22.812 NUCLEAR ENERGY ECONOMICS POLICY ANALYSIS S'04

Classnote

The Economics of the Nuclear Fuel Cycle: (1) Once-Through Fuel Cycle

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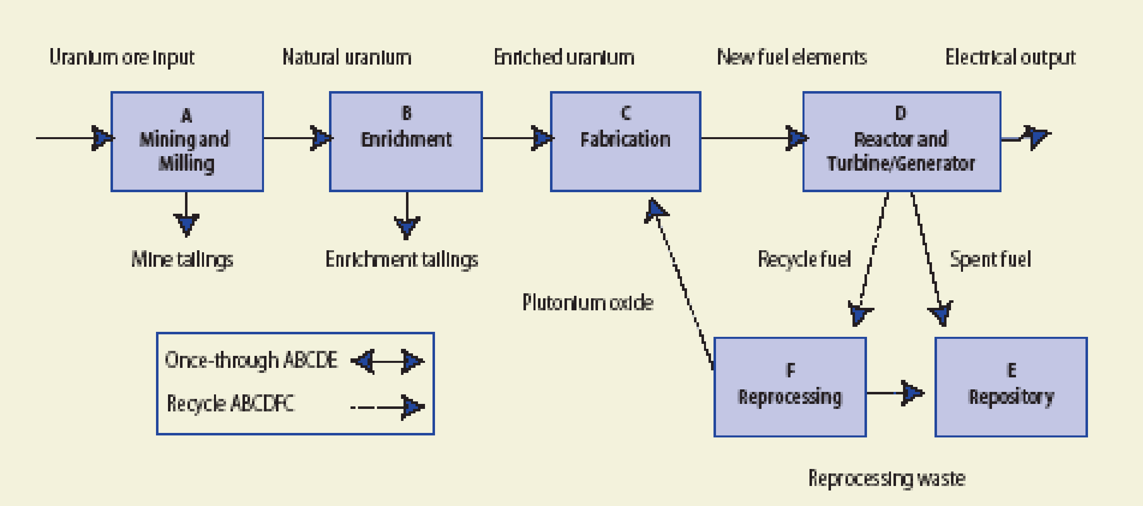
1. Introduction

- A complex cycle of industrial operations is required to prepare and manufacture fresh fuel for nuclear power reactors and to manage 'spent' (irradiated) fuel after it is discharged. The particular characteristics of the nuclear fuel cycle depend on the type of reactor that is being supported. Here we will concentrate mainly on the fuel cycle for light water reactors (LWRs)

- One of the objectives of this module is to develop a simple model for estimating the contribution of the nuclear fuel cycle to the overall cost of nuclear energy. We will not discuss each of the stages of the cycle in great detail, but in each case we will provide some background on current costs and likely trends.

- The basic flowsheet for the LWR fuel cycle is shown below:

Figure A-1.1 Fuel Cycle Diagram



Deutsch, John, Ernest Moniz et al. "The Future of Nuclear Power: An Interdisciplinary MIT Study." Massachusetts Institute of Technology, 2003 (ISBN 0-615-12420-8). Available at http://web.mit.edu/nuclearpower/. p. 101.

- A key distinction is between 'open' and 'closed' fuel cycles. In the open or once-through fuel cycle, the spent fuel discharged from the reactor is treated as waste. In the closed fuel cycle, the spent fuel is reprocessed, and the products are partitioned into uranium, plutonium, and the residual material, mostly fission products, which is treated as high level waste.

- We begin by considering the once-through fuel cycle.

2. Stages of the nuclear fuel cycle

- The nuclear fuel cycle can be divided into three stages: the front-end, which extends from the mining of uranium ore to the delivery of fabricated fuel assemblies to the reactor; at-reactor; and the back-end, which starts wiith the shipping of spent fuel offsite and ends with the disposal of high level waste.

Mining:

- Uranium mining is the first stage of the fuel cycle. Uranium ore deposits are found in many parts of the world. The main producing nations today are the United States, Australia, South Africa, Canada, Russia, and other nations of the former Soviet Union.

- Large deposits of uranium ore typically contain only a few tenths of a percent of uranium, although a few very rich deposits in Canada and Australia contain 10-20% uranium. The ore is processed in a uranium mill to produce 'yellowcake', a concentrate containing 85-90% by weight of uranium oxide (U_3O_8). The mill is typically located close to the mine site in order to minimize the cost of transporting the ore. The non-uraniferous material which constitutes the vast bulk of the ore is rejected at the mill. This material, known as the *mill tailings*, contains most of the radioactive daughter products of uranium that were present in the ore, and must be stabilized to prevent the release of these radioisotopes (including radon gas) into the environment.
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Conversion and Enrichment

- In the next stage of the cycle, the yellowcake is purified and converted to uranium hexafluoride (UF_6), the only stable compound of uranium that is volatile at temperatures close to ambient. UF_6 is the feed material for the uranium enrichment stage, in which the weight fraction of the fissile isotope ^{235}U is increased from 0.711% up to about several percent -- the fissile concentration needed for LWR fuel. Different isotopes of the same element exhibit identical chemical behavior, so considerable ingenuity is needed to devise physical separation means. The isotopic enrichment of uranium is one of the most technically challenging stages of the fuel cycle.

- The two main enrichment technologies in commercial use today are gaseous diffusion and the gas centrifuge process. For several decades gaseous diffusion plants produced almost all of the enriched uranium used in nuclear power reactors, and still today account for most of the world's enrichment capacity. The process relies on the slight (less than 1%) mass difference between molecules of $^{235}UF_6$ and $^{238}UF_6$. Gaseous UF_6 is pumped under pressure across a semi-porous diffusion barrier. The lighter $^{235}UF_6$ molecules have a slightly higher probability of diffusing through the barrier, and the gas on the downstream side is thus slightly enriched in the fissile isotope, while the undiffused gas is slightly depleted (see Figure 1).

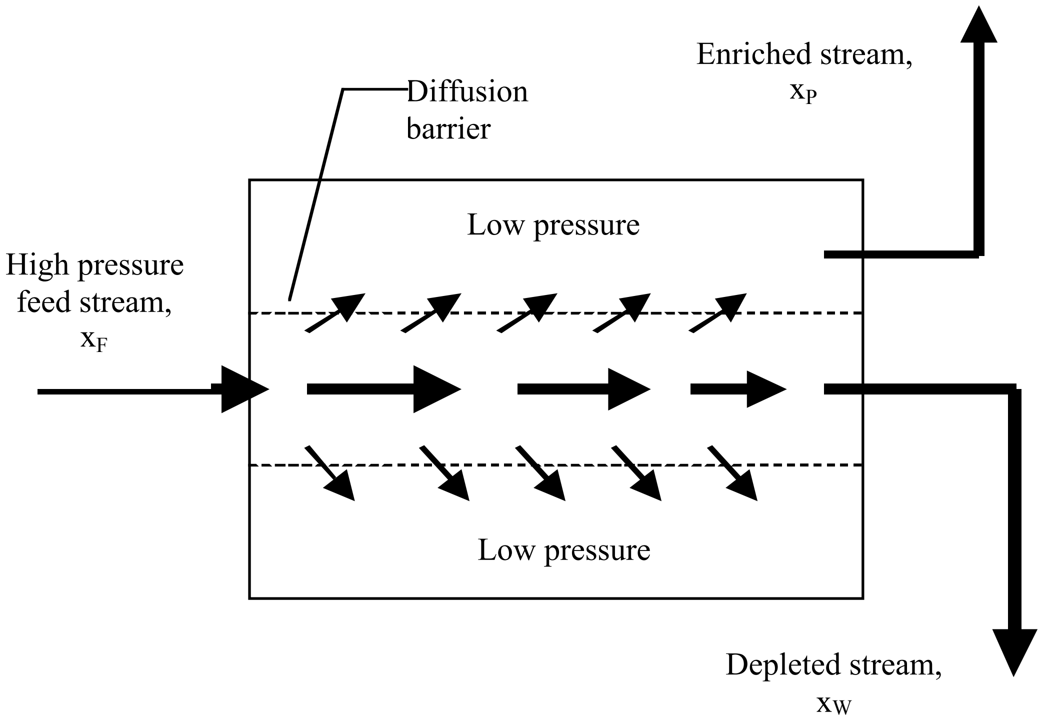

Figure 1: Schematic of a gaseous diffusion stage

- The ratio of U-235 to U-238 in the downstream gas rises only by a very small amount, and more than 1000 stages are needed to achieve a U-235 enrichment of 3%.

- The performance of each enrichment stage is described by the separation factor, α, given by the expression:

$$\alpha = \frac{\dfrac{x_P}{1 - x_P}}{\dfrac{x_W}{1 - x_W}}$$

  where x_P and x_W are the weight fractions of U-235 in the enriched and depleted product streams respectively. The stage separation factor for a gaseous diffusion stage is 1.00429. (An analogous separation factor is used to characterize other isotope separation processes too.)

- The stages are arranged in a ‘cascade’, in which the enriched product from one stage becomes the feed to the next highest stage, while the depleted product becomes the feed to the next lowest one. The feed stream is introduced into a central stage of the cascade, while the enriched product and depleted 'tails' streams are withdrawn from each end (see Figure 2).

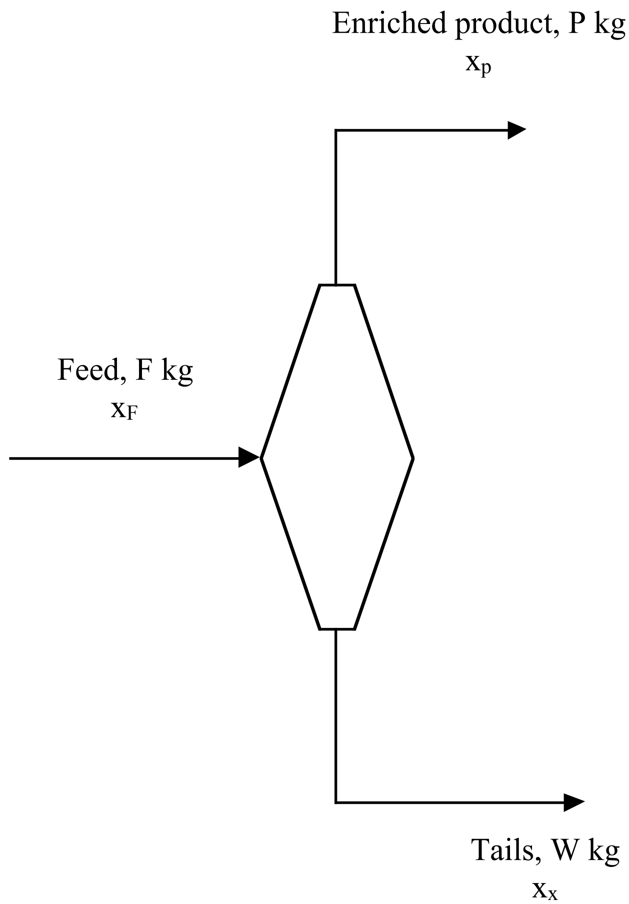

Figure 2: An enrichment cascade

An overall material balance on the cascade yields:

$$F = P + W \qquad \text{eq. (1)}$$

and a material balance on the U-235 isotope leads to

$$Fx_F = Px_P + Wx_w \qquad \text{eq. (2)}$$

where F, P, and W are the masses of uranium in the feed, product, and tails streams respectively, and x_F, x_P, and x_w are the weight fractions of U-235 in the three streams.

In these equations, P and x_P are determined by the in-core fuel management scheme; x_F is given by the U-235 content of natural uranium (0.711%); and x_W is set to optimize enrichment plant operations. Thus we have two equations in two unknowns (F and W). Solving for F, we get that:

$$F = P\left(\frac{x_p - x_W}{x_F - x_W}\right)$$

Example: For a cascade enriching natural uranium to 3% in U-235 at a tails assay, x_w, of 0.2%, solving equations (1) and (2) gives:

$$F = P\left(\frac{x_P - x_W}{x_F - x_W}\right) = 5.48P$$

i.e., to produce one kilogram of 3% enriched uranium product requires about 5.5 kilograms of natural uranium feed.

- Gaseous diffusion plants are extremely large and very capital intensive, and use large amounts of energy. A full-scale gaseous diffusion plant can consumes 2000-3000 megawatts of electric power, enough to meet the needs of a city of half a million or more people. Commercial-scale plants are today operating in the United States, Russia, and France.

- The gas centrifuge process, the other leading enrichment technology, also relies on the small mass difference between molecules of $^{235}UF_6$ and $^{238}UF_6$. In this case the separation is achieved in ultra-high-speed centrifuges. UF_6 gas introduced into the centrifuges is subject to centrifugal acceleration thousands of times greater than gravity. The heavier $^{238}UF_6$ molecules tend to congregate at the centrifuge wall, while the gas at the axis is enriched in $^{235}UF_6$. The overall separation factor in an optimally designed centrifuge is roughly 1.4 – much higher than in a gaseous diffusion stage. However, the throughput of each machine is small, because of materials and mechanical constraints that limit the size of the centrifuge and its rotation speed. To produce commercial-scale quantities of enriched uranium tens or hundreds of thousands of centrifuges must therefore be piped together in a cascade. Gas centrifuge cascades are even more capital-intensive than gaseous diffusion plants, but only consume about 5% of the energy. An Anglo-Dutch-German consortium operates the only full-scale gas centrifuge enrichment plants in service today. USEC, the American enrichment corporation, has announced its intention to build a new gas centrifuge plant to replace its aging gaseous diffusion plant at Paducah, Kentucky.

<u>Fuel Fabrication</u>

- In the <u>fabrication</u> stage, the UF_6 is first converted to UO_2 and the UO_2 is then formed into pellets, the pellets are sintered, and then stacked into zircaloy tubes. Sufficient space is left in the tube for the fission product gases to accumulate without overpressurizing the tube, an end-cap is added, and the tube is sealed. The tubes (or rods) are then fastened together to make assemblies. In a typical PWR, the rods are assembled into a 17x17 square array.

[Note: A useful technical presentation on the stages of the front-end of the cycle prepared by Argonne National Laboratory can be found at:
http://web.ead.anl.gov/uranium/guide/prodhand/sld001.cfm]

Reactor Operation -- Irradiation: Batches, Cycles and Energy Generation

- A typical PWR core has
  - ~ 200 assemblies (~ 12 feet long)
  - ~ ~300 rods/assembly (~ 0.5" diameter)
  - ~ 200 fuel pellets/rod → ~ 8,000,000 pellets
- Nuclear fuel is typically loaded in staggered 'batches' consisting of 1/n th of the total number of in-core assemblies (the 'batch fraction'). Typical values of n are 3 or 4.
- The period between refueling outages is called the 'refueling cycle length', T_c.
- The energy extracted from a given batch of fuel is expressed in terms of the fuel burnup, B, reported in MWD (thermal) per Metric Ton of Initial Heavy Metal (or MWD(th)/MTIHM)
- Example: n = 3

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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

Utilities prefer to have cycles that are multiples of 1/2 year in length, so as to be able to match their refueling outages with periods of low power demand (spring and fall in most parts of the country.) For many plants, T_c has been 1 year in the past, but utilities are rapidly switching to longer cycles (18 months, or two years.)

- 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 <u>all</u> n batches in the core during one cycle is equal to the energy produced by <u>one</u> 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:

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

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:

E_b (kwhr(e)/batch) = B_d (MWD(th)/MT) x 24 (hr/day) x 1000 (kw/MW) x η x P (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

- Note, for a batch fraction of 1/n, steady state is achieved after n cycles, to a first approximation.

3. <u>Material Balance on the Front-End of the Nuclear Fuel Cycle</u>

- Three key functions:
  - Electric power system manager
  - In-core fuel manager
  - Out-of-core fuel manager
- The system manager specifies the required output from the power plant (capacity factor, refueling interval)
- The in-core fuel manager provides the specifications for each fuel batch, using in-core physics and fuel management codes to meet target energy production.
- The out-of-core fuel manager is responsible for timely delivery of each fuel batch, which involves purchasing fuel and fuel cycle services.
- <u>Example</u>: Assume the following steady-state specifications.

K = 1000 MWe

T_c = 1.5 years

CF = 90%

η = 0.33

n = 3

With this information, we can calculate the size of a steady-state fuel batch, since as noted previously the energy output per batch over its in-core lifetime = energy output of entire core over one cycle.

Energy output per batch = 1000 (MWe) x 365 x 1.5 x 0.9 (days/cycle) x 1/0.33 (MWD(th)/MWD(e))

= 1.49×10^6 MWD(th) per batch

And if B_d = 50,000 MWD(th)/MTHM, we have that the mass of heavy metal in each batch, P, is

P = 1.49×10^6 (MWD(th))/50,000 (MWD (th)/MTHM)= <u>29.8 MTHM</u>

The fuel manager's physics codes will also calculate the initial enrichment of uranium-235, x_p, that is required to attain the desired discharge burnup, B_d. This can be usefully approximated by the following correlation (presented in Zhiwen Xu's doctoral thesis (2003)), which is valid for enrichments up to 20%:

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

And for B_d = 50,000 MWD(th) /MT and n=3, x_p=4.51%.

With this information, we can work back through each of the stages in the fuel cycle to obtain the amount of uranium ore that must be mined for each batch (see Figure 3).

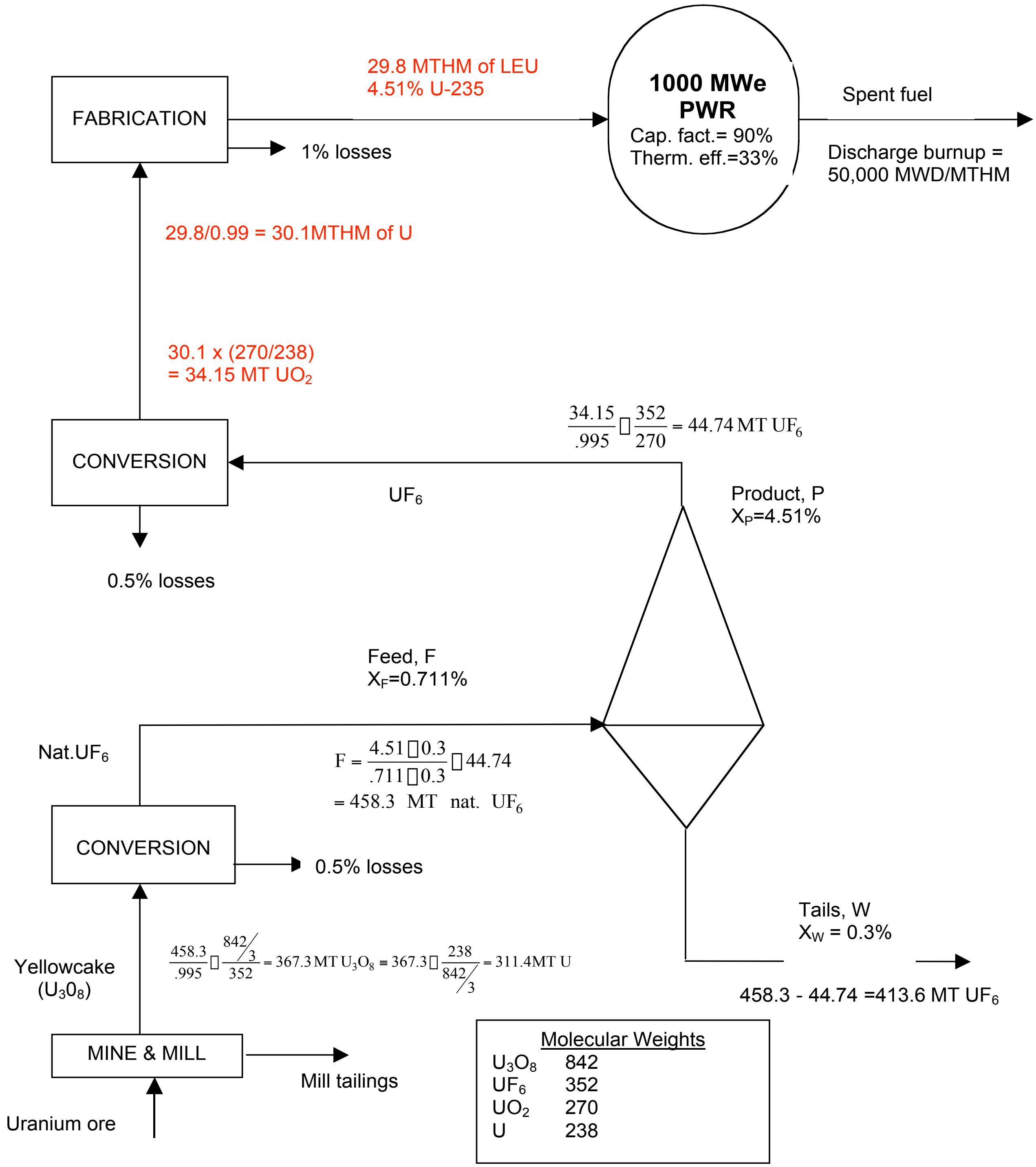


Figure 3: Material balance on the front end of the PWR fuel cycle (Basis: 1 steady state batch; 1000 MWe PWR; thermal efficiency = 33%; 90% capacity factor; 18-month refueling cycle; batch fraction = 1/3; discharge burnup = 50,000 MWD(th)/MT)

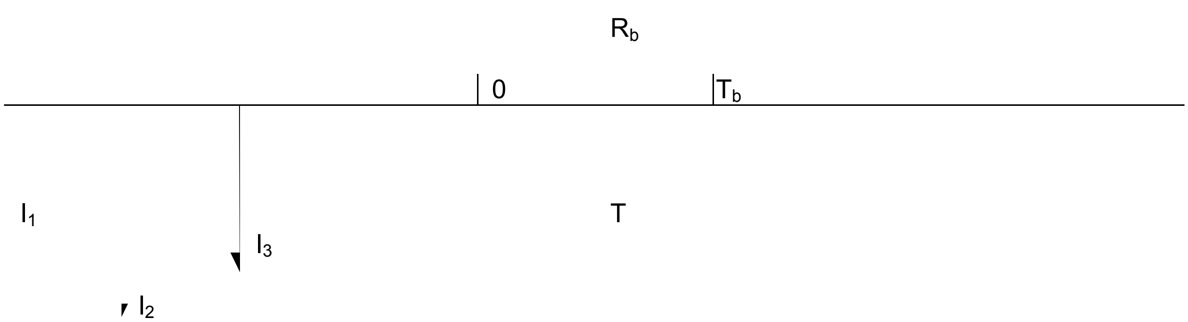
4. Simple Cost Model for A Single Fuel Cycle Batch

- The operations associated with each batch of fuel typically extend over many years, from mining the uranium ore to finally disposing of the high level waste. Payments for these various operations are made at widely differing times. Thus it is important to take into account the time value of money in calculating the overall fuel cycle cost.

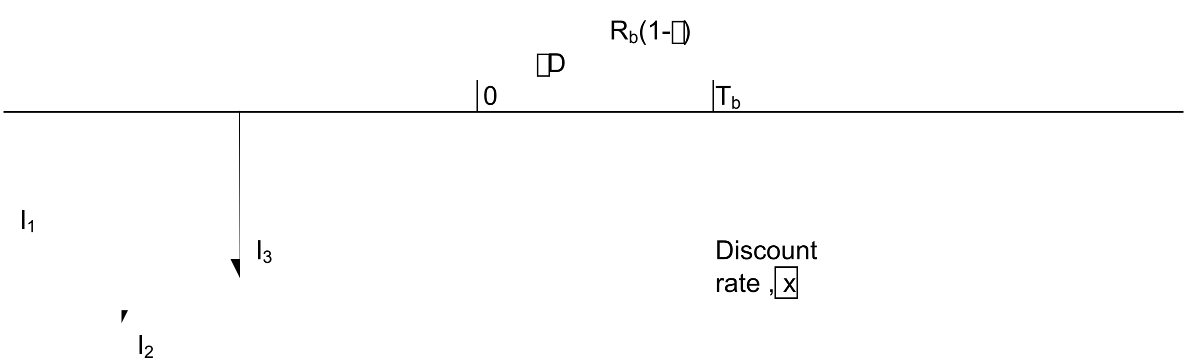
- Recall also that nuclear fuel is not permitted to be expensed for tax purposes, but must be capitalized and depreciated (like buildings or machinery)

- The task is to calculate the revenue stream that is equivalent in a present worth sense to the series of payments on the fuel batch.

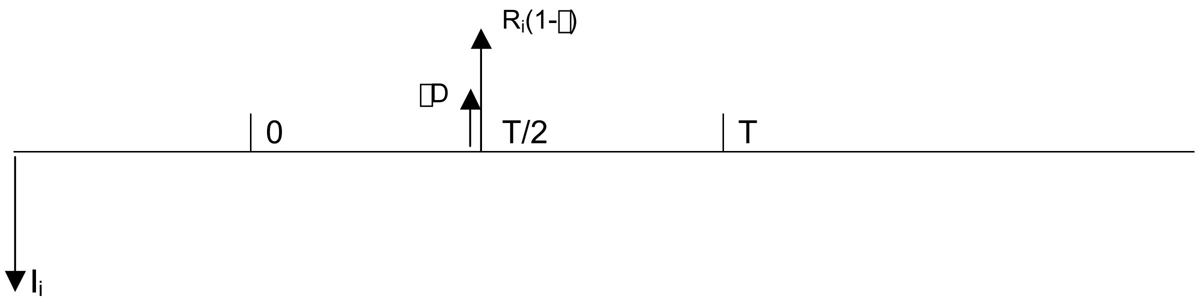
- To make this easier, we will assume that the revenues are received as a single cash flow, R_b, occurring at the midpoint of the in-core fuel irradiation lifetime. We will also assume that the taxes, T, are paid at the midpoint of fuel irradiation.



- We can transform this into the equivalent 'tax-implicit' problem:



- Next, calculate the revenue requirement, R_i, for each I_i.



$$0 = I_i - (1-\tau)R_i e^{-x\Delta T_i} - \tau D e^{-x\Delta T_i}$$

where ΔT_i is the time from cash outlay to irradiation midpoint

Note also that $D = I_i$

$$\therefore R_i = \left(\frac{I_i}{1-\tau}\right)e^{x\Delta T_i} - \left(\frac{\tau}{1-\tau}\right)I_i$$

$$= \frac{I_i}{1-\tau}\left[1 + x\Delta T_i + ... - \tau\right]$$

$$\approx I_i + \frac{xI_i}{1-\tau}\Delta T_i$$

$$\approx I_i + I_i\phi\,\Delta T_i$$

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i.e., the revenue requirement = direct cost + carrying charges for ΔT_I years.

Next, for each fuel cycle transaction, I_i, we can write:

$I_i = M_i \times C_i$

where

M_i = mass processed at stage i
C_i = unit cost of transaction i

we can write that the total cost

$$\approx M_i C_i + \left[M_i C_i\right]\Phi . \Delta T_i$$

and the total batch cost

$$\approx \sum_i M_i C_i + \sum_i \left[M_i C_i\right]\Phi . \Delta T_i$$

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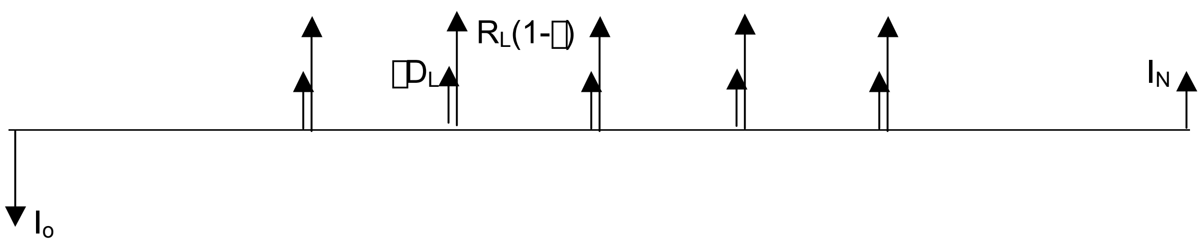
<u>Question: How accurate is this approximation?</u>

We can compare it with the more exact expression for the levelized annual revenue requirement for capital charges we derived previously.

Recall:



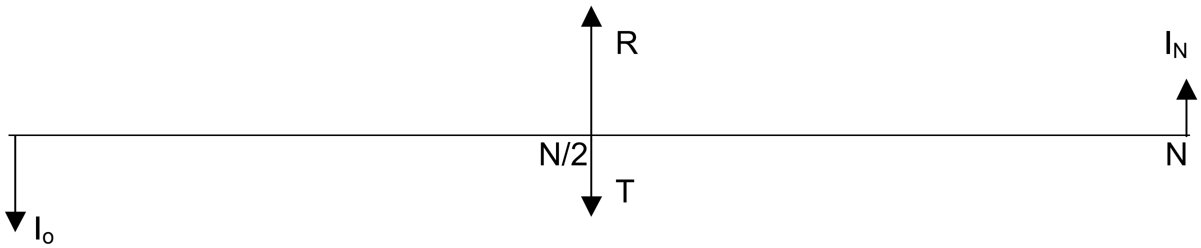
And the levelized annual revenue requirement, R_L is given by

$$R_L = \Phi I_o$$

where, for straight line depreciation

$$\Phi_{SLD} = \left[\frac{1}{1-\tau}\right]\left[(A/P, x\%, N) - \frac{\tau}{N}\left(1 - \frac{I_N}{I_o}\right) - \frac{I_N}{I_o}\left(A/F, x\%, N\right)\right]$$

Compare this with the approximate expression derived above:



We can write that the revenue, R, required to balance this investment if received in a lump sum at N/2 is given by:

$$R = R_o + R_N$$

Where, from the above approximation, we can write that

$$R_o \approx I_o + I_0 \,\square.\,(N/2)$$

$$R_n \approx -I_N + (-I_N)\,\square.\,(-N/2)$$

Therefore,

$$R \approx I_o\left[\left(1 - \frac{I_N}{I_o}\right) + \square.\,(N/2)\left(1 + \frac{I_N}{I_o}\right)\right]$$

The annual revenue requirement can therefore be approximated by R/N,

$$\frac{R}{N} \approx \frac{I_o}{N}\left[\left(1 - \frac{I_N}{I_o}\right) + \square.\,(N/2)\left(1 + \frac{I_N}{I_o}\right)\right]$$

For x=0.1; $I_o/I_N = 0.1$; and $\square = 0.4$, we have

	Exact expression, $\square_{SLD} I_0$	Approximate expression, R/N	Error
N=20	0.1629 I_o	0.1367 I_o	~ 19%
N=5	0.293 I_o	0.2717 I_o	~ 8%

Fuel Cycle Cost for Once-Through Cycle

We can use the approximate cost model for a single fuel cycle batch to estimate the fuel cycle cost for a PWR operating on the once-through fuel cycle according to the material balance shown in Figure 3.

Reference Economic Parameters
(Once Through Fuel Cycle: PWR)

Transaction	Unit Cost	**Lead Time**[□]
Ore purchase	\$30/kg U	2 years
Yellowcake conversion	\$8/kg U	2 years
Enrichment	\$100/kg separative work[+]	1 year
Fuel fabrication	\$275/kg U	0.5 years
Interim spent fuel storage	\$100/kg U	Payable at fuel discharge
Spent fuel encapsulation and final disposal (including transportation)	\$400/kg U	Payable at fuel discharge

[□] Time to start of fuel loading
Duration of irradiation = 4.5 years
[+] See classnote "Additional note on uranium enrichment and separative work"

NOTE: Some minor transactions such as chemical conversion of UF_6 to UO_2 and transportation have been included in the price assigned to a contiguous major transaction.

Material Flows for Once-Through PWR Fuel Cycle in Figure 3
(Basis: 1 kg HM of enriched uranium fuel

Transaction	Mass Flow
Ore purchase	$\frac{311,400}{29,800} = 10.45 \text{ kg U}$
Yellowcake conversion	10.45 kg U
Enrichment	6.23 kg Separative Work[+]
Fuel fabrication	1.01 kg HM
Interim spent fuel storage	1.0 kg HM
Spent fuel encapsulation and final disposal (including transportation)	1.0 kg HM

[+] See classnote "Additional note on uranium enrichment and separative work"

Calculation of Once-Through Fuel Cycle Cost:

Basis: 1 kg of 4.51% enriched uranium (see fuel cycle material balance)

Transaction	Unit Cost, C_i (\$/kg)	Mass Flow, M_I (kg)	ΔT_I (years)	Direct Cost, $M_I C_I$ (\$)	Carrying Charge, $M_I C_I \lambda \Delta T_I$
Ore purchase	30	10.45	4.25	313.5	133
Yellowcake conversion	8	10.45	4.25	83.6	35.5
Enrichment	100 (\$/kg SW)	6.23 kg SW	3.25	623	202.5
Fabrication	275	1.01	2.75	277.8	76.4
Interim SF storage	100	1.0	-2.25	100	-22.5
Final disposal	400	1.0	-2.25	400	-85
TOTAL				1797.9	339.9
GRAND TOTAL				\$2137.8/kg 4.51% U	

(Note: We have assumed λ = 0.1/yr)

We can obtain the fuel cycle cost in c/kwh(e) as follows

Fuel cycle cost (cents/kwh(e) = 2137.8 (\$/kg U) x 1000 (kg/MT) x 1/50,000 (MTHM/MWD) x 1/24 (days/hr) x 1/ 1000 (MW/kw) x 1/0.33 (kwh(th)/kwh(e))

= <u>0.54 cents/kwh(e)</u>

(<u>Note:</u> This is <u>not</u> a levelized cost over the reactor lifetime; it is the fuel cycle cost for the specified batch.)