Theoretical Energy Required Per SWU Using Gaseous Diffusion

- **From thermodynamics**

$$\frac{kWh}{SWU} = \frac{4RT}{M(1-\alpha)^2} \quad \text{where } R = 8.31441 \frac{J}{\text{mole } ^\circ K}$$

T = ° K and M = Molecular Mass

if T= 58° C,

$$\text{min Energy/SWU} = 702 \ \frac{kWh}{SWU}$$

$$\text{actually,} \qquad \approx 2{,}400 \ \frac{kWh}{SWU}$$

History

US Capacity in mid 1970's 17,000,000 SWU/y

Cascade Improvement & Cascade Uprating Prog (1983) $10{,}000{,}000 \ \frac{SWU}{y}$

total $27{,}000{,}000 \ \frac{SWU}{y}$

Because of plant cancellations in 1970's and 1980's, and because of European built plants, there is now considerable excess capacity.

Due to plant closures, the US now has ≈ 19 million SWU/y capacity. This is enough to produce 3.7% fuel to operate over 160-1,000 MWe power plants per year

Currently, over 90% of the world's enriched U comes from gaseous diffusion plants

Centrifuge Method

Date	Events
1938	*JW Beam, Germany in WWII*
1950's	*Germans built larger gas centrifuges*
1960's	*Centrifuges become competitive*
1970	*FRG and Netherlands build a plant*
1976	*Japanese build a plant*
1977	*Carter Administration announces that the next enrichment plant would use the gas centrifuge process.*
1985	*Almost completed gas centrifuge plant (8,800,000 SWU/y) shut down by Reagan administration for laser isotope plant.*

- -

Principles of Centrifuges

- **A rotating drum compresses gas molecules in the cylinder to outer wall**

- **Lighter molecules concentrate in the center**

Figure 3.7

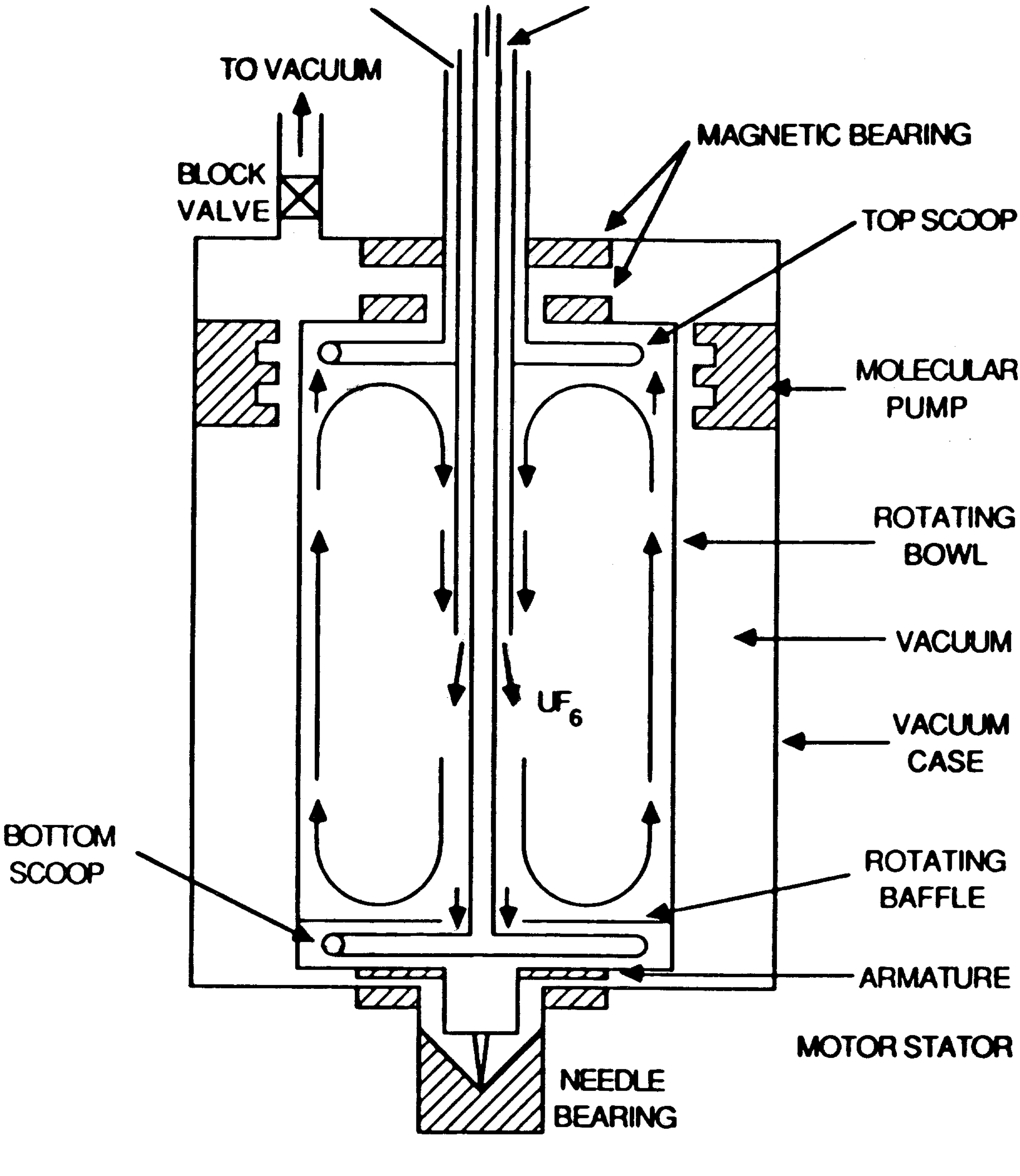


Fig. 3.7 A schematic showing the Zippe centrifuge machine.

Gas Centrifuge factor;

$$\alpha = 1 + \left\{ \frac{\left[M_H - M_L \right] \omega^2 a^2}{2RT} \right\}$$

where; ω = **angular velocity (rad/s)**

a = radius of rotor (inside dimension)

M_H = **Molecular Wt. of** $^{38}UF_6$

M_L = **Molecular Wt. of** $^{35}UF_6$

for 30 cm diameter rotor at 350 $\frac{m}{s}$ **@ 300 °K**

α **= 1.1 to 1.2** ***(Compare to gas diffusion)***

- -

Features

- **Small capacities; a 9,000,000** $\frac{SWU}{y}$ **plant requires 90,000 to 100,000 machines**

- **Reliability - if mean time between failure is 3 years, then more than 3 machines break per h**

- **Lower Power requirements ≈ 50** $\frac{kWh}{SWU}$

  if 1 kWh ≈ 5¢, then;

  Gas centrifuge cost ≈ $2.50/SWU
  Gaseous Diffusion ≈ $120/SWU

Nozzle Method

- **Developed by Becker in FRG, 1960 (later in South Africa, Netherlands)**
- **UF_6 (5%) + H_2 (95%) @ 20 -200 torr forced into orifice (See figure 3.8)**

  $$\alpha = 1.015$$
- **Must be very precise and clean ($\approx 30\mu$)**
- **Smaller number of stages than gaseous diffusion to get to 3% (500 vs 1200)**
- **Slightly higher electricity consumption**

  $$4000 \, \frac{kWh}{SWU}$$

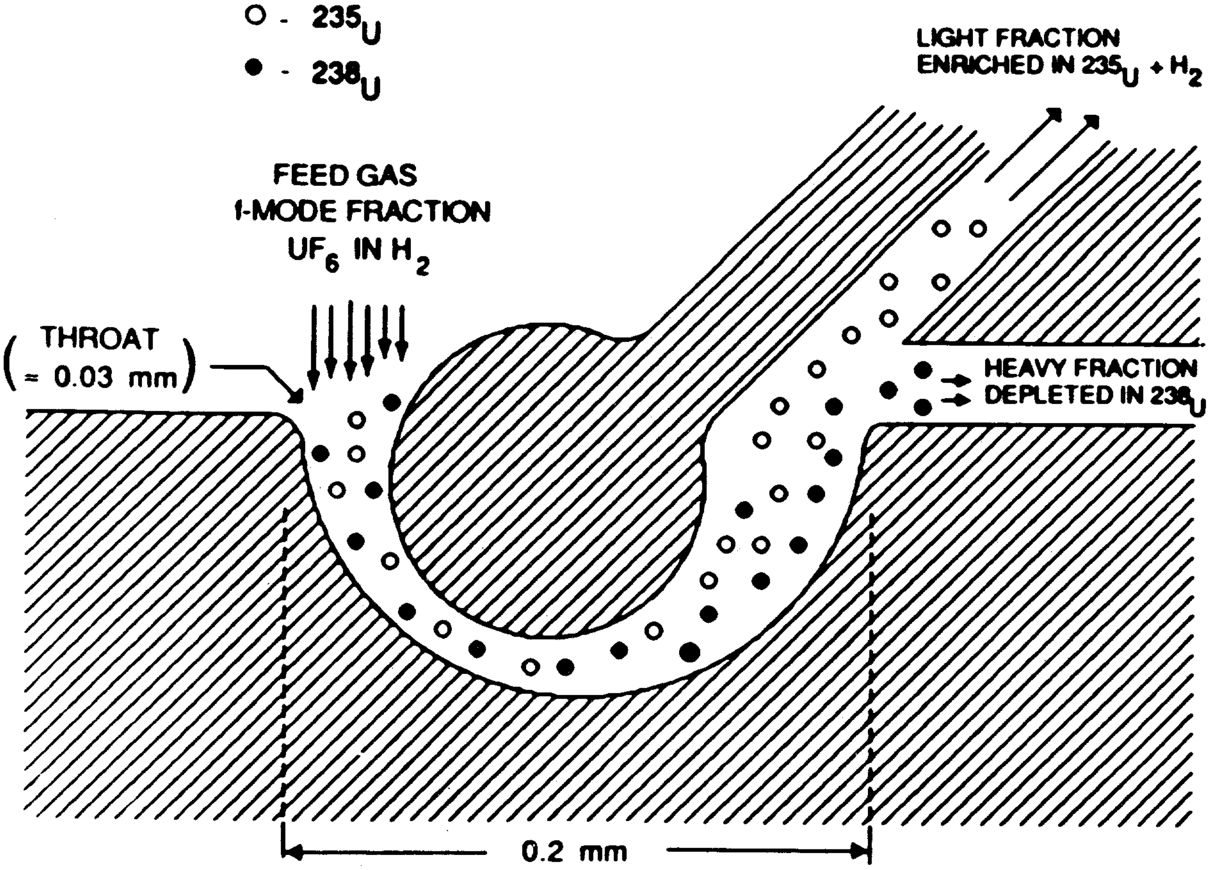


Fig. 3.8 Cross-sectional side view of an enrichment nozzle.

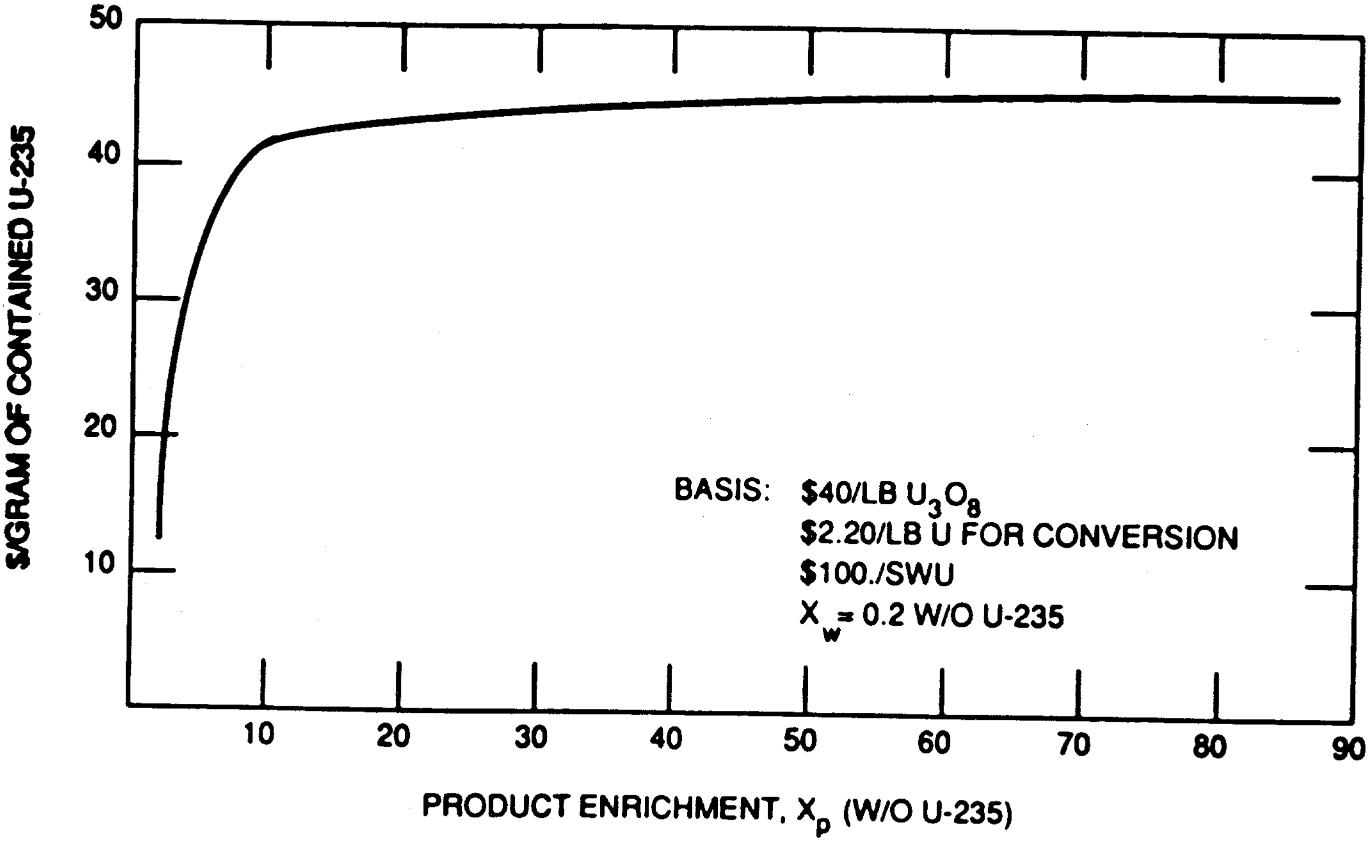


Fig. 1.11 The cost of enriched uranium for enrichment up to 90%, for tails equal to 0.2 and 0.3%.

Atomic Vapor Laser Isotope Separation (AVLIS)

- **First demonstrated in 1975**

  - **Principle relies on many absorption lines in U (300,000)**

- **There is a significant separation between ^{35}U and ^{38}U which can be exploited by the use of variable wavelength lasers.**

Figure 3.9
Figure 3.10

1.) Pool of liquid U formed

2.) Photo excite ^{35}U at 5915Å

3.) Use UV light to ionize excited atom

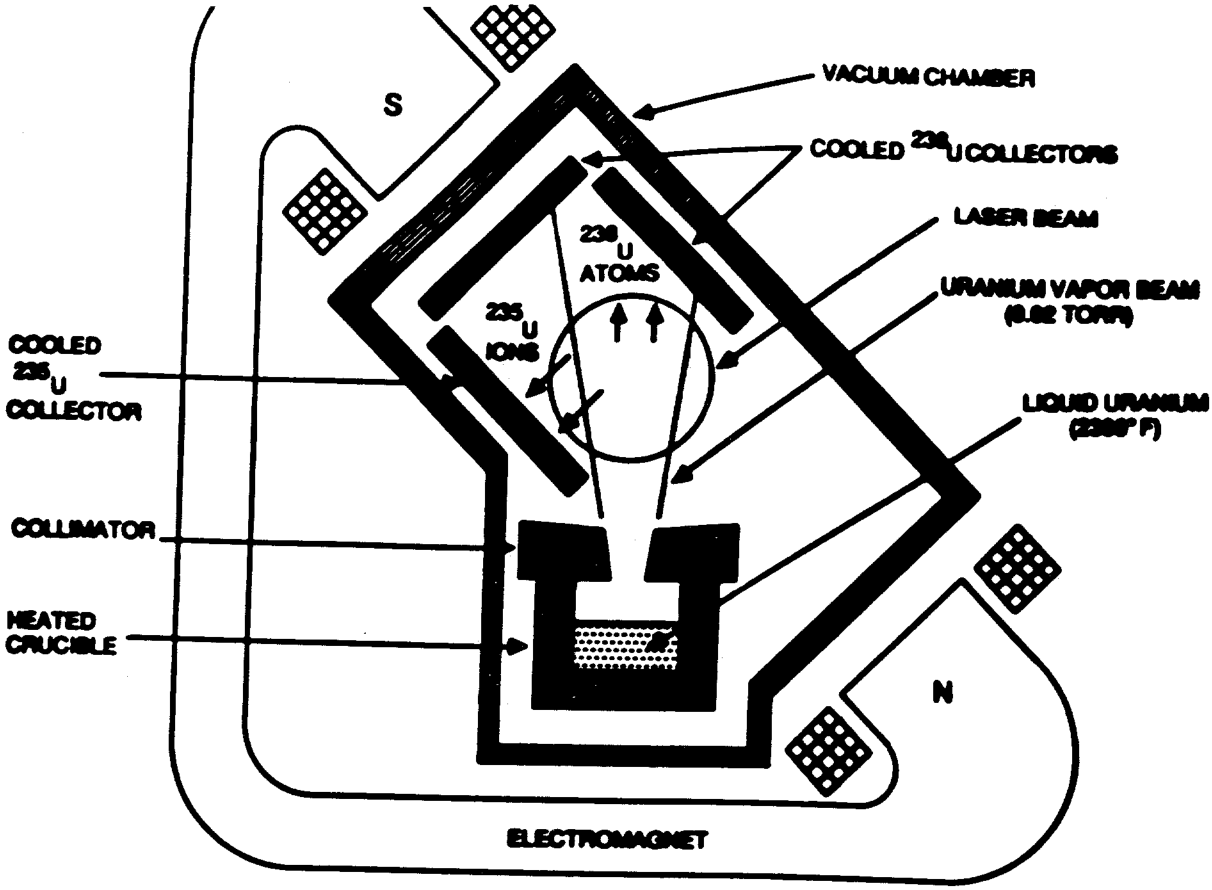
4.) Collect positively charged ^{35}U

$$\text{Advantage - } 300\ \frac{\text{kWh}}{\text{SWU}}$$

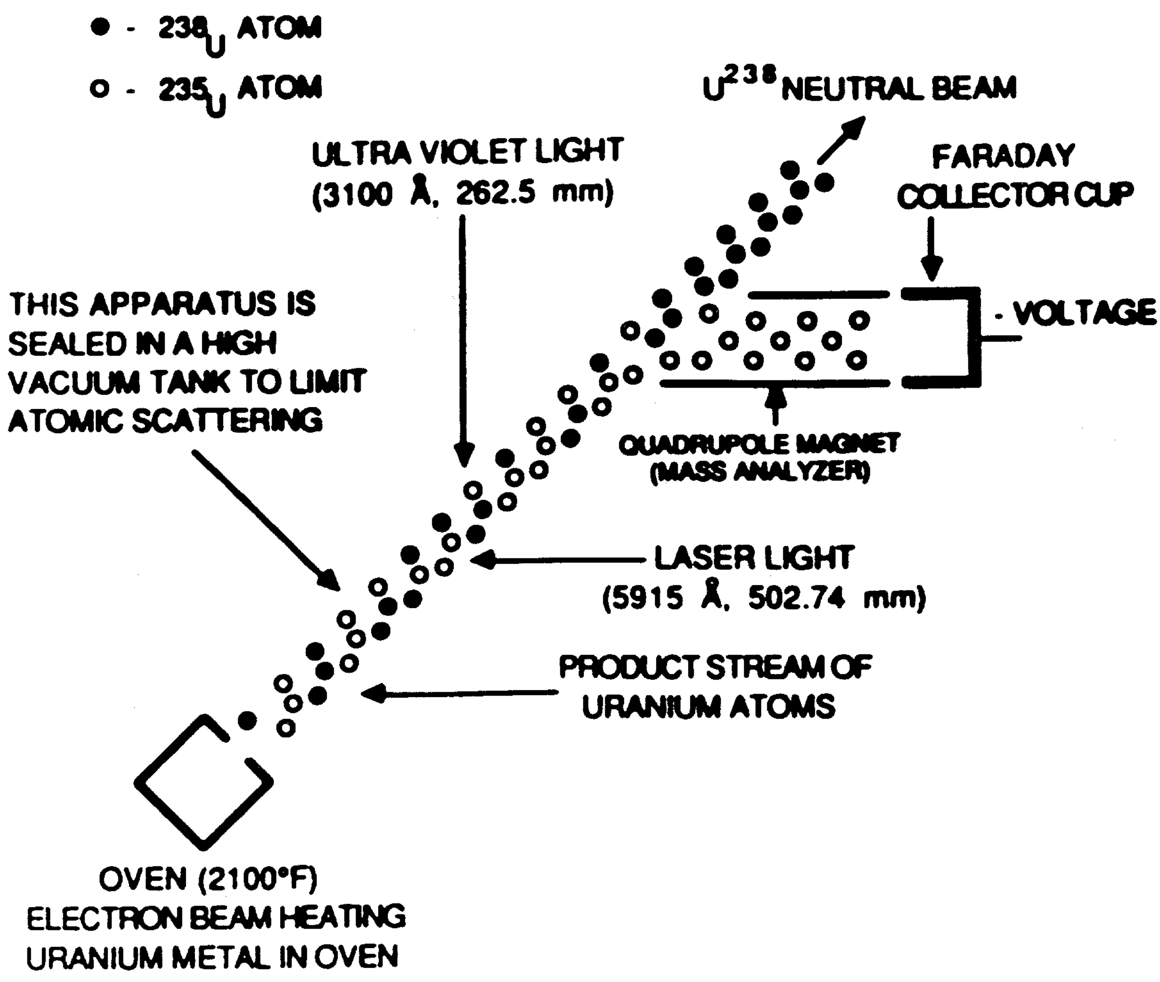
plus less moving parts and higher reliability

- **In June, 1999 the US Government, after spending several billion dollars to develop the AVLIS process, first at Exxon and later at LLNL, abandoned the project**

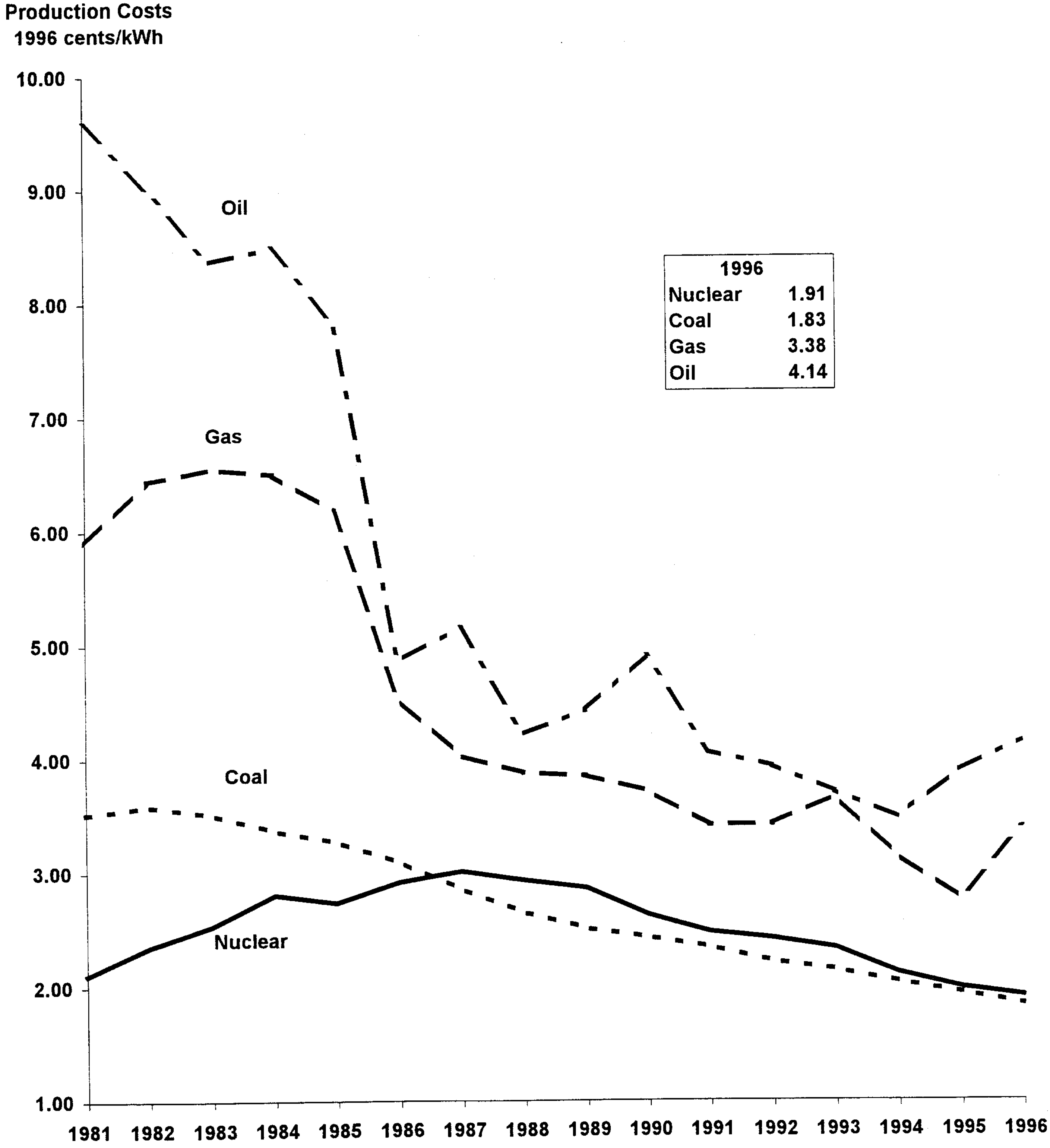
- **The US is now investigating a molecular process called SILEX developed in Australia**



.10 Transverse section of AVCO-Exxon laser uranium isotope separator



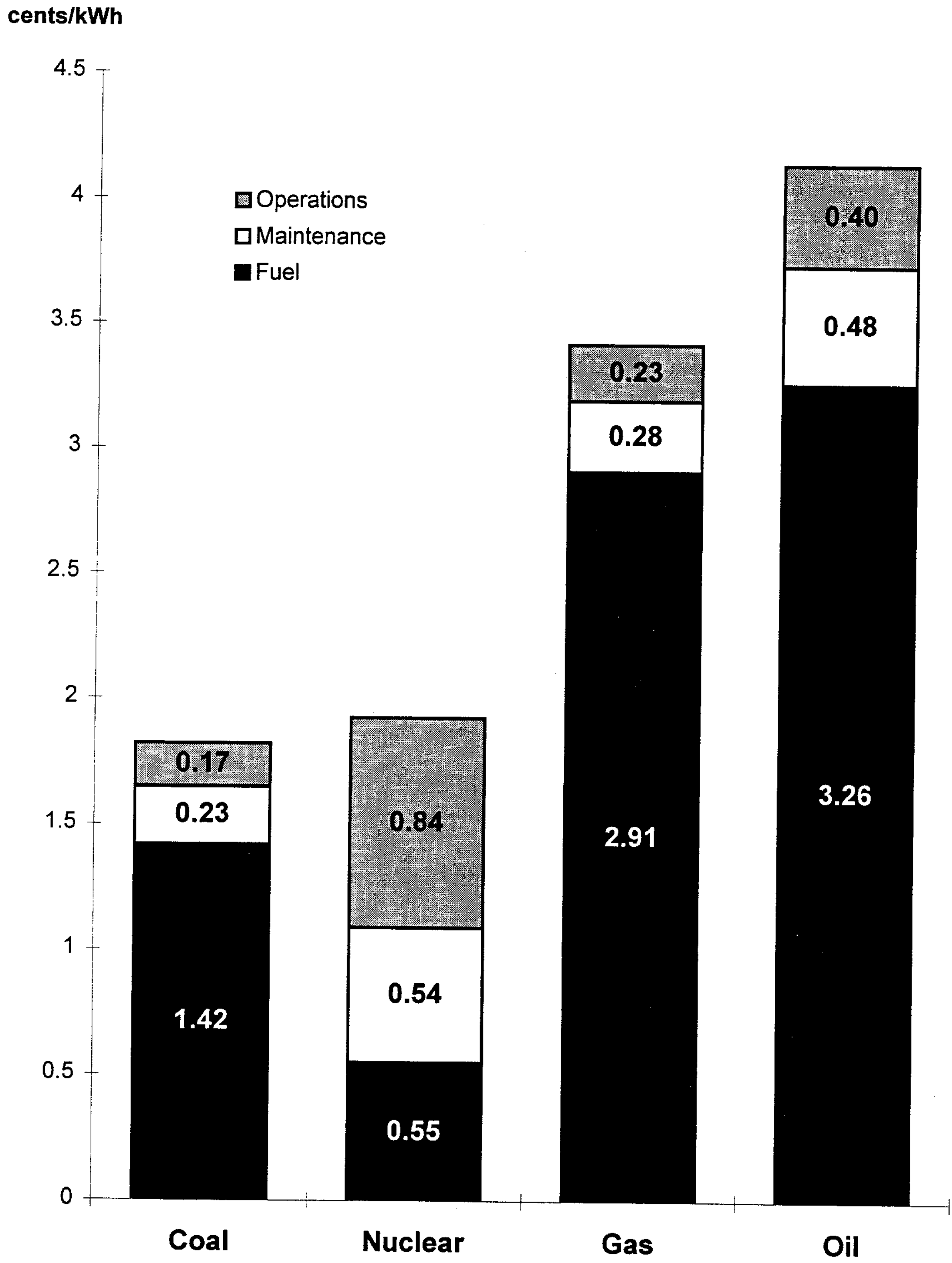
U.S. ELECTRICITY PRODUCTION COSTS *
(Constant 1996 cents/kWh)



* Fuel costs are included.

Source: Utility Data Institute for actual costs; converted to 1996 dollars by NEI.

1996 Distribution of Electricity Production Costs



Source: Utility Data Institute

Overall Costs For Enriched U

$$PE = \frac{(PU + PC)F}{P} + PS \bullet S$$

Price of Enriched U (PE) **Price of Natural U** (PU) **Conversion Costs** (PC) **SWU Costs** (PS)

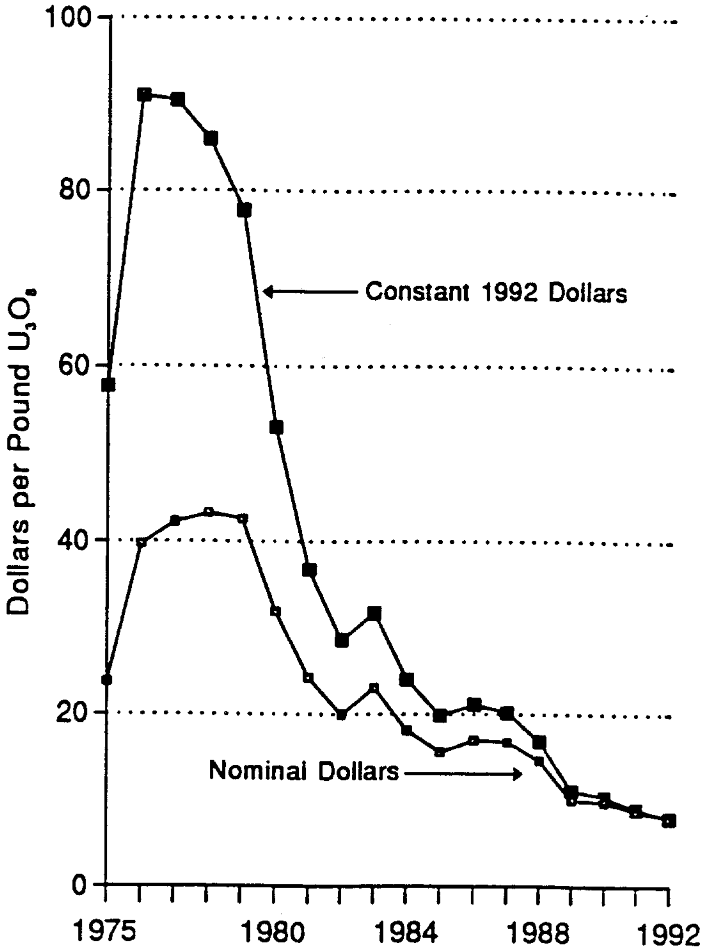
The price of enriched U can be optimized with respect to waste tails

$$\frac{\delta \, PE}{\delta x_w} = 0$$

gives;

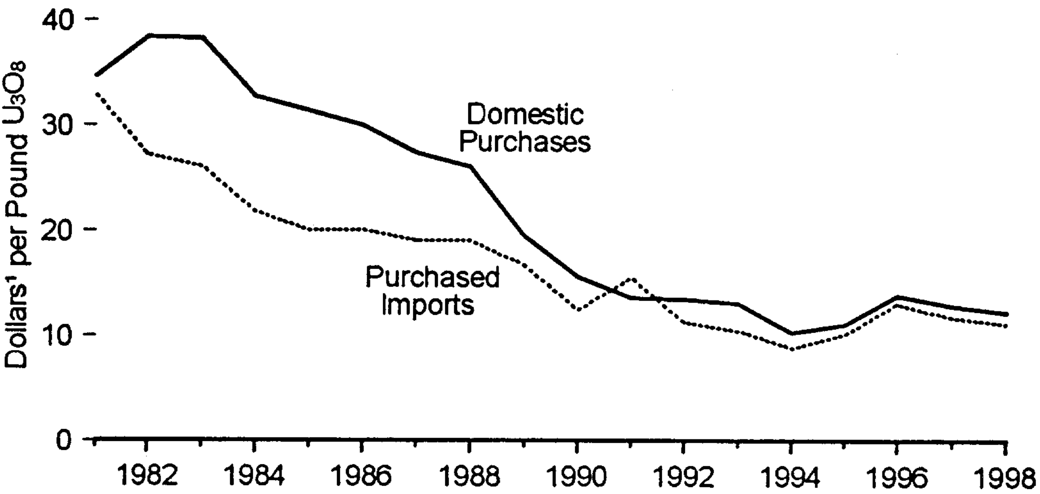
$$\frac{PU + PC}{PS} = \frac{(x_f - x_w) \bullet (1 - 2x_w)}{x_w(1 - x_w)} + (1 - 2x_f)\ln\left[\frac{x_w(1 - x_f)}{x_w(1 - x_w)}\right]$$

Figure 3. Spot-Market Prices for Uranium, 1975-1992



Sources: **Nominal Dollars**–Nuexco, *Monthly Report*, January 1993, p. 39. **Constant Dollars**–Historical Nuexco monetary values converted to 1992 dollars using the Gross Domestic Product Implicit Price Deflators generated for but not published in the *Annual Energy Outlook 1993*, DOE/EIA-0383(93) (Washington, DC, January 1993).

Average Prices, 1981-1998



Source: Table 9.3.

Problem -2

Calculate the cost of enriched U (in $\frac{\$}{kg}$)if the product is 2.8% enriched, the tails assay is 0.25%, and the conversion loss is 0.5%. Assume the price of natural U is $40/kg, the cost of conversion is $6/kg, and the price is $90/SWU.

Answer:

$$\frac{F}{P} = \frac{(2.8-0.25)}{(0.7111-0.25)} = 5.531$$

$$V(x_f) = (2\bullet 0.00711-1) \bullet \ln[\frac{0.00711}{(1-0.00711)}]$$
$$= 4.869$$

$$V(x_p)= (2\bullet 0.028-1) \bullet \ln[\frac{0.028}{(1-0.028)}] = 3.348$$

$$V(x_w)=(2\bullet 0.0025-1) \bullet \ln[\frac{0.0025}{(1-0.0025)}]=5.959$$

$$S=3.348+4.531\bullet 5.959-5.531\bullet 4.869=3.418 \quad \frac{SWU}{kg}$$

$$PE=[\frac{40}{(1-0.005)} +6] \bullet 5.531+90 \bullet 3.418= \$ 563/kg$$

Total Fabricated Costs

$$FF = \left\{ \left[\frac{PU}{(1-\ell_f)\bullet(1-\ell_c)} \right] + \frac{PC}{(1-\ell_f)} \right\} \frac{F}{P} + \frac{PS}{(1-\ell_f)} \bullet S + PF$$

ℓ_c = fraction of U lost in conversion
ℓ_f = fraction of U lost in fabrication
PF = Cost of Fabricated Fuel

Problem -3

What is the cost of fabricated fuel if the cost for fabrication is \$400/kg and there is an 0.8% loss during fabrication. Use the numbers from problem 2 for nat. U, conversion, and enrichments costs.

$$FF = \left\{ \left[\frac{40}{(1-0.005)\bullet(1-0.008)} \right] + \frac{6}{(1-0.008)} \right\} \bullet 5.531$$

$$+ \frac{90}{(1-0.008)} \bullet 3.418 + 400$$

FF= 966 \$/kg

What About Using HEU from Nuclear Weapons?

- **Typically ≈ 90% U-235**

- **U. S. and Russian HEU warheads and stockpiles could contain the equivalent of almost 300 million SWU**

- **World current demand (1996) for enrichment is 32 million SWU/y**

- **If half of the weapons were decommissioned and 75% of that were was converted to LEU, this would amount to 112 SWU.**

- **Therefore, HEU from weapons could replace enrichment services for ≈ 3.5 years.**

Important Points About the Nuclear Fuel Cycle

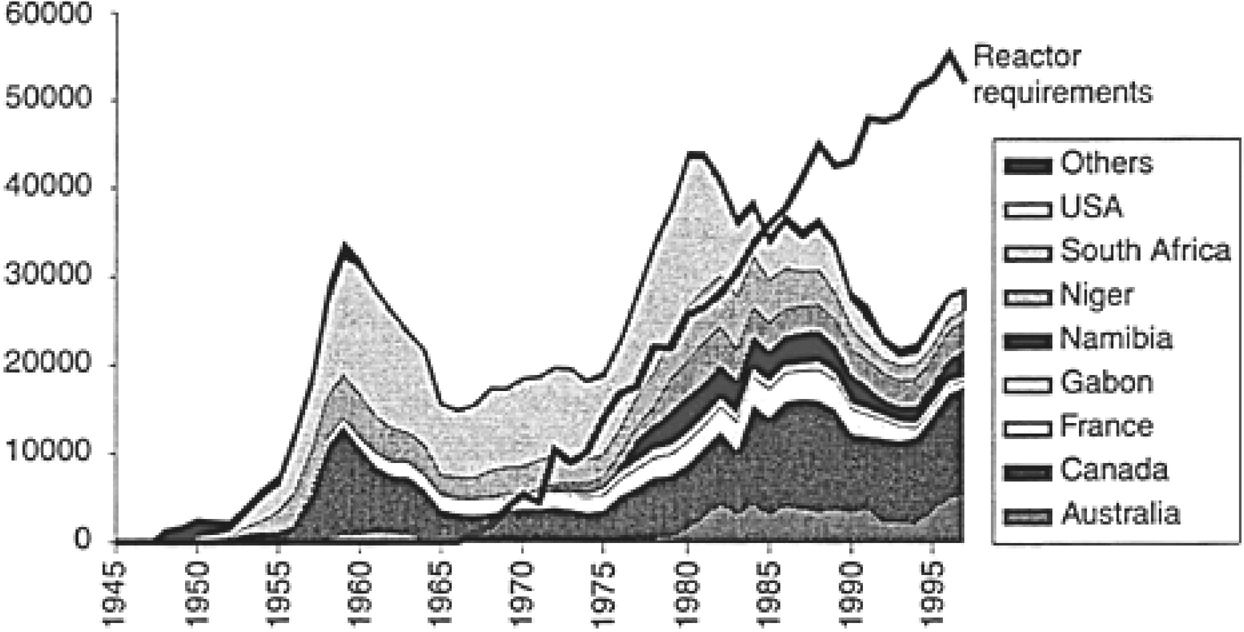
- **Only 10% of U. S. Uranium requirements are met from domestic sources, 90% comes from outside the U. S. (85% from Canada)**

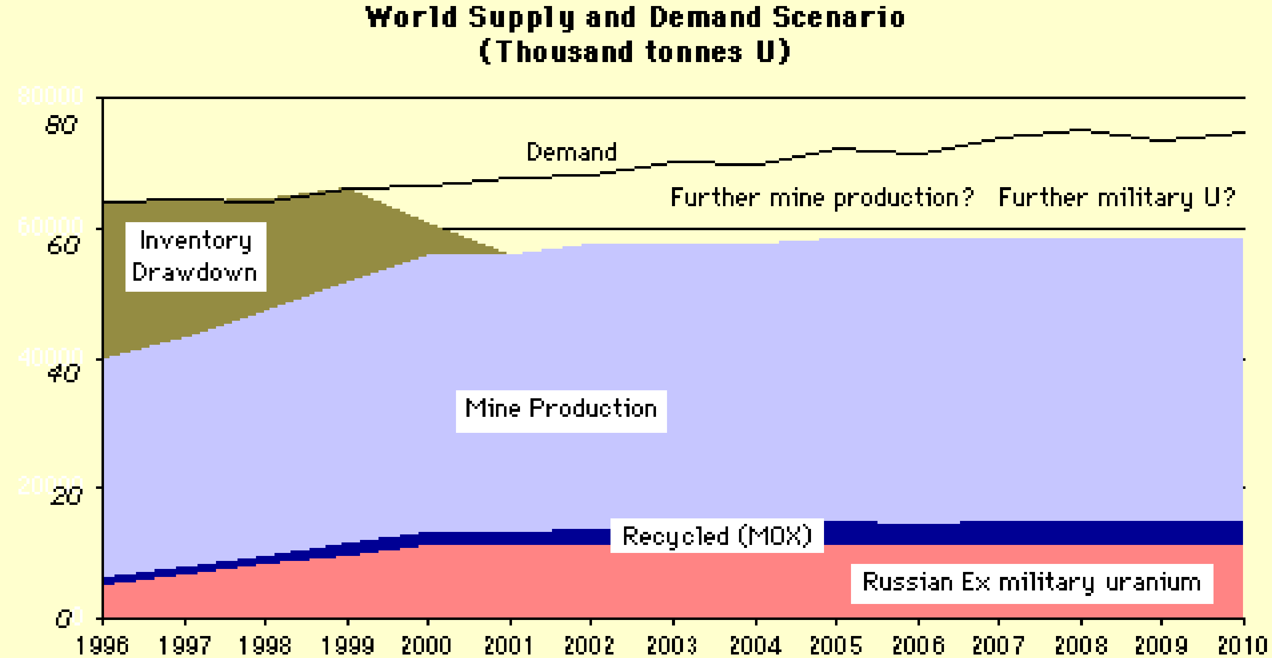
- **Imported Russian HEU could provide 40% US in future**

- **Worldwide Demand for Enrichment-1996 MSWU/Year**

    - **US-11.2**
    - **Eastern Europe-4.3**
    - **Western Europe-12.0**
    - **Far East-6.2**
    - **Other-0.4**
    - **Total ≈ 34**

Facility	**Countries Involved**	**SWU/y Capacity (12/31/95)**	**% of World Market (1994?)**	**Technology Used**
U. S. Enrichment Corp.	U.S.	19.3	≈40 (70% of US)	Gaseous Diffusion
Eurodif	France, Belgium, Spain, Italy	10.8	≈20	Gaseous Diffusion
China Nucl. Energy Ind. Corp.	Peoples Rep. of China	0.5	NA	Gaseous Diffusion
Minatom	Russia	14	≈30	Gas Centrifuge
Urenco	Netherlands, Germany, U. K.	3.4	≈10	Gas Centrifuge
Power Reactor & Nuclear Fuel Dev. Corp.	Japan	0.2	NA	Gas Centrifuge
Japan Nuclear Fuel Industries Company	Japan	0.6	NA	Gas Centrifuge
Atomic Energy Commission	South Africa	0.3	NA	NA
		total-48.7		


60000
50000
40000
30000
20000
10000
0
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
Reactor requirements
Others
USA
South Africa
Niger
Namibia
Gabon
France
Canada
Australia



Sources: Demand & Mine production: *The Uranium Institute 'Global Nuclear Fuel Market, Supply and demand 1995-2015' (reference scenario)*

MOX & Russian ex military: *industry estimates*

Problems Due Monday, Sept. 28, 1999

4.) **Assuming that the price per SWU is $90 and the cost of conversion is $3.3/kgU, what is the price of the U_3O_8 ($lb U_3O_8) beyond which it will cost less to enrich the already mined , purified, and converted (to UF_6) tails that contain 0.2% ^{35}U rather than mine new U?**

[Assume the product will be 3% enriched in either case and the new tails will be 0.1%(when the old tails are enriched). Tails stored as UF_6 cost nothing.]