OPPORTUNITIES IN REACTOR AND FUEL CYCLE TECHNOLOGIES

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SUMMARY

- Reprocessing and recycle systems, in exchange for a potential reduction in long-term risk, impose significant near-term risks:
  - Proliferation and nuclear terrorism risks of widespread civil use of nuclear weapon-usable materials
  - Health, safety and environmental impacts of reprocessing and transuranic-fueled reactors
- Recycling approaches being put forward for deployment will increase these near-term risks to an unacceptable level without providing a clear or significant benefit to long-term waste management
- R&D focus should shift away from reprocessing and fast reactor development and toward innovative ways to improve the safety, security and proliferation resistance of the once-through cycle

RECYCLING IS SLOW, COSTLY AND INEFFECTIVE

- Benefits of reprocessing and recycling for high-level waste disposal can only be realized with a system that separates and fissions heat-generating actinides with very high efficiency
- National Academy of Sciences conclusions (1996):
  - A fast reactor system with 0.65 breeding ratio [0.5 TRU conversion ratio] to reprocess 62,000 t of LWR spent fuel and transmute the resulting TRUs under a declining nuclear power scenario would cost some $500 billion and require approximately 150 years
  - "Merely developing, building and operating the individual components of the system would give little or no benefit. To have a real effect, an entire system of many facilities would be needed in which all the components operate with high reliability in a synchronized fashion for many decades or centuries … the magnitude of the concerted effort and the institutional complexity … are comparable to large military initiatives that endure for much shorter periods than would be required …"
- EPRI/EDF (2009): "The analysis for the specific [recycling] scenario considered shows that it would take many decades, even centuries, for significant waste management benefits to materialize."

EPRI/EDF STUDY

- A recent study by EPRI and EDF is consistent with previous NAS findings
  - A. Machiels (EPRI), S. Massara and C. Garzenne (EDF), “Dynamic Analysis of a Deployment Scenario of Fast Burner Reactors in the U.S. Nuclear Fleet,” Proceedings of GLOBAL 2009, Paris, France, September 6-11, 2009)
- Assumptions of study:
  - Zero-growth scenario with regard to U.S. installed capacity
  - Fast burner reactor deployment from 2038-2044
  - Equilibrium fleet: 2/3 PWRs and 1/3 fast burner reactors (1450 MWe)
  - Burners operate with a TRU conversion ratio of 0.5
    - Fresh fuel requires 38.7% Pu and 6.3% minor actinides at equilibrium
    - Discharge burnup of 180 GWD/t
    - TRU consumption rate about 625 kg per burner
  - Reprocessing loss rate is assumed to be 0.1% for all actinides and all fuel types (not currently achieved in practice)
  - Cooling time before reprocessing is 5 years for all fuel types

TRU INVENTORY GROWTH

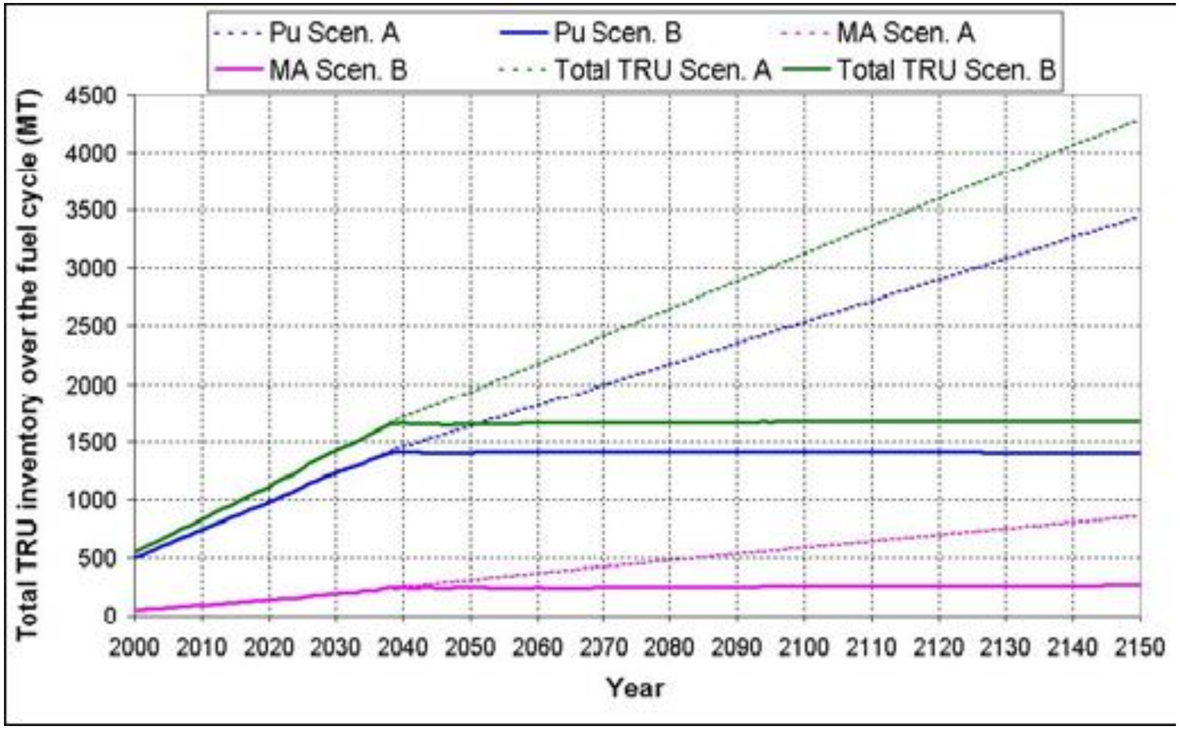


Fig. 9. Total TRU Inventories in the Fuel Cycle –
Comparison between Scenarios A and B.

(From A. Machiels, S. Massara and C. Garzenne, "Dynamic Analysis of Fast Burner Reactors in the U.S. Nuclear Fleet," Proceedings of GLOBAL 2009, Paris, September 6-11, 2009, Paper 9089)

TRU INVENTORY REDUCTION RELATIVE TO ONCE-THROUGH

(Machiels, Massara and Garzenne)

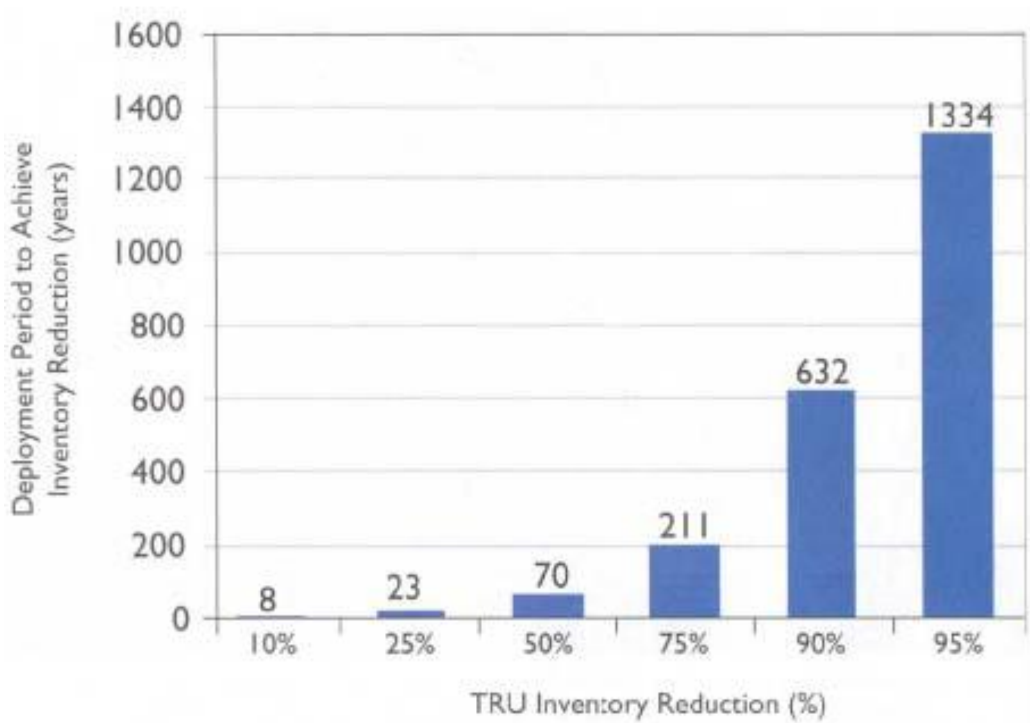


Fig. 10. Reduction in TRU Inventory as a Function of Time, Comparing Scenario B (LWR/Burner) with Scenario A (Oncethrough).

(From A. Machiels, S. Massara and C. Garzenne, “Dynamic Analysis of Fast Burner Reactors in the U.S. Nuclear Fleet,” Proceedings of GLOBAL 2009, Paris, September 6-11, 2009, Paper 9089)

INTERGENERATIONAL EQUITY IN NUCLEAR WASTE DISPOSAL

- The Environmental and Ethical Basis of Geologic Disposal of Long-Lived Radioactive Wastes, Nuclear Energy Agency, 1995:
  - the liabilities of waste management should be considered when undertaking new projects;
  - those who generate the wastes should take responsibility, and provide the resources, for the management of these materials in a way which will not impose undue burdens on future generations;
  - wastes should be managed in a way that secures an acceptable level of protection for human health and the environment, and affords to future generations at least the level of safety which is acceptable today
  - a waste management strategy should not be based on a presumption of a stable societal structure for the indefinite future, nor of technological advance; rather it should aim at bequeathing a passively safe situation which places no reliance on active institutional controls.

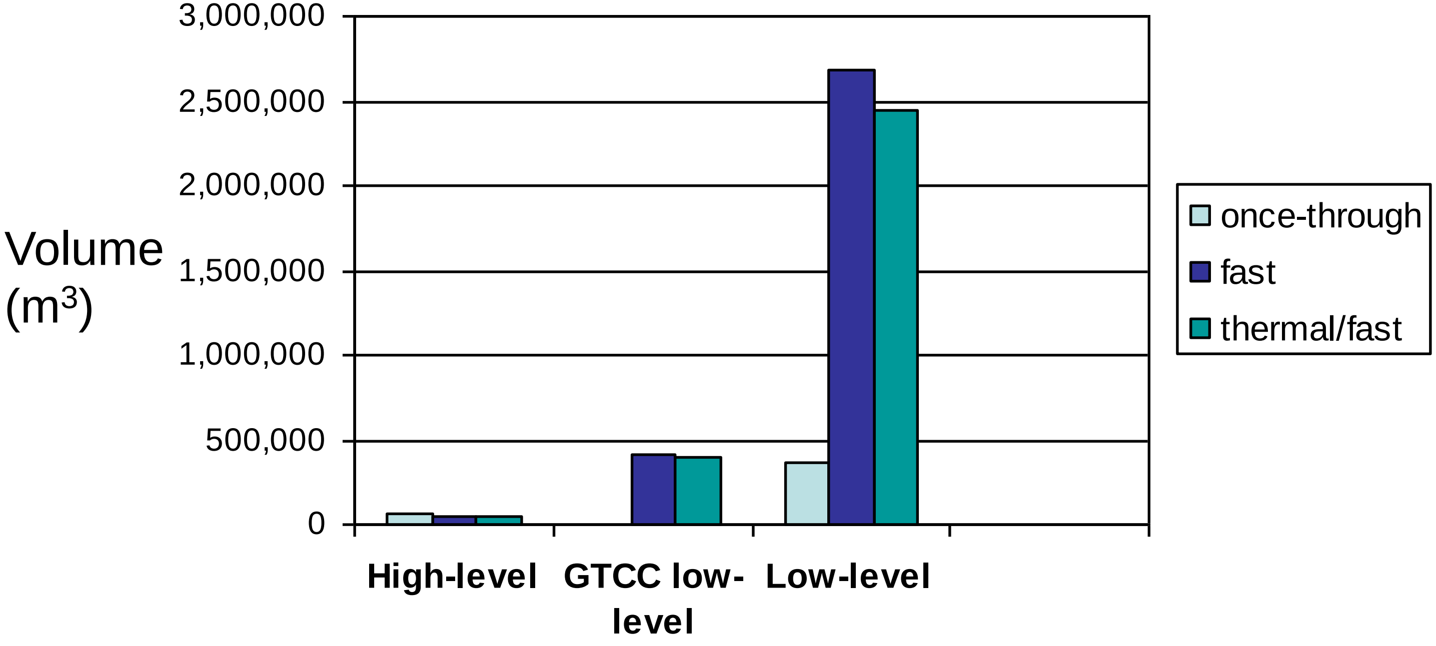
RECYCLING AND INTERGENERATIONAL EQUITY

- Reprocessing and recycling schemes that do not achieve low system-wide inventories of transuranics for many generations are **not consistent** with the intergenerational equity principle

OTHER WASTES

- According to Argonne National Laboratory data, for the fast reactor “recycle” option with Cs/Sr removal, after 50 years
  - Cumulative volume of all waste 7 times that of direct disposal option
  - Cumulative volume of greater-than-class C low-level waste is about 160 times greater than that of direct disposal option
  - Volume of reprocessed uranium comparable to volume of spent fuel
  - High-level waste volume only 25% less than initial spent fuel volume

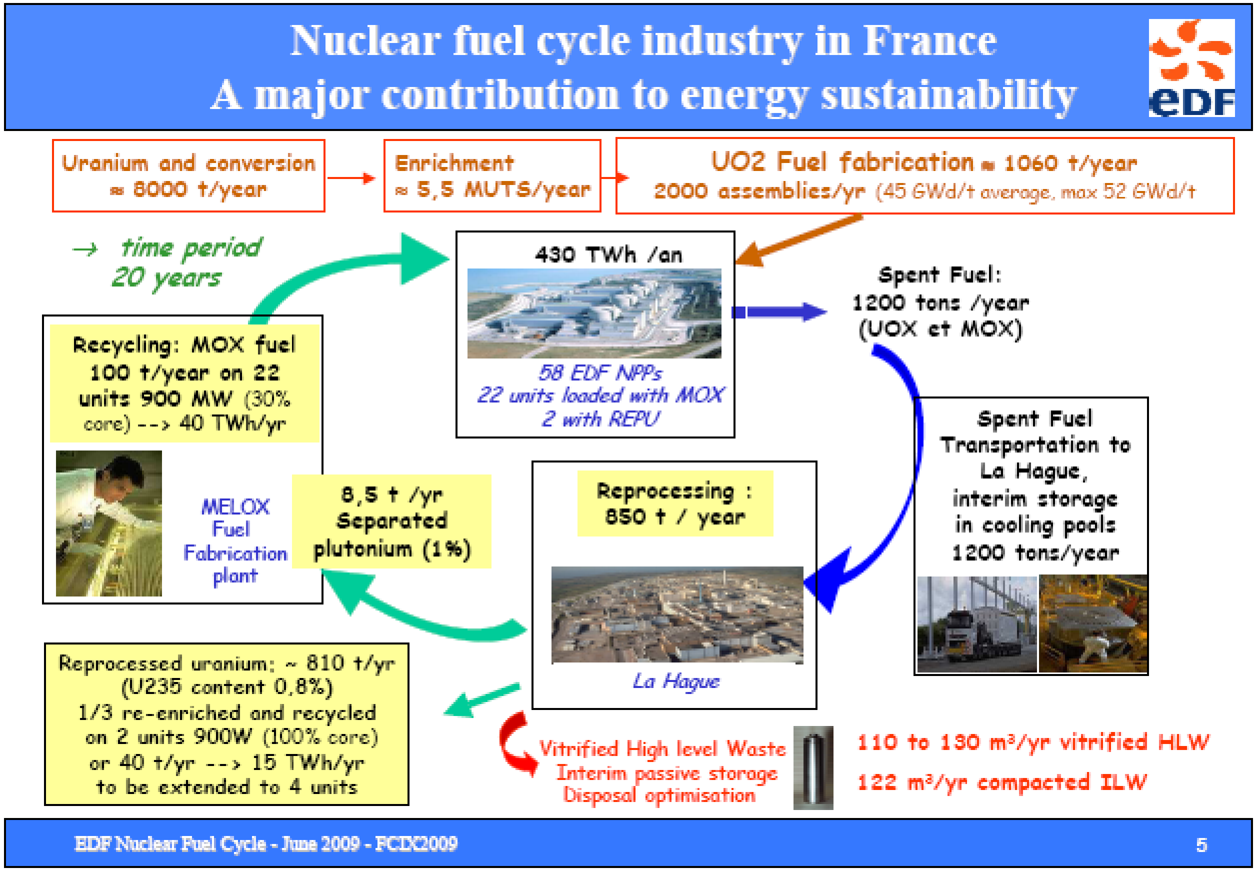
50-YR CUMULATIVE WASTE GENERATION



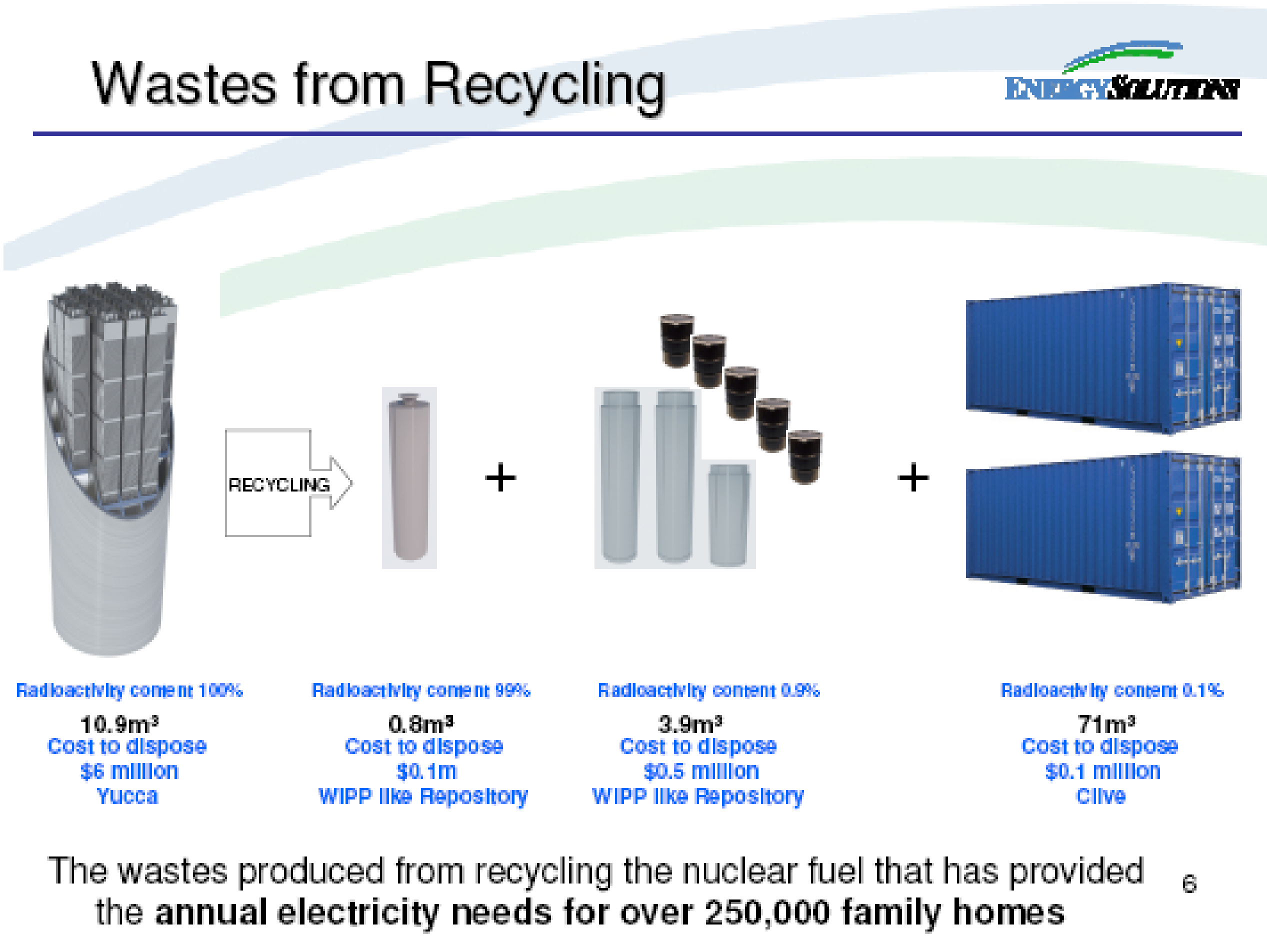
OTHER INDUSTRY ESTIMATES

- Both Electricité de France and Energy Solutions recently presented similar data
  - EdF: reprocessing of 850 metric tons of spent fuel (380 cubic meters) annually produces 110 to 130 cubic meters of vitrified HLW and 122 cubic meters of intermediate level waste (ILW) from **direct fuel processing only**
    - Associated volume reduction: about 36%
    - Simple consolidation of spent fuel rods can do better
  - Energy Solutions: total volume increases 7-fold

Electricité de France data (from Michel Debes, NRC Fuel Cycle Information Exchange, June 2009)



Energy Solutions data
(from Martin Wheeler, NRC Fuel Cycle Information Exchange, June 2009)



FAST REACTORS: SAFETY ISSUES

- Even assuming the existence of highly efficient, low conversion-ratio, actinide-fueled fast reactors, recycling schemes are ineffective – but can such reactors be safely deployed in the first place?
- Unlike light-water-moderated reactors, liquid-metal cooled fast reactors
  - are not in their most reactive configuration: increase in core density could result in rapid increase in reactivity
  - typically exhibit positive coolant reactivity feedback
    - Doppler coefficient much smaller in fast reactors
- No fast reactor designs mitigate all adverse characteristics
  - Doppler coefficient improves as reactor size increases, but sodium void coefficient worsens
- Problems are exacerbated in “burner” reactors
  - No uranium blankets lead to vanishingly small Doppler feedback
  - Large reactivity swings necessary to have efficient burners
  - Large fissile enrichments (up to 50 percent) and short operating cycles further increase terrorism and proliferation concerns
- Large TRU “source term” compared to uranium-fueled LWRs could result in far greater consequences of a severe accident or terrorist attack

PROLIFERATION AND THEFT RESISTANCE

- Are there any credible alternatives to PUREX that would be substantially more proliferation- and theft-resistant, and would therefore not significantly raise the risks of nuclear proliferation and nuclear terrorism relative to the once-through cycle?
- If such an approach can be found
  - can it be implemented at a reasonable cost and with acceptable environmental, safety and health impacts?
  - Would the technology be secure enough to be transferred freely to any country that wants it? On what basis could the U.S. deny the transfer if it is deemed to be proliferation-resistant?

"PROLIFERATION-RESISTANT" RECYCLING DOESN'T EXIST

- The primary approach to proliferation resistance is to replace PUREX by developing new reprocessing technologies that would not produce "separated plutonium"
  - Aqueous processes (UREX+, COEX)
  - Non-aqueous processes (pyroprocessing)
- However, in most cases these processes produce mixtures that are not proliferation- or theft-resistant because they
  - would not be significantly more difficult or hazardous to steal than separated plutonium
  - could be used to make a nuclear weapon, either directly or after minimal chemical processing
- These ideas are not new, and have changed little since the 1970s (unlike the capabilities of terrorists and proliferant states, which have increased)

"SELF-PROTECTION" FROM THEFT

- The plutonium in spent fuel is considered "self-protecting" because the penetrating radiation (primarily emitted by cesium-137) is so intense that anyone attempting to steal spent fuel would risk injury or death
- The dose rate at 1 meter from the midpoint of a typical spent fuel assembly is over one thousand rem (tens of Sievert) per hour for several decades after discharge (lethal dose is around 600 rem)
- In contrast, the dose rate at 1 meter from a bomb's worth of plutonium is on the order of tens of millirem per hour

“SELF-PROTECTION” STANDARDS

- DOE and NRC have used 100 rem/hr at 1 meter as the self-protection standard for decades; establishes thresholds for safeguards and physical protection measures; was adopted by IAEA in its physical protection and safeguards guidance
- This standard has long been regarded as insufficient
- Argonne National Lab study (2006): standard should be 10,000 rem/hr in order to immediately disable thieves
- DOE is now re-evaluating the self-protection threshold: originally proposed to raise self-protection threshold by 40 (to 4000 rem/hr); current proposal is said to be 500 or 1000 rem/hr
- A higher threshold could have a significant impact on security levels (and costs) for many types of material, including power reactor spent fuel

SELF-PROTECTION OF PYROPROCESSING

Electro-refining: The Best for Proliferation Resistance

	Weapon Grade Pu	Reactor Grade Pu	Electro-refining
Production	Low burnup PUREX	High burnup PUREX	✓ Fast reactor Pyroprocess
Composition	Pure Pu 94% Pu-239	Pure Pu 65% Pu-fissile	✓ Pu + MA + U 50% Pu-fissile
Thermal power (w/kg)	2 – 3	5 – 10	✓ 80 – 100
Spontaneous neutrons (n/s/g)	60	200	✓ 300,000
Gamma radiation (r/hr at ½ m)	0.2	0.2	✓ 200

imagination at work

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GE
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ASSESSING SELF-PROTECTION

- Pyroprocessing would have a dose rate greater than 100 rem/hr at 1 meter only for a short period of time, after which it would disappear rapidly
- Mixing Pu with U only (COEX) or U + Np (NUEX) has no appreciable impact on dose rate
- No variant is likely to be self-protecting under a revised standard of 500 rem/hr at 1 meter
- Conclusion: these are all minor modifications of conventional PUREX that would have no significant impact on the ability of skilled adversaries to steal weapon-usable materials and process them to produce weapons

ATTRACTIVENESS FOR WEAPONS

- Study by the nuclear weapons labs assessed the attractiveness of various fuel cycle mixtures for direct use in nuclear weapons (C. Bathke, et al., 2009) concluded that
  - For Pu+U mixtures (e.g. COEX)
    - Attractive for weapons provided U < 82%
  - For Pu+TRU mixtures (e.g. UREX+1a, pyroprocessing),
    - Attractive for weapons provided U < 75%
  - For Pu+Np mixtures (e.g. NUEX)
    - As attractive for weapons as separated plutonium
- Overall, the study confirms that there is little to no reduction in attractiveness associated with UREX+, COEX, NUEX or pyroprocessing compared to PUREX
- Study did not consider possibility of purifying material

WEAKENING PHYSICAL PROTECTION REQUIREMENTS

- NRC Category I security requirements are applicable for facilities possessing Category I quantities of plutonium
- NRC regulations generally do not give credit for dilution or other material properties that may reduce “attractiveness” of strategic special nuclear material
- But in 2009 NRC exempted power reactors possessing MOX fuel from Category I security requirements provided the plutonium content is < 20%
- Industry representatives interested in recycling have asked the NRC to also weaken security standards for transport of MOX fuel to allow ordinary trucks to be used, as opposed to Safe-Secure Trailers (SSTs) generally used to transport weapon-usable materials
- NRC currently considering this proposal in secret

RECOMMENDATIONS

- DOE should reduce emphasis on reprocessing and fast reactor R&D and focus on innovative approaches for enhancing the once-through cycle
- NRC, instead of weakening security standards for weapon-usable materials, should use its regulatory system to promote improved security in the post-9/11 world through more stringent standards