Enrichment and Conversion of Fission Reactor Fuel Elements

- **Two fissile isotopes commonly considered:**
  - ^{235}U **(Use enrichment)**
  - ^{239}Pu **(Use reprocessing)**
- **U.S.(weapons---->submarines---->civilian)**
  1944 present
- **Canada..Commercial..Heavy Water + Nat. U**

Gaseous Diffusion Process - UF_6

• Relies on the fact that UF_6 is solid at RT and a vapor at moderate temperatures.

(Figure)

• Gaseous diffusion relies on the difference in the rate which $^{235}UF_6$ and $^{238}UF_6$ diffuse through a barrier containing many holes.

• The relative speed of the two molecules can be derived from their kinetic energies;

$$kT = \frac{MV^2}{2} \quad M = \text{molecular mass}$$

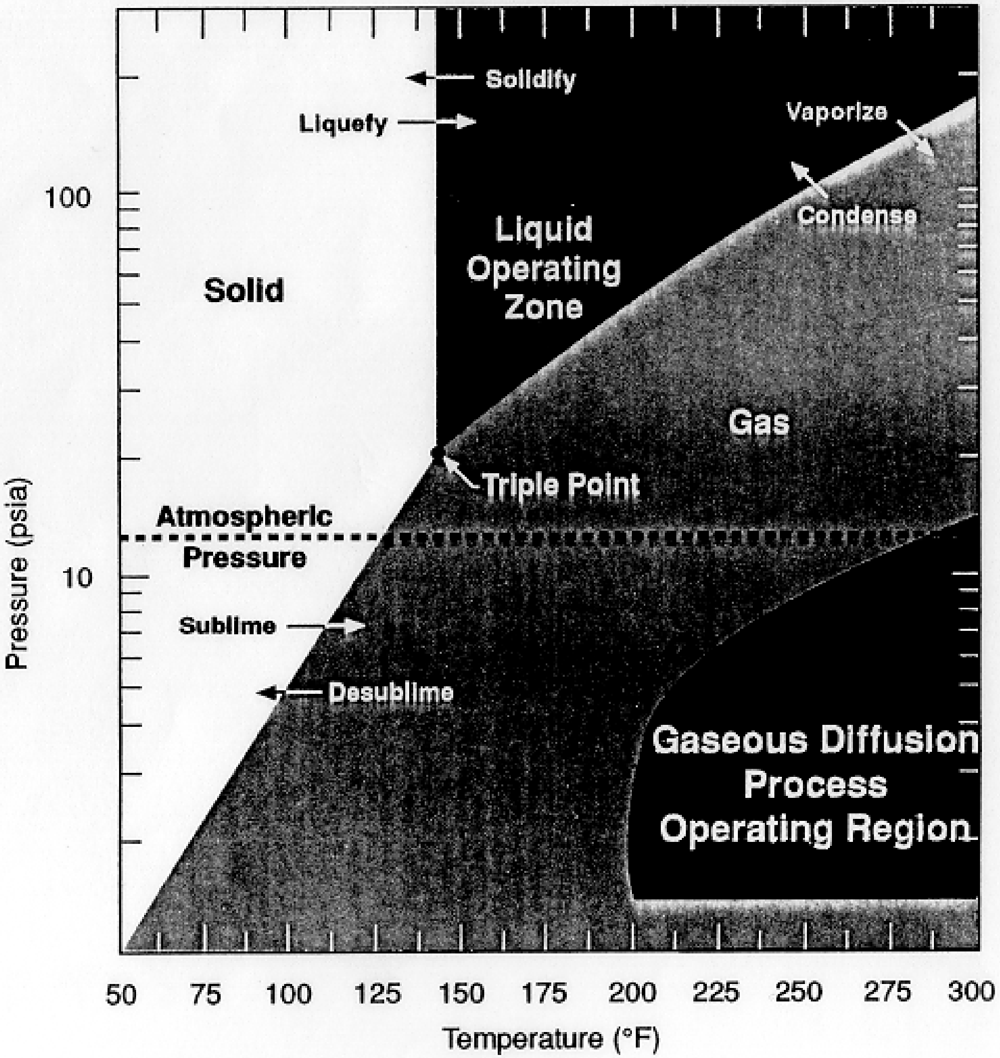
or,

$$\frac{V_L}{V_H} = \sqrt{\frac{M_H}{M_L}} = \alpha$$

GASEOUS DIFFUSION OPERATIONS

UF_6 Phase Diagram

DWG. NO. K/G 93-370R3 GSS



- **Relative frequency at which molecules of different species pass through a small hole is proportional to the speed of the molecule.**

Hence the ratio of $\frac{^{35}U}{^{38}U}$ on the low pressure side is greater than the $\frac{^{35}U}{^{38}U}$ ratio on the high pressure side.

For $^{235}UF_6$ and $^{238}UF_6$, maximum α is;

$$\alpha = \sqrt{\frac{(238 + 6 \bullet 19)}{235 + 6 \bullet 19}}$$

$$\alpha = 1.004289$$

(more realistic value is 1.003 due to down stream back pressure and leaks)

- **Low value of α requires a very large number of steps**

Figures (2)

- **<u>What is the Barrier?</u> (<u>mostly classified</u>)**
    - **Very thin and delicate**
    - **100's of millions of holes/cm3**
    - **≈ 20 Å diameter hole**
    - **Must exclude organic materials and air to avoid plugging**
    - **Materials reported to be sintered Ni and anodized Al**

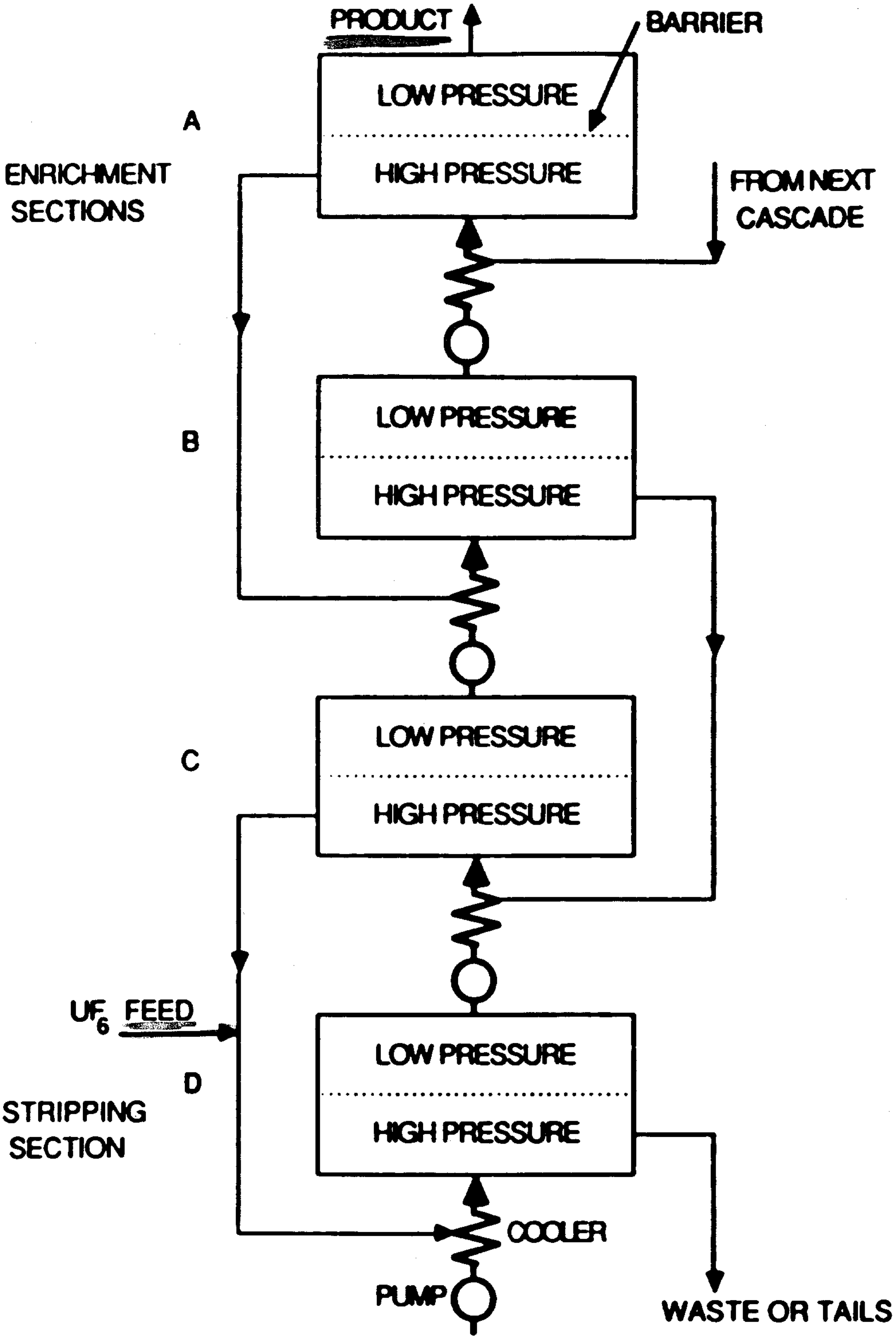
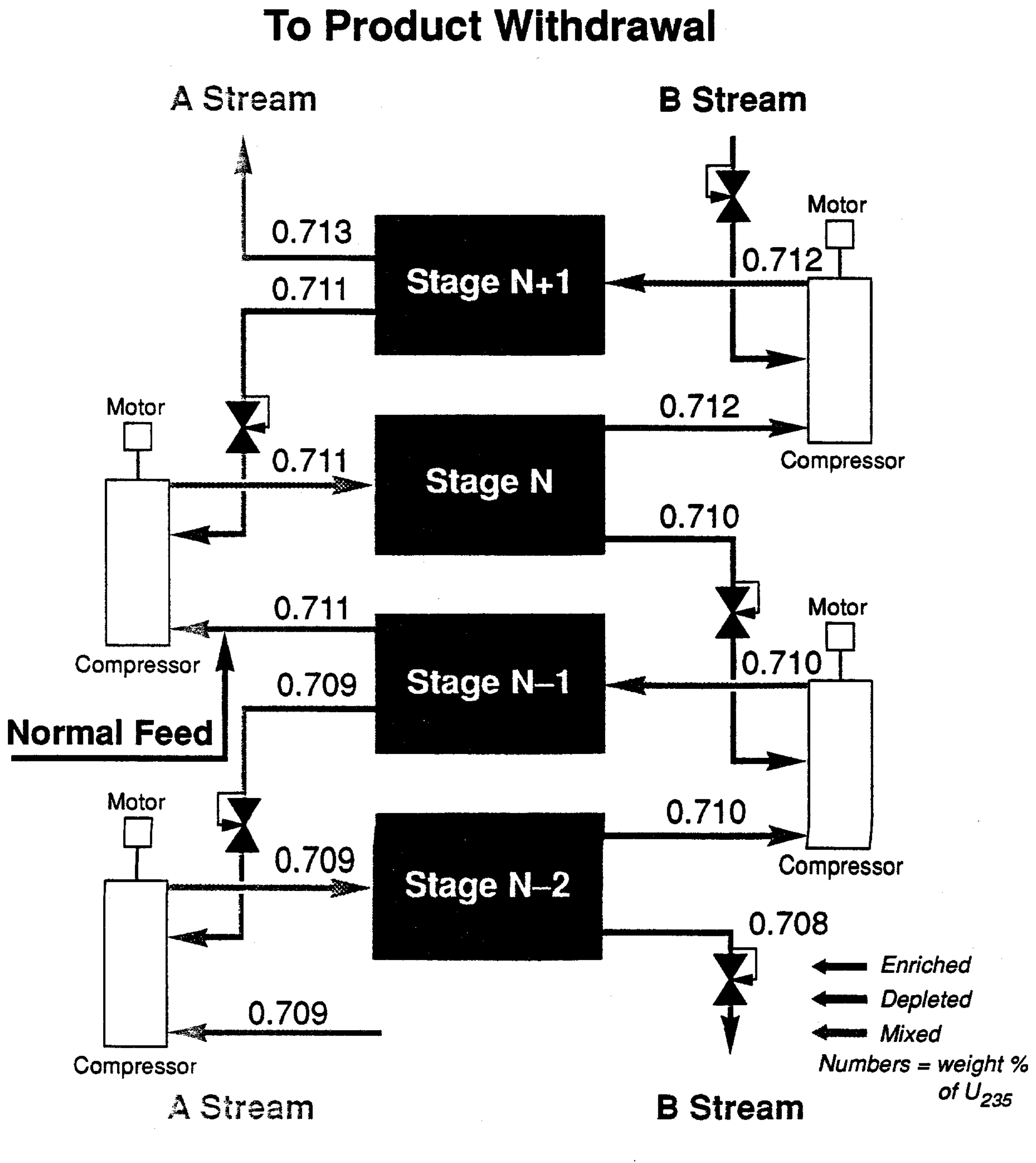


Fig. 3.4 A typical gaseous diffusion cascade for enriching and stripping. Note th
pressure is less than atmospheric in all stages in order to increase the mfp of the mole

GASEOUS DIFFUSION OPERATIONS

Separation At The Normal Feedpoint



To Product Withdrawal

A Stream

B Stream

Motor

0.713

0.711

Stage N+1

0.712

Motor

0.712

Compressor

0.711

Stage N

0.710

Compressor

Motor

0.711

0.710

Compressor

0.709

Stage N–1

Normal Feed

Motor

0.710

Compressor

0.709

Stage N–2

0.708

0.709

Compressor

Enriched

Depleted

Mixed

Numbers = weight % of U_{235}

A Stream

B Stream

To Depleted Withdrawal (0.2–0.4%)

DWG. NO. K/G 93-376R GSS

More complete analysis of U enrichment, see;

Benedict, M, T.H. Pigford, and H.M. Levi, "Nuclear Chemical Engineering", 2nd ed., McGraw Hill Book Company, NY, 1981

Villani, S, ed., "Uranium Enrichment", Springer Verlag, NY, (1979)

Cochran, R. C. and N. Tsoulfanidis, "The Nuclear Fuel Cycle: Analysis and Management", American Nuclear Society, La Grange Park, IL, (1990)

Important Variables and Equations

kg U Feed (F) = kg Enriched U Product (P)
+ kg U Waste (W)

$$x_f^F F = x_p^P P + x_w^W W$$

where x_f = wt. fraction of ^{35}U in feed

x_p = wt. fraction of ^{35}U in product

x_w = wt. fraction of ^{35}U in waste

(Note: F, P, & W could be in kg or kg/unit time)

- 2 eqs. and 6 variables, F, P, W, x_f, x_p, x_w
- Trick is to solve for 2 in terms of the other 4!

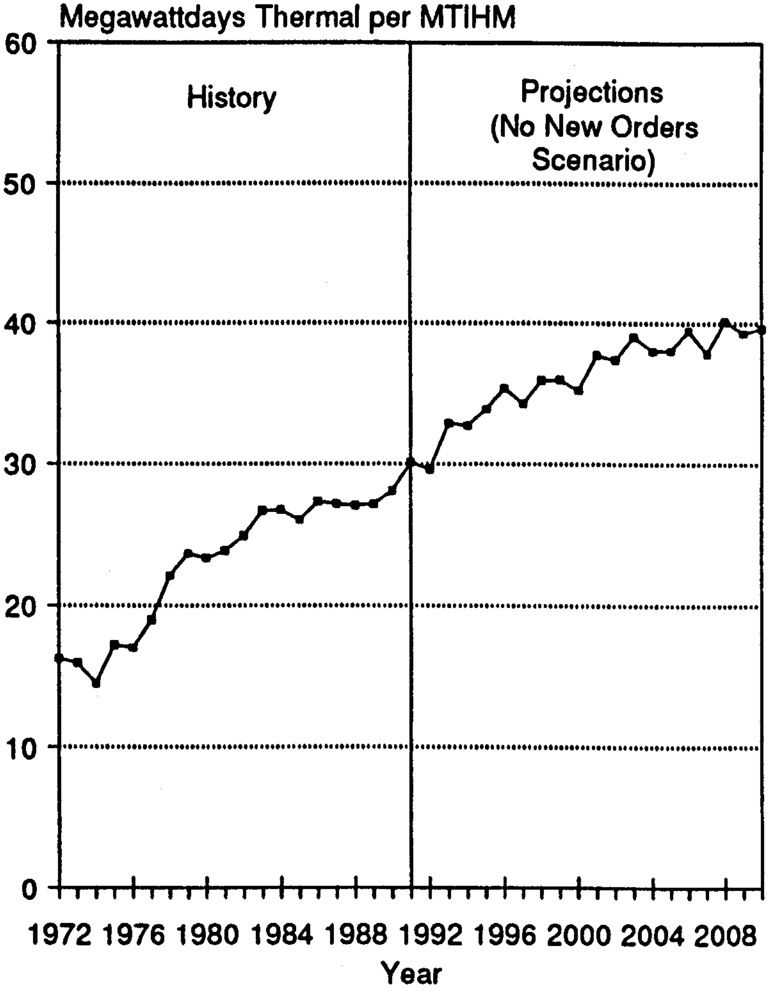
1.) x_f = 0.711% now (1996)
2.) x_p = as requested by the customer
Table 1.1 and 2 figures

3.) x_w = could be between 0.2 and 0.3 %, currently in the U.S. is 0.3%

Table 1.1
Summary of Fuel Characteristics in Fission Power Plants
(After Benedict-1981)

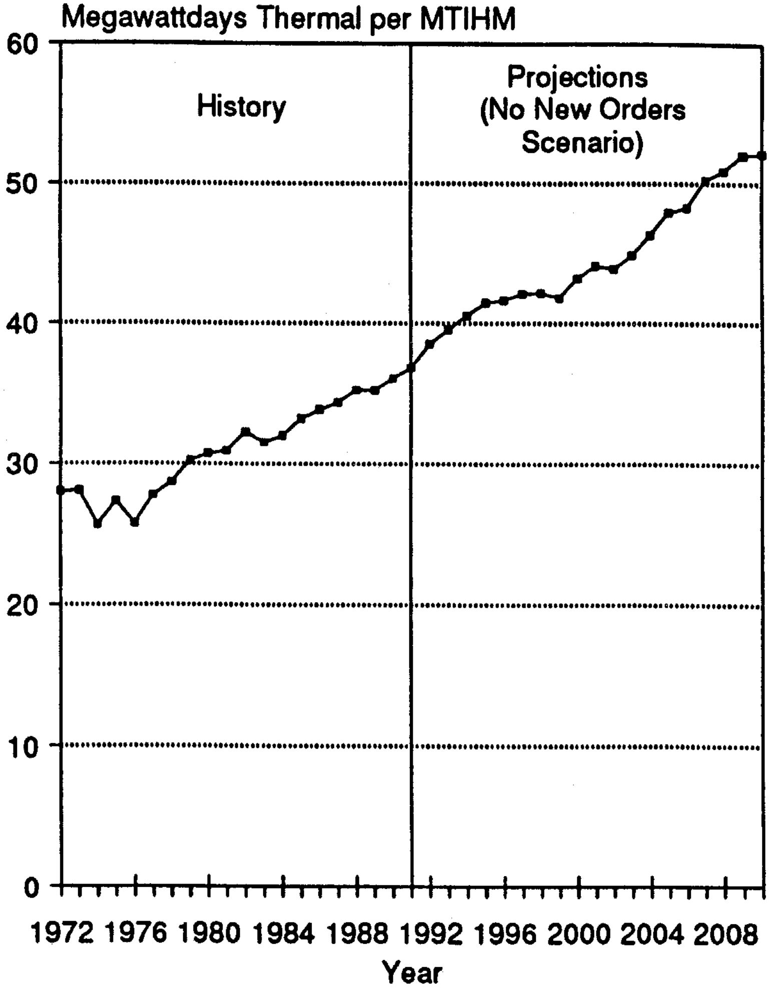
	BWR	**PWR**	**HTGR**	**CANDU**	**LMFBR**
MW(e)	1100	1100	330	508	1200
Thermal Eff.-%	33	33	39	30	40
Assembly Geometry	8x8 9x9	17x17	Hexagonal	Cylindrical	Hexogonal
Assembly Length-m	3.8	3.7	0.78	0.5	1
# of Assemblies	590	180	1482 -6/column	4680 12/channel	360
Core Ht-m	3.8	3.7	4.75	5.95	1
kg Fuel /assembly	270	600	22	37	80
Tot.tonne fuel in core	138	90-100	0.77-^{235}U 16-^{232}Th^{a}	105	29
BU-MWd per MTU	30,000	30,000	100,000	8,000	100,000
≈% Fuel Replaced/y	25	33	18	continuous	Varied
Enrichment-%	1.8	2.8	93	0.711	15-20 ^{239}Pu
Power Density-(kW/liter)	54	100	8	12	280
Linear Ht Rate-kW/m)	19	17	8	26	29
a-Initial Loading					

Figure 7. Average Annual Equilibrium-Cycle Discharge Burnup for U.S. Boiling-Water Reactors,1972-2010



Source: Actual Data: Energy Information Administration, Form RW-859, "Nuclear Fuel Data" (1991). Projections: International Nuclear Model, File CN6933.PRJ.INM92. OUTPUT, August 1992, and Form RW-859, "Nuclear Fuel Data" (1991).

Figure 8. Average Annual Equilibrium-Cycle Discharge Burnup for U.S. Pressurized-Water Reactors, 1972-2010



Source: Actual Data: Energy Information Administration, Form RW-859, "Nuclear Fuel Data" (1991). Projections: International Nuclear Model, File CN6933.PRJ.INM92. OUTPUT, August 1992, and Form RW-859, "Nuclear Fuel Data" (1991).

A PORTSMOUTH DEPLETED CYLINDER STORAGE YARD

89-110-113

4.) P = mass of desired product

One can solve the equations above;

$$F = P\,\frac{(x_p - x_w)}{(x_f - x_w)}$$

$$W = P\,\frac{(x_p - x_f)}{(x_f - x_w)}$$

Feed factor is defined as;

$$\frac{F}{P} = \frac{(x_p - x_w)}{(x_f - x_w)}$$

Waste factor ;

$$\frac{W}{P} = \frac{F}{P} - 1$$

==

How Much Energy is Required to Reach a Given Enrichment?

Define Separative Work Unit (SWU) as;

"resource required to perform the enrichment to the desired level of x_p given x_f and x_w. For gaseous diffusion this is equivalent to electrical energy"

# of SWU's produced by an enrichment plant

during a time period t,

$$SWU = \left[P \bullet V(x_p) + W \bullet V(x_w) - F \bullet V(x_f)\right]t$$

The quantity V(x_i) is called the separation potential and is given by;

$$V(x_i) = (2x_i - 1)\ln\left[\frac{x_i}{1 - x_i}\right]$$

where i = f,p,w

We normally quote SWU's per unit of product (P•t) where P is feed rate.

$$S = \frac{SWU}{P \bullet t} = V(x_p) + \left(\frac{W}{P}\right) \bullet V(x_w) - \left(\frac{F}{P}\right) V \bullet (x_f)$$

$$S = \text{“SWU” factor}, \frac{SWU}{kg}$$

Figure 3.6 plus Schematic

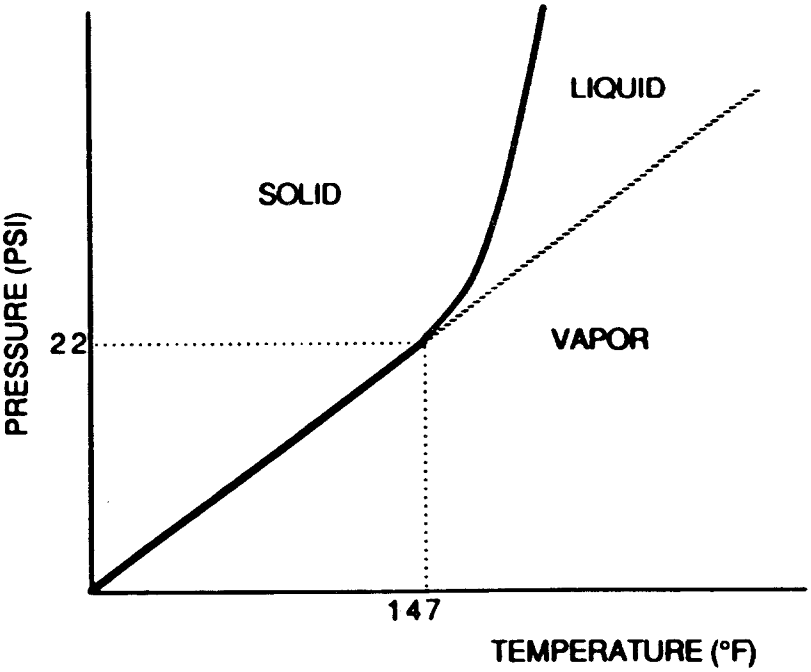


Fig. 3.1 Phase diagram of uranium hexafluoride (UF_6).

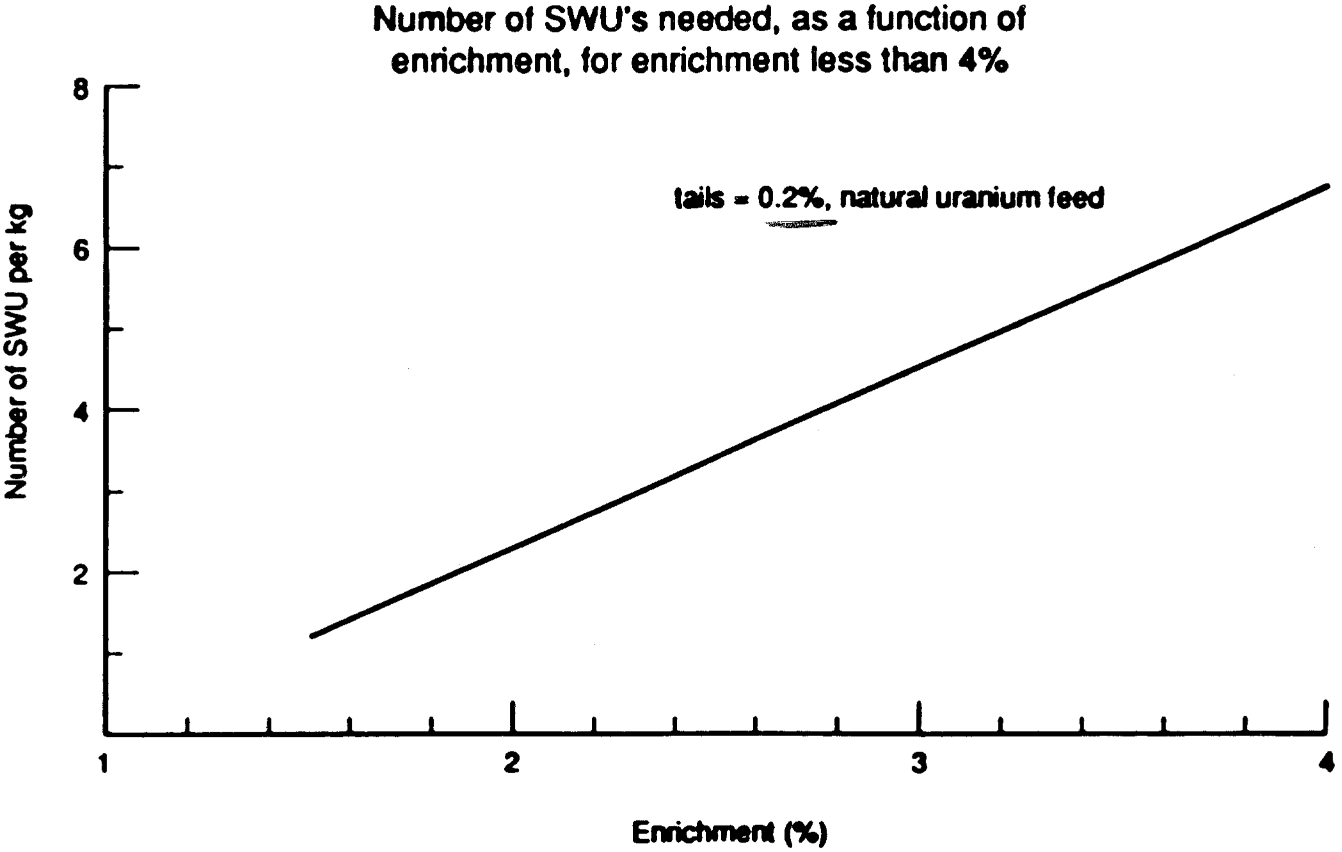
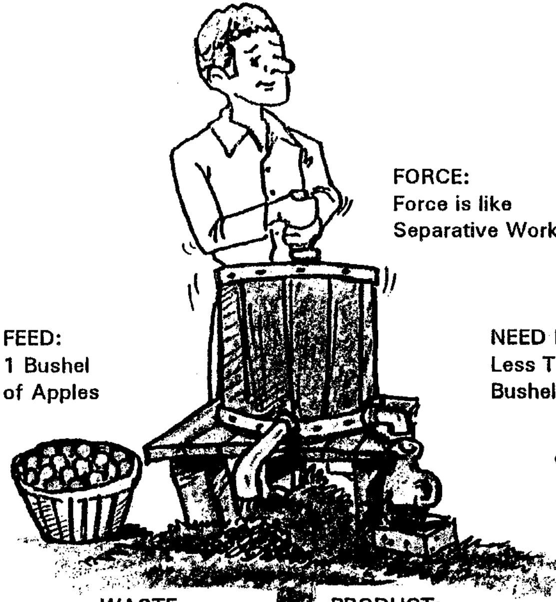


Fig. 3.6 SWUs versus product enrichment; number of SWUs needed, as a function of enrichment, for enrichments of <4%.

SEPARATIVE WORK & TAILS ASSAY ANALOGY

MAKING ONE GALLON OF APPLE CIDER

USUAL OPERATION



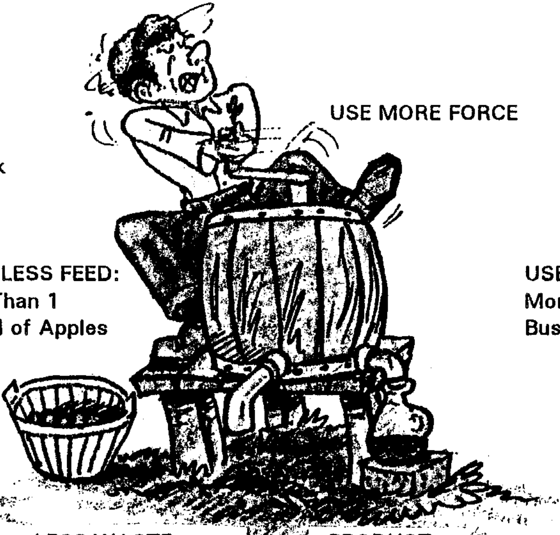
FORCE:
Force is like
Separative Work

FEED:
1 Bushel
of Apples

WASTE:
Peels, Cores,
Seeds & Apples

PRODUCT:
1 Gallon
of Cider

MORE *FORCE*, BUT LESS *FEED*



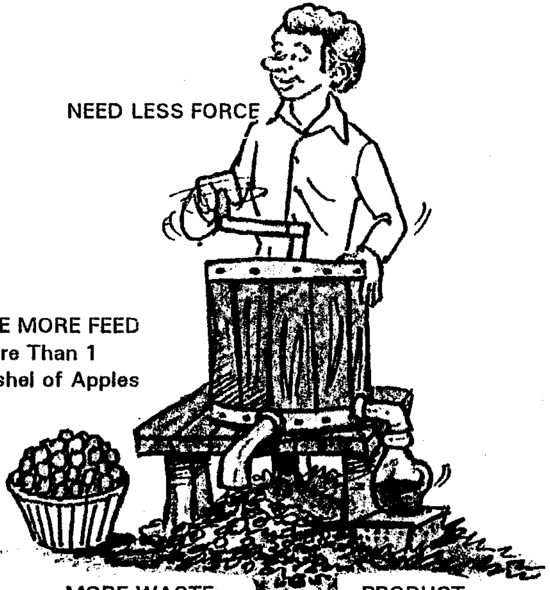
USE MORE FORCE

NEED LESS FEED:
Less Than 1
Bushel of Apples

LESS WASTE:
Fewer Peels, Cores,
Seeds & Apples

PRODUCT:
1 Gallon
of Cider

MORE *FEED*, BUT LESS *FORCE*



NEED LESS FORCE

USE MORE FEED
More Than 1
Bushel of Apples

MORE WASTE:
More Peels, Cores,
Seeds & Apples

PRODUCT:
1 Gallon
of Cider

Problem -1

a.) What is the number of kgs of natural U that has to be provided as feed in an enrichment plant if one requests 30,000 kg of U enriched to 3% in ^{35}U? Assume the tails assay is 0.2%.

b.) What is the number of SWU's needed for separation?

$$\frac{F}{P} = \frac{(3-0.2)}{(0.711-0.2)} = 5.479 \quad \frac{kg\ feed}{kg\ product}$$

Total feed is then;

F= 30,000 • 5.479 = 164,370 kg U feed

b.) $$V(x_f) = (2 \bullet 0.00711 - 1)\ln\left[\frac{0.00711}{1-0.00711}\right]$$

=4.869

$$V(x_w) = (2 \bullet 0.002 - 1)\ln\left[\frac{0.002}{1-0.002}\right]$$

=6.188

$$V(x_p) = (2 \bullet 0.03 - 1)\ln\left[\frac{0.03}{1-0.03}\right]$$

=3.268

S = 3.268 +(5.479-1)(6.188) - (5.479)(4.869)= 4.307

Hence the total number of SWU's is then;

30,000 kg • 4.307 SWU/kg = 129,210 SWUs

Problems Due Friday, Sept. 24, 1999

1.) An enrichment plant has a throughput of 32,000 kgU/day and produces 26,000 kgU as tails. What is the enrichment of the product if the feed is natural U and the tails are 0.25%?

2.) A gaseous diffusion method has been proposed to produce BF_3 enriched to 90% in B^{10}. How many kgs of BF_3 feed (natural B) are needed to produce 1 kg of B^{10} with 8% tails?

3.) Calculate the natural U feed and SWU factors 1 billion years into the future. Assume tails of 0.15% and 3% enriched product;

$t_{1/2}$ (^{35}U) = 7.1×10^8 y,

$t_{1/2}$ (^{38}U) = 4.51×10^9 y.