NUCL 402 Engineering of Nuclear Power Systems

Lecture 16: Global Nuclear Energy Partnership and the Nuclear Fuel Cycle

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GNEP – Overview

- ✓ **The Global Nuclear Energy Partnership is a DOE Program that is part of the Advanced Energy Initiative**
  - **Overriding goal of AEI & GNEP is to produce carbon-free nuclear power**
  - **This is planned to be accomplished by having nations with secure capabilities to sell fuel services to other nations**
    - **These other nations must promise to use fuel only for energy purposes**

GNEP - Overview

✓ **Principles of the GNEP**

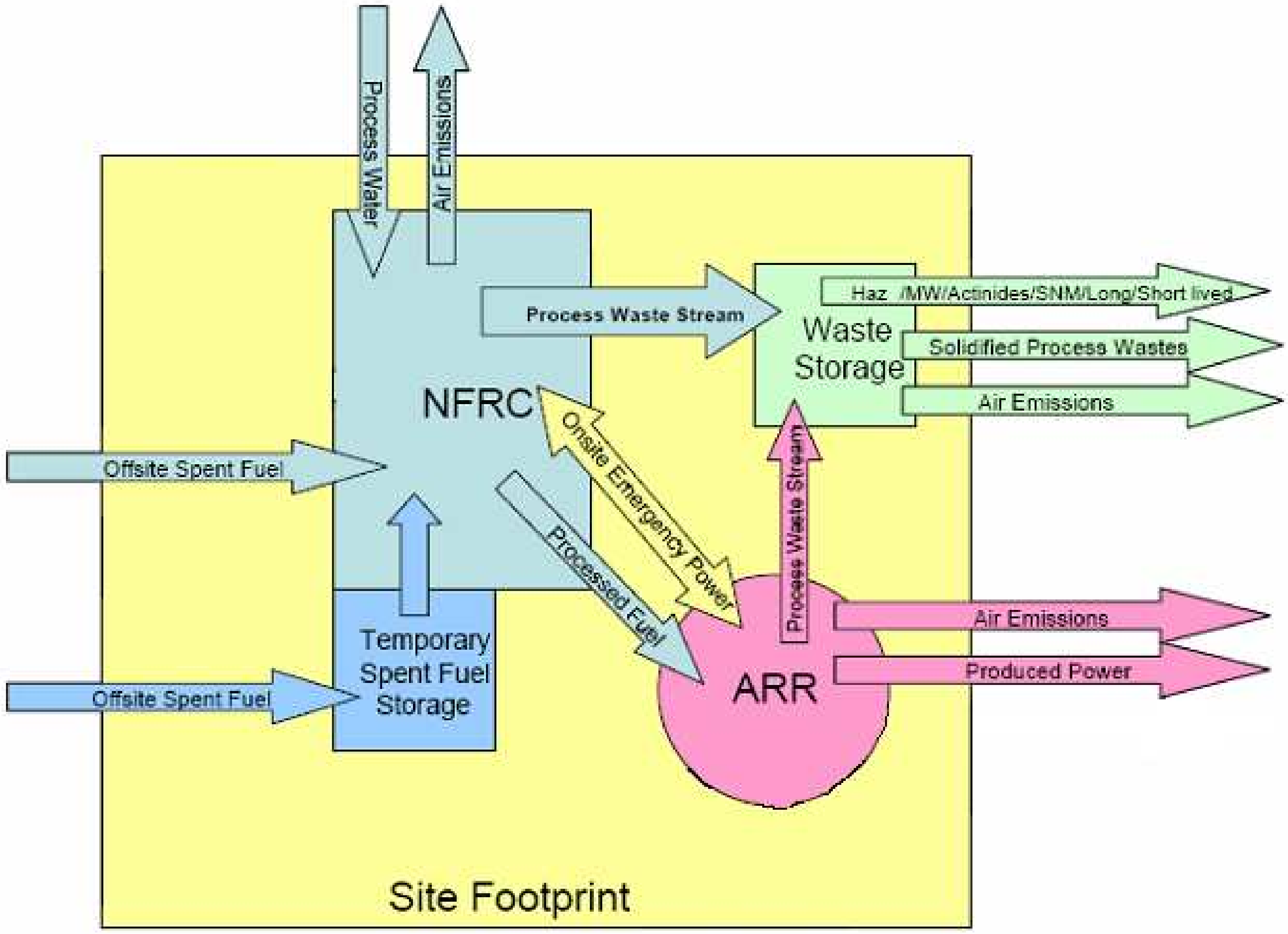
- **Expand nuclear power; provide for safe operation of plants and safe management of waste**
- **Continue to develop nuclear safeguards to ensure nuclear materials are used for peaceful purposes**
- **Establish safe, reliable global fuel services network while reducing the risk of proliferation**
- **Develop fast reactors to consume spent fuel to reduce waste**
- **Develop proliferation resistant reactors to bring nuclear power to developing countries**
- **Develop technology that would stop separation of plutonium from spent fuel, with the goal of eliminating the world's supply of plutonium**

GNEP - Overview

✓ **Three primary components:**

- **Nuclear Fuel Recycling Center (NFRC)**
  - **For separating usable elements from spent fuel**
  - **Also to create actinide rods from these elements for use in the ARR**
- **Advanced Recycling Reactor (ARR)**
  - **For burning actinide fuel rods created at NFRC**
  - **This reduces the amount of waste that needs to be stored**
- **Advanced Fuel Cycle Research Facility (AFCRF)**
  - **For research on transmutation fuels and continuous improvement of fuel cycles**

GNEP - Overview



Simplified Block Diagram Representing NFRC & ARR

Original © INL

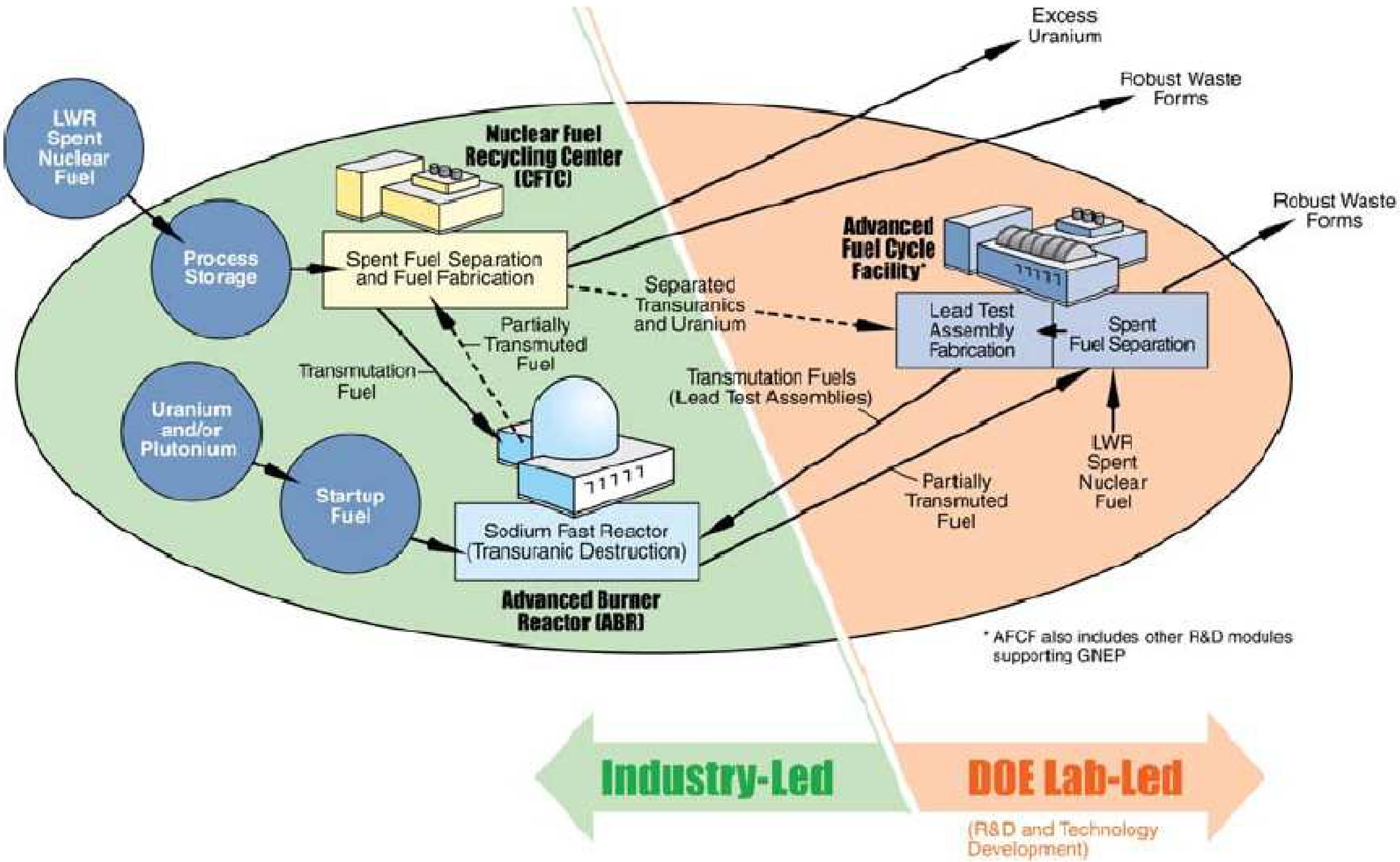
GNEP – Who?

- ✓ **As of Feb. 1, 2008, a total of 20 countries are signatories to the principles of the GNEP:**
  - **Leaders: United States, China, Russia, Japan, and France**
  - **Uranium Suppliers: Australia, Kazakhstan, Canada**
  - **Fuel Service Receivers: Bulgaria, Hungary, Lithuania, Romania, Slovenia, Ukraine, Poland, Ghana, Jordan, South Korea, Italy, Senegal**

GNEP – Economic Impact

- ✓ Overriding economic consideration is to keep nuclear energy cost-competitive with other forms of energy
- ✓ Division of labor in US to come from three primary sources:
  - Operation of factiles: Industry
  - Research: Government Funded Laboratories and Universities

GNEP – Economic Impact



Division of Labor between Industry and Labs © INL

GNEP – Economic Impact

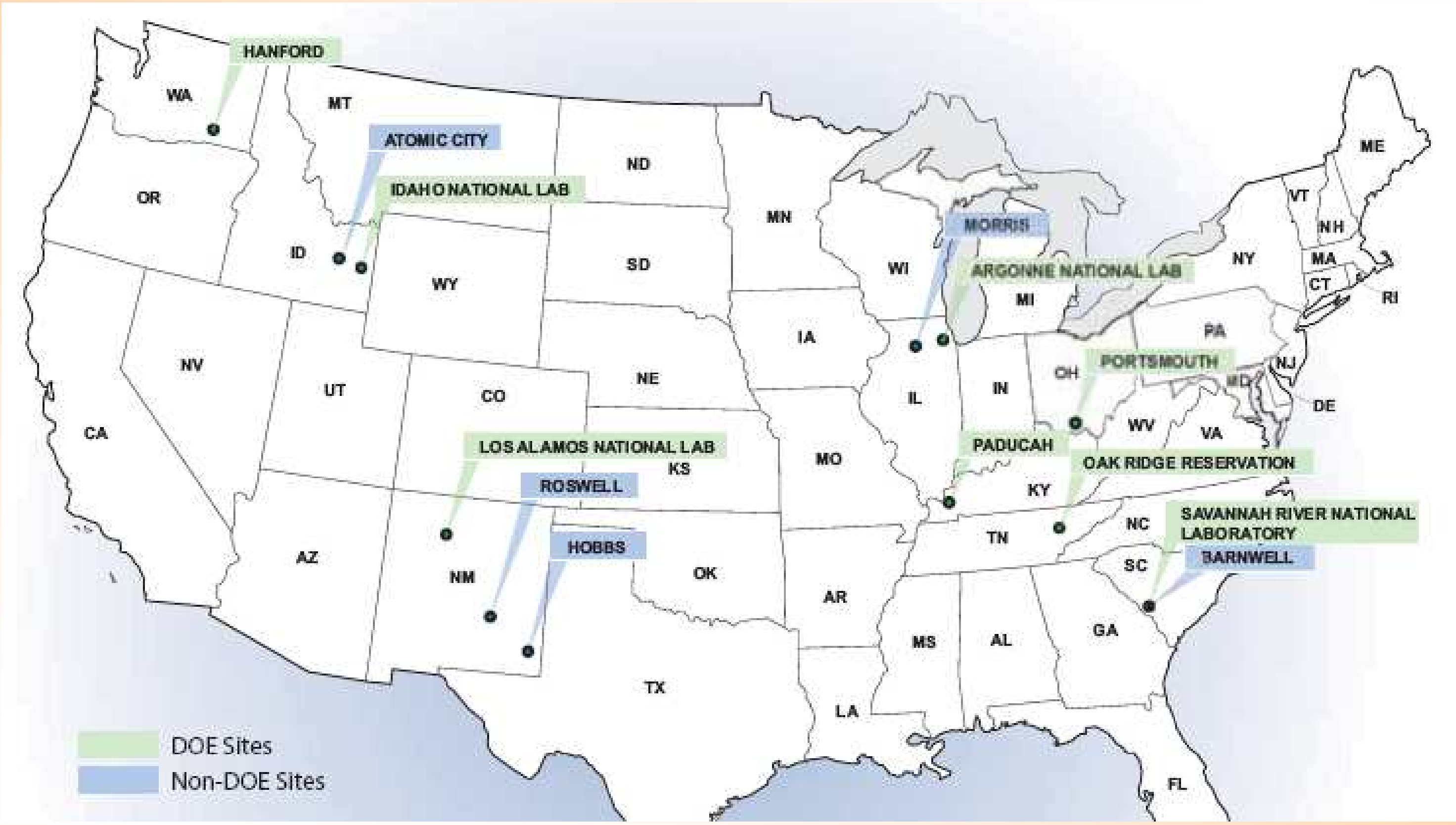
- ✓ **Total cost estimates for GNEP Research (through 2012):**
  - **Systems Integration: $126.3 M**
  - **Spent Fuel Separation Technology: $1010.4 M**
  - **Transmutation Technologies: $1044.8 M**
  - **Transmutation Fuels: $1142.8 M**
  - **Reactors for Deployment: $75.5 M**
  - **Modeling and Simulation: $462 M**
  - **University Programs: $28.5 M**
  - **Other: $20.77+ M**
- ✓ **TOTAL: $3.91 Billion**

Data courtesy of GNEP Technology Development Plan July 25, 2007

GNEP – Environmental Impact

- ✓ **One of the overriding keys of GNEP is to meet the growing world demand for energy without emitting air pollution or greenhouse gases.**
- ✓ **Waste Reduction**
  - **Development of Actinide Burning Reactors**
  - **Utilization of closed-fuel cycles**
- ✓ **Currently 13 sites are under consideration for all 3 primary structures considered crucial to GNEP to be located in the same place**

GNEP – Environmental Impact



Sites Being Considered for Primary Structures

GNEP – Safety & Security

- ✓ **One of the overriding goals of the GNEP is to increase overall safety of nuclear power**
  - **Development of proliferation-resistant fuel cycles and reactors**
  - **Fuel recycling that does not separate pure Plutonium**
    - **Long term goal of eliminating separation of Plutonium completely and eliminating civilian stockpiles**
  - **Proliferation risk reduced by limiting the number of countries with access to enrichment and reprocessing plants.**

Front End and Back End….

The nuclear fuel cycle is the series of industrial processes which involve the production of electricity from uranium in nuclear power reactors

The nuclear fuel cycle, also called nuclear fuel chain, is the progression of nuclear fuel through a series of differing stages.

- ✓ *FRONT END:* the preparation of the fuel, steps in the *service period* in which the fuel is used during reactor operation, and
- ✓ *BACK END:* safely manage, contain, and either reprocess or dispose of spent nuclear fuel.

If spent fuel is not reprocessed, the fuel cycle is referred to as a *open fuel cycle* (or a *once-through fuel cycle*). If the spent fuel is reprocessed, it is referred to as a *closed fuel cycle*.

Fuel Cycle

^{235}U –naturally available

$$^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th^{*} \xrightarrow{\beta} {}^{233}_{91}Pa \xrightarrow{\beta} {}^{233}_{92}U$$

$$^{238}_{92}U + n \rightarrow {}^{239}_{92}U^{*} \xrightarrow{\beta} {}^{239}_{93}Np \xrightarrow{\beta} {}^{239}_{94}Pu$$

Sources of Uranium

4 ppm on earths crust contain U

Relatively high grade ore (1-4%) in Zaire and Canada –primary minerals picthblend and uraninite

$$xUO_2 \cdot yUO_3; 0 < y/x < 2$$

Medium grade (0.1 to 0.5%) in US, Canada, Australia, Gabon, South Afric

Sea water →3 ppb U

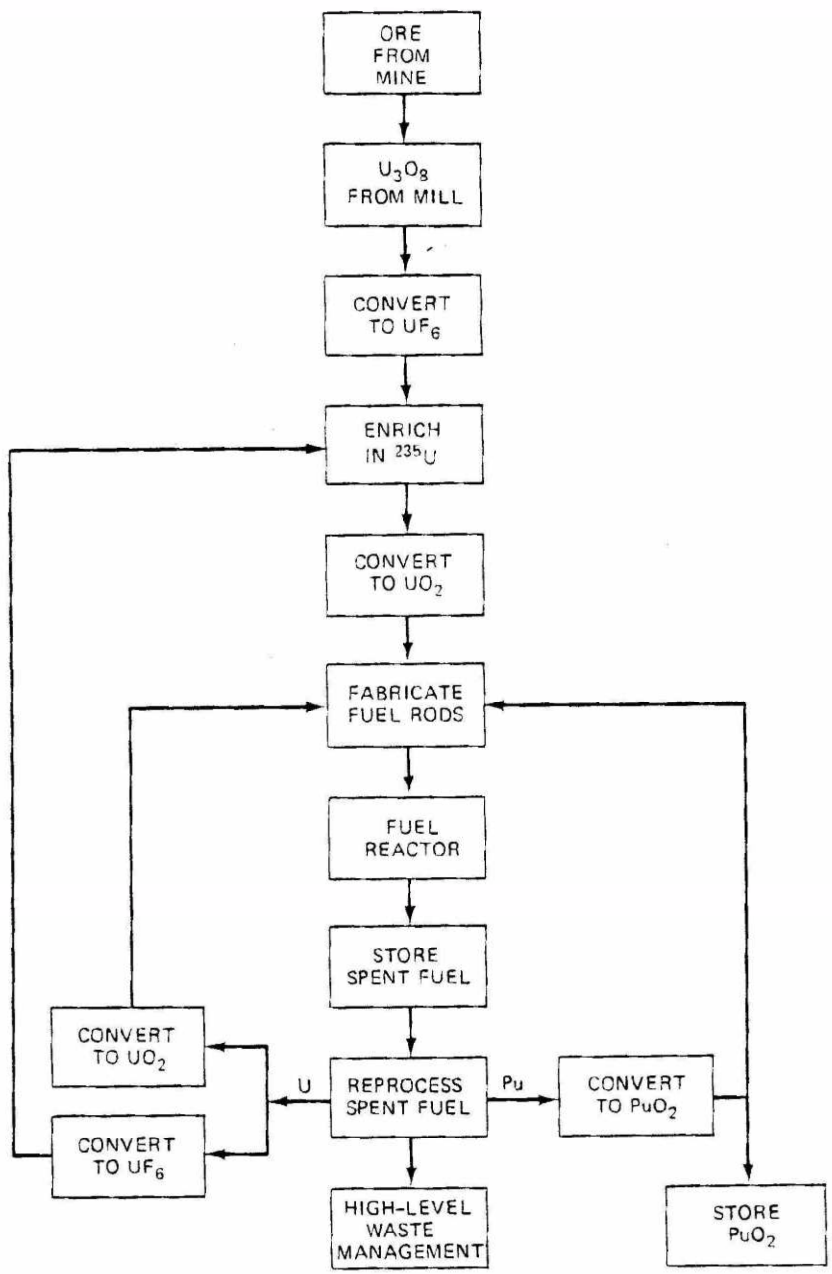
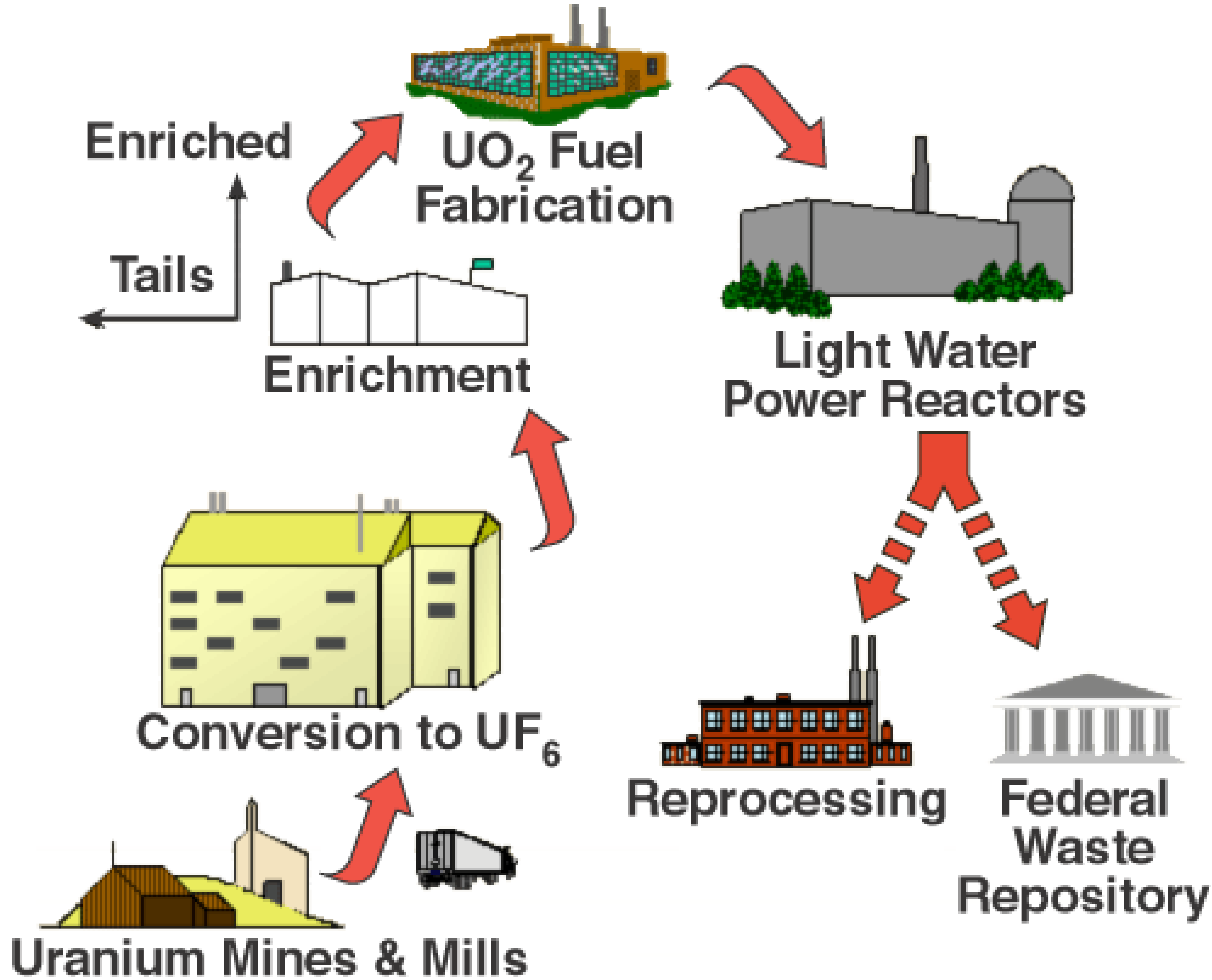
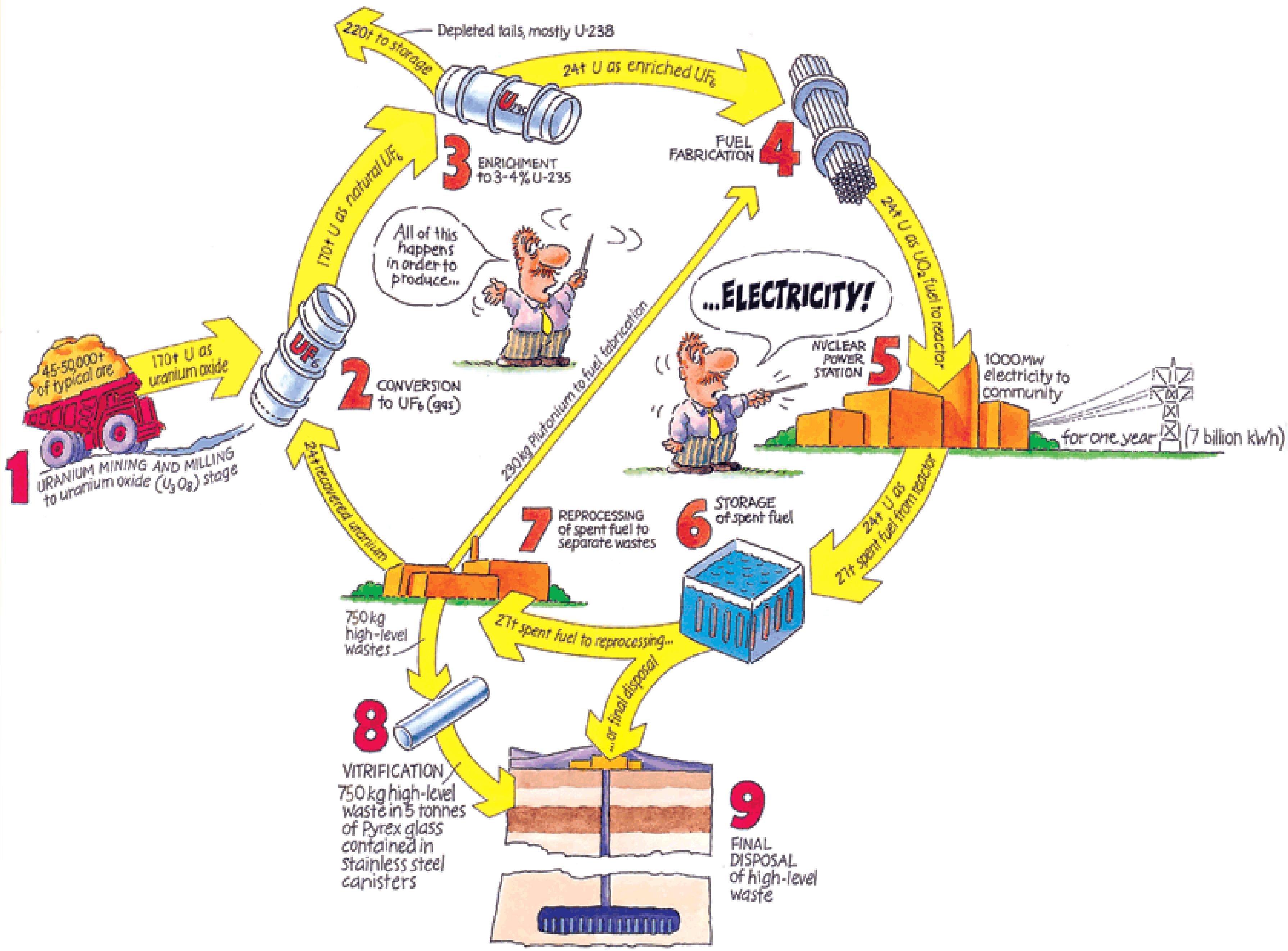


Fig. 8.1. Outline of complete uranium fuel cycle.


Enriched
UO$_2$ Fuel Fabrication
Tails
Enrichment
Light Water Power Reactors
Conversion to UF$_6$
Reprocessing
Federal Waste Repository
Uranium Mines & Mills

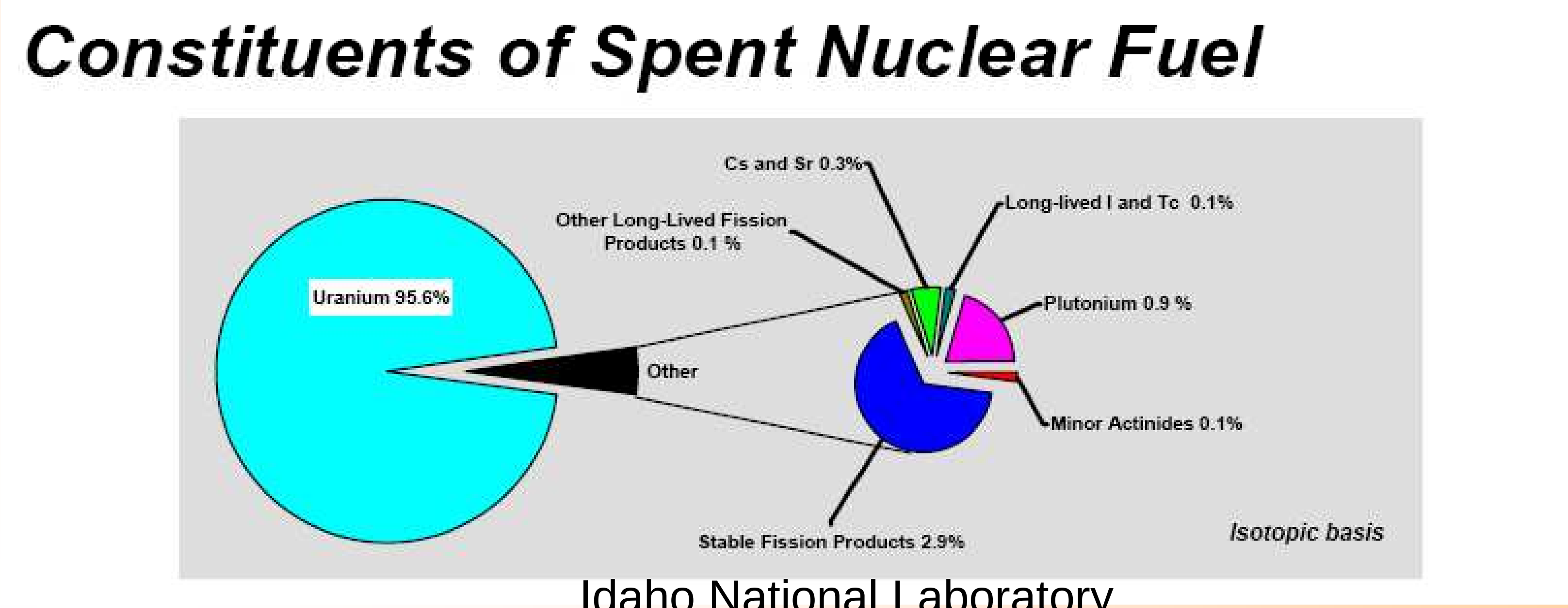


220t to storage
Depleted tails, mostly U-238
24t U as enriched UF_6
3 ENRICHMENT to 3-4% U-235
FUEL FABRICATION 4
170t U as natural UF_6
All of this happens in order to produce...
...ELECTRICITY!
24t U as UO_2 fuel to reactor
45-50,000t of typical ore
170t U as uranium oxide
NUCLEAR POWER STATION 5
1000MW electricity to community
for one year (7 billion kWh)
2 CONVERSION to UF_6 (gas)
230 kg Plutonium to fuel fabrication
1 URANIUM MINING AND MILLING to uranium oxide (U_3O_8) stage
24t recovered uranium
7 REPROCESSING of spent fuel to separate wastes
6 STORAGE of spent fuel
24t U as 27t spent fuel from reactor
750 kg high-level wastes
27t spent fuel to reprocessing...
...or final disposal
8 VITRIFICATION
750 kg high-level waste in 5 tonnes of Pyrex glass contained in stainless steel canisters
9 FINAL DISPOSAL of high-level waste

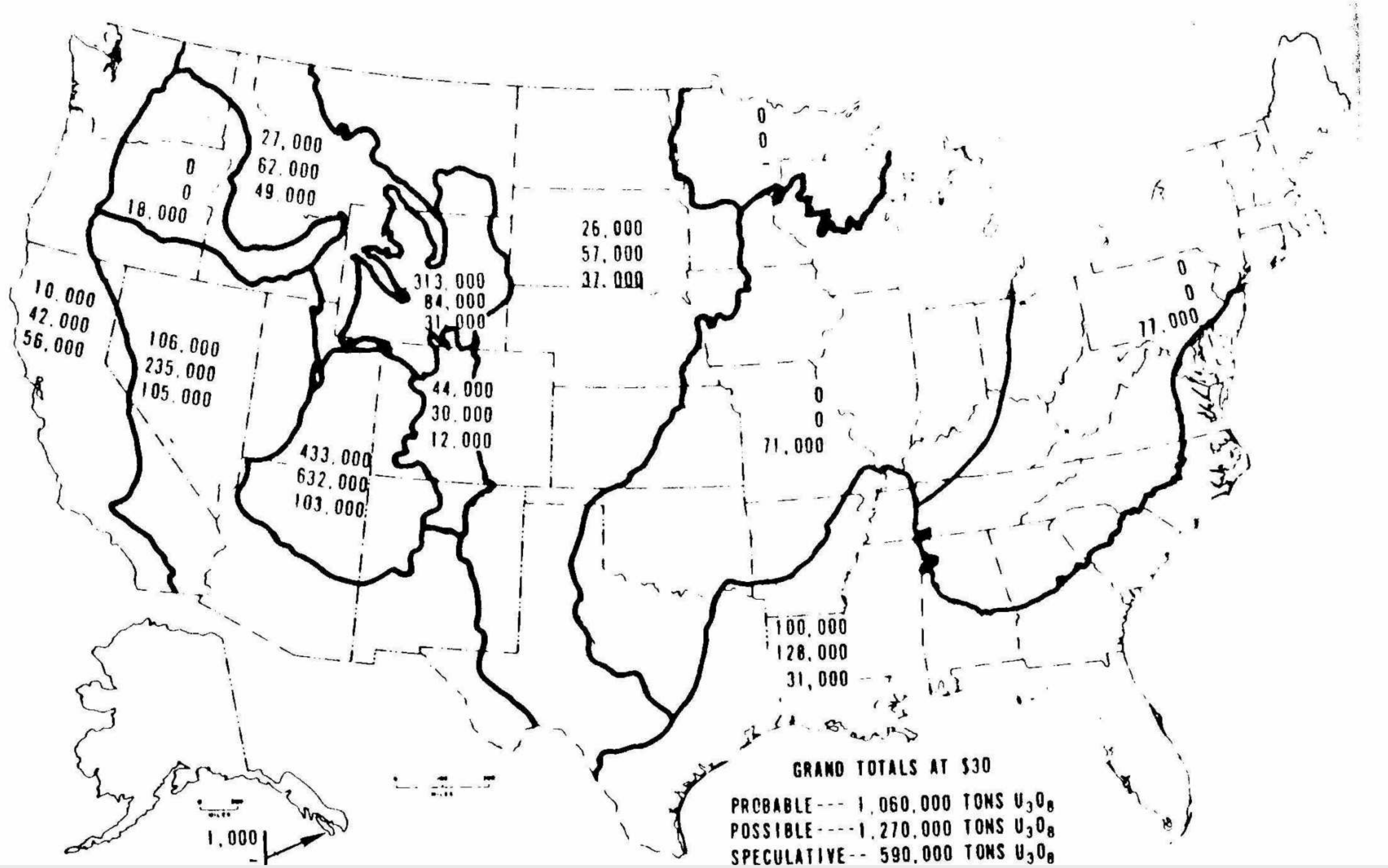
Fuel Cycles

Once Through Fuel Cycle

Amount of fuel wasted- **90 to 95% of nuclear waste could be re-processed and used as fuel.** **(EIR Science & Technology)**



Idaho National Laboratory



US-Colorado Plateau (Arizona, Colorado, New Mexico and Utah) and Wyoming (0.1 to 0.5%) Minerals

Carnotite: ($K_2O_2\ UO_3\ V_2O_5\ xH_2O$) and Autunite: ($CaO\ 2UO_3\ P_2O_5\ xH_2O$)

Uranium Milling and Processing to UO_2

Average ore in US contain 0.2 to 0.25% of U_3O_8

Ore is leached with sulfuric acid to dissolve out uranium

Solvent extraction or ion-exchange procedure to obtain uranium oxide –yellow cake (75 to 80% $U_3O_{8)}$

Yellow cake is treated with ammonia to give ammonium diurinate $(NH_4)_2U_2O_7$

This is then fed to fluidized bed to crack ammonia at 540-640C producing UO_2 brown oxide.

Hydroflorination fluidized bed reaction

Yellow cake is treated with ammonia to $UO_2+4HF \rightarrow 2H_2O + UF_4$ (green salt)

$UF_4+F_2 \rightarrow UF_6$ (hexafluoride) sent to enrichment facility

UO_2 is then obtained from UF_6 by hydrolyzing with water and then treating with ammonia to get ammonia diurinate and crack ammonia

Enrichment

Natural uranium consists, primarily, of a mixture of two isotopes (atomic forms) of uranium. Only 0.7% of natural uranium is "fissile", or capable of undergoing fission, the process by which energy is produced in a nuclear reactor. The fissile isotope of uranium is uranium 235 (U-235). The remainder is uranium 238 (U-238).

In the most common types of nuclear reactors, a higher than natural concentration of U-235 is required. The enrichment process produces this higher concentration, typically between 3.5% and 5% U-235. This is done by separating gaseous uranium hexafluoride into two streams, one being enriched to the required level and known as low-enriched uranium. The other stream is progressively depleted in U-235 and is called 'tails'.

Two enrichment processes exist in large scale commercial use, each uses UF_6 as feed: gaseous diffusion and gas centrifuge. They both use the physical properties of molecules, specifically the 1% mass difference, to separate the isotopes. The product of this stage of the nuclear fuel cycle is enriched uranium hexafluoride, which is reconverted to produce enriched uranium oxide.

Gaseous Diffusion

Different rates at which gases of different molecular weight diffuse through a porous barriers.

Pore size < mean free path of the molecules

Average pore dia 0.05 µm ; 10^6 pores /mm^2

UF_6 is solid at room temp and sublimates to vapor at 56.4C

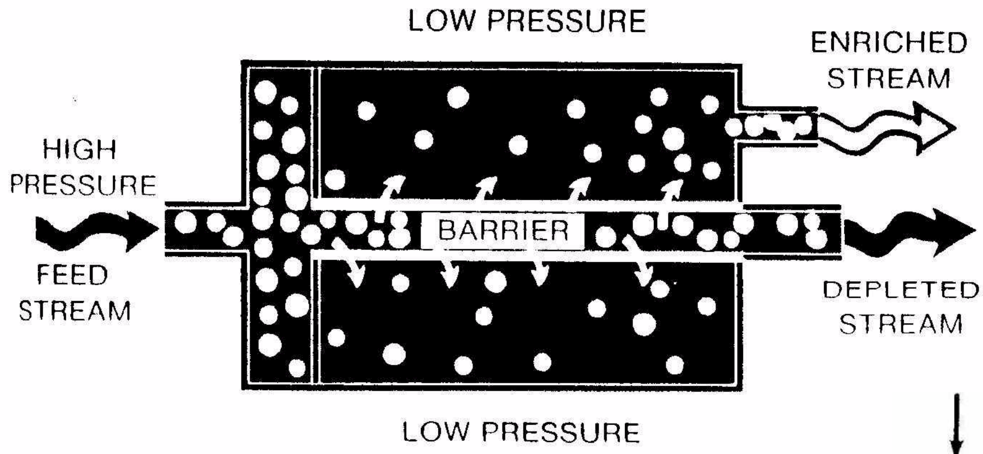
KE= $1/2Mv^2$; if M is different then v will be different if KE is same. For mixture vof gases at uniform temperature KE is same

$$\frac{M_H v_H^2}{2} = \frac{M_L v_L^2}{2}; \alpha^* = \frac{v_L}{v_H} = \sqrt{\frac{M_L}{M_H}}$$

Theoretical Separation factor =1.0043

Stage separation factor $$\alpha = \frac{a/(1-a)}{b/(1-b)}$$

a and b are weight fraction or assay of U235 in enriched and depleted stream respectively α≈1.003 <α* (1.0043)



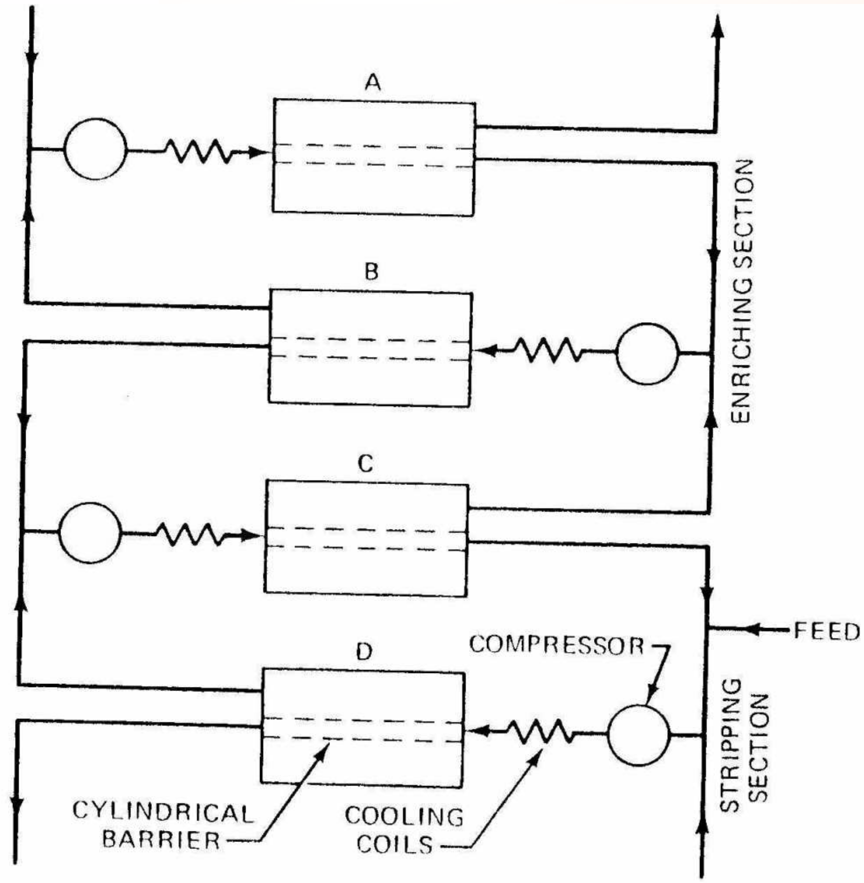
Number of stages in cascade

$$= \left(\frac{2}{\alpha - 1}\right) \ln \frac{x_p/(1-x_p)}{x_w/(1-x_w)}$$

Where x_p and x_w are final assay of U235 in enriched and depleted stream respectively.

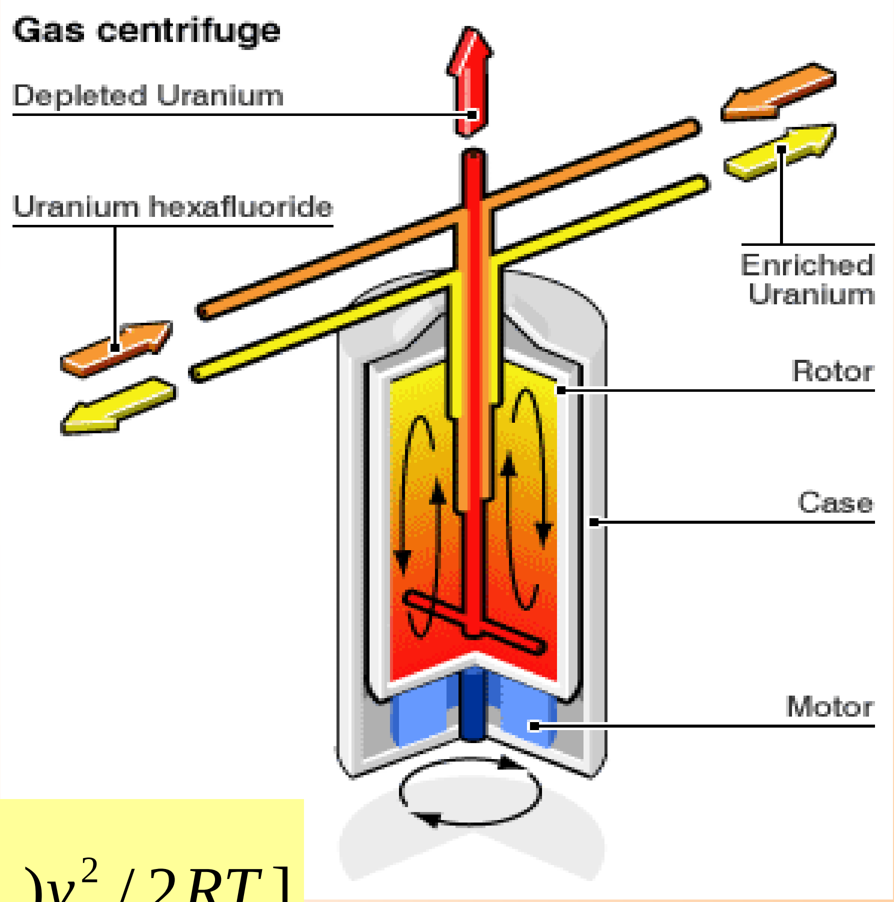
Example: x_p=3% and x_w =0.3%

Number of cascade =1100.



Gas Centrifuge

Principle: Heavier gas molecules move towards the periphery and the lighter ones tend to remain in the center.



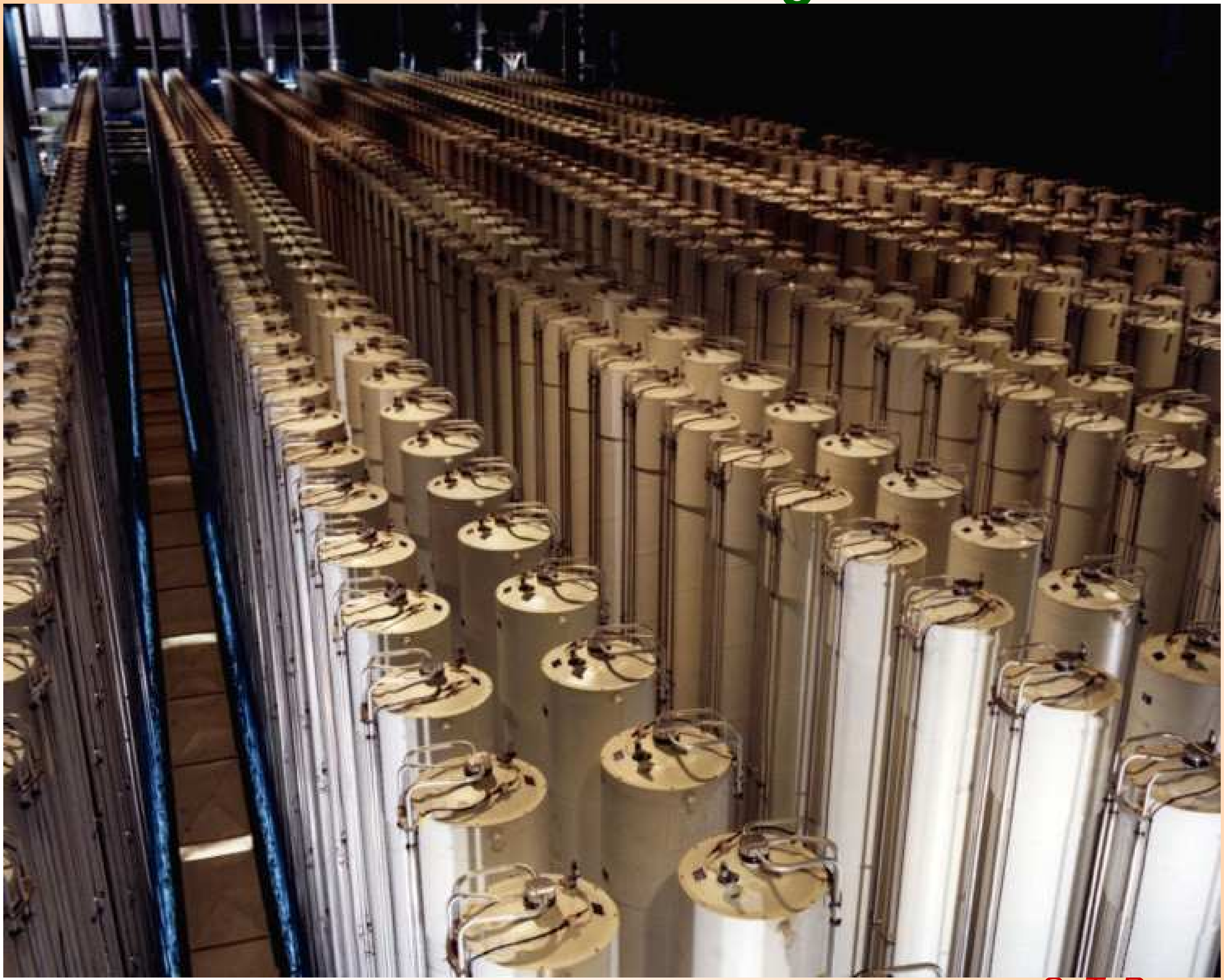
In a force field at equilibrium the gas distribution is $n = n_0 \exp(-E / RT)$

n_0 is concentration of molecule at filed =0 , E= -1/2Mv^2 –the potential energy at distance d from axis where concentration is n .

The separation factor

$$\alpha = \frac{n_{L(0)} / n_{H(0)}}{n_L / n_H} = \exp[(M_H - M_L) v^2 / 2RT]$$

Gas Centrifuge



Material Balance in Separative Work

Total mass

$M_F=M_P+M_T$

For U235 fraction $x_F M_F = x_P M_P + x_T M_T$

So U feed per unit product $\dfrac{M_F}{M_P} = \dfrac{x_P - x_T}{x_F - x_T}$

For natural uranium x_F =0.00711 and for US enrichment facility x_T= 0.002, Thus M_F is directly proportional to x_P. At enrichment x_P the mass U235 is $M_{235} = x_P M_P$. then

$$M_F = \left(\frac{x_P - x_T}{x_F - x_T}\right)\frac{M_{235}}{x_P} \approx \frac{M_{235}}{x_F - x_T} = 196\, M_{235}$$

Cost in Separation

The cost of enrichment is described in terms of a special unit called *the separative work unit.* Separative work can be expressed in terms of a function *V(x)* a value function for assay *x*

$$V(x) = (1-2x)\ln\left(\frac{1-x}{x}\right)$$

The effort expended : Separative work unit *(SWU)*

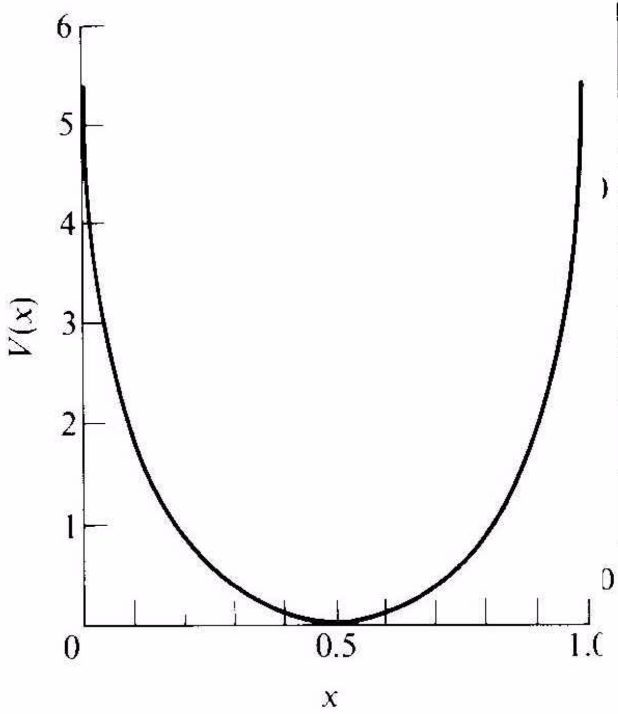
$$SWU = M_P V(x_P) + M_T V(x_T) - M_F V(x_F)$$

$$SWU\,(kg) = M_P[V(x_P) - V(x_T)] - M_F[V(x_F) - V(x_T)]$$

If C_s is cost of a separative work unit *in $/kg*

$$M_P C_P = SWU C_S + M_F C_F - M_T C_T$$

$$C_P = \frac{SWU}{M_P} C_s + \frac{M_F}{M_P} C_F - \frac{M_T}{M_P} C_T$$



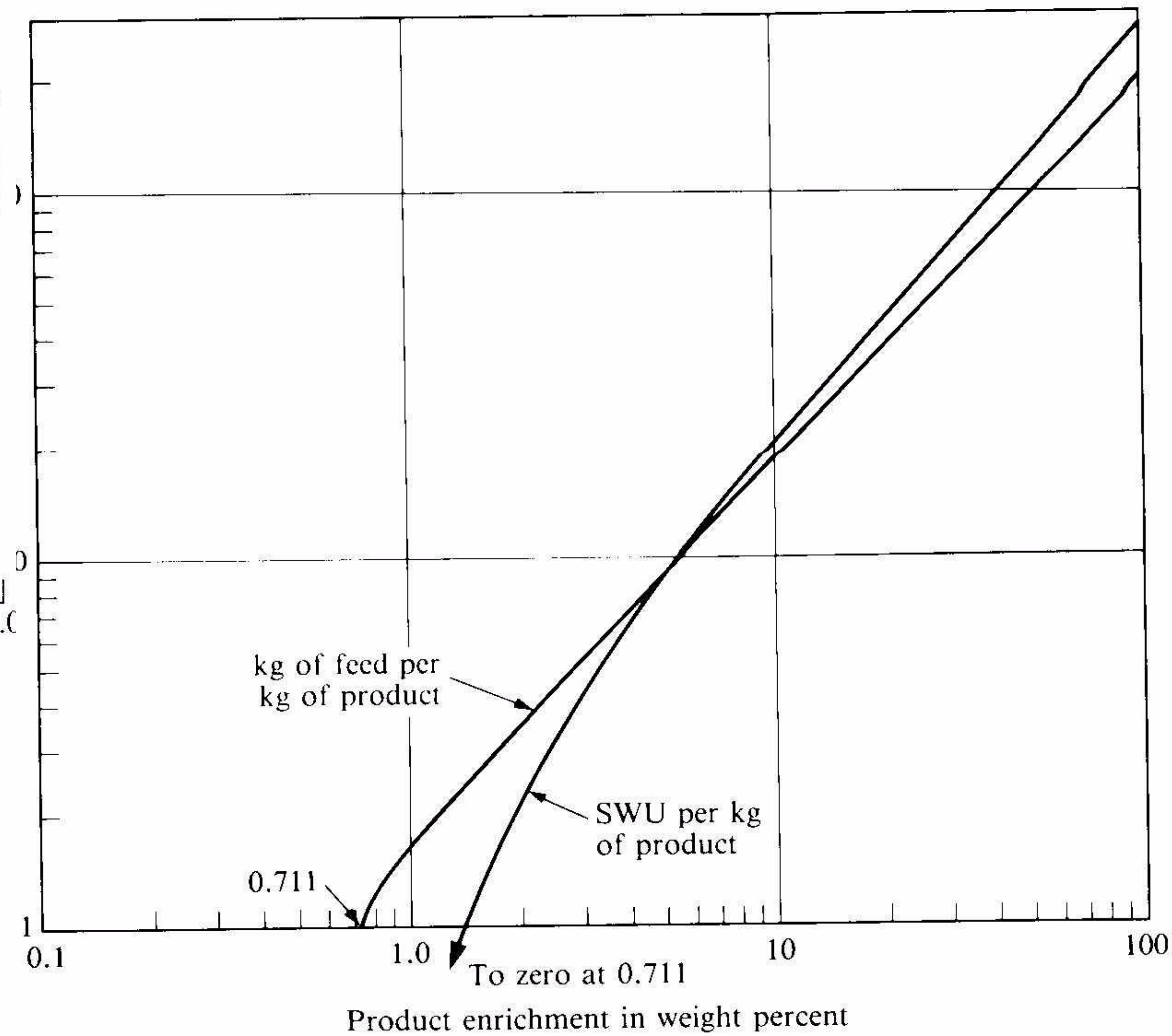


Fig. 4.33 Feed and separative work, in kg, as a function of product enrichment.

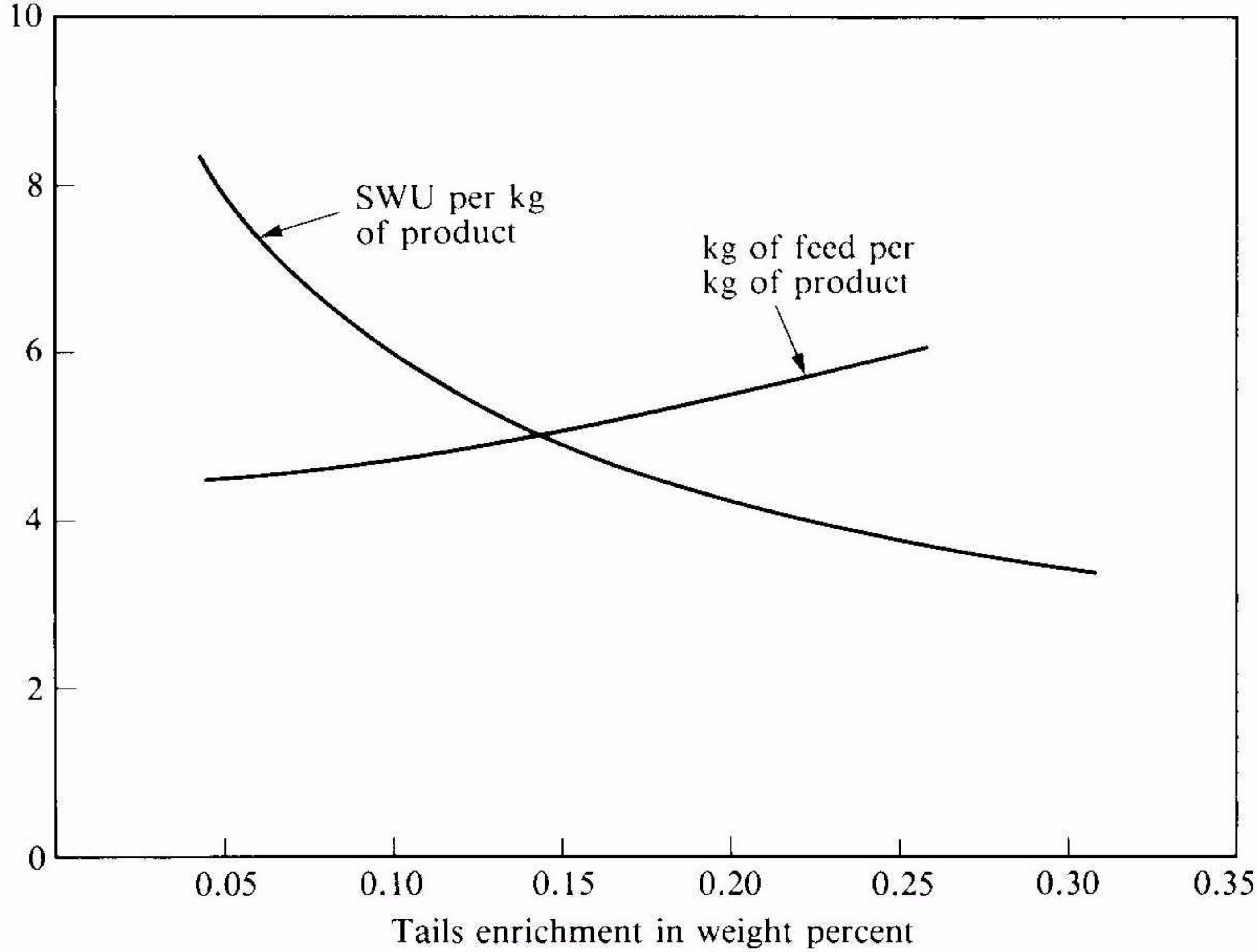


Fig. 4.35 Feed and separative work, in kg, as a function of tails enrichment.

Fuel Cycles
(Nuclear Resource utilization)

Definition- **The extent to which the world's nuclear resources are used compared to the extent to which they could be effectively used.**

Reactor	%fissile in	% fissile out	% Fissile Material Used
Light Water Reactor	3.5%	1.5%	57% (Rouben)
CANDU Reactor	.71%*	.5%*	30% (Rouben)*
Gas Cooled Reactor	8%	4-4.72%	41-50% (Argon)
Breeder Reactor	Ratio of creation to burn up "use" (.95-1.05) (Hitachi)		

*These percentages are based on CANDU core loaded with natural uranium

Fuel Cycles (Resource Limitation)

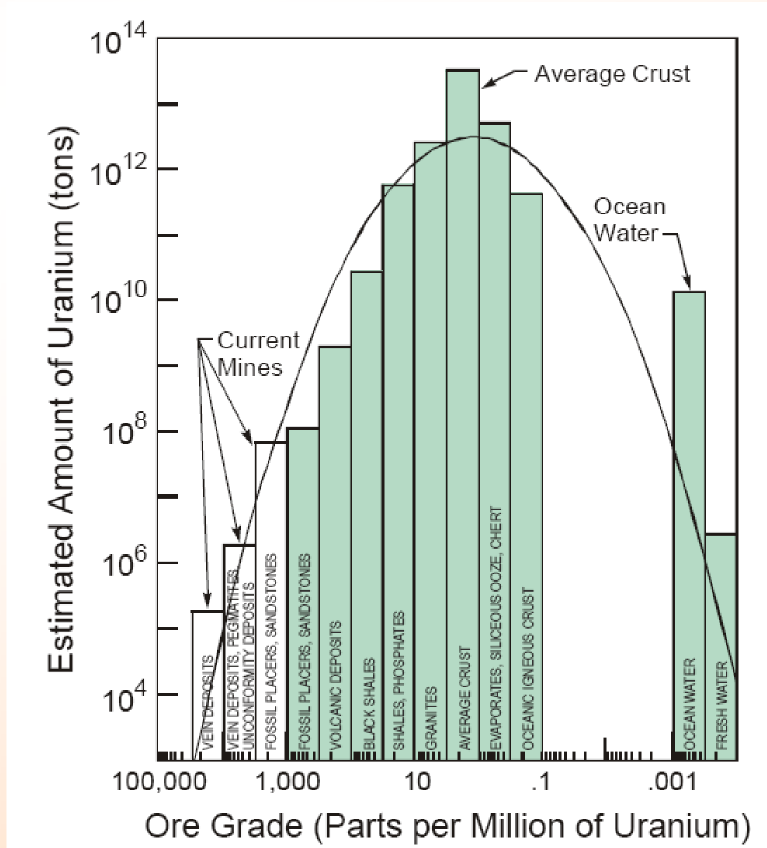
Resource limitation factor: As the price of uranium increases, the amount that can be mined profitably increases.

U.S. Forward-Cost Uranium Reserves by State, December 31, 2003						
	$30 per pound			$50 per pound		
State(s)	Ore (million tons)	Grade[a] (percent U_3O_8)	U_3O_8 (million pounds)	Ore (million tons)	Grade[a] (percent U_3O_8)	U_3O_8 (million pounds)
Wyoming	41	0.129	106	238	0.076	363
New Mexico	15	0.280	84	102	0.167	341
Arizona, Colorado, Utah	8	0.281	45	45	0.138	123
Texas	4	0.077	6	18	0.063	23
Other[b]	6	0.199	24	21	0.094	40
Total	**74**	**0.178**	**265**	**424**	**0.105**	**890**

[a]Weighted average percent U_3O_8 per ton of ore.

[b]Includes California, Idaho, Nebraska, Nevada, North Dakota, Oregon, South Dakota, and Washington.

(EIA)



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