EPRI

Technology of Nuclear Fuel Cycles Pertinent to Material Diversion

NRC Briefing

December 8, 1978

ELECTRIC POWER RESEARCH INSTITUTE

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Technology of Nuclear Fuel Cycles Pertinent to Material Diversion

December 8, 1978
10:00 A.M. to 12:00 Noon

Prepared by

Chauncey Starr	Introduction:	(1) Definition of Issues and Criteria of Diversion
		(2) Generic Nuclear Cycle and Its Diversion Sensitivity
Karl Cohen	Enrichment Facilities and Options	
Joseph Dietrich	Alternative Cycles, Including the Breeder	
Floyd Culler	Barriers to Diversion and the Small Military Reprocessing Plant Options	
Milt Levenson	Reprocessing Options (Purex and CIVEX)	
Chauncey Starr	Closure	

THE ROLE OF TECHNOLOGY IN LIMITING NUCLEAR WEAPONS PROLIFERATION

Optimize the Effectiveness of the Combination of Technology and Diplomacy

DEFINITIONS

PROLIFERATION

- Nuclear weapons acquisition by a non-nuclear state

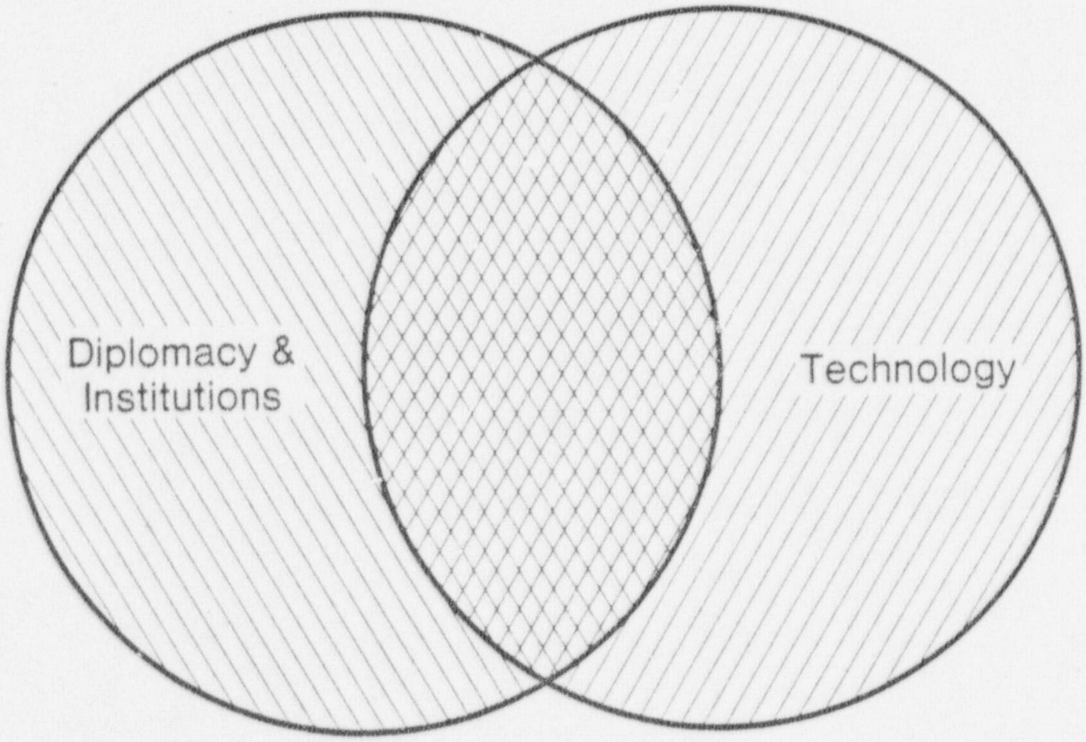
DIVERSION

- Taking material intended for civilian nuclear power (or other peaceful purposes) for weapons

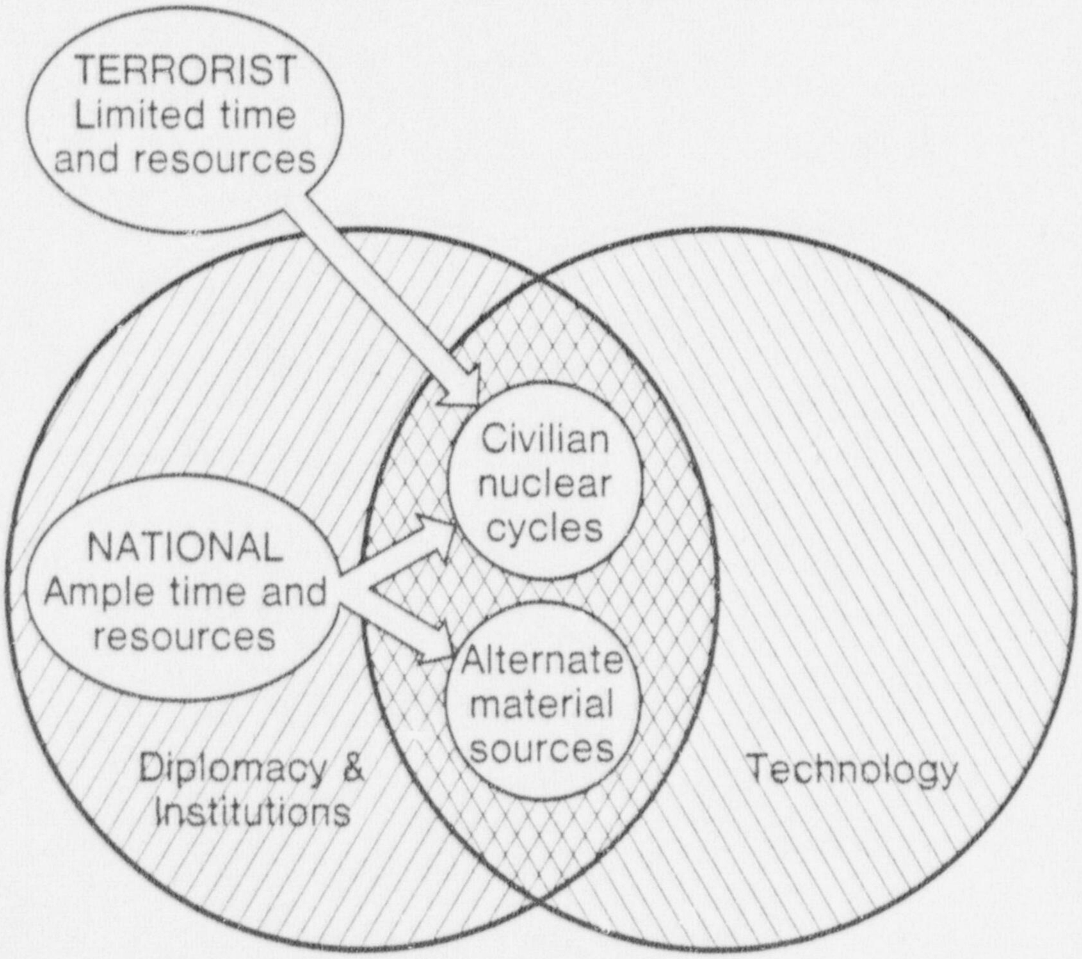
LATENT PROLIFERATION

- Acquiring skills and facilities easily convertible to weapons production on short notice by a non-weapons state

PROLIFERATION CONTROLS

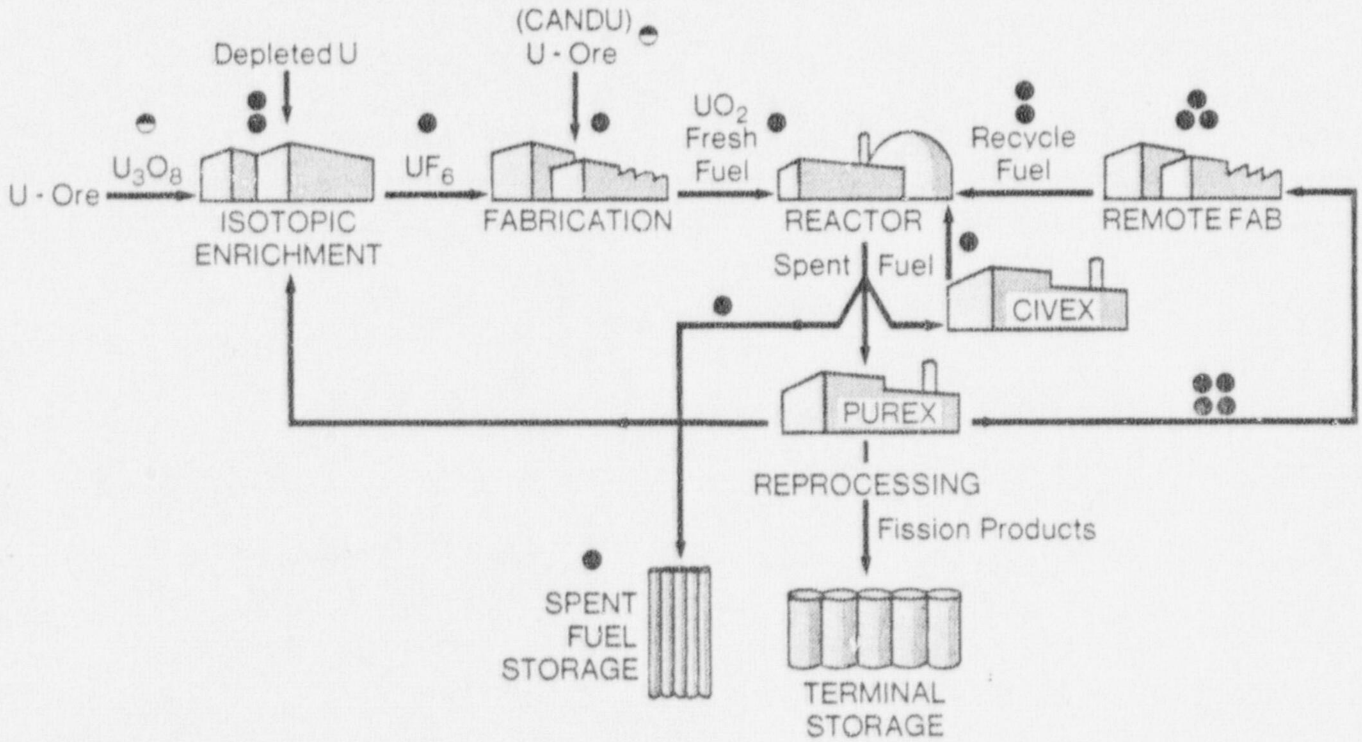


THREATS & CONTROLS



NUCLEAR POWER CYCLE

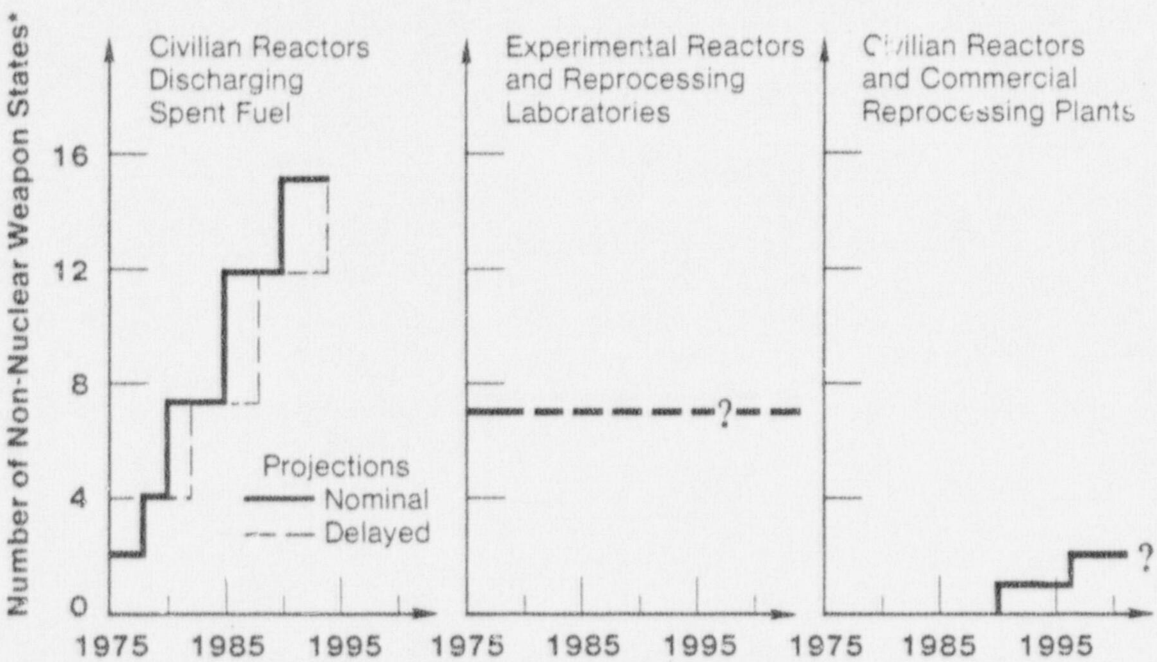
● Relative Diversion Sensitivity



WHAT IS THE PROLIFERATION THREAT ?

- Threat is the increase in numbers of weapons states
- Many non-weapons states will be discharging spent commercial fuel
- Many non-weapons states have experimental reactors and reprocessing laboratories
- Diversion threat from existing small laboratory facilities is independent of commercial activities
- Proliferation threat from commercial nuclear cycles does not occur until after the next decade (excluding European Community, Japan, India, Communist Block and Canada).

ESTIMATED TIMING OF DIVERSION THREATS



* Non-Nuclear Weapons States (excluding European Community, Communist Block, Canada, Japan and India)

WHAT CAN TECHNOLOGY CONTRIBUTE?

- Increase time and resource required for diversion
- Improve accountability
- Increase warning time
- Improve detectability of diverted materials
- Reduce potential usability of fuel materials for weapons
- Provide a secure civilian reprocessing option
- Increase fuel supply options

ISOTOPE SEPARATION

Isotope separation is not a rare phenomenon. It occurs during practically every chemical, physical or biochemical process.

- C^{13}/C^{12} ratio in biosphere tends to be reduced during periods of C fixation.
- O^{18}/O^{16} ratio in limestones allows us to deduce temperature changes of prehistoric seas.
- D is concentrated against H by ~ 2% by ice formation.
- Li^6 can be separated from Li^7 by electrolysis of molten LiCl.
- Moving UF_6 at high speeds around corners separates the uranium isotopes.
- Very large separation can be obtained by processes which select trajectories of individual ions in vacuum.

Selection of an industrial process for concentrating U-235 (or any other isotope) requires a consideration of:

- The elementary separation factor, which determines the number of repetitive operations required.
- The ease of recirculating large volumes of material.
- The energy expended.
- The amount of material in the process, which determines the time required to begin production.

Many processes for uranium

Despite this long list of requirements, the catalogue of methods for separating U-235/U-238 which have serious economic potential is large. Here are a few:

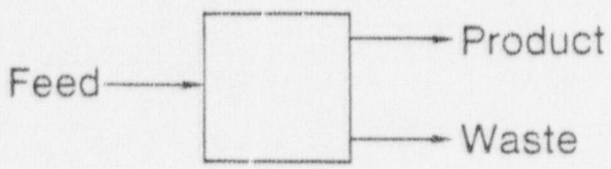
- Gaseous diffusion
- Becker nozzle process
- Other aerodynamic processes; South African vortex process, "Jet Membrane"
- Gas centrifuge
- Chemical exchange
- Ionic and electromagnetic devices (calutron, plasma centrifuges, etc.)
- Lasers (several possibilities)

Each of these new methods may lead to realizations with different characteristics. For example:

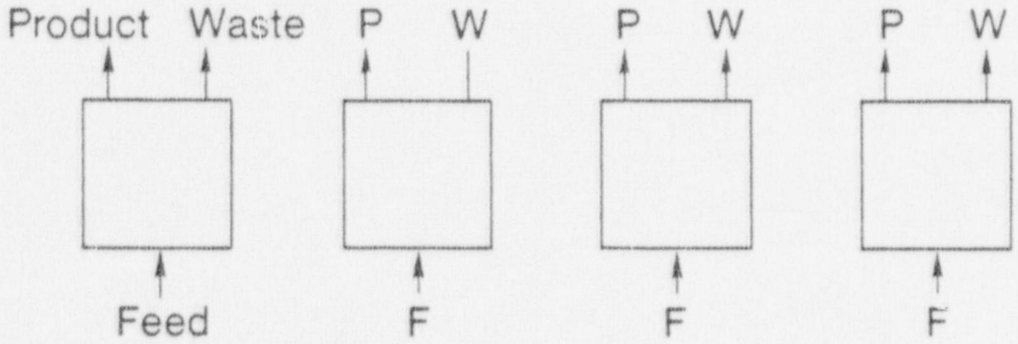
- Large or small centrifuge
- Modular compound stages, or
- Large single stages
- Different scale plants (large or small stages)

ONE-STEP: LASER

- Large separation factor – high or low flows



- Parallel units likely

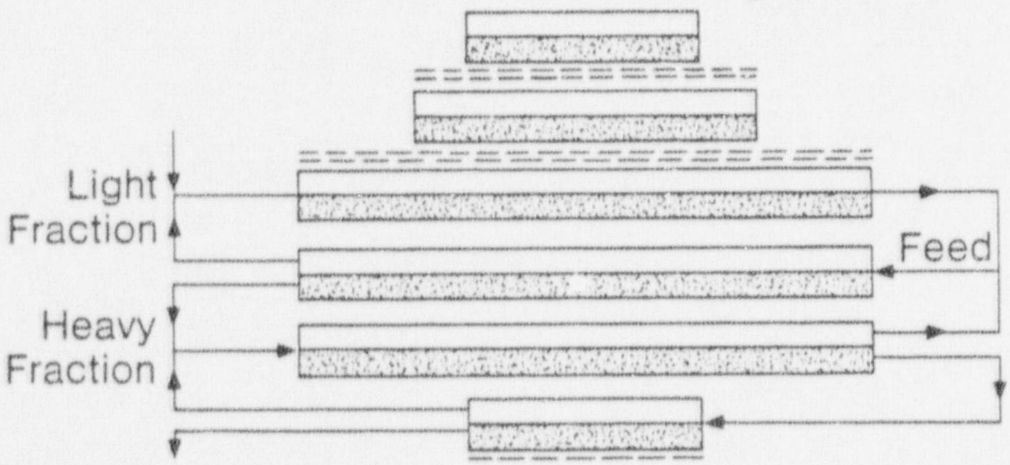


CASCADE OF SIMPLE STAGES
Series Arrangement

- Gaseous diffusion plant
- Becker nozzle process

Generally:

- Small separation factors
- Many stages
- Large interstage flows
- Large pumping energy

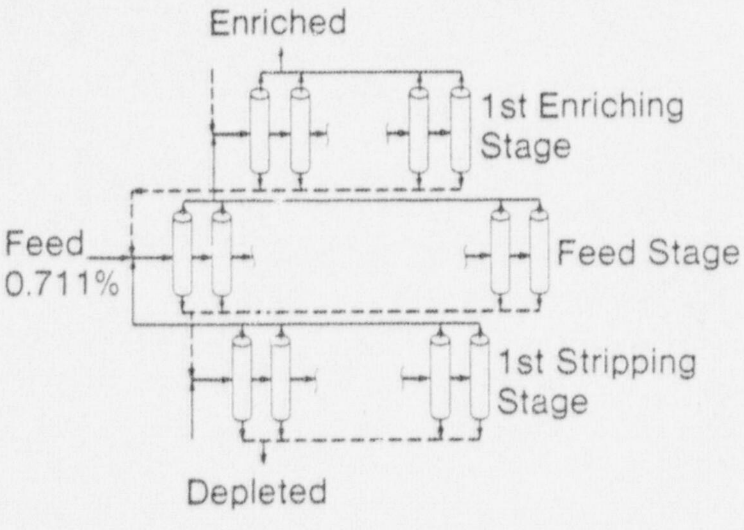


CASCADE OF MODULAR COMPOUND STAGES
Series-Parallel Arrangement

- Counter-current centrifuges
- Chemical exchange

Generally:

- Large separation factors (simple factors compounded internally)
- Small interstage flow
- Small pumping energy



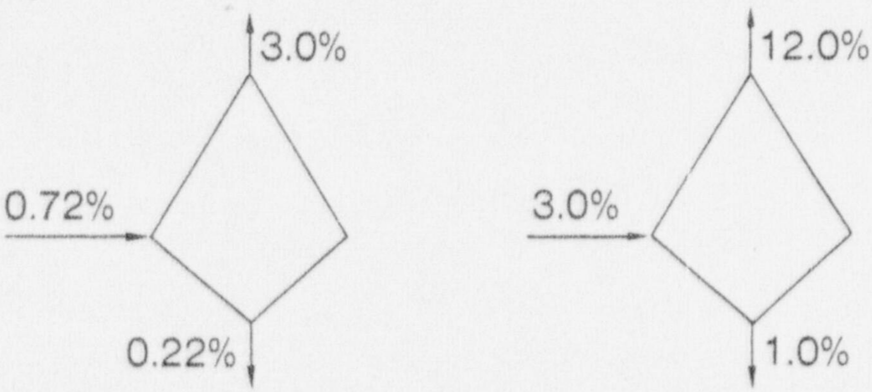
SUMMARY OF PROCESS CHARACTERISTICS

	Low Separation Process	*High Separation Process*
	• Diffusion • Nozzle	• Centrifuge
Throughput per stage	High	Low
Interstage connections	Large	Small
Ease of modification	Low	High
Detectability	High heat output	Low heat output

Most cascades capable of producing low enriched uranium are capable of producing higher enrichment by:

- Cascade modification
- Recycle

Exception: Processes with high uranium inventories



5.66 kg feed/kg product
4.1 SWU/kg product

5.5 kg feed/kg product
4.0 SWU/kg product

SWU: A measure of the amount of separation which is produced by a given separative element. Also, the number of separative elements to produce a given enrichment.

FEED AND SEPARATION WORK REQUIREMENTS TO PRODUCE ONE NOMINAL CRITICAL MASS PER YEAR

20 kg U-235 @ 93% — 10 kg U-233 @ 93%

	Fissile Fraction		*Feed*		*Number of*
	Feed	*Waste*	*(kg U)*	*SWU*	*Centrifuges**
Natural Uranium	0.0072	0.0022	3720	4540	1135
LWR Fuel	0.03	0.01	920	1100	275
Denatured U-233 Fuel	0.85	0.03	160	200	18
Denatured U-233 Fuel	0.15	0.05	90	120	11
Denatured U-233 Fuel	0.20	0.07	70	90	8

* Centrifuge rated @ 4 SWU/yr for U-235/U-238
@ 11 SWU/yr for U-233/U-238

Centrifuge SWU output ~ $(\Delta M)^2$

CHARACTERISTICS OF CURRENTLY DEVELOPED SEPARATION TECHNIQUES

	*Number of Stages**	*Economic Plant Size*	*Present Module Size*	*Level of Technology*
Diffusion	Many	Large	Lg. & Sm.	3
Centrifuges	Several	Small	Small	2 - 3
Nozzle	Many	Large	Large	2
Magnetic	Few	Medium	Medium	4
Laser	Few	?	?	4
Ordinary Chemical Separation	Few	Large	N/A	1 - 2
Commercial Radiochemical Separation	Few	Medium	N/A	3 - 4
Quick & Dirty (or Military Radiochemical Separation)	Few	Small	Small	2

* Number of stages inversely proportional to separation factor.

PROLIFERATION HAZARDS

- A free-standing military enrichment facility using advanced technologies can be difficult to detect.
- Diversion from a civilian facility plus small topping plant is even harder to detect and gives less warning time
- Four times easier to start from partly enriched fuel than from natural uranium
- Fifty times easier to start from U-233 fuel than natural uranium
- Diversion potential by enrichment options is similar to diversion potential from reprocessing facilities with coprocessing or CIVEX.
- Design "hardening" and continuous surveillance (on-line instrumentation) needed to make civilian plants diversion proof.

ALTERNATE FUEL CYCLES: HOW CAN THEY AFFECT THE HAZARD OF WEAPONS PROLIFERATION?

— THE OPTIONS ARE LIMITED BECAUSE OF THE SMALL NUMBER OF POSSIBLE FISSILE AND FERTILE MATERIALS.

— ALTERNATE CYCLES CAN NOT PREVENT PROLIFERATION. THEY CAN ONLY ASSIST INSTITUTIONAL BARRIERS; THEIR COST EFFECTIVENESS IS LOW IN THIS APPLICATION.

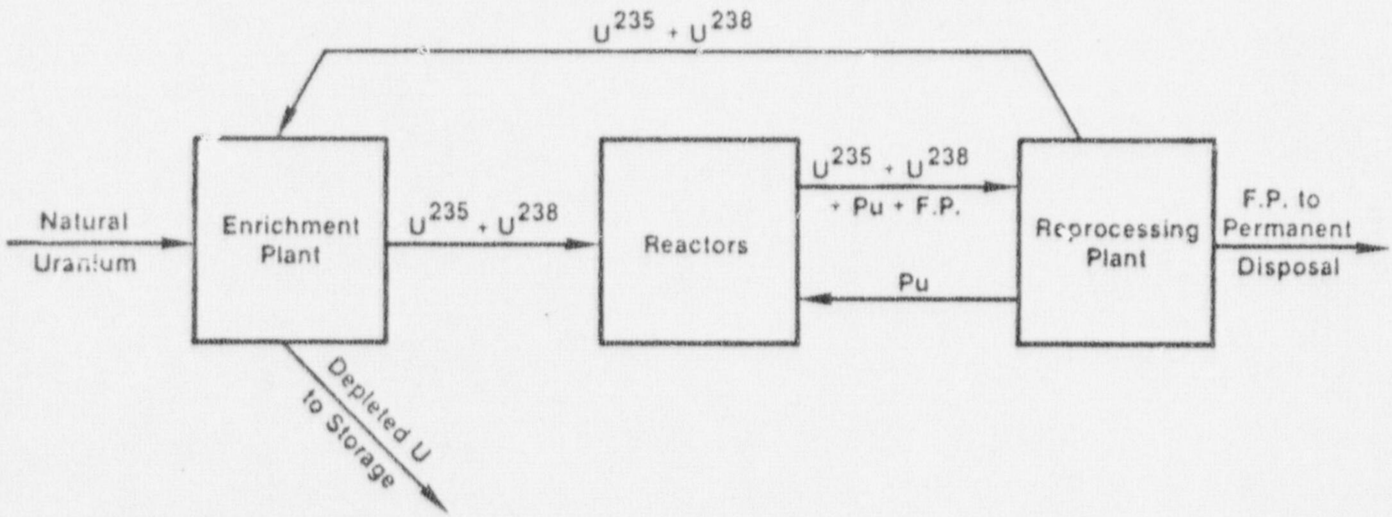
MATERIALS AVAILABLE FOR NUCLEAR FUEL CYCLES

FISSILE	FERTILE
U^{235} (Natural)	U^{238} (Natural)
U^{233} (Made in Reactor)	Th^{232} (Natural)
Pu (Made in Reactor)	

U^{238} + Neutron → Pu

Th^{232} + Neutron → U^{233}

THE URANIUM CYCLE



ECONOMIC AND RESOURCE ADVANTAGES OF THE URANIUM CYCLE

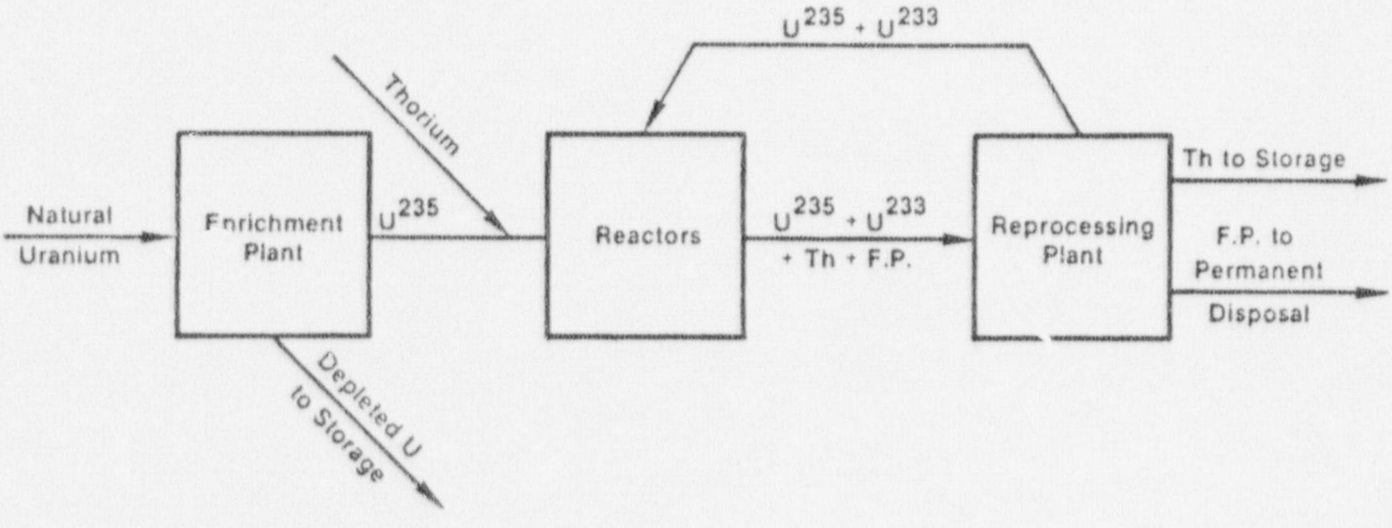
- FISSILE AND FERTILE MATERIAL EXIST TOGETHER IN NATURE — MINIMUM OF ENRICHMENT IS REQUIRED.

- REPROCESSING CHEMISTRY HAS BEEN PROVED IN PRACTICE.

- PLUTONIUM PRODUCED IN LWRS IS AN EXISTING FUEL SOURCE FOR BREEDERS.

- PLUTONIUM IS THE MOST EFFECTIVE BREEDER FUEL.

THE THORIUM CYCLE



CHARACTERISTICS OF THE THORIUM CYCLE

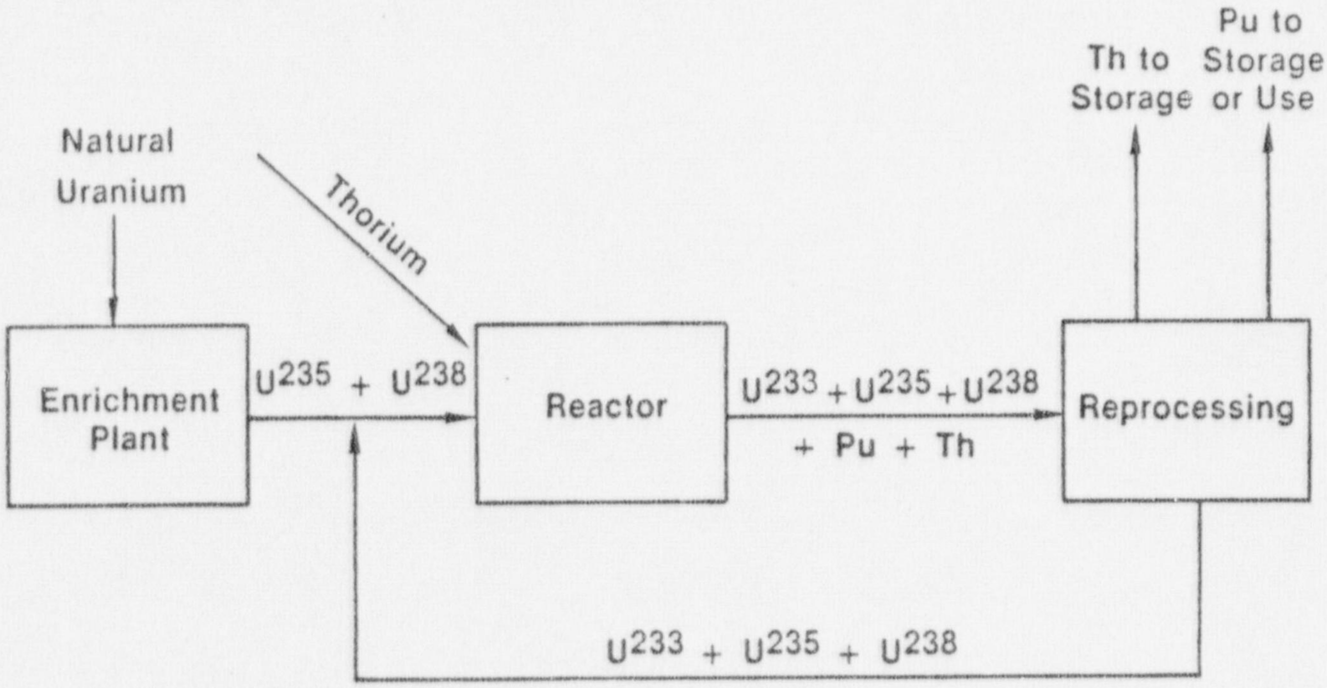
— IS UNATTRACTIVE WITHOUT REPROCESSING AND RECYCLING

— WITH RECYCLING REDUCES SLIGHTLY THE URANIUM REQUIREMENT IN LWRS ($\sim$16%) BUT REQUIRES MINING OF BOTH URANIUM AND THORIUM.

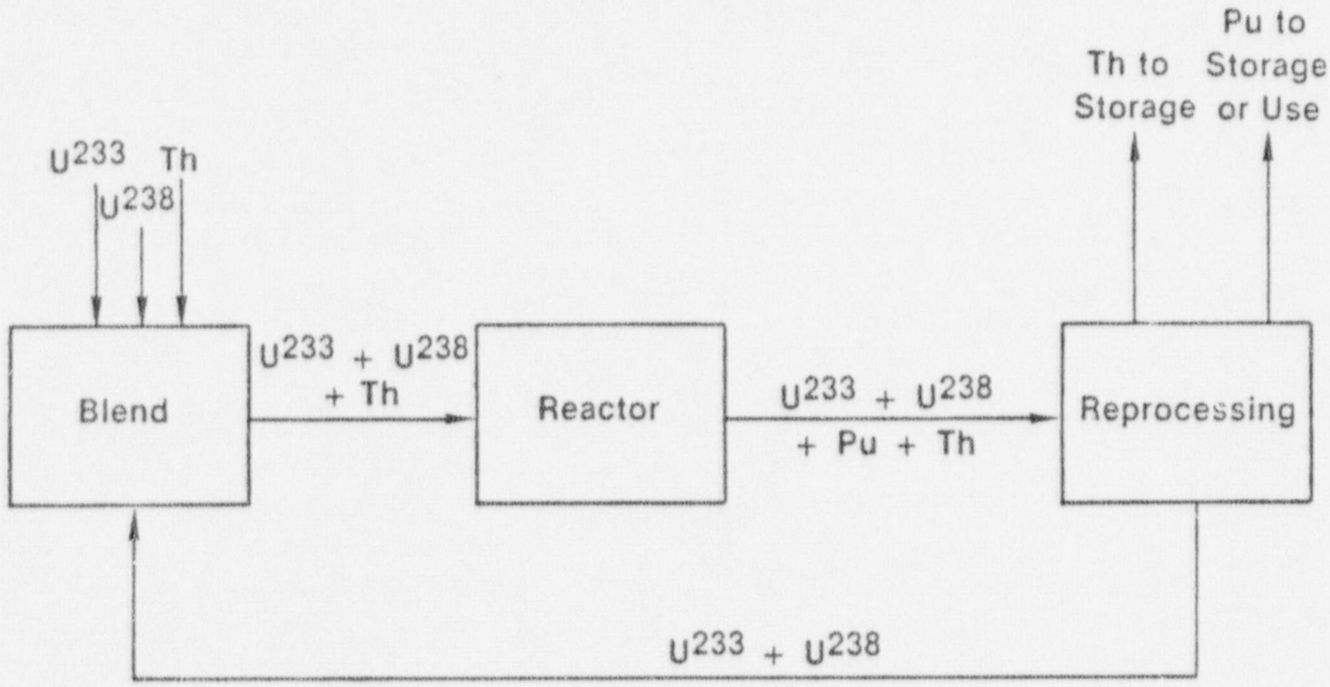
— UTILIZES BOTH U^{235} AND U^{233} AT HIGH ISOTOPIC PURITY— BOTH ARE WEAPON-USABLE MATERIALS

— RECYCLE MATERIAL CONTAMINATED BY A γ -RAY SOURCE (U^{232}), A SIGNIFICANT IMPEDIMENT TO RECYCLING, BUT NO EFFECTIVE DETERRENT TO WEAPON MANUFACTURE ON A NATIONAL SCALE

DENATURED THORIUM CYCLE WITH U^{235} FEED



DENATURED THORIUM CYCLE WITH U^{233} FEED



DENATURED THORIUM CYCLES

— ARE UNATTRACTIVE WITHOUT REPROCESSING AND RECYCLING

— U^{233} AND U^{235} RENDERED UNSUITABLE FOR DIRECT WEAPON USE BY ADMIXTURE OF U^{238}

— RELATIVELY SMALL QUANTITIES OF SEPARATIVE WORK REQUIRED TO UP-GRADE THE U^{233} AND U^{235} TO WEAPONS QUALITY

— SUBSTANTIAL QUANTITIES OF Pu ARE FORMED FROM THE U^{238} USED FOR DENATURING.

— SOME URANIUM SAVINGS ARE POSSIBLE (COMPARABLE TO Th CYCLE IF Pu RECYCLED) BUT REPROCESSING AND REFABRICATION ARE MORE COMPLEX, AND HAVE NOT BEEN DEVELOPED.

Annual Material Flows for a 1000 MWe PWR

Fertile/Fissile Feed Materials		U^{235}/U^{238}	U^{235}/U^{238}	U^{235}/Th	U^{235}/U^{238}, Th	U^{233}/U^{238}, Th
Recycled Materials		None	Pu, U^{235}	U^{233}, U^{235}	U^{233}, U^{235}	U^{233}
Charge (kg)	U^{233}	0	0	414	352	772
	U^{235}	809	636	520	735	55
	Pu*	0	287	0	0	0
	Total Fissile	809	923	934	1,087	827
	U^{238}	26,000	26,000	40	4,646	6,128
	Th	0	0	23,000	18,300	17,358
Discharge (kg)	U^{233}	0	0	422	373	468
	U^{235}	219	176	186	305	59
	Pu*	178	303	3	64	70
	Total Fissile	397	479	611	742	597
	U^{238}	25,400	25,400	34	4,463	5,909
	Th	0	0	22,400	17,800	16,915

* Fissile Pu Isotopes Only

CONCLUSIONS FROM CALCULATED MATERIAL FLOWS FOR ALTERNATE FUEL CYCLES IN THE LWR

— ANNUAL QUANTITIES OF FISSILE ISOTOPE HANDLED DO NOT VARY GREATLY FROM ONE FUEL CYCLE TO ANOTHER.

— ALL FUEL CYCLES YIELD CHEMICALLY SEPARABLE WEAPONS—USABLE MATERIALS IN MULTIPLE-WEAPON QUANTITIES PER YEAR FROM A 1000 MWE NUCLEAR PLANT.

— DENATURED THORIUM CYCLES REDUCE THE QUANTITY OF CHEMICALLY-SEPARABLE WEAPONS-USABLE MATERIALS BY ABOUT A FACTOR OF 5 RELATIVE TO THE U-Pu CYCLE, BUT YIELD A LARGE QUANTITY OF HIGH-QUALITY WEAPONS-USABLE MATERIAL (U^{233} AND U^{235}) RELATIVELY EASY TO SEPARATE ISOTOPICALLY.

THE PRESSURES FOR FUEL RECYCLING

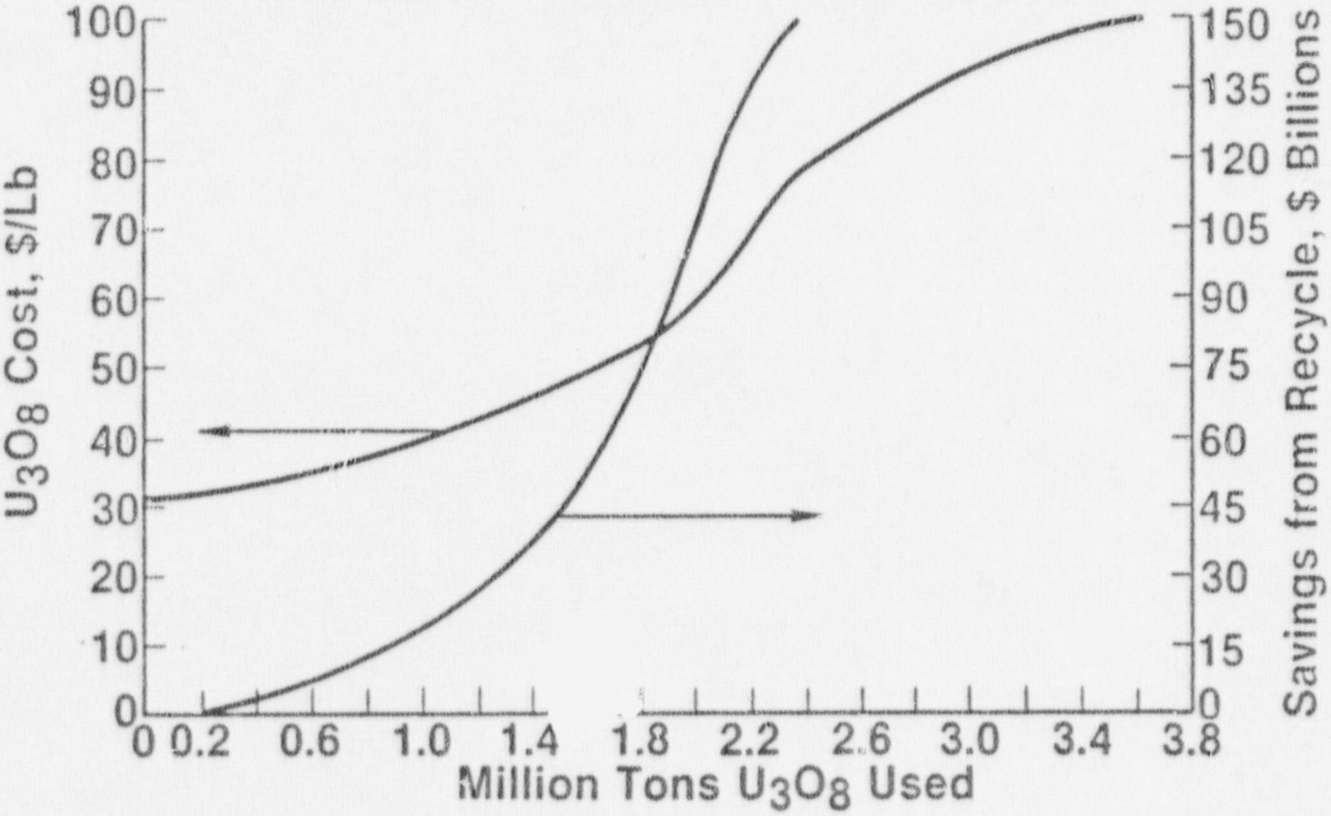
— RESOURCE-POOR NATIONS RECOGNIZE THE BREEDER, WITH FUEL RECYCLING, AS THE ONLY AVAILABLE ROUTE TO ELECTRICAL ENERGY INDEPENDENCE.

— FUEL REPROCESSING IS A NECESSARY PRELUDE TO THE BREEDER.

— EVEN IN THE U. S., WITH SUBSTANTIAL URANIUM RESOURCES, THE RISING COST OF U_3O_8 AS POORER ORE DEPOSITS MUST BE UTILIZED WILL LEAD TO ECONOMIC PRESSURE FOR FUEL RECYCLING IN THE LWR AND UTILIZATION OF THE FAST BREEDER.

POSTULATED COST OF U_3O_8 AS A FUNCTION OF QUANTITY USED, AND RESULTING SAVING FROM FUEL RECYCLING

(1977 Dollars; Recycling Assumed to Break Even When U_3O_8 Cost Is $33/Lb)



CONCLUSIONS

- ALTERNATIVES TO THE URANIUM-PLUTONIUM FUEL CYCLE CANNOT SOLVE THE PERCEIVED PROBLEM OF WEAPONS PROLIFERATION.

- THE ALTERNATIVES MAY OFFER SOME ASSISTANCE TO INSTITUTIONAL CONTROLS, BUT AT A SUBSTANTIAL COST IN MONEY, TIME, AND URANIUM RESOURCES.

- THE DATA ARE AVAILABLE FOR MAKING DECISIONS ON THE EFFICACY OF ALTERNATE CYCLES WHEN USED IN CONJUNCTION WITH INSTITUTIONAL CONTROLS: WE SHOULD PUSH AHEAD RAPIDLY WITH THESE DECISIONS.

BARRIERS TO FISSILE MATERIAL DIVERSION
BACK-END OF FUEL CYCLE

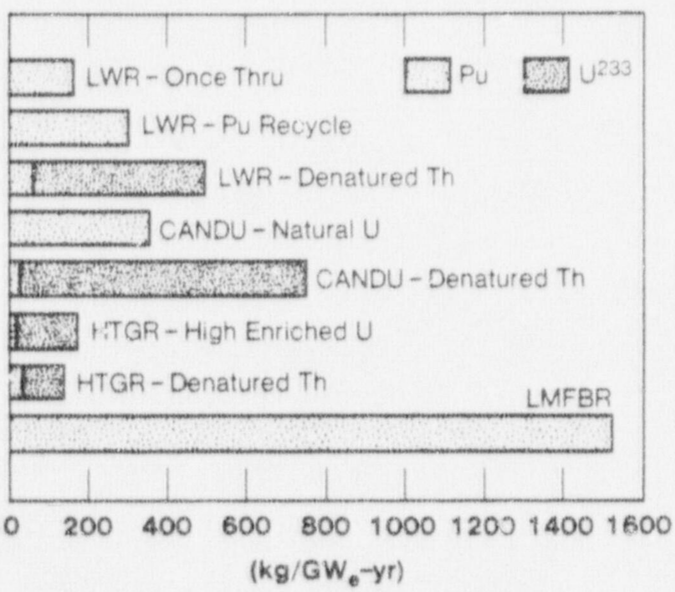
Barrier must provide

- Delay time equal to that required for quick and secret chemical plant
- Built-in characteristics to make fuel dangerous to diverters
- Additional physical deterents and protective systems
- Costs must be commercially acceptable

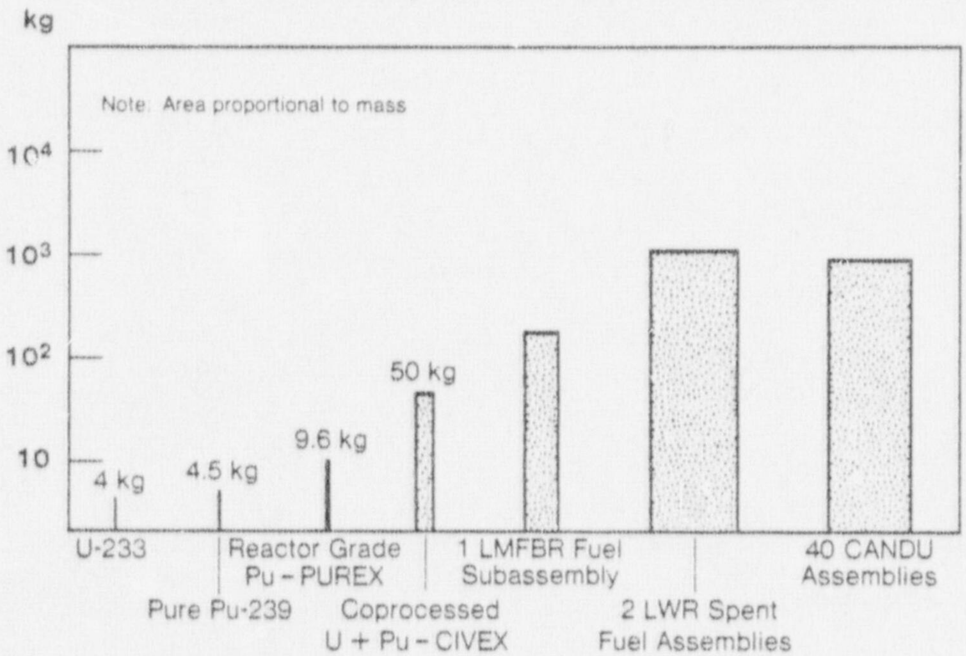
TIME REQUIRED TO PRODUCE 10 kg FISSILE MATERIAL (simple, quick plant)

- Characteristics
  1. Fissile concentration determines quantity of fuel that must be diverted
  2. Breeder fuel stored in Na or in thin walled cooled canister
  3. LWR fuel stored in water-filled canals
- Time required estimates
  1. Large plant greater than 4 years
  2. 10 kg/week plant
     - Oak Ridge (Aug. 1977): 4 – 6 months
     - GAO, Oct. 1978 (EMD-78-104): Credible under some circumstances
- Policy should be to provide cycle with warning time equal to time for construction of quick and simple plant

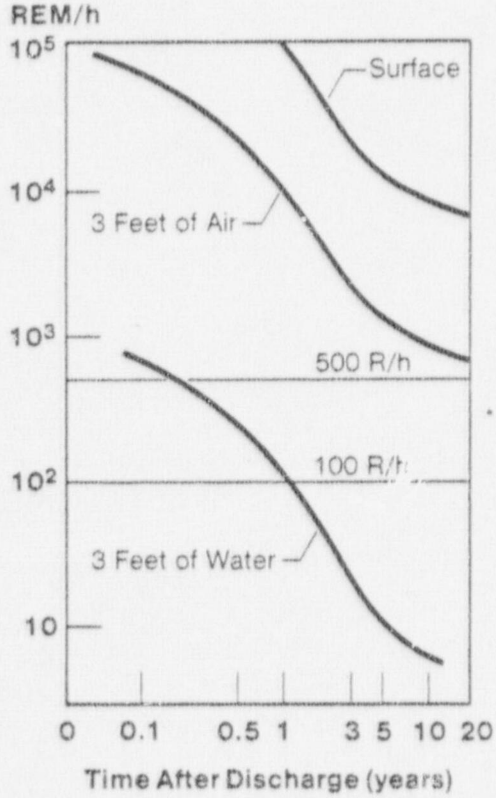
FISSILE ELEMENT DISCHARGE

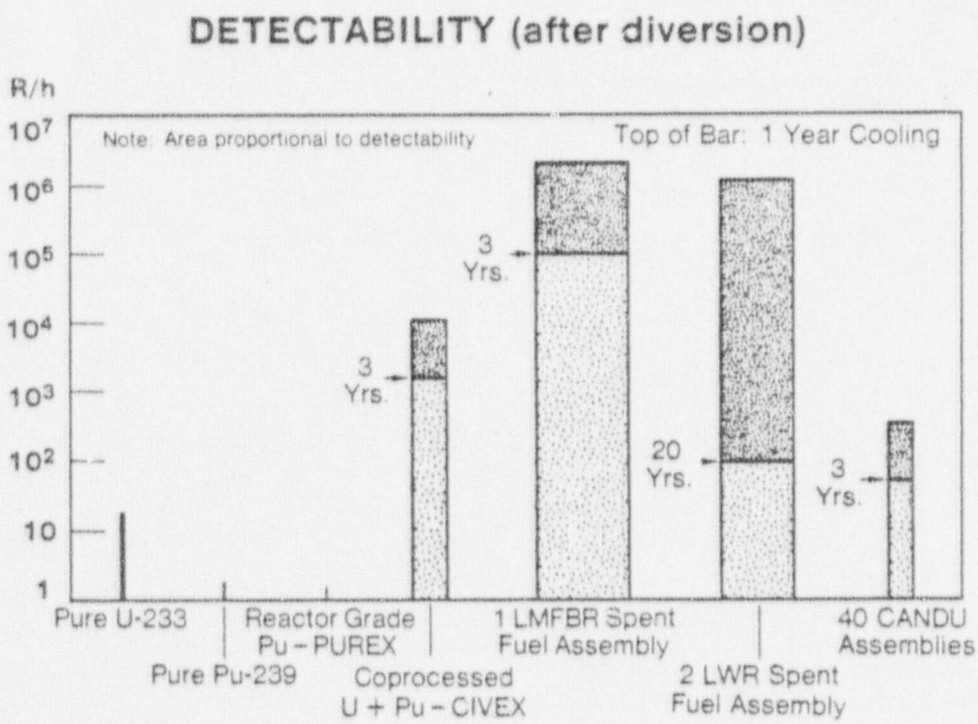


MINIMUM MATERIAL THAT MUST BE DIVERTED FOR ONE WEAPON EQUIVALENT

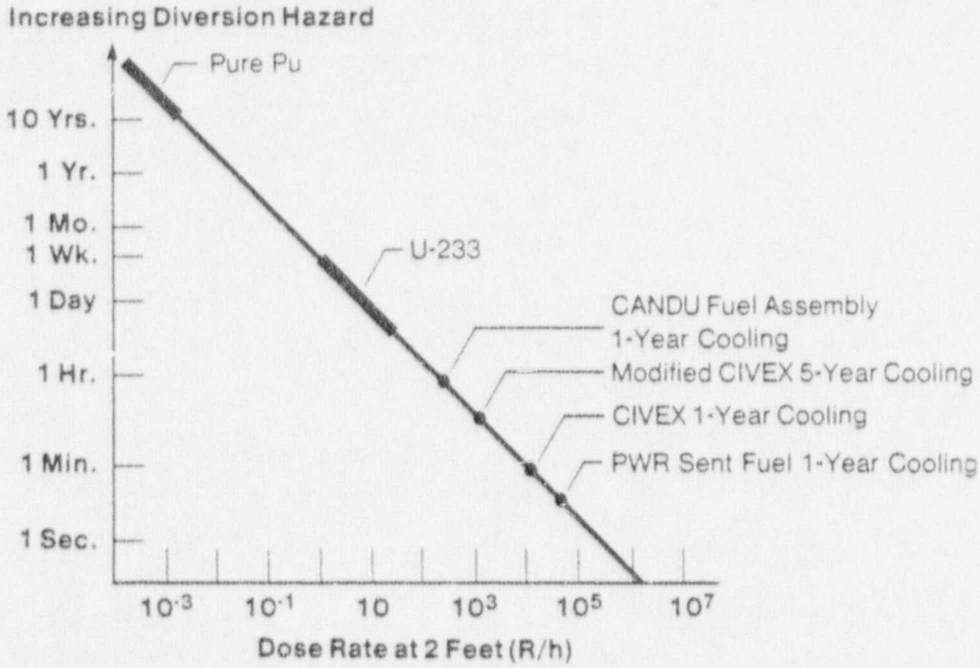


DOSE RATE FROM LWR SPENT FUEL ASSEMBLY

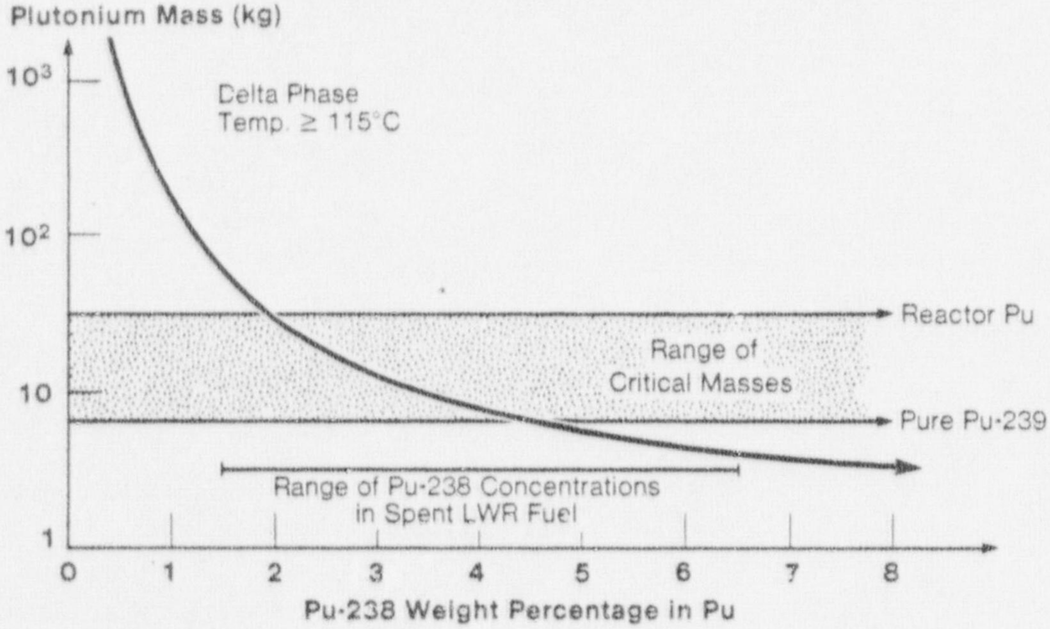



DETECTABILITY (after diversion)
R/h
10^7
10^6
10^5
10^4
10^3
10^2
10
1
Note: Area proportional to detectability
Top of Bar: 1 Year Cooling
3 Yrs.
3 Yrs.
20 Yrs.
3 Yrs.
Pure U-233
Pure Pu-239
Reactor Grade Pu – PUREX
Coprocessed U + Pu – CIVEX
1 LMFBR Spent Fuel Assembly
2 LWR Spent Fuel Assembly
40 CANDU Assemblies

WORKING TIME UNTIL DISABILITY ONSET (150 REM)



Pu-238 CONCENTRATIONS REQUIRED FOR PHASE TRANSITION FROM ALPHA TO DELTA



BARRIERS TO DIVERSION

- Bulk – including weight of shielding
- Radiation – inherent and added
- Lack of purity (U or Th dilution)
- Decay heat – Pu-238 production
- Ease of detection
- Hardening
- Physical isolation by barriers
- Single monitored facility which receives and ships fuel elements
- Guards and physical security
- Means for inspector to intentionally disable plant

REPROCESSING

- System to separate products from a mixture
- Individual steps are standard unit operations*
- Process itself is tailored for specific job
- Feed, products, and waste form can all be specified

* Chemical engineering terminology for process steps such as solvent extraction, distillation, ion exchange, dissolution, etc.

TAILORED MILITARY PROCESSES

Process	Product	Waste
$BiPO_4$	Pu	U, FP, (MS)*, (Pu)
REDOX	U, Pu	FP, NH_4NO_3
Metal recovery	U, (Pu)	FP, (MS)*
Monsanto	Po	Bi
PUREX	U, Pu	FP
Bomb recycle	Pu	Am
Assorted classified	–	–

* Miscellaneous salts of large volume

TAILORED REACTOR FUEL PROCESSES

Process	*Product*		*Waste*
MTR	HEU*		FP, Al
NPR	HEU*		FP, Zr
EBR II **	U, Pu, FP		FP
Molten salt **	U-233	← (Th, Pa) →	FP

* Highly enriched uranium

** Used for experimental reactor only, production process development not completed.

TAILORED SPECIAL PROCESSES

Process	*Product*		*Waste*
Snap	Pu-238	← (Np) →	FP
Thorex	U-233	← (Th, Pa) →	FP
Fluoride volatility	U		Pu, FP
Fluoride volatility	U, Pu		FP
Specific products	Np, Ca, Am, Sr, Cs		–

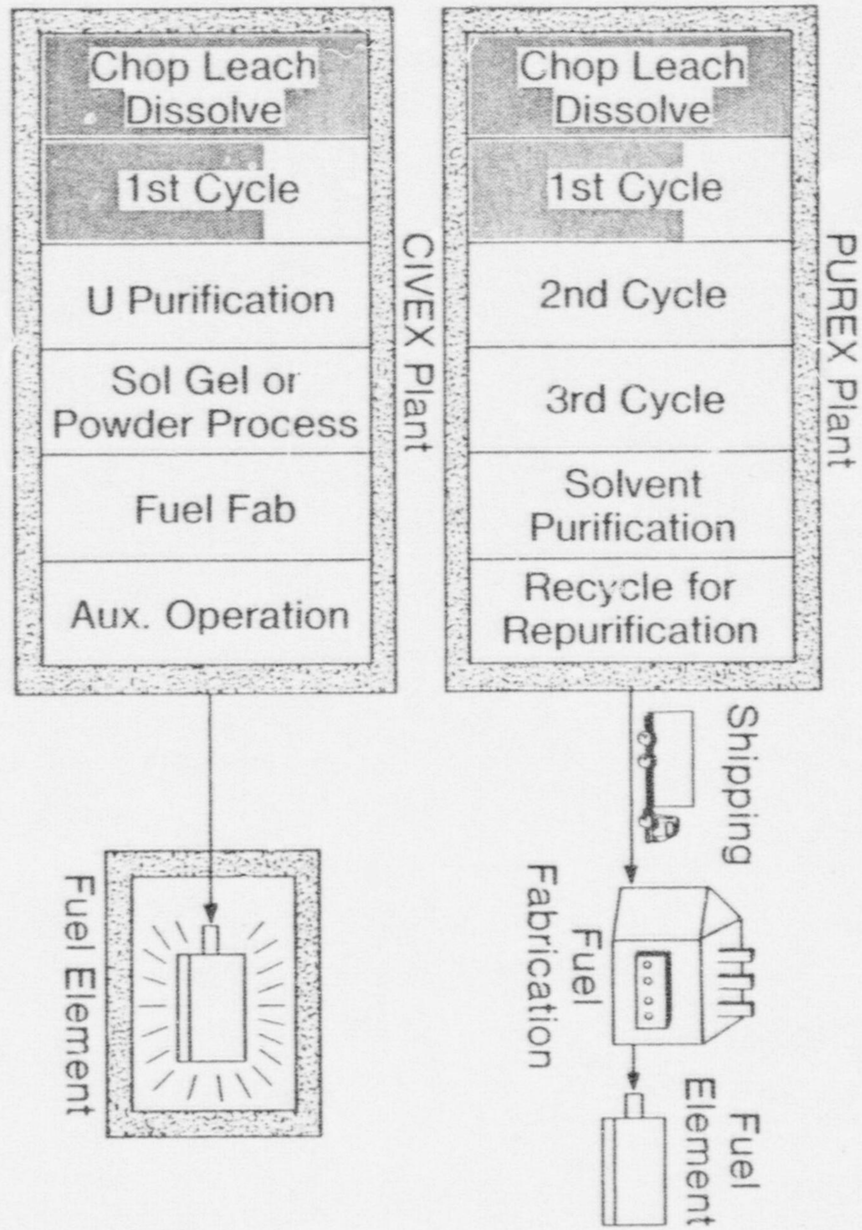
CIVEX CRITERIA

- No pure fissionable material
- Purification as complex as from stored fuel
- Time to purify approximately that from stored fuel
- Process and plant modification not the most "attractive" way to purify
- Very high diversion detection probability

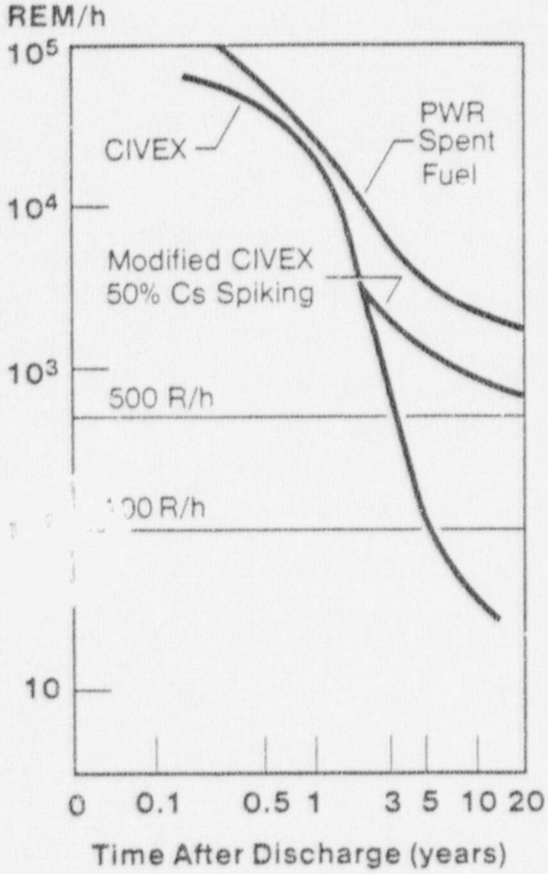
CIVEX PROCESS TECHNICAL OPTIONS

Entire family of options

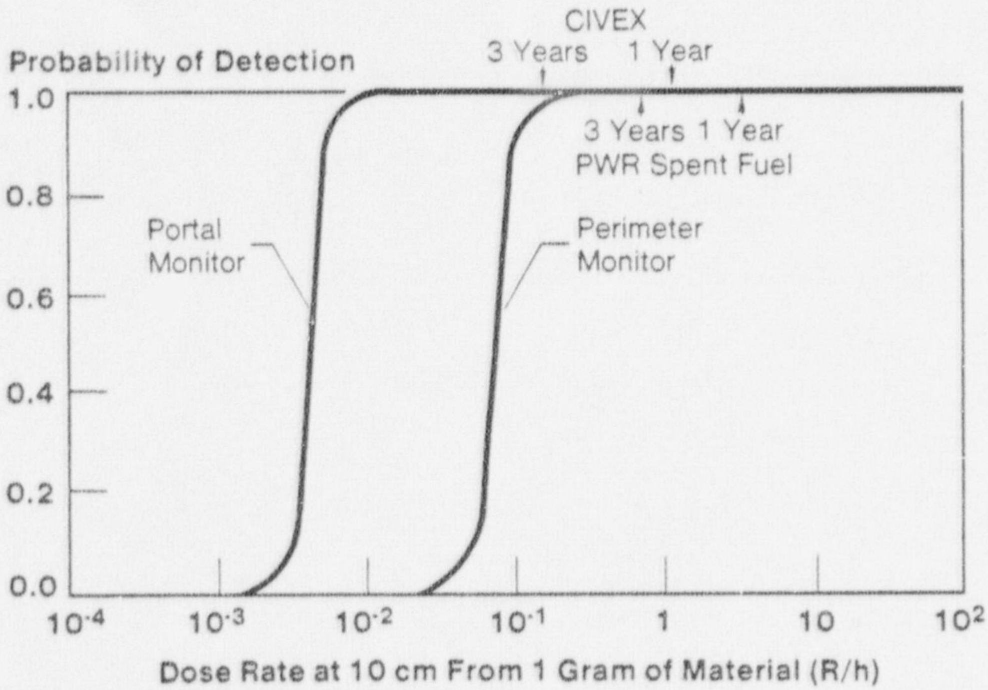
- Solvent extraction/fluoride volatility/sol gel fuel
- Solvent extraction/fluoride volatility/pellet fuel
- Recycle of fixed Cs
- Pyrometallurgical processes
- Np-237/Pu-238 deterrent


Chop Leach
Dissolve
1st Cycle
U Purification
Sol Gel or
Powder Process
Fuel Fab
Aux. Operation
CIVEX Plant
Fuel Element
Chop Leach
Dissolve
1st Cycle
2nd Cycle
3rd Cycle
Solvent
Purification
Recycle for
Repurification
PUREX Plant
Shipping
Fuel
Fabrication
Fuel
Element

DOSE RATE FROM LWR SPENT FUEL ASSEMBLY IN 2 FEET OF AIR



DETECTION PROBABILITY OF DIVERTED FUEL



CLOSURE

- All reactor cycles have similar diversion sensitivity
- Technical barriers can minimize diversion risks from terrorists or sudden national decisions
- Premeditated national diversion is the principal risk
- Technology cannot prevent premeditated national diversion
- Technology can aid inspection
- Technology can increase warning time
- Diversion from enrichment facilities is an independent threat
- Plant operating skills are not suitable for engineering design and development
- Nuclear cycle design information is widely disseminated
- Practical know-how comes from direct development experience
- Commercial availability of a reprocessing plant would remove need for independent national developments
- LWR/FBR/CIVEX system reduces diversion risk from recycling to level of stored spent fuel
- Reasonably achievable technical hardening can substantially reduce the probability of the fuel cycle as a source of weapons material

INTERNATIONAL ARRANGEMENTS REQUIRED FOR THE EFFECTIVE USE OF DIVERSION-RESISTANT TECHNOLOGY

- Technology cannot work alone. It needs international political agreements and institutions to be effective.
- Key to cooperation by any nation with international arrangements is confidence:
  - In the availability of a fuel supply not subject to external political decisions
  - In the efficacy of international inspection procedures
  - In international sanctions as a response to disclosed diversion activities
- The IAEA will need to
  - Promulgate safeguarding and accountability rules
  - Strengthen its international inspectorate
  - Establish technical criteria for inspectability of nuclear cycles, power and research
  - Establish real-time international flow patterns of nuclear materials
  - Provide mechanisms for unambiguous determination of diversion based on technical signals