Enrichment of uranium and production of plutonium

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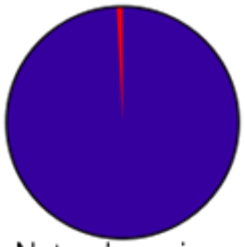
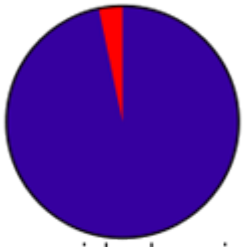
Levels of uranium enrichment

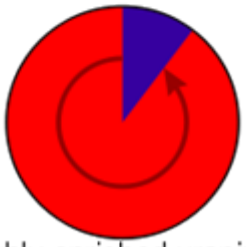
- **Natural uranium**: 0.72% ^{235}U
- **Low-enriched uranium**: < 20% 235U
  - Reactor grade: 3-4% ^{235}U
- **Highly-enriched uranium**: > 20% ^{235}U
  - Weapons grade: ~ > 90% ^{235}U



Natural uranium
> 99.2% U-238
0.72% U-235

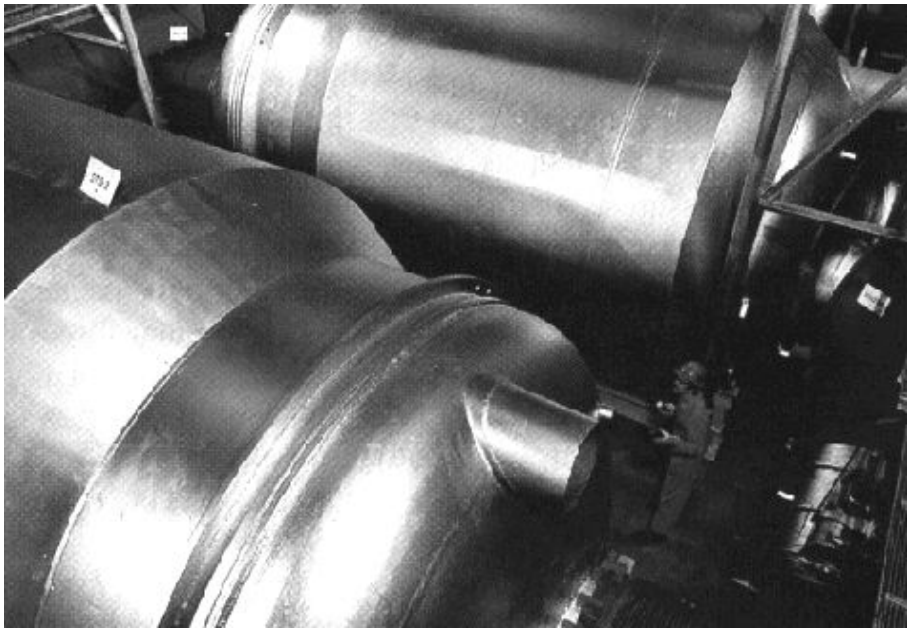


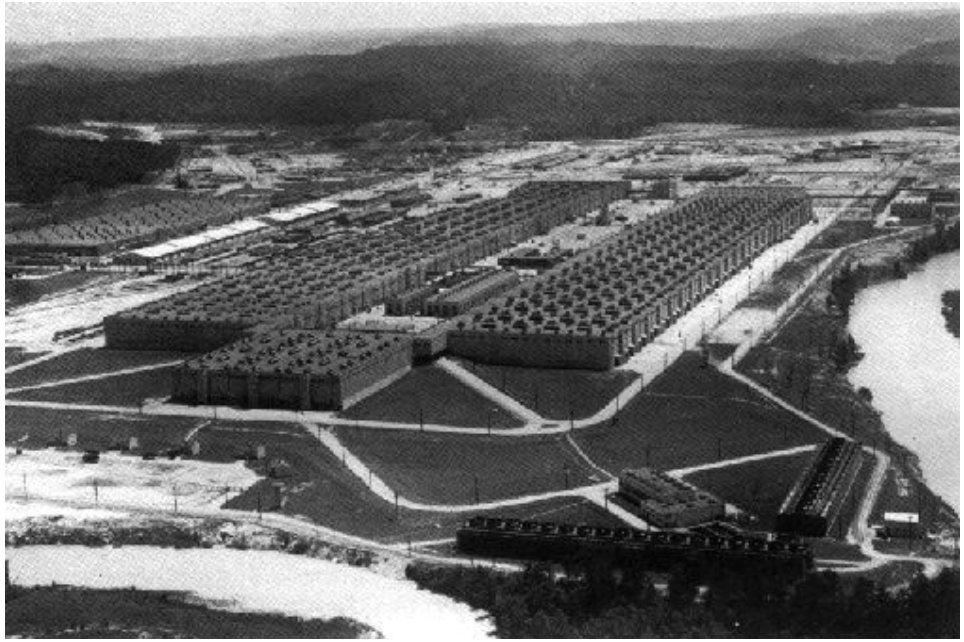
Low-enriched uranium
(reactor grade)
3-4% U-235



Highly enriched uranium
(weapons grade)
90% U-235

Commercial enrichment today: from gas diffusion to centrifuge enrichment

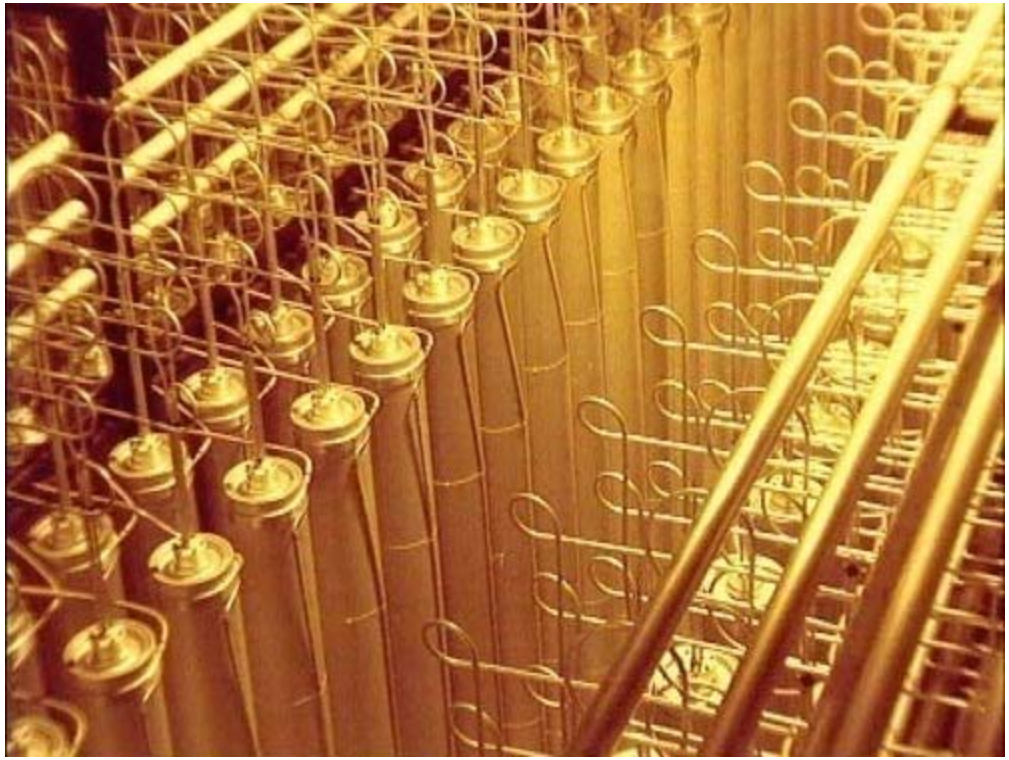




- Single stage of diffusion plant

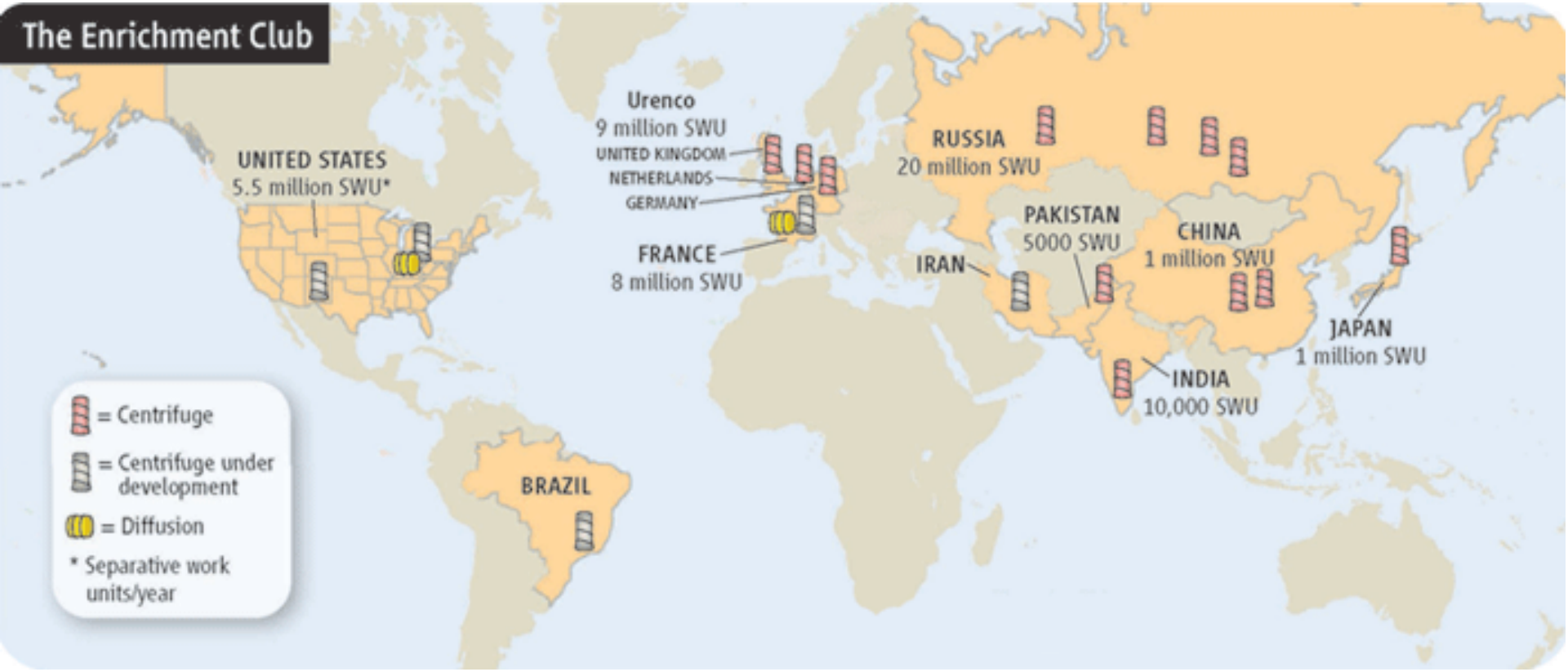
- Gas diffusion plant in Oak Ridge, TN

Commercial enrichment today: from gas diffusion to centrifuge enrichment



Urenco, Almelo (NL)

Uranium enrichment today



Science (2007), “Uranium enrichment: spinning a nuclear comeback”, D. Charles

Comparison: centrifuge/gas diffusion

Separation factor

$$\alpha = \sqrt{\frac{m_2}{m_1}} = \sqrt{\frac{352}{349}} = 1.00429$$

$$m_1 = 235 + 6*19 = 349\ (^{235}UF_6)$$
$$m_2 = 238 + 6*19 = 352\ (^{238}UF_6)$$

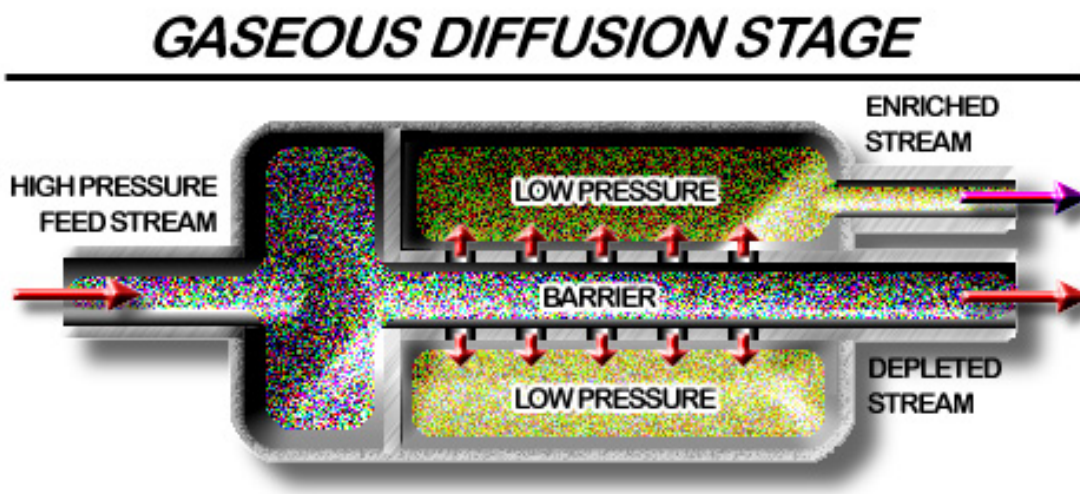
$$\frac{1}{2} m_1 v_1^2 = \frac{1}{2} m_2 v_2^2 \qquad \frac{v_1}{v_2} = \sqrt{\frac{m_2}{m_1}}$$

Separation factor (1.3 to 1.6)

- Proportional to peripheral velocity squared V^2
- Proportional to rotor length L
- Inversely proportional to temperature T

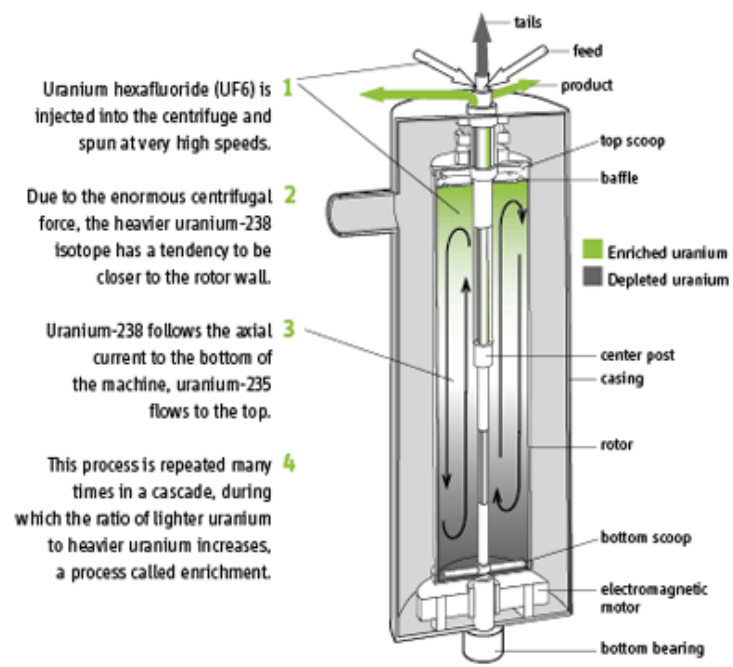
Each stage increases enrichment by at least 20%

Need tens of stages to produce LEU



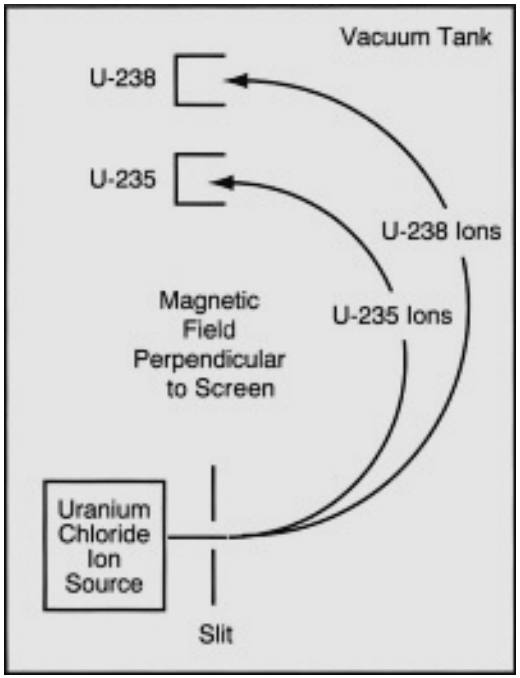
Each stage increases enrichment by less than 1%

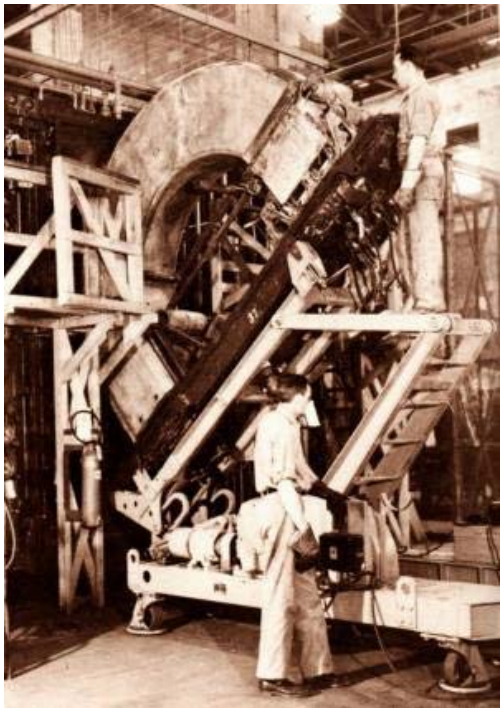
Need 100s stages to produce LEU



Other methods: Electromagnetic separation

- Calutron (Berkeley): Y-12 plant
- Iraq program: planning 140 calutrons



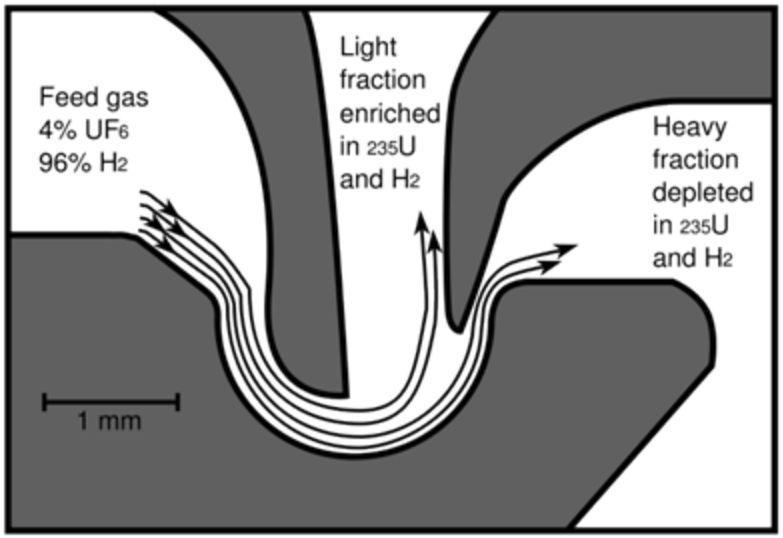


ABANDONED: Not competitive

Other methods: Aerodynamic enrichment

Aerodynamic enrichment – based on centrifugal force separation

- Nozzle separation
- Vortex separation



South Africa (vortex)

Separation factor = 1.015

ABANDONED: Not competitive

Other methods: laser separation

- Laser separation methods (3rd generation)
  - AVLIS
  - SILEX
    - Still not fully developed: harder to master compared to centrifuges
- Proliferation concern: easy to hide, potentially very economically competitive
- April 30, 2008 - "**GE Hitachi Nuclear Energy Selects Wilmington, N.C. as Site for Potential Commercial Uranium Enrichment Facility**"
  - **Global Laser Enrichment, subsidiary of GE Hitachi will develop Silex laser enrichment technology**

Comparison of technologies

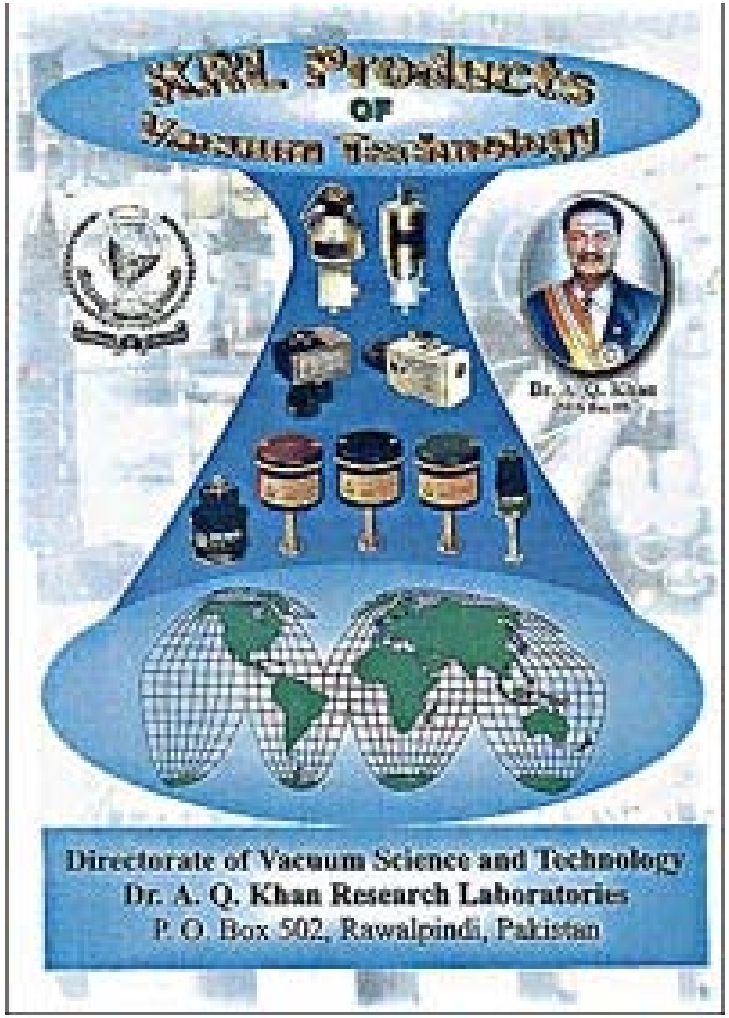
	Approx. Power Requirements (kWh/SWU)	
Method	Industrialized country	Developing country
Electromagnetic	2,500-7,500	25,000-75,000
Gas diffusion	2,000	3,000
Centrifuge	50-200	600
Laser (AVLIS)	100	600

	Degree of Difficulty		
Method	Obtaining parts	Technology	Concealment
Electromagnetic	Low	Moderate	High
Gas diffusion	High	High	High
Centrifuge	HIgh	High	Moderate
Laser (AVLIS)	High	Very high	Low

Ref: Mozley (1998)

Current focus: centrifuge enrichment

- A. Q. Khan network (started 1970s):
  - Technology spread Urenco technology to Iran, North Korea, and Libya



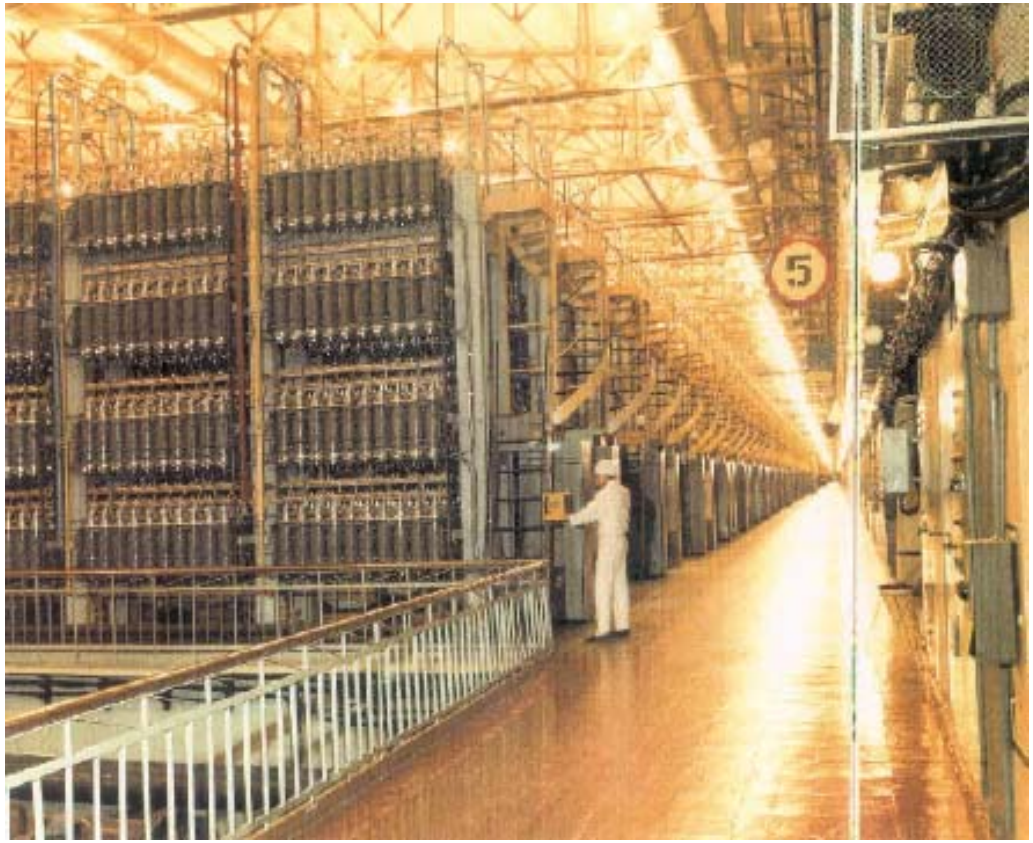
Centrifuge enrichment

The technology:

- Separative capacity. SWU units (kg SWU/year)
  - Tells us how many centrifuges we need in order to perform a certain job (feed, product, tails) in a certain time.
  - Efficiency of a plant measured in how many kWh electricity required to produce 1 kg SWU
- The enrichment process is highly non-linear. Most of the effort (2/3) consists of increasing enrichment from natural to 3-5% (fuel standard).
- Materials: aluminum, maraging steel, carbon fiber
- Peripheral speed: 350-1000 meters/second
- Diameter: 0.13 – 0.6 meters
- Length: 0.5 to 15 meters
- SWU: 1 to 400 kg SWU/year
  - P-1: 2 kg SWU/year
  - P-2: 5 kg SWU/year

Centrifuge enrichment

- About 130,000 kg SWU (130 MT SWU) are needed to produce the LEU fuel for a 1,000 MWe reactor for one year.
- The same enrichment capacity could produce enough weapon-grade uranium for 26 nuclear weapons per year (assuming 25 kg of 93%-enriched uranium per weapon).
- Natanz, 150-250,000 kgSWU/year (150-250 MT SWU/year), can fuel 1-2 nuclear power plants per year (approx.)



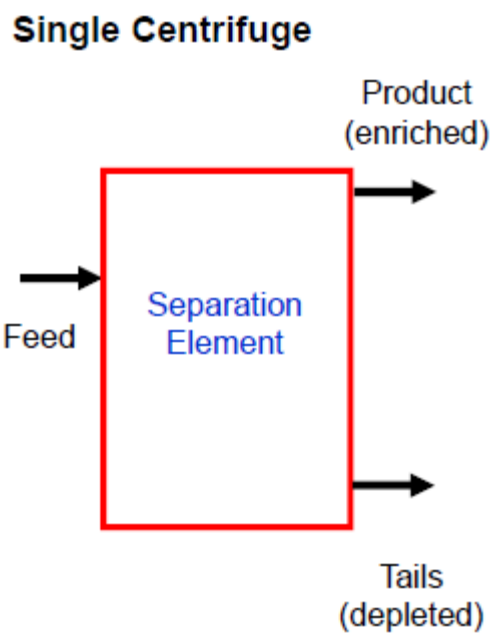
Subcritical, short centrifuges in Angarsk, Russia (1600 MT SWU/year = 12 power plants)

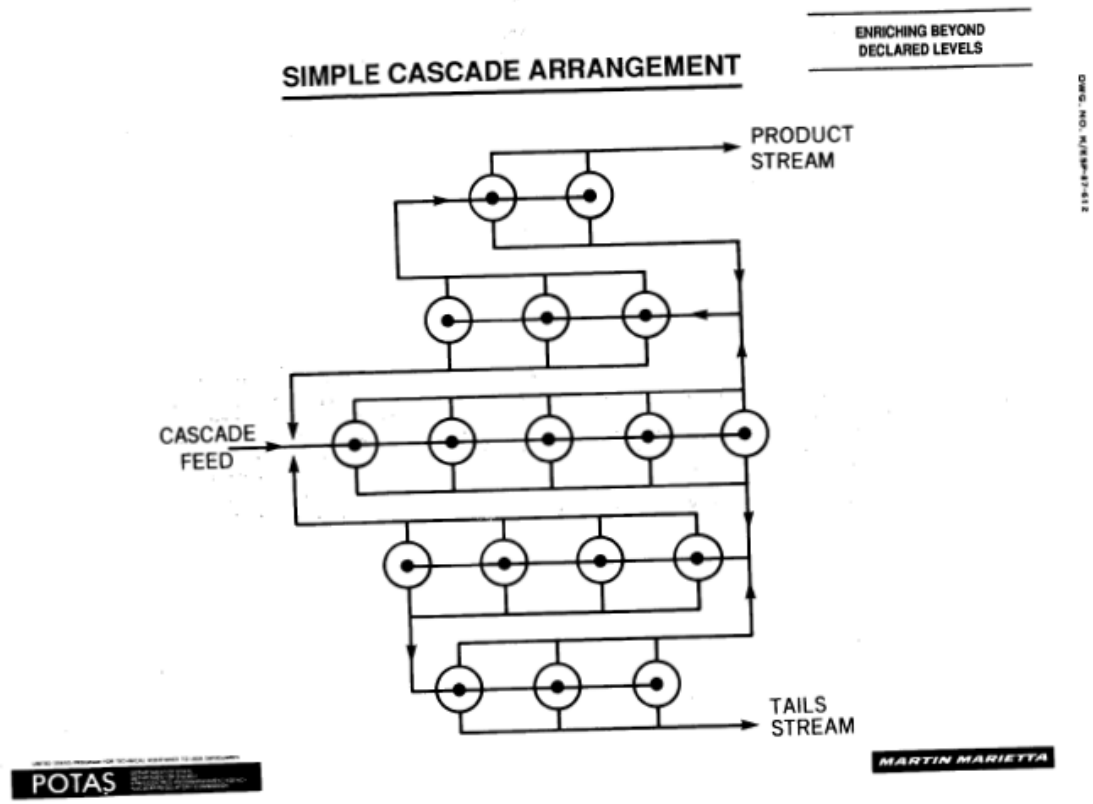
Cascade hall in Almelo (Urenco, NL), 3500 MT SWU/year = 27 nuclear power plants

US Centrifuge Plant (USEC)

3500 MTSWU/year = 27 nuclear power plants

Centrifuge arrangement: ideal cascade





$F = P + W$ (volumetric flow rates)

$Fz_F = Py_P + Wx_W$

$F/P = (y_P - x_W) / (z_F - x_W)$

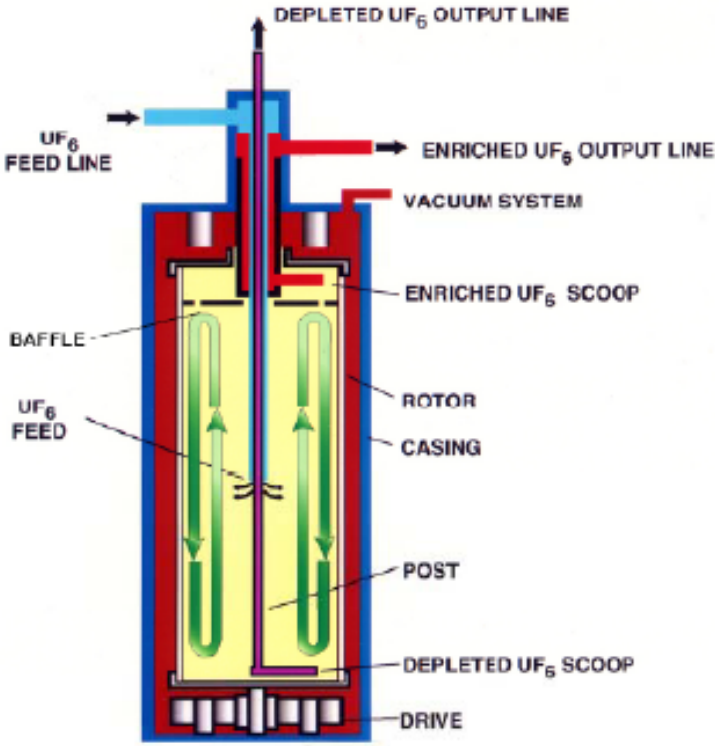
$W/P = (y_P - z_F) / (z_F - x_W)$

IDEAL CASCADE

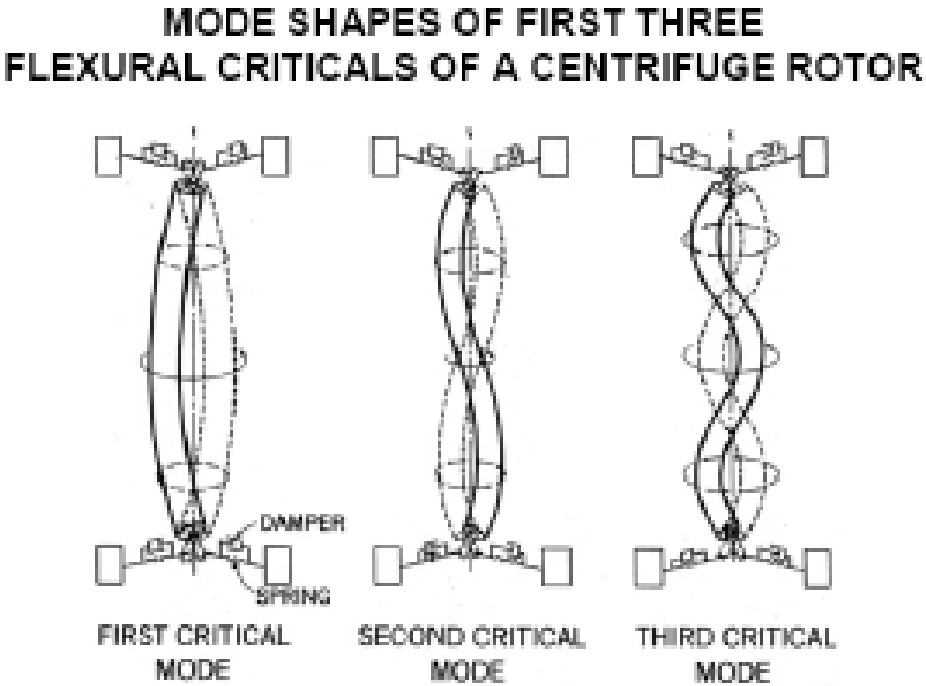
For a given stage i, the product from the previous stage, i-1, and the waste from the next higher stage, i+1, have the same composition, that is:

$y_{i-1} = x_{i+1} = z_i$

Technical challenges operating centrifuges



Schematic of Gas Centrifuge



Why centrifuges a proliferation concern?

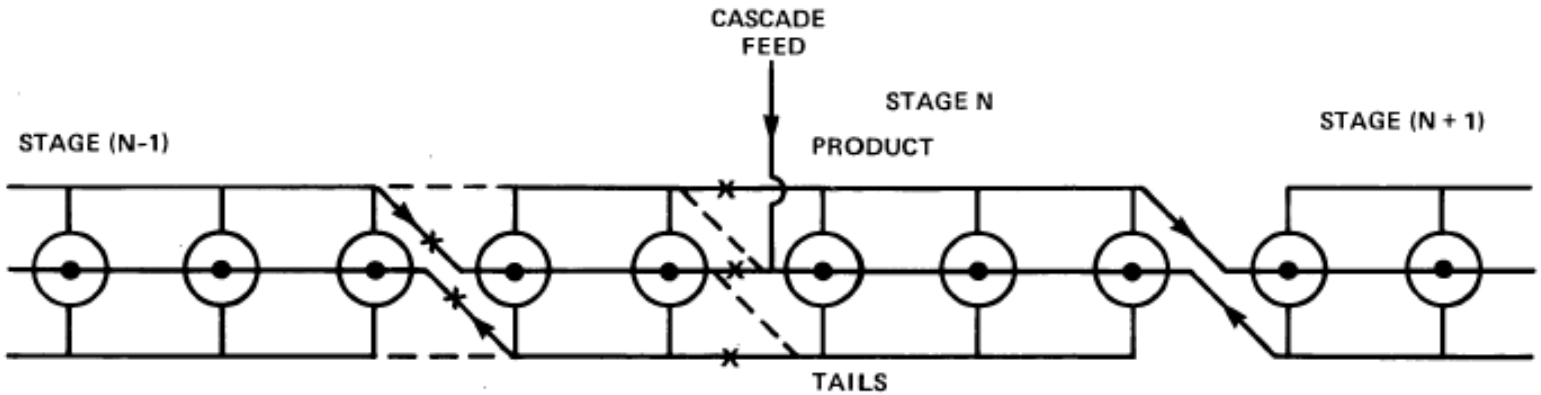
- High separation factor
- Small inventory
- Short equilibrium time

From LEU to HEU:

- Batch recycle
- Cascade reconfiguration

How many P2 (5 kg SWU/year) do you need to produce 100 kg/year of 90% enriched uranium (about four bombs worth) from 0.7% with a tails assay of 0.3%? You need 20,000 kg SWU/year. Since each centrifuge can perform 5 kg SWU/year at full capacity, 4000 centrifuges will be required, operating for one year.

CASCADE RECONFIGURATION TO INCREASE NUMBER OF STAGES



EXAMPLE SHOWN, "MOVES" TWO CENTRIFUGES FROM STAGE N TO STAGE (N-1)

- - - - - - NEW LINES ADDED

——— EXISTING LINES

—×— EXISTING LINE BLOCKED

Summary

- Proliferation concerns center around gas centrifuge and laser enrichment
- Even though centrifuge technology (materials, designs, etc.) can be very complex, states like Iran have been able to produce LEU using old Urenco technology
- Current estimates of time to breakout in Iran on the order of 1-2 years
- Need more timely detection and more intrusive safeguards

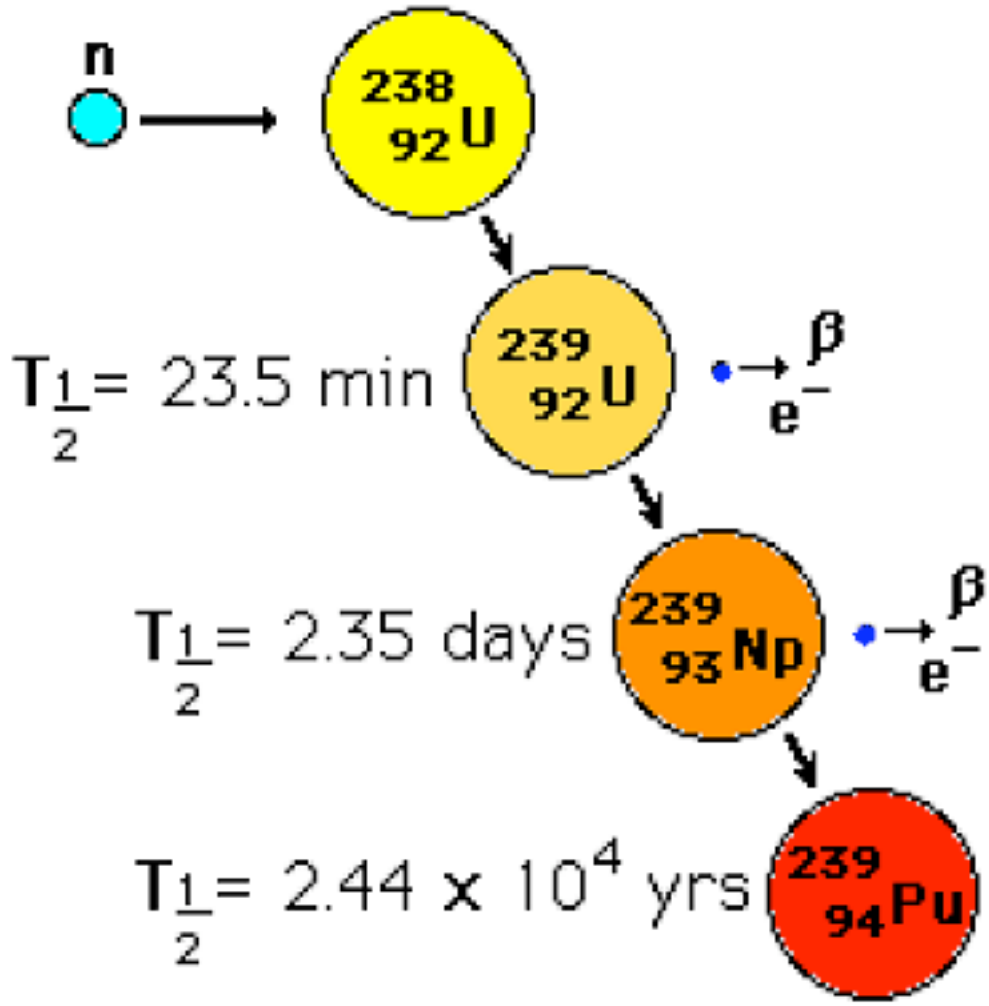
Plutonium Production

Periodic Table of the Elements

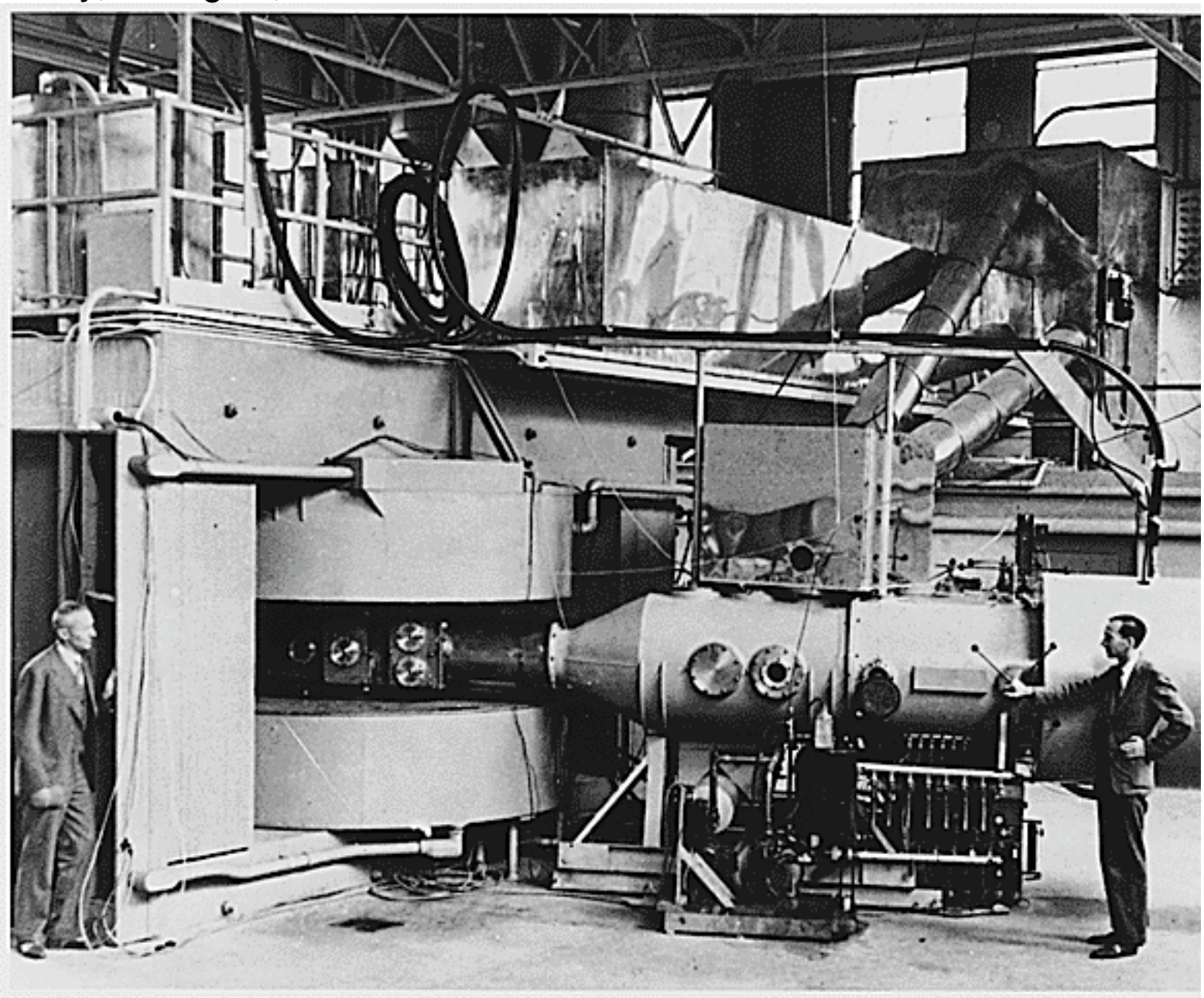
- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

1 H																	He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	1 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	1 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	3 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	5 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Ti	82 Pb	83 Bi	84 Po	85 At	8 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

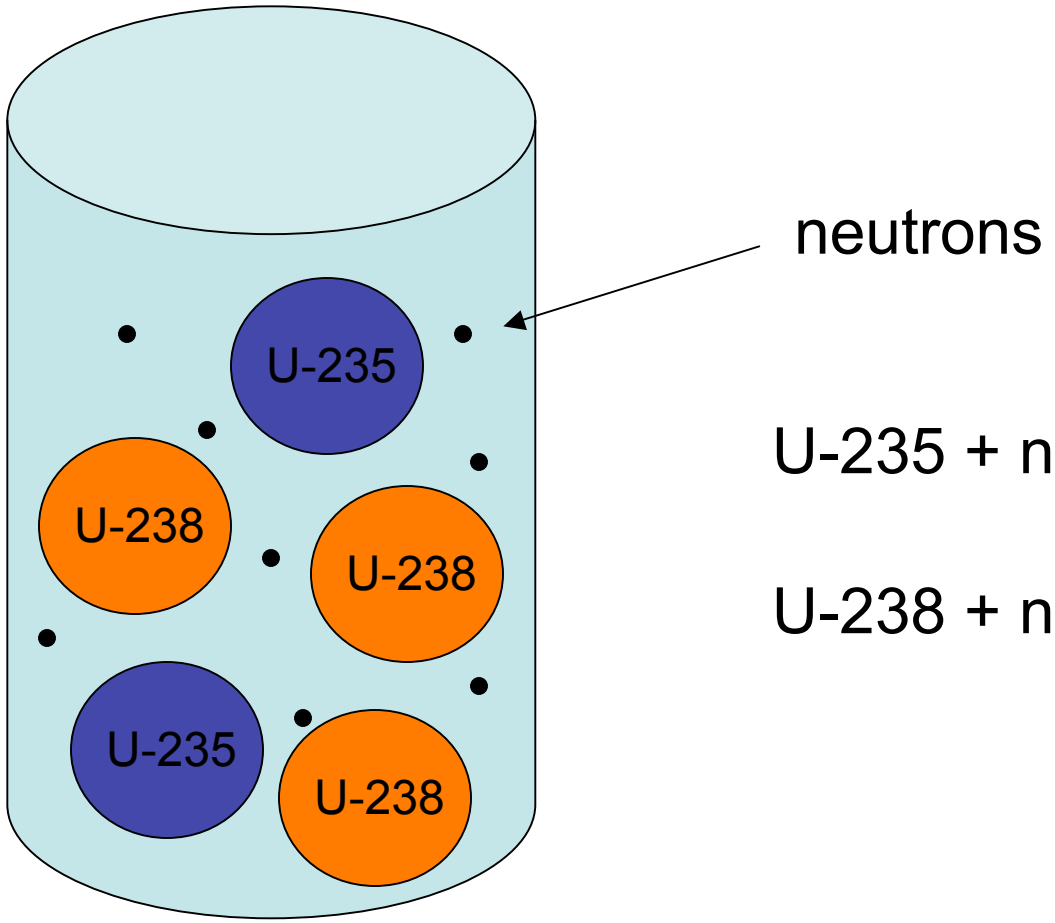
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr


n
238 92 U
T1/2 = 23.5 min
239 92 U
β
e−
T1/2 = 2.35 days
239 93 Np
β
e−
T1/2 = 2.44 x 10^4 yrs
239 94 Pu

60-inch cyclotron at the University of California Lawrence Radiation Laboratory, Berkeley, in August, 1939



Use reactor as neutron source



U-235 + n ⇒ fission + n

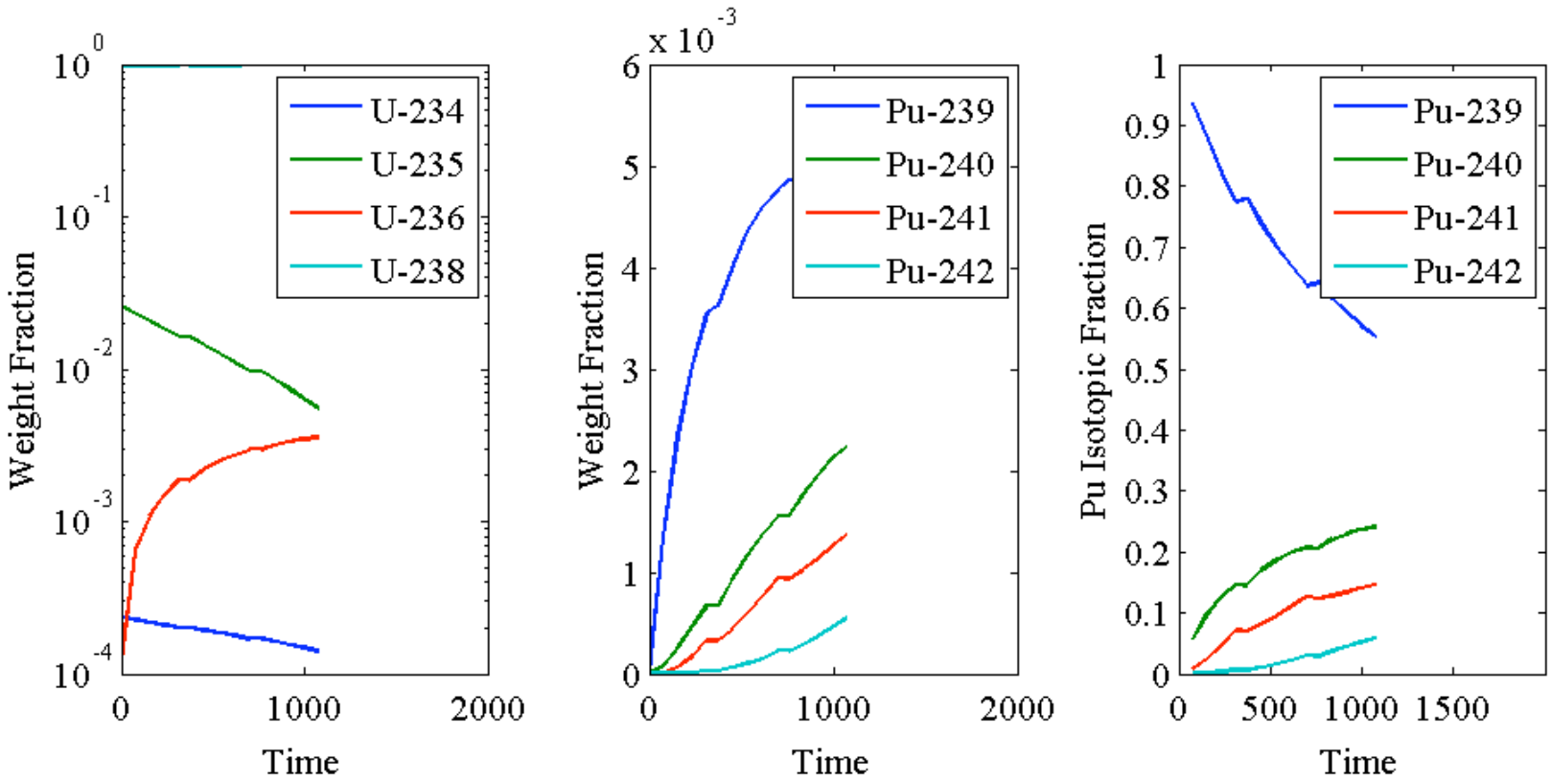
U-238 + n ⇒ Pu-239

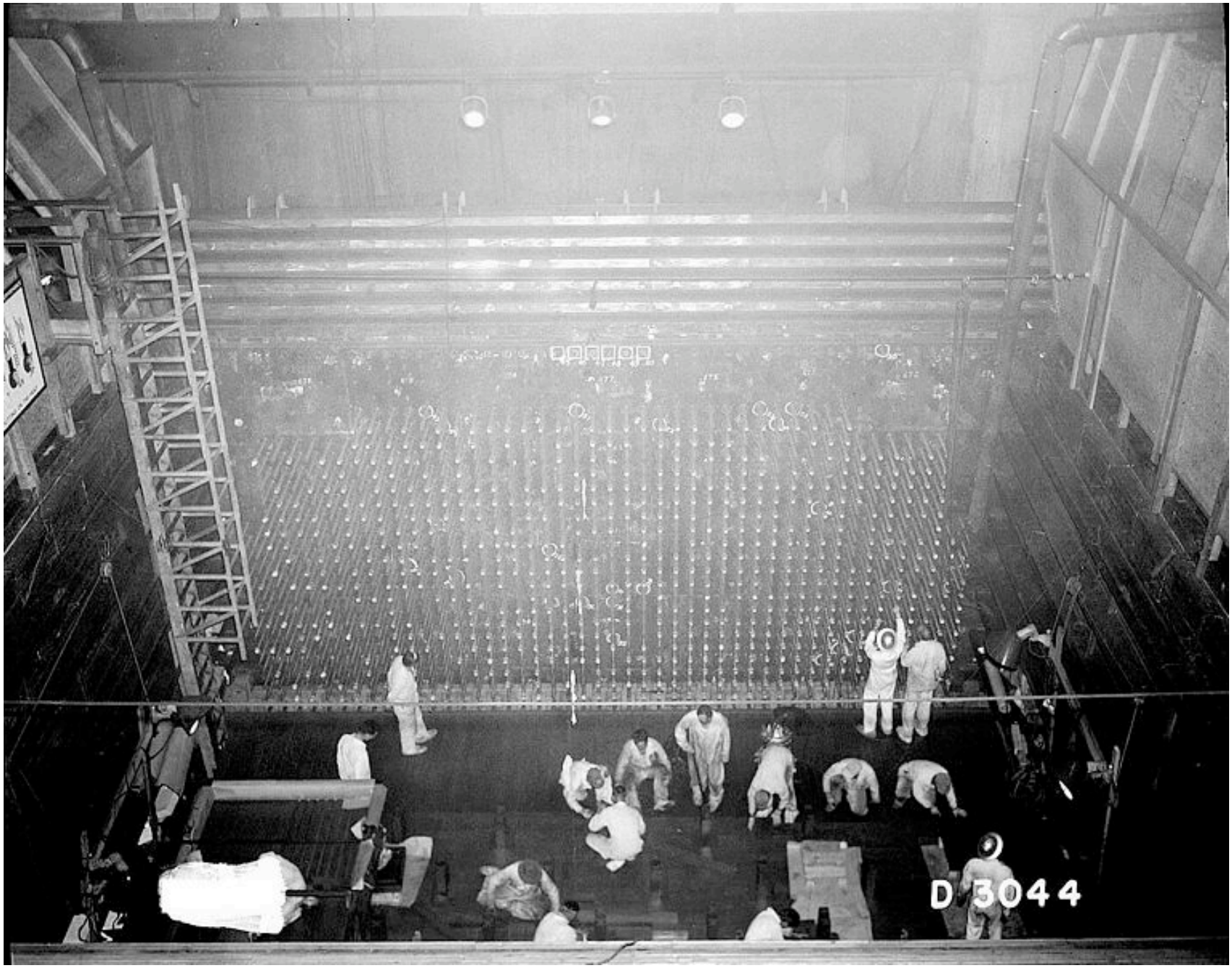
U-238 + n ⇒ Pu-239

Pu-239 + n ⇒ Pu-240

Pu-240 + n ⇒ Pu-241

Higher isotopes of Pu not as desirable for weapons ⇒ short exposure time




D 3044

Production reactors are different:

- not efficient for power generation.
- graphite/D2O moderator better than water

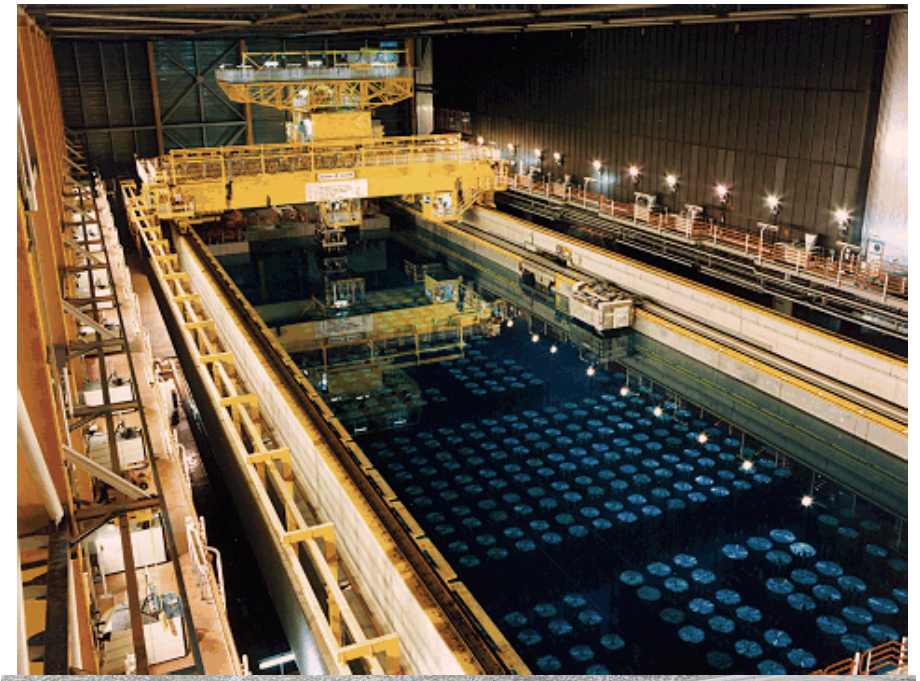
But Power Reactors produce Pu, too

- 1 MW(t)xday=1g Pu: 100MW(t) reactor produces bomb/2months
- 20T/yr worldwide
- targets/blankets
- UO2 instead of metal
- not “weapons grade”

Reprocessing

U/Pu in spent fuel mixed with FP-need to separate

- cool (~160 days) 4-6 ft of dense concrete shielding, 30 ft of water
- chop
- dissolve in HNO3
- Tri-butyl phosphate (TBP)+kerosene separate act/FP (common)
- pulse tube/mixer-settlers
- separate U-Pu
- form metal (less common) Pu is ready to use



Proliferation: how hard is this? Not hard.

Reactor:
- easier than power reactor
- CP-1 took 1 month construction
- scaling took 2 yrs
- graphite not hard to get
- BNL research reactor good model:
    - 30 MW, 60 T fuel, 700T graphite
    - 9 kg Pu/yr
    - 8 people, $20M, 3 yrs

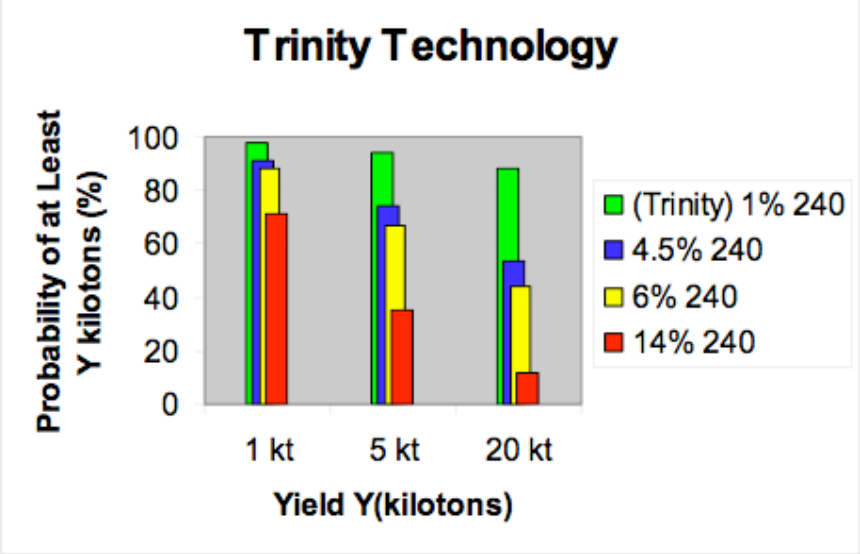
Reprocessing:
- OR study ‘76 gives easy design
- 4-6 months construction
- 10kg Pu in first week, then 5kg/day after
- quick, cheap, small

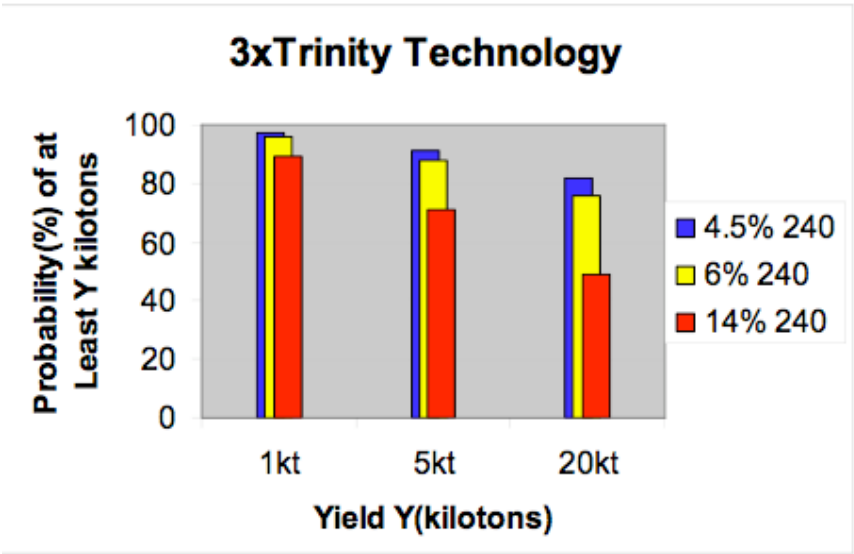
Underdeveloped country could build production complex in a few years, with nuclear industry it’s almost trivial.

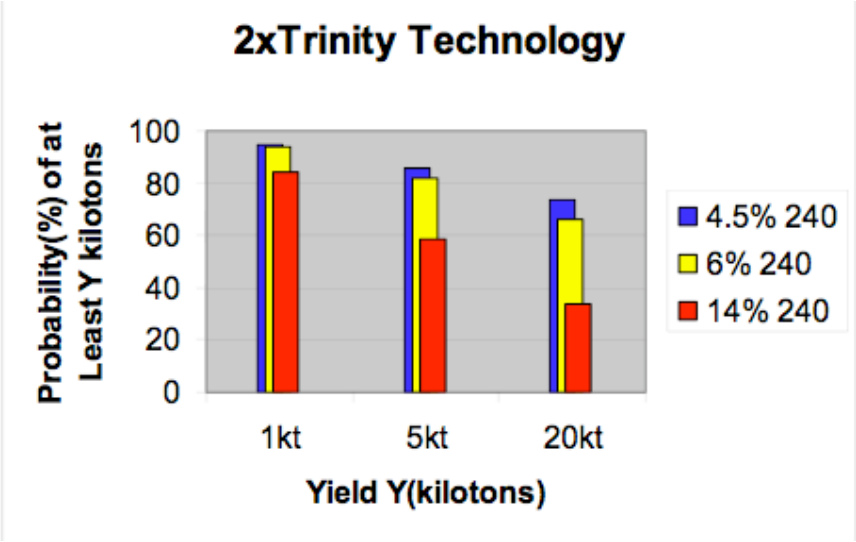
New complex would likely be detectable:

- Special materials
- Heat signature
- Venting

But you don’t even need special complex







Don’t need special Pu to make a bomb.

LWR:
•Reactors refuel ~1/3 of the core at a time
•VVER-1000 has ~71TU fuel, 330kg Pu at first cycle
•After first cycle, material is ~85% Pu-239

Or:
•Blankets/targets: osiraq->11kg/150 days (70MW)

D2O:
•Arak IR-40(MW) ~ 9kg/yr

Accelerator based transmutation: not pulled off commercially