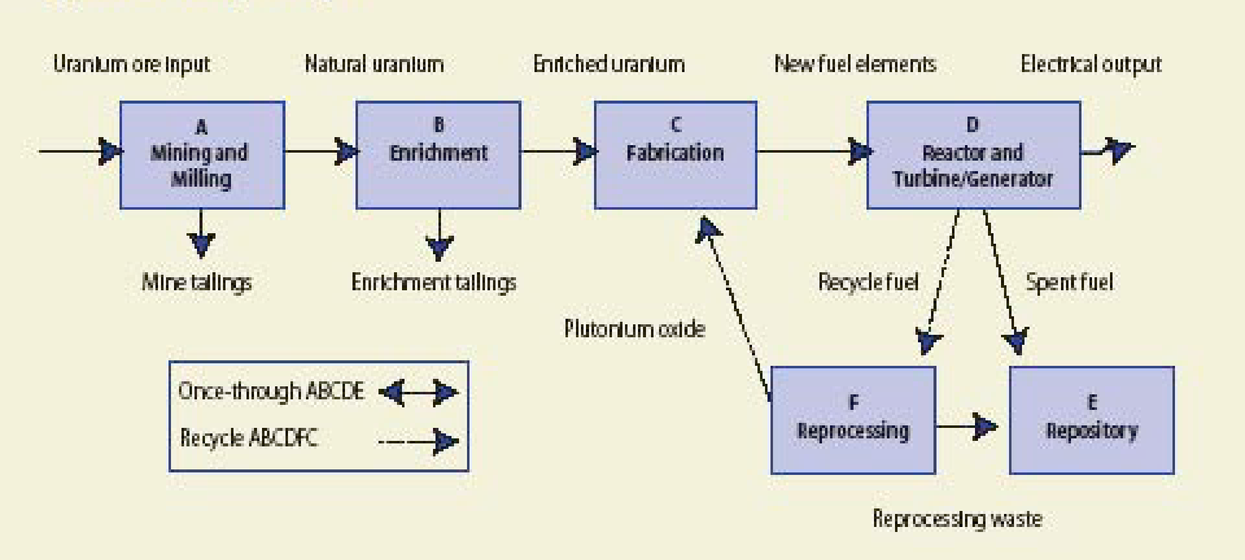
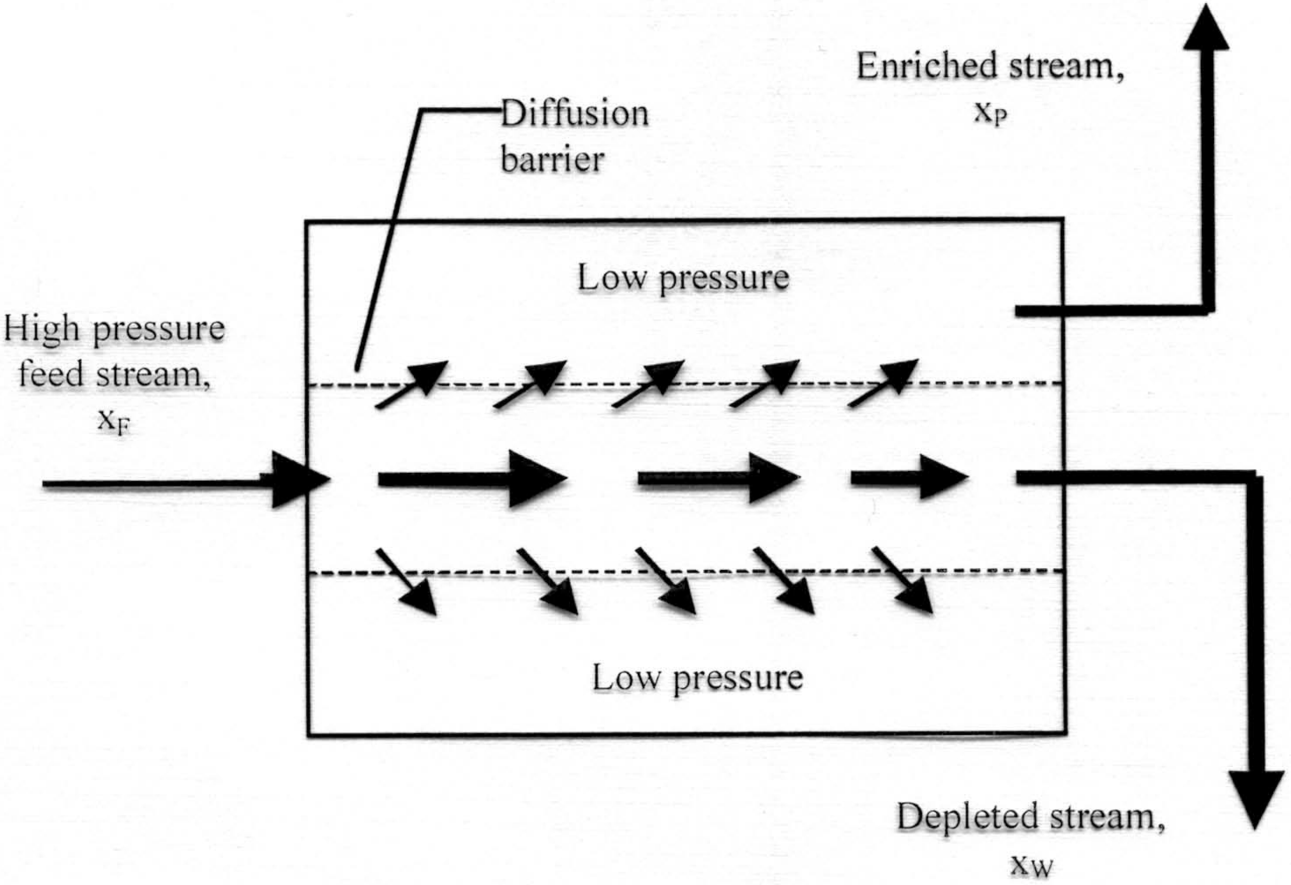
The Economics of the Nuclear Fuel Cycle

March 29, 2004

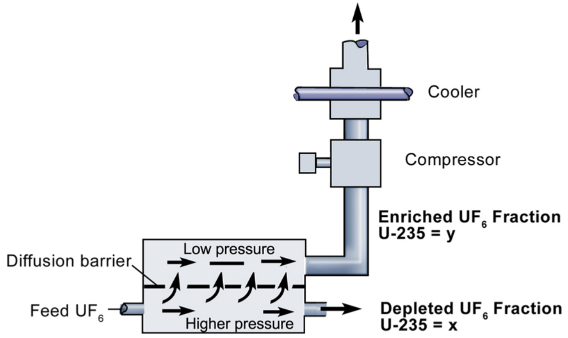
Figure A-1.1 Fuel Cycle Diagram





GASEOUS DIFFUSION STAGE

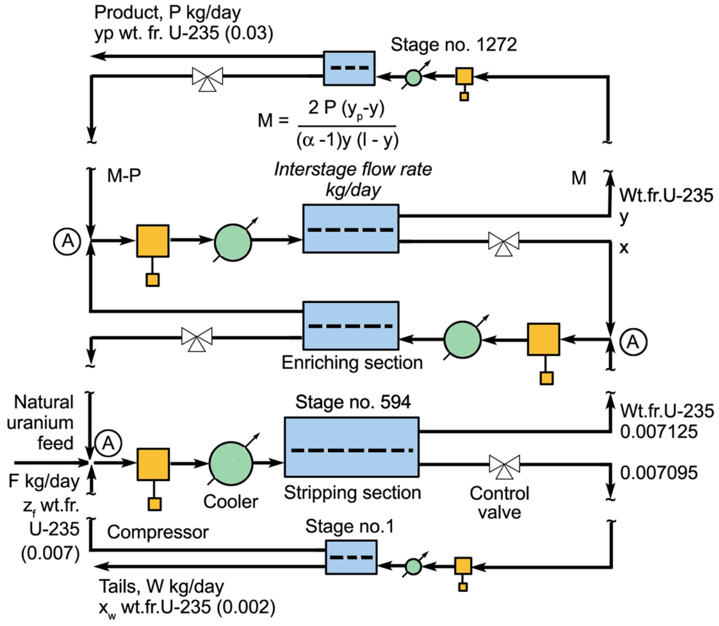
Gaseous diffusion stage



Separation factor

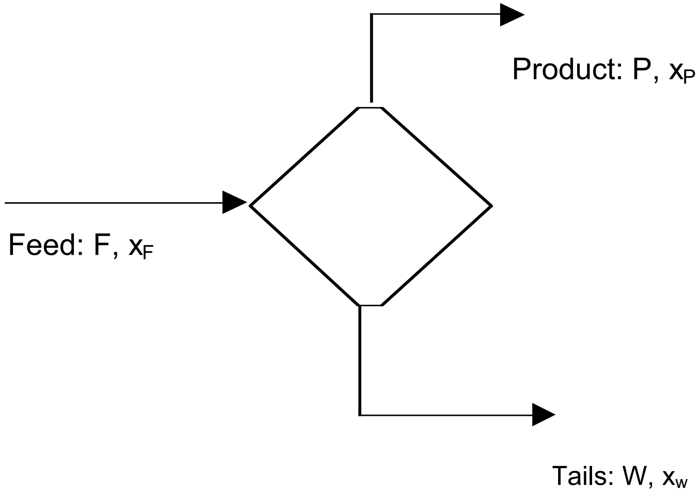
$$\alpha \equiv \frac{y(l-x)}{x(l-y)} = \sqrt{\frac{{}^{m}238_{UF6}}{{}^{m}235_{UF6}}} = \sqrt{\frac{352}{349}} = 1.00429$$

Ideal gaseous diffusion cascade



$$M = \frac{2\,P\,(y_p - y)}{(\alpha - 1)y\,(l - y)}$$

Enrichment Plant Material Balance



Product: P, x_P

Feed: F, x_F

Tails: W, x_w

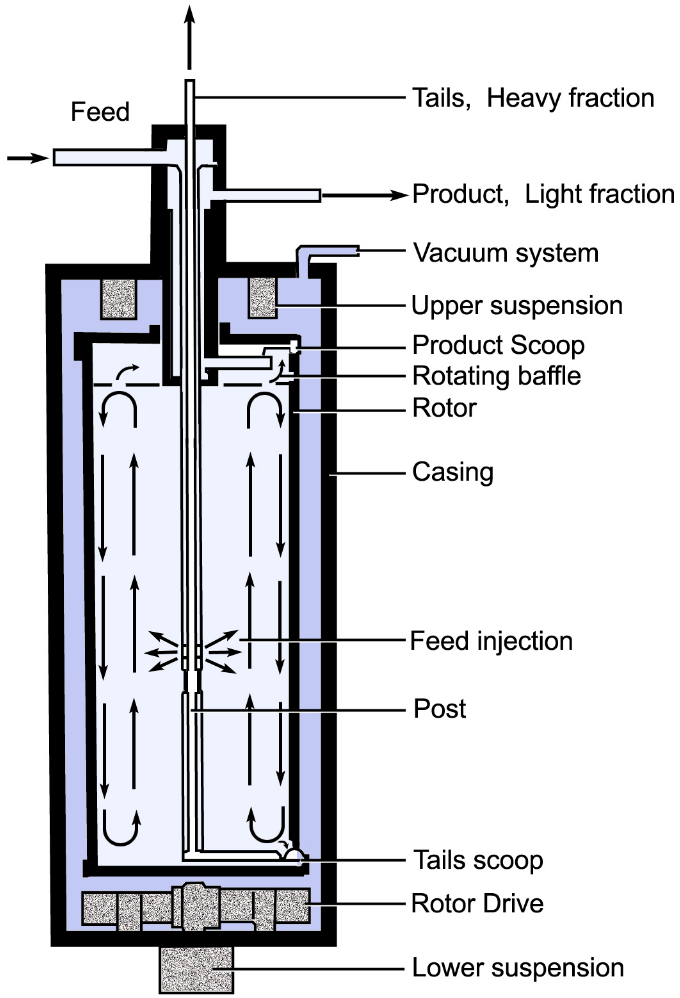
Material balance on U: $F = P + W$

Material balance on U-235: $Fx_F = Px_P + Wx_W$

$$F = P\left[\frac{x_p - x_W}{x_F - x_W}\right]$$

and for $x_P = 0.03$, $x_F = 0.00711$, $x_W = 0.002$, $\underline{F/P = 5.5}$

Countercurrent gas centrifuge with internal combustion



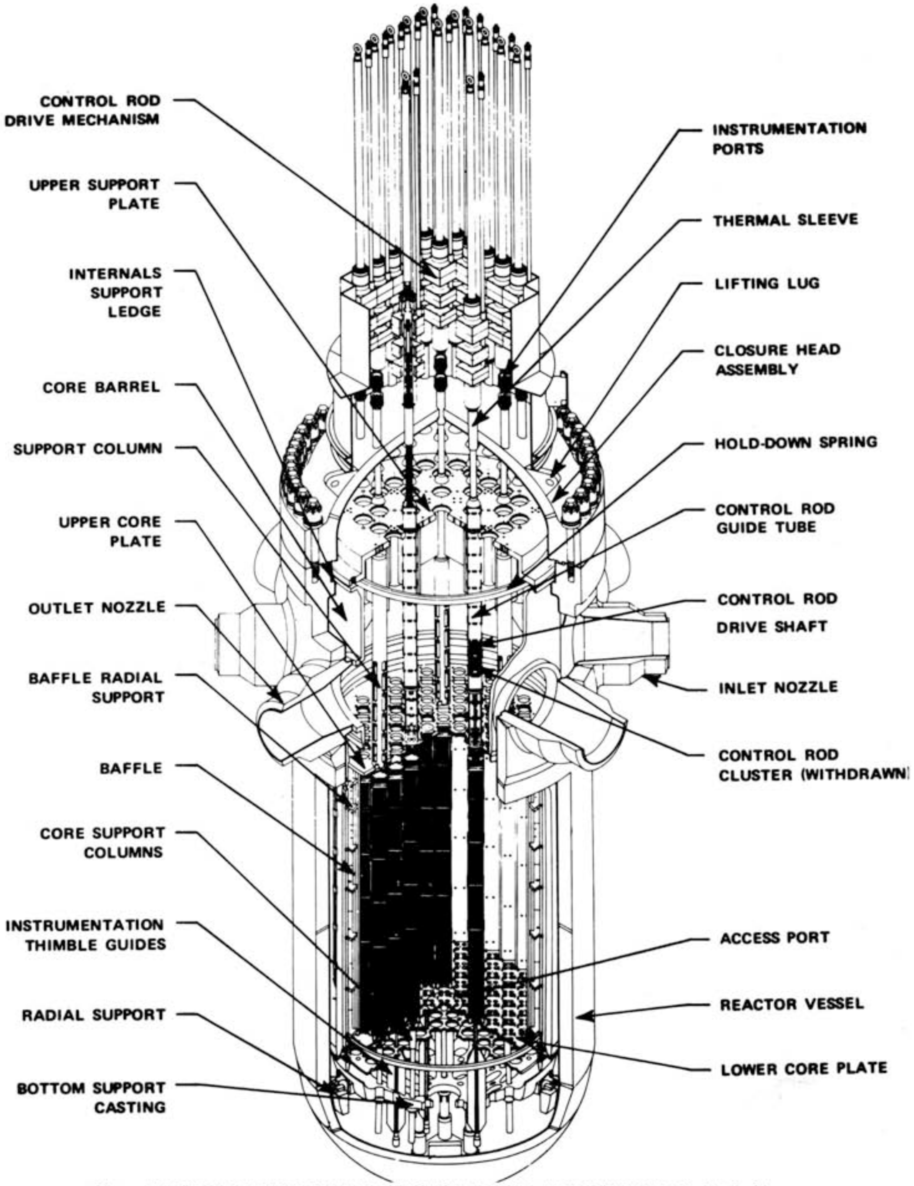
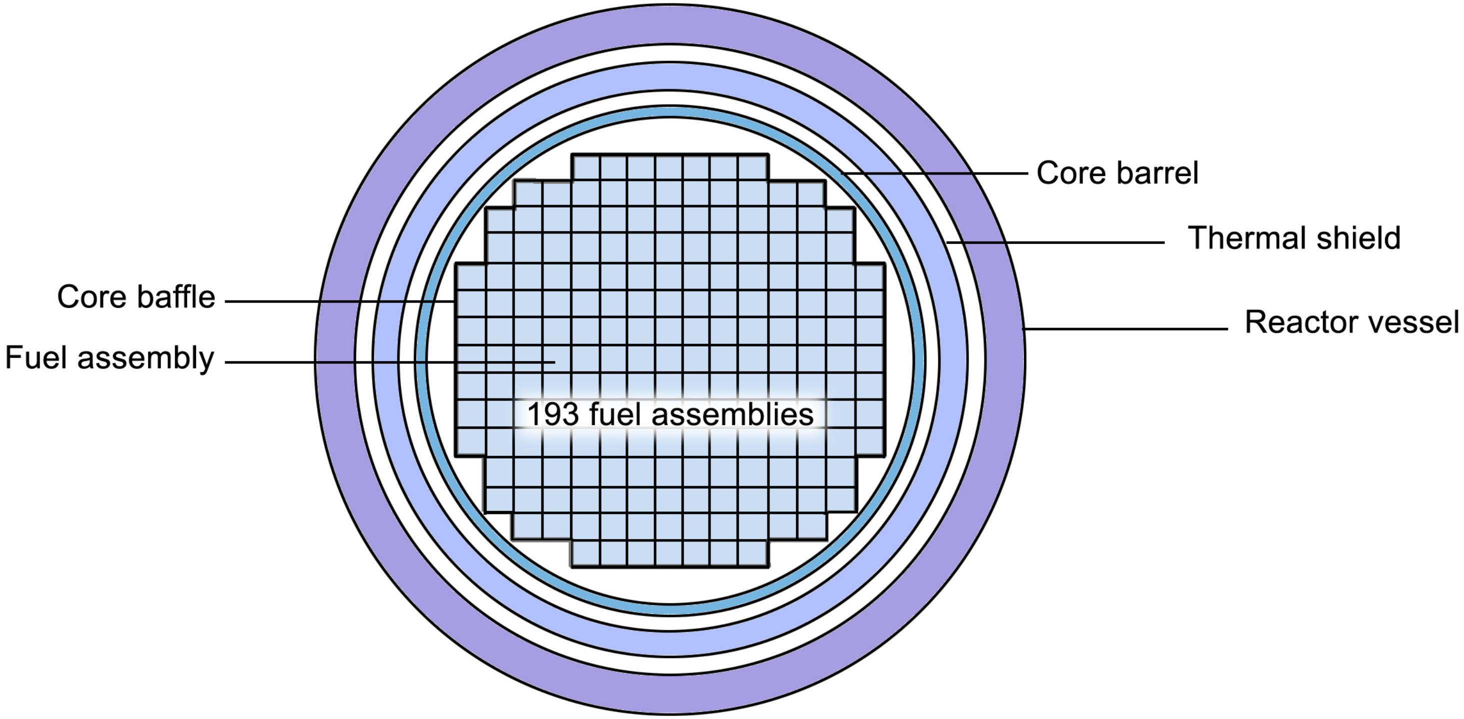


Figure 5-4. PRESSURIZED-WATER REACTOR VESSEL AND INTERNALS. (At Left) The core of a pressurized-water reactor is contained in a large steel vessel through which coolant flows. After passing into an inlet nozzle, the water flows down between the core barrel and the vessel wall, until it reaches the plenum beneath the core; there it turns upward to flow through the core and out one of the outlet nozzles to the steam generators. The top of the reactor vessel, which is removable for refueling, supports mechanisms for driving control rods. (Figure courtesy of Westinghouse Electric Corp.)

Source: US Energy Information Agency (http://eia.doe.gov/cneaf/nuclear/page/nuc_reactors/pwr.html)

Core cross section of PWR



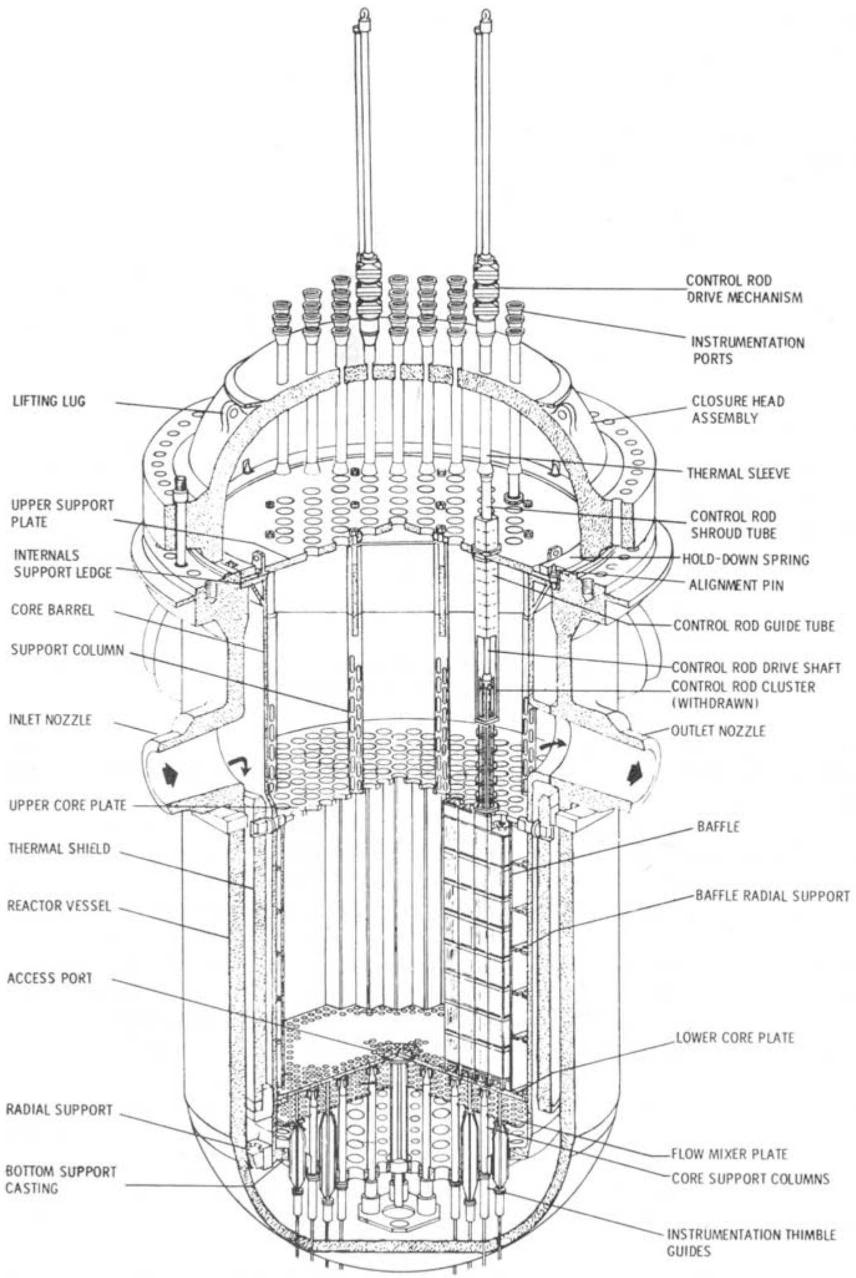
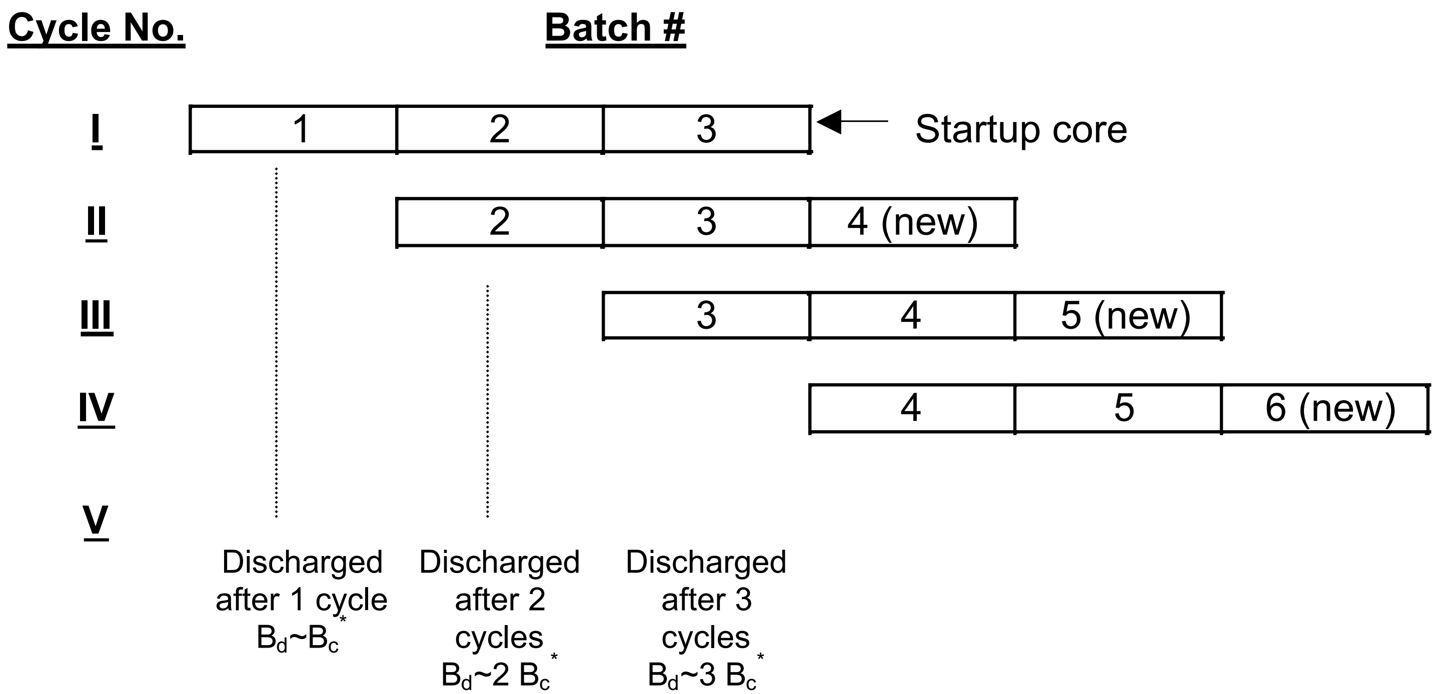


Figure 3.16 Cutaway view of large PWR.

Source: US Energy Information Agency (http://eia.doe.gov/cneaf/nuclear/page/nuc_reactors/pwr.html)

PWR Batch Refueling Scheme
(Batch fraction = 1/3)



Cycle No.

Batch #

I 1 | 2 | 3 ← Startup core

II 2 | 3 | 4 (new)

III 3 | 4 | 5 (new)

IV 4 | 5 | 6 (new)

V

Discharged after 1 cycle $B_d \sim B_c$*

Discharged after 2 cycles $B_d \sim 2\ B_c$*

Discharged after 3 cycles $B_d \sim 3\ B_c$*

*Useful approximation. In practice, need to track B_d with computer codes

Energy from a fuel batch

If the batch fraction is 1/n, under steady state conditions each batch remains in the core for n cycles.

Similarly, at steady state the energy produced by all n batches in the core during one cycle is equal to the energy produced by one batch during its total residence time in the core (i.e., n cycles.).

Thus the total electrical energy produced by a given batch during its in-core lifetime at steady state is:

$$\boxed{E_b\ (\text{kwh(e)/batch}) = 8766\ (\text{hrs/yr}) \times CF \times K\ (\text{kwe}) \times T_c\ (\text{yr})}$$

where:

CF = cycle average capacity factor (including refueling downtime)

K = plant rating (kwe)

T_c = cycle length (yrs) including downtime

We can also write that the energy produced per batch is:

$$\boxed{E_b\ (\text{kwhr(e)/batch}) = B_d\ (\text{MWD(th)/MTHM}) \times 24\ (\text{hr/day}) \times 1000\ (\text{kw/MW}) \times \eta \times P\ (\text{MT})}$$

where:

B_d = discharge burnup of the fuel (MWD(th)/MT of heavy metal)

η = thermodynamic efficiency (Mwe/MW(th))

P = batch fuel inventory (MT of heavy metal)

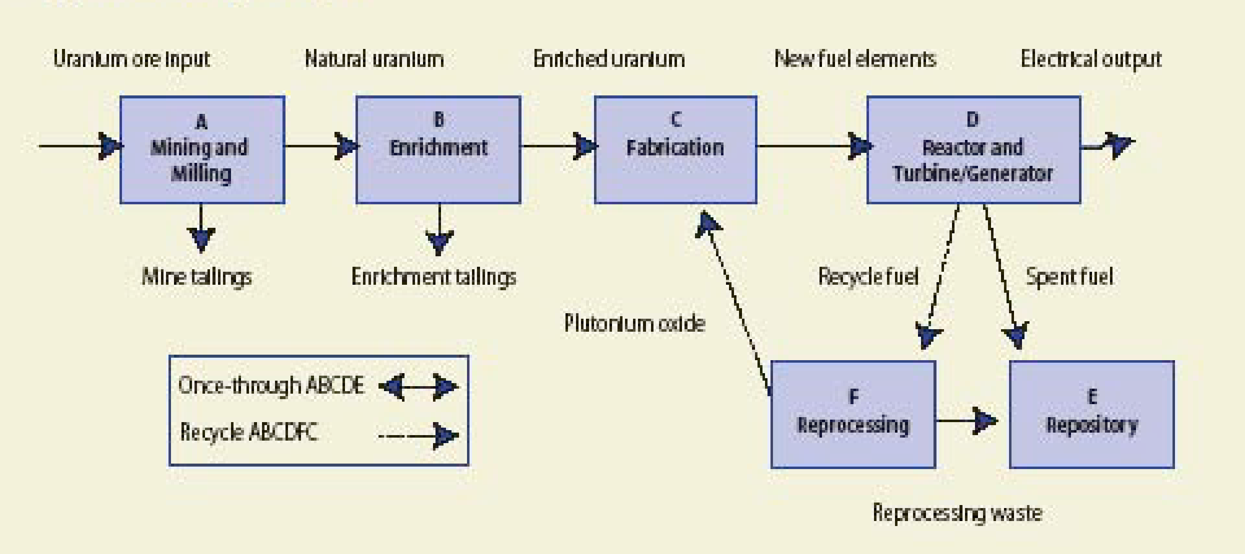
Also,

$T_b = n\ T_c$

$B_d = n\ B_c$

And P, the fuel inventory per batch = Total core inventory/n

Figure A-1.1 Fuel Cycle Diagram



Material balance on the front end of the cycle

Assume:

$K = 1000$ MWe

$T_c = 1.5$ years

CF = 90%

$\eta = 33\%$

$n = 3$

In-core fuel inventory = 89.4 MTHM

Hence we can calculate:

- Energy output per batch, $E_{b,}$ (at steady state)
- Mass of fuel (as heavy metal), P, per batch
- Discharge burnup of spent fuel, B_d (MWDth/MTHM)

Image removed due to copyright considerations.

Approximate Correlation: Initial enrichment (x_P) vs. discharge burnup (B_d)

$$\boxed{x_p = 0.41201 + 0.11508\left(\frac{n+1}{2n}B_d\right) + 0.00023937\left(\frac{n+1}{2n}B_d\right)^2}$$

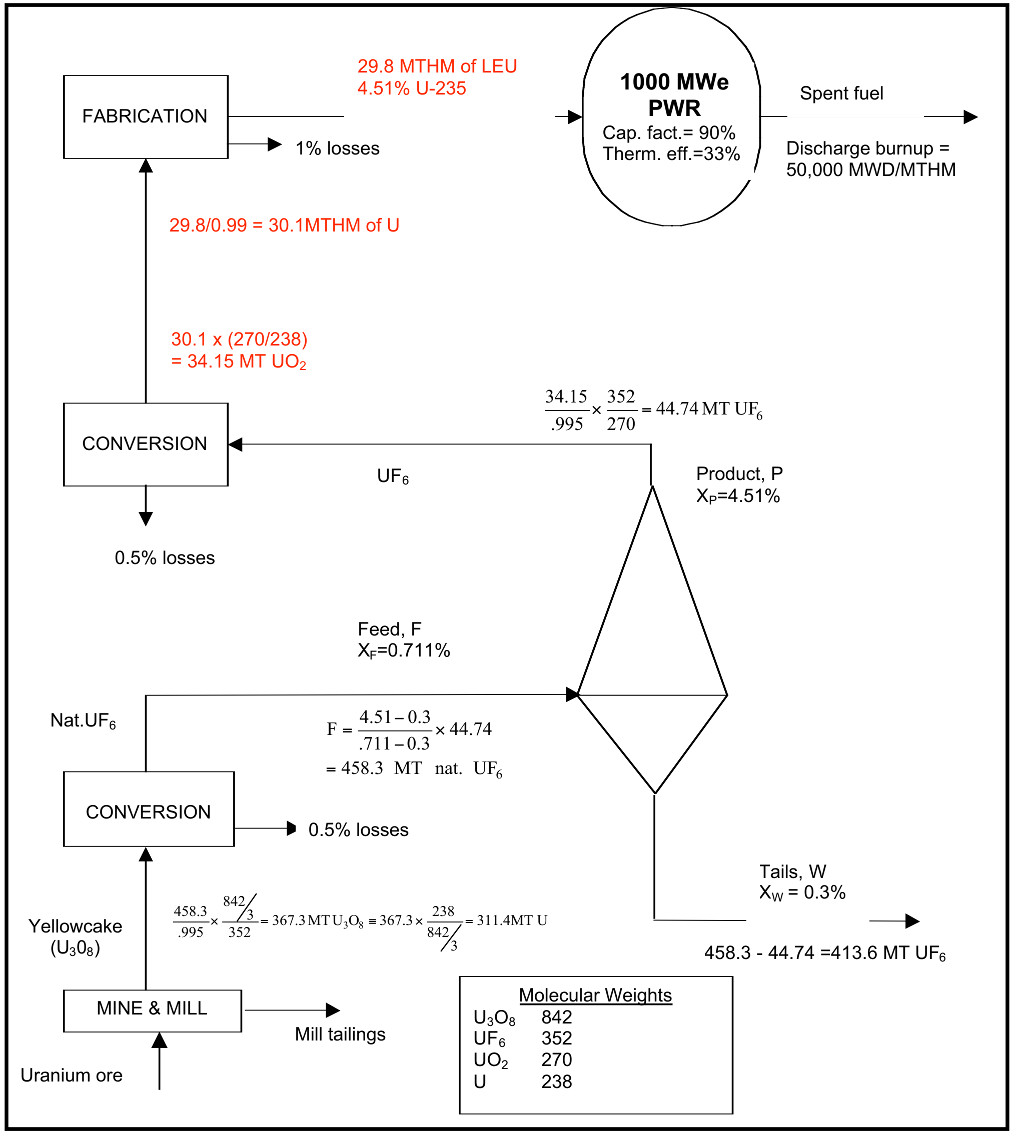
where n = number of batches

(valid for $x_p < 20\%$)

Source: Zhiwen Xu, NED Doctoral Dissertation, 2003

Material balance on the front end of the PWR fuel cycle

(Basis: 1 steady state batch; 1000 MWe PWR; thermal efficiency = 33%; 90% capacity factor; 18-month refueling cycle; batch fraction = 1/3; discharge burnup = 50,000 MWD(th)/MT))



FABRICATION

29.8 MTHM of LEU
4.51% U-235

1% losses

1000 MWe PWR
Cap. fact.= 90%
Therm. eff.=33%

Spent fuel

Discharge burnup = 50,000 MWD/MTHM

29.8/0.99 = 30.1MTHM of U

30.1 x (270/238)
= 34.15 MT UO_2

$$\frac{34.15}{.995} \times \frac{352}{270} = 44.74\,\text{MT UF}_6$$

CONVERSION

UF_6

0.5% losses

Product, P
X_P=4.51%

Feed, F
X_F=0.711%

Nat.UF_6

$$F = \frac{4.51-0.3}{.711-0.3} \times 44.74$$
$$= 458.3\ \text{MT nat. UF}_6$$

CONVERSION

0.5% losses

Tails, W
X_W = 0.3%

458.3 - 44.74 =413.6 MT UF_6

Yellowcake
(U_3O_8)

$$\frac{458.3}{.995} \times \frac{842/3}{352} = 367.3\,\text{MT U}_3\text{O}_8 \equiv 367.3 \times \frac{238}{842/3} = 311.4\text{MT U}$$

MINE & MILL

Mill tailings

Uranium ore

Molecular Weights

U_3O_8	842
UF_6	352
UO_2	270
U	238