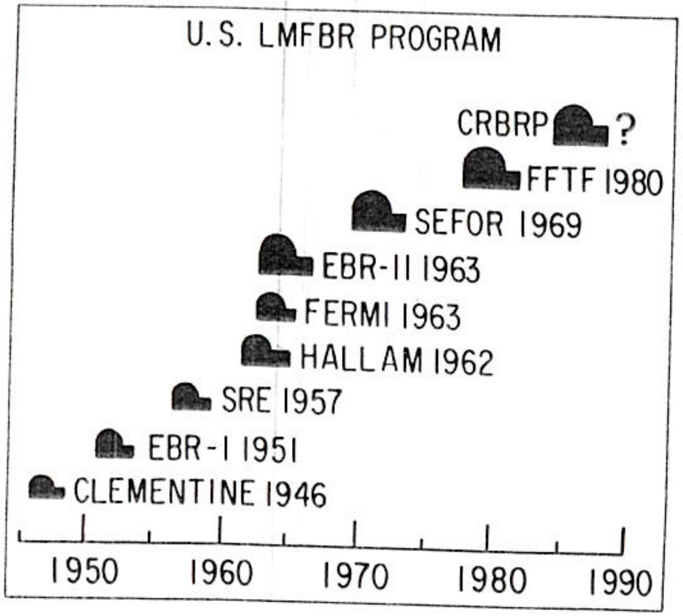

DIRECTOR'S SPECIAL COLLOQUIUM

"THE PROPER ROLE OF THE BREEDER REACTOR"

by

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November 18, 1980
2:00 p.m.
Auditorium, Bldg. 362

Refreshments Will Follow

11/18/80

"The Proper Role of the Breeder Reactor," talk at Director's Special Colloquium, Argonne National Laboratory, Argonne, IL. (111880PRBR)

111880PRBR

The Proper role of the Breeder Reactor

November 18, 1980
Argonne National Laboratory

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Kennedy School of Government

and

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OUTLINE

Background
- Breeder Fundamentals
- Nuclear Power Benefits
- Breeder Proliferation Hazards in Perspective

The Proper Role of the Breeder Reactor

- Introduction

  - Limited Uranium Resources

  - Startup on LWR Plutonium

- WHAT TO DO?
  - Proposal

  - Other Alternatives

  - Non-proliferation characteristics of the Proposal

- Implications for U.S. Breeder R&D Program

CONCLUSION

How Manage the Breeder Reactor?

Conservative Proposal:

Fuel "normal" first-generation LMFBR with 11.5 tonnes* ("11.5 T") of U-235 as 20% in U-238. [Conventionally, LMFBR would be started with 7.5 T of fissile Pu]. Reprocess and recycle fuel in normal manner, feeding the LMFBR with 1.2 T annually of depleted or natural U.

At 0.25% tails, 11.5 T of U-235 comes from 3100 T of U_3O_8, which will then fuel this LMFBR for 2000 years. Also invested must be 2300 T-SWU at $75,000 / T-SWU or $170 million. [3.5 million T of U_3O_8 → 1100 LMFB

Redesign of LMFBR core to minimize U-235 inventory can reduce costs. Molten-salt "breeder" with no out-of-core inventory and 2.5 T of U-235 in-core ~~will~~ would allow 5000 1000-MW(e) reactors to operate for 500 years. Continued operation with U_3O_8 costs of $1000/lb would be tolerable.

Ref: "Nuclear Fuel Cycles and Waste Management," A.P.S.

Benefits/–

Arbitrary deployment rate (independent of LWR or breeder history).

Lower-cost, greater safety potential, possibly higher efficiency because no constraint of high conversion ratio. C.R. = 1 is fine.

Earlier availability of useful breeder.

Potential increased benefits from lower-cost advanced isotope separation techniques, lower-inventory breeder/converters.

Cost/– less than 3 mill/kwh compared with LMFBR under deployment conditions ideally suited to LWR-LMFBR transition.

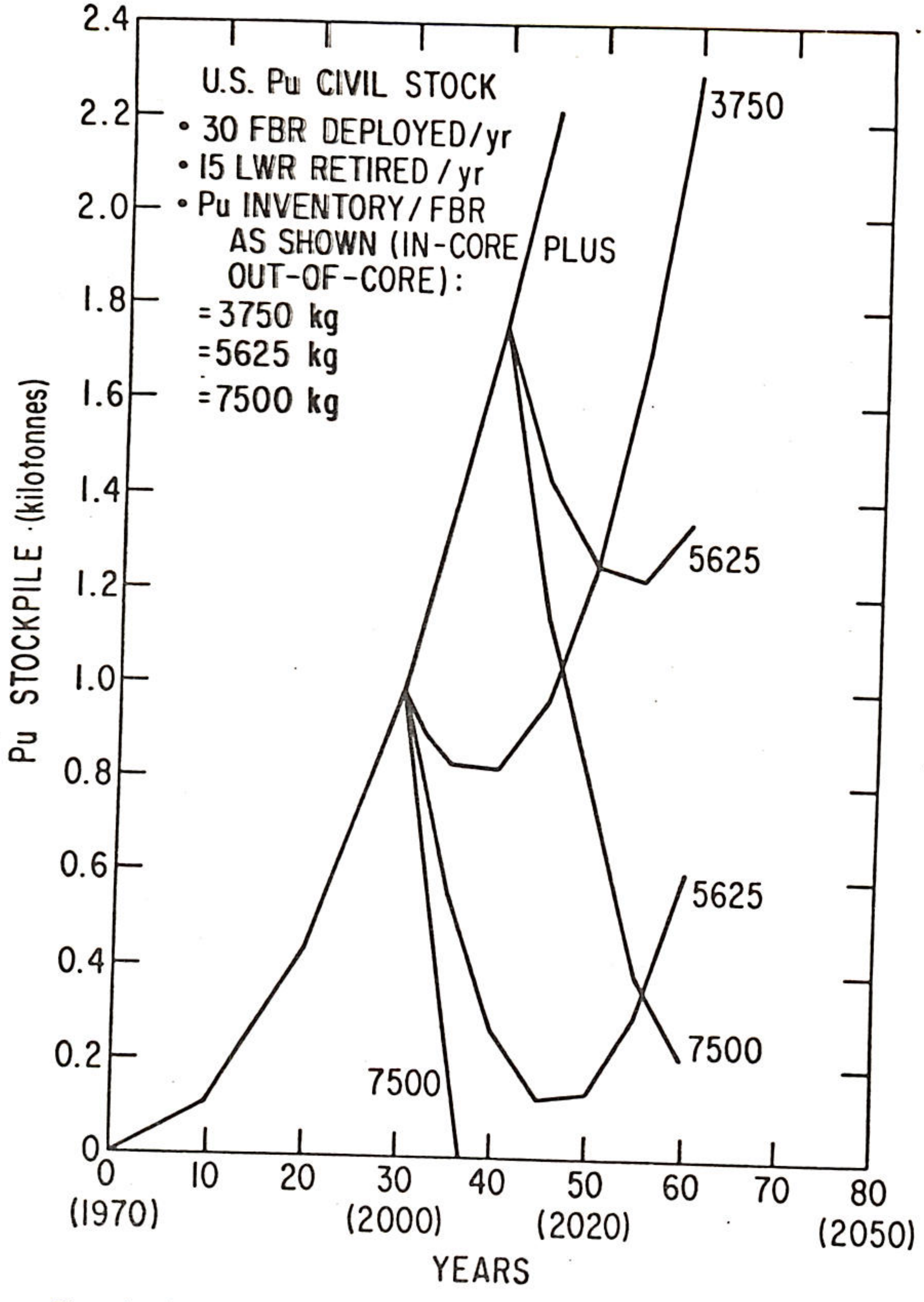


Figure 1. U. S. civil plutonium stockpile vs. year of introduction of the FBR (year 2000 or 2010), with 3 assumptions as to required Pu inventory of each FBR. This figure was provided to the author by the Director of Energy Research (DoE) June 20, 1978. Note that while the NASAP assumes a "3750 kg FBR", a memo of July 7, 1978 to the Director of Energy Research (DoE) from the Acting Director, Office of Fuel Cycle Evaluation (DoE) notes that "it is reasonable to assume that lower inventory FBRs, such as the 5625 kg/GWe design shown in your curves, could be available if required."

From TABLE AV-2 of Ref. 1

Economic Penalty to Start 1000 Mw Fast Breeder with Enriched U^{235}

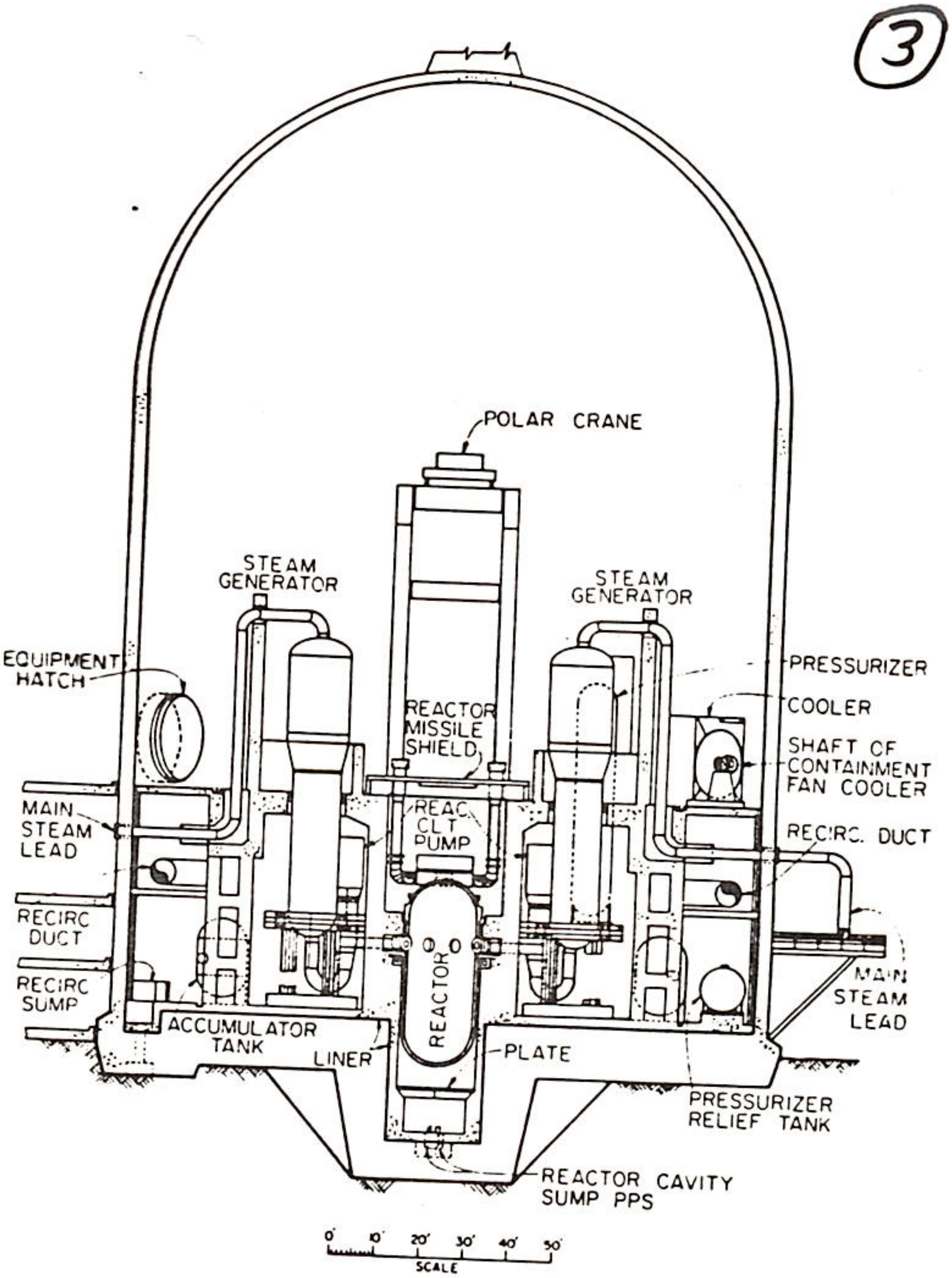
	Water-reactor Plutonium	20% U^{235} in Uranium (with separate core reprocessing and recycle)
Fissile amount required from external source for start-up and replacement loadings, kg.	7,500	11,250
Value of fissile material, $/kg fissile (a)	19,900	31,000
Total cost of fissile material, $million	149	349
Loss of breeding-gain fissile production:		
kg fissile Pu	0	1,700
$million	0	34
Contribution to fuel cycle cost levelized over 30-year breeder plant life (b)		
Purchase of fissile material for start-up mill/kwhr	2.2	5.3
loss of breeding-gain fissile production mill/kwhr	0	0.3
Relative total, mill/kwhr (c)	2.2	5.6
Levelized fuel cycle cost, mill/kwhr (c)	2.0	5.4

(a) Plutonium value is calculated for alternative use as a water-reactor fuel.

(b) Calculated from time schedule of fissile purchases and sale, using utility discount factor of 0.0755/yr.

(c) The relative total _not_ the total fuel cycle cost. Later credits from breeding gain fissile production and cost of fabrication and reprocessing result in an estimated LMFBR levelized total fuel cycle cost of about 2.0 mill/kwhr (Stauffer et al, 1975).

FIG. 6. Typical PWR containment, from Unit 2 Diablo Canyon, Pacific Gas and Electric Company.



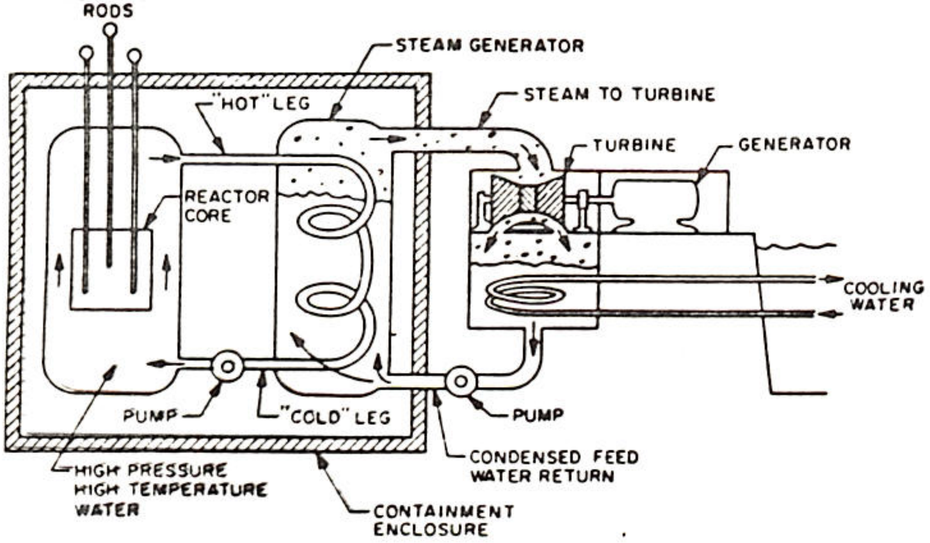


FIG. 5. Schematic idealization of pressurized-water reactor power system components.

energy released in the reaction resides in the kinetic energy of the fission products. As shown in Table 3A-1, the fissioning of one atom of ^{235}U leads to the release of about 200 MeV of heat; in more practical units, complete fissioning of 1 g of ^{235}U releases about 1 megawatt-day of thermal energy.

Table 3A-1

End Products and Energies from fission of 235U (from Bennet, 1973)

End-product	Emitted Energy (MeV)
Fission products	168
Fission neutrons	5
Prompt γ radiation	7
Fission product decay	
β radiation	8
γ radiation	7
neutrinos	12
Capture γ radiation	5
Total	212

In order to sustain a chain reaction, one of the neutrons emitted in the fission must cause another fission before it is captured by some nonfission process or leaks out of the reactor core. The number of neutrons emitted in a fission is given in Table 3A-2. The average energy of the emitted neutrons is about 2 MeV spread out over the spectrum shown in Figure 3A-2.

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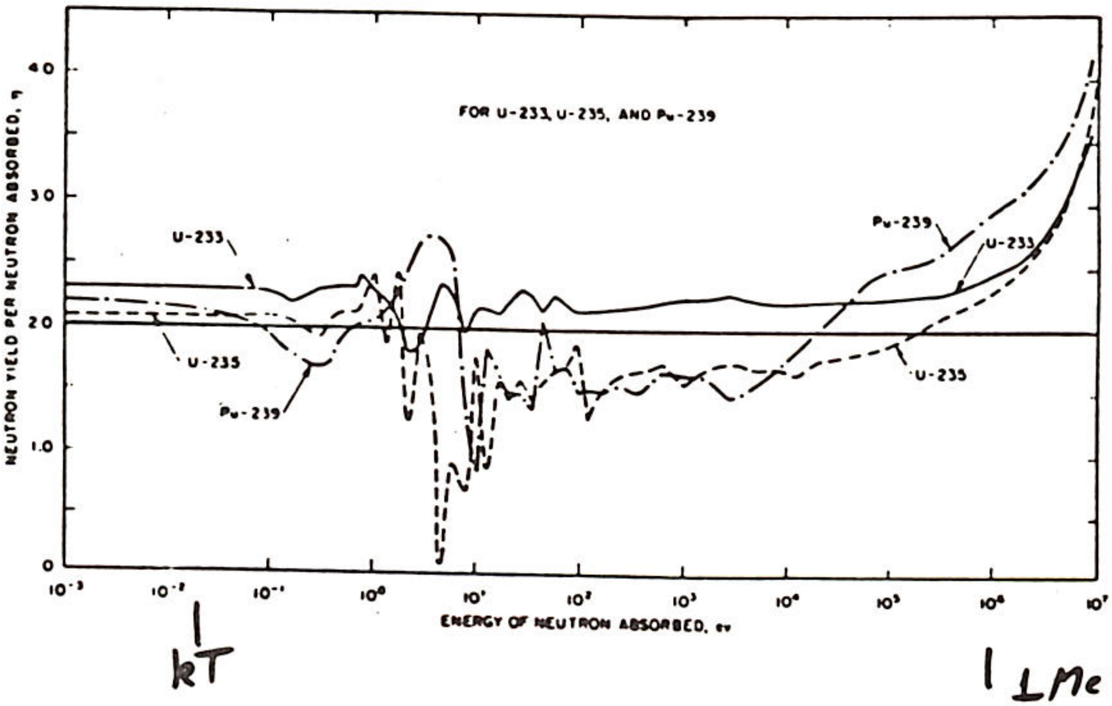

Figure 3A-4. Neutron yield (η) per neutron absorbed for ^{233}U, ^{235}U, and ^{239}Pu (from ERDA-1541).

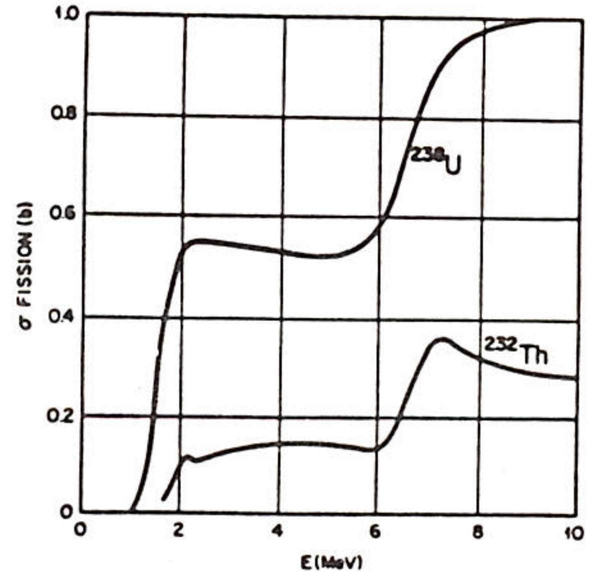

Figure 3A-5. Fission cross-section of ^{232}Th and ^{238}U (ORNL/TM-5565).

⑥

Table 3A-4

Assumed characteristics of model PWR and BWR enriched uranium reactors (ORNL, 1976)

	PWR	BWR
Electric Power, Mw(e) (net)	1000	1000
Thermal power, Mw(th)	3077	3067
Avg. spec. power, Mw(th)/Mg[a]	37.5	23.8
Avg. burnup, Mw(th)-days/kg	33.	27.5
Refueling interval, days[b]	365.25	365.25
Steady State Charge, kg[c]		
U-234	9.57	10.1
U-235	903	838.5
U-236	76.6	90.3
U-238	26450	31315
Total U	27350	32250
Steady State Discharge, kg[c]		
U-235	219	233
Total U	26,150	31100
Fissile Pu[d]	170	198
Total Pu[e]	248	282

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[a] Based upon full power and total fuel charged.

[b] At 80% load factor

[c] Annual charge and discharge of one third of PWR and one quarter of BWR.

[d] Plutonium isotopes ^{239}Pu and ^{241}Pu.

[e] ^{238}Pu + ^{239}Pu + ^{240}Pu + ^{241}Pu + ^{242}Pu.

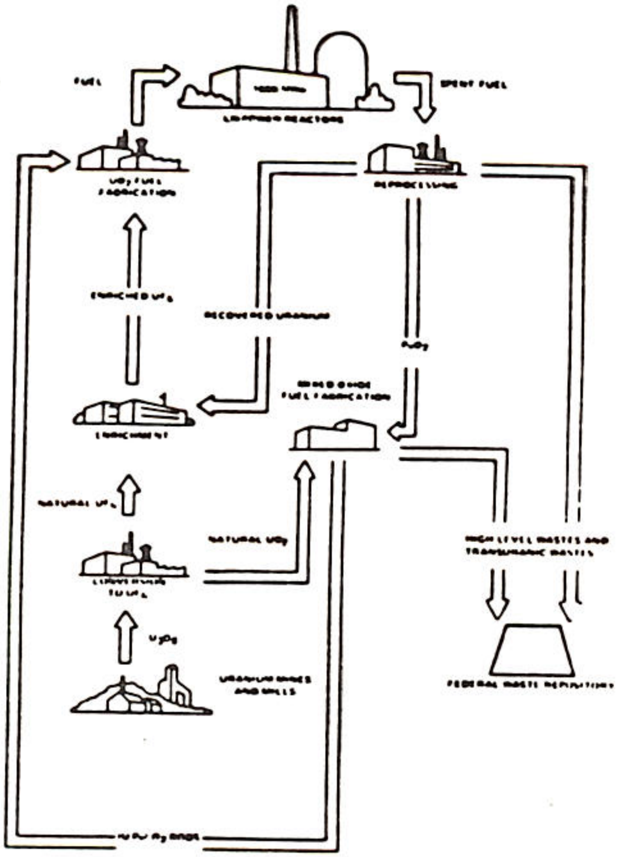
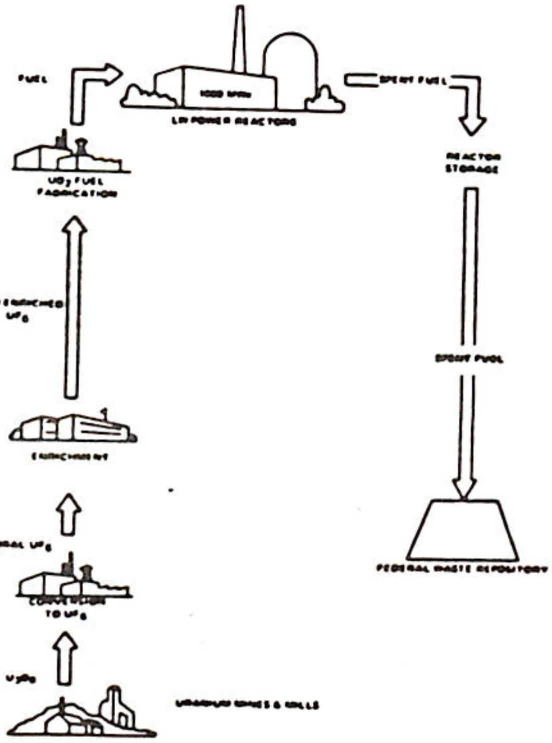
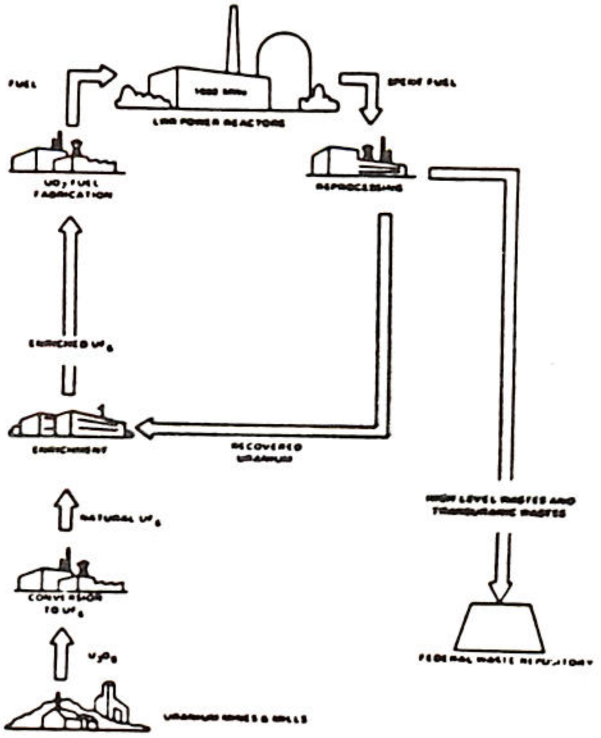


Figure 3B-3. Light water reactor fuel cycle--uranium and plutonium recycle (GESMO).





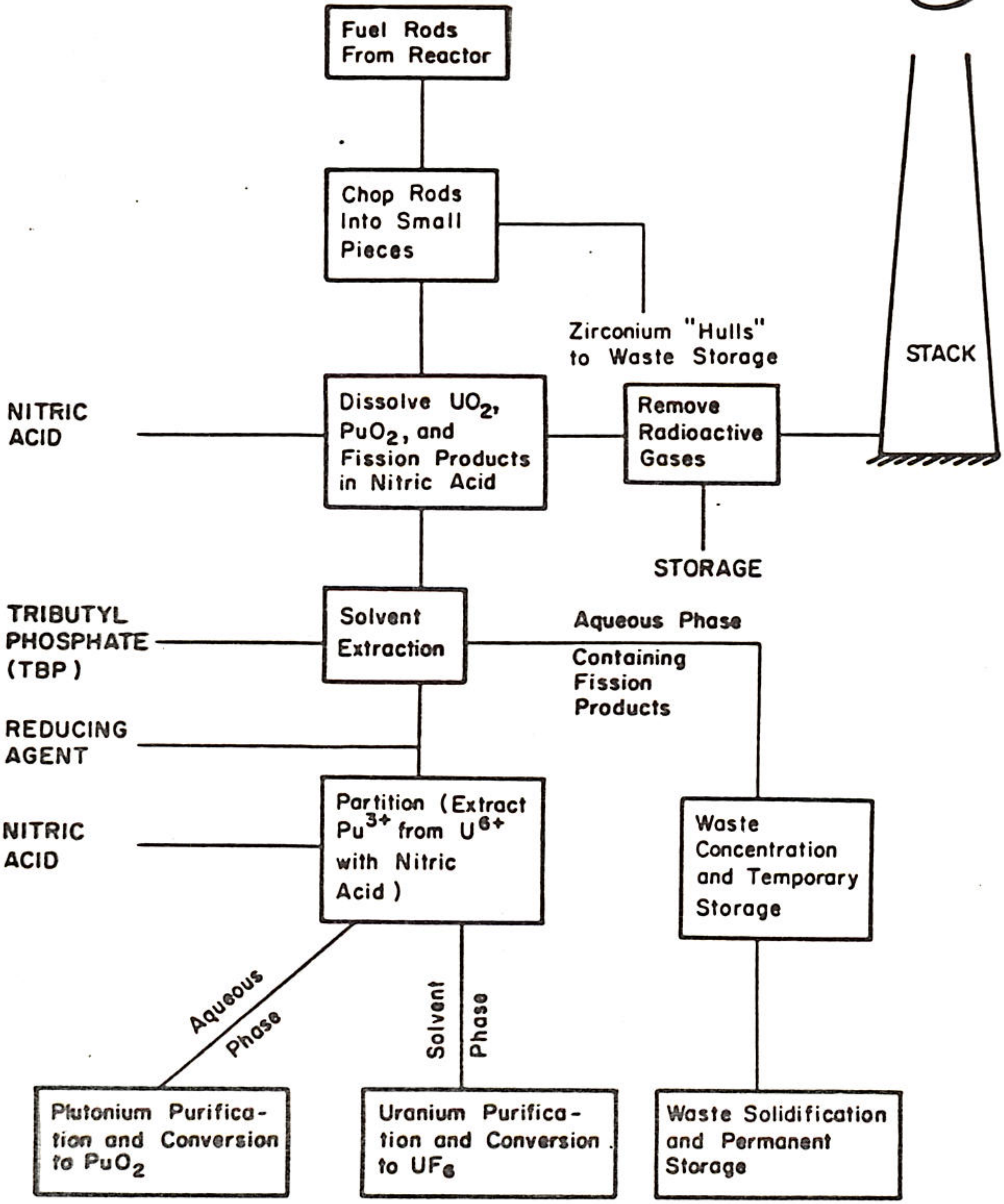


Figure 1. Elementary steps in nuclear fuel reprocessing by the purex process.

⑨

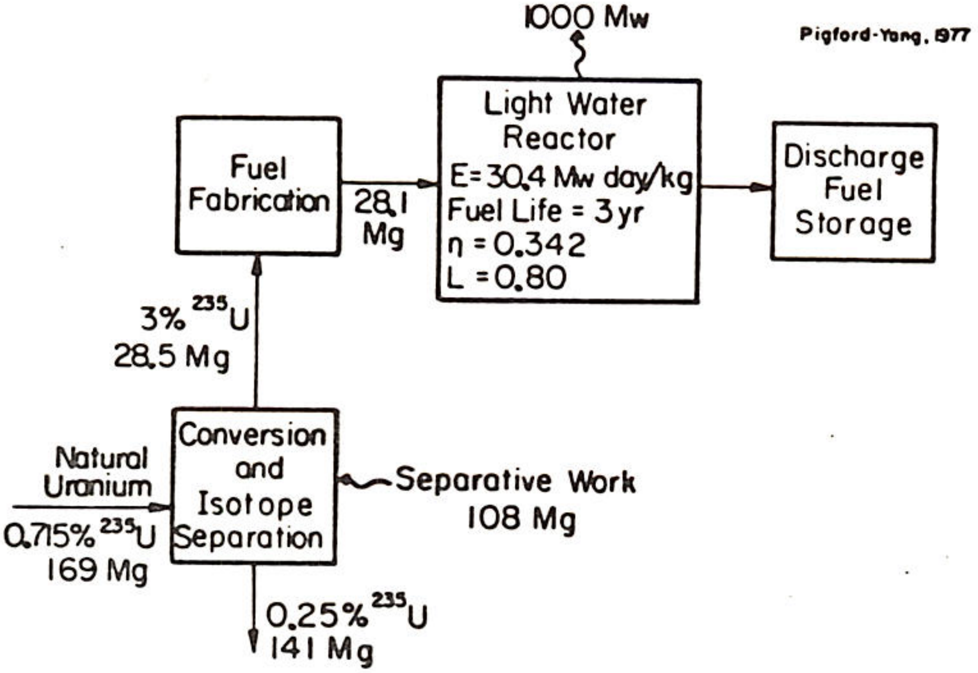


Figure 5. Material flowsheet for pressurized water reactor no reprocessing.

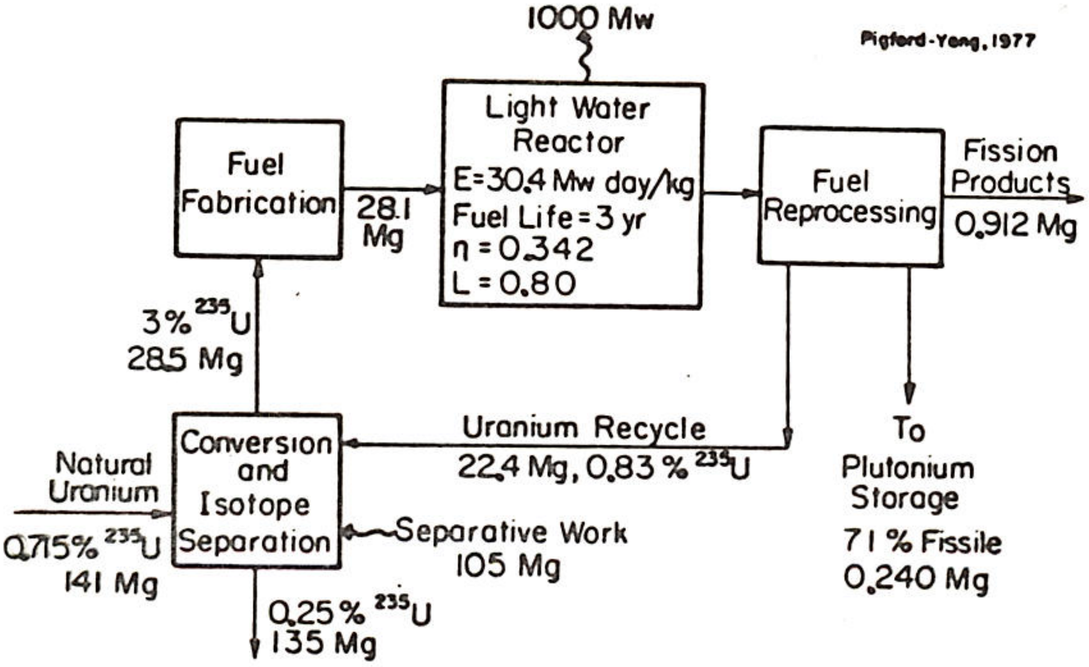


Figure 6. Material flowsheet for pressurized water reactor with uranium recycle and plutonium storage.

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For each of the fuel cycle options data were developed (Pigford & Choi, 1977; Pigford and Yang, 1977; Shapiro, *et al.*, 1977) for the initial loading of fuel in the reactor and for the charge and discharge quantities and compositions of each replacement loading throughout the reactor life. The cost of electrical energy generated by each batch of fuel was determined, and the fuel cycle cost levelized over the 30-yr. plant life was calculated.

Table 16
Unit Costs, Recoveries, Process Times and Fuel Cycle Operations

Operation	Unit Cost in 1976 dollars[a] \$/kg	Recovery factor in operation	Time of Expenditure	
			Relative to beginning of fuel operation yr	Relative to fuel discharge yr
U_3O_8 purchase (\$28 per pound of U_3O_8)	\$72.64/kg U	1.00	-2	
U_3O_8 to UF_6 conversion	\$3.50/kg U	0.995	-1.5	
Isotope Separation	\$75.00/kg SWU	1.00	-1.0	
UO_2 conversion and fabrication	\$95.00/kg U	0.99	-0.5	
Shipment of discharge fuel	\$15.00/kg HM	1.00		+0.75
Fuel processing	\$165.00/kg HM	0.99 Pu, U		+1
Waste management-federal repository	\$50.00/kg HM	1.00		+11
PuO_2 - UO_2 conversion fabrication	\$198.00/kg HM	0.99	-0.5	
Shipment of fissile Pu (as PuO_2)	\$40.00/kg Pu	1.00	-0.75	
Canal storage of discharge fuel	\$5.00/yr kg HM	1.00		+1,2,..
Long-term storage of discharge fuel in repository	\$100.00/kg HM	1.00		+11

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[a] "HM" denotes heavy metal, i.e., total actinides charged to the reactor. All unit cost data are from NRC (USNRC, 1976), except the cost of fuel reprocessing. The reference cost of UO_2 fuel reprocessing was derived in Section IV-E9. (See Table 13.) MOX fuel reprocessing is assumed to cost 20% more than UO_2 reprocessing.

⑪

G3b. *Costs of the Fuel Cycle with Reprocessing and Uranium-Plutonium Recycle.*

The fuel cycle costs for reprocessing with uranium-plutonium recycle can be calculated directly from the cycle-by-cycle data on the fuel material quantities charged and discharged to the reactor. For self-generated recycle no plutonium or uranium is sold or purchased. Instead, the recovered plutonium is recycled, when available, thereby reducing the amount of natural uranium and of enrichment service which must be purchased for subsequent cycles. The plutonim is followed through the five successive recycles during the 30-yr. period, and it is assumed that the plutonium in a given batch of discharge fuel is the same as that later recovered from reprocessing, i.e., a cross-over between fuel batches in reprocessing is neglected. In this way the continued build-up of the higher-mass isotopes of plutonium, e.g., ^{242}Pu, and their effect upon reactivity and burnup are properly taken into account.

Similarly, the uranium recovered from fuel reprocessing is recycled for isotopic enrichment to 3% ^{235}U, further reducing the amount of natural uranium and enrichment which must be purchased for later replacement fuel loadings. It is assumed that discharge UO_2 fuel is reprocessed separately from discharge MOX fuel, to avoid the degradation in isotopic concentration of ^{235}U that would otherwise occur if the two types of discharge fuel were reprocessed together. The uranium recovered from the discharge MOX fuel is stored.

Table 17

Fuel Cycle Cost for a Pressurized Water Reactor With No Reprocessing of the Discharge fuel (30-year levelized cost in 1976 dollars with unit costs from Table 16)

	Fuel Cycle Cost mill/kwh
U_3O_8 purchase	2.72
U_3O_8 to UF_6 conversion	0.12
Isotope Separation	1.51
Fuel conversion and fabrication	0.55
Total cost of fuel charged to reactor	4.90
Storage of discharge fuel for 11 years	0.13
Ship to federal repository	0.02
Store in federal repository	0.17
Total Fuel Cycle Cost	5.22

(12)

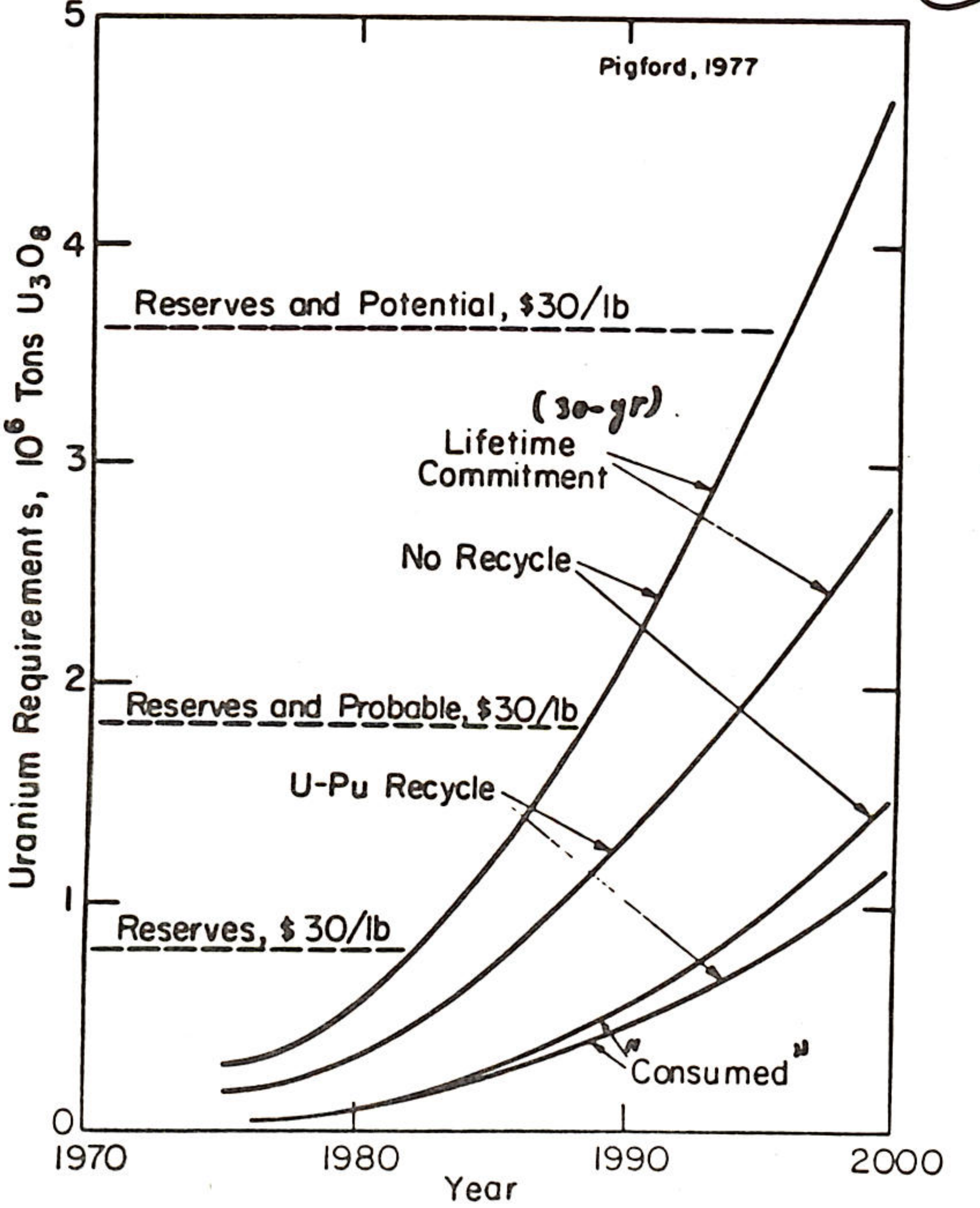

Figure 10. Ore requirements for U.S. nuclear power industry for the high growth case. (0.25% ^{235}U in depleted uranium)

Table 17

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Total cost of fuel charged to reactor	4.90
Storage of discharge fuel for 11 years	0.13
Ship to federal repository	0.02
Store in federal repository	0.17
Total Fuel Cycle Cost	5.22

⑬

Table 25

Total Cost of Electrical Energy from Pressurized-Water Reactor
(70% load factor, yearly charge on capital investment = 16%/yr., reference unit costs of fuel cycle operations)

	Storage of discharge fuel mill/kwh	Reprocessing discharge fuel, recycle U and Pu mill/kwh	Reprocessing discharge fuel, U recycle, 10-yr Pu storage and recycle mill/kwh	10-yr. storage of discharge fuel, U-Pu recycle mill/kwh
Capital cost	26.1	26.1	26.1	26.1
Operating cost	2	2	2	2
Fuel cycle cost	5.2	4.8	5.3	5.0
Total cost of electrical energy	33.3	32.9	33.4	33.1
Percentage difference	0	-1.2	+0.3	-0.6

G3I. ERDA Analysis aof the Benefits of Reprocessing and Recycling Light Water Reactor Fuel

The unit costs used by ERDA in its analysis (ERDA, 1976) of the benefits of reprocessing and recycle are listed in Table 26. Alto listed, for comparison, are the reference unit costs used in our present study (from Table 16). The most important difference is in the unit cost of reprocessing.

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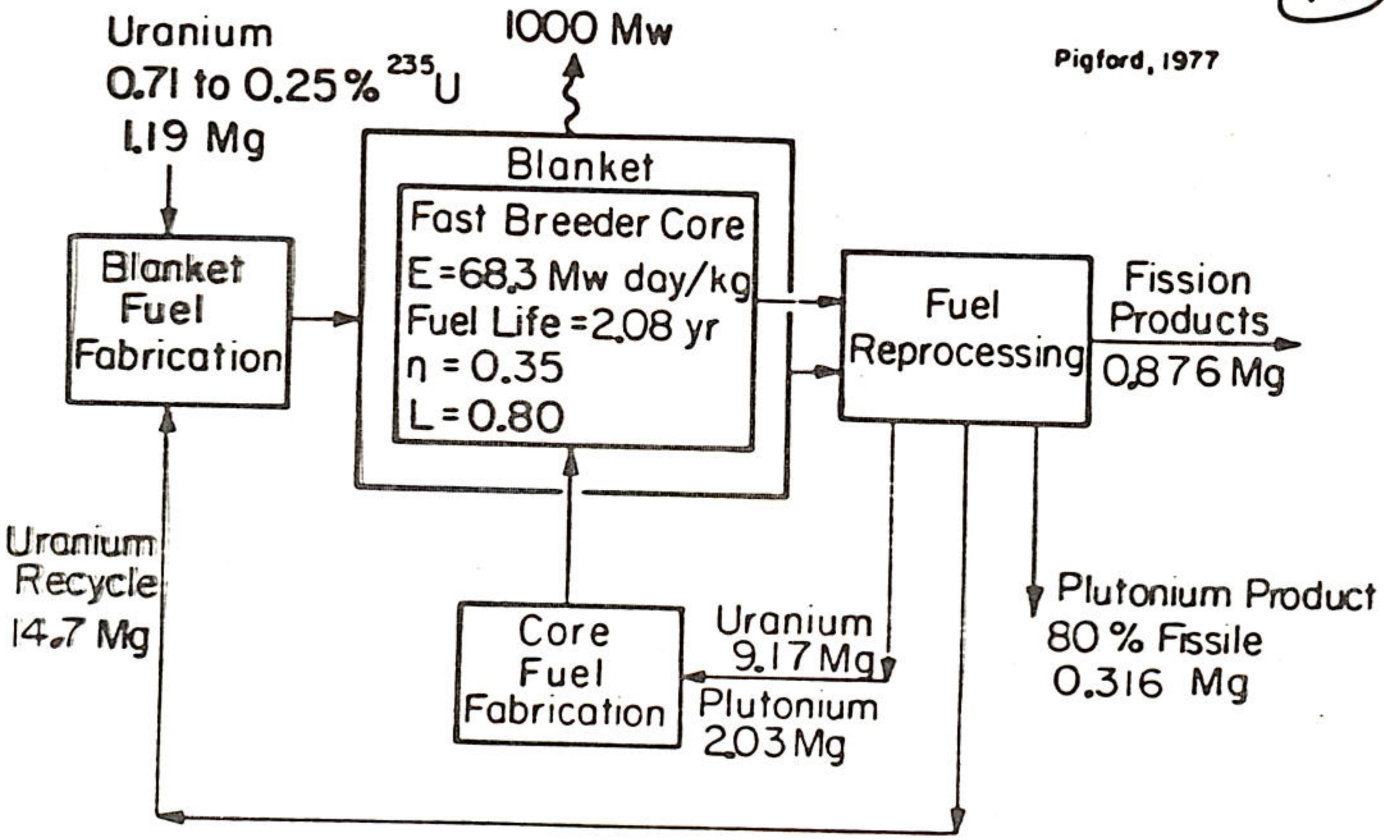

Figure 10. Annual quantities for LMFBR fueled with natural or depleted uranium (equilibrium fuel cycle, Greebler, 1977)

Table 5

Fissile, Ore, and Enrichment Requirements to Start a First-Generation Fast Breeder Reactor with Water-Reactor Plutonium (1000 Mw Electrical Power, 80% capacity Factor)

		start with 20% U-235 *
Fissile Pu required for fast breeder start-up [a]	7500 kg	11500 kg
Operation of U-Fueled water reactor to generate Pu start-up inventory	43.8 Gw Yr	—
U ore chargeable to loss of Pu-recycle in water reactors:		U ore needed for start
0.20% depleted U	2980 short tons U_3O_8	2820 short tons
0.25% depleted U	3210 short tons U_3O_8	3110 short tons
Additional separative work due to loss of Pu-recycle in water reactors:		Mg SWU
0.20% depleted uranium	1200 Mg	2560 Mg
0.25% depleted uranium	1020 Mg	2330 Mg

Example: To start up 1 GW of FBR requires that 4.38 Gw of LWR be operated for 10 yr. without Pu recycle. Total ore required = 8490 short tons U_3O_8 (0.25% depleted U). Total ore attributable to breeder start-up = 2980 short tons.

[a] Based upon 3000 kg fissile Pu for the initial core plus 4500 kg for replacement loadings before Pu in discharge fuel is recycled (Greebler, 1977). [2.5 Core loads, total]

* Based upon 4500 kg ^{235}U for the initial core plus sufficient replacement loadings until reactor is self sustaining on reycle fissile material. Although lower ^{235}U loadings are possible for a breeder core optimized for ^{235}U fueling, the purpose here is to start-up a core optimized for steady-state fueling on bred plutonium (Geebler, 1977).

The data in Table 5 indicate that over a 30-year operating life, three uranium-fueled light water reactors could produce enough plutonium to start up two fast breeders, if no plutonium were to be recycled in water reactors. Alternatively, nine water reactors operating during their last ten years of life without plutonium recycle will generate enough plutonium to eventually start up two breeders. The 1974 ERDA projections of U.S. nuclear power growth indicated a growth to 124 GW of fast breeder capacity by the end of the century, along with 644 GW of light water reactors. Calculations (Pigford and Ang, 1975) of the amount of start-up plutonium required for such a large scale of breeder introduction showed that plutonium recycle in water reactors would have to be discontinued in the early 1990's to insure sufficient plutonium for breeder start-up. However, events since 1974 suggest that such a rapid introduction of breeders is not likely, and delays in LWR fuel reprocessing and in the construction of additional LWR fuel reprocessing facilities seem more likely to result in an over supply in the 1990's of plutonium which can be extracted from water reactor fuel.

Table AV-2

Economic Penalty to Start 1000 Mw Fast Breeder with Enriched ^{235}U

	Water-reactor Plutonium	20% ^{235}U in Uranium: With separate core reprocessing and recycle	20% ^{235}U in Uranium: Without separate core reprocessing and recycle
Fissile amount required from external source for start-up and replacement loadings, kg.	7,500	11,250	18,000
Value of fissile material, $/kg fissile[a]	19,900	31,000[f]	31,000
Total cost of fissile material, $10^6	149	349[d]	558
Loss of breeding-gain fissile production:			
kg fissile Pu	0	1,700	1,700
$10^6	0	34	34
Contribution to fuel cycle cost levelized over 30-year breeder plant life[b]:			
Purchase of fissile material for start-up, mill/kwhr	2.2	5.3[e]	7.0
loss of breeding-gain fissile production, mill/kwhr	0	0.3	0.3
Total, mill/kwhr[c]	2.2	5.6	7.3
^{235}U penalty, mill/kwhr	0	3.4	5.1

[a] Plutonium value is calculated for alternative use as a water-reactor fuel.

[b] Calculated from time schedule of fissile purchases and sale, using utility discount factor of 0.0755/yr.

[c] This is *not* the total fuel cycle cost.

All at 0.25% tails.

d. Including 2330 Mg SWU at $75,000/Mg SWU → $\$175 \times 10^6$

e. If LIS or other reduces SWU cost by factor 4, this goes to ~ 3.3 mill/kwh.

f. Including $15200/kg in charges assumed for isotope separation