Clean Nuclear Power
-
Part 1: Fuel Cycle

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Safety and Logistics

- **Please familiarize yourselves with the nearest exits**
- **In case of emergency, WALK, DO NOT RUN!**

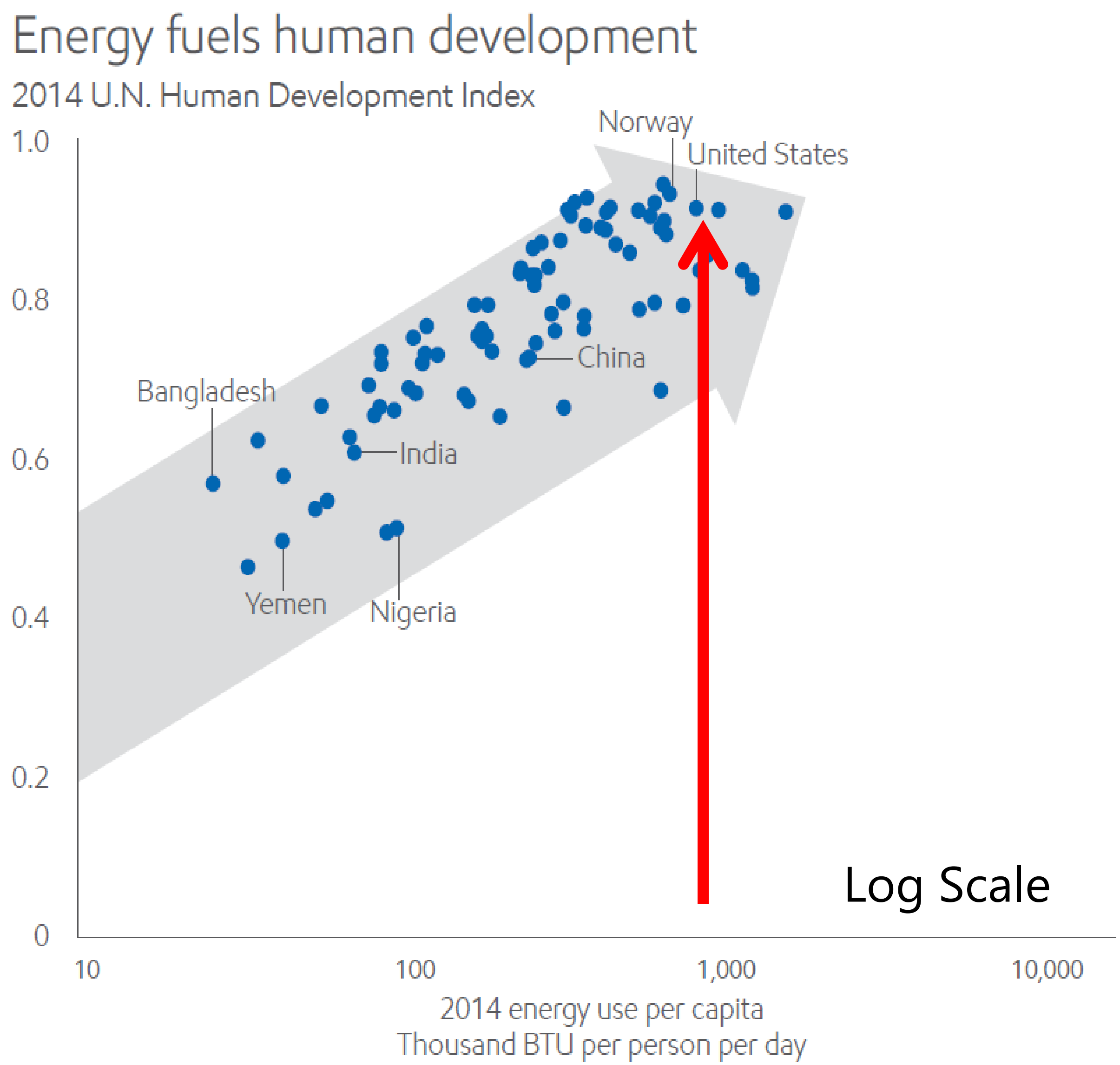
About the Speaker: Ara Barsamian

Godiva Zero Power Reactor

- **BS, MS (Engineering)**
- **Member AIChE, ASTM, ISA, ILTA**
- **Exxon Research & Engineering:**
  - **Mainly responsible for computerized fuels production world-wide:**
  - **Gasoline, Diesel, Bunker Fuel**
  - **Consultant to Jersey Nuclear on AVLIS and nuclear explosives for stimulation of depleted oil, fields**
- **3X Corporation: President, ABB Simcon: VP, Refinery Automation,**
- **RAI: blending consultant**

Why Nuclear Power?

High Standards of Living Require MORE ENERGY

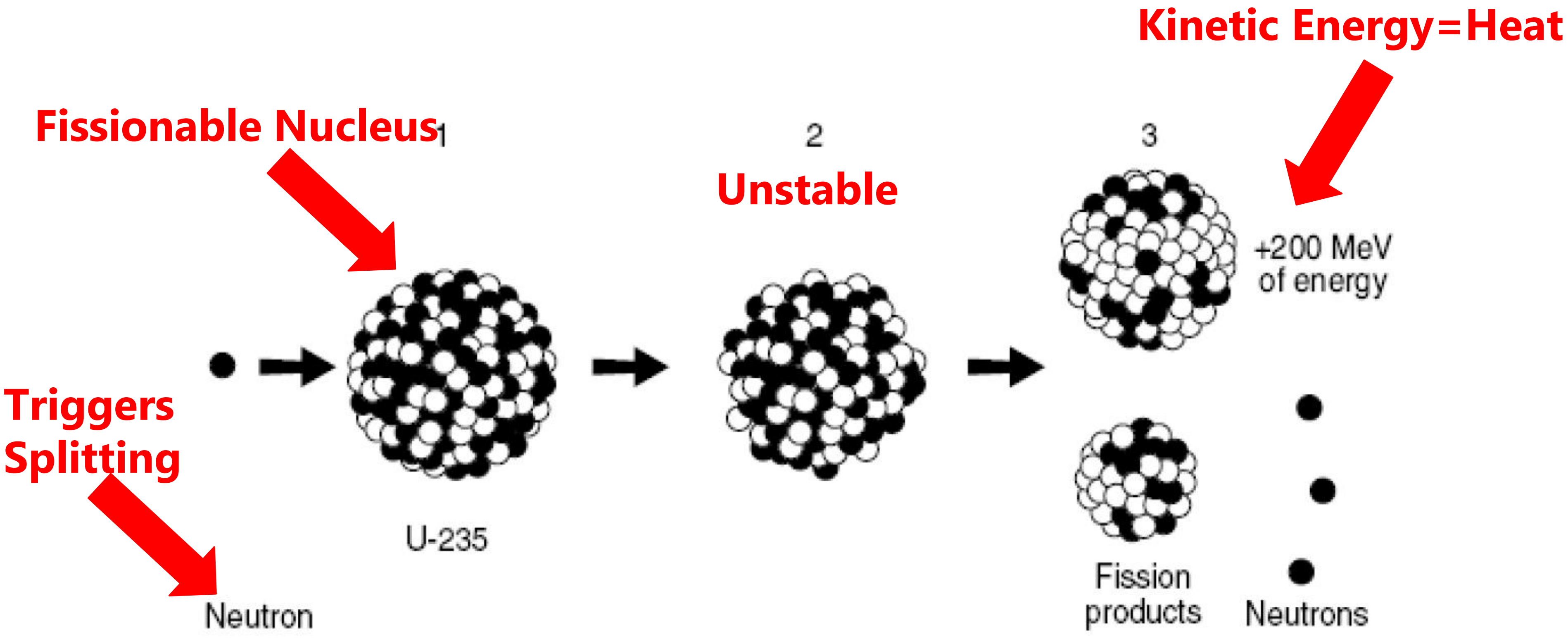


Why Nuclear Power?

- **Pro's**
  - **No GHG, SOX, NOX, VOC**
  - **Very cheap, predictable cost**
  - **Inexhaustible (for millenia)**
- **Con's**
  - **Politics, high construction costs (US, EU), disposition of waste**

Basis of Nuclear Energy

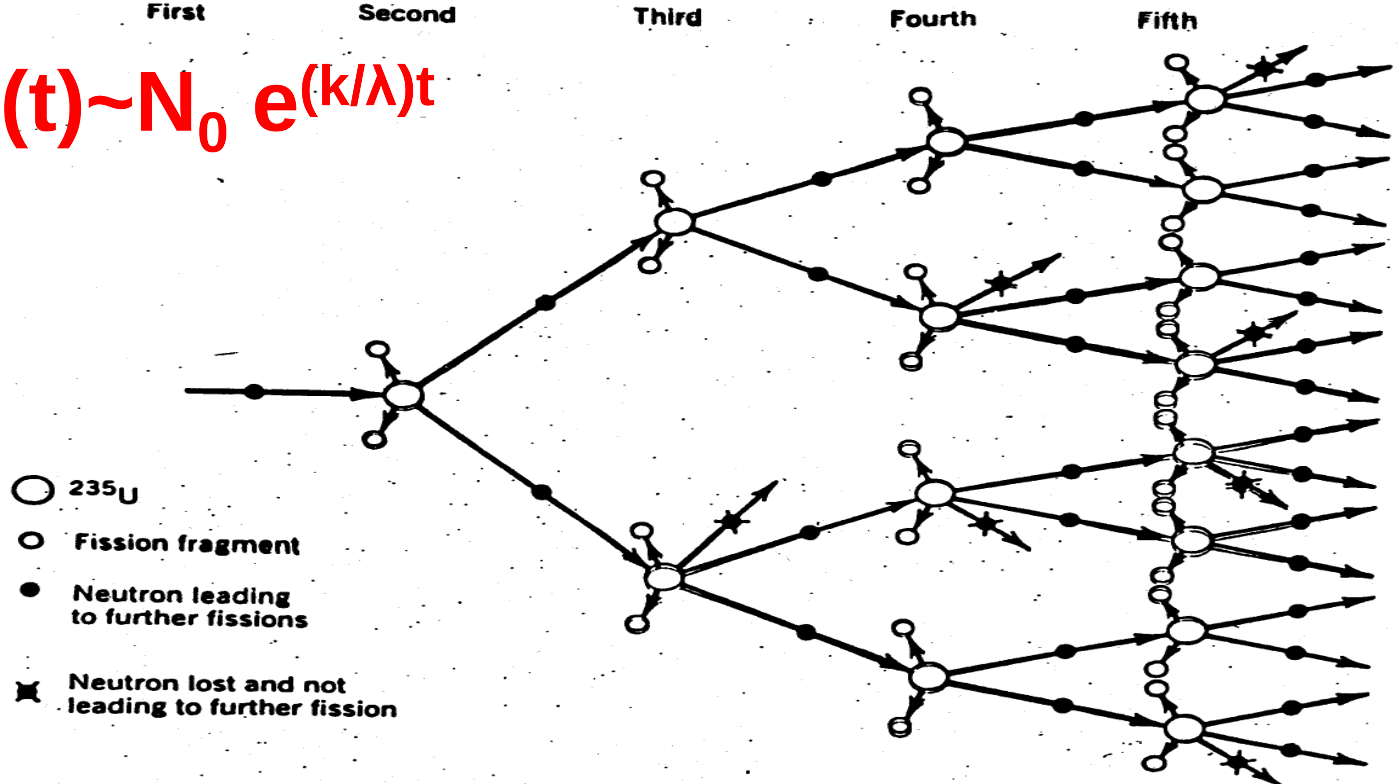
- **Splitting Atoms=Unbalanced Binding Energy=Mass Defect=Energy=mc^2**



Basis of Nuclear Energy

- **Fission results in 2 or more neutrons, which in turn cause more fissions, making possible an exponential (divergent) chain reaction, releasing more and more (kinetic) energy**

$$N(t) \sim N_0\, e^{(k/\lambda)t}$$



Chain Reaction Needs a Critical Mass

A self-sustaining sequence of fissions needs a minimum mass for the initial neutrons to create new fissions: depends on speed of neutrons, shape of mass, type of fissile material

$$N(t)=\sim N_0\ e^{(k/\lambda)t}$$

Λ=mean n-gen time

k>1: supercritical
k=0: critical
k<0: subcritical

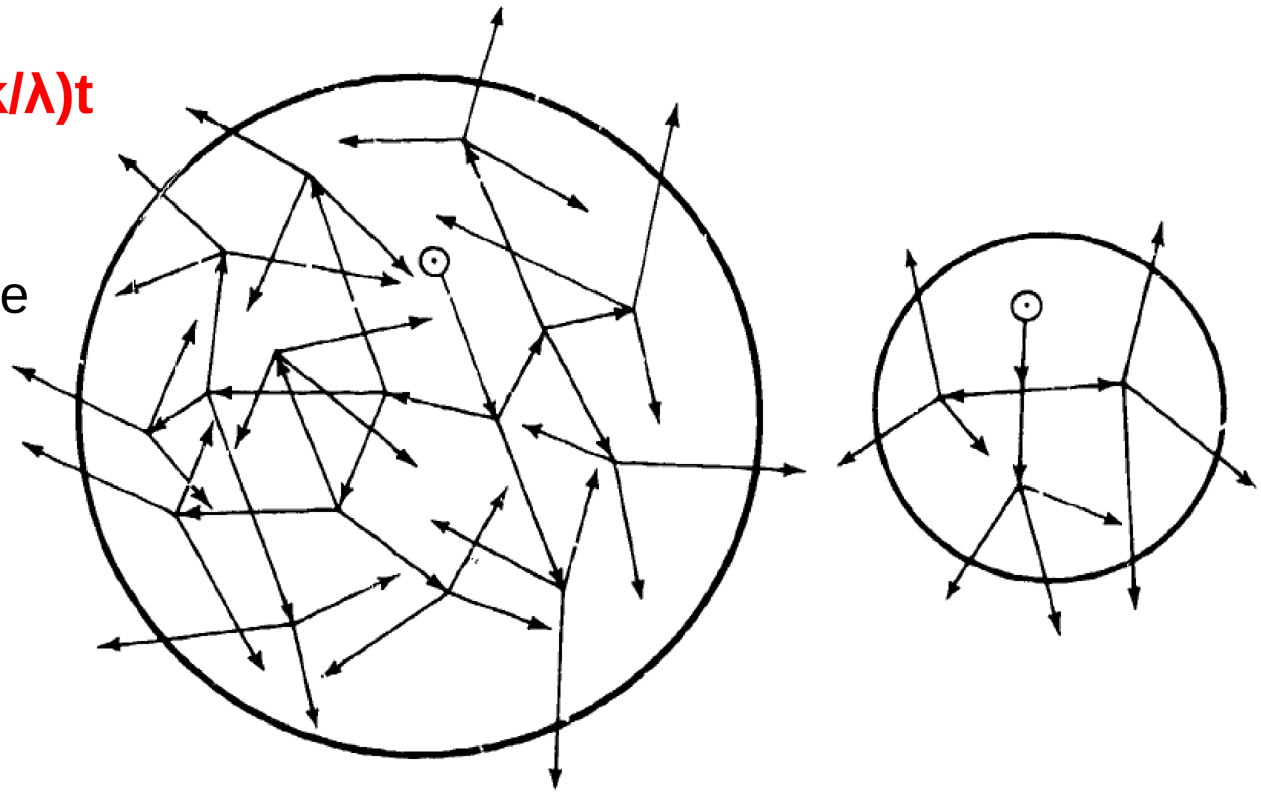


Figure 1.48. Effect of increased mass of fissionable material in reducing the proportion of

Nuclear Fission Basics

- **Fission process (by neutrons) needs fissionable materials**
  - **Typically ACTINIDES (U, Th, Pu)**
- **Classes of Actinides**
  - **Fissionable (only by hi speed neutrons)**
  - **Fissile (by neutrons of all energies)**

Nuclear Fission Basics

- **Best Material has high fission cross-section (ease of splitting)**
  - **Typically U235, and Pu239**
  - **U238 (common isotope) needs high energy (fast) neutrons; hence not good for power reactors**
- **U235 is only 0.7% of natural Uranium (U238), hence need for enrichment in isotope 235**

Nuclear Fission Basics

- **Can we use natural Uranium (99% U238, 0.7% U235), for power reactors?**
  - **Yes, if we use "moderators" to slow down fission neutrons so they can fission the tiny amount of U235 (0.7%) in the natural Uranium**
  - **Original reactors (Fermi's Pile) and Hanford Plutonium reactors did just that**
    - **Used graphite as moderators**
  - **Disadvantage: they are huge, and have poor efficiency**

Nuclear Fission Basics

- **Light Water Reactor (LWR) more efficient than moderated reactors**
  - **Do not use moderator like Graphite or Heavy Water to slow down neutrons**
  - **fuel is natural Uranium (U238), enriched to ~5% U235**
  - **Advantage:**
    - **they are smaller, and have good efficiency**
    - **Produce less Plutonium for weapons**

Nuclear Fuel Cycle

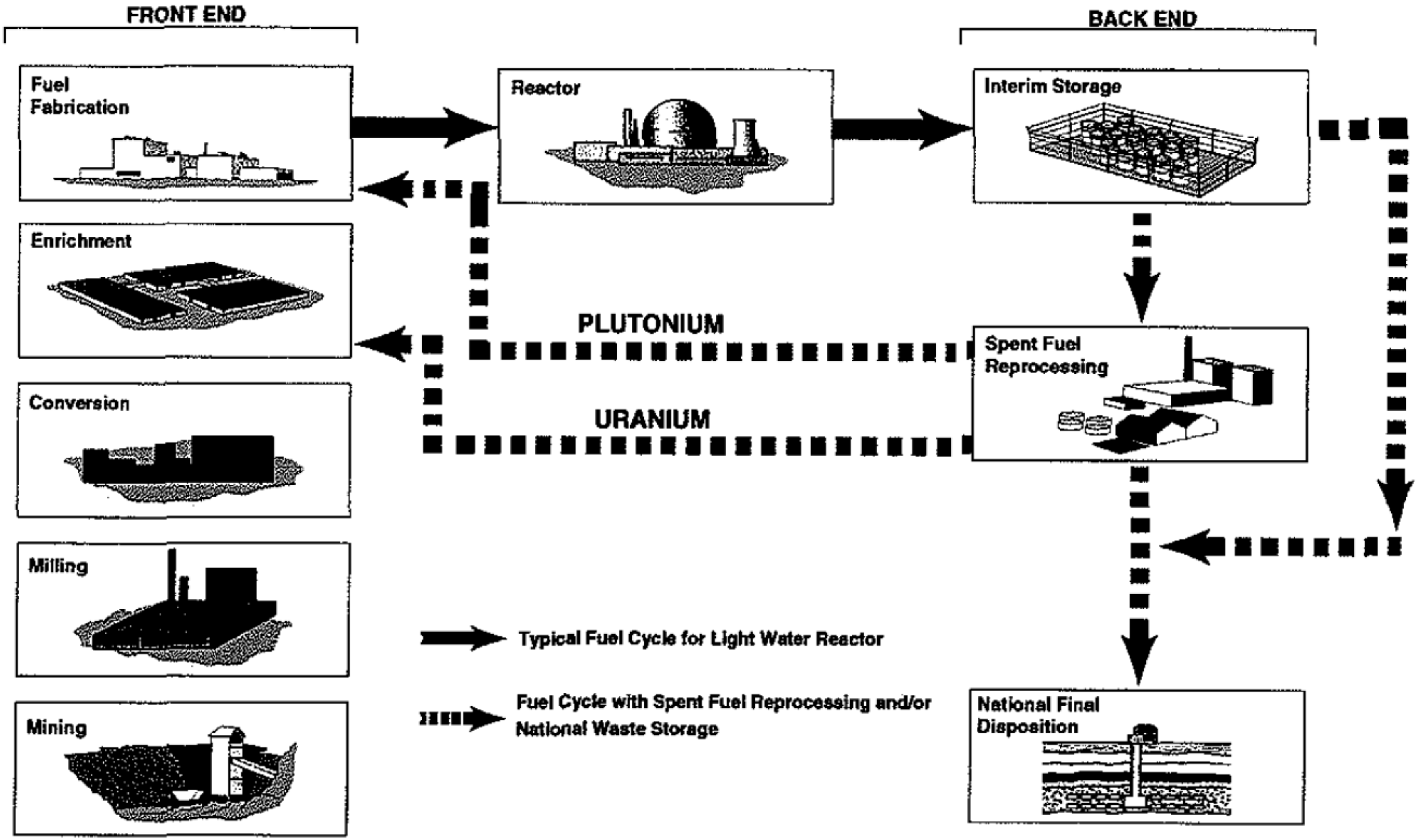
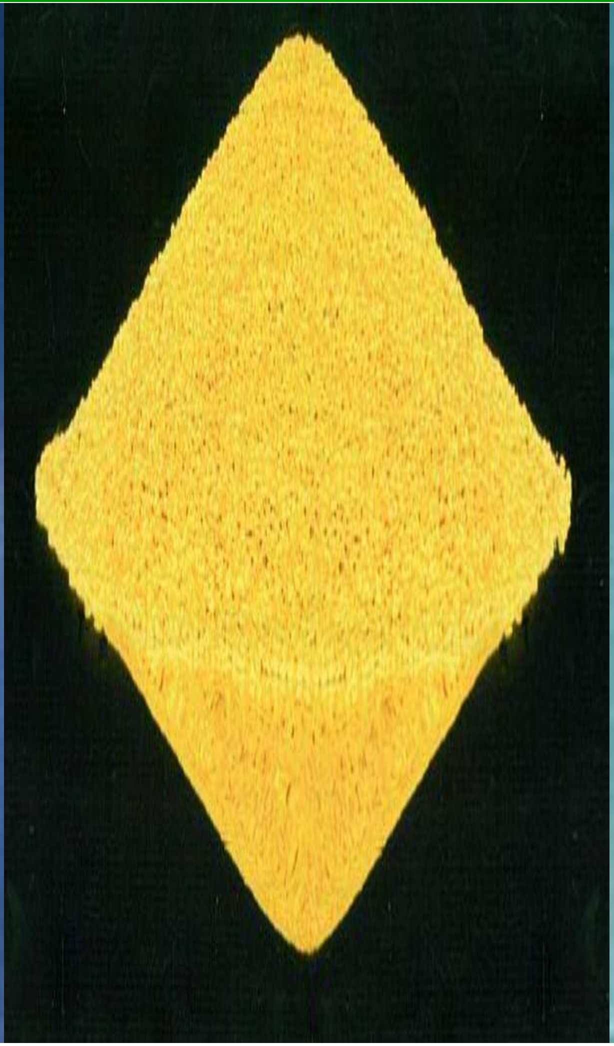


Fig. 1. The nuclear fuel cycle.

Ore to Yellowcake to UF6 Gas



Ore: Pitchblende

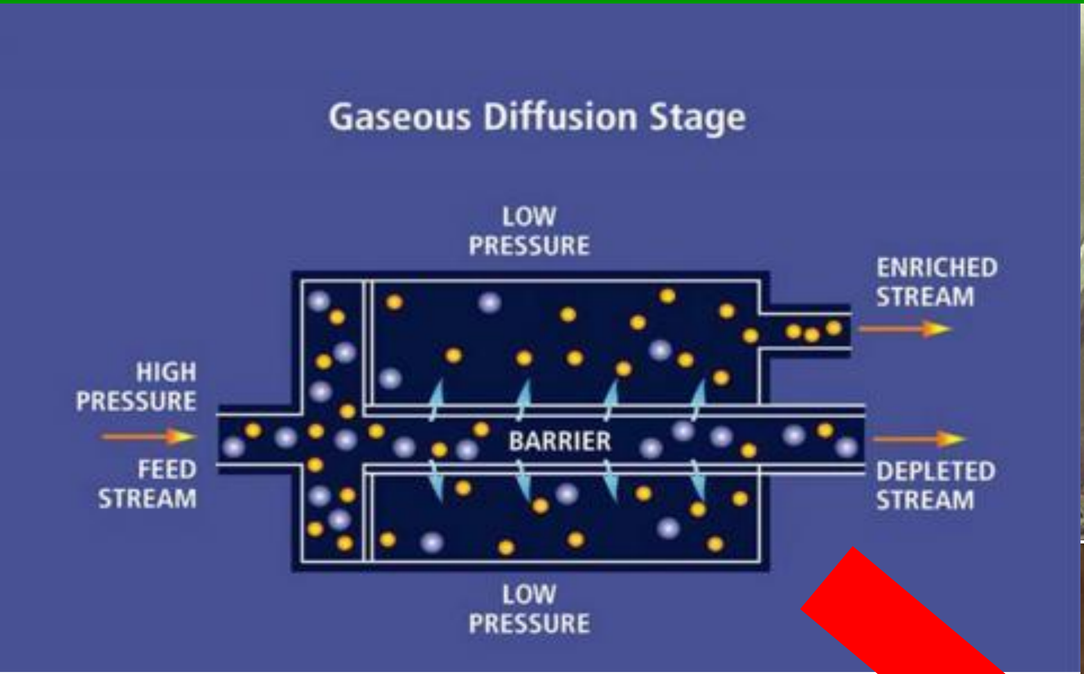
Yellowcake: U3O8

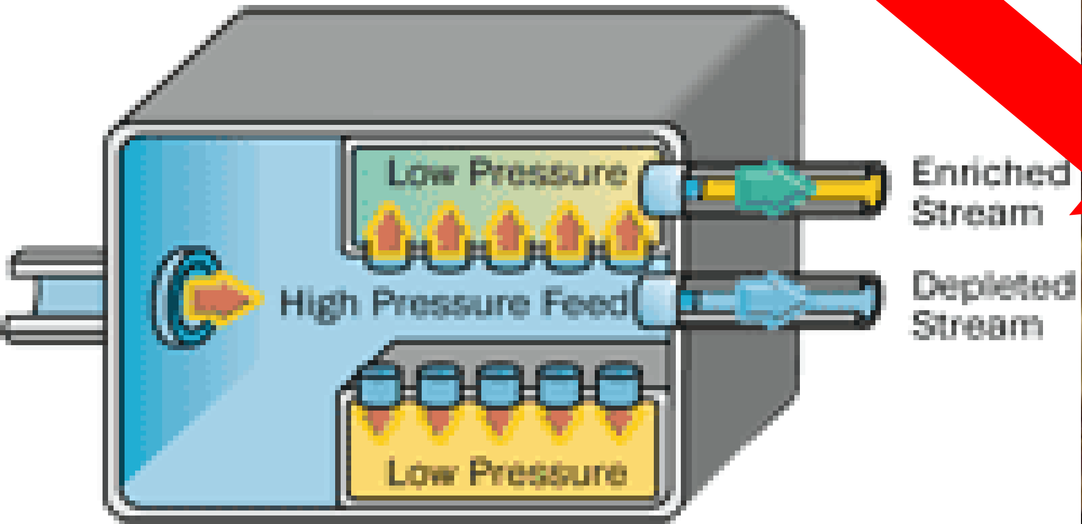
UF6 Gas

Enrichment Methods for U235

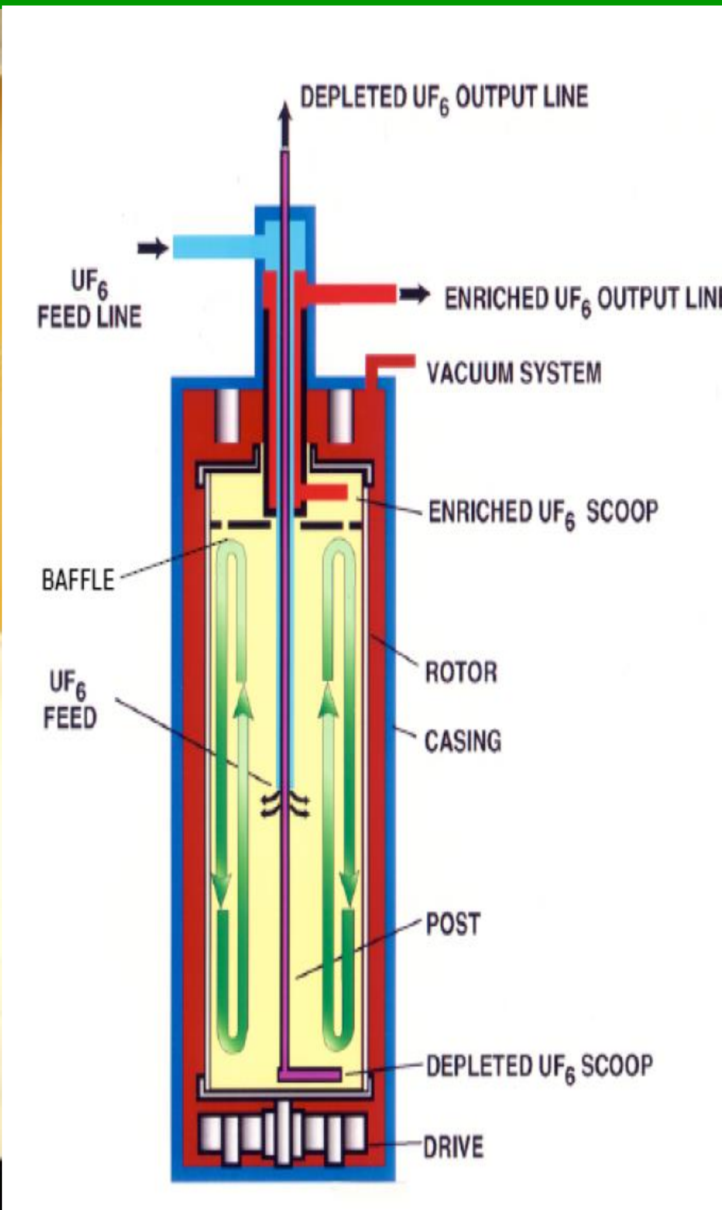
Based on	Examples
Diffusion in a pressure gradient	Gas centrifuge[a] Separation nozzle Vortex tube
Diffusion principles	Gaseous diffusion[a] Mass diffusion Thermal diffusion
Phase equilibrium principles	Distillation
Chemical equilibrium principles	Chemical exchange Ion exchange
Photo excitation principles	Atomic vapor laser isotope separation (AVLIS) Molecular laser isotope separation (MLIS)
Electromagnetic principles	Plasma separation process (PSP) Electromagnetic isotope separation (EMIS) Plasma centrifuge

1. Enrichment by Gaseous Diffusion





2. Gas Ultra Centrifuge



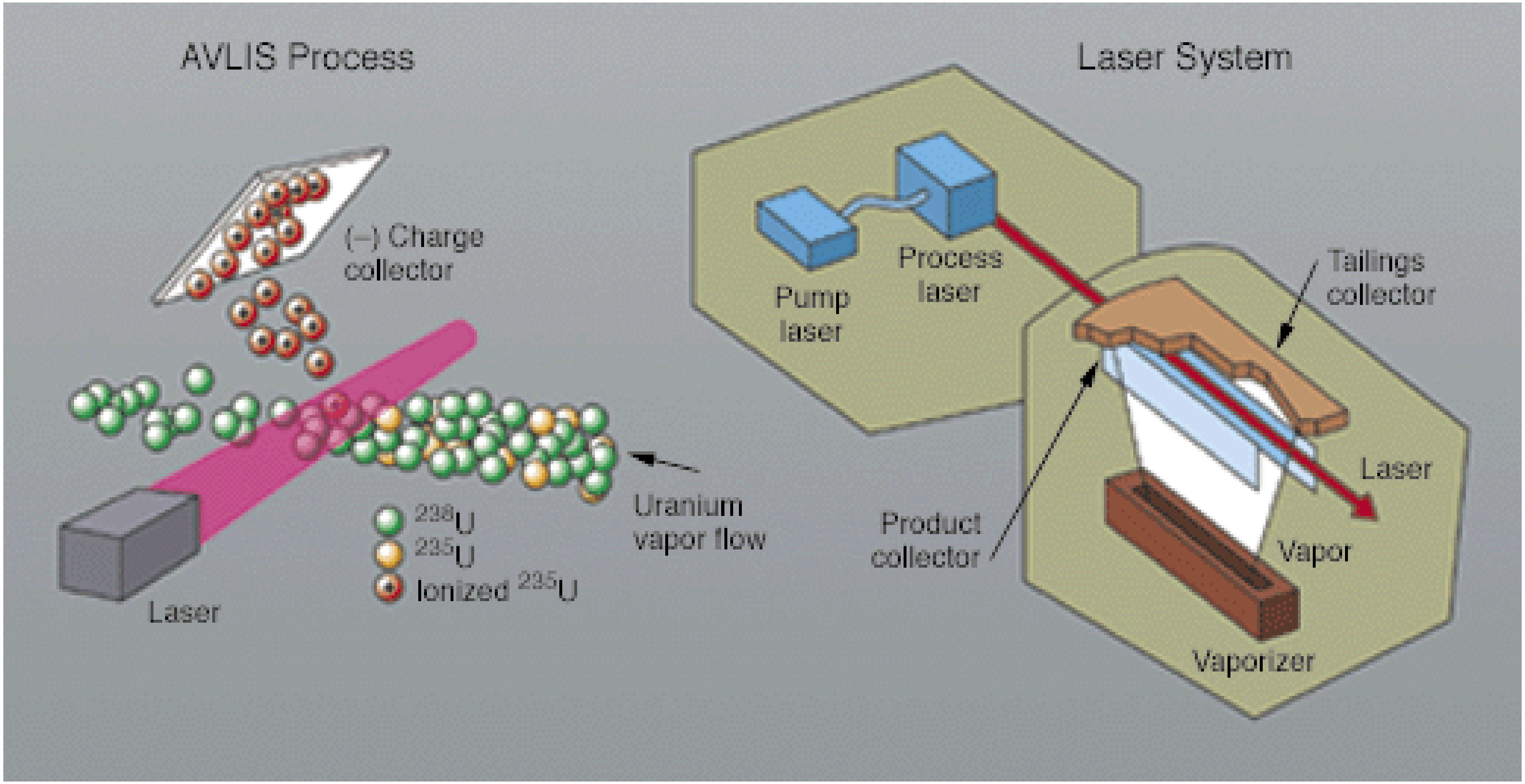
Gas Ultra Centrifuges

	Rotor	Dia cm	Height m	SWU kg/yr
P-1	aluminum	10	2	> 2
P-2	maraging steel	15	1	> 5
TC10	maraging steel	15	3.2	> 20
TC12	carbon fiber	20	3	40
AC-100	carbon fiber	60	12	330

Table 3. Comparison of the enrichment processes

Enrichment process	Separation factor	Throughput	Specific inventory (kg/U/SWU/year)	Specific energy consumption (kWh/SWU)	Capital costs
Gaseous diffusion	1.004	High	0.1–0.3	2400	Reference
Gas centrifuge	>1.3	Low	–0.0005	100	Higher
Aerodynamic					
—Vortex tube	1.03	High	0.003	3500	Comparable
—Separation nozzle	1.015	High	0.002	2500–3500	Comparable
Chemical exchange	1.0026	High	1.1	360[a]	Lower
Ion exchange	1.001	High	0.1–0.4	140[a]	Lower
Laser					
—Molecular	2–6	Moderate	Low	150	Lower
—Atomic vapor	2–6	Moderate	Low	150	Lower
Electromagnetic isotope separation (EMIS)	~30	Very low	N/A	High	Much higher

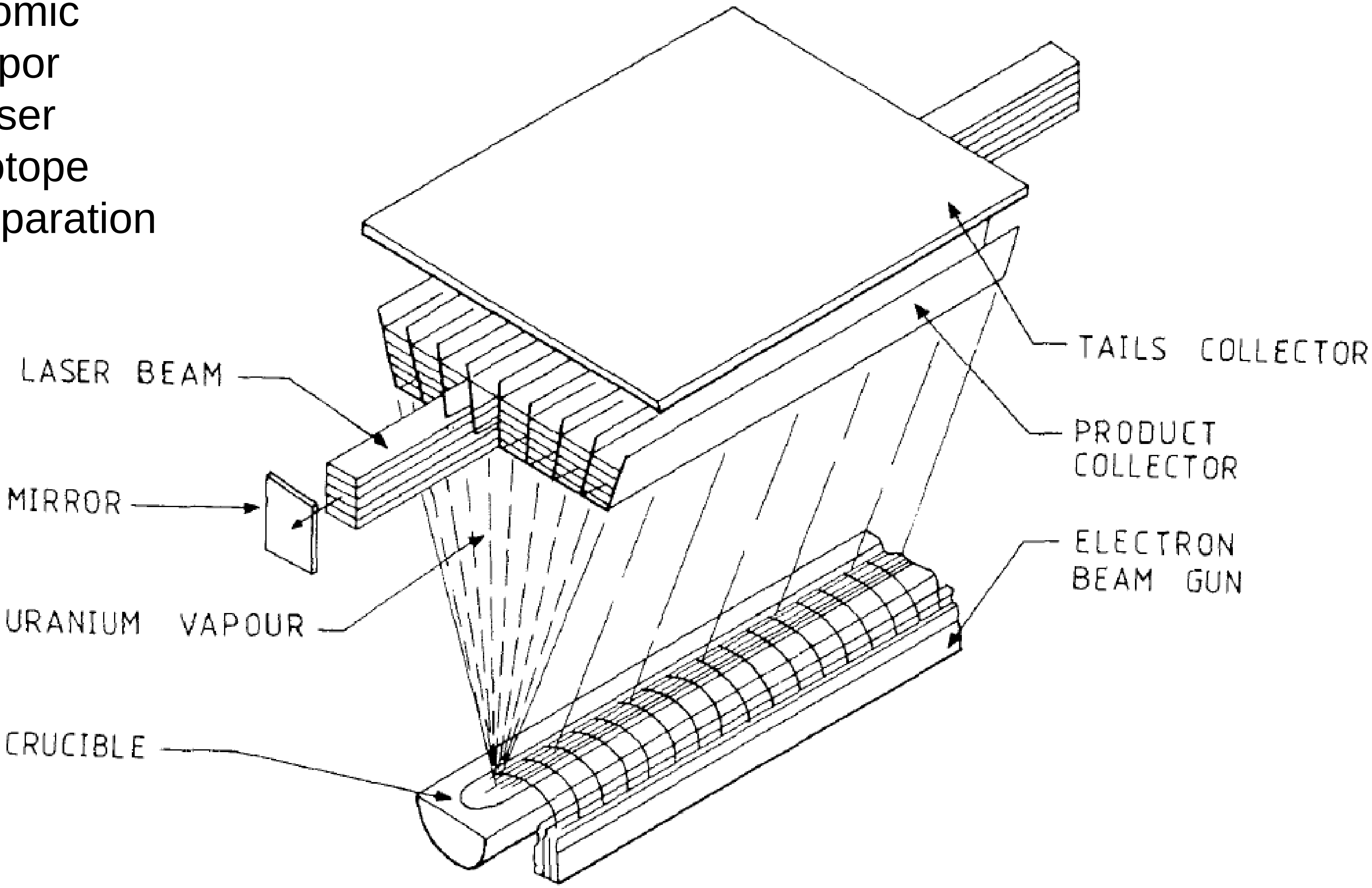
3.1 AVLIS
(atomic vapor laser isotope separation)



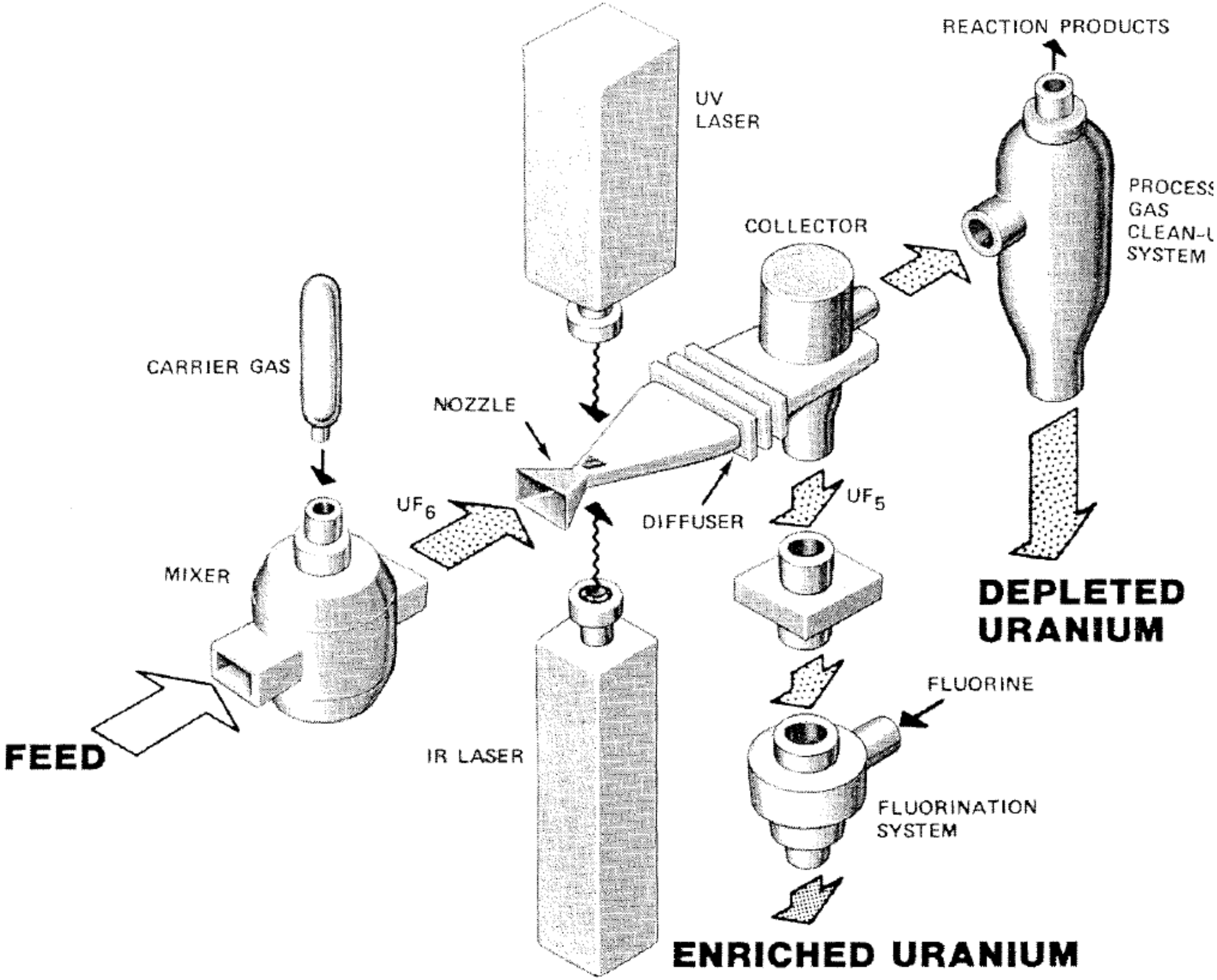
In the laser system used for the LIS uranium enrichment process (right), electrons from the ^{235}U atoms are separated (left), leaving positively charged ^{235}U ions that can be easily collected for use.

3.1 Laser – AVLIS

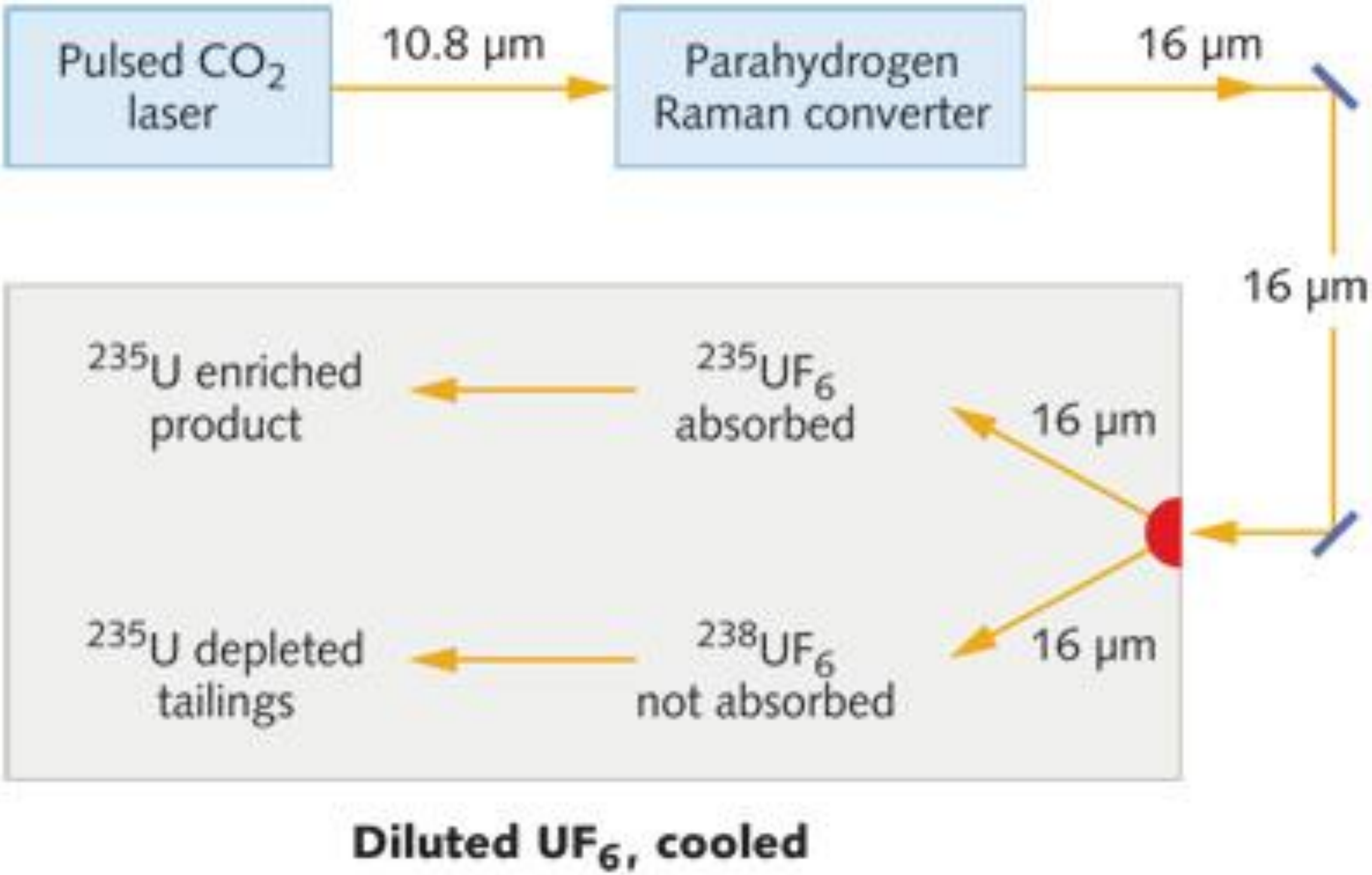
Atomic
Vapor
Laser
Isotope
Separation



3.2 SILEX/Molecular Isotope Separation



SILEX

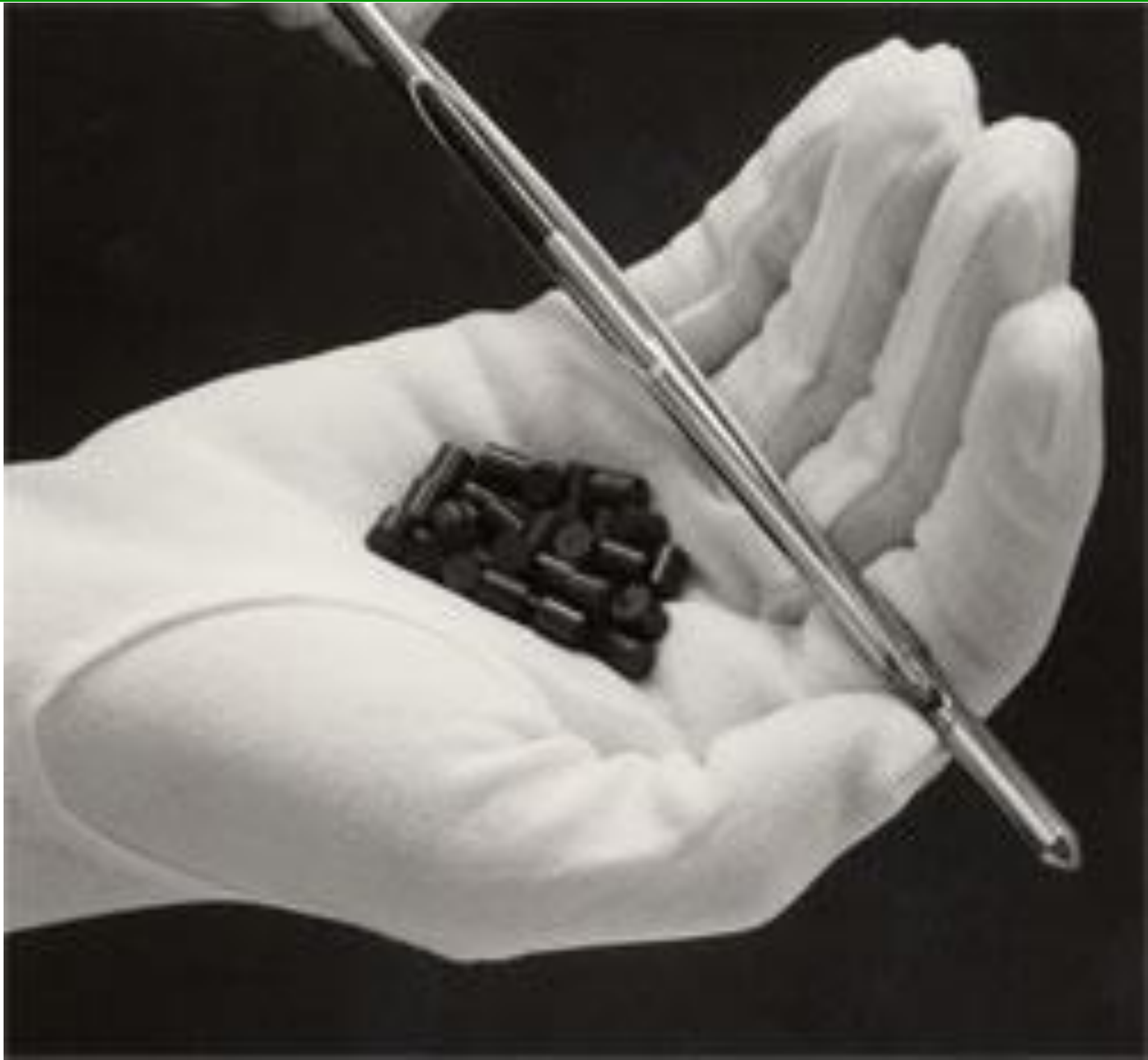


Pulsed CO_2 laser
10.8 μm
Parahydrogen Raman converter
16 μm
16 μm
^{235}U enriched product
$^{235}UF_6$ absorbed
16 μm
^{235}U depleted tailings
$^{238}UF_6$ not absorbed
16 μm
Diluted UF_6, cooled

Reactor Fuel Fabrication

Steps

1) **Convert Enriched U235 to UO2 (pellets)**
2) **Encase pellets in a sheath of Zirconium Alloy (old reactors had Aluminum sheathing)**



Reactor Fuel Fabrication

Steps

1) **Convert Enriched U235 to UO2 (pellets)**
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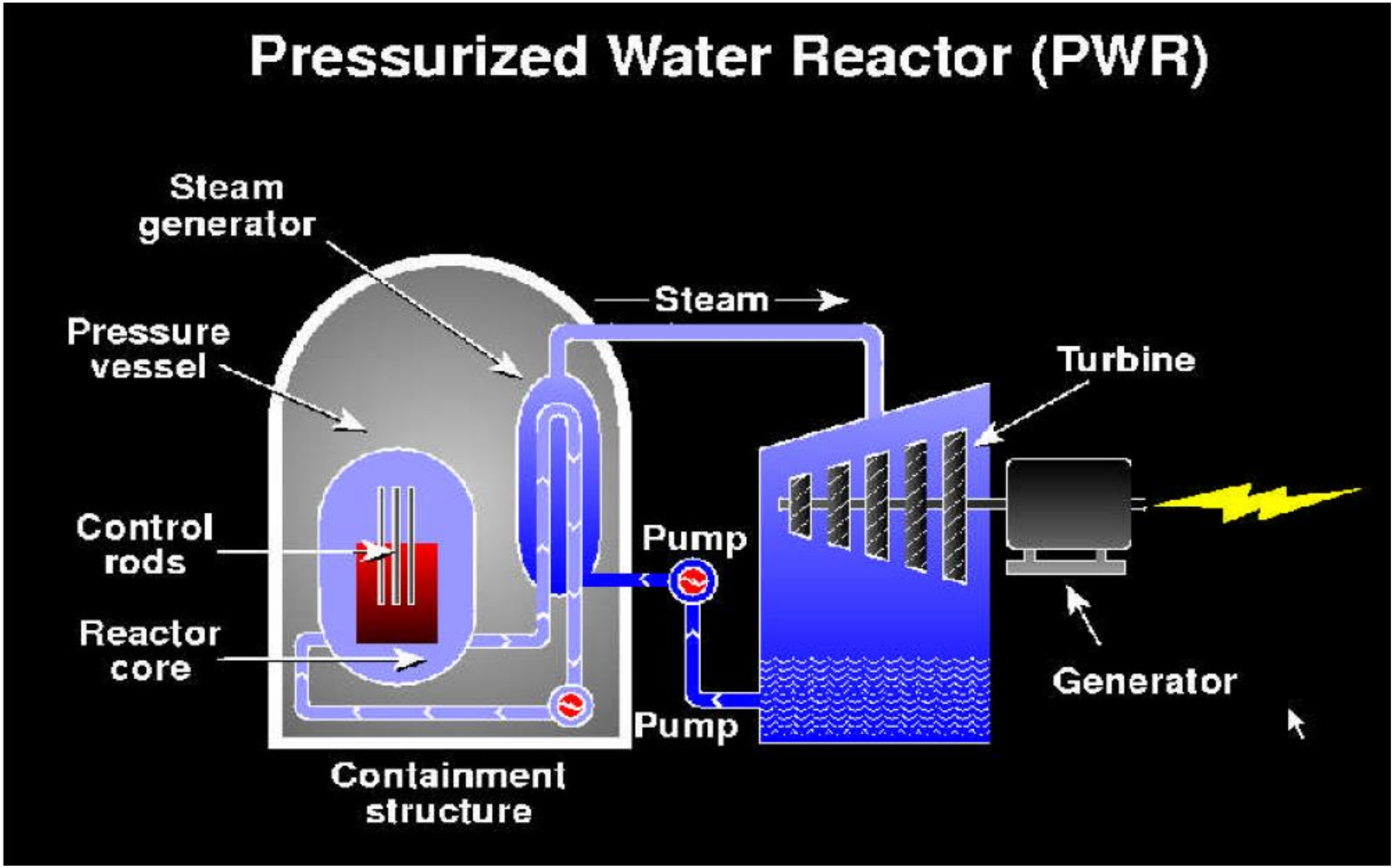
(a) Fuel Rod Inspection, no shielding

Burning Fuel in a Power Reactor



Spent Fuel Reprocessing

- Most reactors fuel burn-up limited
  - Poison build-up (e.g. Xe) slows/stops fission reaction (absorbs neutrons!!!)
- Most U235 still intact and can be re-used
- U238 in fuel absorbs neutrons and becomes Plutonium 239, also fissile
  - supports chain reaction and produces power
- Need to Recover $$$ U235 and Pu239

Spent Fuel Reprocessing

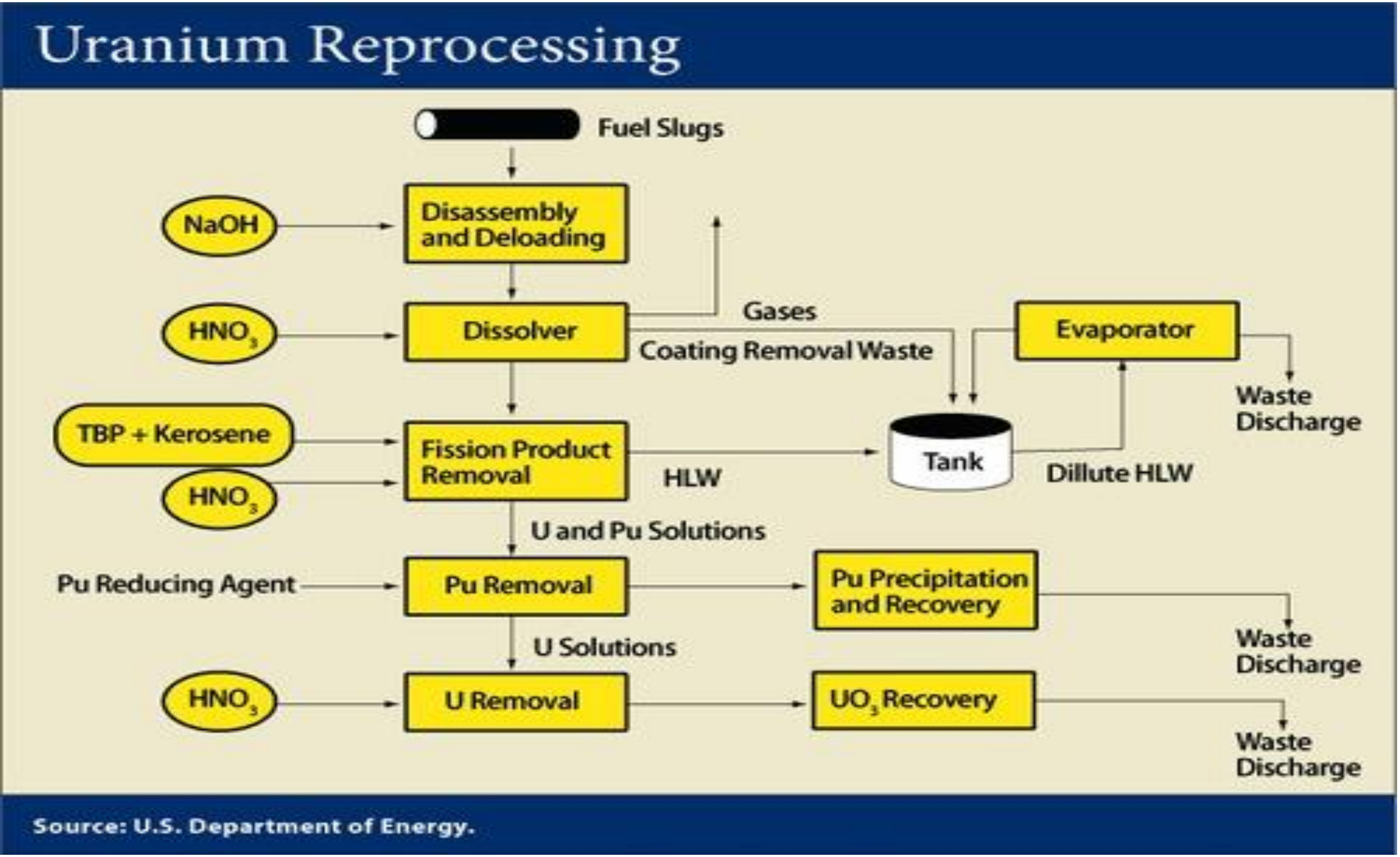
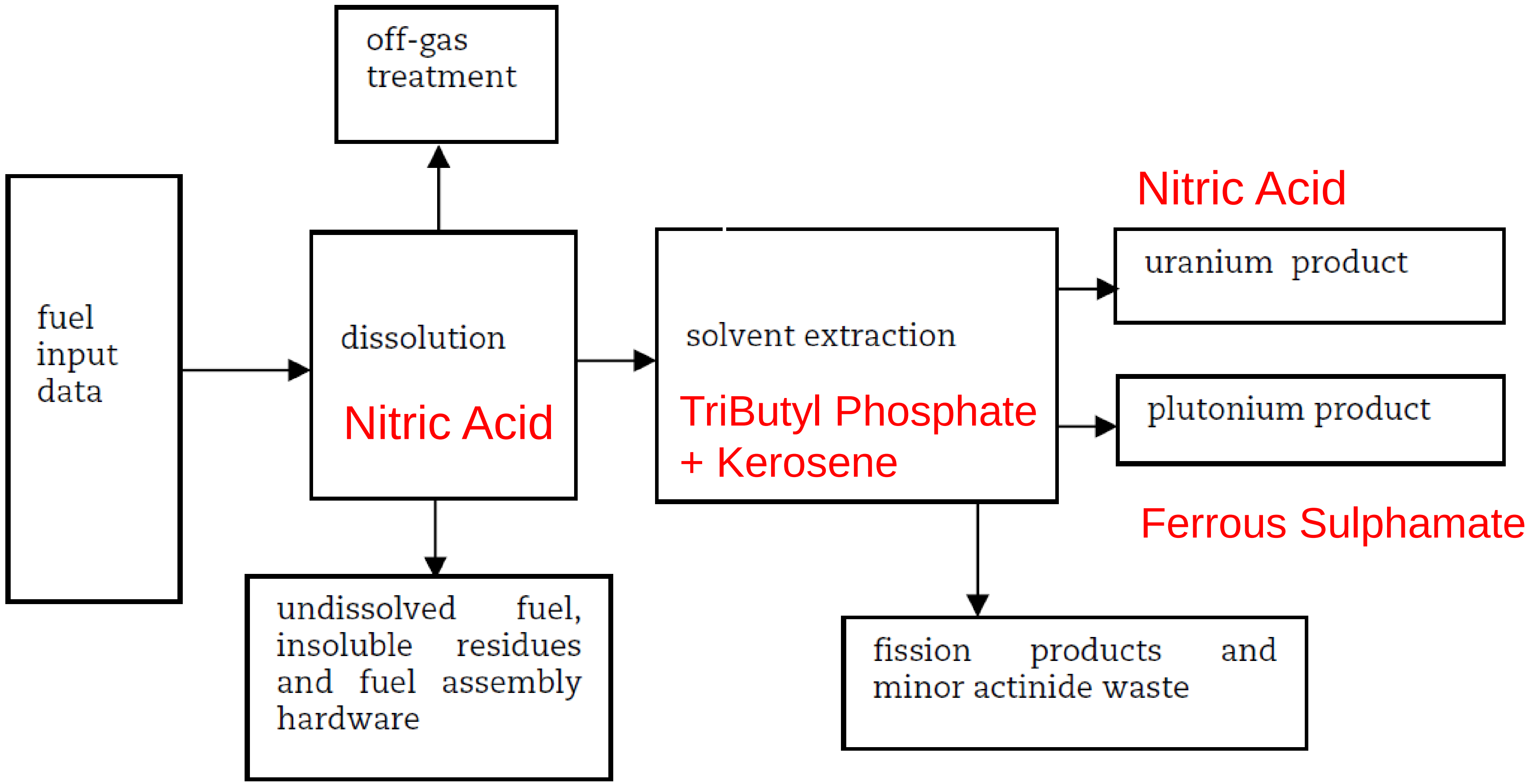
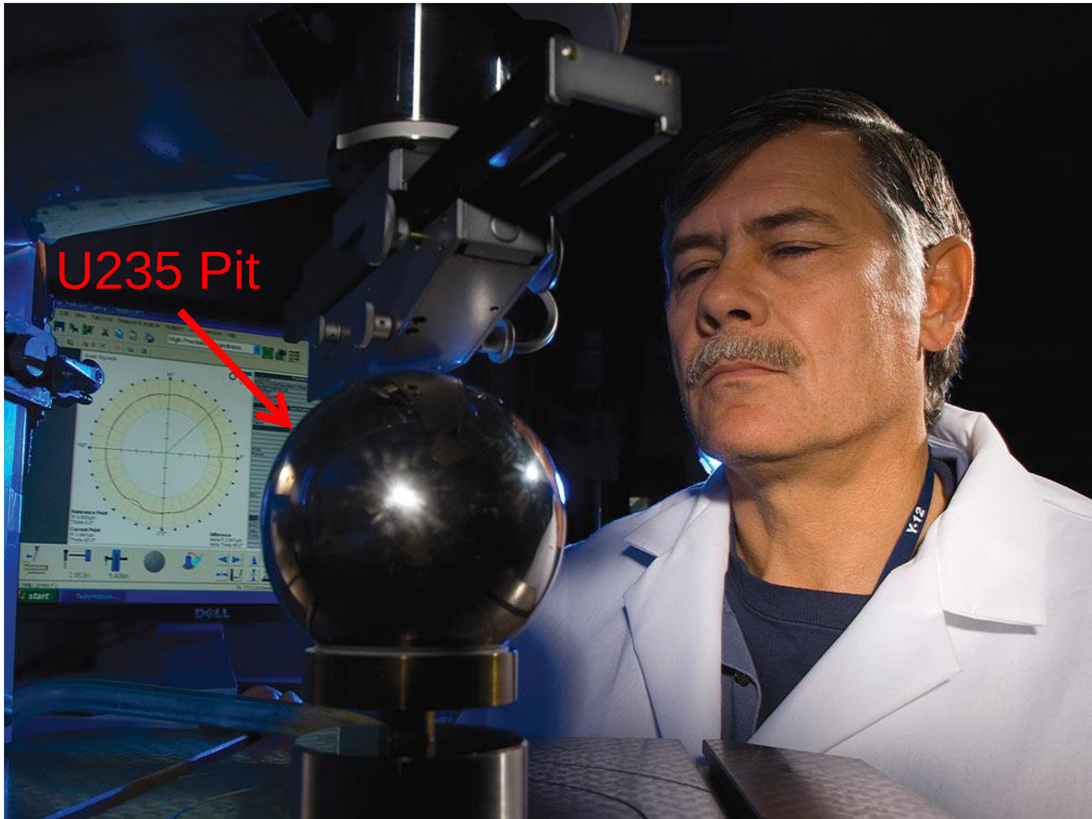


Figure 1: Schematic description of standard PUREX flowsheet



Megatons to Megawatts!!!

- **End of Cold War= Tens of Thousands of Nuclear Weapons Cores of HEU235 and Pu239 became SURPLUS!!!**



Megatons to Megawatts!!!

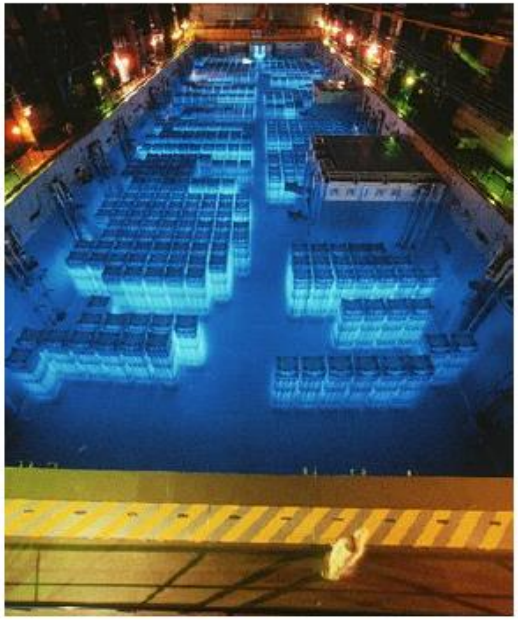
- **Surplus Cores of HEU235 and Pu239**
  - **HEU235 cores converted to UO2 Oxide, downblended from 94% enrichment with U238 to make ~5% U235, and then pressed into fuel pellets for LWR**
  - **Pu239 cores of ~94% enrichment converted to PuO2 Oxide, and them mixed with UO2**
    - **Result: MOX (mixed Oxide of U235~93% and Pu239~7%), pressed into ceramic pellets**
    - **About 30 reactors in EU use MOX**
  - **Concerns about proliferation (recover Pu239!)**

Spent Fuel Waste Handling

- **Issue: Spent Fuel Waste Radioactivity**
  - **Short lived fission products: Cs, La, Xe, etc.**
    - **Intensely radioactive, decays to half every 7 hrs**
    - **Decay Heat - cooling ponds before reprocessing or long terms storage**
  - **Long lived fuel: low level radioactivity**
    - **Pu239 - 24,000 yrs, Natural U- millions of years**
- **No national strategy what to do**

Spent Fuel Waste Handling

- Currently stored in pools or dry storage at the 60+ nuclear reactor sites in the U.S.
- Generated at approximate rate of 2100 MTHM/yr
- Slated for direct disposal into Yucca Mountain geologic repository
    - Yucca Mountain is not licensed or open at this time, spent fuel inventory will exceed legislated capacity before it is opened



Summary

- **Plentiful Nuclear Fuel Available for Millenia**
  - **Natural U for (Heavy Water or Graphite) HWR**
  - **U enriched to ~5% U235 for LWR**
  - **MOX of Pu239 and HEU235 for fast reactors**
- **New**
  - **Ultra-Safe Reactor Technology, e.g. pebble-bed reactor**
  - **Modular nuclear reactor for predictable cost and performance**
- **Politics and ignorant public**
  - **still fearful of nuclear power (80+% France’s Electricity, 0 accidents)**