

NE585
NUCLEAR FUEL CYCLES
Front end of the nuclear fuel cycle
3

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Learning objectives

Demonstrating how the nuclear fuel cycle is an holistic system

Explaining why the nuclear fuel cycle is what it is

Apply principle of SWU

Model a nominal solvent extraction system

Model enrichment processes

Demonstrate principles of enrichment and conversion

Some of Chapter 4 in the book

Check out [Pandora's promise](#) if it's still on Netflix

There's a lot of pictures here

Learning nodes

Nuclear fuel cycle overview

Locations of current domestic fleet

Plant closures

Nuclear power around the world

Planned construction

Components of the nuclear fuel cycle

Mining

Milling

Conversion

Enrichment

Separative Work Unit (SWU)

Fuel fabrication

Macro reactor operation

CP-1

Hanford B reactor

EBR-I

EBR-II

TREAT

Military use

Reactor concepts

Generations

PWR

BWR

CANDU

Aqueous reprocessing

More learning nodes

Enrichment

History

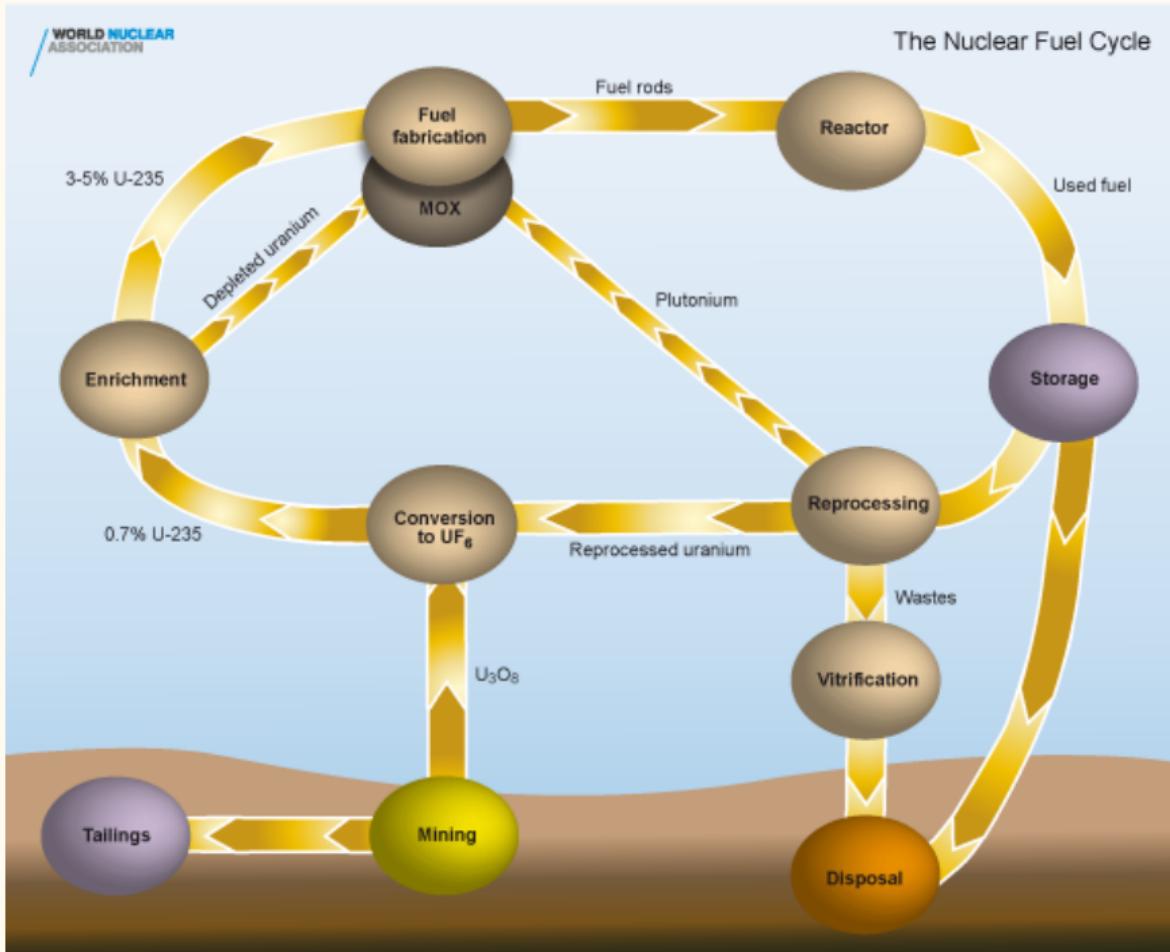
Processing

Tails

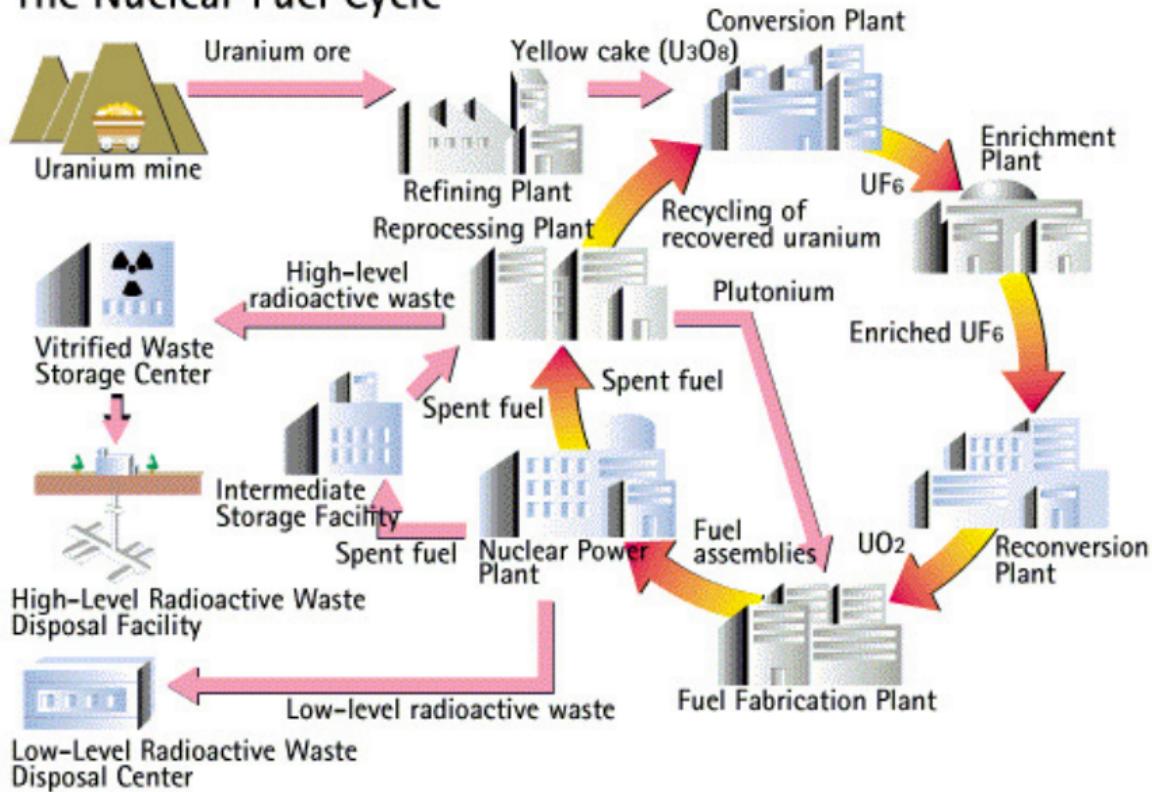
Conversion

Processing

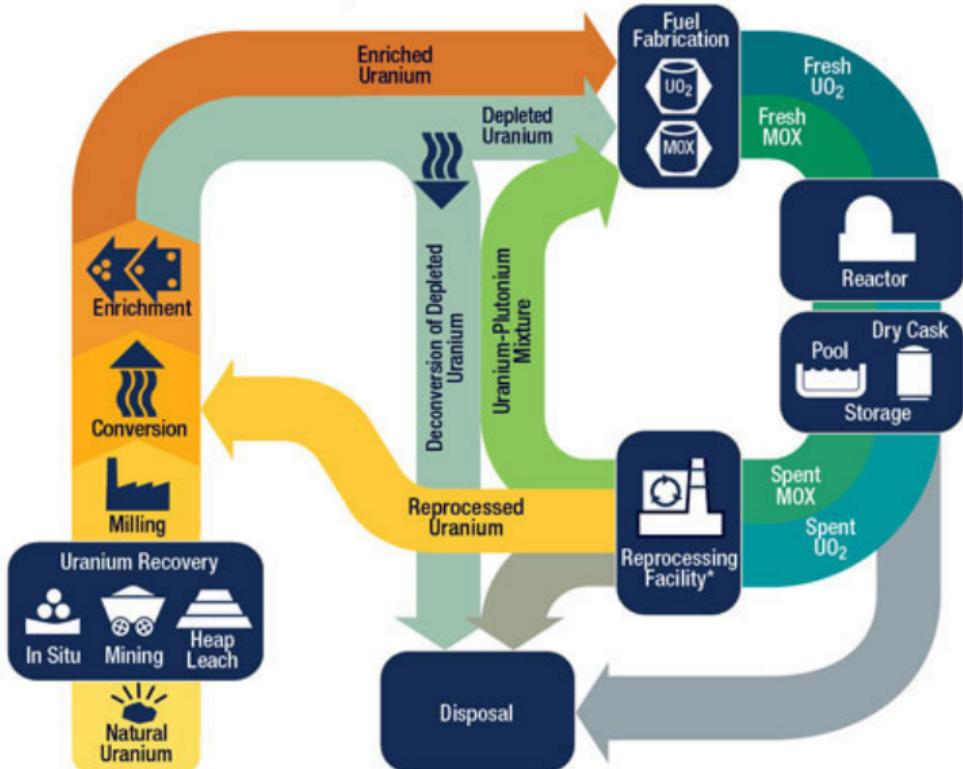
Nuclear fuel cycle overview



The Nuclear Fuel Cycle



The Nuclear Fuel Cycle



* Reprocessing of spent nuclear fuel, including mixed-oxide (MOX) fuel, is not practiced in the United States.

Note: The NRC has no regulatory role in mining uranium.

As of January 2019

Look at the fuel cycle as systems engineering

Mining

Making the fuel (saw Areva plant in Richland)

What a reactor does and the different kinds

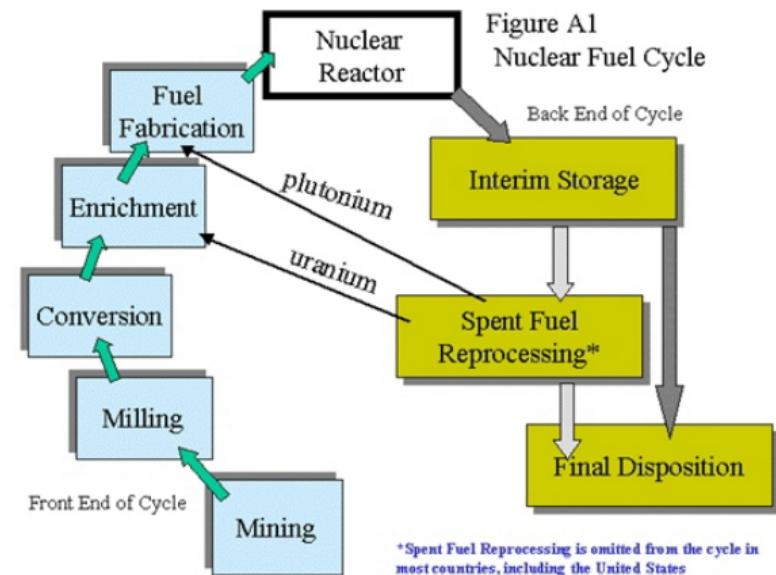
Recycling (what kinds and how)

Back-end management (storage and disposal)

The fuel cycle has a lot of technical but institutional issues too

How are they functionally dependent?

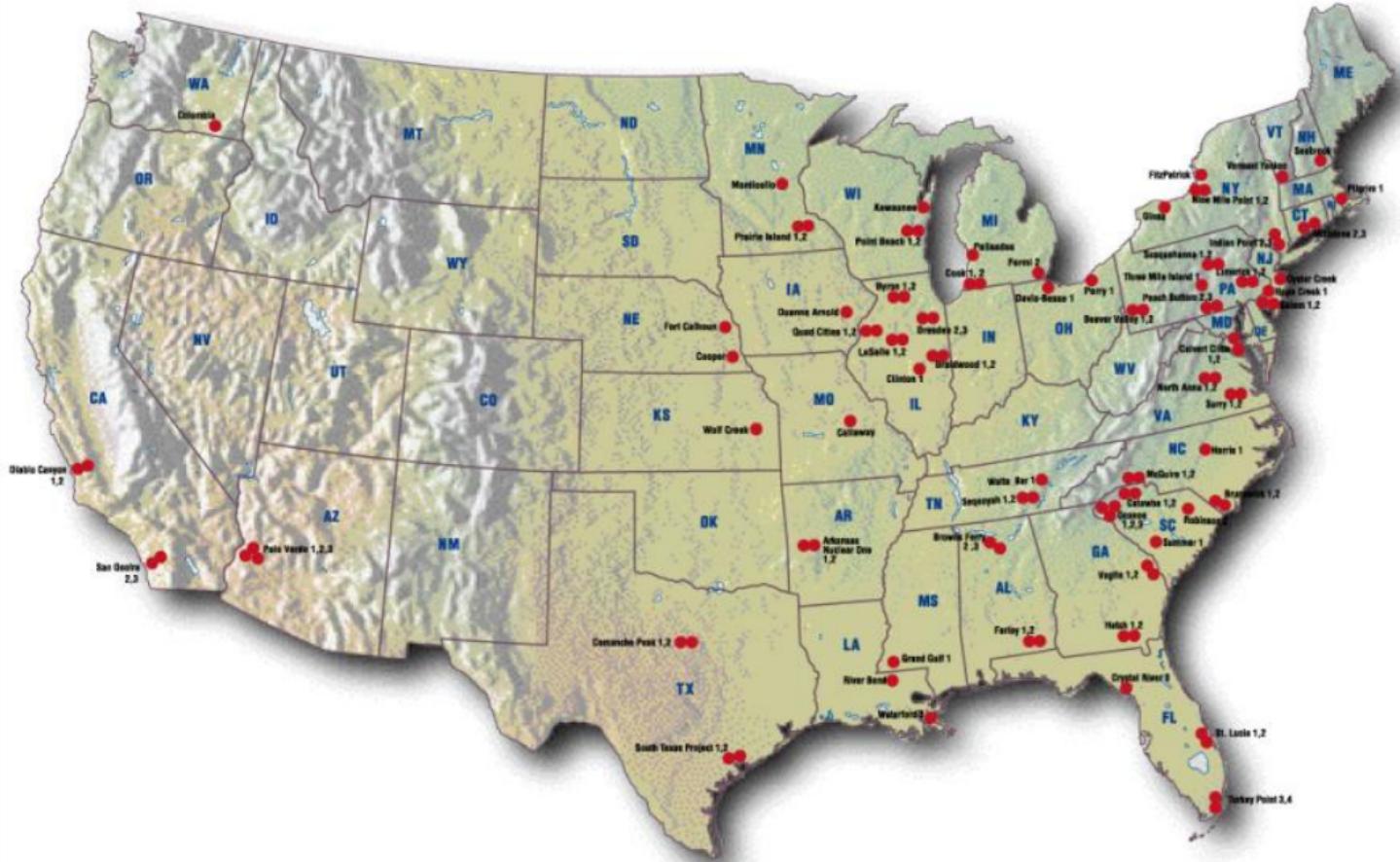
The fuel used in the commercial reactors is UO_2 or $(Pu + U)O_2$



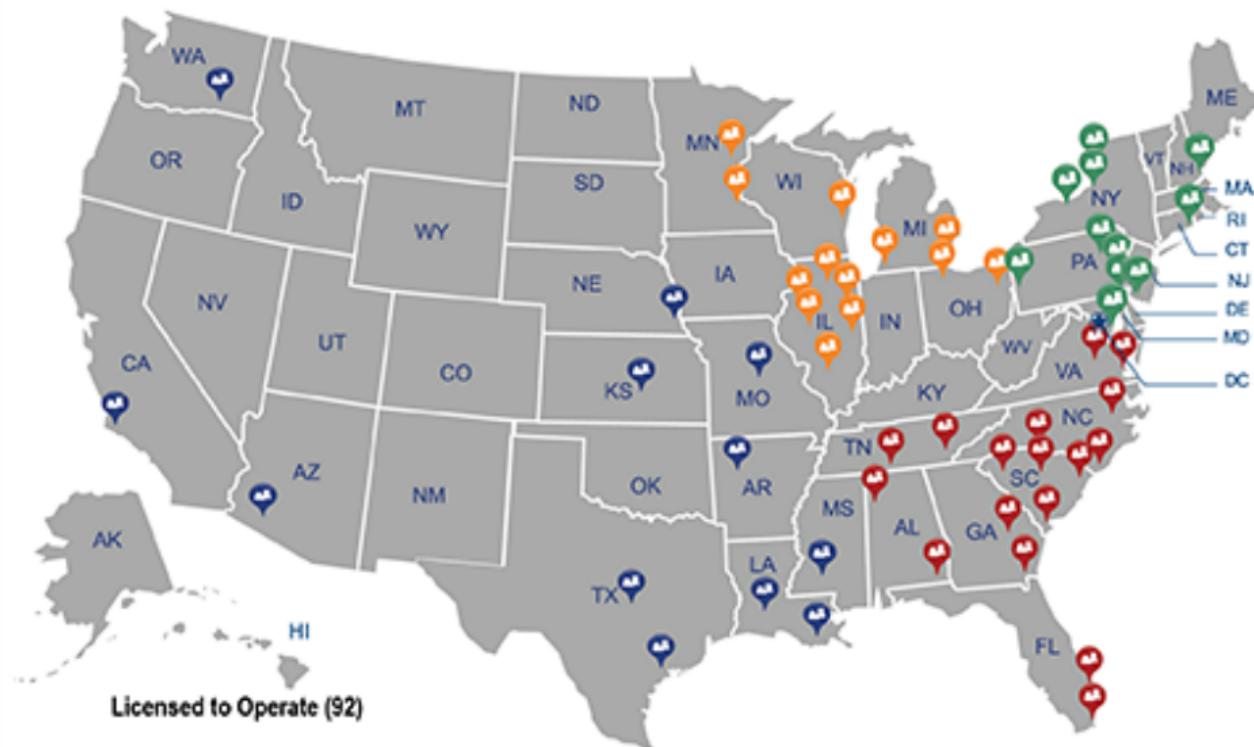
Front end – Making the fuel and putting it in the reactor

Back end – What happens when you take it out of the reactor

Locations of current domestic fleet



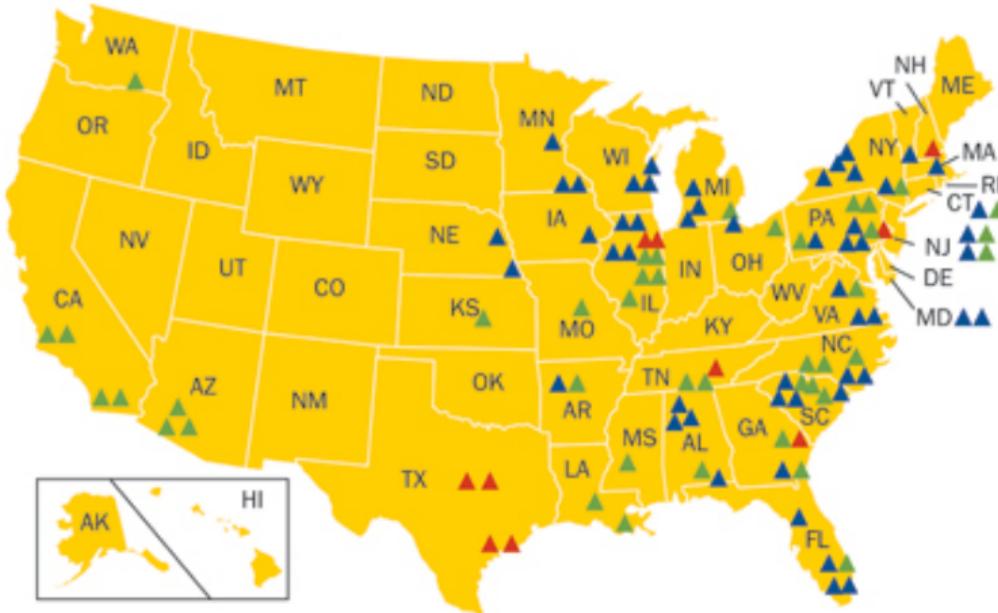
U.S. Operating Commercial Nuclear Power Reactors



Source: U.S. Nuclear Regulatory Commission - As of February 2023

NRC **list of power reactor units**

U.S. Commercial Nuclear Power Reactors—Years of Operation



Source: U.S. Nuclear Regulatory Commission

Plant closures

Losing Power: Prospects Dimming for U.S. Nuclear Plants

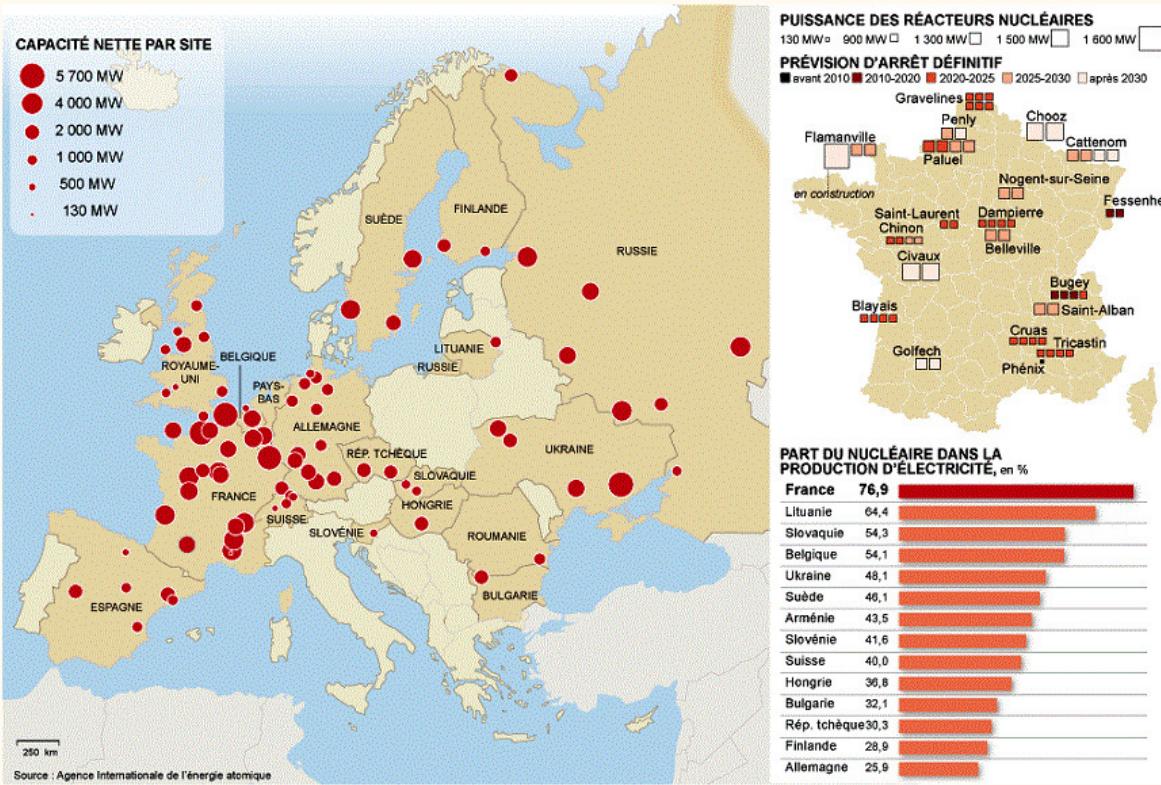
Four companies announced nuclear plant closures in 2013 — representing the first shutdowns in 15 years and an unprecedented single-year retrenchment for the U.S. nuclear industry. Experts say at least ten other plants could be forced to close because of low power prices, rising costs and other woes.



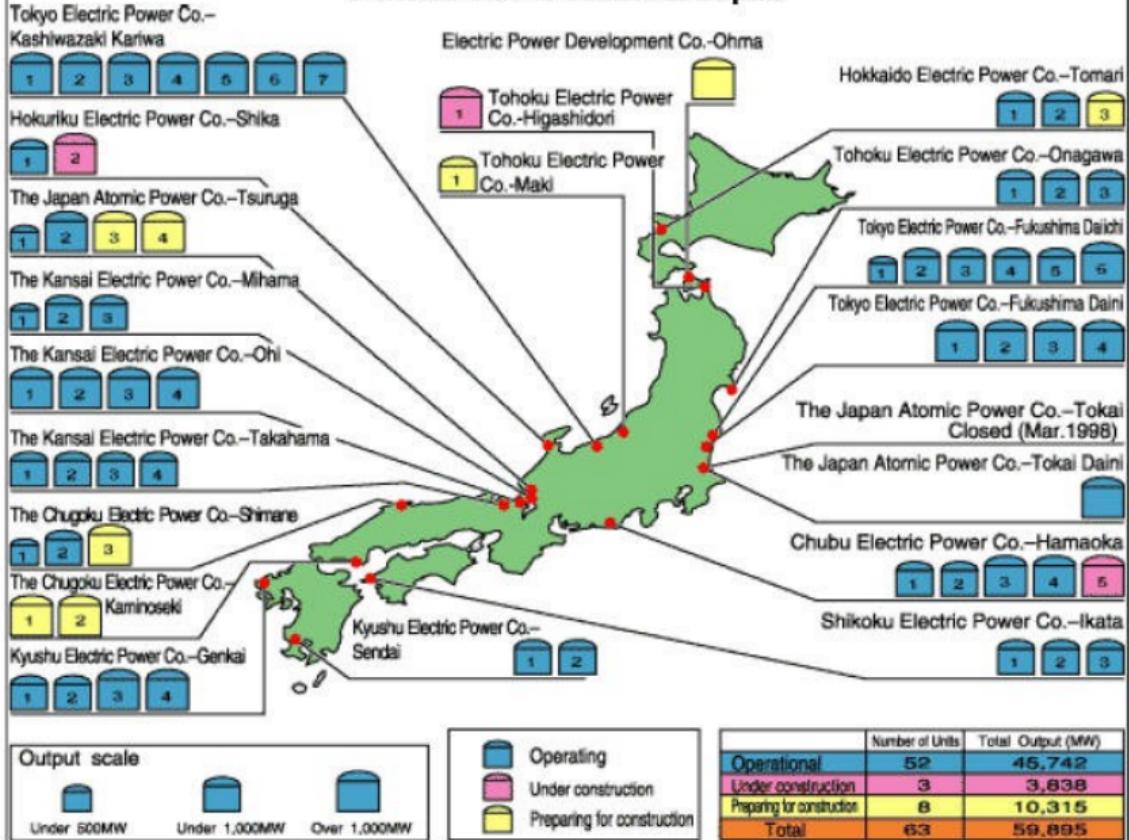
SOURCES: Nuclear Regulatory Commission; Mark Cooper, Vermont Law School; Google Maps; InsideClimate News research

PAUL HORN / InsideClimate News

Let's look at other nations



Nuclear Power Plants in Japan



Where are they going to dispose of everything?



Economist.com

Same problem

EJA Infographics ①

국내 핵발전소 운영 및 건설 현황* (Nuclear power plants' operation and construction in South Korea)

운영 중 핵발전소
(Operational NPPs)
21기(Units)/18,716MW

건설 중 핵발전소
(Under construction NPPs)
7기(Units)/8,600MW

계획 중 핵발전소
(Planning NPPs)
6기(Units)/8,600MW

영광(Younggwang)
#1 1986.08.25. 950
#2 1987.06.10. 950
#3 1995.03.31. 1000
#4 1996.01.01. 1000
#5 2002.05.21. 1000
#6 2002.12.24. 1000



가압형경수로(PWR) 가압형중수로(PHWR,CANDU)
연구용원자로(Research reactor)

상업운전개시일 / 용량(MW)
Commercial Operation / Capacity (MW)

울진(Ulchin)
#1 1988.09.10. 950
#2 1989.09.30. 950
#3 1998.08.11. 1000
#4 1999.12.31. 1000
#5 2004.07.29. 1000
#6 2005.04.22. 1000

신울진(Shin-Ulchin)
#1 (2016.06) 1400
#2 (2017.06) 1400
#3 (2020.06) 1400
#4 (2021.06) 1400

월성(Wolsong)
#1 1983.04.22. 679
#2 1997.07.01. 700
#3 1998.07.01. 700
#4 1999.10.01. 700

신월성(Shin-Wolsong)
#1 (2012.03) 1000
#2 (2013.01) 1000
#3 **
#4 **

고리(Kori)
#1 1978.04.29. 587***
#2 1983.07.25. 650
#3 1985.09.30. 950
#4 1986.04.29. 950

신고리(Shin-Kori)
#1 2011.02.28. 1000
#2 (2011.12) 1000
#3 (2013.09) 1400
#4 (2014.09) 1400
#5 (2018.12) 1400
#6 (2019.12) 1400
#7 (2022.06) 1500
#8 (2023.06) 1500

* 제5차 전력수급계획(2010~2024)을 바탕으로 에너지정의행동이 작성 (2011.8. 현재)

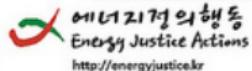
** Energy Justice Actions created, based on The 5th Basic Plan of Long-Term Electricity Supply and Demand(2010-2024). (Aug. 2011)

** 신월성 3.4호기 부지로 선정되었으나, 중저준위 핵폐기장으로 품고 변경.

*** This site was decided as the Shin-wolsong #3,#4 site, but as a change of intermediate nuclear waste dump site.

*** 설계 수명(30년)이 완료되었으나, 정부 승인으로 10년 수명연장.(2008년 1월 17일)

*** Design life(30years) had been completed, but government approved life extension, for 10 years. (17 January 2008)





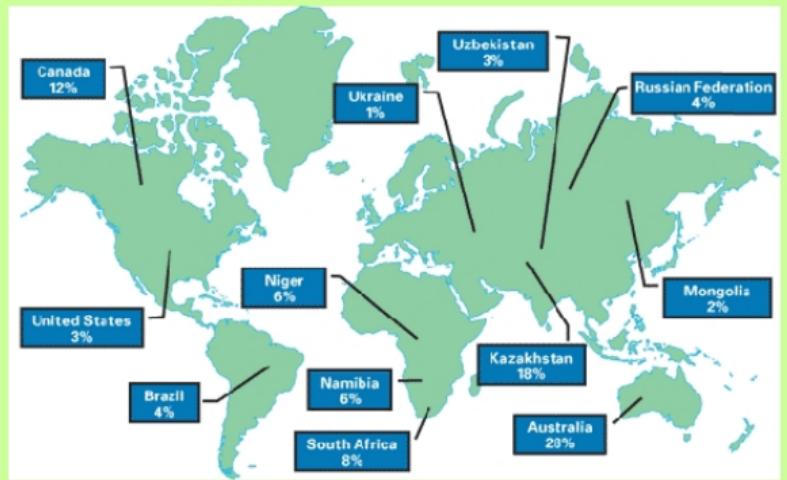
Planned construction

Components of the nuclear fuel cycle

Mining

The Nuclear Fuel Cycle

International Mining



Extract the ore from the ground

What do you do if you don't have it?

Check out Australia

Milling

Uranium ore is refined by milling

The ore contains UO_2 , UO_3 and other heavy metal oxides

Usually using solvents to leach it from the ground

Then it is chemically treated to obtain ‘yellowcake’

Lots of contaminated scrap is produced though (mill tailings)

Usually dumped as sludge in ponds (lots)

Radioisotopes (radon), heavy metals, chemicals, etc.

We have plenty of uranium resources

But what if we decide it is too harmful to mine?

Conversion

U_3O_8 is converted to UF_6 prior to enrichment

Mined U contains ^{234}U , ^{235}U , ^{238}U , .0054%, .72%

Because it is a gas at not so high temperature which is easier for enrichment

Enrichment

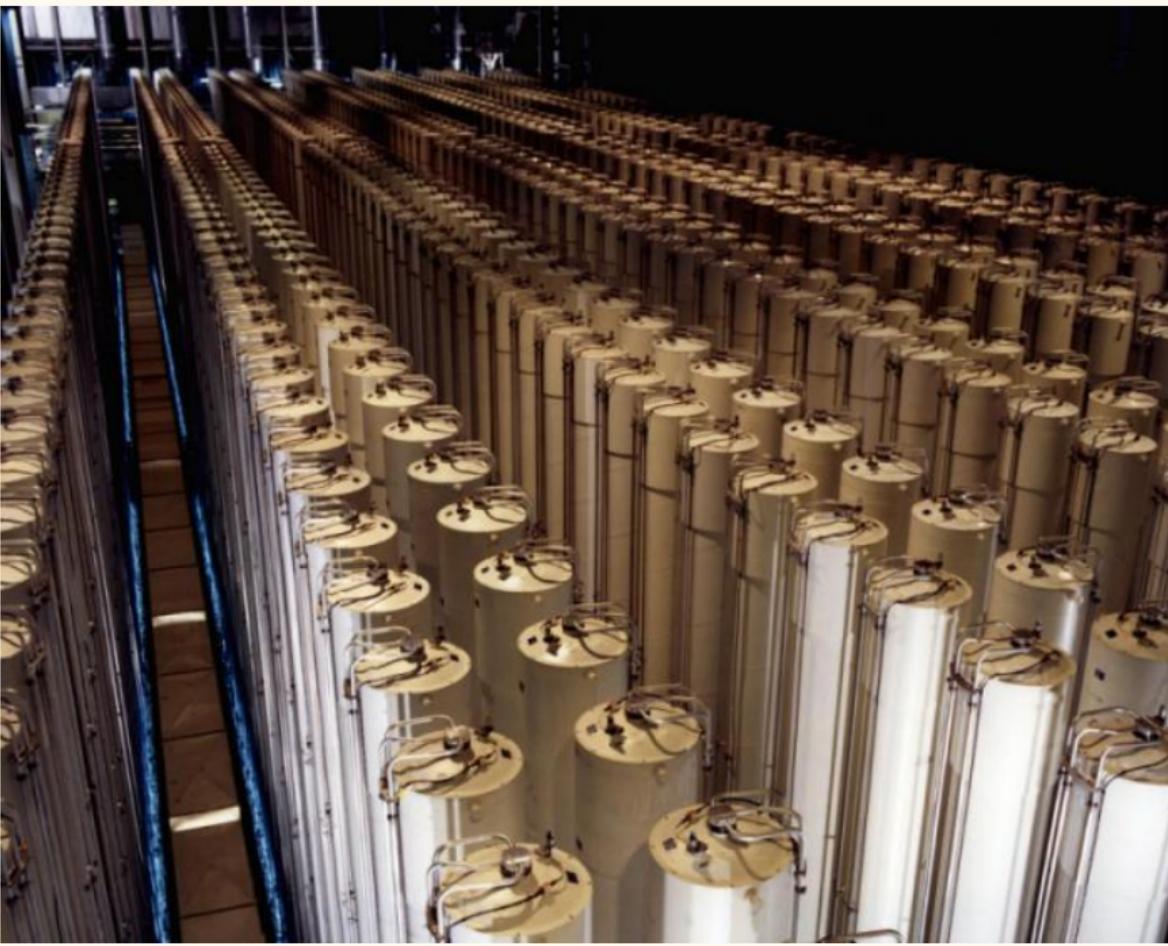
UF_6 gas is then enriched with ^{235}U

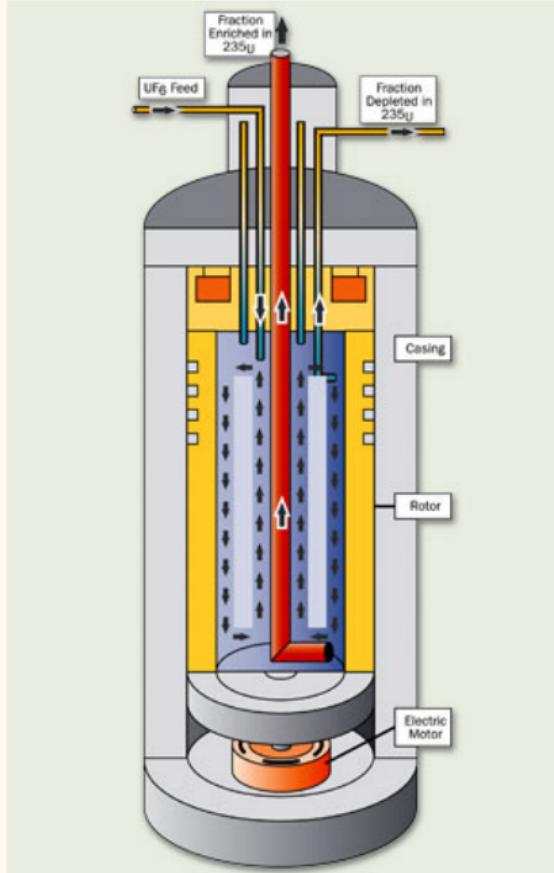
Enriched to 3% to 5%

The byproduct is depleted uranium DU

Used for armor and bullets

Any idea why?





Separative Work Unit (SWU)

SWU is the amount of work to enrich uranium from natural abundance to reactor/weapon grade

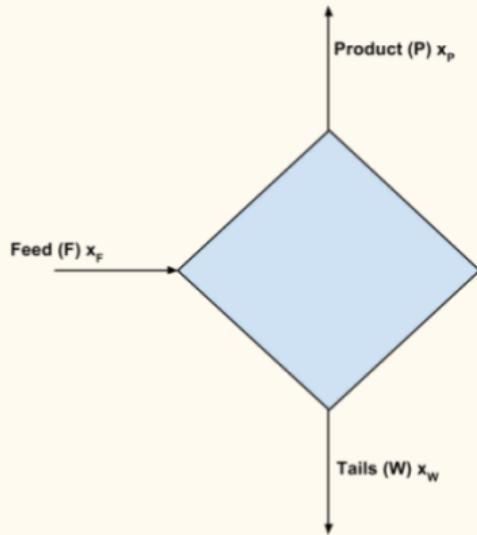
Dumb acronyms are why people hate nuclear

$$x_F = 0.0072 \quad (1)$$

$$x_P = 0.03 - 0.05 \quad (2)$$

$$x_W = 0.0002 - 0.0003 \quad (3)$$

Amount of feed for target product increases linearly with x_P by mass conservation



$$F = P + W \quad (4)$$

$$F \cdot x_F = P \cdot x_P + W \cdot x_W \quad (5)$$

SWU measures thermodynamic work to separate isotopes

SWU has units of kg because of course it does

Separation potential is a measure of differences in Gibbs free energy

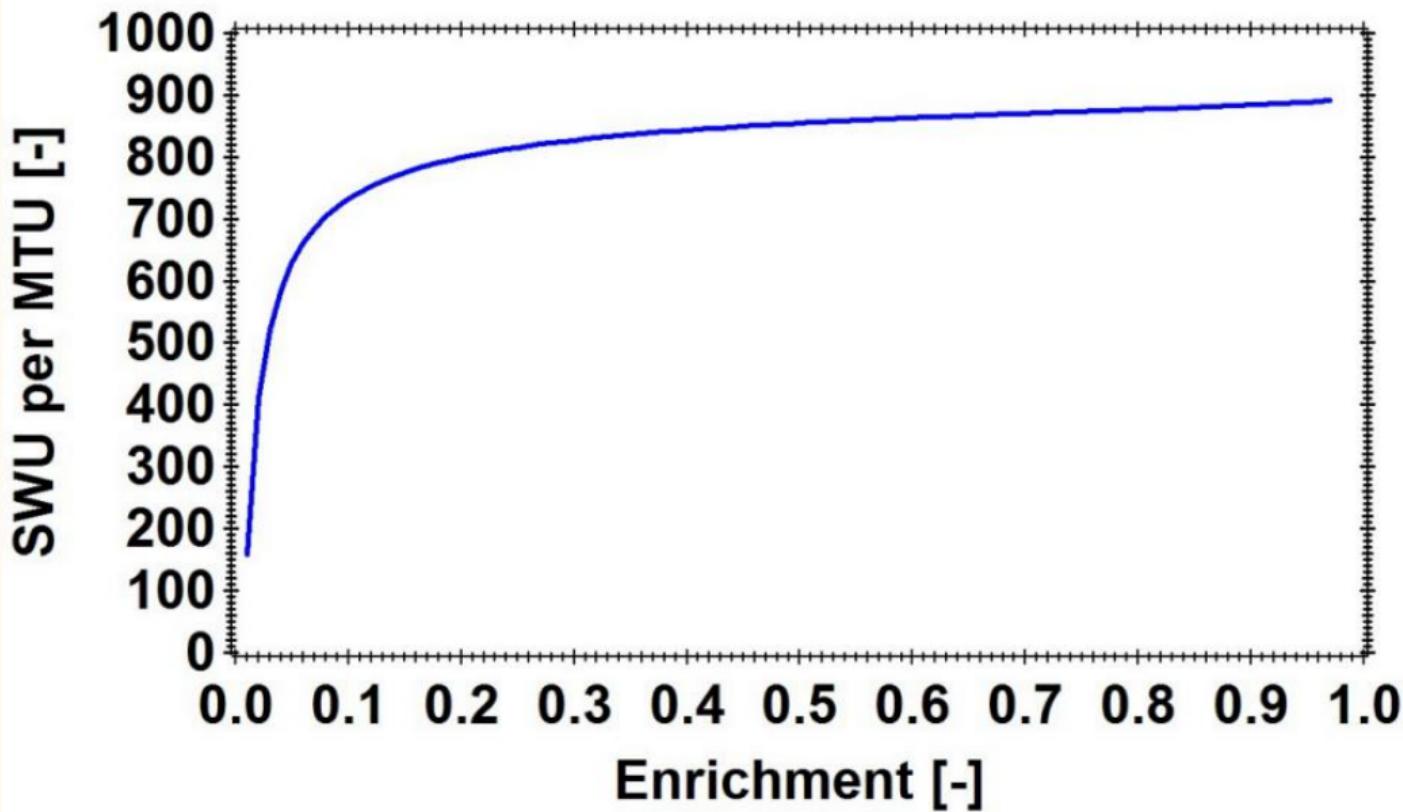
$$SWU \equiv [P \cdot V(x_P) + W \cdot V(x_W)] - F \cdot V(x_F) \quad (6)$$

$$V(x_i) \equiv (2x_i - 1) \cdot \ln \frac{x_i}{1 - x_i} \quad (7)$$

$$\frac{SWU}{P} = V(x_P) + \frac{W}{P} V(x_W) - \frac{F}{P} V(x_F) \quad (8)$$

The derivation is based on entropy changes

Change in entropy in **binary mixture of gases**



Fuel Fabrication

The fuel fabrication process (LWRs) makes ceramic UO_2 pellets

Why ceramic?

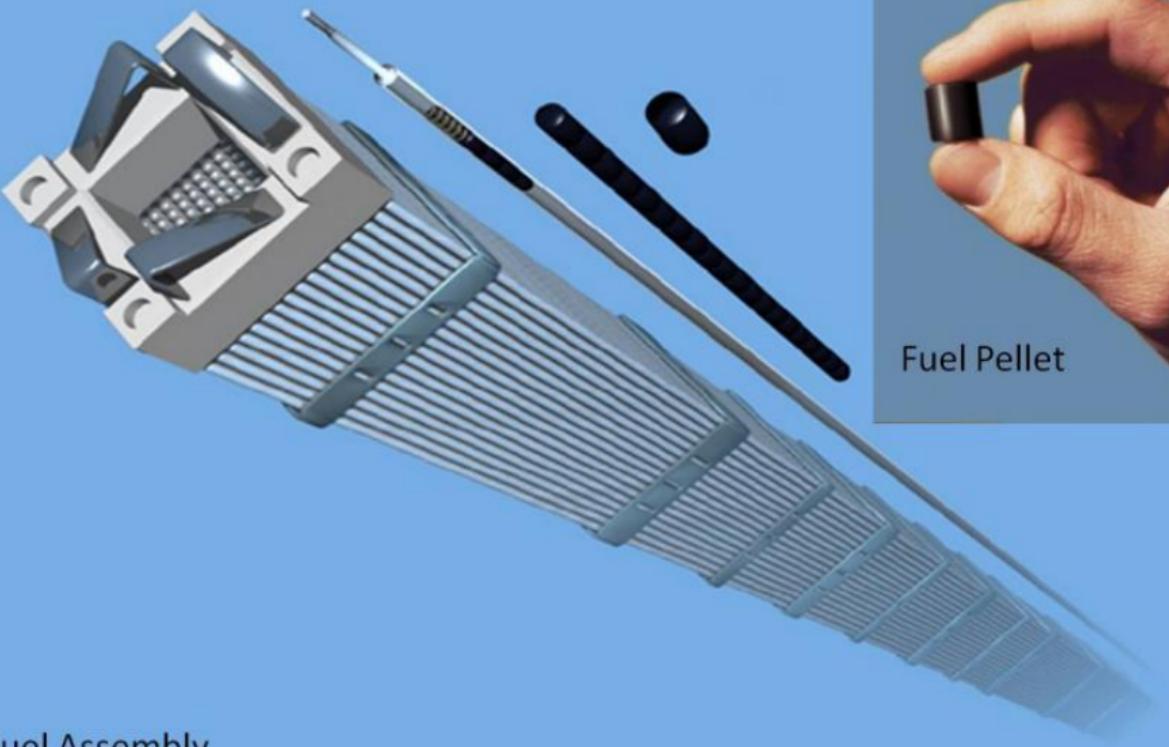
Is there anything better?

Fuel rods contain a Zr-based alloy

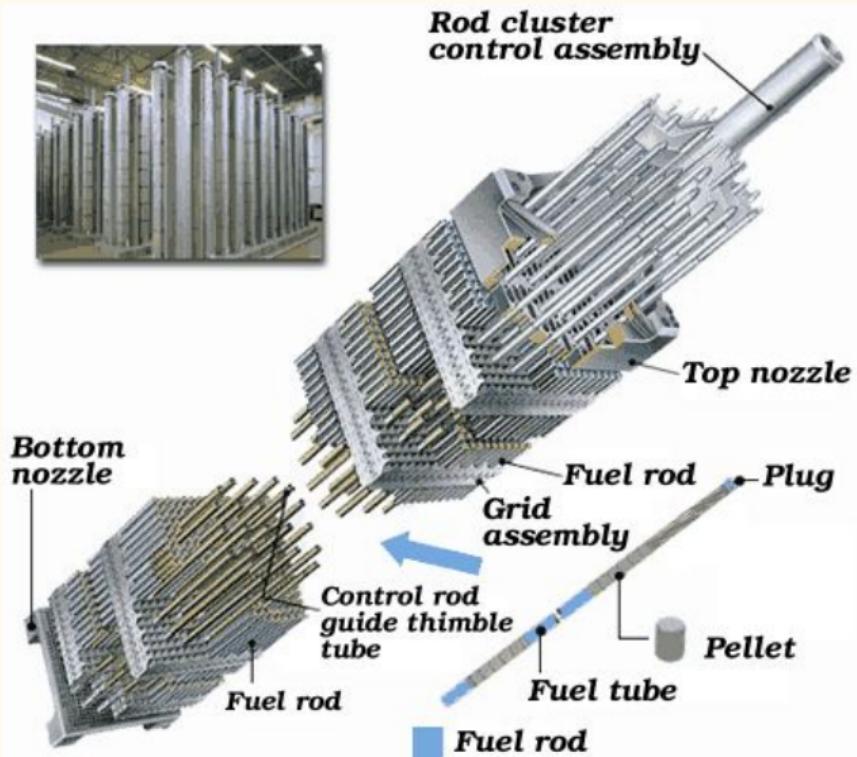
Also generates hydrogen gas



That's kind of what happened at Fukushima



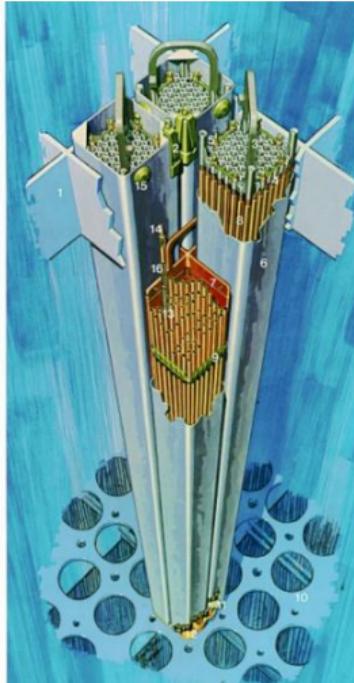
Fuel Pellet



**BWR/6 FUEL
ASSEMBLIES
& CONTROL
ROD MODULE**

- 1.TOP FUEL GUIDE
2.CHANNEL
FASTENER
3.UPPER TIE
PLATE
4.EXPANSION
SPACER
5.LOCKING TAB
6.CHANNEL
7.CONTROL ROD
8.FUEL ROD
9.SPACER
10.CORE SUPPORT
ASSEMBLY
11 LOWER
TIE PLATE
12.FUEL SUPPORT
PIECE
13.FUEL PELLET
14-END PLUG
15 CHANNEL
SPACER
16.PLENUM
SPRING

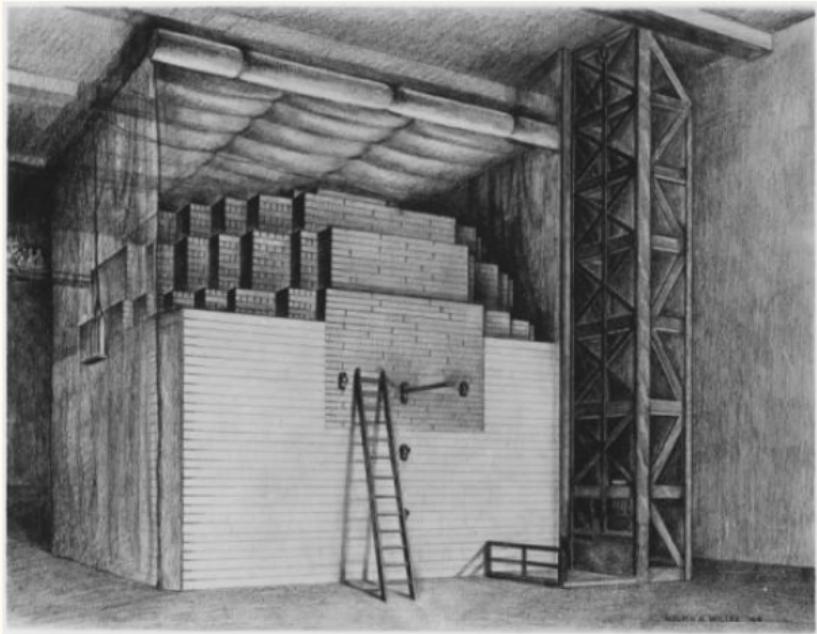
GENERAL  ELECTRIC



Macro reactor operation

Chicago Pile-1 (CP-1)

The first man made reactor was constructed at University of Chicago in 1942

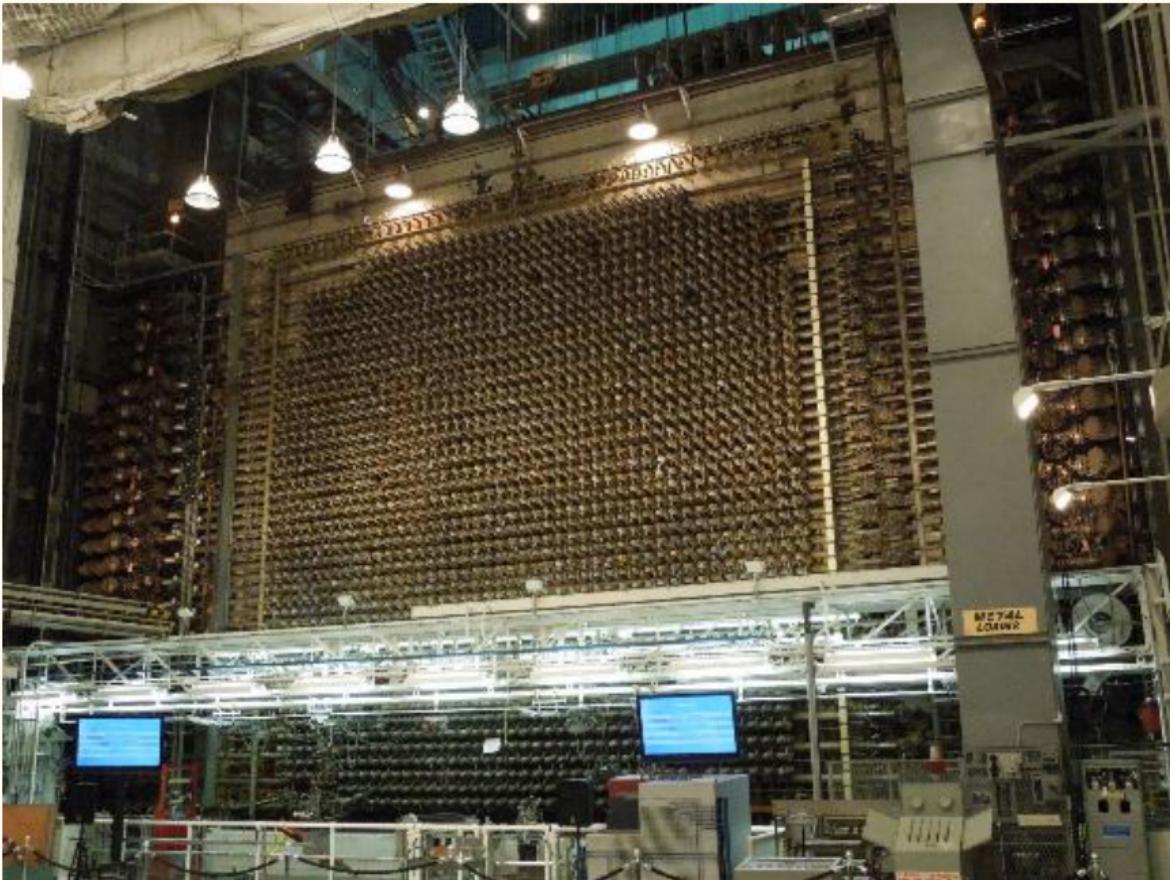


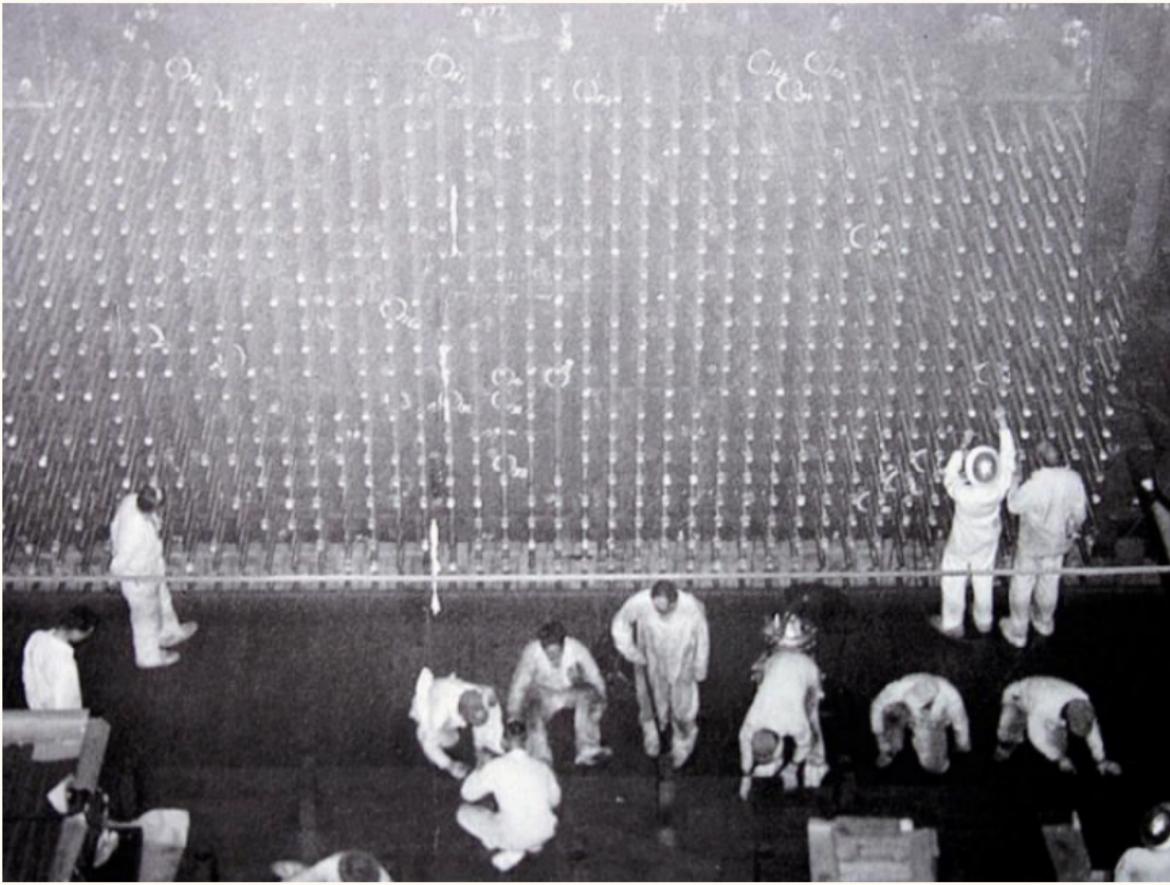
Made of uranium and graphite blocks

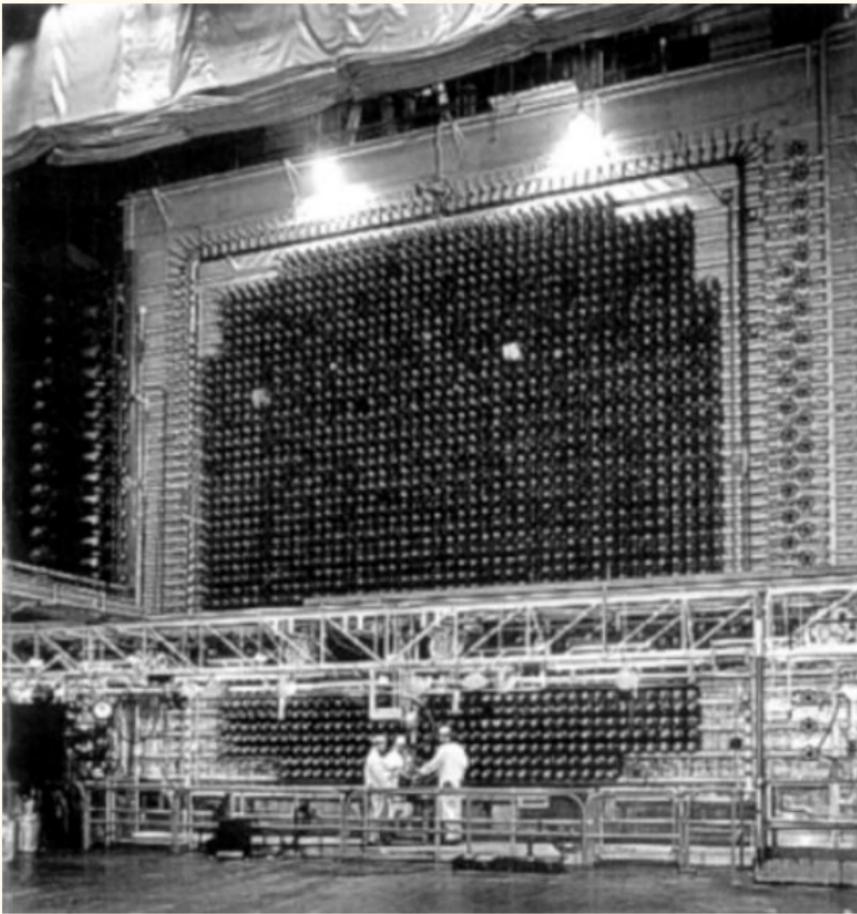
Cadmium coated rods

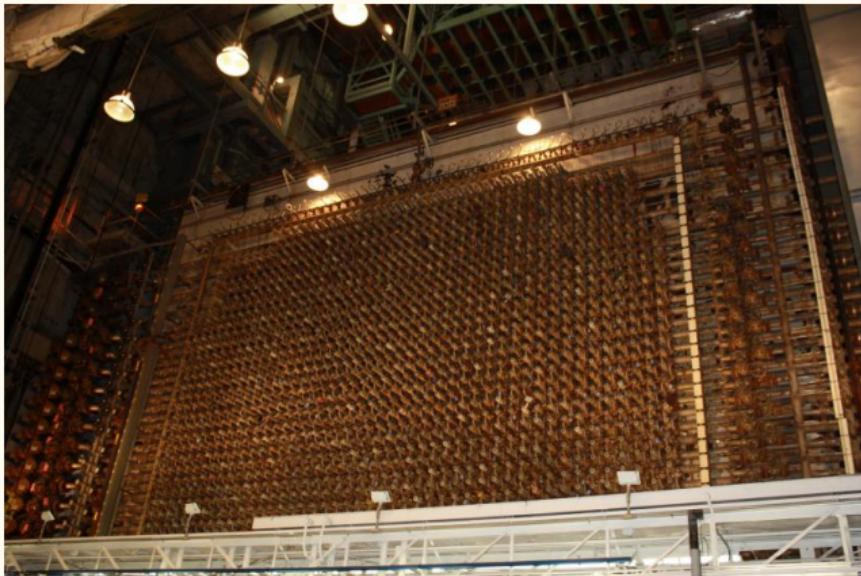
And I have a piece of the graphite

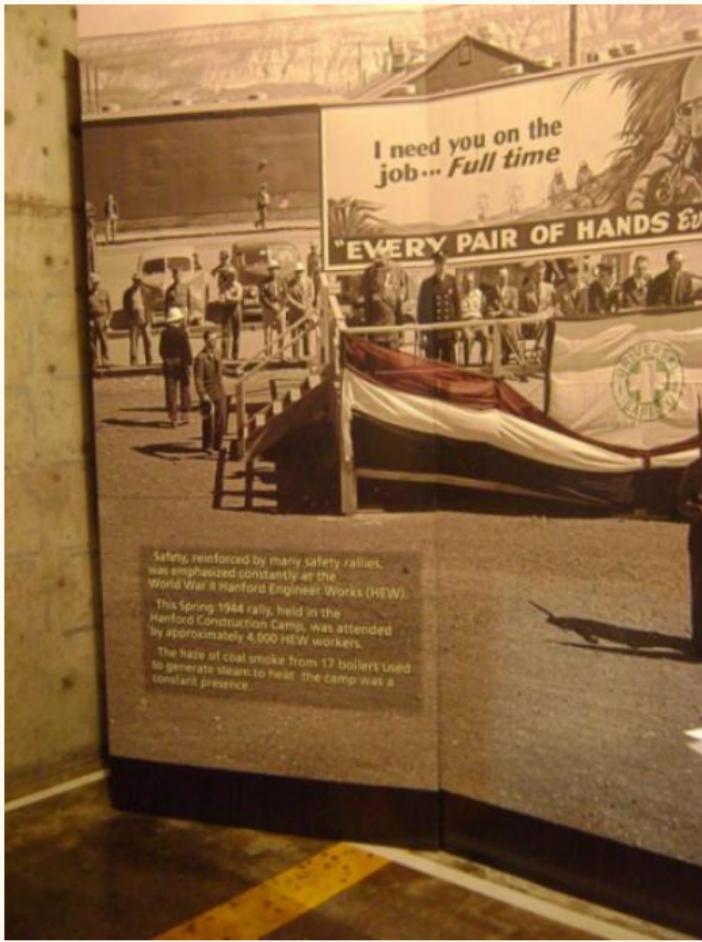
Let's look at pictures of the Hanford B reactor
Same design as CP1









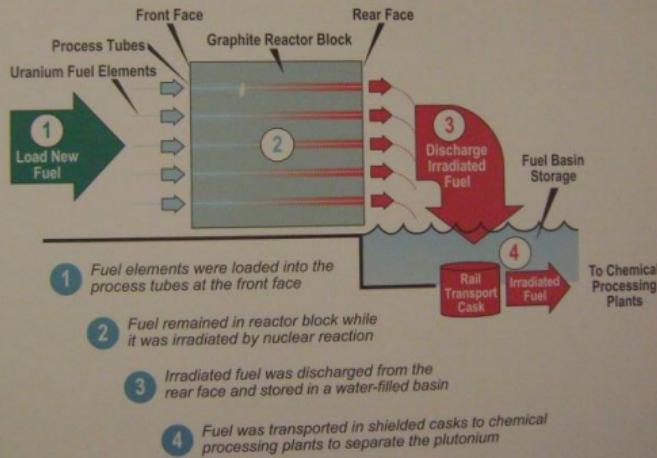


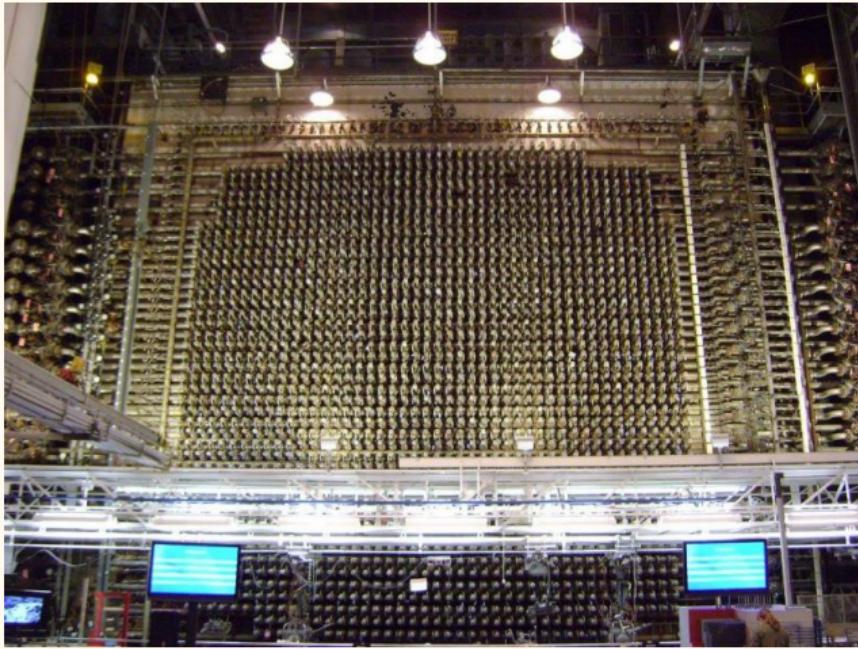




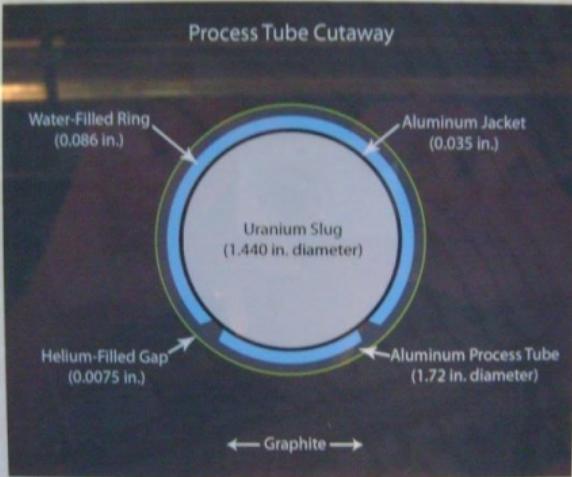
Hanford's Historic B Reactor

Simplified Reactor Operation



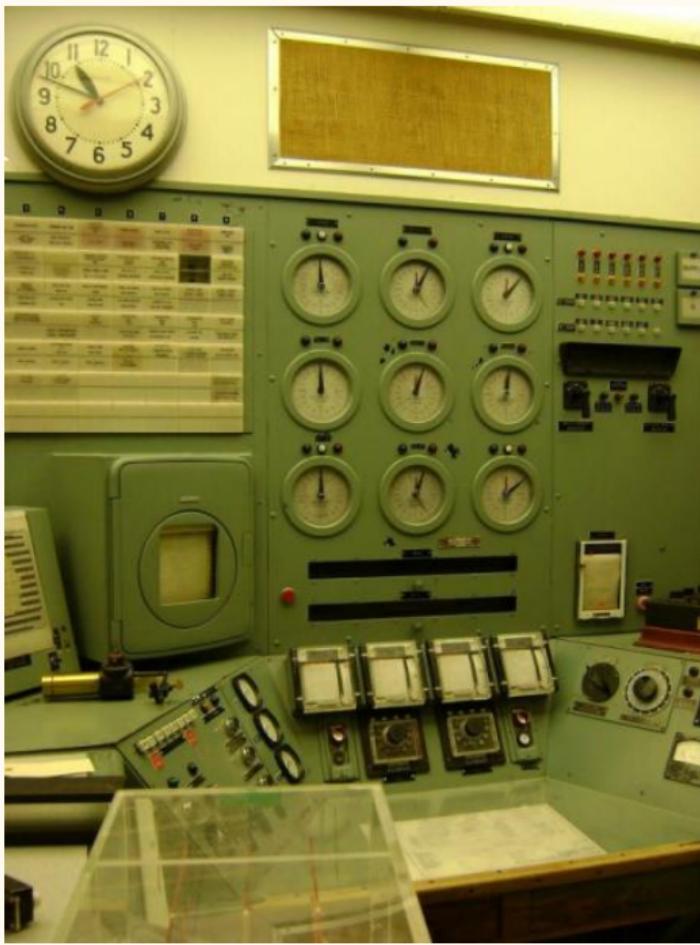


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A. E. E.

10 MR/HR 100 MR/HR 1 R/HR 10 R/HR

Natural reactor

A natural reactor actually happened about 2 billion years ago

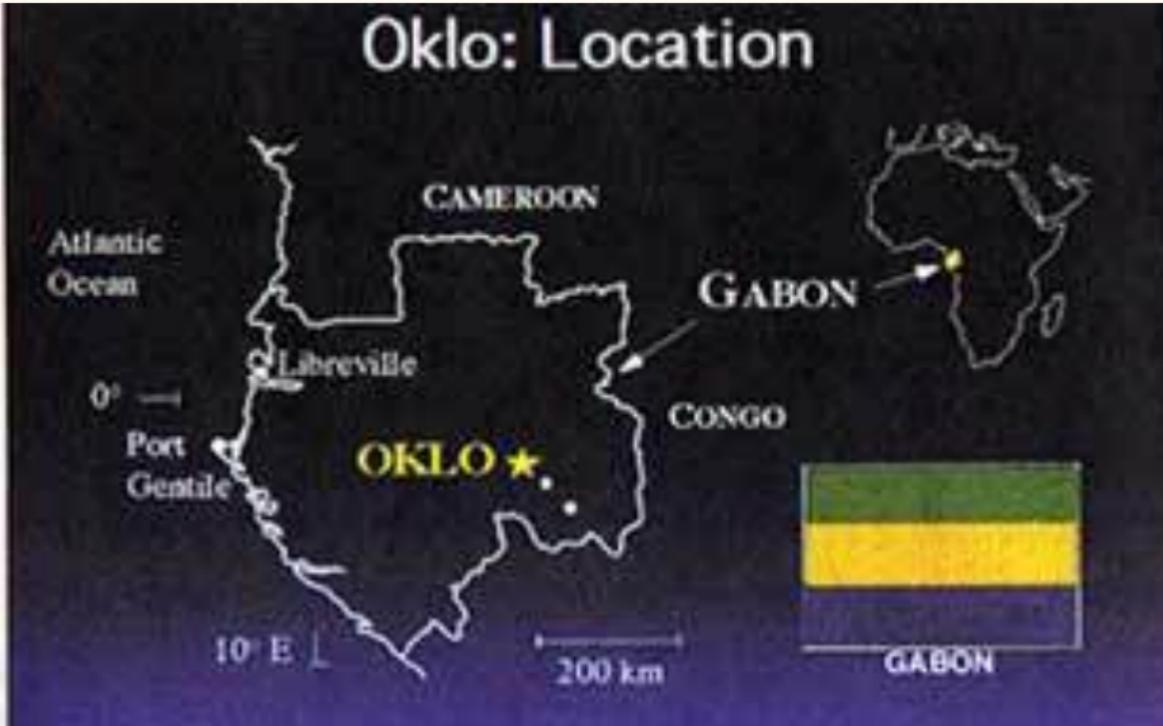
16 sites operated for about 10^5 years at 100 kW thermal

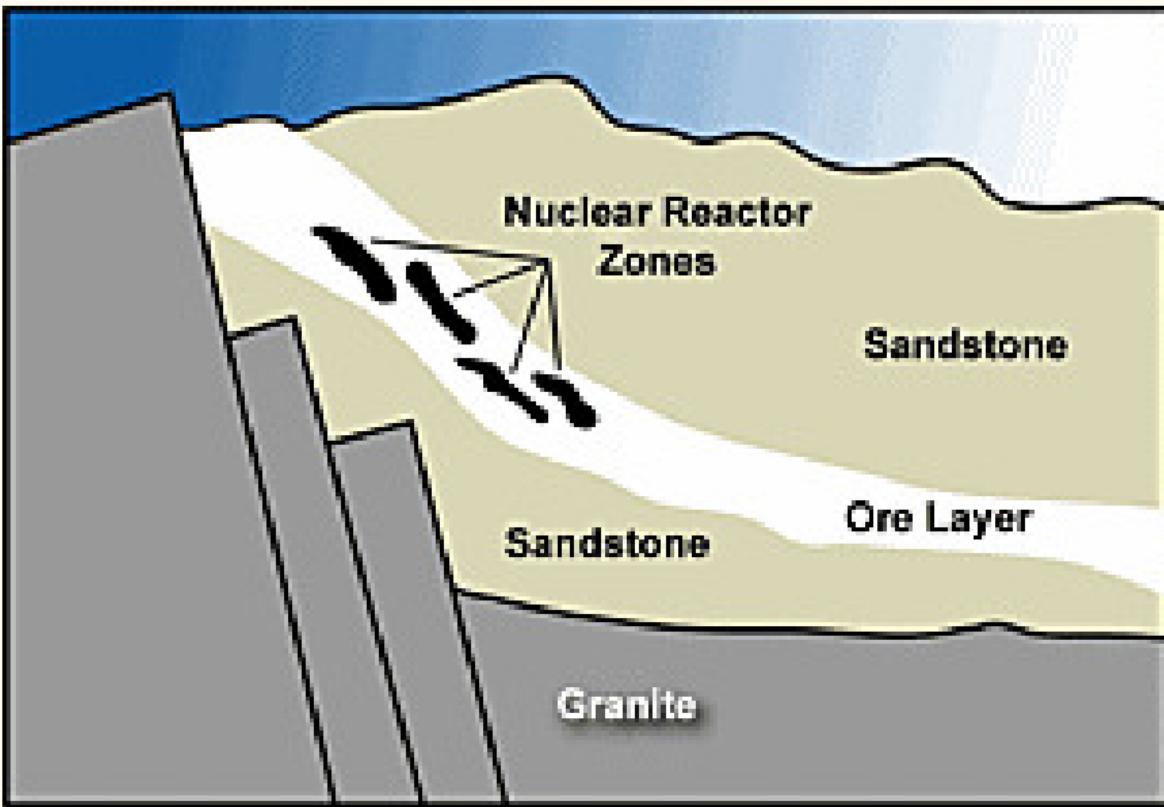
French company found samples of 0.60% of ^{235}U

How much is there normally?

Uranium rich mineral deposits were infiltrated by groundwater which served as moderator

Oklo: Location





EBR-I

EBR-I was the first reactor to generate electricity

In 1951 - now a [museum](#), open to the public for free

About 200 kW of electricity

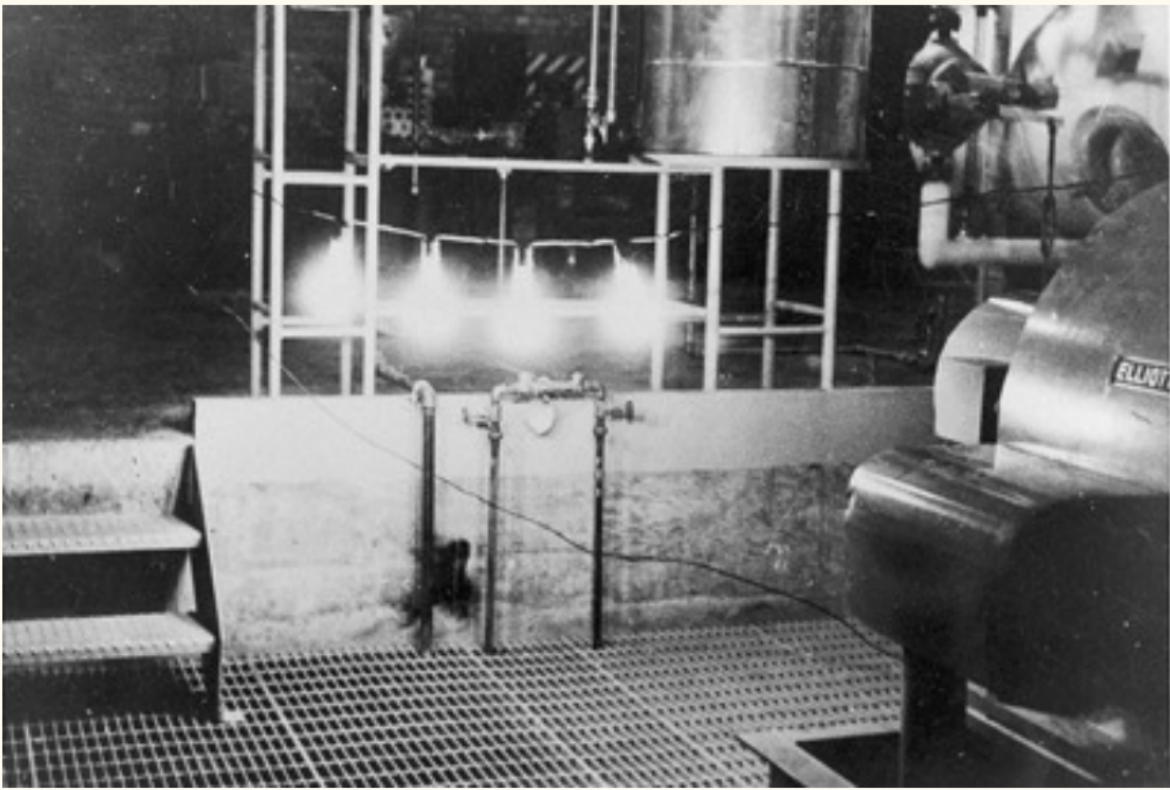
Also was a breeder and first to confirm Fermi's theory

'Fast' reactor, metal fuel and molten salt designs

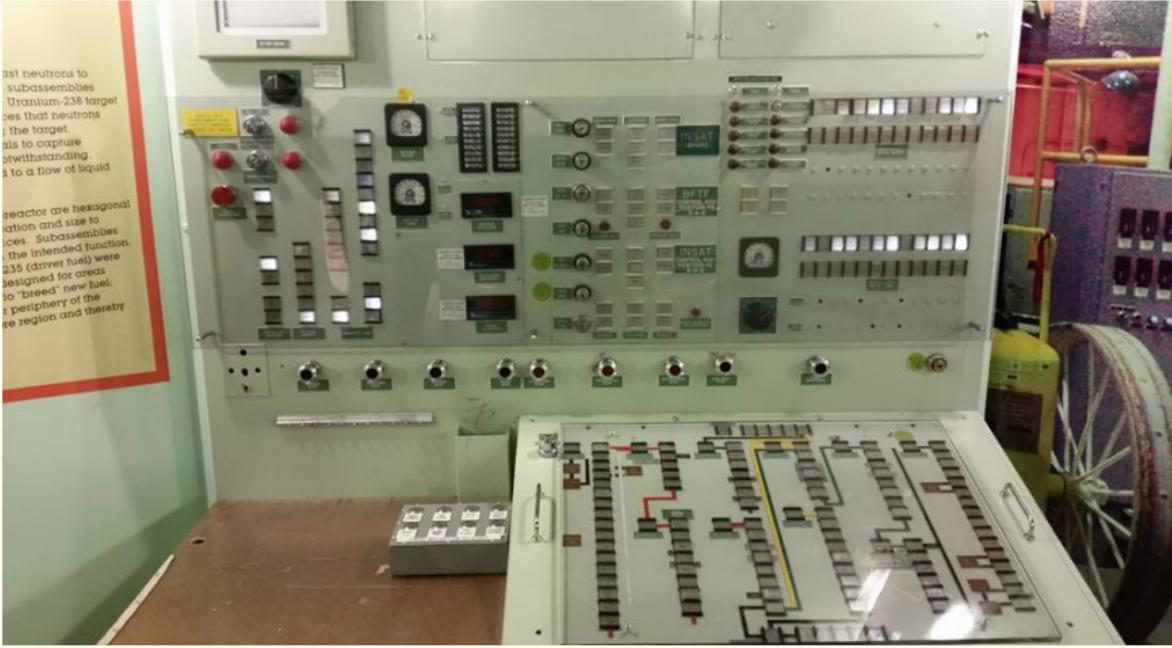
Then the commercial reactors switched to ceramic and water

Why?

Now the so called Generation IV reactor designs use metals and salts



More pictures







The EBR-II Difference

**The Accidents at Three Mile Island,
Chernobyl and Japan would not have
happened with EBR-II technology.**

In three decades of operation, EBR-II had proven that a nuclear reactor could be designed, built, and maintained to produce electricity on a large scale, to recycle and reuse its own spent fuel (while producing still more usable fuel), and to rely on the laws of nature to achieve emergency shutdown without posing a threat to workers, the environment, or the public.

In the end, however, the pioneering reactor fell victim to events far beyond the walls of its towering steel dome.

Why is EBR-II world

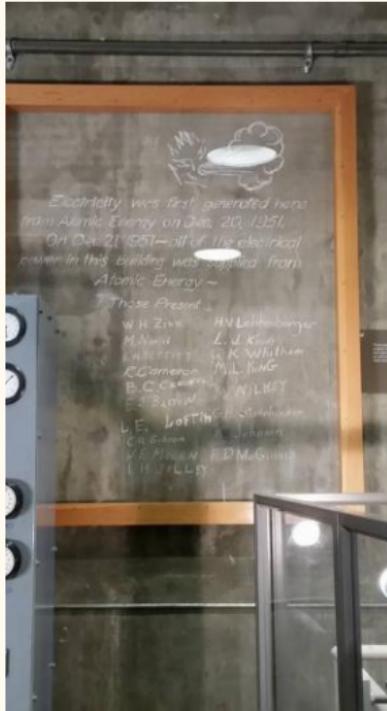
There are only two nuclear-reactor cores active in the world today. The others have been closed down.

These include ones that EBR-II would shut down.



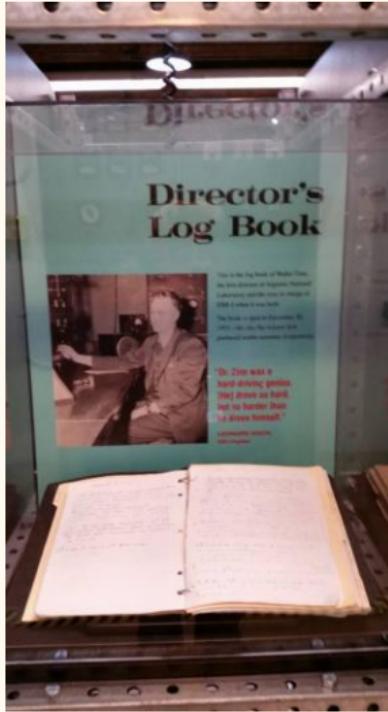


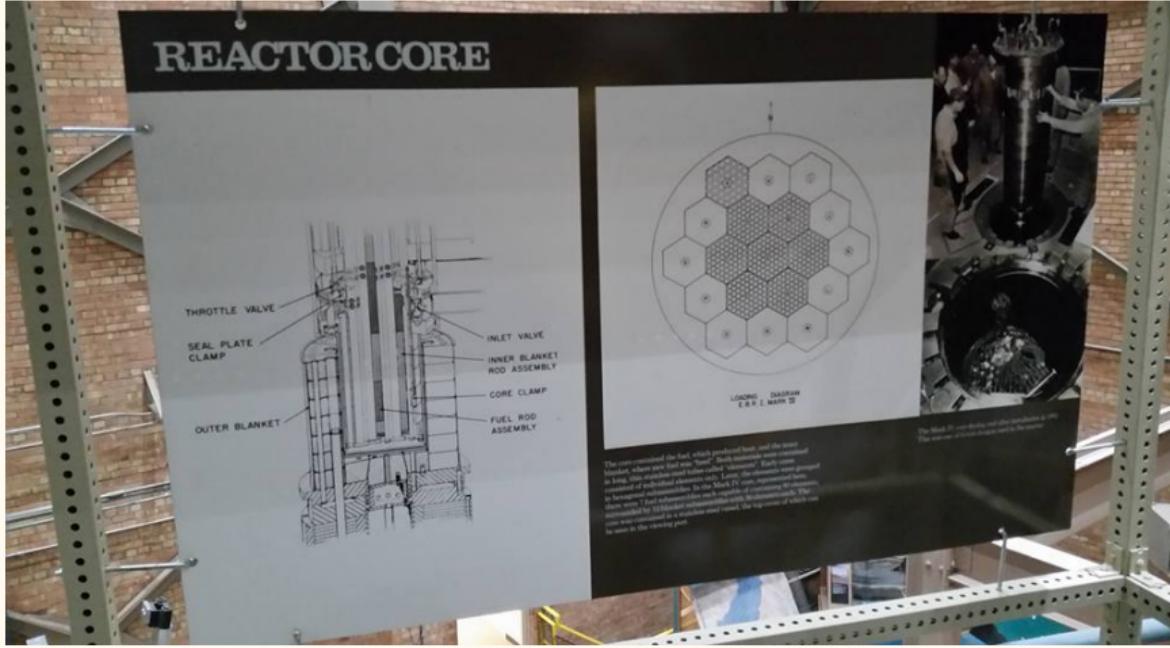
















A NaK for Keeping Cool

You're looking at part of the EBR-I cooling system. These pipes carried an alloy of sodium (elemental symbol Na) and potassium (elemental symbol K), or NaK. Everyone called it "nack".

No one had used NaK as a coolant before. The reactor's designers chose it because it:

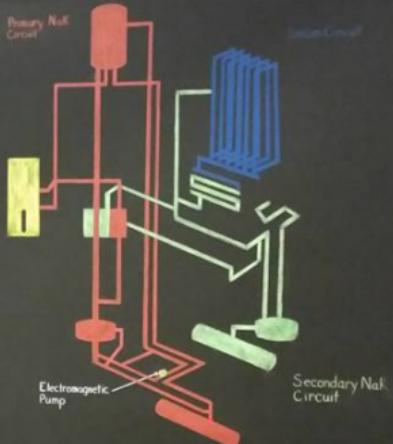
- Stays liquid over a wide range of temperatures - it doesn't boil away

- Transfers heat very efficiently - takes heat away from the reactor core, keeping it cool

- Allows neutrons from the reactor core to collide with the Uranium-238 in the breeding blanket and make more fuel

But NaK isn't perfect. It burns upon exposure to air or water and corrodes many materials. The designers had to invent new techniques and equipment, such as an electromagnetic pump that would keep the NaK circulating without moving parts.

This cooling system worked without fail for the life of the reactor.



"[With NaK] they were walking into a cutting edge, completely unknown technical situation...they handled it beautifully."

Leon Walters
Argonne Laboratory senior technical advisor



EBR-II

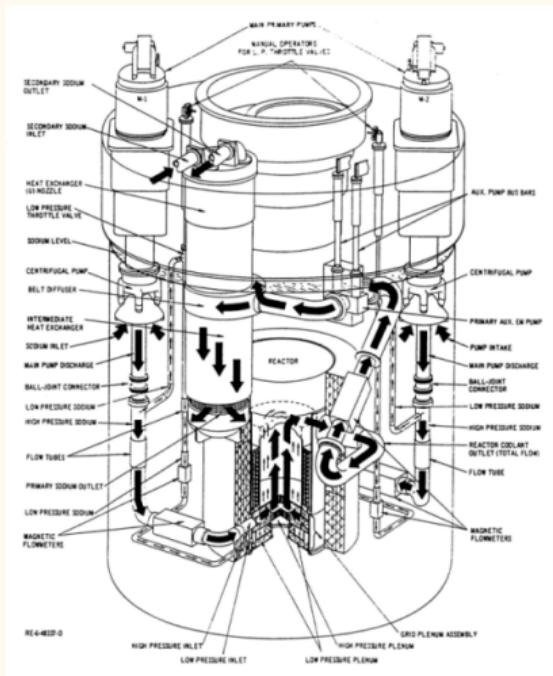
EBR-II is an Sodium Fast Reactor (SFR) design for 62.5 MW that operated from 1964 to 1994

19 MW electricity operated for 30 years with no accidents

Engineering scale facility

Breeder reactor with onsite reprocessing (pyroprocessing)

Famous test of **passive safety systems**



TREAT

TREAT is an air cooled, graphite moderated thermal reactor

Operation from 1959 to 1994

Transient reactor tests to simulate all sorts of reactor accidents

George Imel

Restarted and working on experiments!

Because of Fukushima, TREAT accident tolerant fuels

Everyone is excited

100 kW; transients up to 19 GW



Military use

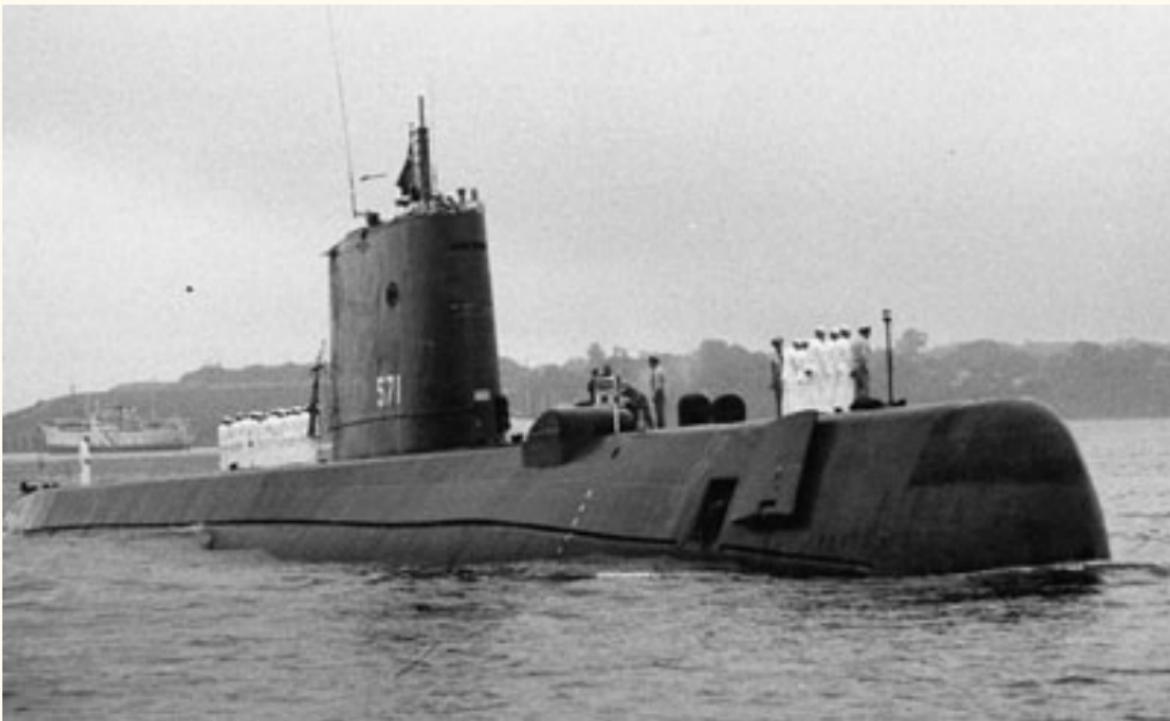
Nuclear reactors are used on submarines and aircraft carriers

Nautilus launched in 1954

25 year life span

Nimitz-class aircraft carriers have 2 reactors, about 100 MW, 23 year life span

How about now?





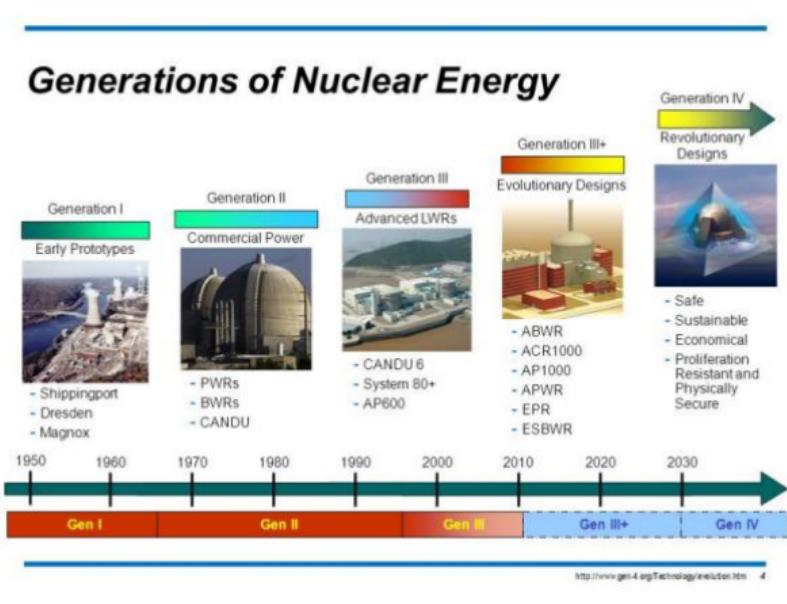
Watch out for the **danger zone**

Reactor concepts

Generations

Reactors were first built in the 1950s

Generations of Nuclear Energy



Gen IV is essentially based on Gen I

Different material for fuels and coolant

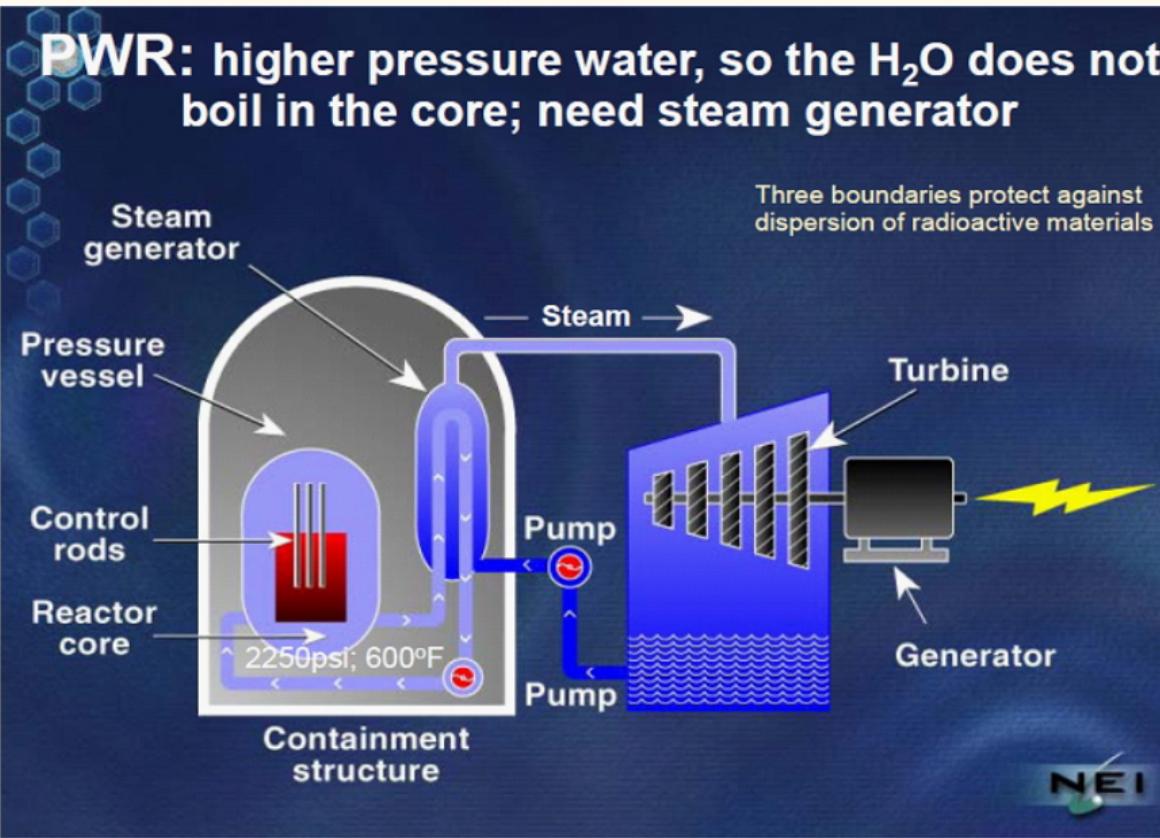
Moderators not needed for some

Passive safety systems

Proliferation issues – so they say

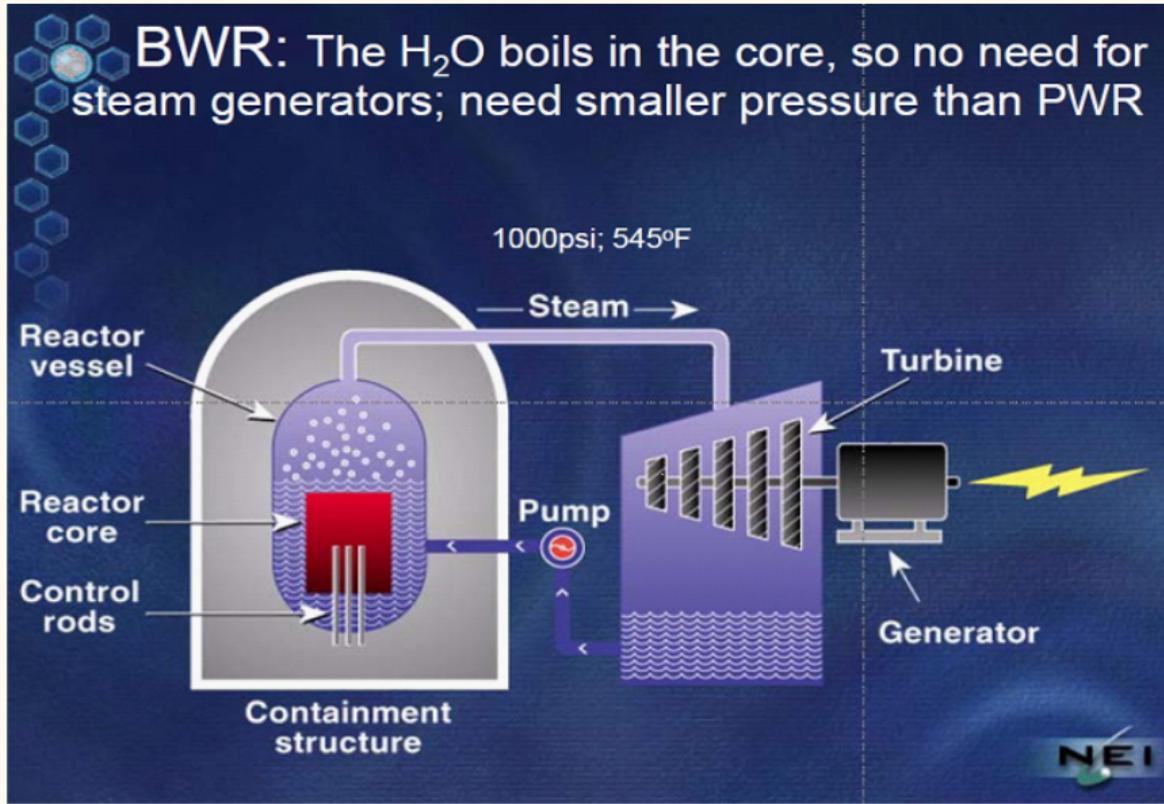
PWR

The PWR heats water but does not boil



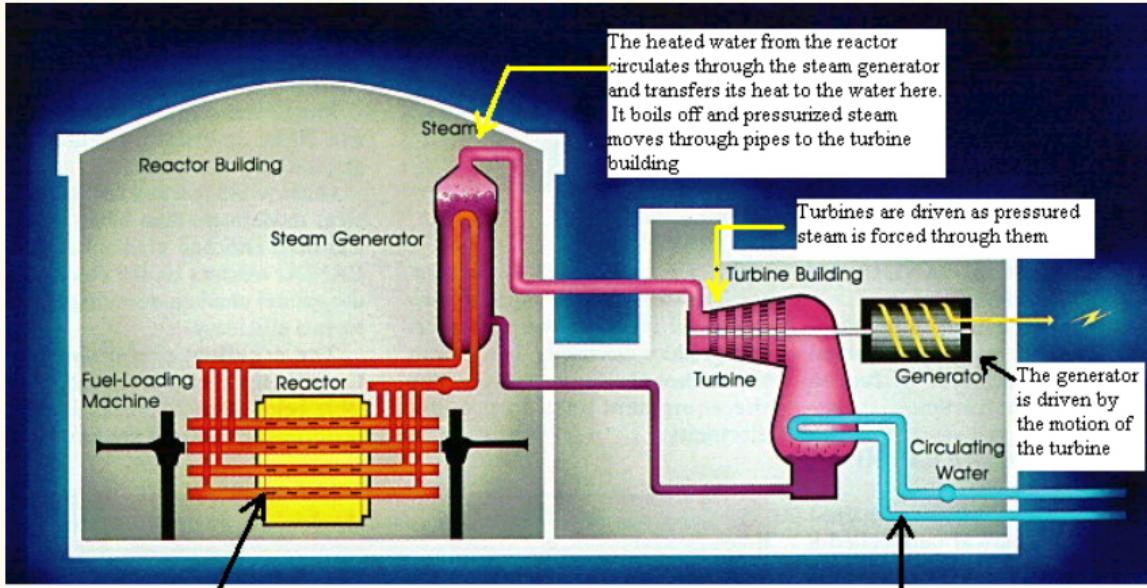
BWR

The BWR does boil water in the reactor vessel



CANDU

The CANDU design uses heavy water (moderator) and natural uranium (also thermal)



Reactor contains U-235 with heavy water moderator. Heat energy from nuclear reactions is carried away by water which cools the reactor. The water is found in the pipes and is isolated from the nuclear material

The heated water from the reactor circulates through the steam generator and transfers its heat to the water here. It boils off and pressurized steam moves through pipes to the turbine building

Turbines are driven as pressurized steam is forced through them

Turbine



Generator

The generator is driven by the motion of the turbine

Circulating Water

Circulating water from an external source (lake) is used to absorb the heat from the steam. This cools it and condenses it to be pumped back into the steam generator. An undesired side effect is thermal pollution of the lake as the now warm circulating water is pumped back.

More on CANDU

Used in Canada and marketed to other nations

South Korea, China, India have some

PWR design (two loops)

The heavy water is less absorbing so natural U can be used

But also more collisions would be needed than in LWRs

The core would be bigger

But can use used fuel from LWRs and a Th cycle

So is there an advantage? Technical? Institutional?

The CANDU design uses heavy water (moderator) and natural uranium (also thermal)



Aqueous reprocessing

Aqueous recycling is the commercially available process for LWRs

Terry Todd leading expert

Major nations are France, Japan, Russia, India

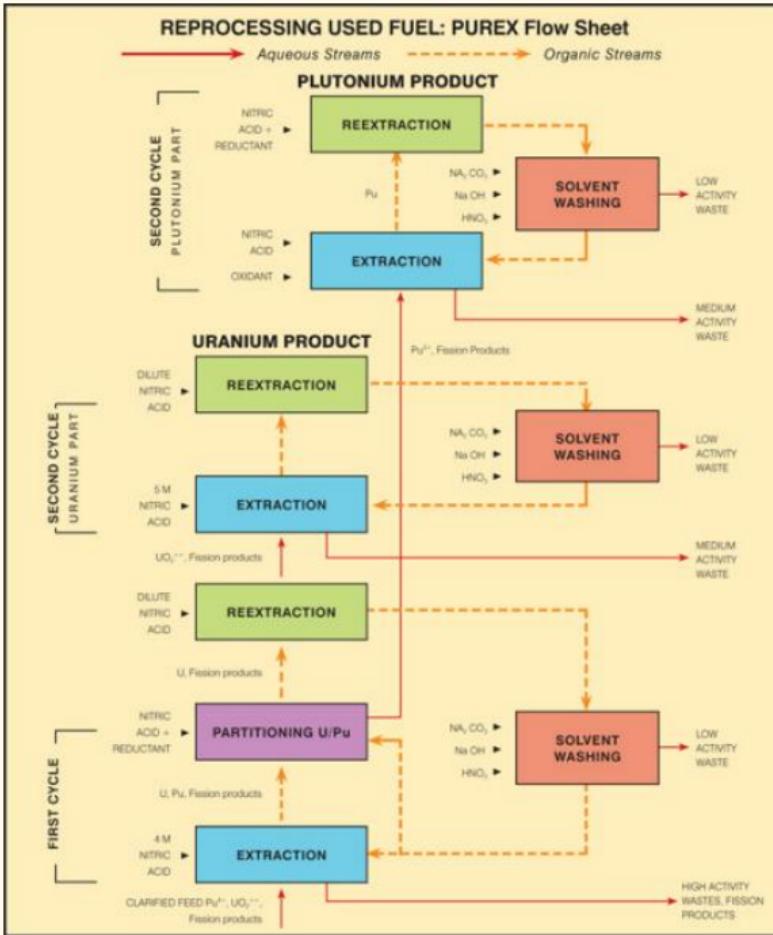
'Recycle' is better for the brand

About 1% 235U and 1% Pu in used fuel

The most common is PUREX

This uses an organic phosphate and nitric acid

Solvent extraction process where U and Pu are separated



U and Pu are chemically separated through organic solvent equilibrium extraction

U and Pu exist in a number of valence states

Because of different redox potentials, reduction or oxidation can be done to one without disturbing the other

Each exhibits different solubilities in organic solvent TBP

- (1) Chop up everything, remove FP gases, dissolve in aqueous solution
- (2) Separate U/Pu from fission products by dissolving in solvent
- (3) Reduce Pu to 3+ because it is highly insoluble in solvent (U 6+)
- (4) Back extract Pu into aqueous solution
- (5) Strip U from solvent into aqueous solution

U and Pu are chemically separated through organic solvent equilibrium extraction

Aqueous solution is nitric acid

Does generate a lot of liquid waste

Mass transfer to solvent phase – extraction

Mass transfer to aqueous phase –“ stripping

Mass transfer operates in a continuous, multistage, countercurrent mode

High separation factor

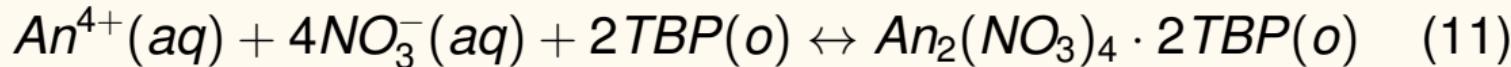
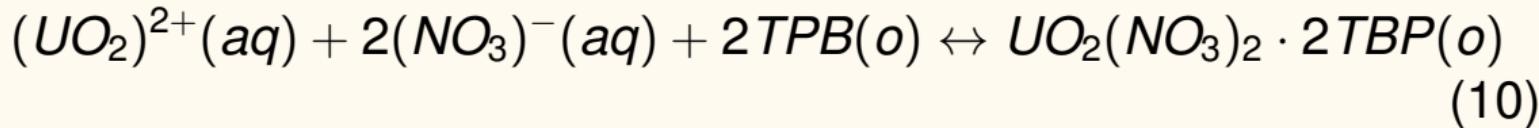
High processing rates

Streams flow countercurrently, so concentration is relatively constant

Solvent must be recycled because it's not cheap

First applied to extract Pu for weapons production in 1952 at Hanford site

Metals in 4+ and 6+ are extracted



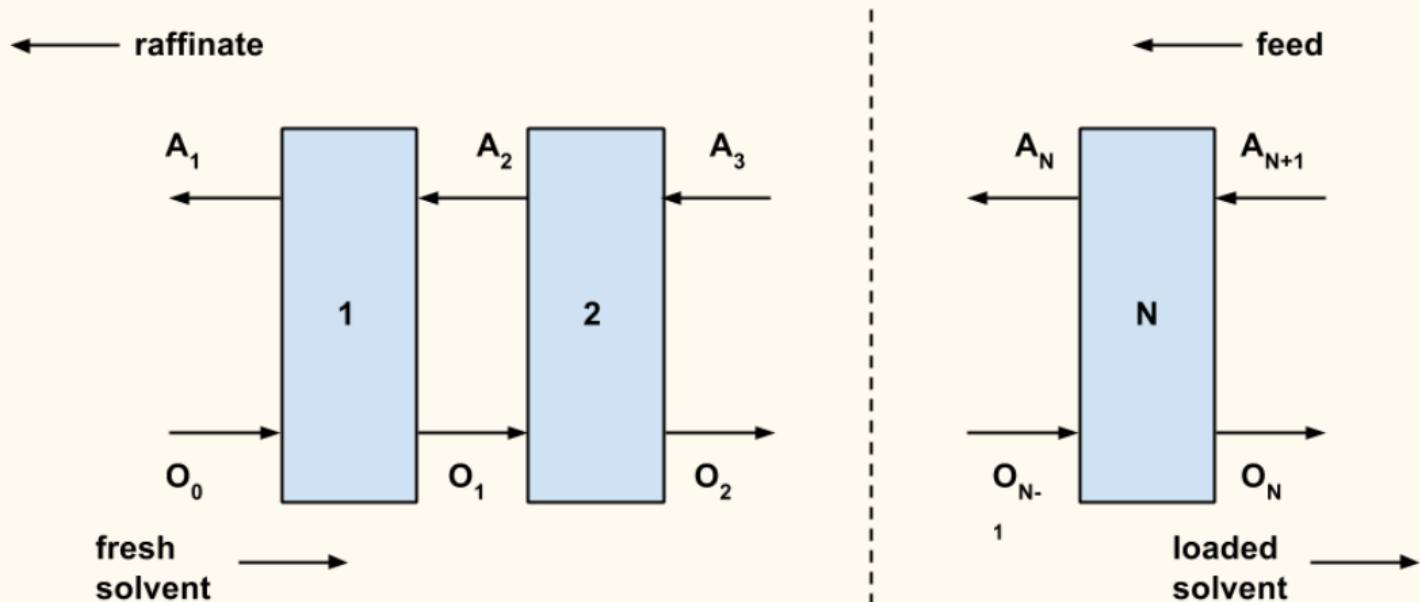
Pu (as 4+) co-extracted with U

Anything 3+ or lower is not

Waste is vitrified into a borosilicate glass waste form for disposal

Well characterized material with 50+ years of scientific study

Very stable



Typical mass conservation is used to model solvent extraction

This is from Benedict

Distribution coefficient = organic/aqueous phase concentration at equilibrium

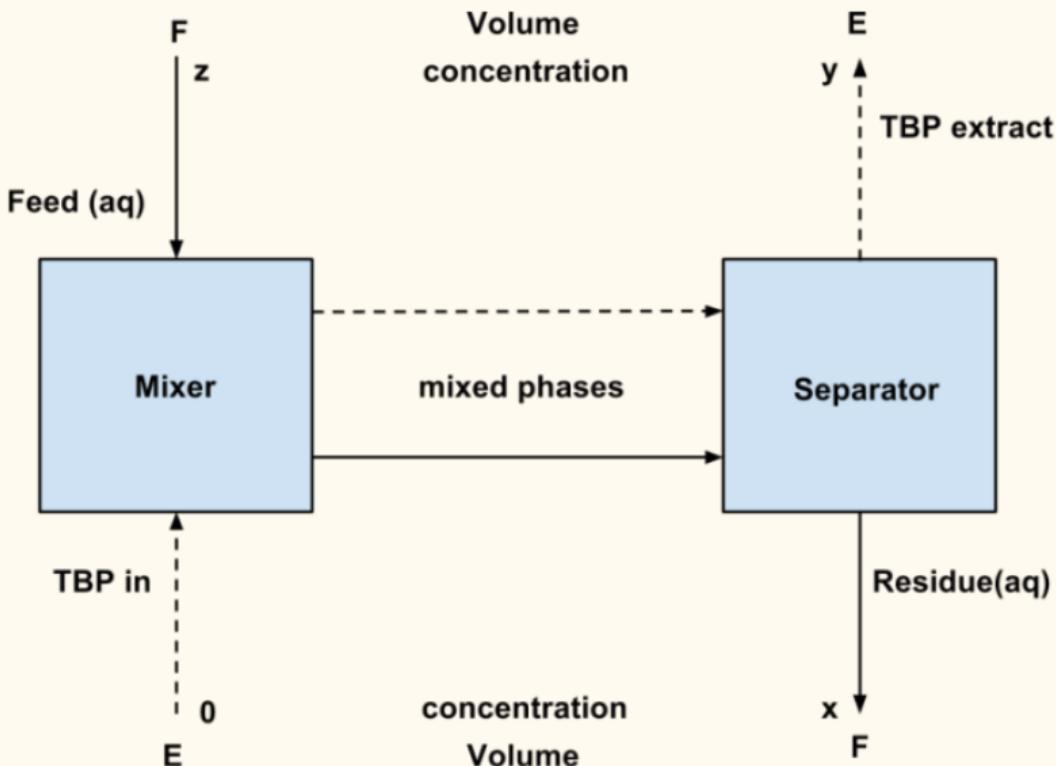
$$D \equiv \frac{y}{x} \quad (12)$$

When an aqueous solution of an extractable component is brought into equilibrium with an immiscible solvent for the component and the two phases are then separated, the component will be found distributed between the two phases

We then derive the material balance on the extractable component

$$Fz = Fx + Ey \quad (13)$$

With D for the system defined before



Derive the concentration that is extracted

$$D \equiv \frac{y}{x} \quad (14)$$

$$Fz = Fx + Ey \quad (15)$$

$$\therefore y = \frac{Dz}{1 + \frac{ED}{F}} \quad (16)$$

And the fraction extracted is –

$$\rho = \frac{Ey}{Fz} = \frac{1}{1 + \frac{F}{ED}} \quad (17)$$

For design then, you only need 3 parameters

Derive the solvent feed needed for a given extraction fraction

$$\frac{E}{F} = \frac{\rho}{D(1 - \rho)} \quad (18)$$

What is the functional dependence of $E(\rho)$?

Amount of used fuel isn't actually a variable

Reduce the amount of solvent by using multiple contact stages

With many stages, high extraction fraction can be obtained

Solvent is expensive, so recycling stages are also added to strip out extract

Multiple components can be extracted from organic phase if D is different enough

So this would be needed to completely separate U, Pu

Physical conditions affecting D –

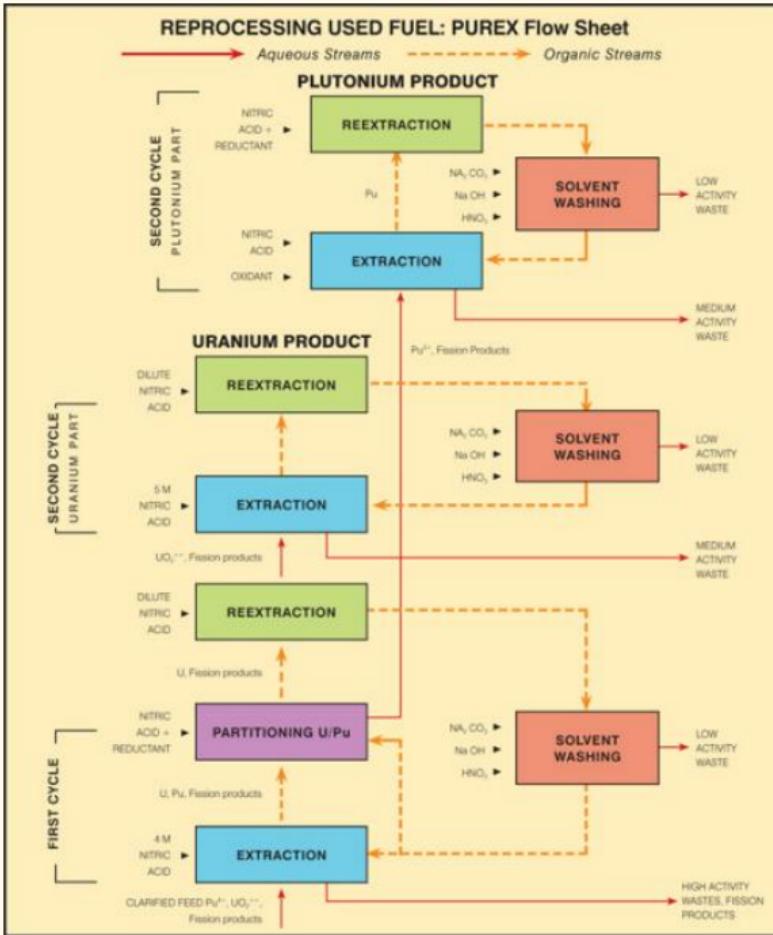
Element extracted

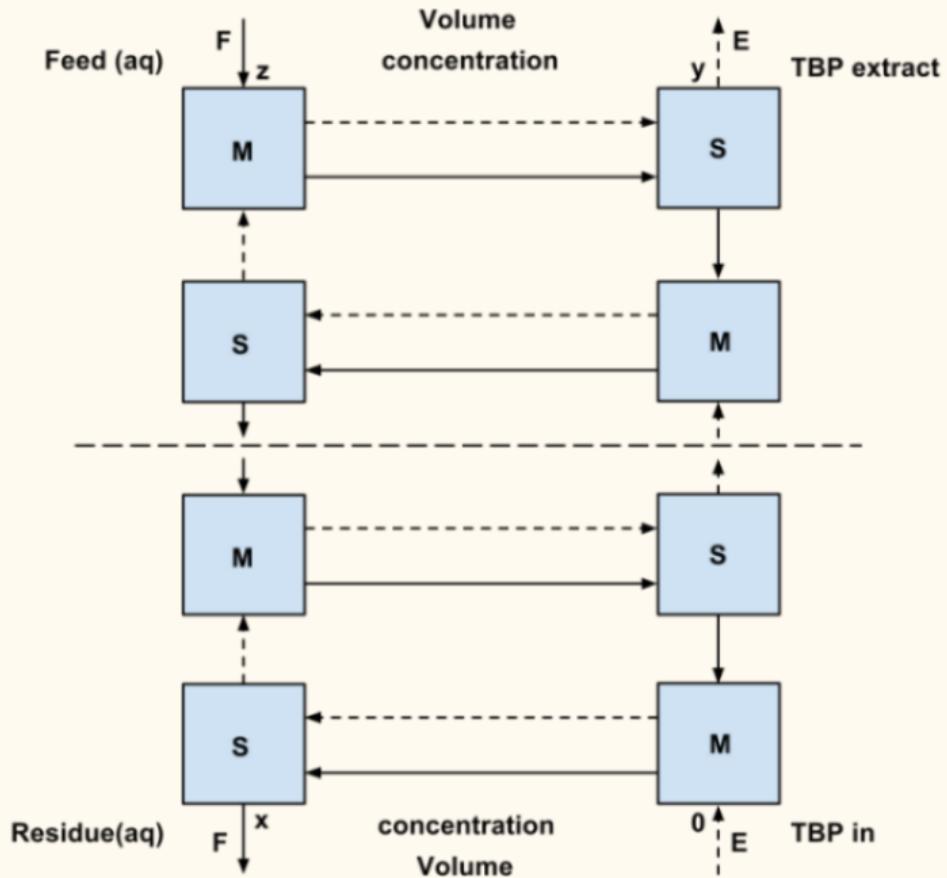
Redox potential of aqueous phase

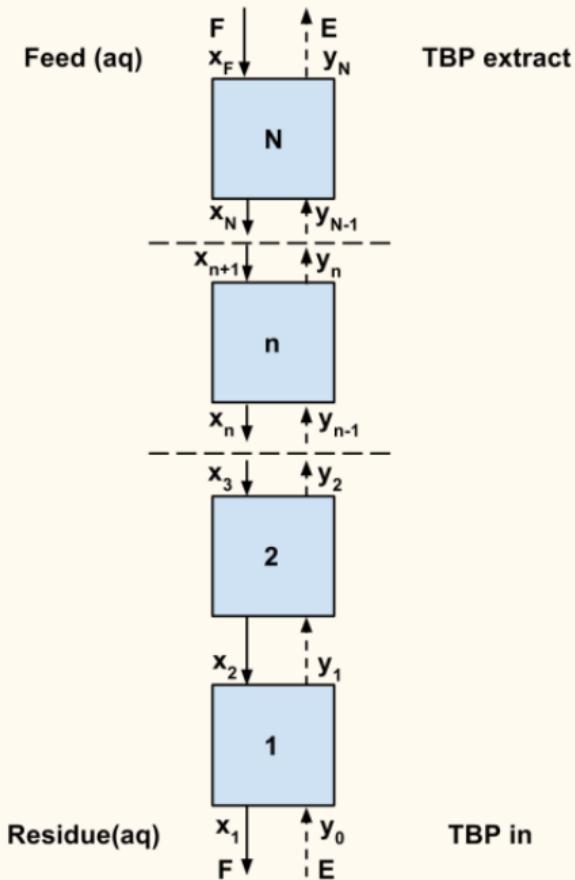
Solvent

Concentrations

$[H^+]_{aq}$







Now apply same mass conservation to multistage extraction

Assume equilibrium between phases

Material balance on extractable component below stage n –

$$Ey_0 + Fx_n = Ey_{n-1} + Fx_1 \quad (19)$$

$$y_{n-1} - y_0 = \frac{F}{E}(x_n - x_1) \quad (20)$$

∴ for any stage –

$$y_n \equiv D_n x_n \quad (21)$$

McCabe-Thiele diagram can be used for constructing graphical solution for stage concentrations

Basically gives the number of stages for an extraction concentration x_F

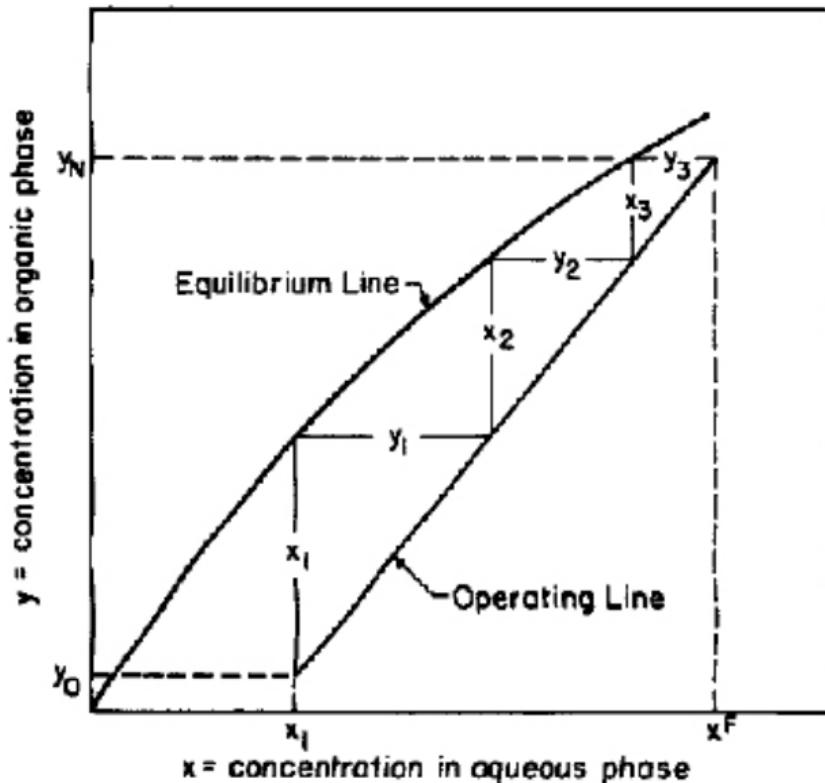
By graphing $y_{n-1} - y_0 = \frac{F}{E}(x_n - x_1)$ on y versus x

Construct operating line to satisfy the above and pass through x_1, y_0 with slope $\frac{F}{E}$ relative to equilibrium line $y_n = D_n x_n$

Cannot really change equilibrium line because it is based on D

Reduce the concentration of the extractable component from x_F to x_1 with $\frac{F}{E}$

Start at x_1, y_0 and move up



Derive the extraction factor for multiple stages

$$\rho \equiv \frac{Ey_N}{Fx_F} \quad (22)$$

Or –

$$1 - \rho = \frac{x_1}{x_F} \quad (23)$$

What does this tell us?

And feed ratio can be defined in terms of $f(\rho)$ as –

$$\frac{E}{F} = \frac{\rho x_F}{y_N - y_0} \quad (24)$$

**How many stages for complete extraction?
What does that look like on McCabe-Thiele?**

Apply these concepts to model multistage extraction based on Kremser equation

$$y_{n-1} - y_0 = \frac{F}{E}(x_n - x_1) \quad (25)$$

$$y_n \equiv D_n x_n \quad (26)$$

$$\beta \equiv \frac{DE}{F} \quad (27)$$

Then –

$$y_n = \beta(y_{n-1} - y_0) + Dx_1 \quad (28)$$

$$y_N = \frac{\beta^N - 1}{\beta - 1}(Dx_1 - y_0) + y_0 \quad (29)$$

This can also be applied if there are two extractable components in the feed

$$D_A \ D_B \ \beta_A \ \beta_B \quad (30)$$

Define decontamination factor. What does this mean?

$$f_{AB} \equiv \frac{\rho_A}{\rho_B} \quad (31)$$

$$f_{AB} = \frac{\beta_A}{\beta_B} \left(\frac{\beta_A^N - 1}{\beta_B^N - 1} \right) \left(\frac{\beta_B^{N+1} - 1}{\beta_A^{N+1} - 1} \right), \quad y_0 = 0 \quad (32)$$

Conversion & Enrichment

Uranium enrichment derived from World War II

Needed to make bombs

Then used the uranium for submarines

When moving to commercial power, infrastructure already in place

Gaseous diffusion first invented at Oak Ridge

Uranium hexafluoride used for enrichment

Yellowcake needs to be purified first

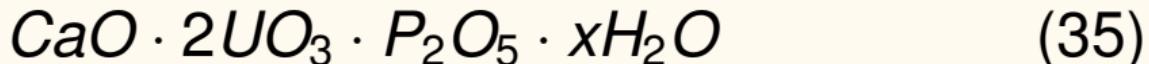
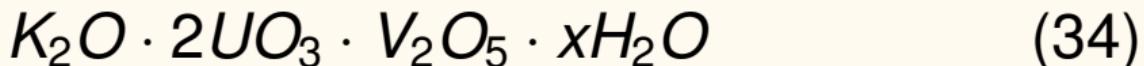
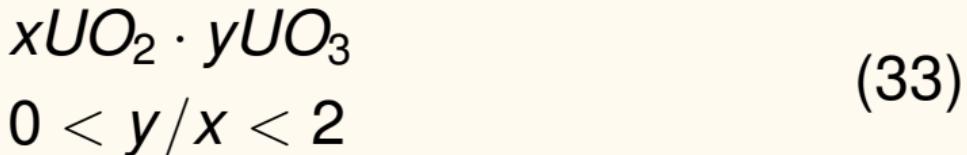
Impurities are rare earths, chlorine cadmium

Uranium readily forms chemical compounds (lots of oxidation states)

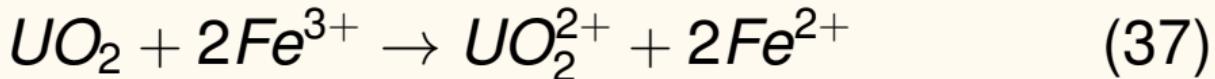
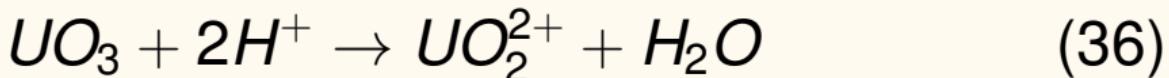
Can be extracted by organic solvents

Uranium forms complexes that can be precipitated out

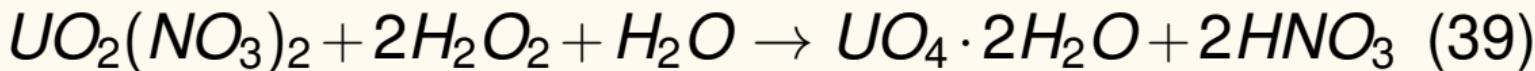
There are different forms that are mined



Goal is to get it as UO_3^{2+} and then acid or alkaline leaching



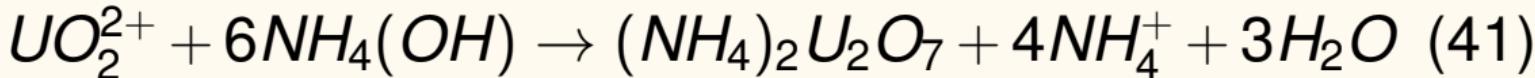
Acid leaching is like PUREX using organic solvent



Precipitates uranium peroxide



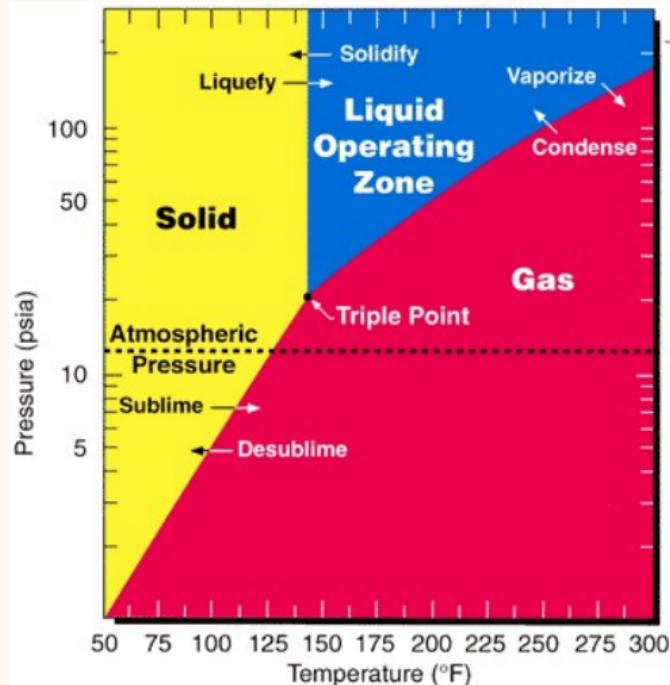
Or use ammonium hydroxide



Then dry and calcine to get UO_3

If alkaline leaching is used, recover U_3O_8

Uranium hexafluoride has favorable properties



Solid at room temperature

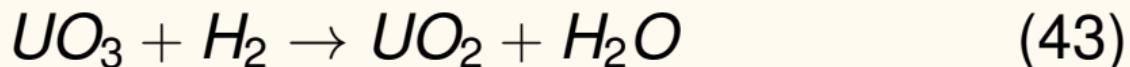
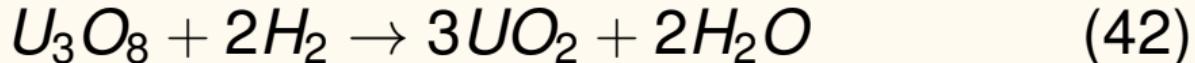
Easy to handle

Relatively low pressure

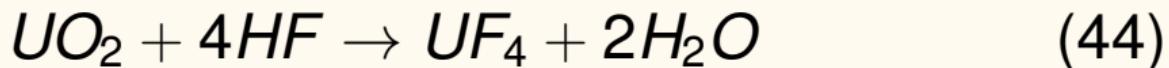
Not too high temperature to sublime

Conversion applies hydrofluor process

Crushed U_3O_8 and UO_3 is reduced by hydrogen to get 'crude' UO_2



Then –



UF_4 is a solid green salt with a high melting point ($1700^{\circ}F$)

Treated with fluorine gas and distilled –



Enrichment based on different diffusion rates

Separation factor –

$$\alpha \equiv \frac{v_5}{v_8} = \sqrt{\frac{m_8}{m_5}} \quad (46)$$

Based on kinetic energy of the molecule $kT = \frac{1}{2}mv^2$

This just says lighter molecules move faster

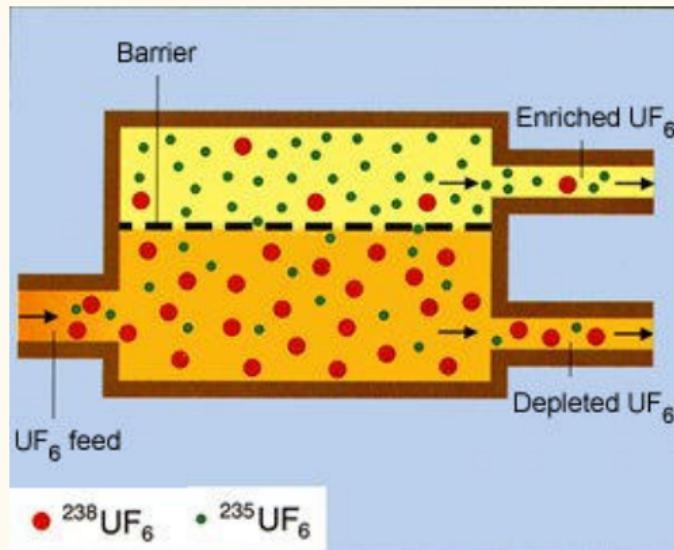
$\alpha = 1.004289$ for uranium enrichment

Higher value, easier enrichment

This isn't that high

Low enrichment takes a lot of energy

Cascades are designed to enrich



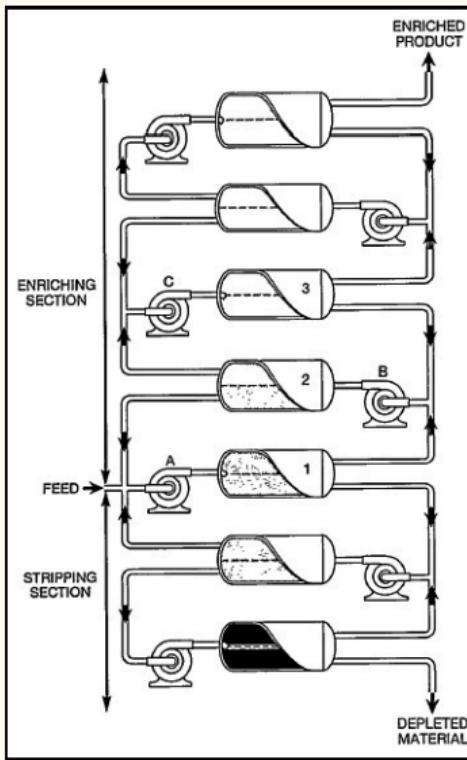
Basic operation is the stage

Join stages to form cells

Cells form unit

Together all that is a cascade

Enriching and stripping stages added for efficiency



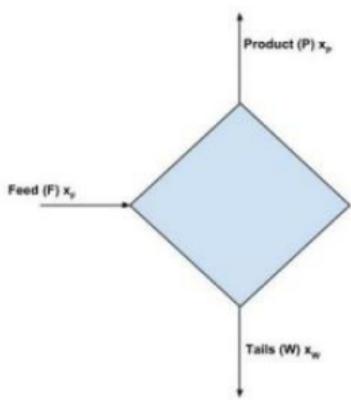
Feed enters to A-1

Enriched feed goes through B-2

Depleted through the bottom stage

Moving up is higher enrichment

Enrichment based on mass conservation



$$F = P + W \quad (47)$$

$$x_F F = x_P P + x_W W \quad (48)$$

Separation factor ratio between product and tails –

$$\alpha \equiv \frac{x_P(1 - x_P)^{-1}}{x_W(1 - x_W)^{-1}} \quad (49)$$

And mass flow

x_F = weight fraction ^{235}U feed into system

x_P = weight fraction ^{235}U product (enrichment target)

x_W = weight fraction ^{235}U waste stream (depleted U)

F = mass flow rate feed

P = mass flow rate product

W = mass flow rate waste stream

Derive feed factor

x_F fixed at 0.00711

x_P enrichment target

x_w 0.002 - 0.003 depends on company

Feed factor gives mass of U needed to feed into system for target enrichment –

$$\frac{F}{P} = \frac{x_P - x_W}{x_F - x_w} \quad (50)$$

Similarly waste factor –

$$\frac{W}{P} = \frac{x_P - x_F}{x_F - x_W} = \frac{F}{P} - 1 \quad (51)$$

How are tails managed?

Only one company enriches by gaseous diffusion

1992 – United States Enrichment Corporation established under Energy Policy Act

1998 – privatized with so you can buy stock

Operates plant in Paducah up to 5%

Enrichment also done by centrifuge

1970 – established with United Kingdom, Dutch, Germany

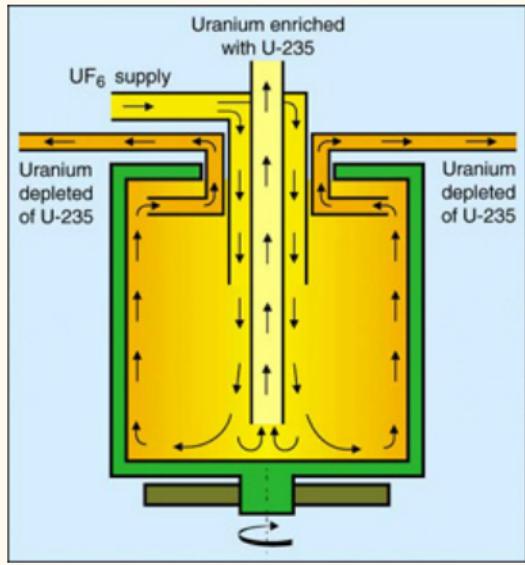
1977 – Construction of US plant in Ohio, but Reagan scrapped it in favor of laser

Rotating drum causes centrifugal force to compress gas molecules to the outer wall

Velocity of molecules separates differing those of differing weights

Light molecules collect near center of drum

Still based on conservation of mass



Lighter U^{235} molecules collect toward center

Rotational motion of the centrifuge accelerates gas molecules toward wall

Counteracting diffusive force thermal motion of molecules seeks to distribute the gas evenly

Two forces balance to create a dynamic equilibrium

Pressure distribution in the rotor that is function of the molecular mass

$$\alpha = \exp \frac{(m_8 - m_5)\omega^2 a^2}{2RT} \approx 1 + \frac{(m_8 - m_5)\omega^2 a^2}{2RT} \quad (52)$$

$$p(r) = p_0 \exp \frac{m\omega^2 r^2}{2RT} \quad (53)$$

Design based on separative power

$$SWU = \frac{\pi \rho D L}{2} \left(\frac{\Delta m \omega^2}{2 R T} \right)^2 \quad (54)$$

density of uranium hexafluoride; isotope self-diffusion; mass difference; length of rotor

Proportional to length and 4th power of speed

Inverse to temperature squared

What does this say about how to design the centrifuge?

It's actually small SWU per centrifuge, so up to 100,000 needed for 9 million SWU/y

That would be needed for industrial scale

There are only 3 companies in the USA interested in centrifuges

USEC Inc. (USEC)

Louisiana Energy Services (LES)

AREVA Enrichment Services (AES)

USEC submitted application to operate a commercial facility

American Centrifuge Plant (ACP) August 2004

NRC issued a license April 2007

Construction of the facility is currently on hold (did not get DOE grant)

Chapter 11 in 2014 – now called [Centrus Energy Corp](#)

Louisiana Energy Services activity

LES submitted license application NRC December 2003 for a 3 million SWU/year facility

One-third of the United States demand

Lea County, New Mexico

June 2006 – NRC issued LES a license to construct and operate

Began operations in June 2010 while continuing construction

Part of [URENCO](#)

July 2014 – All cascades operational

AREVA Enrichment Services (AES) activity

December 2008 – AES submitted a license application for Eagle Rock Enrichment Facility to NRC

18 miles west of Idaho Falls!

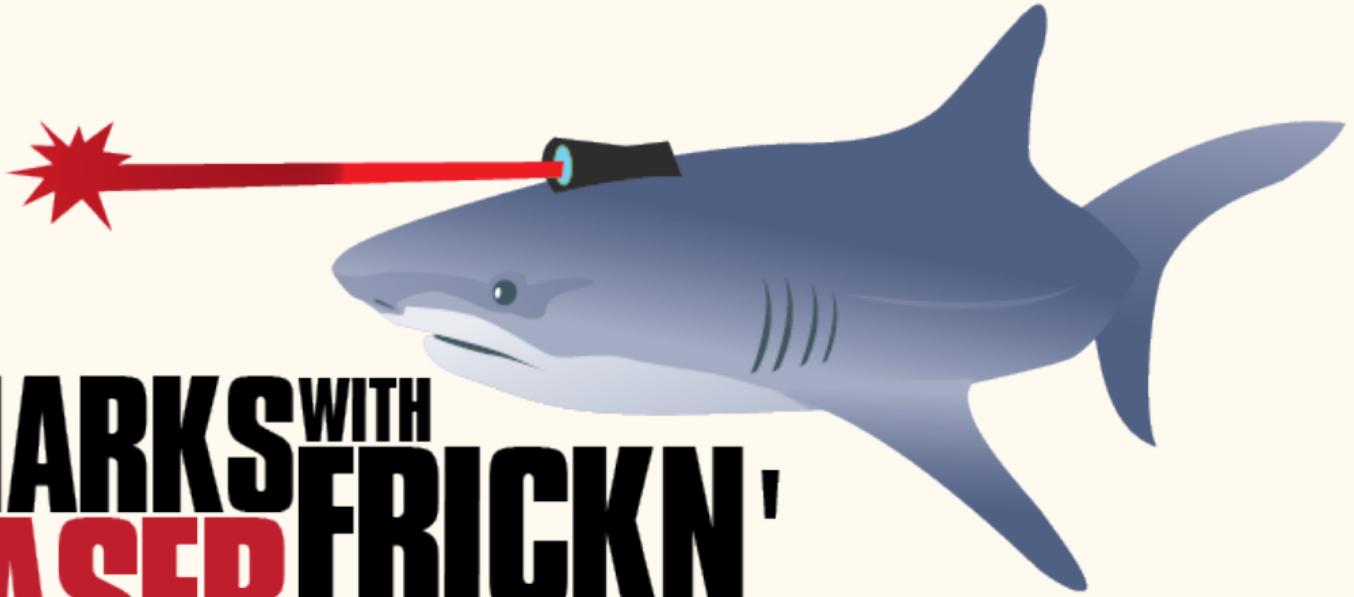
September 2010 – NRC issued the Safety Evaluation Report ([NUREG-1951](#))

February 2011 – Final Environmental Impact Statement ([NUREG-1945](#))

October 2011 – NRC issued AES license to construct and operate the [Eagle Rock Enrichment Facility](#)

[Construction currently inactive](#)

Lasers can be used for enrichment



**SHARKS WITH
LASER FRICKN'
BEAMS**

Is laser enrichment any good?

Started in 1985

Absorption spectrum of uranium metal vapor

More than 300,000 lines at visible wavelengths

Sufficient displacement between lines

Selective excitation of ^{235}U based on laser wavelength

Requires liquid uranium at $2300^{\circ}C$

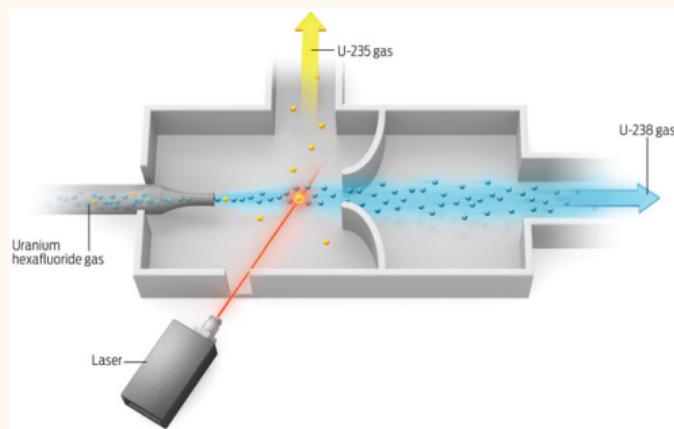
Laser at 5915 angstroms to excite ^{235}U

Ultraviolet light at 3100 angstroms ionizes ^{235}U

Then it is collected in a Faraday cup

Low throughput, high temperature, high energy

Current developments



GE got an [operating license](#)

Doesn't seem like much progress, limited testing with DU in Paducah

Different process than what we were just talking about though

Looking to construct in Wilmington



Molecular separation uses uranium hexafluoride

Uses different vibrational and rotational states between isotopes

Almost the same procedure

^{235}U molecule is dissociated and precipitates to a $^{235}UF_5$ powder

Need to reduce the vapor pressure to 77K



SILEX seems to be state of the art

Uses carbon dioxide laser at 10.8 um and amplified to 16 um

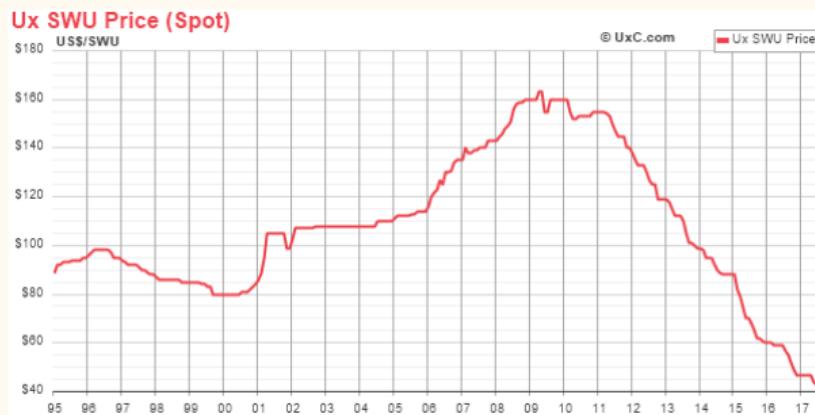
Infrared spectrum

Preferentially excites $^{235}UF_5$

Again trapped electromagnetically

Still inefficient due to laser frequency

Price used to be set by government



From Atomic Energy Act 1954

Prices then set by USEC based on market conditions

Used to be high because of high energy requirements of gaseous diffusion plants

What now?

World capacity is estimated at 60 million SWU

World enrichment capacity

US demand at 15 million SWU per year

Import a lot from Europe, Russia, China

What's the problem here?

