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**Alternatives to
Proposed Replacement Production Reactors**

University of California

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Hatice S. Cullingford

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ABBREVIATIONS

AEC	Atomic Energy Commission, a former federal agency, disbanded by the Energy Reorganization Act of 1974	IAEA	International Atomic Energy Agency
AIF	Atomic Industrial Forum	INEL	Idaho National Engineering Laboratory
ANL-W	Argonne National Laboratory-West	LLW	Low level wastes (containing minimal transuranic elements)
ATR	Advanced Test Reactor	LMFBR	Liquid metal fast breeder reactor
BNFP	Barnwell Nuclear Fuel Plant	LOFT	Loss of Fluid Test Facility
BNL	Brookhaven National Laboratory	LWBR	Light-water breeder reactor
BWR	Boiling water reactor, a version of an LWR	LWR	Light-water reactor
CANDU	Canadian deuterium-uranium reactor	m	Minutes
CRBRP	Clinch River Breeder Reactor Plant	MeV	Million electron volts
d	Day	MFRP	Midwest Fuel Recovery Plant
DoD	Department of Defense	MOX	Mixed oxide reactor fuel (containing both plutonium and uranium)
DOE	Department of Energy	MW(e)	Megawatts, electrical
DOT	Department of Transportation	MW(th)	Megawatts, thermal
EBR-II	Experimental Breeder Reactor	NFS	Nuclear Fuel Services
EPA	Environmental Protection Agency	NRC	Nuclear Regulatory Commission, a federal agency, successor to regulatory functions of AEC
ERDA	Energy Research and Development Administration, a federal agency, successor to all nonregulatory functions of the Atomic Energy Commission. Merged to become DOE.	ORNL	Oak Ridge National Laboratory
ETR	Engineering Test Reactor	ORR	Oak Ridge Research Reactor
FFTF	Fast Flux Test Facility	PWR	Pressurized water reactor, a version of an LWR
FY	Fiscal Year	RPR	Replacement production reactor
HEDL	Hanford Engineering Development Laboratory	RRY	Reference reactor year. A 1000-MW(e) reactor, assumed to be operating at 80% of its maximum capacity for one year.
HEPA	High-efficiency particulate air filters	SGHWR	Steam-Generating Heavy-Water Reactor (British)
HFBR	High Flux Beam Reactor	SRP	Savannah River Plant
HFIR	High Flux Isotope Reactor	SSCR	Spectral shift control reactor
HLW	High level wastes	t	Metric ton
HM	Heavy metal	TRU	Transuranic
HWR	Heavy-water reactor		

ALTERNATIVES TO PROPOSED REPLACEMENT PRODUCTION REACTORS

by

Hatice S. Cullingford

ABSTRACT

To insure adequate supplies of plutonium and tritium for defense purposes, an independent evaluation was made by Los Alamos National Laboratory of the numerous alternatives to the proposed replacement production reactors (RPR). This effort concentrated on the defense fuel cycle operation and its technical implications in identifying the principal alternatives for the 1990s. The primary options were identified as (1) existing commercial reactors, (2) existing and planned government-owned facilities (not now used for defense materials production), and (3) other RPRs (not yet proposed) such as CANDU or CANDU-type heavy-water reactors (HWR) for both plutonium and tritium production. The evaluation considered features and differences of various options that could influence choice of RPR alternatives. Barring a change in the US approach to civilian and defense fuel cycles and precluding existing commercial reactors at government-owned sites, the most significant alternatives were identified as a CANDU-type HWR at Savannah River Plant (SRP) site or the Three Mile Island commercial reactor with reprocessing capability at Barnwell Nuclear Fuel Plant and at SRP.

I. INTRODUCTION

The growing disparity between production of plutonium and tritium and the demand for these materials has become a major national defense concern. Until recently, plans for nuclear weapon materials management relied upon the Savannah River Plant (SRP) for production and chemical processing. Earlier, the N-Reactor and Purex Plant at the Hanford Engineering Development Laboratory (HEDL) were also in the production/processing network of the defense fuel cycle. However, as technology develops and present reactors become dated, it is vitally important to upgrade production reactors to assure availability of plutonium and tritium beyond the 1990s. The current Department of Energy (DOE) plan is to upgrade the SRP and Hanford facilities and to examine the proposals for seven types of replacement production reactors (RPR) listed in Table I.

Los Alamos National Laboratory began this study as an independent evaluation of all possible alternatives to the proposed RPRs. The most important issues were investigated during the course of the study, including

- Fuel cycle requirements for production of plutonium and tritium
- Technology base for operability
- Power production
- Flexibility for quality, quantity, and alternate materials
- Schedule
- Location
- Resource efficiency
- Cost
- Safeguards
- Social and institutional acceptability.

TABLE I
PROPOSED RPRs

1. LWR	Light-Water Reactor (PWR type)
2. HTGR	High-Temperature Gas (Cooled) Reactor
3. RNR	Replacement N-Reactor
4. LMFBR	Liquid-Metal (Cooled) Fast Breeder Reactor
5. LTHWR	Low-Temperature Heavy-Water Reactor
6. HTHWR	High-Temperature Heavy-Water Reactor
7. ENB	Electronuclear Breeder
^a 8. GCFR	Gas-Cooled Fast Reactor
^a 9. MSBR	Molten Salt Breeder Reactor

^aEliminated by initial screening.

After examination of available options, several possibilities were identified: (1) use of existing commercial reactors, (2) use of existing and planned government-owned facilities that are not currently used for defense material production, and (3) other RPRs, such as Canadian deuterium-uranium reactors (CANDU) or CANDU-type heavy-water reactors (HWR). Appen-

dices address nuclear fuel reprocessing, transportation of nuclear fuel materials, and several long-term solutions in the form of accelerators and fusion-fission reactors. Physical science and technology are emphasized in this study, but the final choice also must take into account economic, political, social, institutional, and legal issues.

II. THE DEFENSE FUEL CYCLE

Figure 1 shows a generalized block diagram of the defense fuel cycle that produces plutonium and tritium. A nuclear production plant is the source of irradiation for the ^{238}U fuel and ^6Li target. A typical fission reaction occurring in a nuclear reactor is illustrated by

As the reactor is operated, fissile (fissionable) ^{239}Pu is produced by neutron absorption in ^{238}U ,

As suggested in Fig. 2, a self-sustaining chain reaction will need only one of the several neutrons produced per fission to cause another fission.¹ The interaction of fission-produced neutrons with matter is also illustrated in Fig. 2. Because an average fission event produces two or three neutrons, surplus neutrons are available for "capture" by the fuel itself, a lithium-containing target, the reactor structures, and the coolant. Reacting with the

Fig. 1.
Generalized defense fuel cycle.

Fig. 3.
The PWR concept.

Fig. 4.
The BWR concept.

A commercial LWR is shut down annually for refueling; one-third of a PWR core and one-fourth of a BWR core are replaced at each fueling. Typical isotopic composition of plutonium in discharged LWR fuel is given in Fig. 5. Exact values depend on individual reactor design, operation, and initial fuel composition.^{3,4} Table III(a) lists nominal plutonium isotope composi-

tions of spent fuel from UO_2 -fueled BWRs, based on calculations using a 3.2% ^{235}Pu enrichment for a 33 MW-d/kgHM burnup.^{5,6} For comparison, the uranium and plutonium composition of fresh and spent MOX (UO_2 and PuO_2 , mixed oxide) LWR fuel is also given in Table III(b) for a 33 MW-d/kgHM burnup and a fissile (^{235}U , ^{239}Pu , and ^{241}Pu) content of 4.1%.

TABLE II
REPRESENTATIVE CHARACTERISTICS
OF A COMMERCIAL LWR*

	PWR	BWR
Coolant	Ordinary water (H ₂ O)	Ordinary water (H ₂ O)
Moderator	H ₂ O	H ₂ O
²³⁵ U enrichment (%)	2-4	2-4
Fertile (bred) nuclide	²³⁸ U(²³⁹ Pu)	²³⁸ U(²³⁹ Pu)
Core	Rod assemblies	Rod assemblies
Annual uranium (U ₃ O ₈) requirements at equilibrium (t)	129	121
Lifetime uranium (U ₃ O ₈) requirements (t)	4100	4020
Net electric power [MW(e)]	1000	1000
Thermal power [MW(th)]	3077	3067
Avg. burnup [MW(th)-d/kg]	33.0	27.5
Refueling interval (yr)	1	1

*Based on reference reactor year (RRY).

Fig. 5.

Typical amount and isotopic composition of plutonium in discharged fuel as a function of burn-up in an LWR.

Reference 7 reported that a standard power reactor produces about a kilogram of plutonium per day. These data indicate that fuel design and fuel management can be technically adjusted in existing LWRs to produce plutonium in fuel assemblies and tritium in lithium-containing target assemblies at calculable quantities and quality. Electricity production is compromised, however, because of fuel design changes or more frequent refueling to tailor the discharge fuel and target content. For example, the effect of replacing one-ninth of the fuel rods in a PWR core with lithium target rods can be estimated. The power decrease of approximately 10% could be compensated by an increase in the ²³⁵U enrichment in the fuel. If the target rods contained a 95% ⁶Li enrichment, about a 10% greater uranium enrichment is required. Tritium production rate then would be about 0.18 kg/yr from target rods in eight instrument wells of existing PWRs.

TABLE III(a)

**URANIUM AND PLUTONIUM COMPOSITION
OF FRESH AND SPENT UO₂ LWR FUEL
FOR 33 MW-d/kgHM BURNUP^a**

	Fresh Fuel	Spent Fuel
Total Uranium (kg/tHM)	1000	956
Isotopic Composition (weight %)		
²³⁵ U	3.2	0.8
²³⁶ U	0	0.4
²³⁸ U	96.8	98.8
Total Plutonium (kg/tHM)	0	9
Isotopic Composition (weight %)		
²³⁸ Pu	---	1.4
²³⁹ Pu	---	55
²⁴⁰ Pu	---	25
²⁴¹ Pu	---	13
²⁴² Pu	---	5
Other Actinides (kg/tHM)	0	0.6

TABLE III(b)

**URANIUM AND PLUTONIUM COMPOSITION OF
FRESH AND SPENT MOX LWR FUEL FOR
33 MW-d/kgHM BURNUP^a**

	Fresh Fuel	Spent Fuel
Total Uranium (kg/tHM)	946	930
Isotopic Composition (weight %)		
²³⁵ U	0.7	0.35
²³⁶ U	0	0.08
²³⁸ U	99.3	99.6
Total Plutonium (kg/tHM)	54	33
Isotopic Composition (weight %)		
²³⁸ Pu	1.7	4
²³⁹ Pu	50	36
²⁴⁰ Pu	27	31
²⁴¹ Pu	15	18
²⁴² Pu	7	11
Other Actinides (kg/tHM)	0	2

^aAdapted from Refs. 5 and 6.

LWRs also could be altered to increase neutron use by introducing heavy water (D₂O) into the system immediately after refueling, creating a spectral shift control reactor (SSCR).¹ A greater portion of neutrons are then absorbed by ²³⁸U, converting it to ²³⁹Pu. The uranium use of an SSCR would be similar to that of a (once-through) CANDU (discussed in Sec.III.C.1.) or an LWR with uranium and plutonium recycles.

2. **Fuel Cycle.** Spent fuel rods from existing LWRs contain plutonium, some higher actinides, and a residue of fissile uranium.² In the US, about 4300 t of irradiated spent fuel are being stored now and 74 licensed reactors are discharging spent fuel at the rate of about 900 t per year.⁸ Figure 6 shows the once-through fuel cycle without reprocessing and recycling of valuable uranium and plutonium from spent fuel. This uranium and plutonium can be separated from the fission products and from each other and new reactor fuel elements could then be formed. With this recycling process, the fuel cycle shown in Fig. 7 includes the following individual steps.^{2,9}

- Mining
- Milling
- Refining and conversion
- Enrichment
- Reprocessing of spent fuels to separate and recover uranium and plutonium from radioactive wastes and from one another*
- Conversion of recovered uranium*
- Reenrichment of recovered uranium*
- Conversion (to enriched UF₆)
- Fabrication of enriched uranium pellets
- Conversion of recovered plutonium to a solid form (for example, PuO₂)*
- Combination of recovered plutonium with uranium for making mixed oxide fuel, fabrication of pellets, encapsulation in fuel rods, and assembling into fuel elements
- Spent fuel storage
- High level and transuranic waste storage and disposal*

Nuclear fuel reprocessing is discussed in Appendix A.

A separate cycle is needed to produce tritium from the ⁶Li-containing target. Individual steps of this cycle are given below.

- Mining
- Milling

*These operations are omitted in the once-through fuel cycle.

Fig. 6.
Once-through nuclear fuel cycle.

- Refining and conversion
- Reprocessing of spent target to separate and recover lithium and tritium from radioactive wastes and from one another
- Conversion of recovered lithium
- Reenrichment of recovered lithium
- Conversion (to lithium alloy or compound)
- Fabrication of target rods and assembly into target elements
- Tritium storage
- Spent target storage
- Waste storage and disposal

After transportation from the reactors, fuel and target could be processed to separate plutonium and tritium at existing reprocessing facilities at SRP, Idaho Falls, and the Barnwell Nuclear Fuel Plant (BNFP). Transportation in the civilian nuclear fuel cycle is discussed in Appendix B.⁶

Fig. 7.
LWR fuel cycle with uranium-plutonium recycle.

The plant at Three Mile Island, Pennsylvania, is an example of how a commercial reactor could be used for the defense fuel cycle although it might be temporarily idle for political reasons.¹⁰ Unit 1 could be operated for production of electricity [800 MW(e)] and defense materials while the needed repairs were being completed in Unit 2.

B. Existing and Planned Government-Owned Facilities

1. Production Capability. The potential production capability of existing and planned government-owned facilities was investigated, including demonstration, test, research, and training reactors. The results of a study of DOE facilities are listed in Table IV (Ref. 11). Based on this study, the currently operating Fast Flux Test Facility (FFTF) and planned Clinch River Breeder Reactor Plant (CRBRP) show potential for material output in the next century. Both FFTF and CRBRP are liquid metal (cooled) fast breeder reactors (LMFBR). The fast neutrons produced in an LMFBR can produce a larger number of fission neutrons upon absorption by fissile materials than can thermal (slower) neutrons in an LWR.

FFTF, a liquid sodium-cooled, fast test reactor located at HEDL, uses mixed oxide fuel (a mixture of plutonium oxide and depleted uranium oxide) in 0.0058-m-diam fuel pins clad by stainless steel 316 (SS 316). Two hundred and seventeen pins are bundled in a fuel assembly in a hexagonal array. The rated power level is 400 MW(th) without electricity generation capability. Table V lists the characteristics of FFTF. Designed for a 30-year lifetime, it reached criticality in 1980 and is currently used for fast reactor fuels and materials testing.

Although using FFTF for defense materials production is feasible, the production rate will be low, for example, 44 kg of plutonium or 0.5 kg of tritium per year. Because it is located in the same government reservation as the N-Reactor and the Hanford Purex Plant, it might be possible to reprocess fuel and target assemblies there. However, this would require expansion and modification of the Purex plant.

CRBRP is to be a demonstration LMFBR with a power level of 975 MW(th) and 375 MW(e) (see Fig. 8 and Table V). Its fuel elements are similar to the FFTF fuel assemblies; in addition, blanket assemblies are scattered heterogeneously throughout the core, using pins consisting of depleted uranium (²³⁸U). It is technically feasible to use CRBRP for defense materials

production in addition to electric power generation. Estimated plutonium or tritium production is about 210 kg and 2.6 kg per year, respectively, but could be optimized to 340 kg and 4.3 kg per year. Another alternative might involve tritium production by an accelerator located with CRBRP at Oak Ridge, Tennessee, using electric power generated by CRBRP to produce plutonium (see Appendix C discussion).

Other government-owned facilities such as training reactors and naval reactors owned by DoD were investigated for production capability. Because these reactors are used for other DoD programs and are highly optimized for small power generation, infrequent refueling, and highly enriched fuel, they are not good candidates for production of defense materials.

2. Fuel Cycle. Table V also lists the characteristics of a commercial scale LMFBR for comparison with FFTF and CRBRP. The LMFBR development was planned to help extend natural resources indefinitely by establishing a plutonium economy as illustrated in Fig. 9. The Atomic Energy Commission (AEC) began groundwork in the late 1950s, and US long-range plans anticipated commercial use of mixed oxide fuels in LWRs by the 1980s.² In the early 1960s the first commercial uranium and plutonium reprocessing plants were built and operated by Nuclear Fuel Services at West Valley, New York, and by Eurochemic in Mol, Belgium. Larger reprocessing plants with improved fuel-handling technology were built in the early 1970s at Barnwell, South Carolina, and La Hague, France. Research was also initiated to solve the problems of treatment and permanent storage or disposal of nuclear waste.

Assuming a 30-day decay time, a 1000-MW(e) LMFBR core loaded with depleted uranium plus recycled plutonium and uranium typically will have the isotopic composition of extracted plutonium shown in the following table.

Pu	%	kg
236	2×10^{-6}	3×10^{-5}
238	0.1	1.4
239	71.6	1460.6
240	25.1	510.8
241	2.4	48.4
242	0.8	15.5
Total	100%	2037 kg

TABLE IV
PRODUCTION CAPACITY OF DOE-OWNED REACTORS

Reactor	Laboratory	Fuel	Fuel Type	Coolant	Reflector	Operation Life	Plant Availability	Programmatic Availability	Thermal Power [MW(th)]	Optimal Conversion Ratio	Optimal Pu ^a Production (kg/yr)	Optimal T ^a Production (kg/yr)	Confidence Factor for Optimal Production	Best Estimate ^b Pu Production (kg/yr)	Best Estimate ^b T Production (kg/yr)	Confidence Factor for Best Estimate Production	Annual Operating Costs (Million \$)
CRBRP	Oak Ridge Tenn.	Pu ^c	Oxide Pellets	Na	²³⁸ U	1985/2015	0.75	0.0 or 1.0	975	1.20	340	4.3	<0.5	210	2.6	0.75	Not available
FFTF	HEDL	Pu ^c	Oxide Pellets	Na	Stainless Steel	1981/2011	0.75	0.5	400	1.20	140	1.8	<0.5	44	0.5	0.75	75
LWBR	Shipping Port	²³³ U	Oxide	LW	Thoria	1977/1985	0.70	0	236	1.00	---	---	---	---	---	---	---
ATR	INEL	93% ²³⁵ U	Al/U metal	LW	Be	1967/2007	0.70	0.20	250	0.80	55	0.7	<0.3	1.6	0.04	0.8	15
ETR	INEL	93% ²³⁵ U	Al/U metal	LW	Be	1957/1987	0.90	1.00	175	0.80	49	0.6	<0.3	7.1	0.18	0.8	7
HFIR	ORNL	93% ²³⁵ U	Al/U metal	LW	Be	1965/1995	0.94	0.50	100	0.80	29	0.4	0.4	6.7	0.17	0.9	4
EBR-II	ANL-W	67% ²³⁵ U	U metal	Na	Stainless Steel	1961/1991	0.70	1.00	62.5	1.00	17	0.2	<0.3	---	---	---	16
LOFT	INEL	U	Oxide	LW	LW	1978/1988	0.70	1.00	50	0.80	11	0.1	<0.2	---	---	---	40
HFBR	BNL	93% ²³⁵ U	Al/cermet	HW	HW	1965/1995	0.80	0.65	40	0.80	10	0.1	<0.3	1.0	0.02	0.8	2.3
ORR	ORNL	93% ²³⁵ U	Al ₂ O ₃ cermet	LW	Be	1958/1988	0.85	1.00	30	0.80	8	0.1	<0.3	1.2	0.03	0.3	1.5
							Total		2318		659	8.3		272	3.5		
Other (91 research reactors with individual power ratings less than 30 MW)							Totals		2439		685	8.6					

^aOptimal estimates are based on conversion efficiency (isotopes produced per fission) x fissions per full power x plant availability (assume 100% programmatic availability) and assumes no coproduction of tritium and plutonium.

^bBest estimates are based on approximate calculations of test space production rates x plant availability x programmatic availability and assumes no coproduction of tritium and plutonium.

^cPlutonium driver fuel for CRBR and FFTF contains approximately 12% ²⁴⁰Pu.

Fig. 8.
An LMFBR plant.

From this table we can estimate the plutonium production of CRBRP by using a scale factor of 0.375, based on the power production: 548 kg of ^{239}Pu per year, compared with 210 kg in Ref. 11.

Existing reprocessing facilities at SRP, Idaho Falls, and BNFP are candidates for fuel processing, plutonium separation, target processing, and tritium separation. Associated costs of such an operation should be evaluated.

C. Other Concepts

Commercial HWRs promise great production potential for defense materials. Future alternatives may also include fusion-fission reactors for coproduction of plutonium and tritium and pure fusion reactors and accelerators for tritium production—both of which will be discussed in Appendix C.

1. Production Capability. Heavy water as a moderator has some advantages for thermal reactors because it has a lower capture cross section than that of light water. The improvement in neutron economy allows use of natural uranium as a fuel, eliminating the need for enrichment and thereby simplifying the use of other fissile materials as fuel.² variety of HWRs, including Fugen, Cirene, Atucha, CANDU, and SGHWR, have been developed throughout the world.¹² The only commercial HWR at present is the CANDU, designed and developed by Atomic Energy of Canada, Ltd. Figure 10 shows CANDU's fuel and heavy-water coolant confined to a system of pressure tubes, with a heavy-water moderator at low pressure in the intervening spaces. The heavy-water coolant flows through the fuel channels and produces steam with ordinary water in the steam generators.

A typical CANDU fuel bundle consists of an array of rods that are considerably larger than those for an LWR

TABLE V
COMPARISON OF LIQUID METAL FAST BREEDER
PARAMETERS*

Design Parameters	FFTF	CRBR	Commercial and Commercial Prototype
Thermal power [MW(th)]	400	975	3800
Net electric power [MW(e)]	---	350	1500
Overall plant efficiency (%)	---	35.9	39.5
Number of primary loops	3	3	3
Containment diameter/depth below operating floor/height above operating floor (m)	41/24/33	57/26/52	51/26/50
Fuel material	Oxide	Oxide	Oxide
Cladding material	SS 316	SS 316	Low swelling/ SS 316
Fuel rod diameter (m)	0.0058	0.0058	0.0069
Fuel rod pitch/diameter ratio	1.26	1.26	1.24
Number fuel rods/assembly	217	217	271
Number fuel assemblies	76	198	318
Number blanket assemblies	None	150	234
Number control/safety assemblies	6/3	15/4	27/4
Core height/diameter (m)	0.91/1.22	0.91/1.89	1.22/3.1
Peak fuel burnup (MW-d/kg)	80	150	150
Breeding ratio	---	1.2	1.25
Doubling time (yr)	---	23	12/15
Vessel diameter/length (m)	6.31/13.35	6.31/16.40	7.16/18.14

*Adapted from "Report of the Liquid Metal Fast Breeder Reactor Program Review Group," US Energy Research and Development Administration, ERDA report, ERDA 1 (January 1975).

and contains natural uranium rather than enriched UO_2 . The low fuel burnup in natural uranium requires frequent fuel rod replacement, but the Canadian design allows for continuous refueling without shutting down the reactor. Thermal efficiency is 30%, lower than that for LWRs (which is about 33%).

A 1000-MW(e) CANDU contains about 130 t of natural uranium, as UO_2 , in 0.012-m-diam Zr-Nb-clad rods that are assembled in circular arrays of 37 rods per assembly. Operating with natural uranium, with only 0.7% ^{235}U , annual fuel burnups are about 7.5 MW-d/t. The annual natural uranium charge has a fissile content of about 940 kg, and the annual discharge contains about 220 kg ^{235}U and 350 kg of ^{239}Pu . Table

VI shows annual production and characteristics of material for uranium-fueled CANDU reactors with (1) no recycle and (2) a self-generated plutonium recycle for equilibrium fuel cycles.

Significant tritium production occurs in the heavy-water moderator because of neutron activation of the heavy water ($\text{D} + ^1_0\text{n} \rightarrow \text{T} + \gamma$) as shown in Fig. 2. Approximately 0.1 kg/yr of tritium is generated at steady state after approximately 15 yr of operation in a 1000-MW(e) reactor.¹³ Ontario Hydro, a Canadian power company, is developing a tritium removal and recovery system from the moderator and estimates a total cumulative production potential of 39.6 kg of tritium during the life of the eight Pickering reactors.

TABLE VI

**INPUT-OUTPUT CHARACTERISTICS
OF A 1000-MW(e) URANIUM-FUELED CANDU
REACTOR WITH (1) NO RECYCLE AND (2)
A SELF-GENERATED PLUTONIUM RECYCLE^a**

(1)	
Natural uranium	131 t
Fuel burnup	7.5 MW-d/kg
Spent fuel composition	
²³⁵ U	0.17%
Fissile Pu ^b	0.27%
(2)	
Natural uranium	60 t
Fuel burnup	16 MW-d/kg
Spent fuel reprocessed	
Fission products	1.008 t
²³⁸ U	58.3 t
Recycled Pu ^b	0.187 t

^aAdapted from Ref. 2, equilibrium fuel cycle assumed.

^bFissile Pu: ²³⁹Pu and ²⁴¹Pu.

To increase tritium production, a fraction of the fuel assemblies can also be replaced by target assemblies containing ⁶Li, as in other reactors. However, this would mean two tritium separation facilities, one for the moderator and another for the target.

CANDU reactors are not licensed in the US. However, a conceptual design of a large heavy-water reactor for US siting was developed recently.¹² Table VII lists the design parameters of this pressurized HWR. Various studies on licensing of CANDUs have concluded that there is no reason why the HWR should not be licensable in the US.^{12,14,15}

2. Fuel Cycle. Table VII indicates the CANDU fuel cycle with a self-generated plutonium recycle.² Reference 1 reported that annual discharge of fissile plutonium in spent fuel from the slightly enriched HWR core is lower than that discharged from the LWR and is less than half the discharge of the natural uranium-fueled system. Thus, it is easier to optimize a natural uranium-fueled HWR for maximum plutonium production. Such a reactor, however, has the highest uranium core requirements, as shown in Fig. 11.¹⁶

TABLE VII

DESIGN PARAMETERS OF AN HWR FOR US SITING

Output	
total fission	4029 MW
gross electrical	1344 MW
net electrical	1260 MW
Coolant	Heavy water (D ₂ O)
Moderator	D ₂ O
D ₂ O Inventory	0.65 t/MW(e)
Pressure tubes	740
material	Zr-Nb
inside diameter	103.3 mm
wall thickness	5.79 mm
Active core size (height/diameter)	5.94 m/8.76 m
Lattice pitch	0.286 m
Fuel load	8880 bundles
U	163 t
UO ₂	185
Fuel bundle (37 elements)	
length/diameter	495.3 mm/102.49 mm
Cladding	Zr

Fig. 11.
Cumulative uranium ore requirements for the CANDU power plant.

Because the present SRP reactors are a low-temperature type HWR, the US has considerable experience with operating and reprocessing fuel and target assemblies for plutonium and tritium production.

IV. DISCUSSION OF ALTERNATIVES

The features of these various alternatives to RPRs were studied and compared for defense material production on a unit capability basis. A qualitative comparison of the most significant alternatives, that is, existing LWRs, FFTF/CRBRP, and HWRs, is summarized in Table VIII. All alternatives with significant potential also provide electric power production and exhibit flexibility for quantity, quality, and alternate material production. Environmental impact, safety, and fuel cycle economics were estimated to be similar, although a detailed analysis was not performed.

A. Production Capability

Existing LWRs and HWRs have high production capabilities because of inherent flexibility for quantity, quality, and alternate defense material products. The FFTF/CRBRP alternative was rated less than high because they produce a lower level of power than does a commercial LWR or HWR.

TABLE VIII

QUALITATIVE COMPARISON OF SIGNIFICANT ALTERNATIVES^a

	Production Capability ^b	Product Assurance ^c	Resource Efficiency ^d	Fuel Cycle ^e
Existing LWRs	High	High	Less than medium	High
FFTF/CRBRP	Less than high	Medium	High	Medium
HWRs	High	High	Medium	Less than high

^aBased on availability at a government-owned site.

^bProduction flexibility for quantity, quality, and alternate products.

^cTechnology base and state of development (system dependability).

^dUranium resource utilization.

^eFuel fabrication, reprocessing, and waste management.

B. Production Assurance

The state of development, and therefore the system dependability, is highest with the LWR. Seventy-four nuclear reactors, with a combined rate capacity of 55 000 MW(e), are licensed to operate in the US. HWRs, rated second, are higher than FFTF/CRBRP because nine CANDU reactors already are operating with a total rated power of 3017 MW(e).

C. Resource Efficiency

The FFTF/CRBRP alternative was rated highest in resource efficiency because they are LMFBRS, and can be optimized for minimum moderation (slowing of the neutron energy) to achieve the highest possible yield of fission neutrons per fissile neutron absorption. Thus, uranium resource efficiency is highest with an LMFBRS (oxide breeder), followed by CANDUs, and LWRs.

D. Fuel Cycle

Fuel cycle technology, that is, fuel fabrication, reprocessing, and waste management, was investigated for each alternative. The LWR fuel cycle was judged the most developed in all areas, followed by HWRs because of the experience with the SRP reactors. Although the fuel fabrication for FFTF/CRBRP is available, reprocessing and waste management have not been demonstrated. The approximate amount of reprocessed fuel is given below for several reactors, based on Ref. 1.

Reactor Type	RRY Reprocessing Amount
LWR	25 t
LMFBR	20 t
CANDU	115 t
CANDU (Pu recycle)	60 t

E. Summary

Existing LWRs and new HWRs have approximately the same potential for defense production activities. However, a detailed cost-benefit analysis is needed to quantify this potential. The FFTF/CRBRP alternative is also very attractive because of already invested federal funding and their locations at government-owned sites.

Without further analysis, the FFTF/CRBRP option appears to be the most cost-effective alternative, but has a higher risk in product assurance.

V. CONCLUSIONS

To assure the required production levels of plutonium and tritium beyond 1992, more fuel cycle options are now available than in the 1940s and 1950s. In addition to the proposed RPRs being considered, the only practicable solutions for plutonium and tritium production are HWRs (such as CANDU and CANDU-type reactors) or existing commercial power reactors at a government site.

Each option is viable only with accompanying separation facilities for its specific fuel and target assemblies. The real potential of these alternatives depends on the availability of BNFP for reprocessing and on the resource economics of the associated fuel cycle. If the defense fuel cycle were to include reprocessing of spent fuel from commercial reactors, a constant source of plutonium would be possible. Tritium requirements, including target reprocessing, could then be met with dedicated nuclear facilities such as reactors or even accelerators. However, the traditional "Atoms for Peace" attitude toward commercial power reactors and other institutional reasons might preclude the use of existing commercial reactors.

Barring a change in the US approach to separation of civilian and defense fuel cycles, and without the use of existing commercial reactors at government sites, the most viable alternatives are CANDU-type HWRs at SRP site and the Three Mile Island reactors, with transportation of spent fuel and reprocessing capability at BNFP and SRP.

A. Use of Existing Commercial Reactors

Production of tritium, plutonium, or both, can be achieved in any existing commercial reactor with implementation of certain changes in the reactor core design, fuel mix, fuel management, or a combination of all three, depending on production goals and optimization economics. This alternative becomes particularly operable if the reactor(s) are located in a government-owned site or if they are idle for political reasons. Spent fuel could be transported to a reprocessing facility for separation of plutonium and/or tritium. BNFP and the

tritium separation facility at SRP appear well suited for reprocessing.

The US government could buy or lease an existing commercial reactor for defense materials production, if provision could be made for separation of defense materials from spent fuel. The issue of whether each commercial reactor should be required to produce defense materials depends on the federal government assuming responsibility for reprocessing of all spent fuels. If the defense cycle includes reprocessing of civilian spent fuel, plutonium production would be assured, as outlined in the national fuel cycle discussed in Sec. II. To produce tritium, either special target assemblies would be used in the commercial reactors or special dedicated nuclear facilities (reactors or accelerators) would be built to assure the required amounts. Serious consideration should be given to integrating the civilian fuel cycle with the defense fuel cycle and to assigning fuel fabrication and reprocessing responsibility to DOE.

B. Use of Existing and Planned Government-Owned Facilities

The most significant potential among those DOE facilities not now being used for defense material production involves the use of FFTF and CRBRP in production of plutonium and tritium. Core fuel designs and fuel management should be altered to optimize production. Fuel and target reprocessing might be done at Hanford Purex Plant and Idaho Chemical Processing Plant, respectively. However, if BNFP were available, its use, with target processing at SRP, might be more cost effective. A cost-benefit analysis is recommended for net results.

Training and naval reactors owned by DoD do not provide a rational alternative because of technical, programmatic, and cost-benefit reasons.

C. Construction of HWRs

Another significant alternative is to construct CANDU or CANDU-type HWRs at government sites. If a purchase from Canada is not possible because of political and economic reasons, a pressurized HWR could be built by a US reactor manufacturer. By locating such a reactor at the SRP site, reprocessing could be done for fuel and target at BNFP and at SRP, respectively. More study is needed to assess the economics of plutonium and tritium production in such a system.

BNFP has potential for becoming a multiple purpose reprocessing plant for spent fuels from LWRs, LMFBRs, and HWRs. An engineering evaluation of its operability is recommended to resolve the present controversy about its design (see Appendix A).

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APPENDIX A

NUCLEAR FUEL PROCESSING

In an LWR fuel cycle with uranium and plutonium recycle, as shown in Fig. A-1, the sensitive facilities (that is, with high risk for safeguards) are the enrichment plant, the fuel reprocessing plant, and the recycle fuel fabrication plants. When LMFBRs operate in tandem with LWRs, these facilities remain the same.

Figure A-2 shows a fuel reprocessing facility where spent fuel is processed to separate uranium and plutonium as products. A block diagram of this facility is presented in detail in Fig. A-3,¹⁷ where various chemical and physical separations are followed by conversion of

uranium to UF_6 and plutonium to PuO_2 products by the Purex process.

BNFP in South Carolina was built "to recover both uranium and plutonium from irradiated fuel elements which are discharged from light water moderated and cooled nuclear power reactors."¹⁸ The plant can process annually 1500 t of uranium in fresh fuel elements that had a fissile content of up to 5% ^{235}U or the equivalent

for plutonium fuels. BNFP can process irradiated nuclear power reactor fuel consisting of uranium oxide, or a mixture of plutonium oxide and uranium oxide, clad in stainless steel or zirconium alloys. Tables A-I-III provide a comparison of BNFP with other commercial reprocessing facilities, outlining their similarities, differences, and major waste systems.⁹

Fig. A-1.
Low-enrichment uranium-plutonium fuel cycle.

Fig. A-2.
A fuel reprocessing facility.

TABLE A-I
PRINCIPAL SIMILARITIES AMONG BNFP AND OTHER
COMMERCIAL REPROCESSING FACILITIES

Item	BNFP	NFS	MFRP
Fuel unloading and storage	Underwater	Underwater	Underwater
Headend process	Chop-leach	Chop-leach	Chop-leach
Stored fuel	Spacing	Spacing	Spacing
criticality safety			
Fuel chopping	Mechanical shear	Mechanical shear	Mechanical shear
Fuel dissolution	Nitric acid	Nitric acid	Nitric acid
material			
Fuel dissolution technique	Semicontinuous	(No similarity)	Semicontinuous
Fuel dissolution	Baskets in dissolvers	Baskets in dissolvers	(No similarity)
Solvent cleanup	Alternate contact with sodium carbonate and nitric acid solutions	Alternate contact with sodium carbonate and nitric acid solutions	Alternate contact with sodium carbonate and nitric acid solutions
Final exhaust	Roughing and HEPA	Roughing and HEPA	(No similarity)

TABLE A-II
PRINCIPAL DIFFERENCES AMONG BNFP AND OTHER
COMMERCIAL REPROCESSING PLANTS

Item	BNFP	NFS	MFRP
Location	South Carolina	New York	Illinois
Design capacity	5 tU/d	1 tU/d	1 tU/d
Shearing	Entire fuel elements including end fittings	End fitting removed before shearing	Pins removed from fuel elements before shearing pins only
Criticality control in dissolver	Soluble poison	Geometric limitations	Geometric limitations
Fuel dissolution technique	Semicontinuous	Batch	Semicontinuous
Fuel dissolution equipment	Baskets in dissolvers	Baskets in dissolvers	Vibratory leacher tray
HA contactor	Centrifugal contactor	Pulse column	Pulse column
Partitioning technique	Electropulse column	Solvent extraction with chemical valence adjustment	Ion exchange
Interim high level waste storage form	Acidic solution (1-5 molar)	Basic solution	Calcined solid
Iodine removal from process off-gas	Mercuric nitrate/iodine scrubbers plus iodine/silver zeolite adsorption beds	Silver reactor	Sodium hydroxide scrubbers, heated silver zeolite
Process vent filters	Roughing and HEPA	HEPA	Packed fiberglass filter
Final exhaust filters	Roughing and HEPA	Roughing and HEPA	Sand filter
Feed clarification	Centrifuge	None	None
Tritium disposal	As vapor up stack	As water to creek	As vapor up stack
Uranium product form	Nitrate solution	Nitrate solution	Hexafluoride
Liquid effluent	Noncontaminated	Contaminated	Noncontaminated

TABLE A-III

MAJOR WASTE STREAMS FOR FUEL REPROCESSING PLANTS^a

Plant	Gaseous Effluents	Liquid Wastes		Solid Wastes
		High Level	Other than High Level	
NFS	To atmosphere by iodine scrubber, HEPA filters, 61-m stack.	Stored onsite as neutralized liquid in tanks in vault. ^b	Controlled release to creek.	Stored onsite in drums in impervious clay deposits.
MFRP	To atmosphere by iodine scrubber, sand filter, 91-m stack.	Converted to solid. Stored onsite in containers under water in storage basin. ^c	Stored onsite in tanks in vault as immobile salt cake.	Stored onsite in underground lined vault. ^c
BNFP	To atmosphere by iodine scrubber, silver zeolite adsorber, HEPA filters, 100-m stack.	Stored onsite as acidic liquid in tanks in vault. ^d	Stored onsite in tanks in vault.	Stored onsite in concrete or steel drums. ^c

^aInformation in this table has been compiled from the safety analysis reports for these facilities. Only the NFS plant has actually generated waste to date.

^bPlans were to add tanks for storage of high level radioactive liquids in acidic conditions for ultimate conversion to solids and transfer to a Federal storage facility.

^cBefore shipment to Federal storage facility.

^dPlans for solidification of high level radioactive liquid wastes for transfer to Federal storage facility.

APPENDIX B

TRANSPORTATION IN NUCLEAR FUEL CYCLE

Use of existing commercial reactors to produce defense materials (as discussed in Secs. II and III.A) would require transportation of spent fuel to reprocessing facilities. Several studies have been performed to identify radioactive material transportation requirements and transportation systems to meet these requirements for nuclear fuel cycles.^{19,20}

The LWR fuel cycles under consideration include the once-through (Fig. B-1) and the uranium-plutonium recycle (Fig. B-2). Heavy-metal shipments are shown by double arrows and low level waste (LLW) shipments are

designated by either a single arrow (TRU waste) or a dashed arrow (non-TRU waste). Federal regulations regarding the transportation of radioactive materials are contained in the code of Federal Regulations, Titles 10 and 49; an overview of the regulatory structure is given in Fig. B-3.

Reference 6 reported estimated transportation costs associated with LWR once-through and recycle fuel cycles for shipment of fuel, high level wastes (HLW) and LLW. Table B-I summarizes their estimates in 1979 dollars.

Fig. B-1.
Transportation in an LWR once-through fuel cycle.

Fig. B-2.

Fig. B-3.

TABLE B-1

**SUMMARY OF RADIOACTIVE MATERIAL TRANSPORTATION COSTS
FOR LIGHT-WATER REACTORS^a**

		Annual Transportation Cost, \$000 ^b					
Transportation Segment	Description	Once-Through		U/Pu Recycle			
		Cost	% of Total	UO ₂ -Fueled LWR		MOX-Fueled LWR	
				Cost	% of Total	Cost	% of Total
HM1	Natural UF ₆	\$ 26	5	\$ 20	3	\$ 0	0
HM2	Enriched UF ₆	12	2	12	2	0	0
HM3	UO ₂ fresh fuel	26	5	26	4	0	0
HM4	UO ₂ spent fuel	252	52	282	44	0	0
HM5	Recycle UO ₂	0	0	4	1	0	0
HM6	Natural UO ₂	0	0	0	0	4	0.4
HM7	MOX fresh fuel	0	0	0	0	132	12
HM8	MOX spent fuel	0	0	0	0	554	52
HM9	Recycle PuO ₂	0	0	0	0	84	8
HM10	High level waste	0	0	64	10	64	6
W1	UO ₂ fabrication waste	6	1	6	1	0	0
W2	UO ₂ reactor waste	166	34	166	26	0	0
W3	MOX fabrication waste	0	0	0	0	0	1
W4	MOX reactor waste	0	0	0	0	166	15
W5	Reprocessing clad waste	0	0	26	4	26	2
	TRU waste	0	0	2	0.3	2	0.2
W6	Reprocessing non-TRU waste	0	0	29	5	29	3
Total annual cost		\$490		\$640		\$1100	

^aResults are normalized to 1000-MW(e) reactor design power and assume a nominal 70% capacity factor.

^bIn 1979 dollars.

APPENDIX C

ACCELERATORS AND FUSION REACTORS

High-energy particle accelerators and future fusion reactors could be used with fission systems to produce fissile materials. Such an accelerator breeder has been proposed as an RPR to produce plutonium and tritium (see Table I). In Appendix C accelerator tritium breeders, fusion-fission reactors, and pure fusion reactors are discussed.

actinides in the system. The charged particles could be made to strike a target such as lead to produce a shower of neutrons, which would convert the fertile blanket surrounding the target to tritium (see Fig. C-1).

The blanket material then would be processed to recover the tritium thus produced.

Such a system would use large amounts of electrical energy to run the accelerator and to produce kilogram quantities of tritium. If the cost of the accelerator and its operation is low enough that tritium is produced at an acceptable price, an accelerator breeder might be realized in our future. For example, it is possible that the CRBRP-generated electric power (375 MW) could run an accelerator to produce several kilograms of tritium (see Fig. C-2).

I. Accelerator Tritium Breeders

Accelerators have been used for many years to produce particle beams with energies to thousands of MeV. A moderately high energy device producing charged particles such as protons or deuterons has a potential to breed tritium from a fertile assembly containing lithium. This concept differs from the proposed electronuclear breeder in that it has no uranium or

Fig. C-1.
Accelerator tritium breeder concept.

Fig. C-2.
Operation of CRBRP in tandem with a linear accelerator to produce plutonium and tritium.

Fig. C-3.
A fusion fission hybrid to produce plutonium and tritium.

II. Fusion Reactors

The present fusion reactor development involves the following reaction that produces 17.6 MeV in the form of neutron and α -particle energy.

Magnetic confinement and inertial confinement concepts are the two main lines of reactor development. As illustrated in Fig. C-3, the fusion-produced neutrons may be used to convert a fertile material, ${}^{238}\text{U}$, to a fissile material, ${}^{239}\text{Pu}$, or to convert ${}^6\text{Li}$ to tritium. A pure fusion reactor would contain only lithium, in pure or compound form, in the blanket region to make the tritium needed as fuel for the fusion process. A fusion-fission reactor would produce not only tritium to be self sufficient but also fissile materials such as ${}^{239}\text{Pu}$.^{*}

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