Crash course in nuclear power generation

Ruaridh Macdonald

PhD Student, Nuclear Science and Engineering (NSE)

Alumni Mentor

Who’s this guy

Ruaridh (Rory) Macdonald

PhD student in NSE (Course 22)

Undergrad at MIT (‘12); Mission 2012 student

  PhD: Nuclear weapons verification

  Masters: Toughened small, solid fuel, fluoride salt cooled reactors

  Undergrad: Fast reactor design; nuclear data; computational methods

GRT at Simmons

Plan for talk

1) Brief introduction to how a plant works (5 mins)
2) Nuclear fuel cycle (10 mins)
3) Thorium vs. Uranium (5 mins)

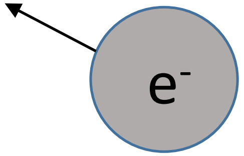
Disclaimers: Won’t present different reactor designs
Won’t say too much about safety / accidents
I may say some inaccurate things

Feel free to send me questions:

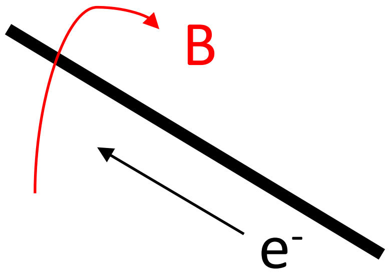
rmacd@mit.edu

What’s Power All About?

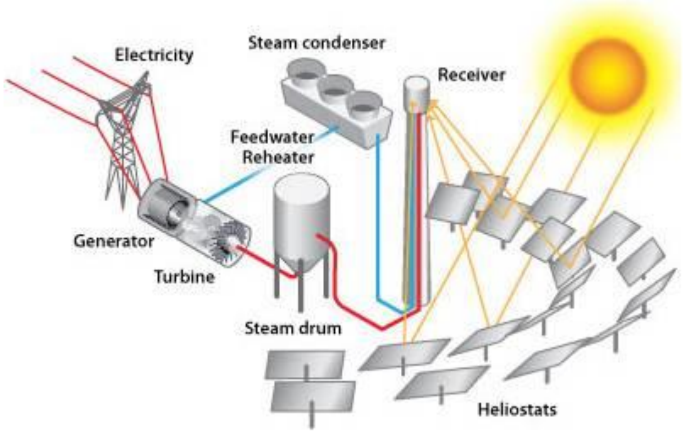
All electricity is about making electrons move

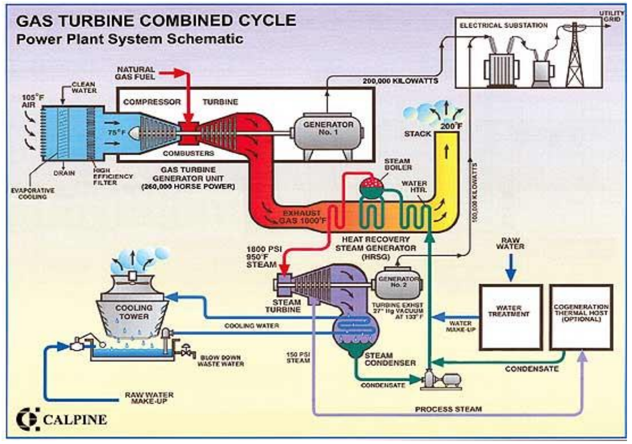


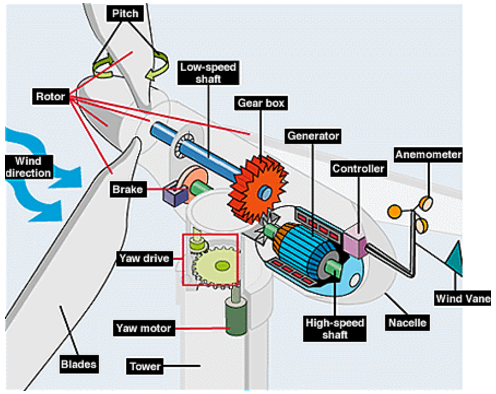
The easiest way to do that is to spin a magnet

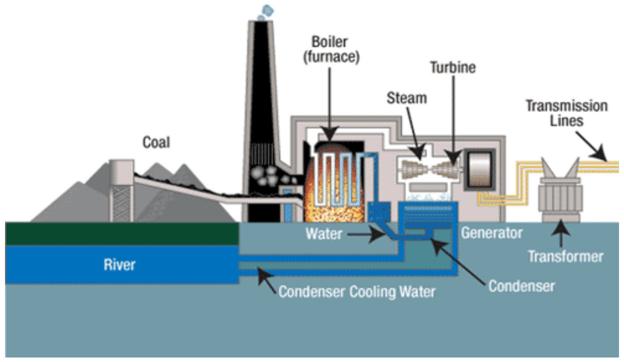


(Almost) All industrial power is about creating rotary motion. Normally using **hot gas for a turbine**

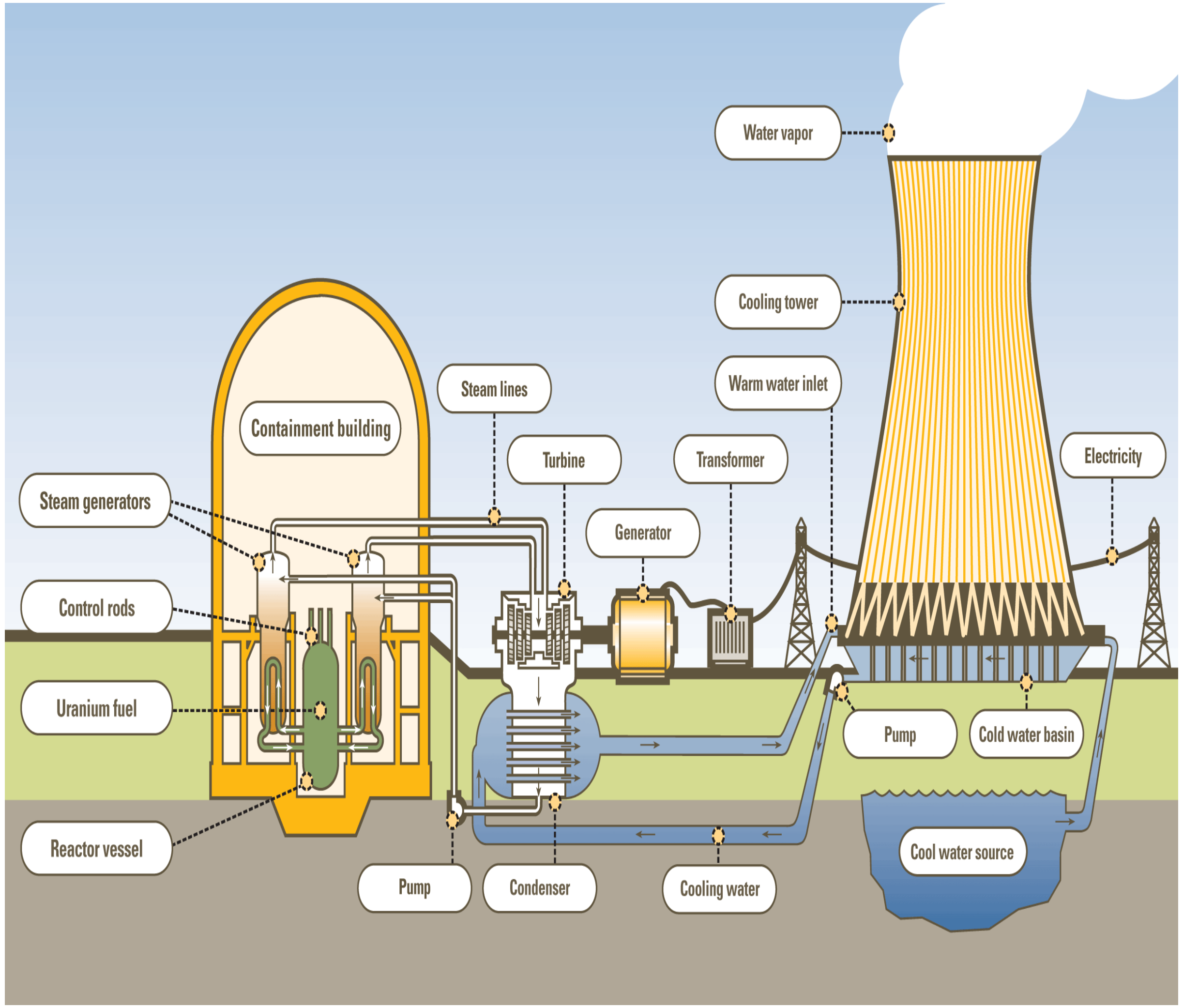


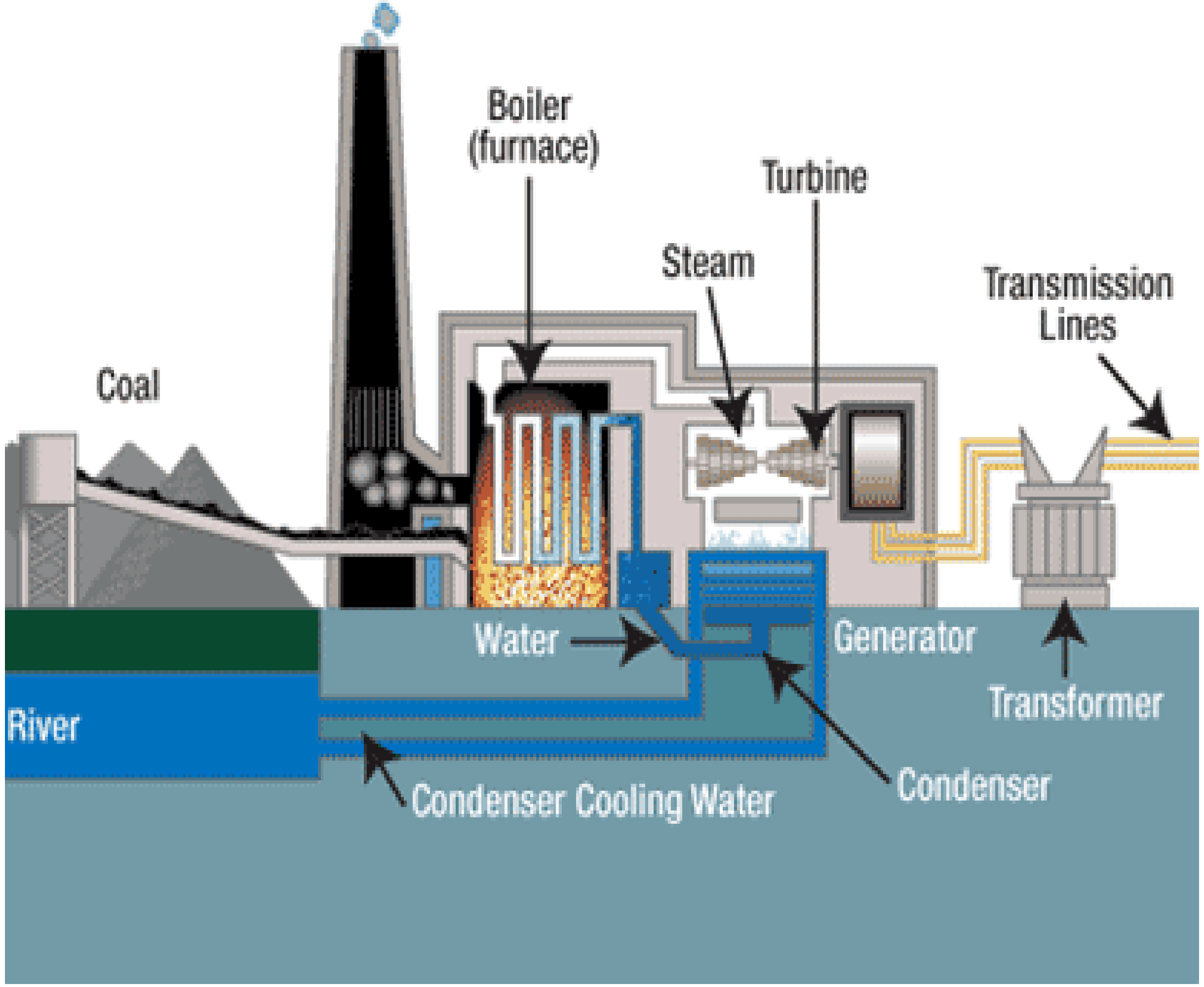






Nuclear Power Plant vs. Coal Plan



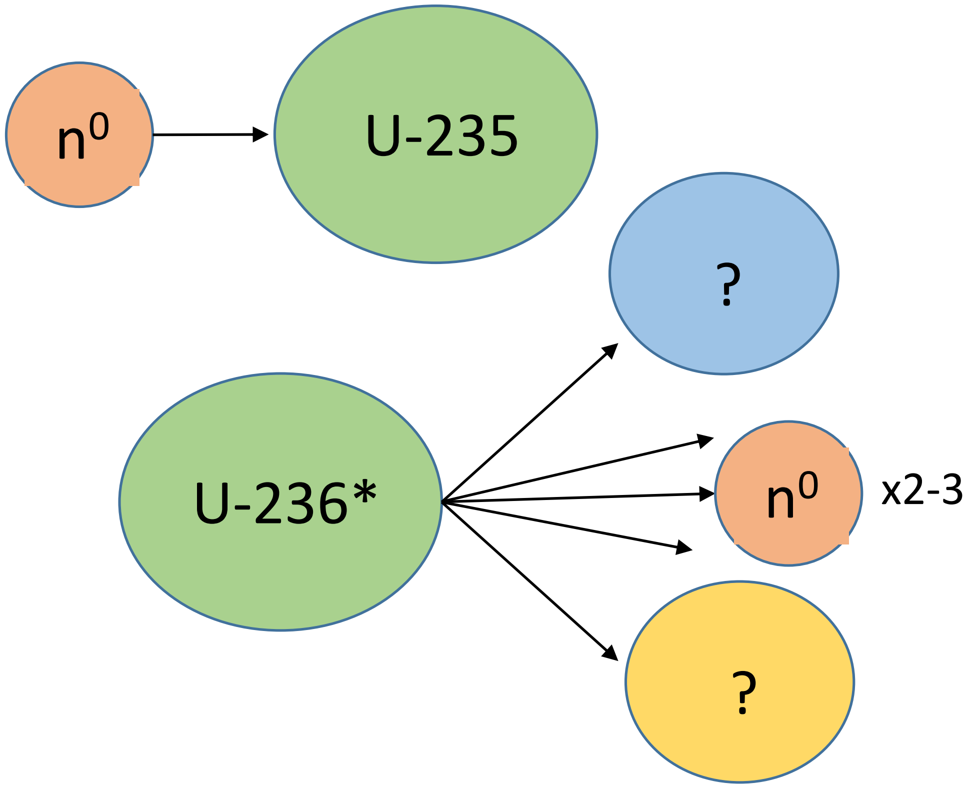


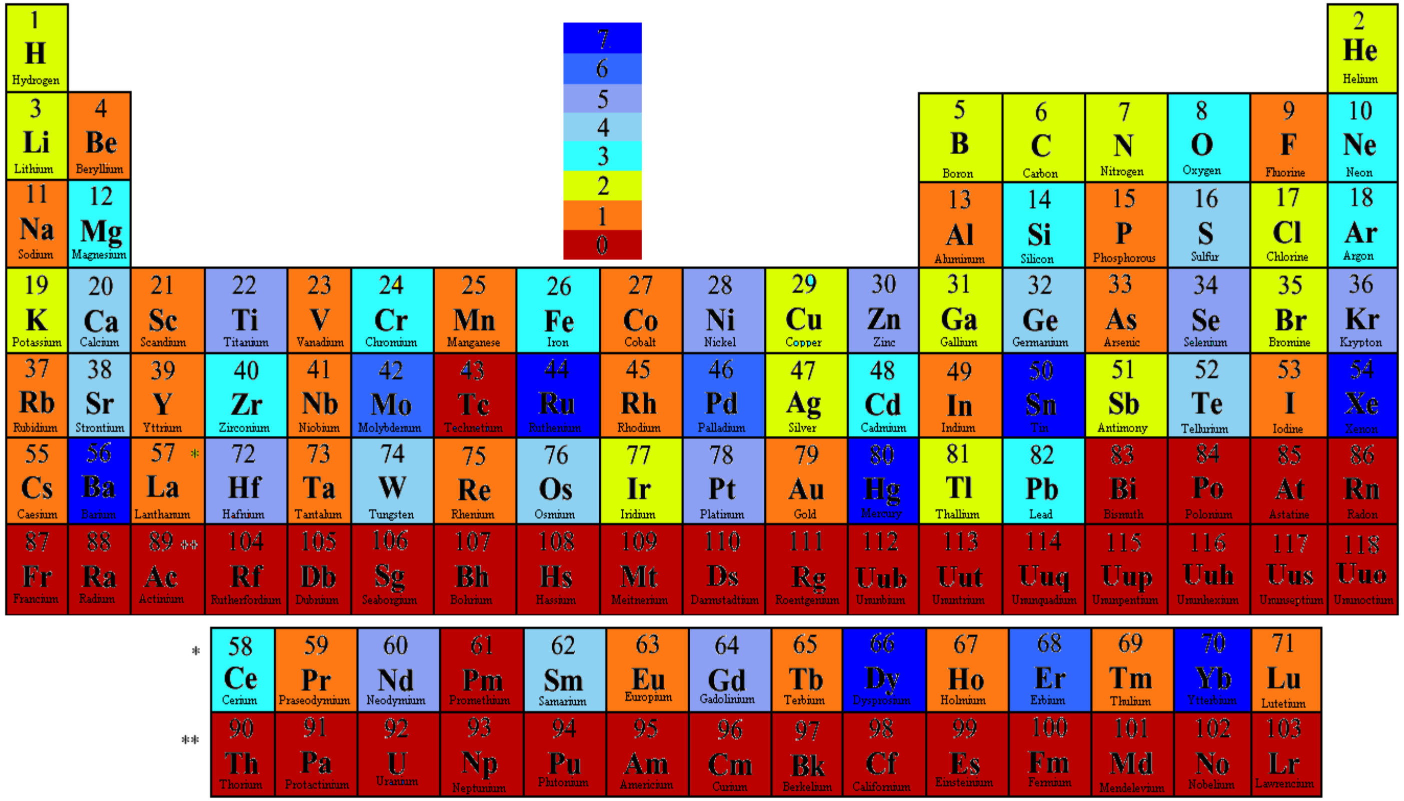
Nuclear Heat

Nuclear power generates heat from fission of heavy isotopes

Uranium 233, 235 (238)

Plutonium 239





7
6
5
4
3
2
1
0

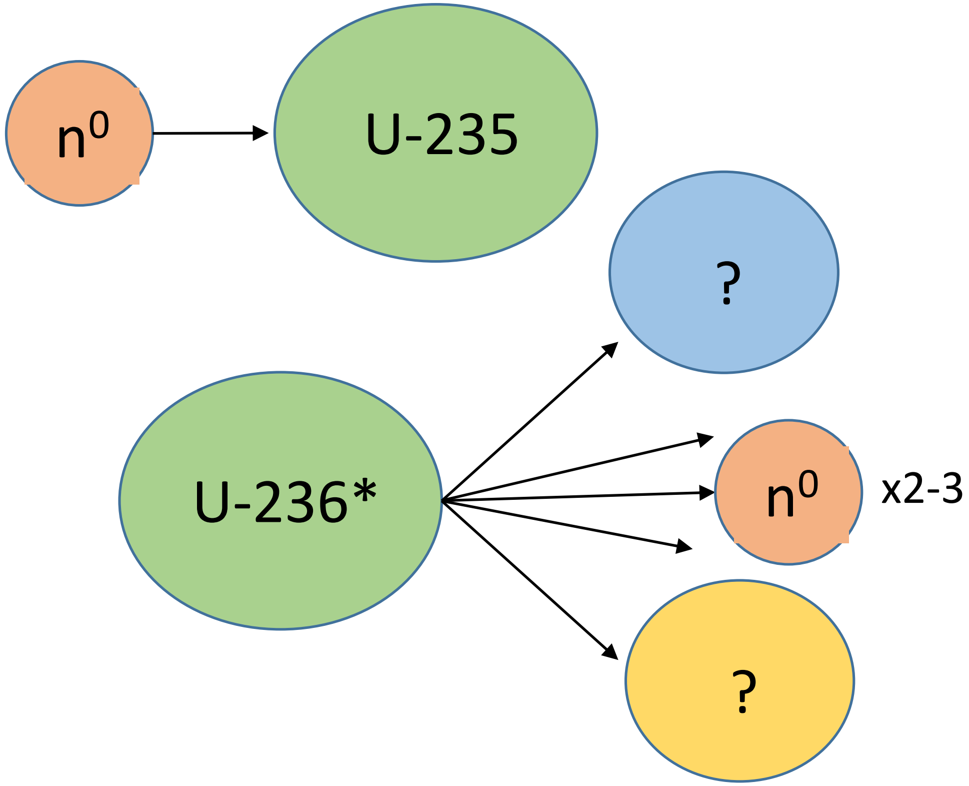
1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorous	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Caesium	56 Ba Barium	57 * La Lanthanum	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89 ** Ac Actinium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Uub Ununbium	113 Uut Ununtrium	114 Uuq Ununquadium	115 Uup Ununpentium	116 Uuh Ununhexium	117 Uus Ununseptium	118 Uuo Ununoctium
		*	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium	
		**	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium	

Nuclear Heat

Nuclear power generates heat from fission of heavy isotopes

Uranium 233, 235, (238)

Plutonium 239



n^0

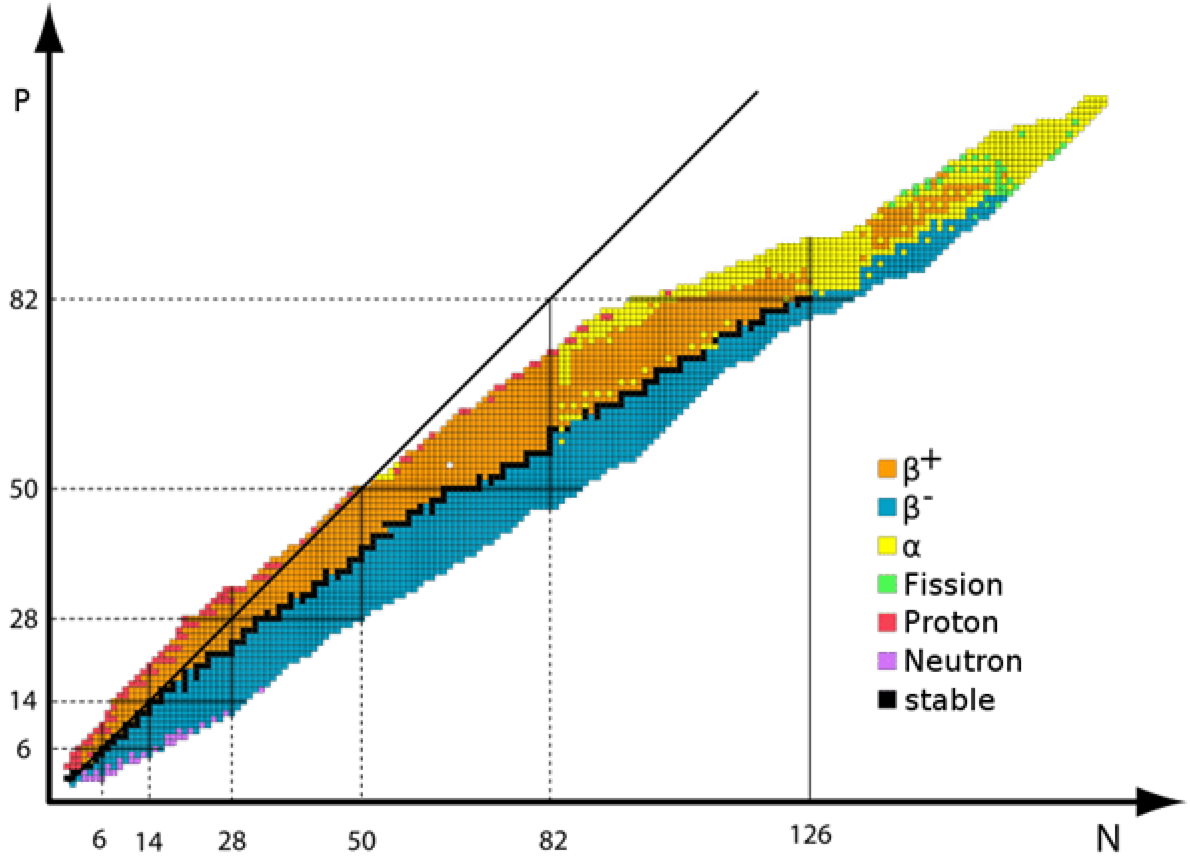
U-235

U-236*

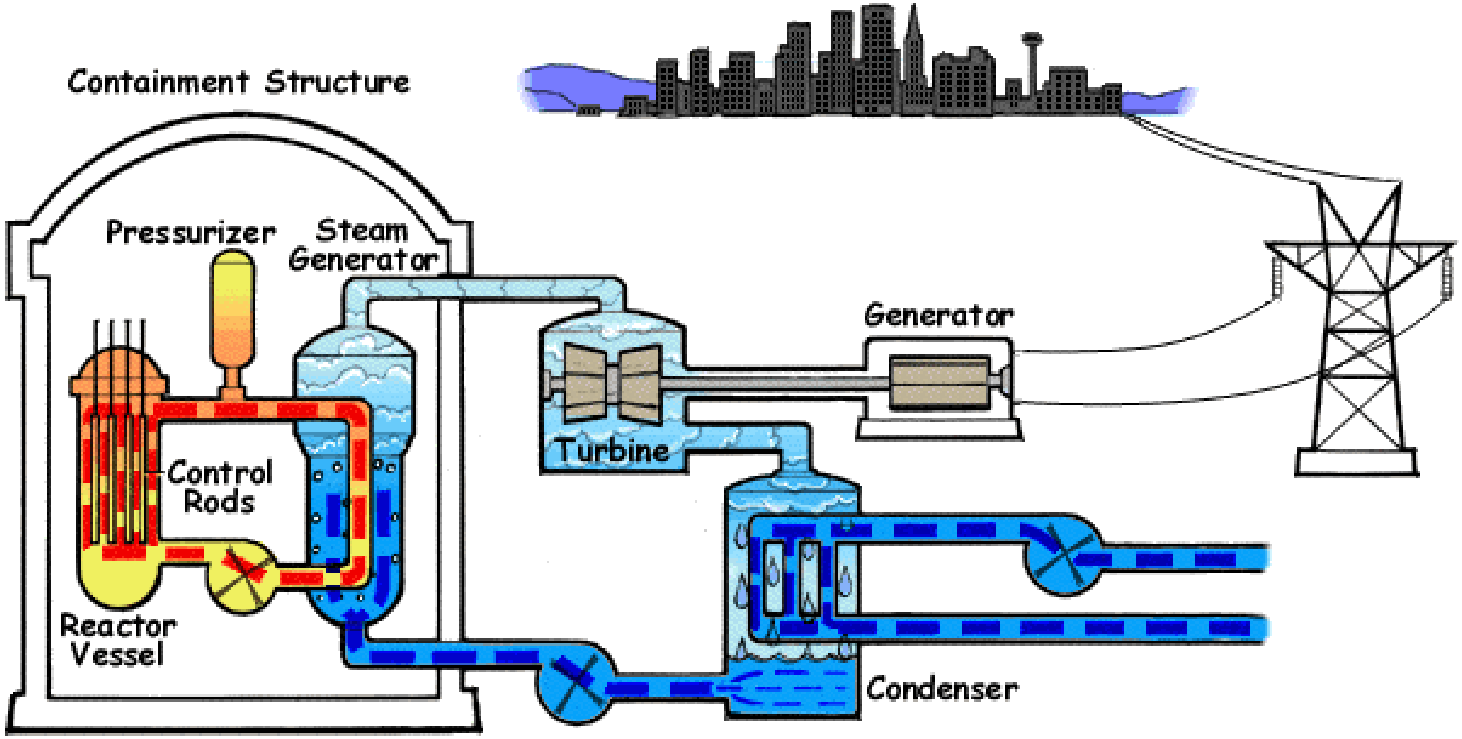
?

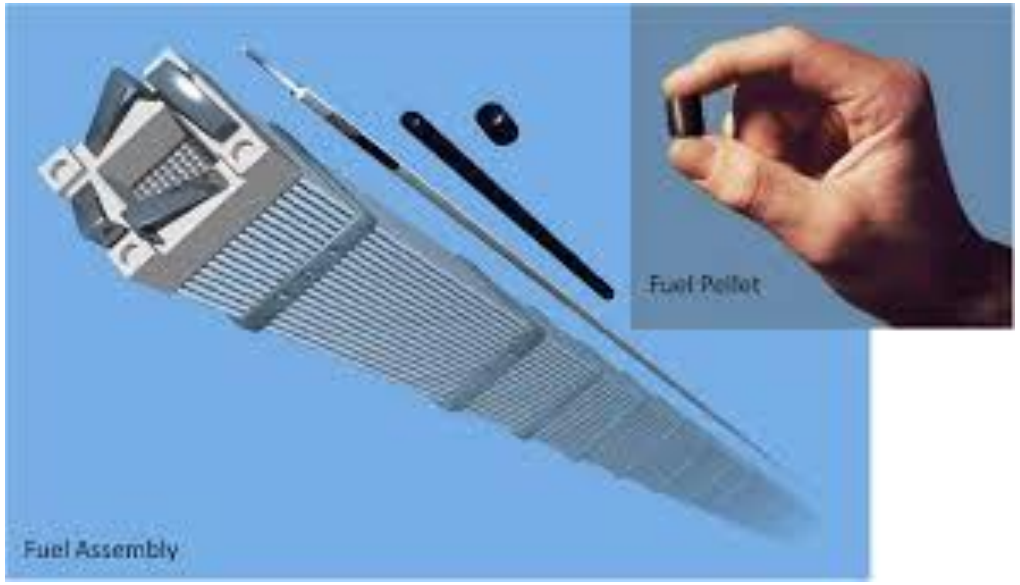
n^0 x2-3

?



Plant Operation





Water coolant removes heat from fuel assembly (~200 / core)
Fuel assembly made of fuel rods (~0.5 ton fuel / assembly)
Assemblies come in a variety of shapes (hex, circle, square)

Plant Operation

Multiple options exist for the coolant:

- Light water, heavy water, CO_2, helium, fluoride salts, lead, sodium, organic fluids, …

In a thermal reactor, the coolant also ‘slows down’ neutrons.

- Thermal or fast reactors

Reactors are designed to be stable systems

- If you increase the power / temperature, the reactor physics will try to reduce power
- In some designs the opposite happens if you try to decrease power

Designs focus on passive safety. Makes it very difficult / expensive to change designs

Nuclear plants are designed for stable power (95%+ capacity factor)

- Modern plants can change output (50-100% @ 5%/min, depending on design)

Fuel Cycle Options

Once through Cycle – Store all of the fuel assembly as waste

Closed Cycle – ‘Recycle’ most of the fuel for reuse. Store the rest;

Mixed / hybrid Cycle – ‘Recycle’ some of the fuel

Choices driven by:

1) Technical abilities of different nations
    - Types of reactor available
    - Reprocessing tech. available
2) Politics of nuclear material control
    - Reprocessing isolates high purity Pu-239 for nuclear weapons

Nuclear Fuel

Natural uranium is only made of 0.71% U-235, our main fuel. The rest is U-238

Not all countries have uranium deposits

- It can be extracted from seawater (3.3E8 litres / kg U)

You have to enrich it after mining. 20% is legal limit.

- Most plants use 3-5%. Most US permits are for 5%. Some reactors use nat. U

After being in the reactor the fuel will contain lots of new isotopes

- U-238, U-235, Pu-239, Pu-other - can be reused in new fuel
- Fission products - radioactive daughter particles
- Minor actinides - heavy particles created by non-fission absorption

Most of these are radioactive but to different degrees and for different amounts of time

- Different strategies for storage

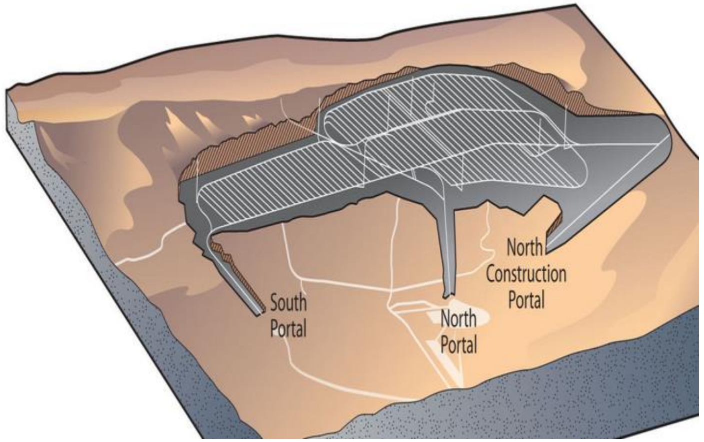
Waste Storage

Immediately after use - Spent fuel pool

After 1->2 years - Interim storage

After 10+ years - Multiple options

Geological Repository



Deep borehole

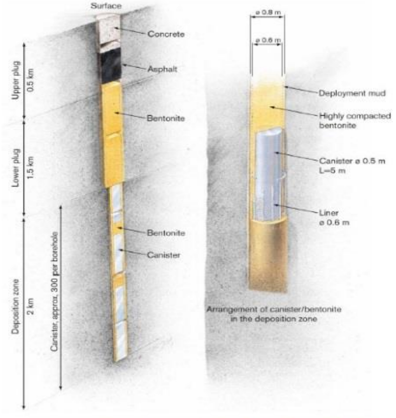


Figure 2. Schematic design for disposal in deep boreholes (SKB, 2010).

On-site storage

Once through

Simplest fuel cycle

Weapons material is never available

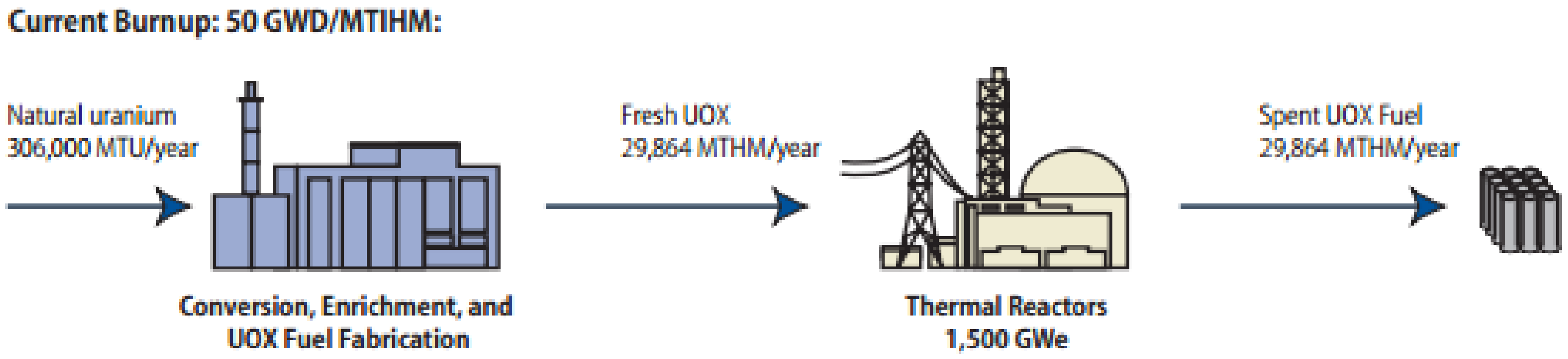
Produces the most waste

Least efficient use of fuel material

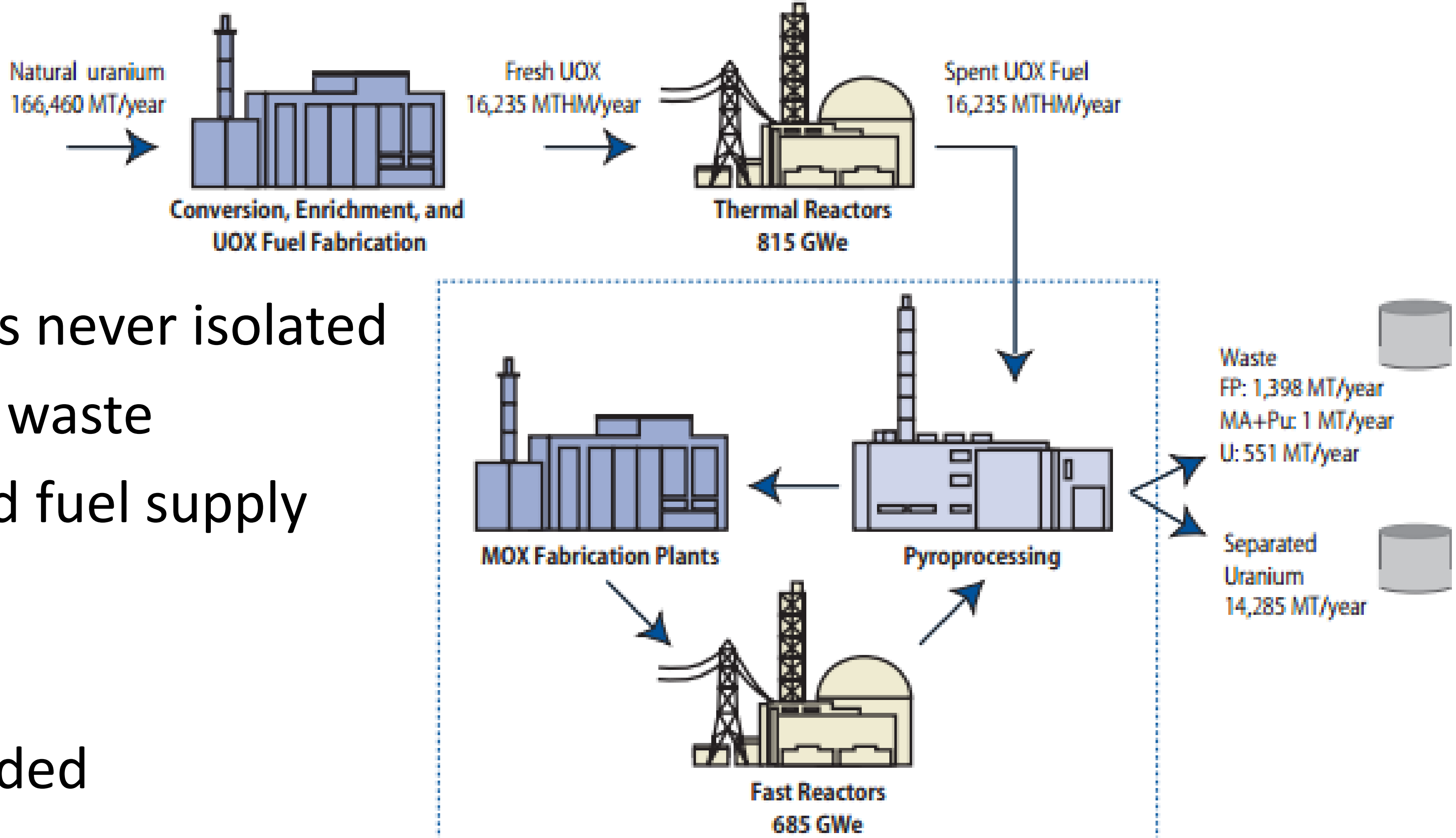
Still a good choice compared to other power sources

Politically accepted

Cheapest upfront cost



Closed Cycle



Weapons material is never isolated

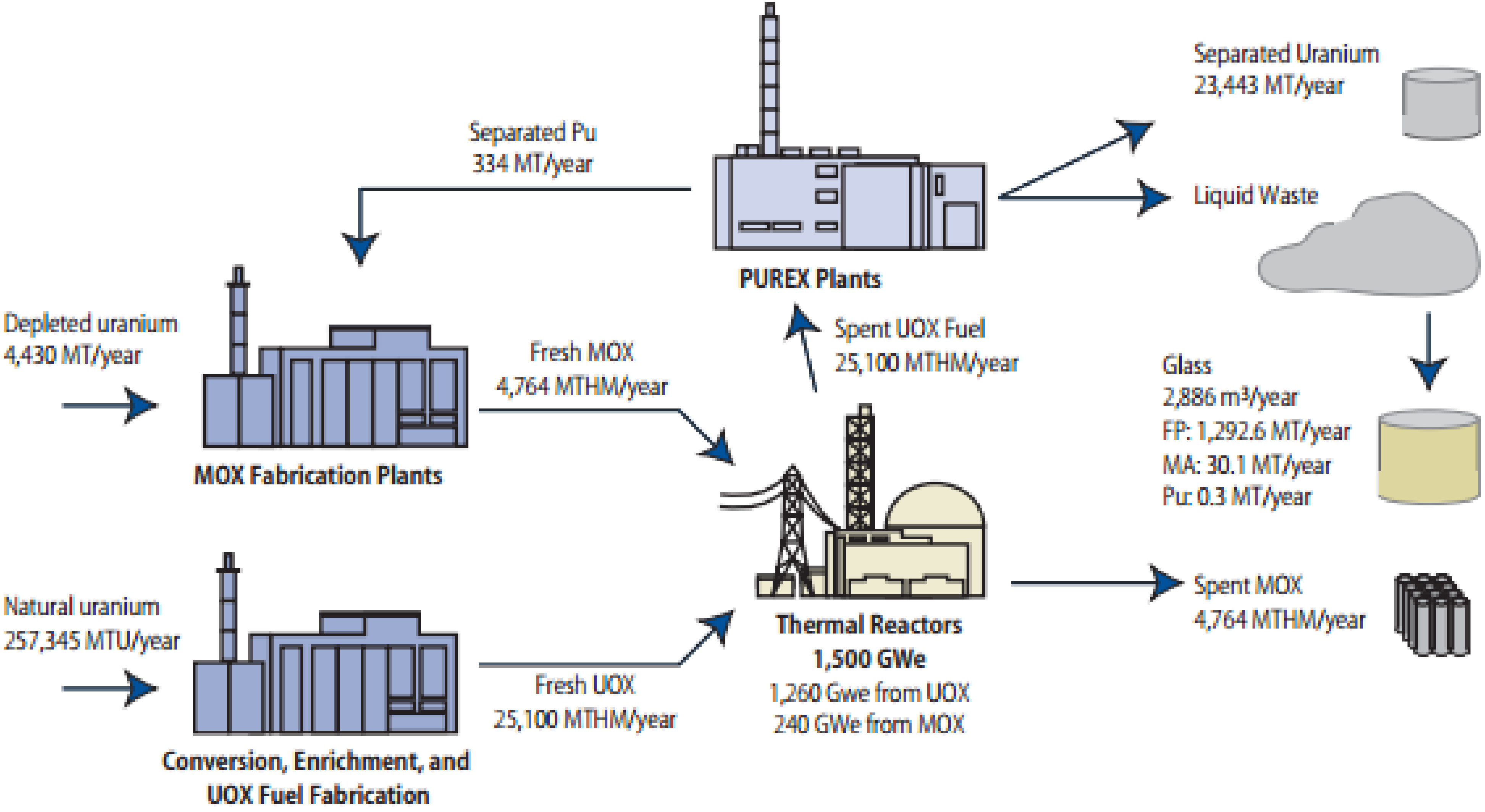
Produces very little waste

Effectively unlimited fuel supply

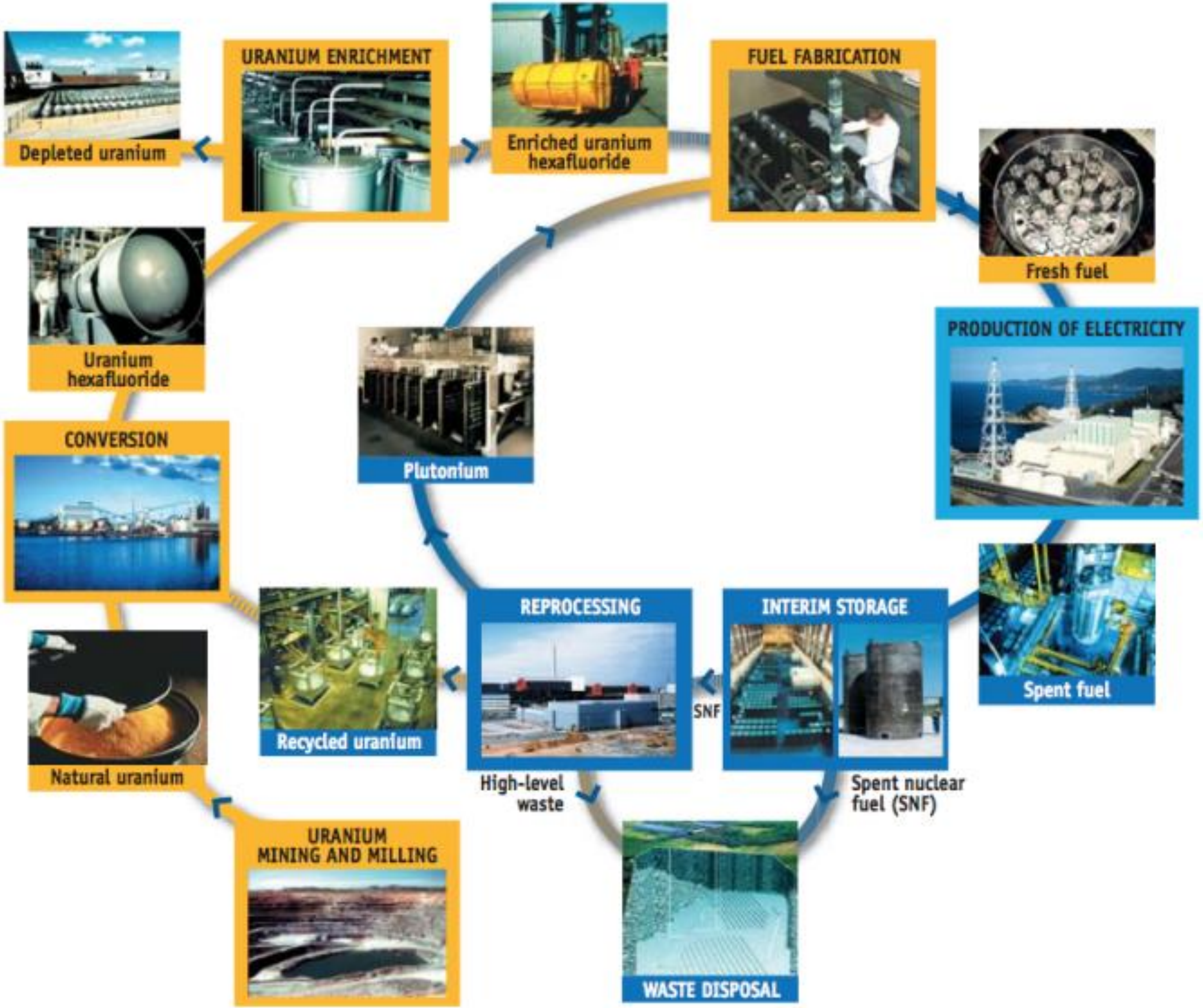
Politically difficult

Lots of R&D $$ needed

Mixed / hybrid Cycle



Full Cycle


URANIUM ENRICHMENT
Depleted uranium
Enriched uranium hexafluoride
FUEL FABRICATION
Fresh fuel
Uranium hexafluoride
PRODUCTION OF ELECTRICITY
Plutonium
CONVERSION
Spent fuel
REPROCESSING
INTERIM STORAGE
SNF
Recycled uranium
Natural uranium
High-level waste
Spent nuclear fuel (SNF)
URANIUM MINING AND MILLING
WASTE DISPOSAL

Thorium

Thorium is mostly Th232

It is not fissile. It absorbs a neutron to become U233, which is fissile

It needs another fissile material to maintain a chain reaction

It is three times more abundant than uranium in the Earth’s crust

Thorium reactors can be fast or thermal breeder reactors

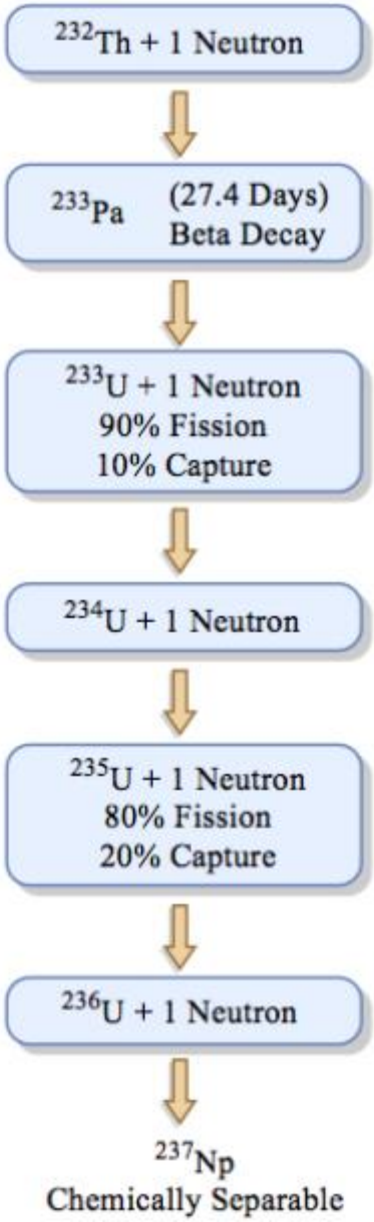
It produces the most neutrons per fission

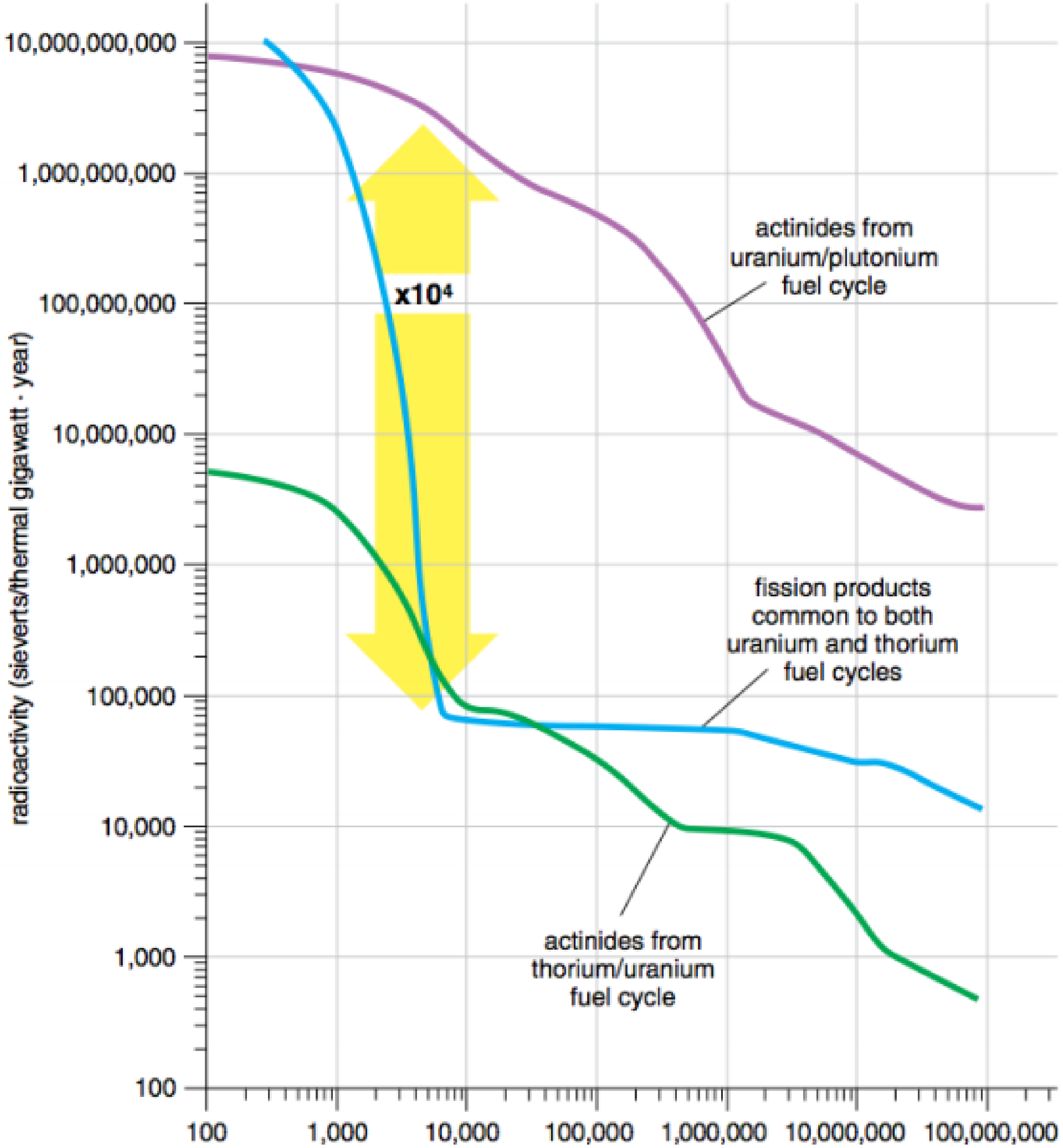
Has higher thermal conductivity and melting point

Easier to run the reactor safely

Fewer minor actinides are produced

Remaining ones have shorter half life

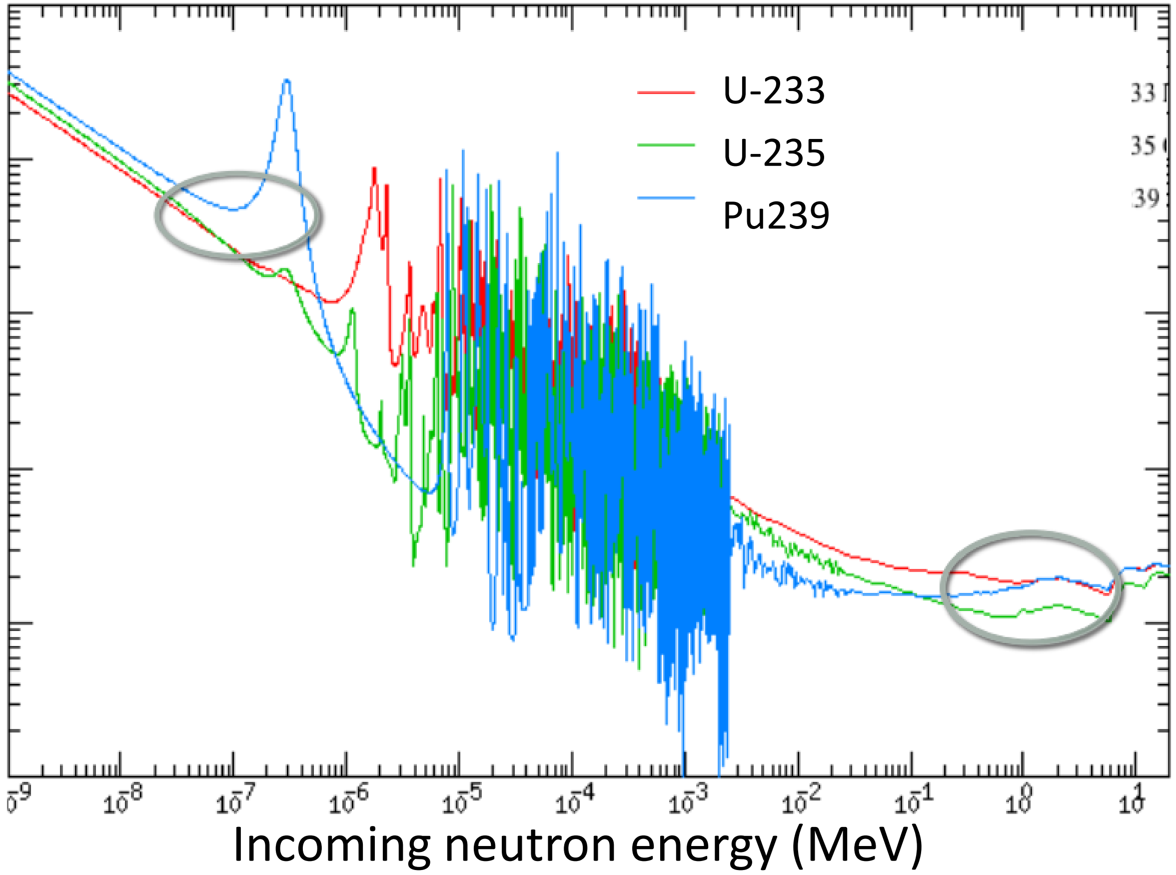



radioactivity (sieverts/thermal gigawatt · year)
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
100
1,000
10,000
100,000
1,000,000
10,000,000
100,000,000
x10⁴
actinides from uranium/plutonium fuel cycle
fission products common to both uranium and thorium fuel cycles
actinides from thorium/uranium fuel cycle

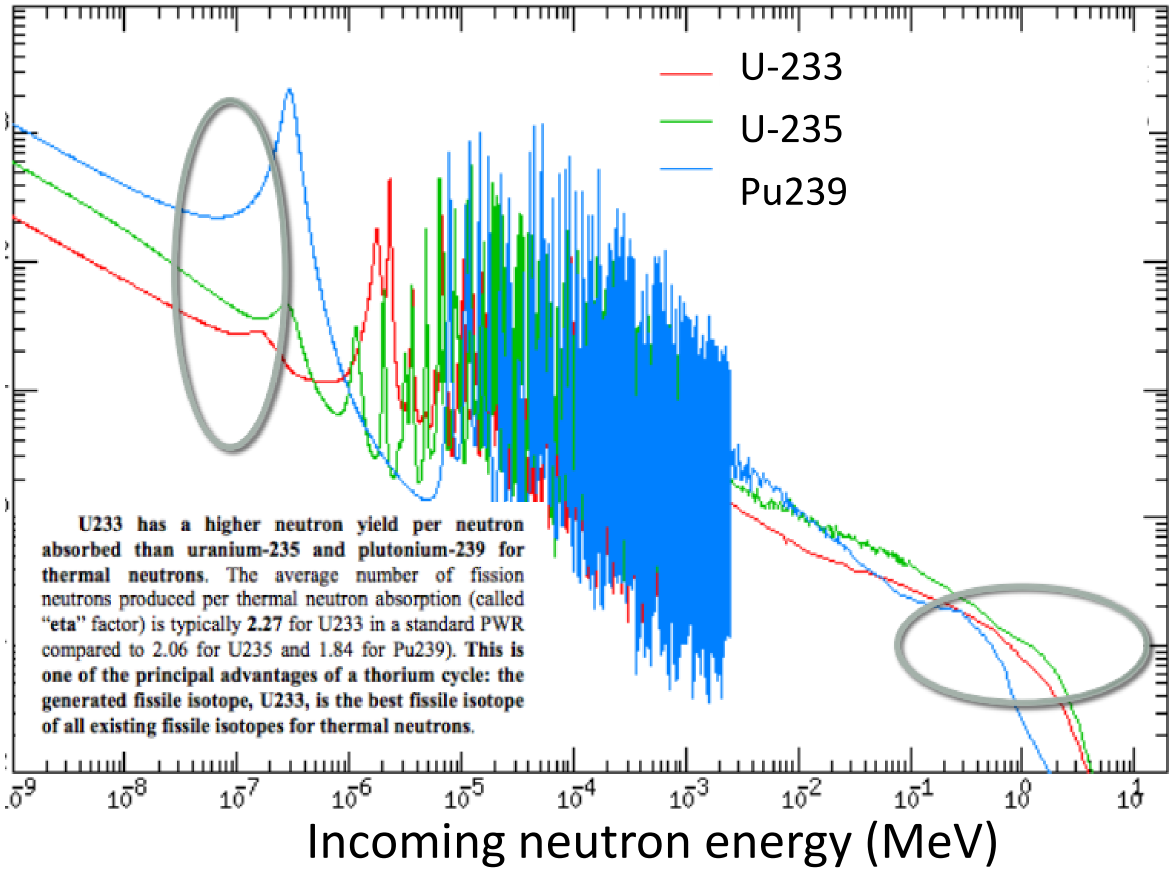
Thorium vs. Uranium

U-233 is more likely to fission when irradiated than U-235 or Pu-239

~ Prob[fission if neutron hits U-233]



~ Prob[not-fission if neutron hits U-233]



U233 has a higher neutron yield per neutron absorbed than uranium-235 and plutonium-239 for thermal neutrons. The average number of fission neutrons produced per thermal neutron absorption (called "**eta**" factor) is typically **2.27** for U233 in a standard PWR compared to 2.06 for U235 and 1.84 for Pu239). **This is one of the principal advantages of a thorium cycle: the generated fissile isotope, U233, is the best fissile isotope of all existing fissile isotopes for thermal neutrons.**

Thorium

While the waste is shorter lived, some of it posses a significant health risk

- High energy gamma radiation -> more difficult to shield
- Most of this is from U-232 daughters, originally created from Th-232

This makes it difficult to reprocess the fuel as different facilities are needed

- However, it also makes it more difficult to use Th in a weapon

Once U-233 is made, it has superior performance

- However, neutrons are needed to get there
- This requires fuel to stay in reactor for longer -> difficult with some designs
- This makes Th unappealing in a once through cycle