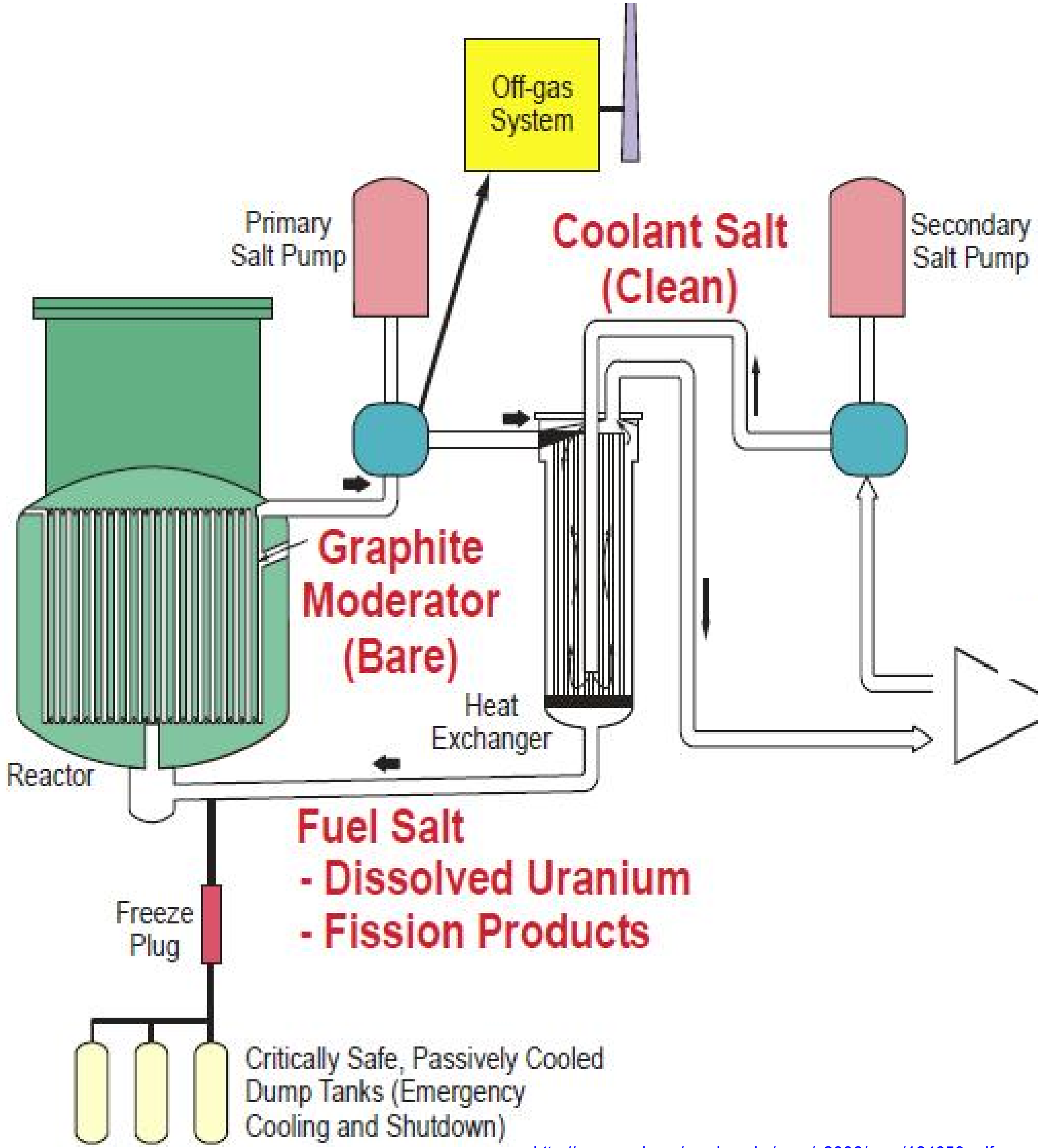
"humankind's whole future depended upon this"

The Molten Salt Reactor Experiment ran from1965 to 1969.

Salt flowed through channels in this graphite core.

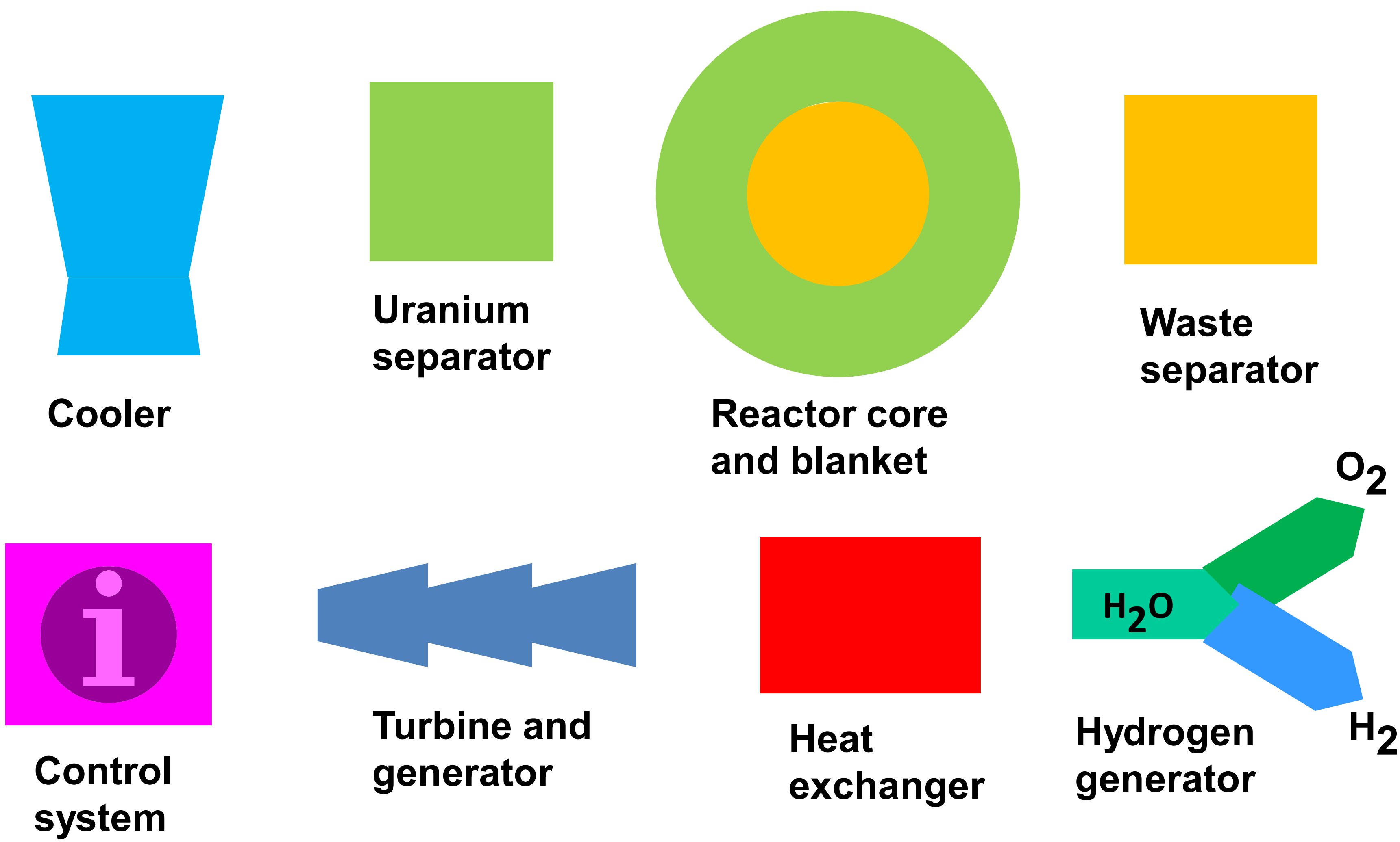
The Molten Salt Reactor Experiment succeeded.

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



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

Aim High! Develop the Liquid Fluoride Thorium Reactor.



Aim High!
Develop a small modular reactor.

Small LFTR modules can be transported by trucks.

100 MW, < $200 million

Affordable to developing nations

Power sources near points of use
-- low transmission line losses
-- less vulnerable to terrorism

Multiple units for large power stations

Incremental capital investments

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.

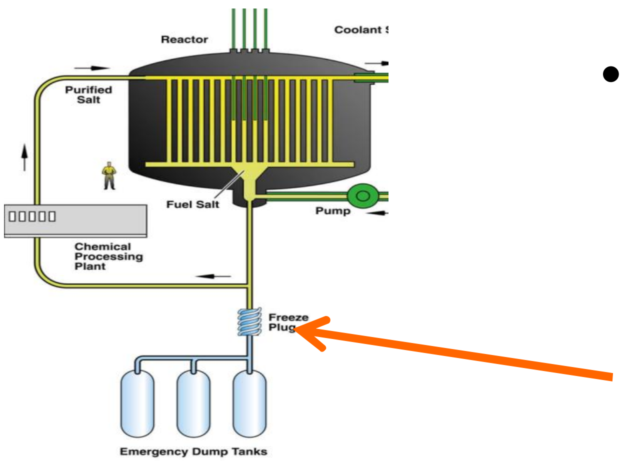
Aim High!
Design aesthetic structures.

Can a cooling tower be graceful?

Cora Kent painted Boston's Rainbow Gas Tank.

Aim High! Use automated controls, backed by inherent passive safety.

- Use high reliability systems for automated, unattended plant operations.

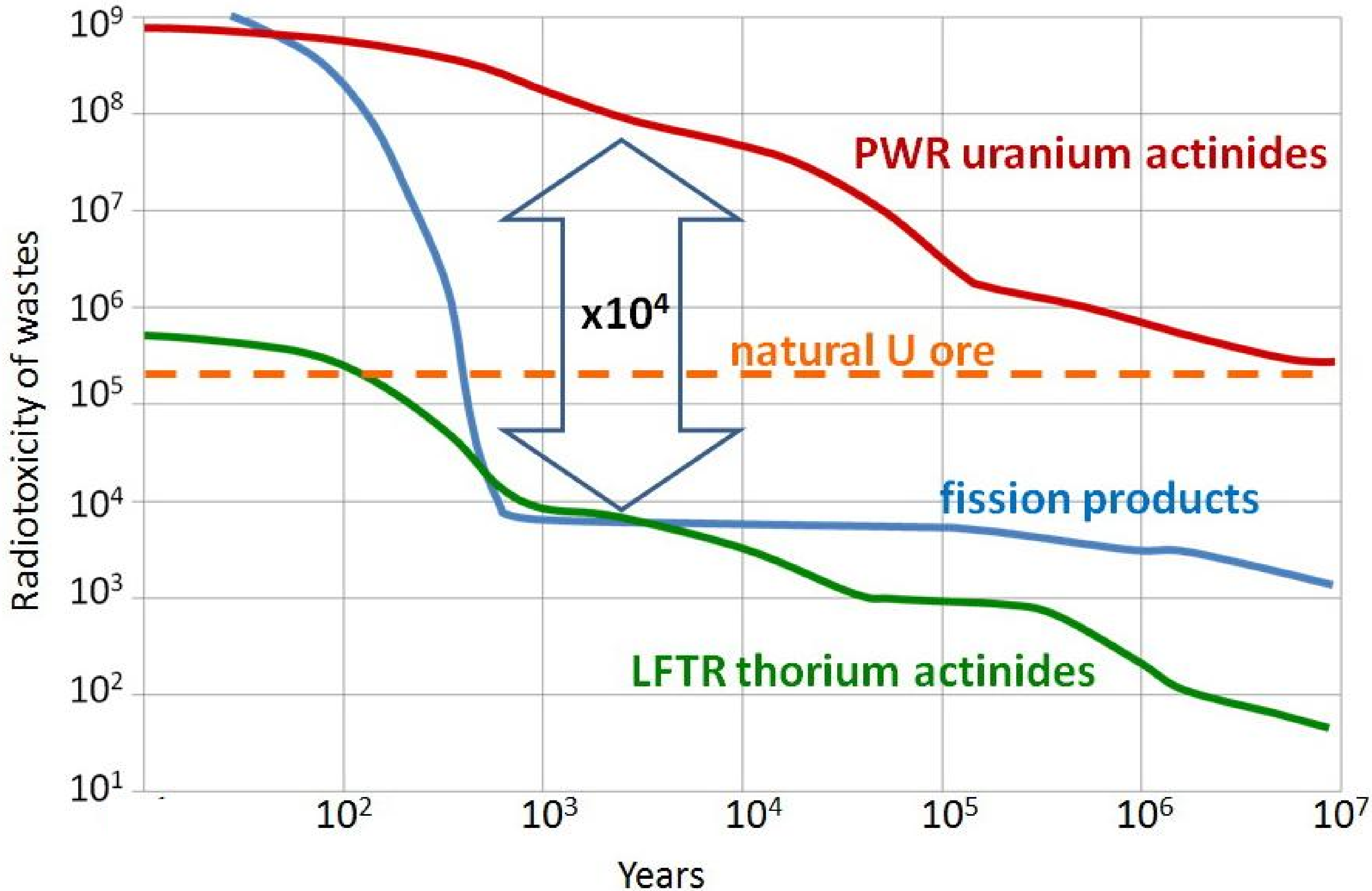


- In event of loss of power or control the freeze plug melts, molten salt flows into containment, cools, solidifies.

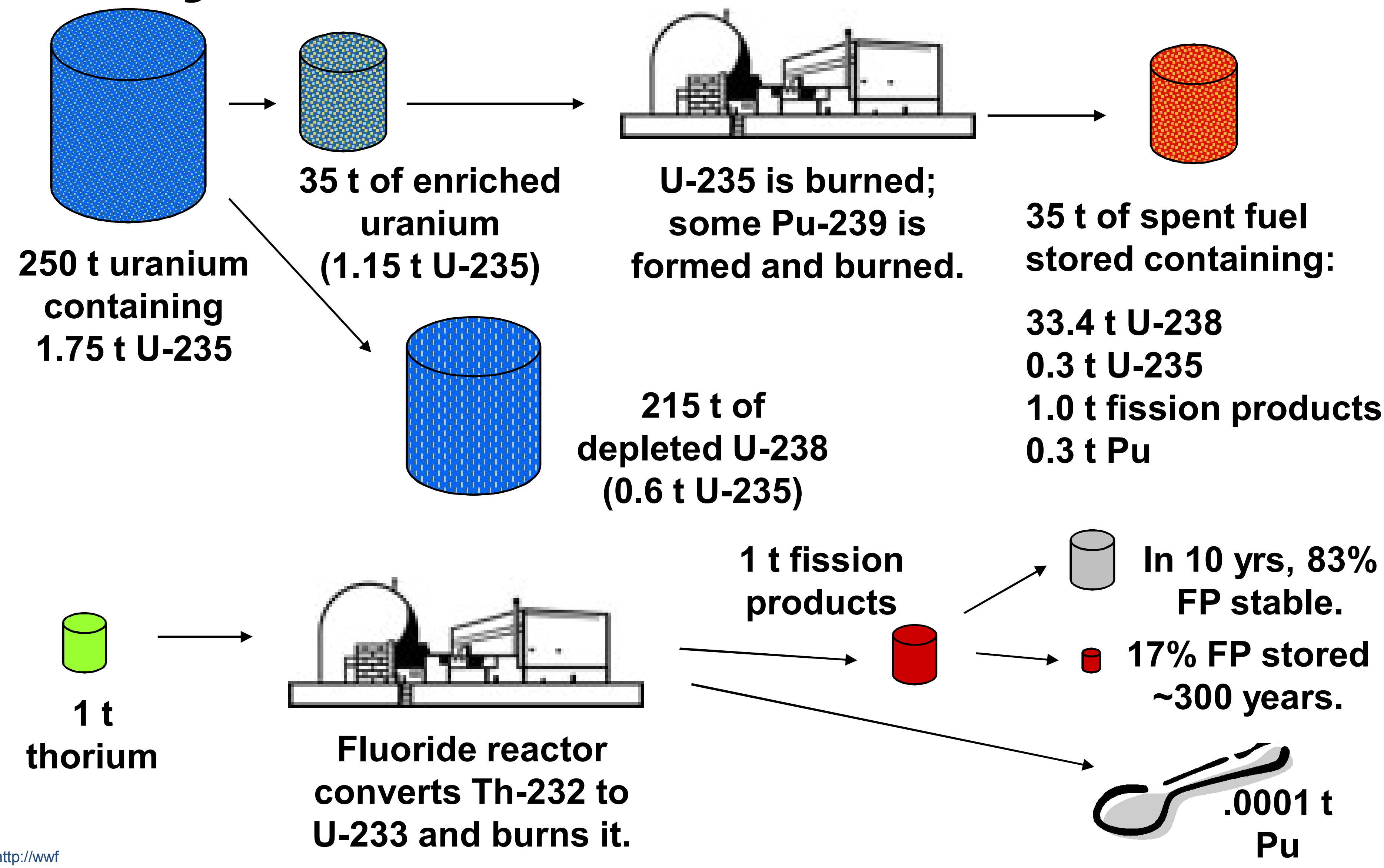
Freeze plug.

- Reduce on-site workers.
  -- Lower operational costs.
  -- Low risk of safety over-rides, operator error, experimentation, terrorism

Aim High! Produce less long lived radiotoxic actinide waste.



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



http://wwf

Atomic physicist Edward Teller promoted the LFTR to the last month of his life.

FISSION REACTORS

TECHNICAL NOTE

THORIUM-FUELED UNDERGROUND POWER PLANT BASED ON MOLTEN SALT TECHNOLOGY

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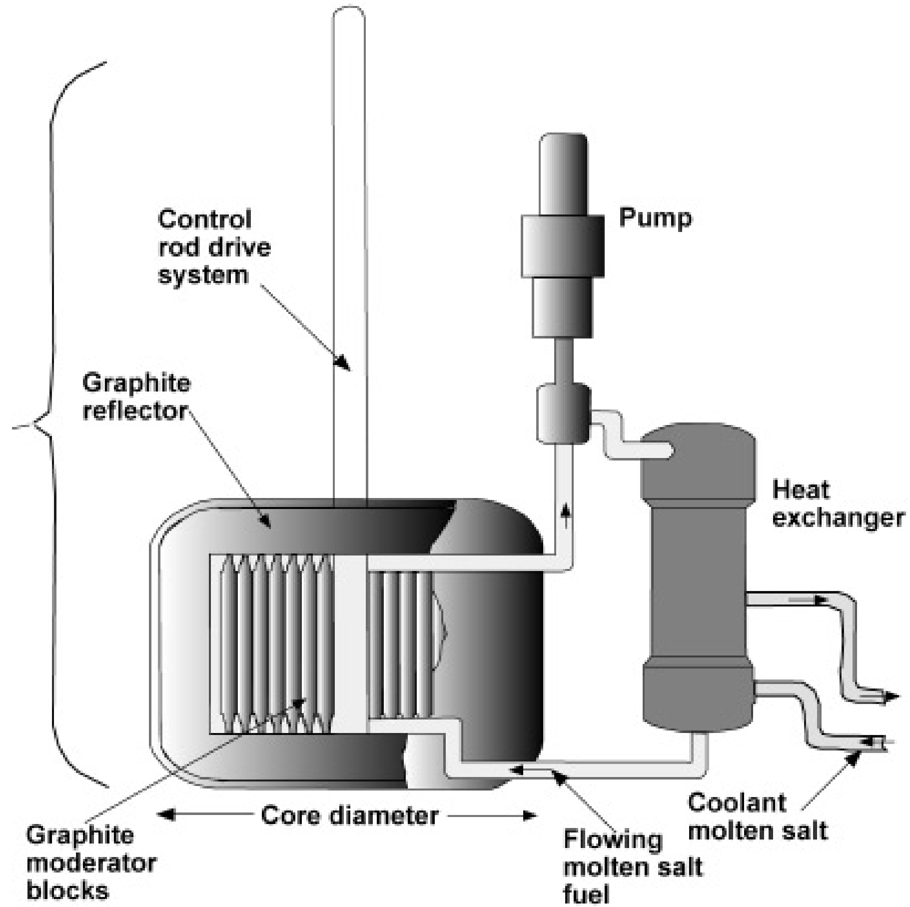
Livermore, California 94551

Received August 9, 2004
Accepted for Publication December 30, 2004



http://www.geocities.com/rmoir2003/moir_teller.pdf

Aim High!

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5. **Energy cheaper than from coal**

Energy cheaper than from coal is crucial.

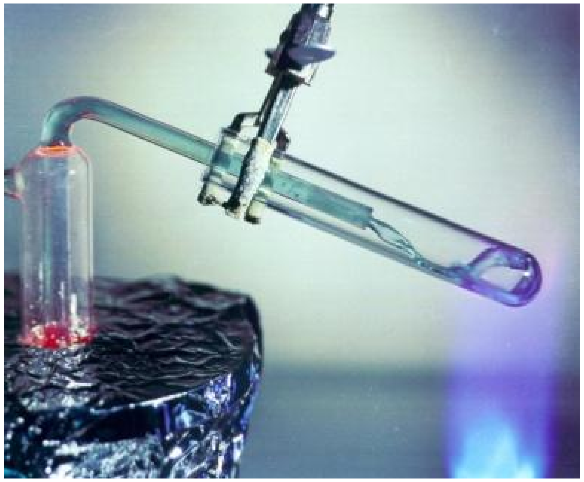
Copenhagen failed.

Coal costs $40 a ton –
$0.02 / kWh just for the coal.

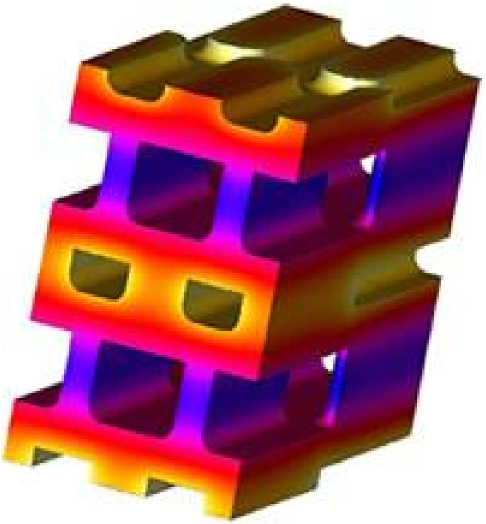
The median of five cost estimates for molten salt reactors is < $2/watt.

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

High thermal energy efficiencies keep LFTR compact at low cost.

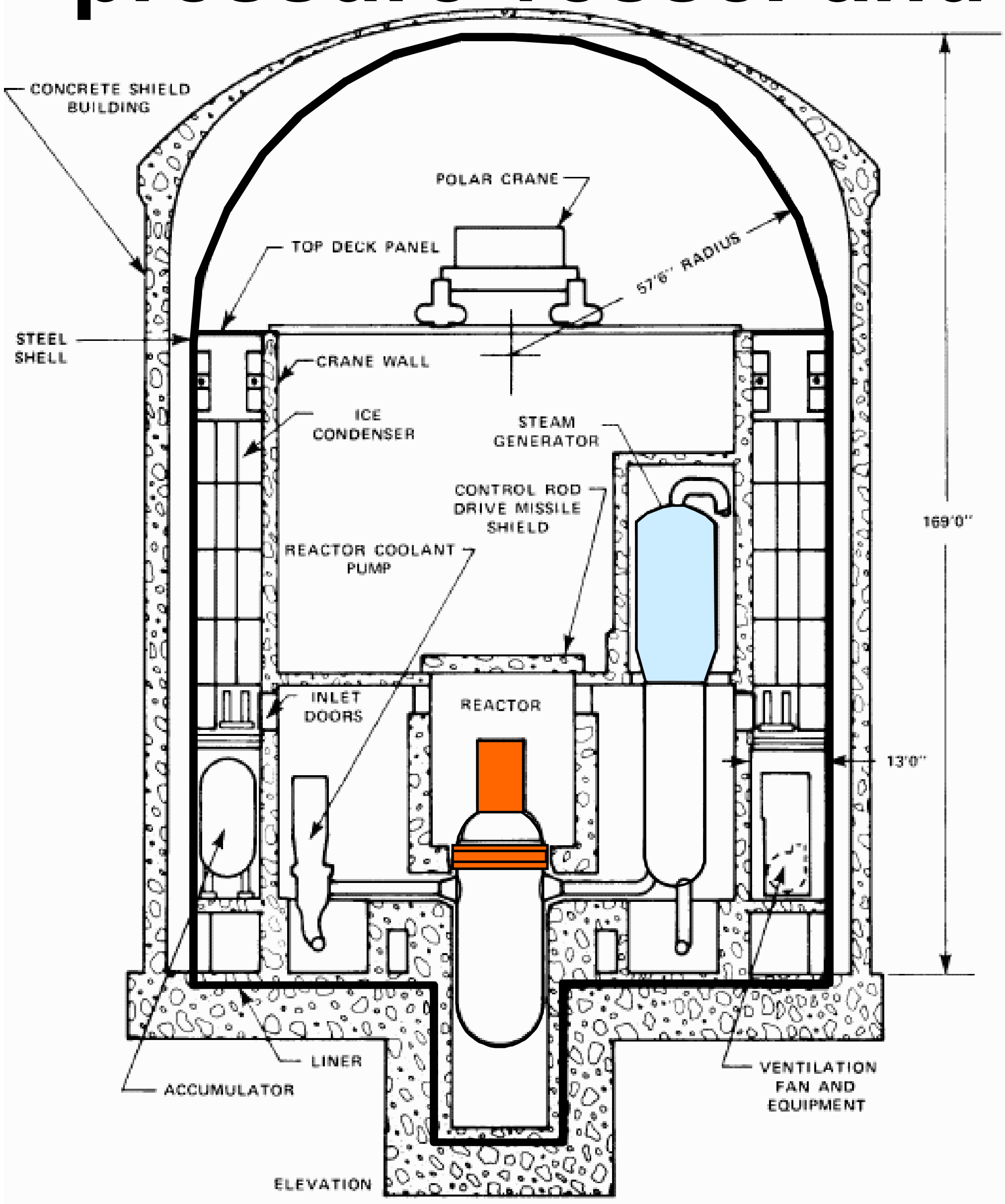


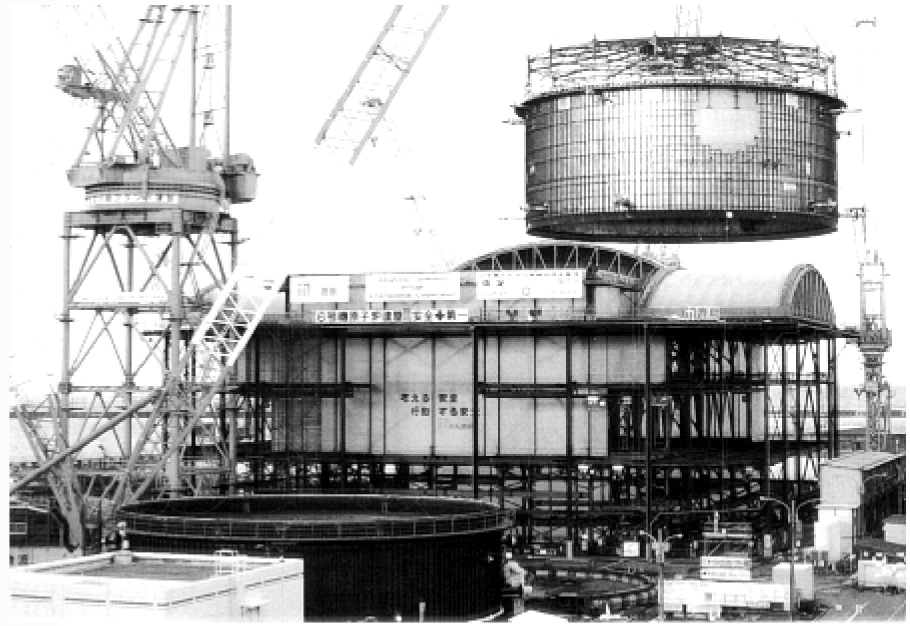
High thermal capacity heat exchange fluid



Carbon composite high temperature heat exchanger

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

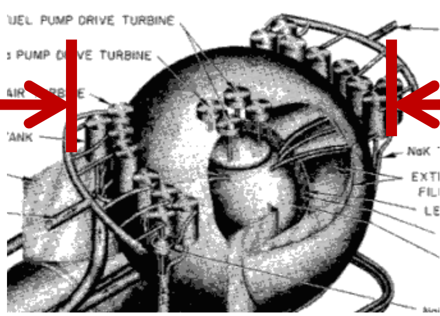




GE-Hitachi ABWR
1,356 MW
36 x 29 meter containment
1,000 ton crawler cranes

The Westinghouse AP-1000 is massively larger than LFTR.

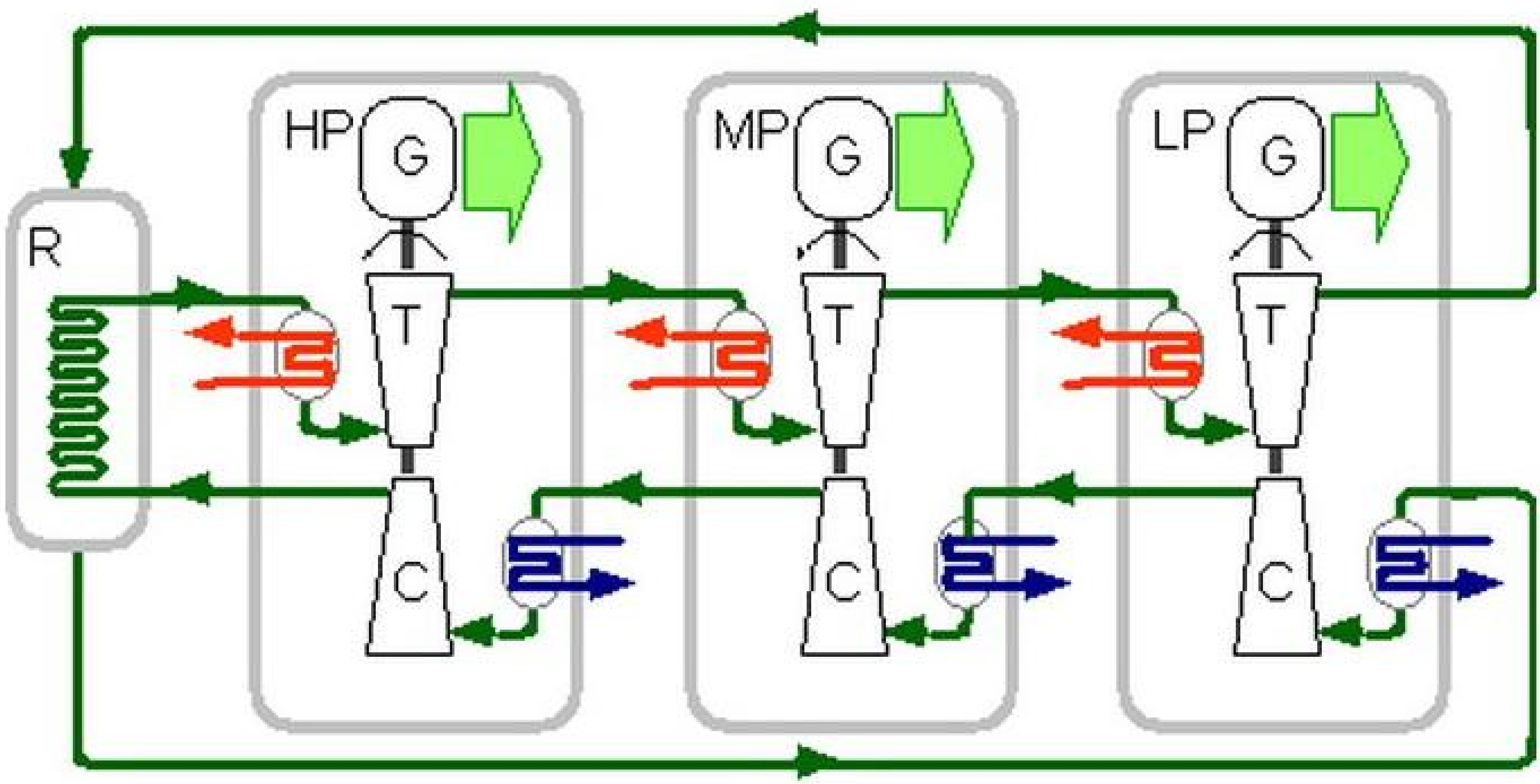
1.4 m



1.4 m

AP-1000
Samen, China

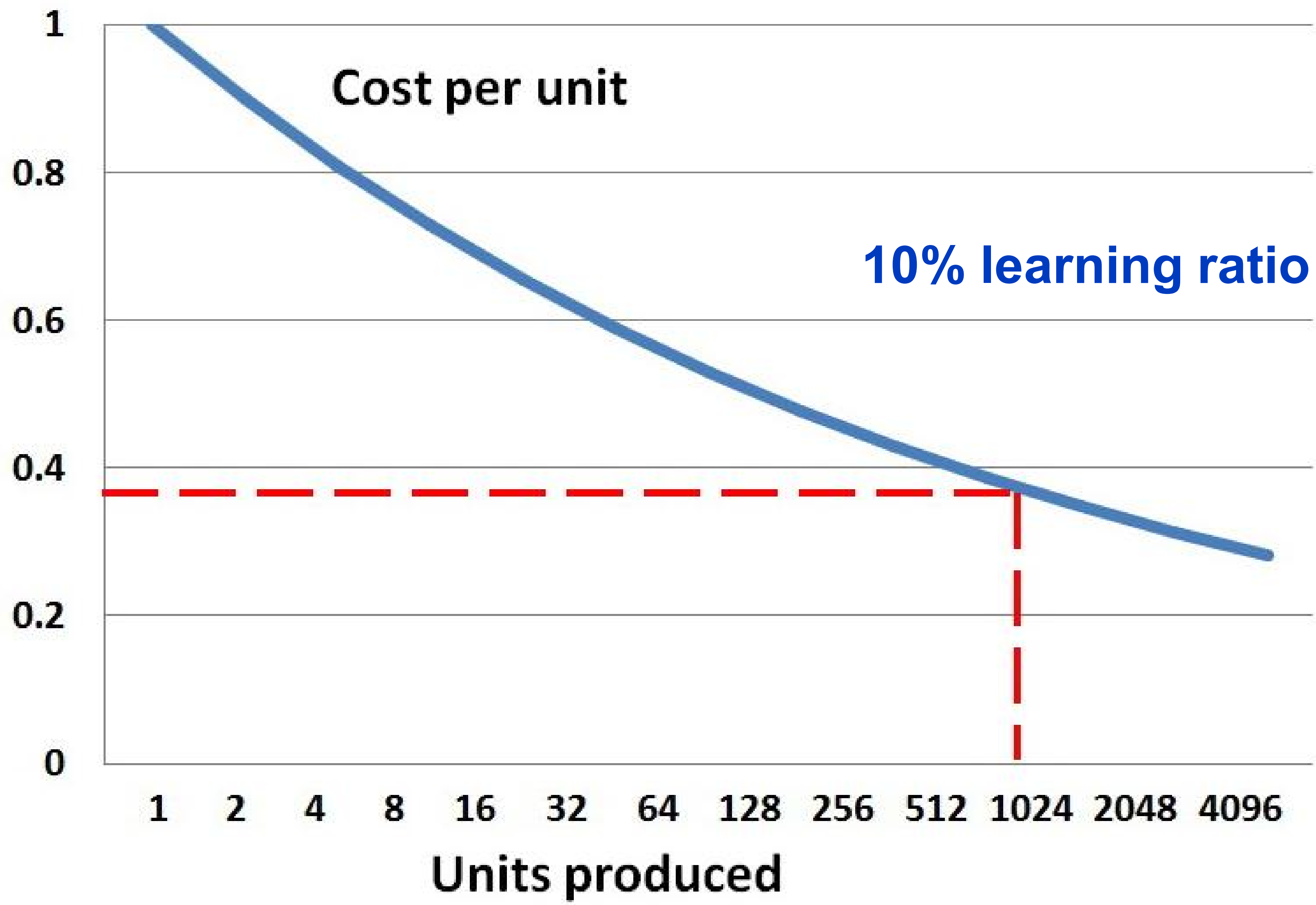
Compact closed cycle Brayton turbine raises power conversion efficiency.



Halving rejected heat enables air cooling.

Boeing factories produce a $200 million aircraft every day.

The learning curve reduces costs.



Aim High!

Electricity cheaper than from coal.

100 MW LFTR	$ Cost	$ per mo, 40 yrs, 8%	$ per KWH @ 90%
Construction	200,000,000	1,390,600	0.0214

http://www.bloomberg.com/apps/news?pid=20601080&refer=asia&sid=aV_2FPIVxISE

Aim High!
Electricity cheaper than from coal.

100 MW LFTR	$ Cost	$ per mo, 40 yrs, 8%	$ per KWH @ 90%
Construction	200,000,000	1,390,600	0.0214
100 kg U startup	5,000,000	35,000	0.00054
Thorium fuel	30,000/yr	2500	0.000004

http://www.bloomberg.com/apps/news?pid=20601080&refer=asia&sid=aV_2FPIVxISE

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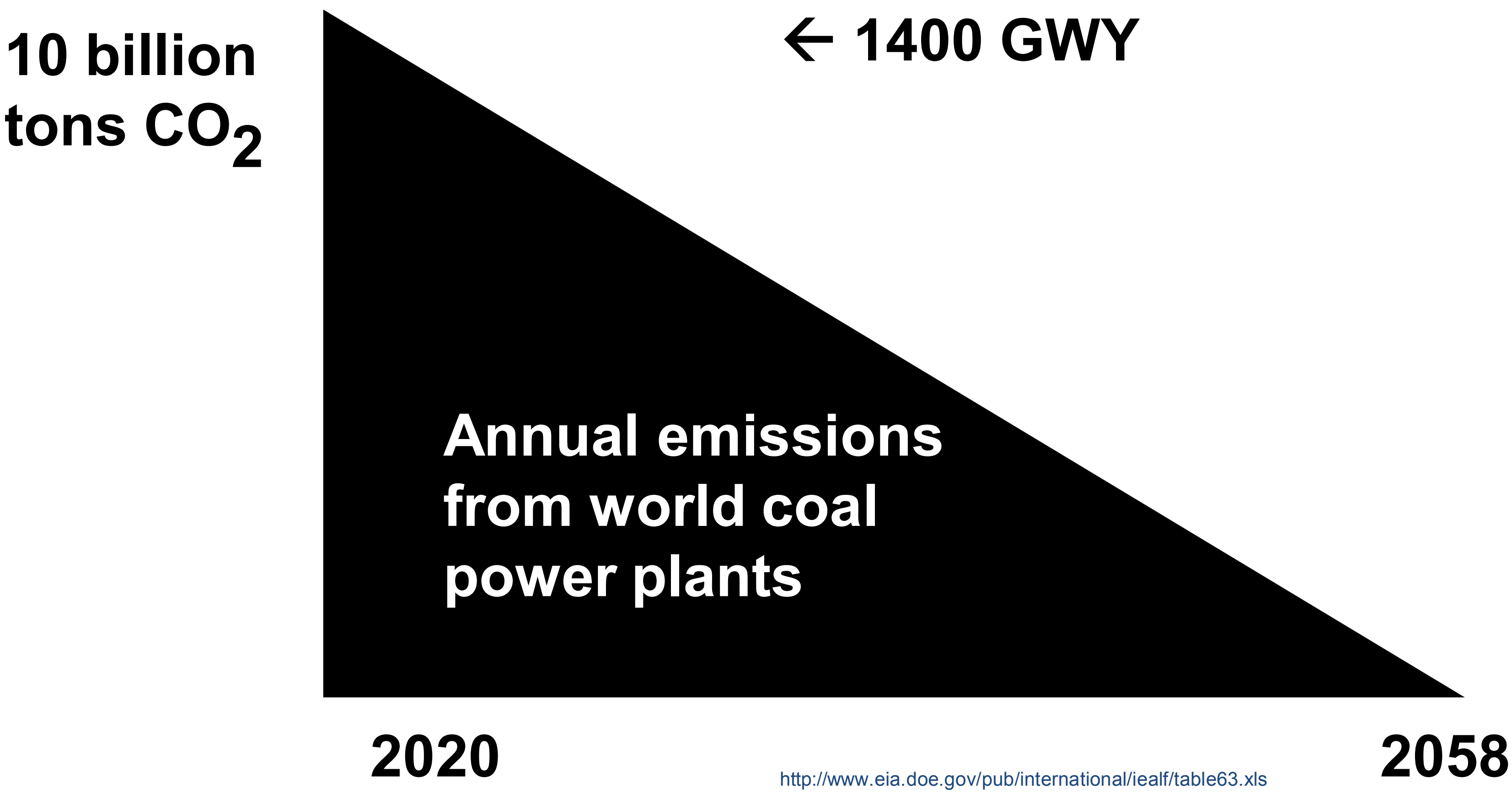
100 kg U startup	5,000,000	35,000	0.00054
Thorium fuel	30,000/yr	2500	0.000004
Decomm (½ const)	100,000,000	960	0.0000015
Operations	1,000,000/yr	83,333	0.00128
TOTAL			0.023

http://www.bloomberg.com/apps/news?pid=20601080&refer=asia&sid=aV_2FPIVxISE

Aim High!

Check global warming.

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

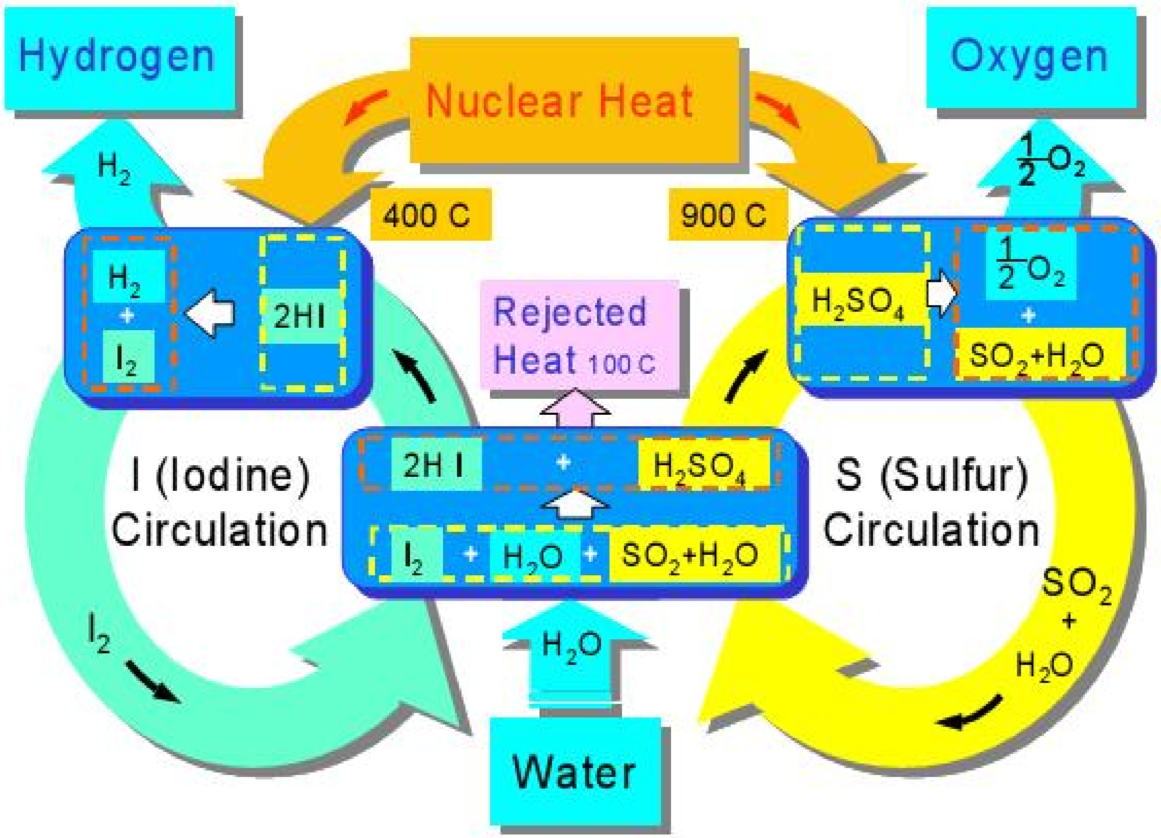


http://www.eia.doe.gov/pub/international/iealf/table63.xls

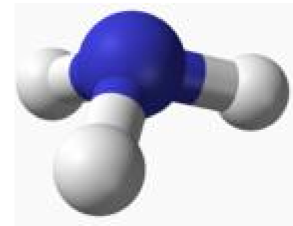
Aim High!

Synthesize vehicle fuel.

Dissociate water at 900°C to make hydrogen, with sulfur-iodine process.

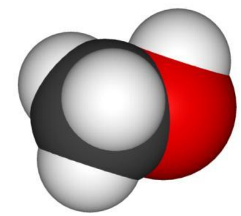


http://wwwtest.iri.tudelft.nl/~klooster/reports/hydro_slides_2003.pdf

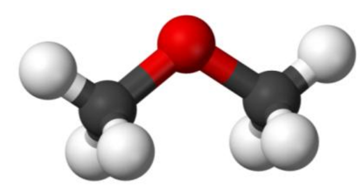


Ammonia

$CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$



Methanol for gasoline



Dimethyl ether for diesel

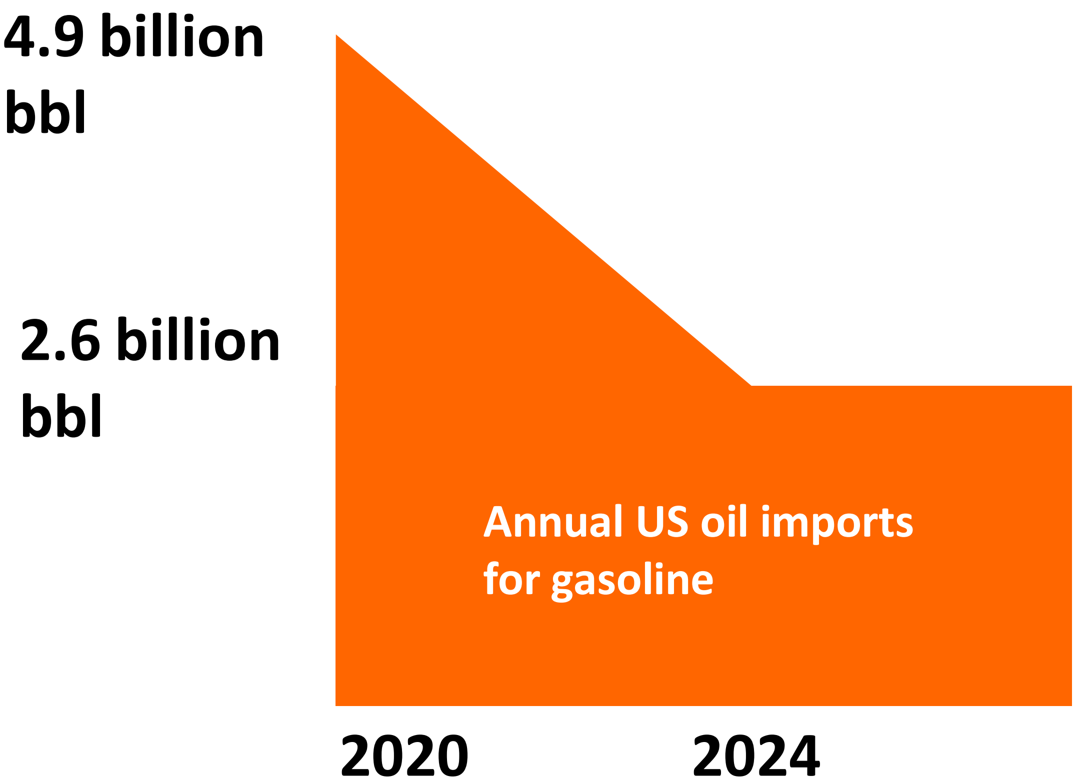
Aim High! Cut US oil imports.

Dissociate H_2 and synthesize fuel (50% x 50% efficiency).
Standard LFTR makes 250,000 bbl/year.
Install one LFTR each week.

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

Electric cars help cut oil imports.

Chevy Volt recharges with 8 kWh for 40 miles.
A 100 MW LFTR can power 300,000 cars.
Install one LFTR each week until half the 125,000,000, 20-mpg fleet is replaced.

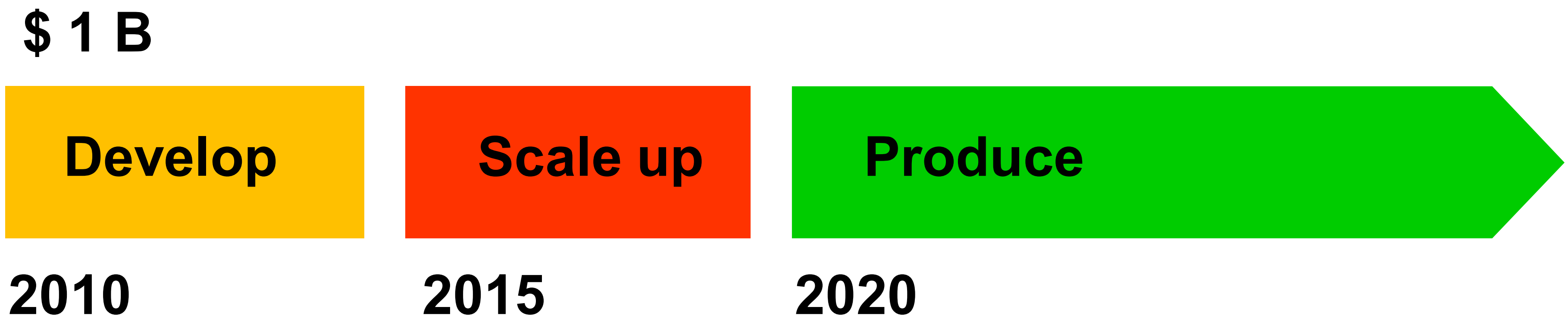


Best use of petroleum fuel is for airplanes.

http://farm4.static.flickr.com/3112/2654553896_fe93088b30_o.jpg

http://www.boeing.com/commercial/gallery/787/index1.html

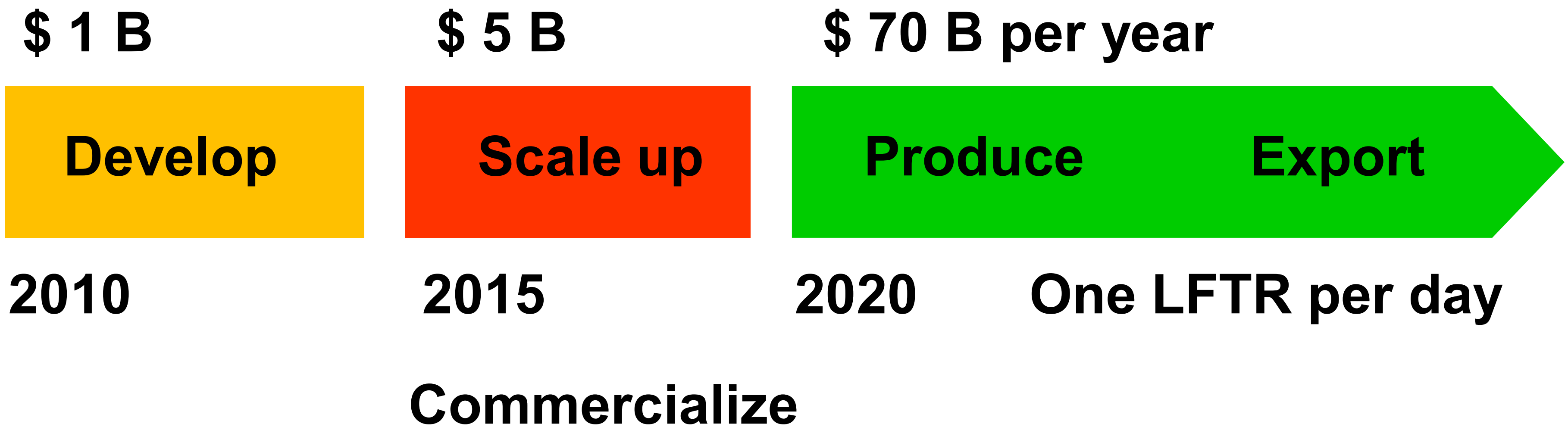
Aim High! Develop a prototype LFTR in 5 years.



Rickover's Shippingport was built in 32 months.

Weinberg-engineered Oak Ridge X-10 was built in 9 months.

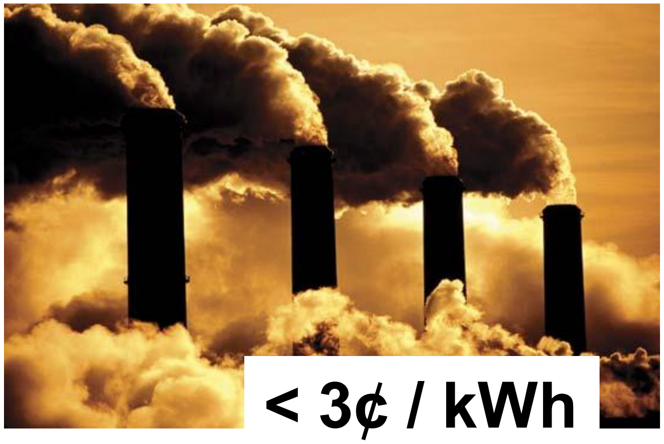
Aim High! A $70 billion industry.



Aim High! Meet aggressive goals?

A new energy source that

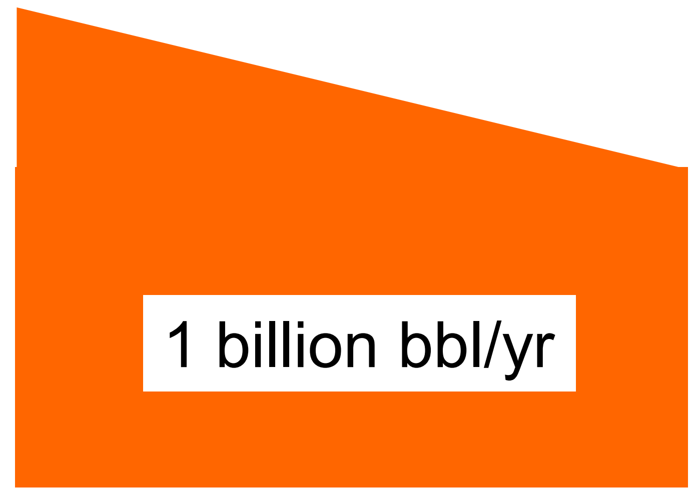
1. Produces electricity cheaper than from coal,



Aim High! Meet aggressive goals?

A new energy source that

1. Produces electricity cheaper than from coal,
2. Synthesizes vehicle fuel,



Aim High! Meet aggressive goals?

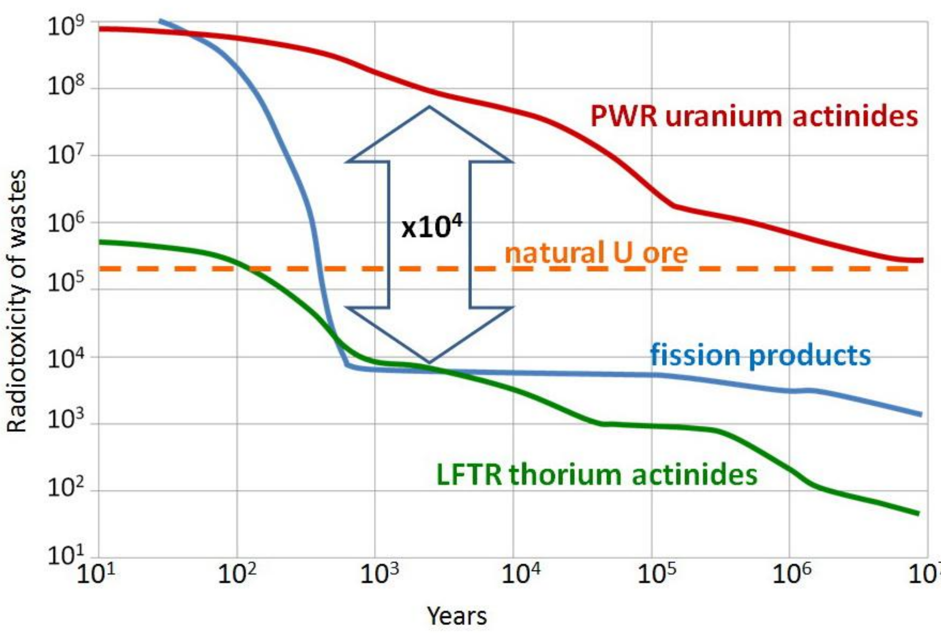
A new energy source that

1. Produces electricity cheaper than from coal,
2. Synthesizes vehicle fuel,
3. Is inexhaustible,

Aim High! Meet aggressive goals?

A new energy source that

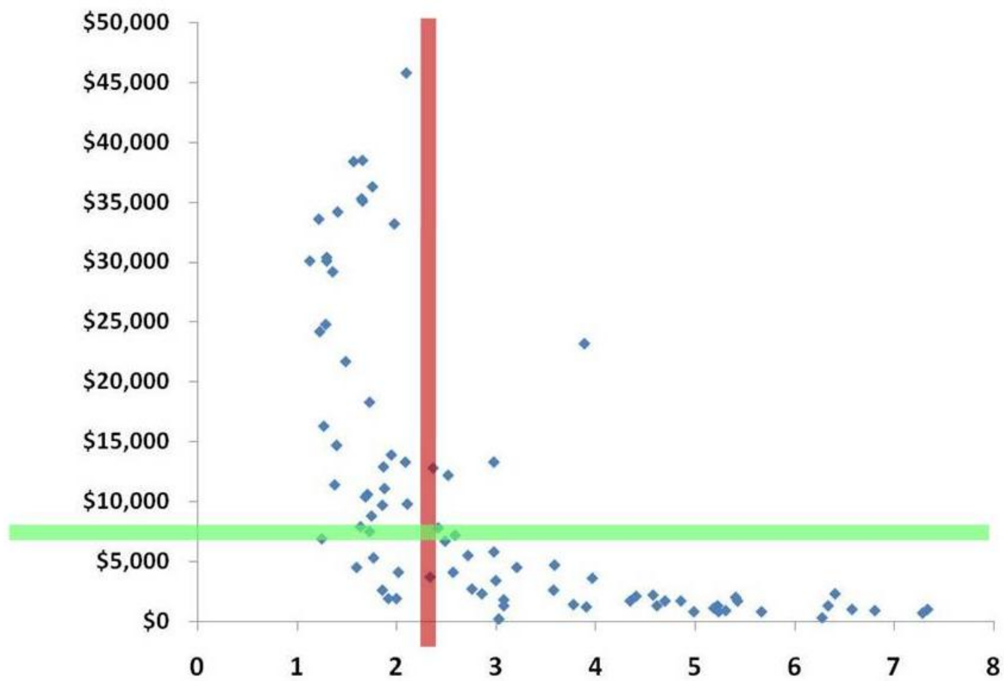
1. Produces electricity cheaper than from coal,
2. Synthesizes vehicle fuel
3. Is inexhaustible,
4. Reduces waste



Aim High! Meet aggressive goals?

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.



Aim High! Meet aggressive goals?

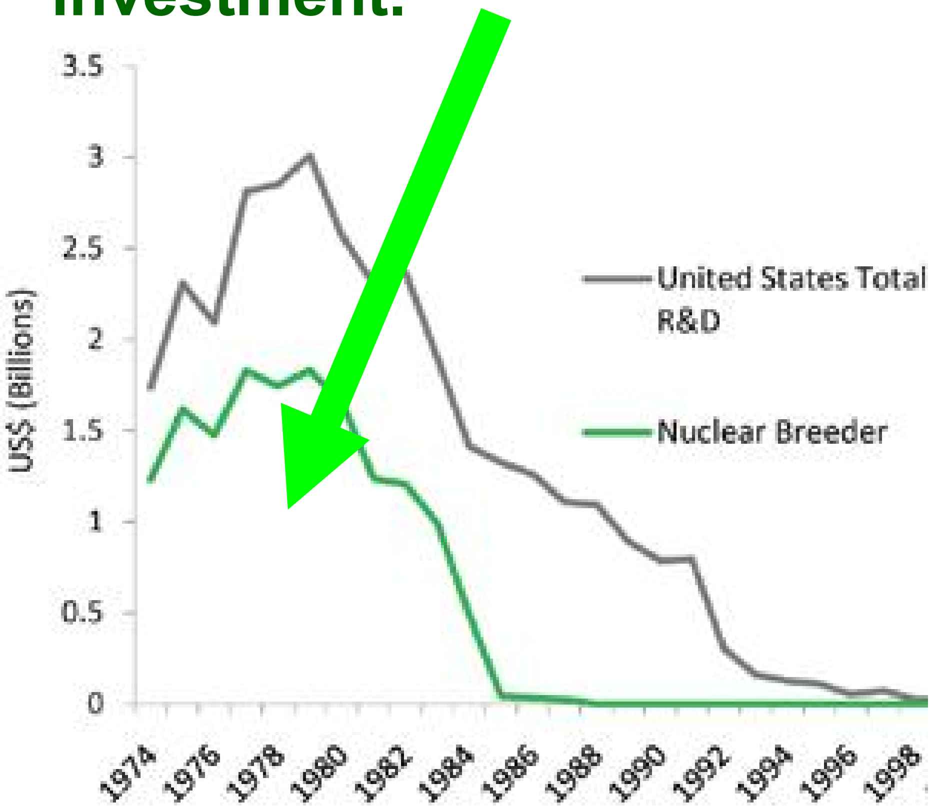
A new energy source that

1. Produces electricity cheaper than from coal,
2. Synthesizes vehicle fuel,
3. Is inexhaustible,
4. Reduces waste, and
5. Is affordable to developing nations.

- Checks global warming.
- Enables worldwide prosperity and population stability.

But US advanced nuclear fission R&D has dropped – near zero for breeders.

$16 billion ($2011)
Cumulative LMFBR investment.



2011 DOE Nuclear Energy budget items

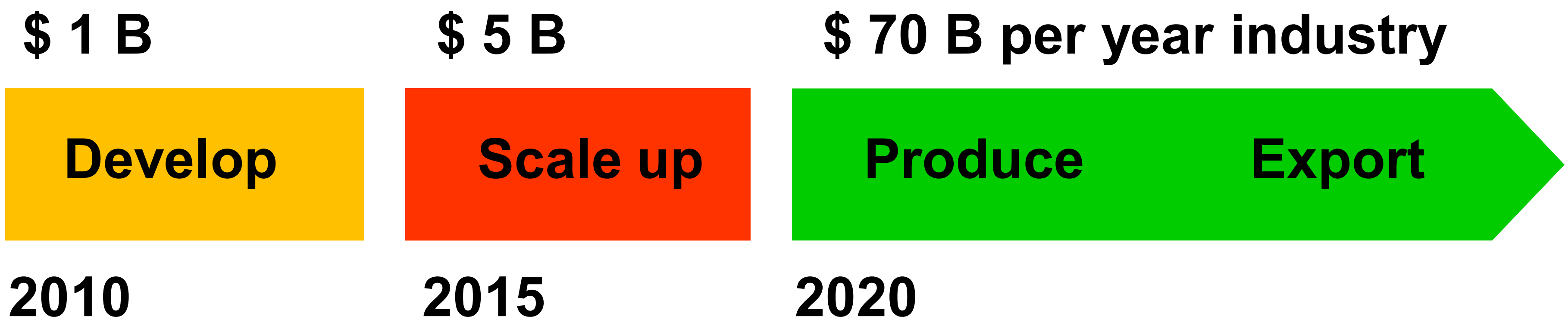
$103 million
NGNP high temperature gas reactor with TRISO fuel.

$22 million
Advanced reactor concepts, principally fast reactors.

$40 million
Advanced fuel cycles, but no liquid fuel, no closed fuel cycle.

IAEA, via Inter. Panel on Fissile Materials Feb 2010

LFTR benefits are measurable.



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

Avoid carbon taxes.

Improve world prosperity.

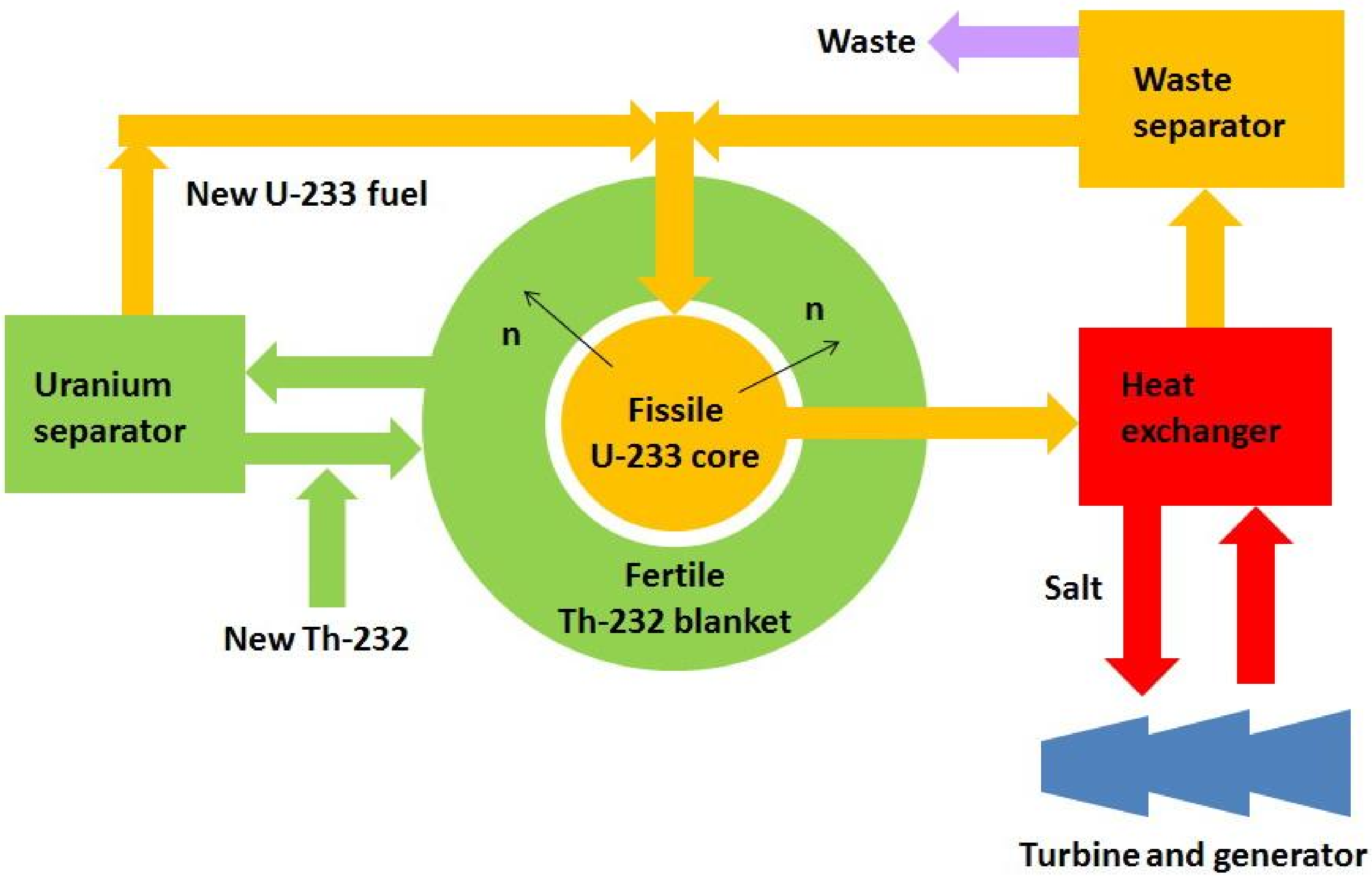
Check world population growth.

Reduce radiotoxic waste; consume world fissile stocks.

Use inexhaustible thorium fuel, available in all nations.

Thank you. Aim High!

Liquid Fluoride Thorium Reactors



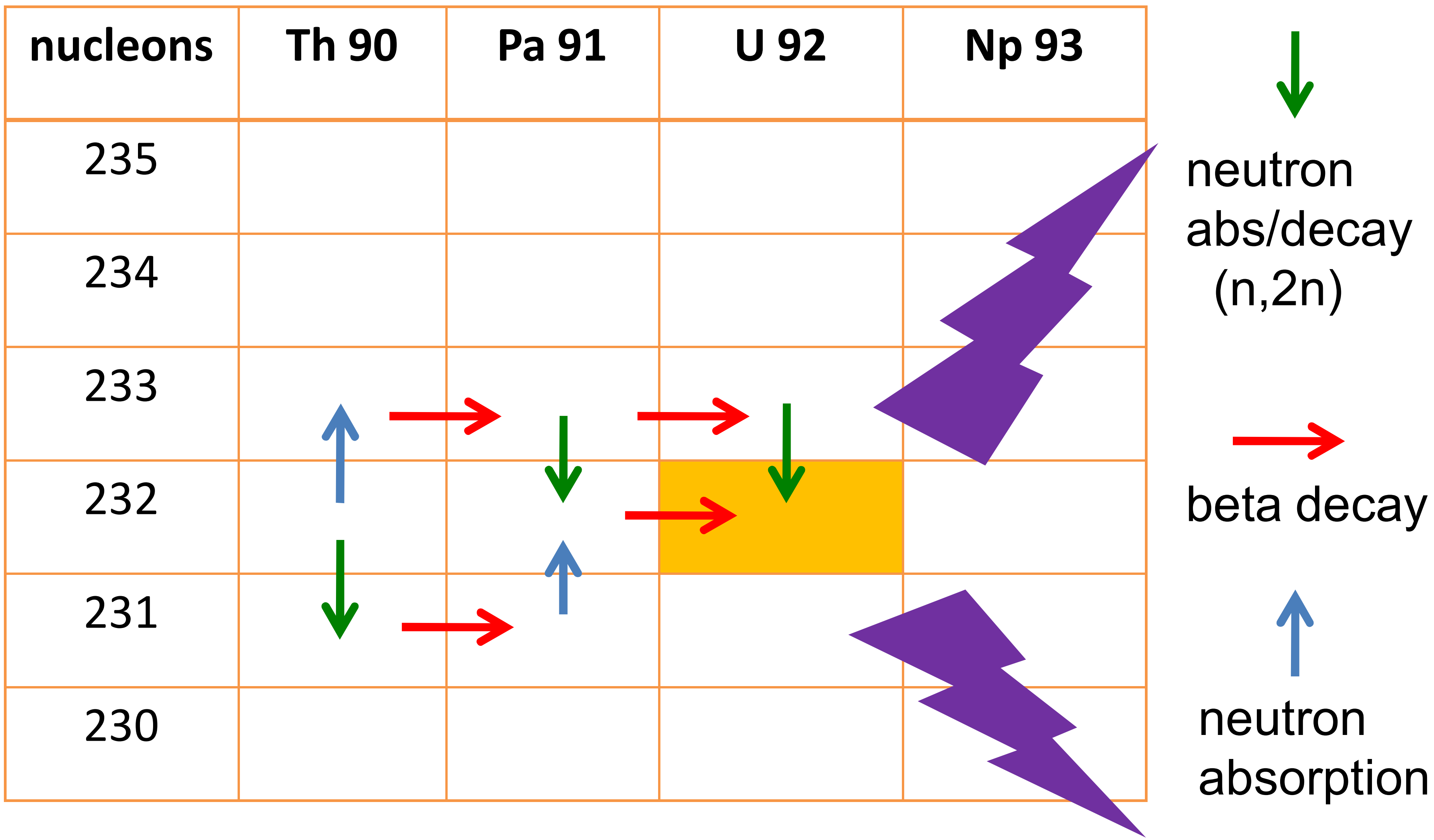
Energy cheaper than from coal.

[redacted]

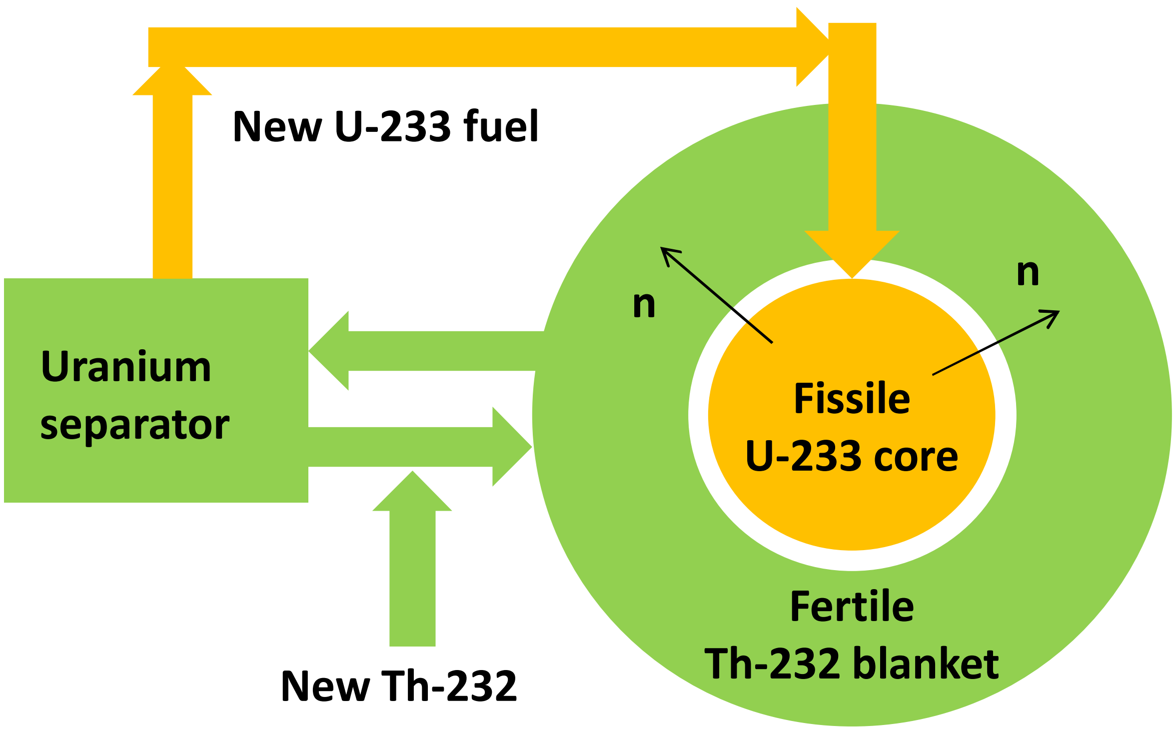
Aim High!

Questions?

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.

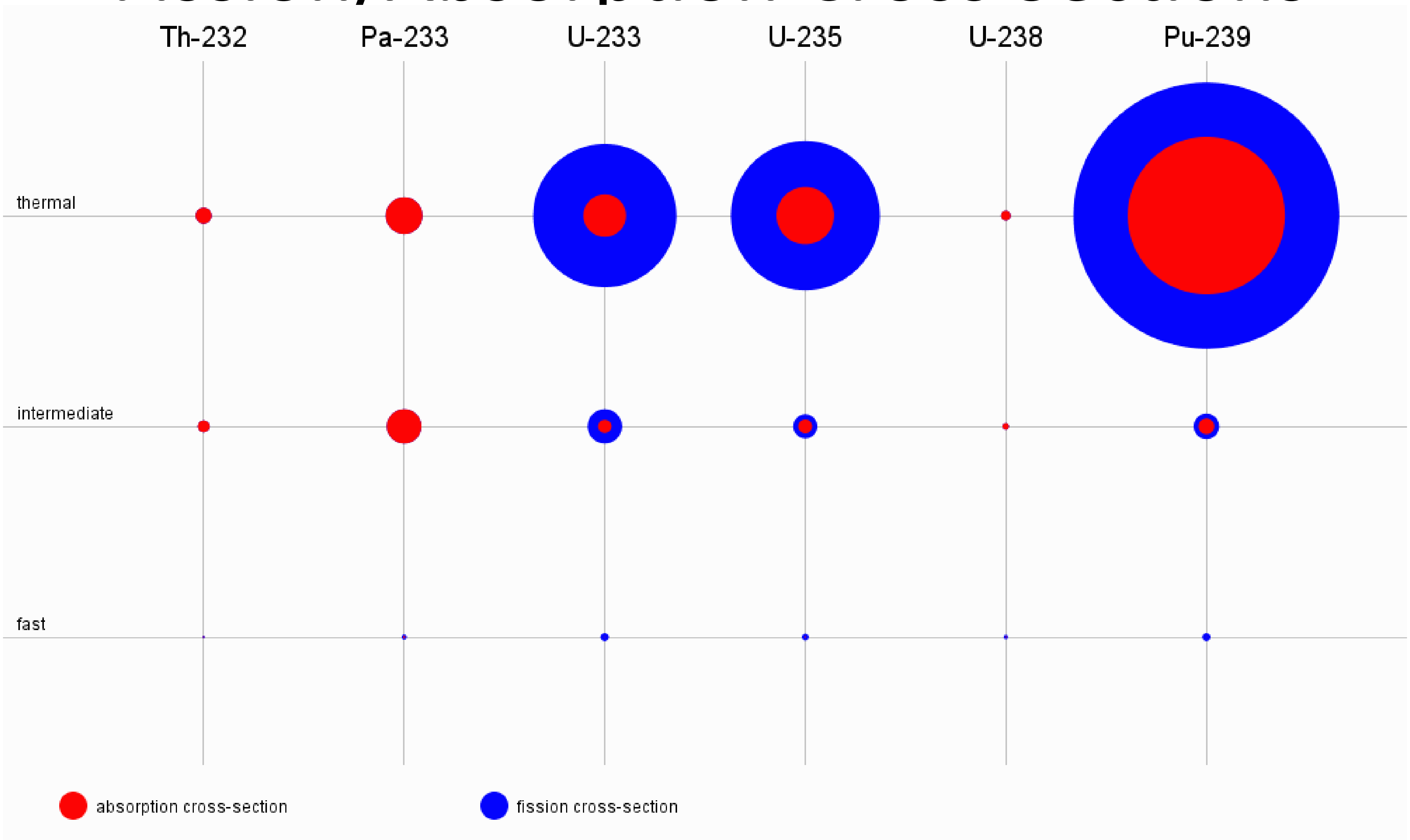
U-232 contamination will be 0.13%.

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

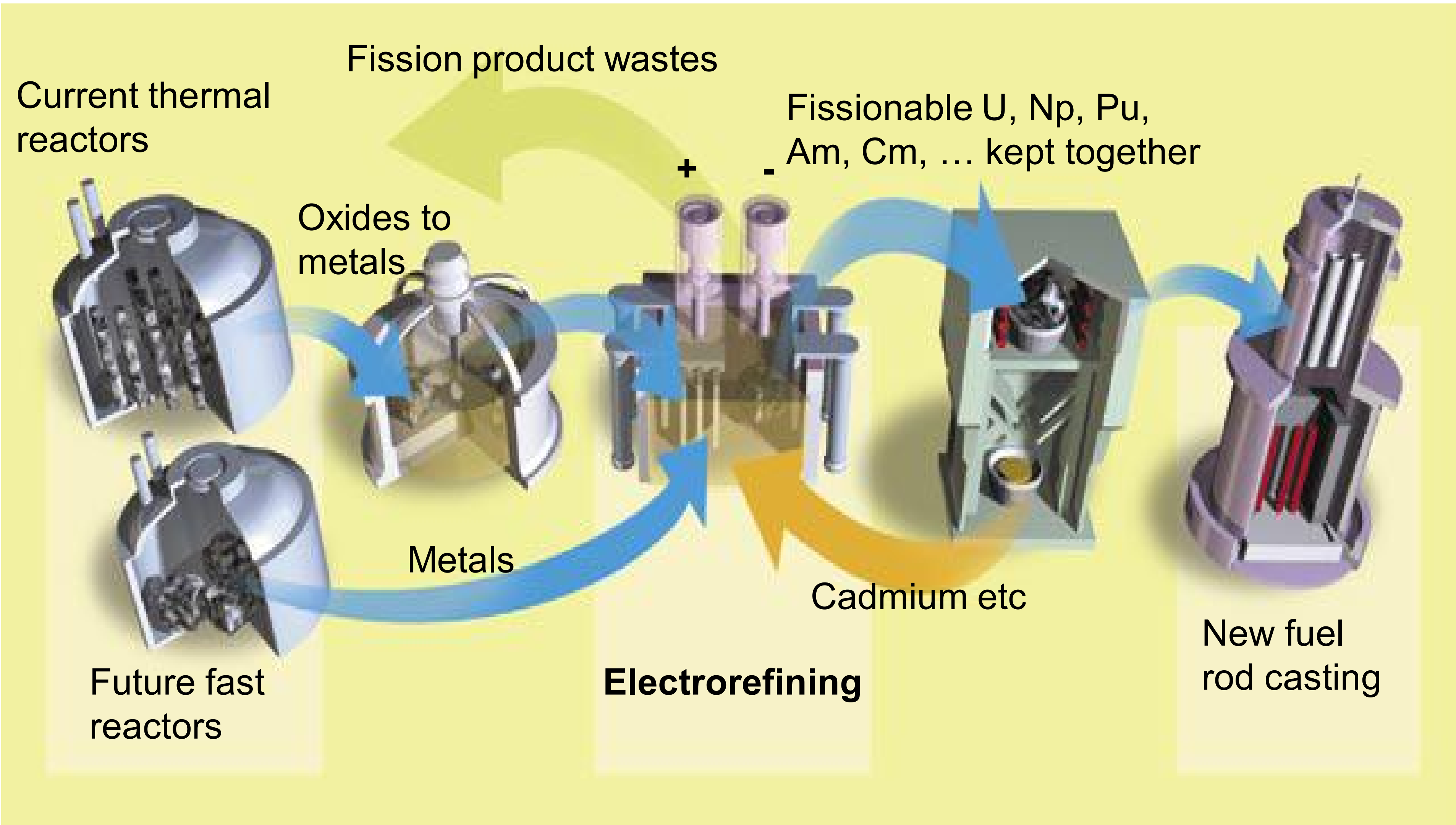
After 72 hours of exposure a weapons worker will likely die.

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

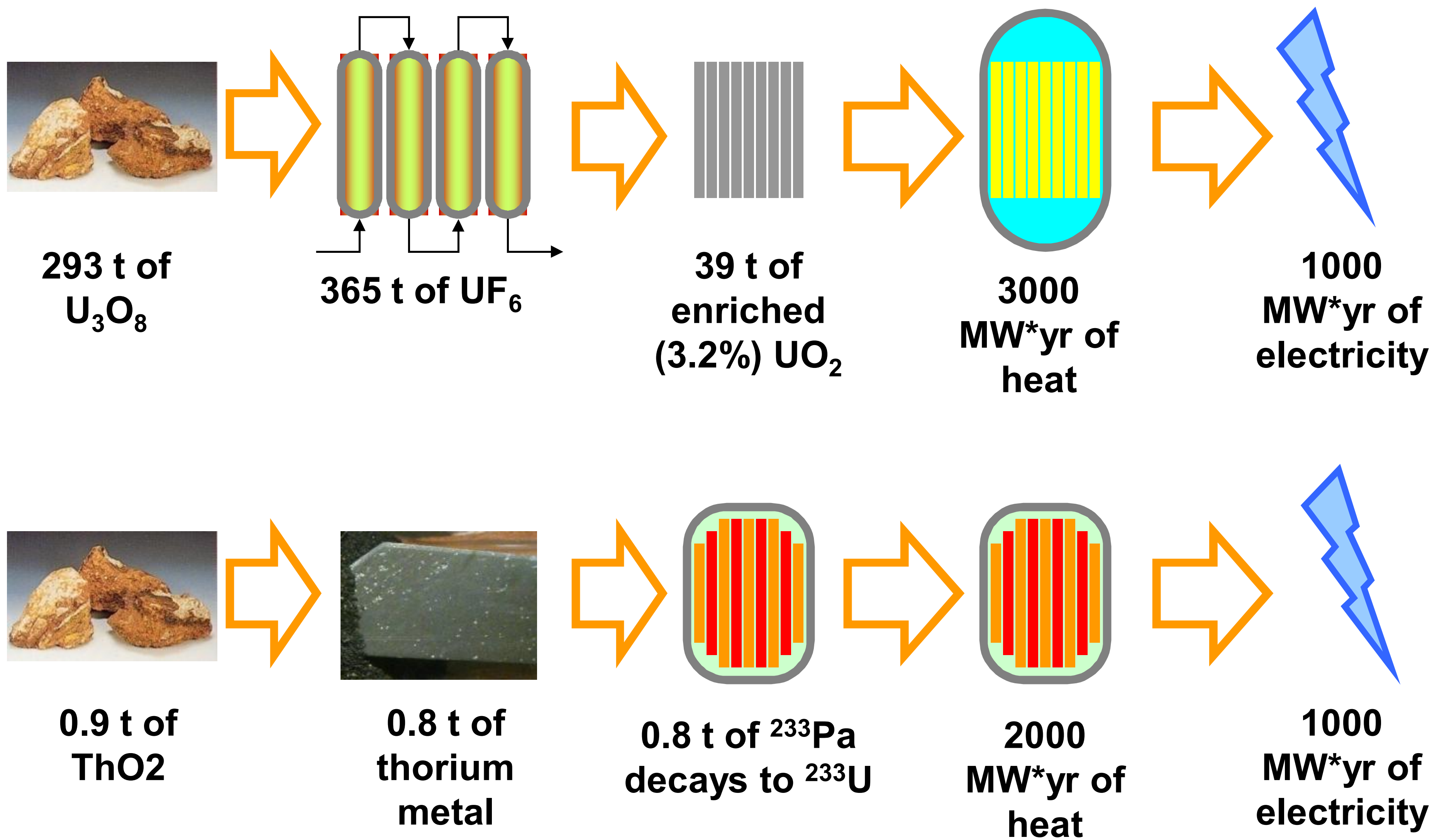
Fission/Absorption Cross Sections



Integral Fast Reactor



All thorium can be burned, but only 0.7% of uranium is fissile U-235.



WISE nuclear fuel material calculator: http://www.wise-uranium.org/nfcm.html

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