The Abdus Salam
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International Atomic Energy Agency

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Joint ICTP/IAEA School on Physics and Technology of Fast Reactors Systems

9 - 20 November 2009

Integral Fast Reactor and Associated Fuel Cycle System

Part 1. Overall Technical Rationale

YOON IL CHANG
Argonne National Laboratory
USA

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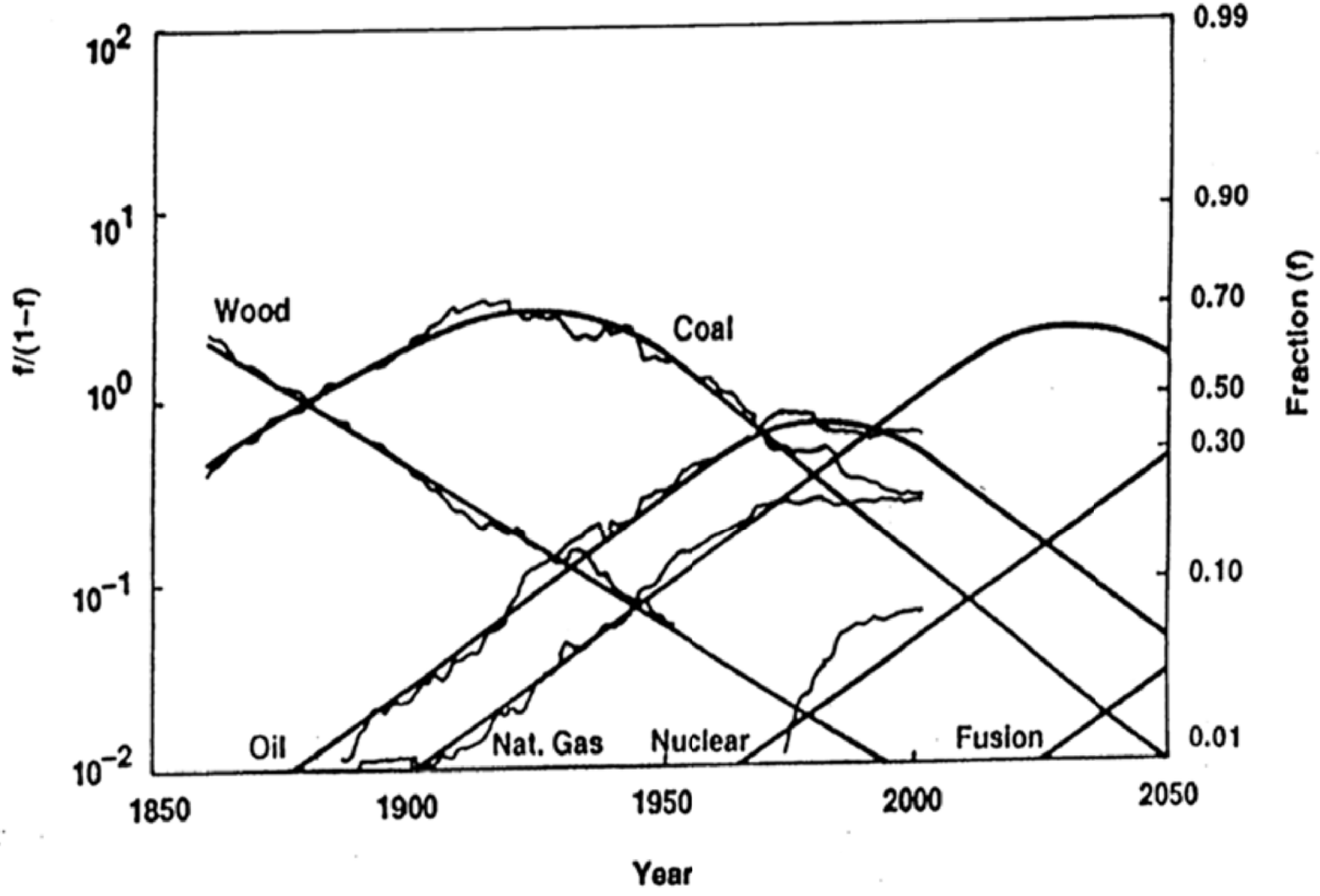
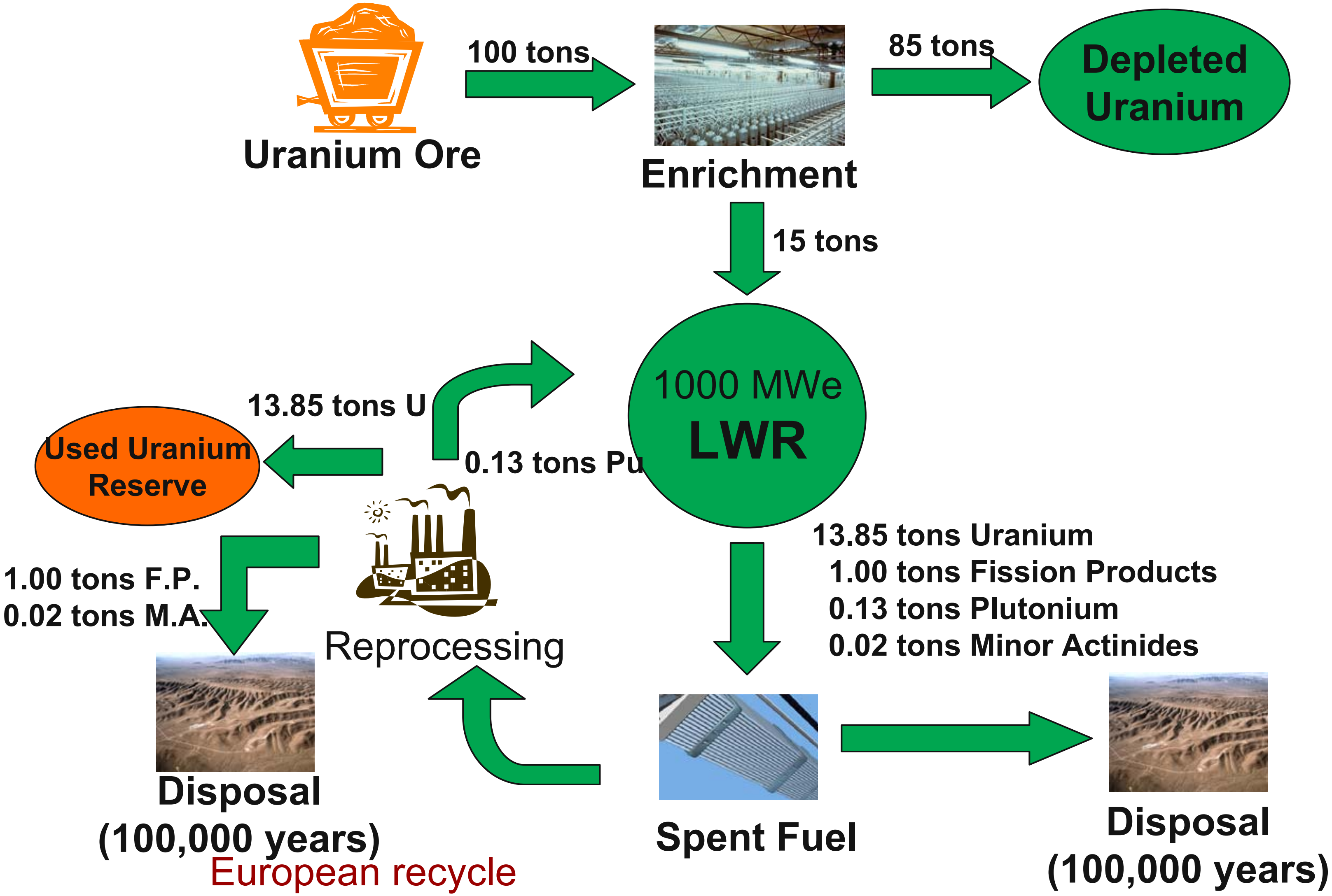
Primary Energy Substitution Model (Source: Marchetti)



Uranium utilization is <1% in LWR (Annual Mass Flow)



Uranium Ore

100 tons

Enrichment

85 tons

Depleted Uranium

15 tons

1000 MWe
LWR

13.85 tons U

Used Uranium Reserve

0.13 tons Pu

Reprocessing

1.00 tons F.P.
0.02 tons M.A.

Disposal
(100,000 years)

13.85 tons Uranium
1.00 tons Fission Products
0.13 tons Plutonium
0.02 tons Minor Actinides

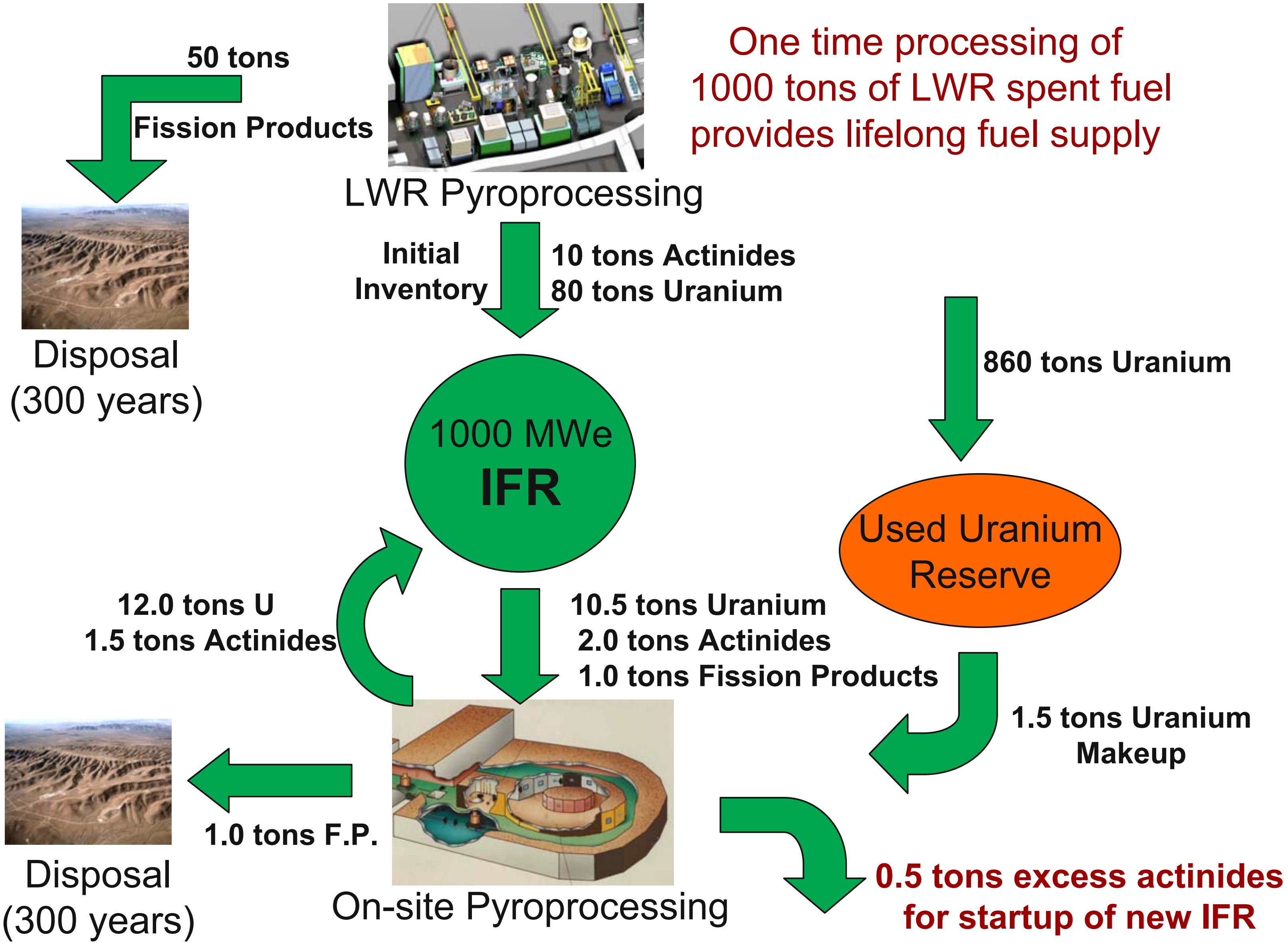
Spent Fuel

Disposal
(100,000 years)

European recycle
- Saves 15% uranium
- But no reduction in waste life

Direct disposal is
the current U.S. policy

IFR is self-sufficient after initial startup



One time processing of 1000 tons of LWR spent fuel provides lifelong fuel supply

LWR Pyroprocessing

50 tons

Fission Products

Disposal
(300 years)

Initial Inventory

10 tons Actinides
80 tons Uranium

860 tons Uranium

1000 MWe
IFR

Used Uranium Reserve

12.0 tons U
1.5 tons Actinides

10.5 tons Uranium
2.0 tons Actinides
1.0 tons Fission Products

1.5 tons Uranium Makeup

1.0 tons F.P.

Disposal
(300 years)

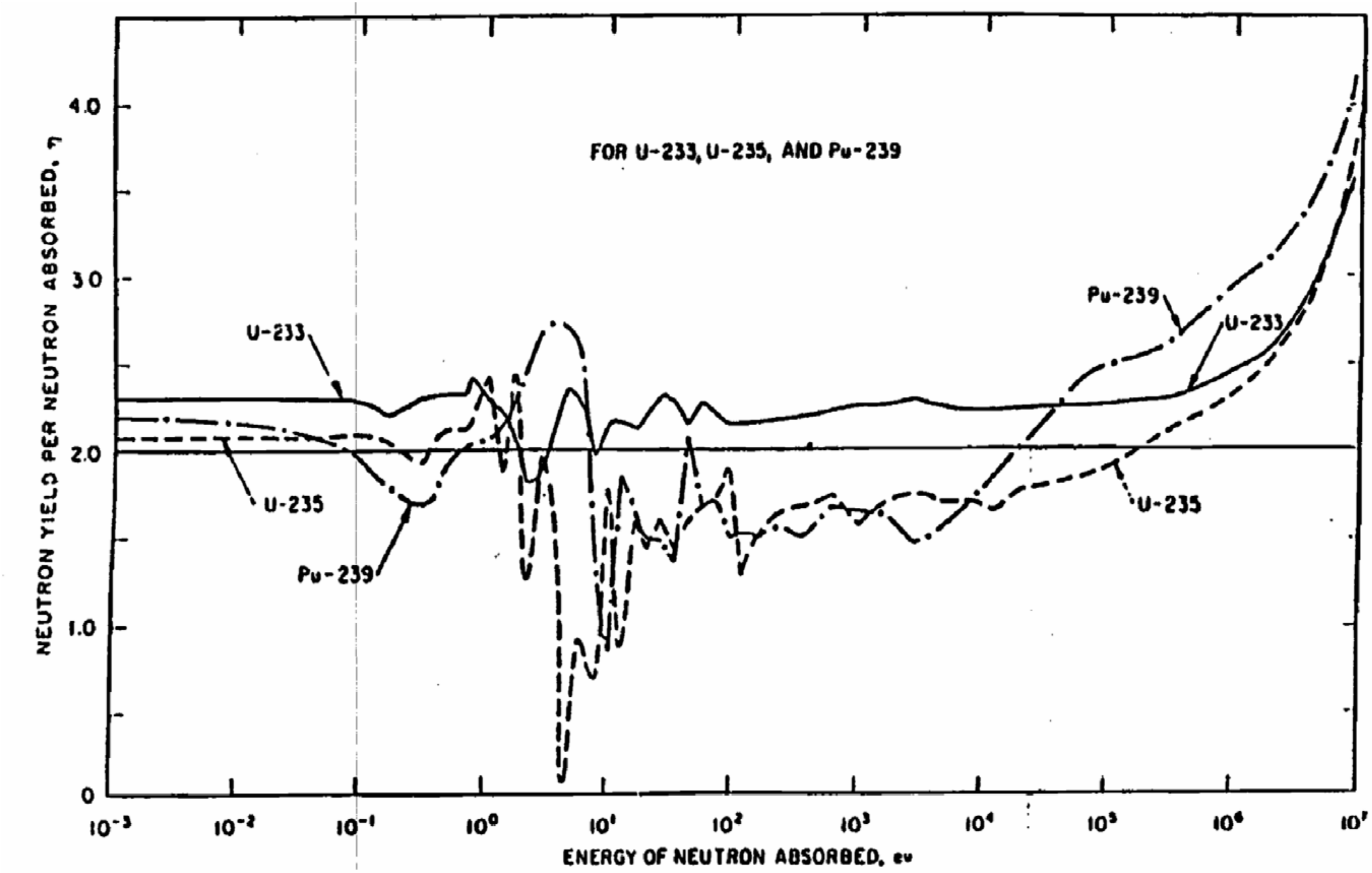
On-site Pyroprocessing

0.5 tons excess actinides for startup of new IFR

Fundamental Rationale for Fast Reactors

- Current commercial reactors utilize less than one percent of uranium resources.
- Fast reactors can utilize essentially all through recycling, except for small losses in processing, resulting in a hundred-fold improvement.
- Intrinsic nuclear characteristics make this distinction.
- Therefore, if nuclear is to contribute a significant portion of future energy demand growth, then fast reactors will have to play a key role.

Neutron Yield vs. Spectrum



Breeding Ratio

- BR = Fissile production/Fissile destruction (integrated)
- Alternative expression based on neutron balance:

  $BR = \eta - 1 + \varepsilon - A - L - D$, where

  η = number of neutrons by fission in fissile isotopes

  ε = number of neutrons by fission in fertile isotopes

  A = number of neutrons absorbed in non-fuel materials

  L = number of neutrons lost by leakage

  D = independent of the neutron balance but accounts for decay loss

  (All normalized to neutron absorption in fissile isotopes)

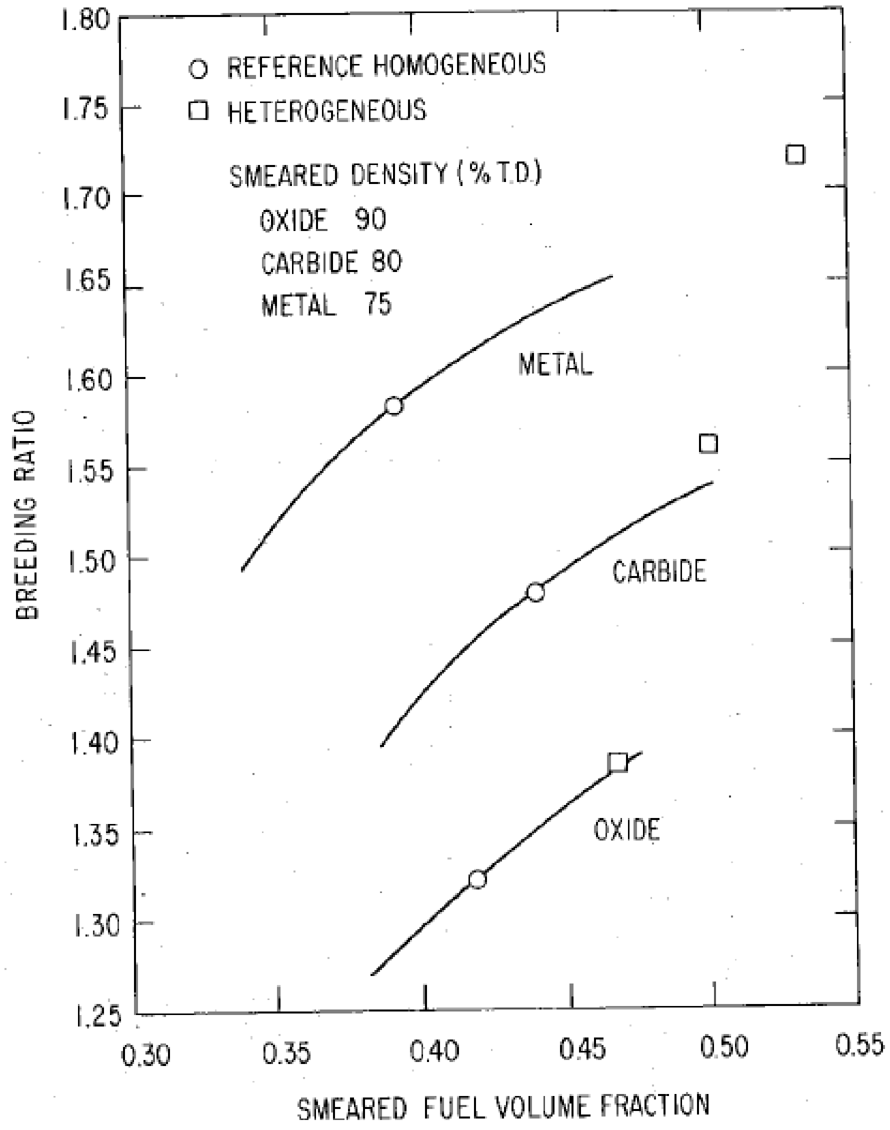
Comparison of Neutron Economy (reactor types)

	HWR	LWR	FBR
η	2.03	1.92	2.28
ε	0.02	0.09	0.36
$\eta - 1 + \varepsilon$	1.05	1.01	1.64
Losses: Structure	0.09	0.03	0.16
Coolant	0.03	0.08	0.01
Fis. Prod.	0.11	0.16	0.06
Leakage	0.08	0.15	0.05
Decay	-	-	0.03
Subtotal	0.31	0.42	0.31
Excess Neutrons (CR or BR)	0.74	0.59	1.33

Comparison of Neutron Economy (fuel types)

	Oxide	Carbide	Metal
η	2.283	2.353	2.450
ε	0.356	0.429	0.509
$\eta - 1 + \varepsilon$	1.639	1.782	1.959
Losses: Structure	0.158	0.131	0.127
Coolant	0.010	0.009	0.008
Fis. Prod.	0.055	0.058	0.058
O, C, Zr	0.008	0.009	0.025
Leakage	0.046	0.051	0.082
Decay	0.031	0.029	0.032
Subtotal	0.308	0.279	0.332
Excess Neutrons (BR)	1.331	1.503	1.627

Breeding Ratio as a function of Fuel volume fraction



Neutron Economy

- Dictated by η, which depends on neutron spectrum: the harder, the better
- Spectrum hardening is controlled by heavy atom density (or fuel volume fraction over coolant or structures)
- High fuel volume fraction (more precisely, heavy atom density) is achieved by:
  - High density fuel
  - Tight lattice: hexagonal
  - Large pin diameter
  - Less coolant area
  - Less structural area

Integral Fast Reactor (IFR) Initiative

- Following the cancellation of the CRBR Project, the fast reactor technology program, funded at hundreds of millions of dollars a year, faced a rapid ramp-down.
- The IFR program was initiated at Argonne in 1983 as a new technology direction for future fast reactors, addressing key concerns:
  - The CRBR licensing was dominated by the hypothetical core disruptive accident scenario, and hence this combined with the TMI-2 accident required a new safety design approach.
  - Waste management, nonproliferation, and economic considerations required a new innovative fuel cycle technology.

Sodium Coolant Properties

- Sodium has a high boiling point: 881°C (1618°F)
- Hence, the reactor system can operate near atmospheric pressure, and coolant containment is straightforward.
- Furthermore, sodium is non-corrosive to structural materials, and hence sodium components are highly reliable.
- These properties can be exploited to achieve inherent passive safety to a highest level.

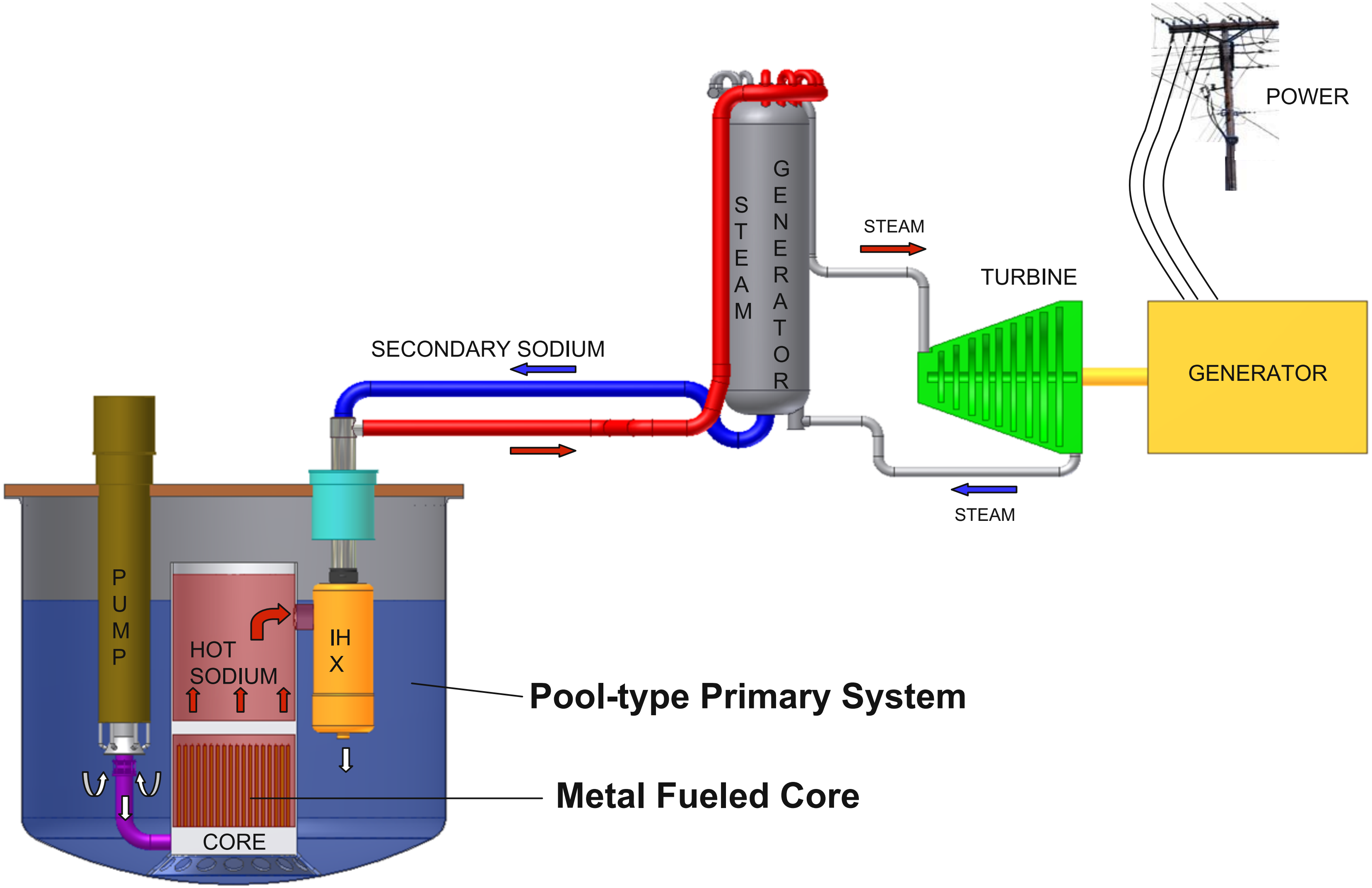
What is Integral Fast Reactor (IFR)?

	Current Generation LWR	Next Generation IFR	Principal Impacts
Coolant	Water	Liquid sodium	Non-pressurized system
Neutron energy	Thermal (<1 eV)	Fast (>100 keV)	Breeding capability
Fuel type	Oxide	Metal	Inherent passive safety
Fuel Cycle	Aqueous reprocessing	Pyro-processing	Waste management solution, proliferation-resistance, economics

Inherent Passive Safety

- For a large scale deployment of nuclear energy, much enhanced inherent passive safety characteristics are required.
- Fast reactors can be designed to provide such characteristics, which maintain safety even in the events of operator error or safety system malfunction.
- Inherent passive safety potential was demonstrated in landmark tests conducted on EBR-II in April 1986:
  - Loss-of-flow without scram from full power
  - Loss-of-heat-sink without scram from full power

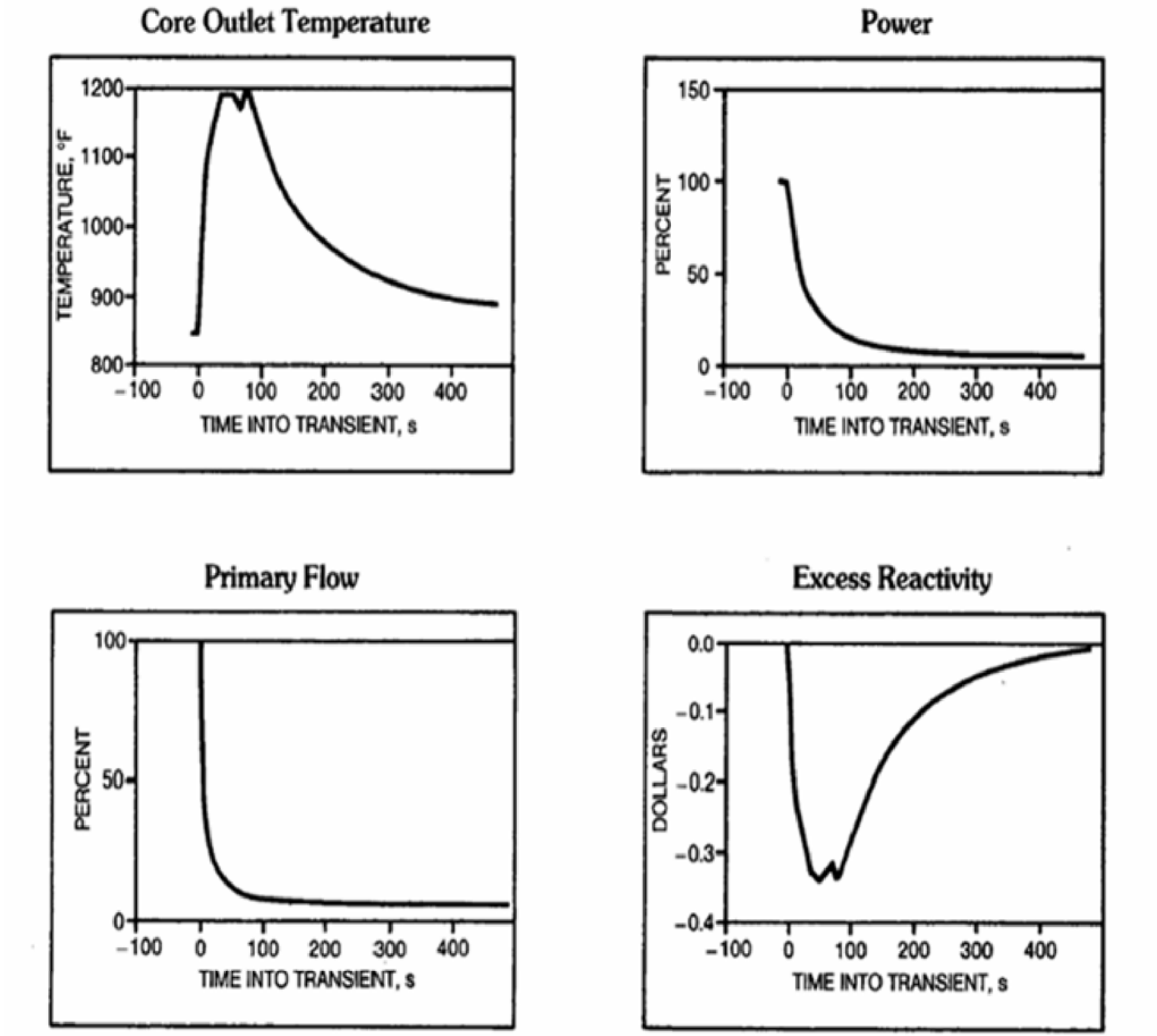
Schematics of IFR Plant



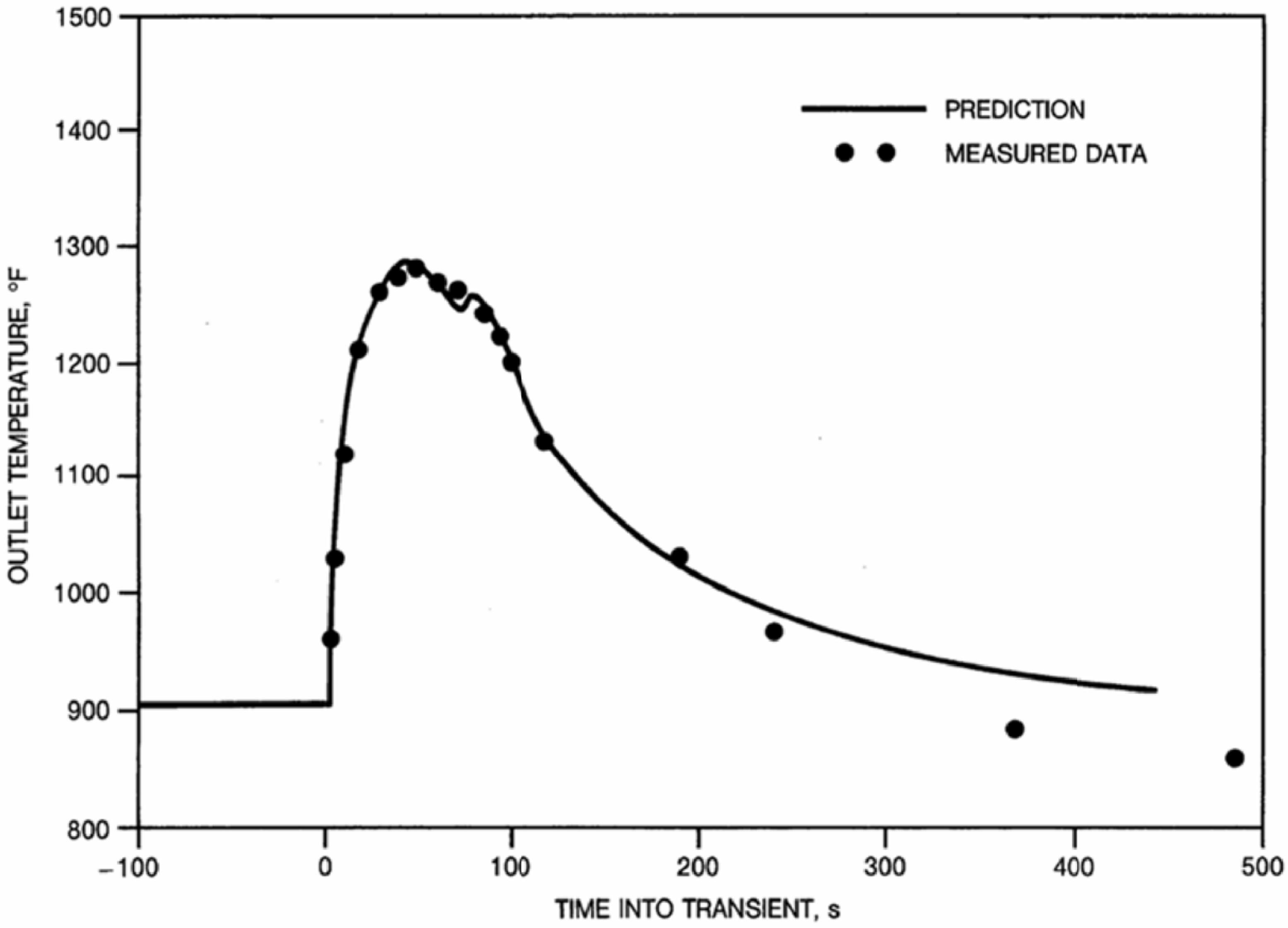
Pool-type Primary System

Metal Fueled Core

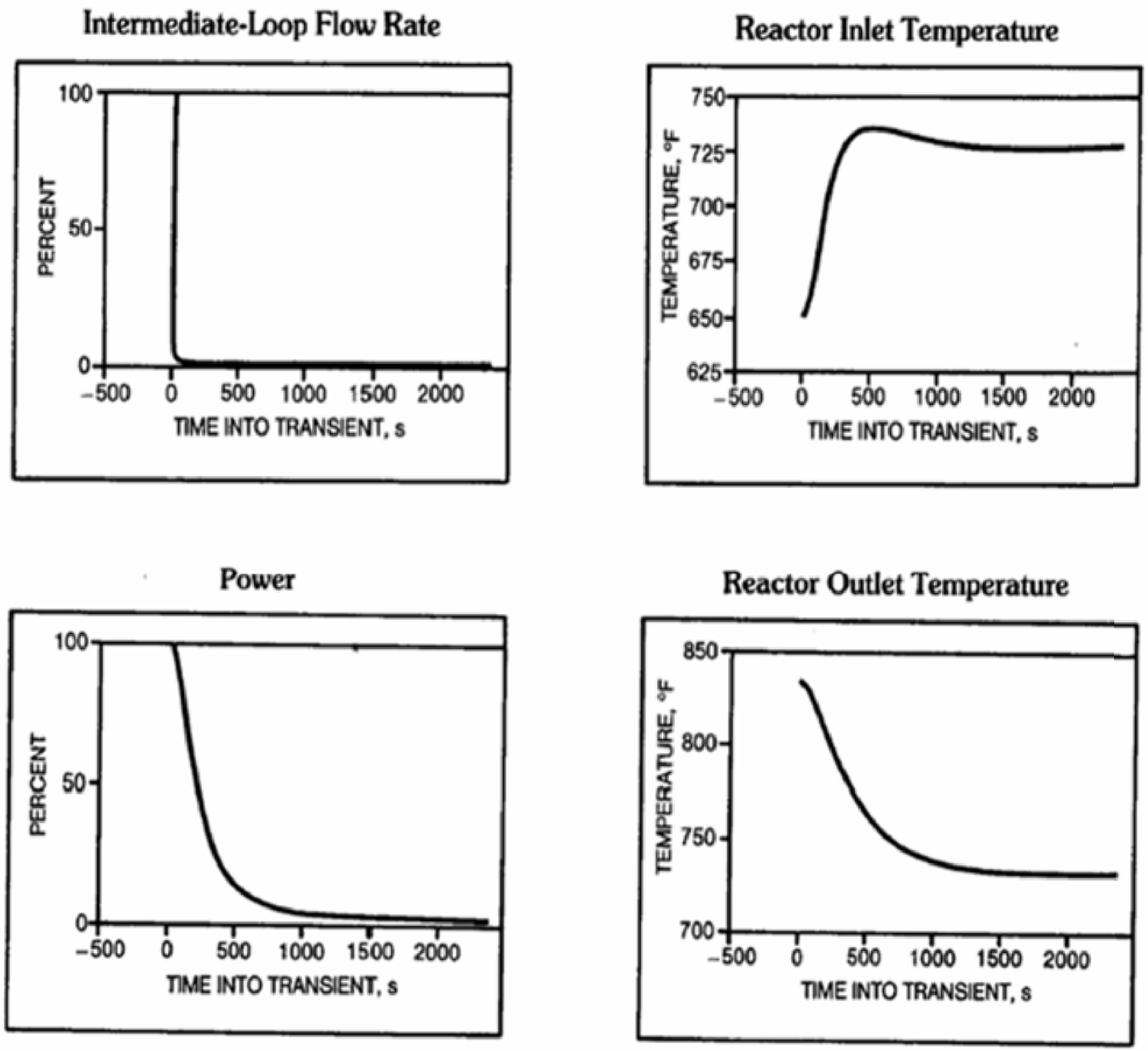
Loss-of-Flow w/o Scram Sequence



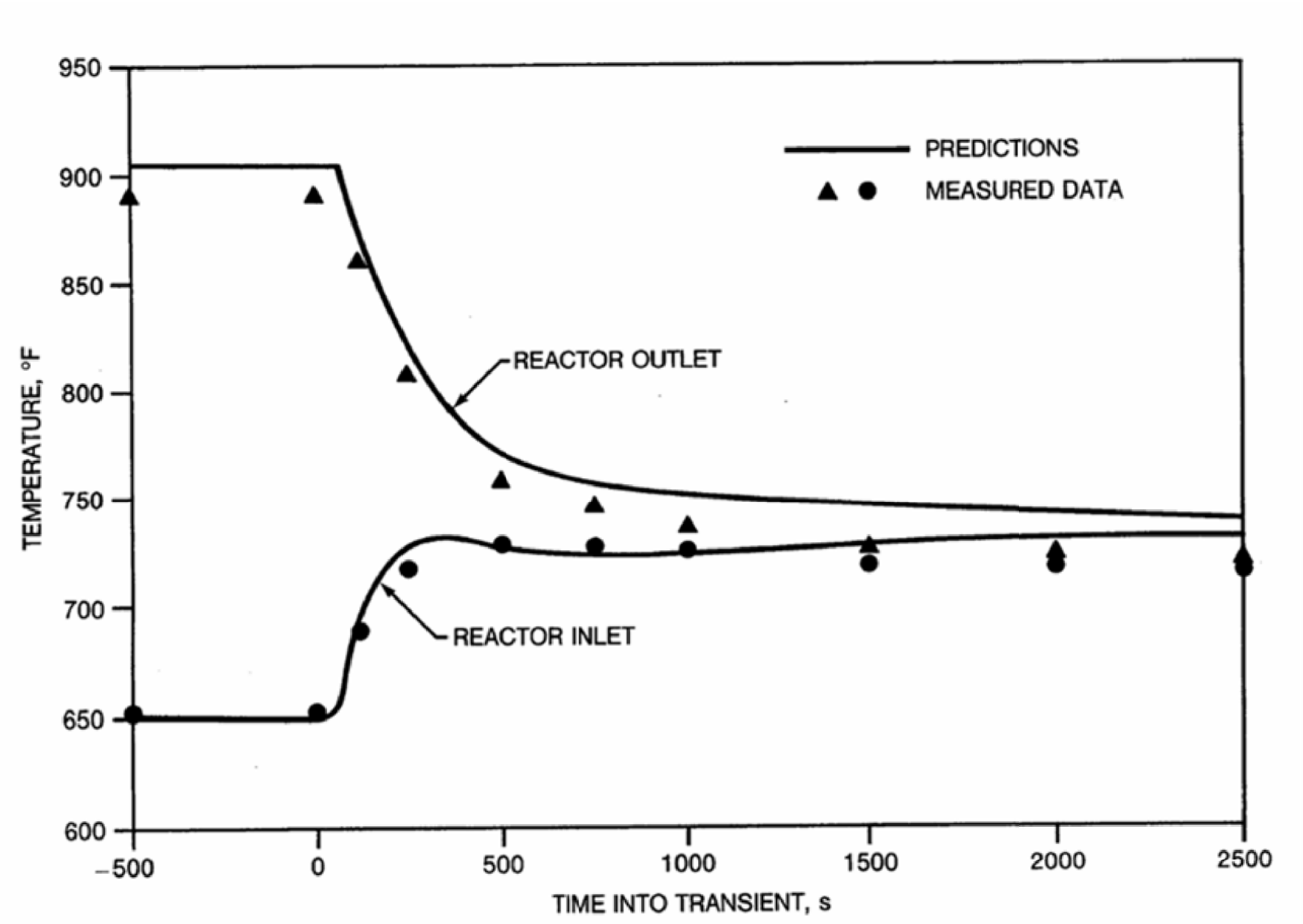
Loss-of-Flow without Scram Test



Loss-of-Heat-Sink w/o Scram Sequence



Loss-of-Heat-Sink without Scram Test



Key Contributors to Inherent Passive Safety

- Large margin to boiling temperature with sodium coolant.
- Pool design provides thermal inertia.
- Low stored Doppler reactivity due to high thermal conductivity (hence, low temperature) of metal fuel.
- Hence, the inherent passive safety characteristics are achieved only in the IFR-type fast reactors.

Inherent Passive Safety is a Key Attribute of IFR

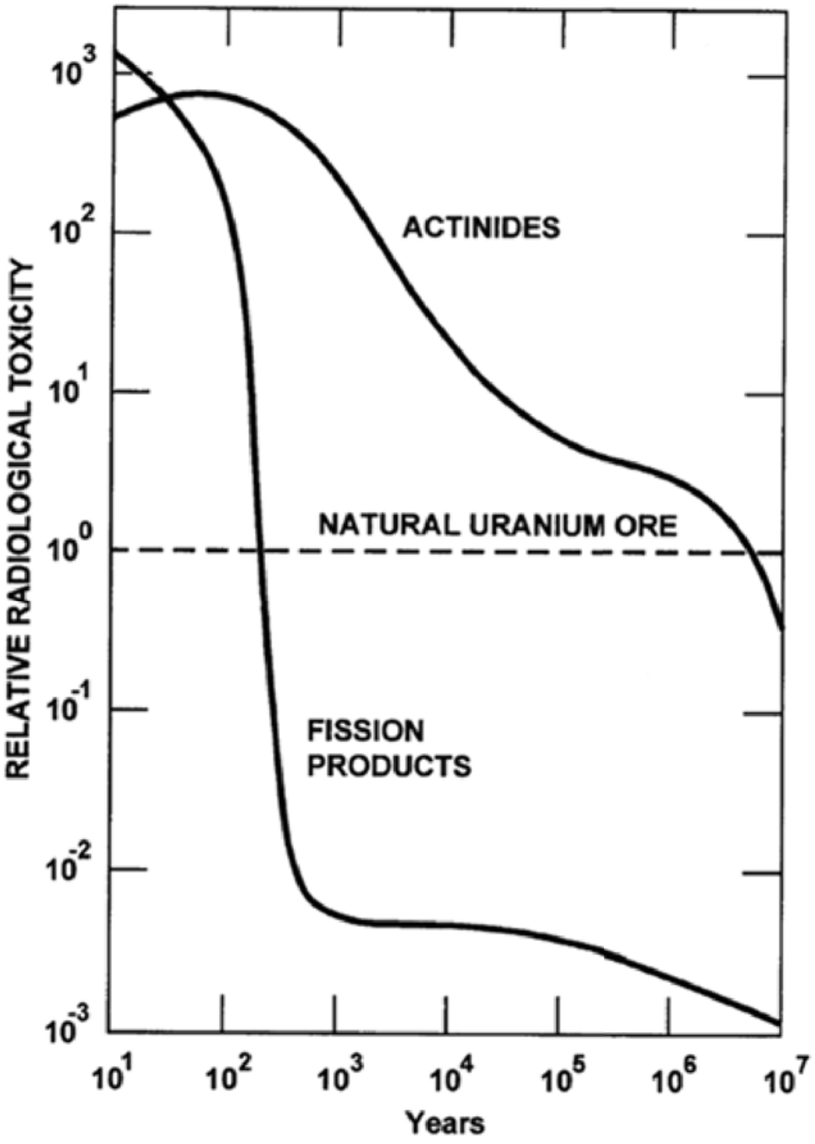
- For a large scale deployment of nuclear energy, much enhanced inherent passive safety characteristics are required.
- Fast reactors can be designed to provide such characteristics, which maintain safety even in the events of operator error or safety system malfunction.

Waste Management Benefits

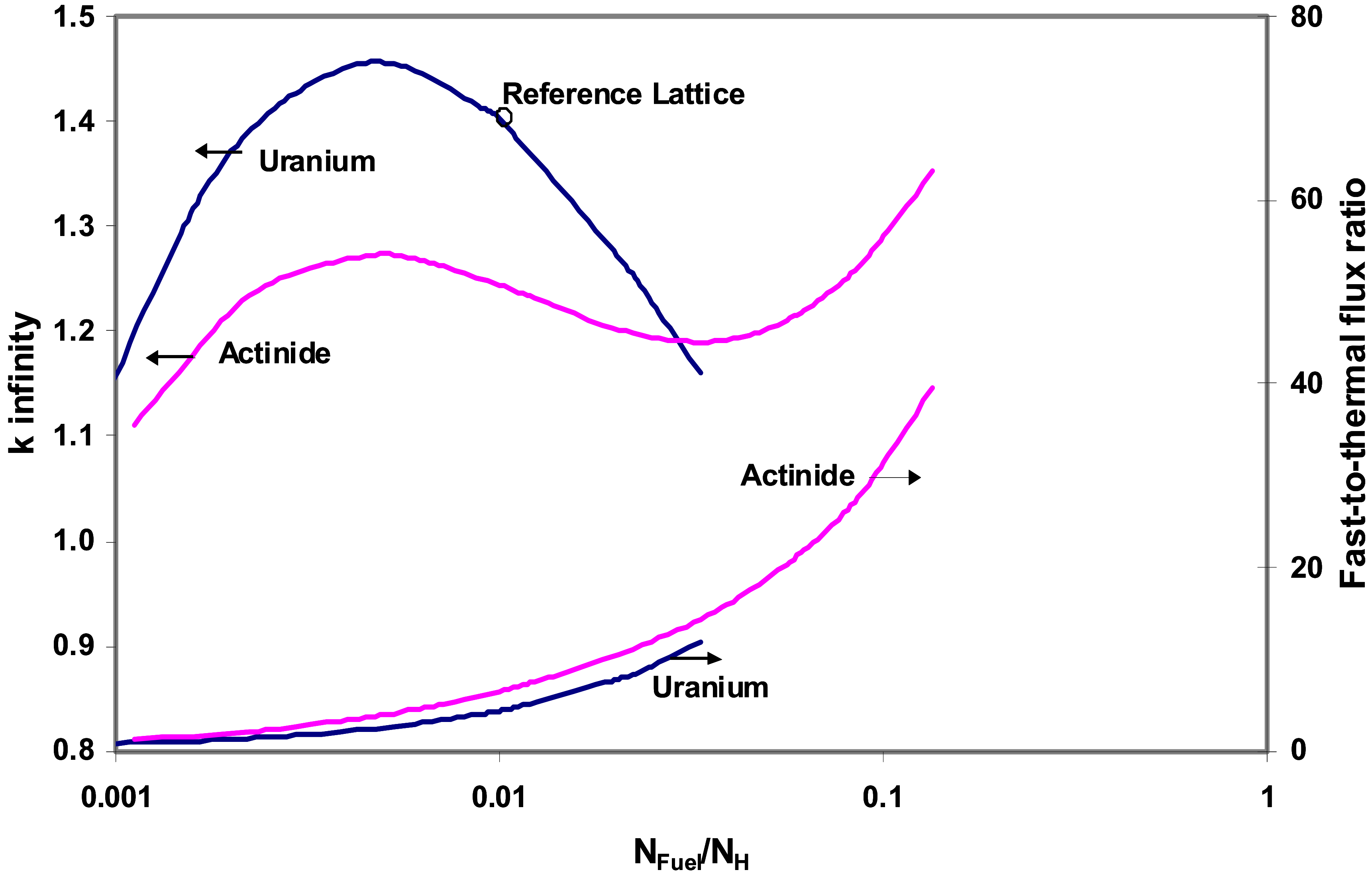
- Long-lived actinides are the long term radiological risks.
- Actinides can be burned only in fast reactors (in fact, generating energy at the same time).
- Actinides also contribute to long term decay heat, which limits the disposal per unit area. Hence, actinide burning in fast reactors can increase the repository space utilization in the long term.

Radiological Toxicity of Spent Fuel

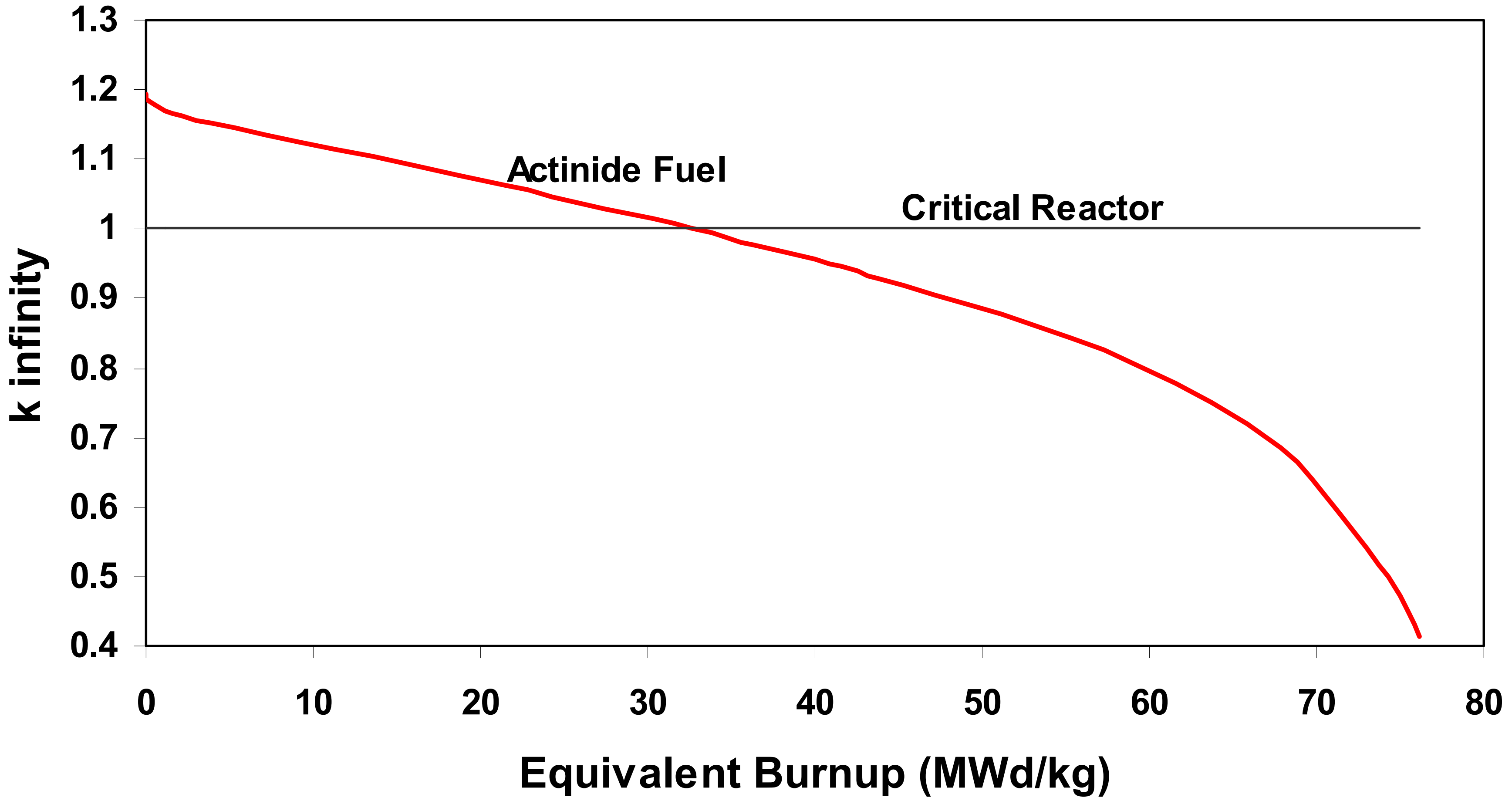
- Radiological toxicity of fission products drops below the natural uranium ore level in about 300 years.
- Radiological toxicity of actinides stays above the natural uranium ore and about three orders of magnitude higher than fission products for millions of years.



Spectral Behavior of U and Actinide Lattices



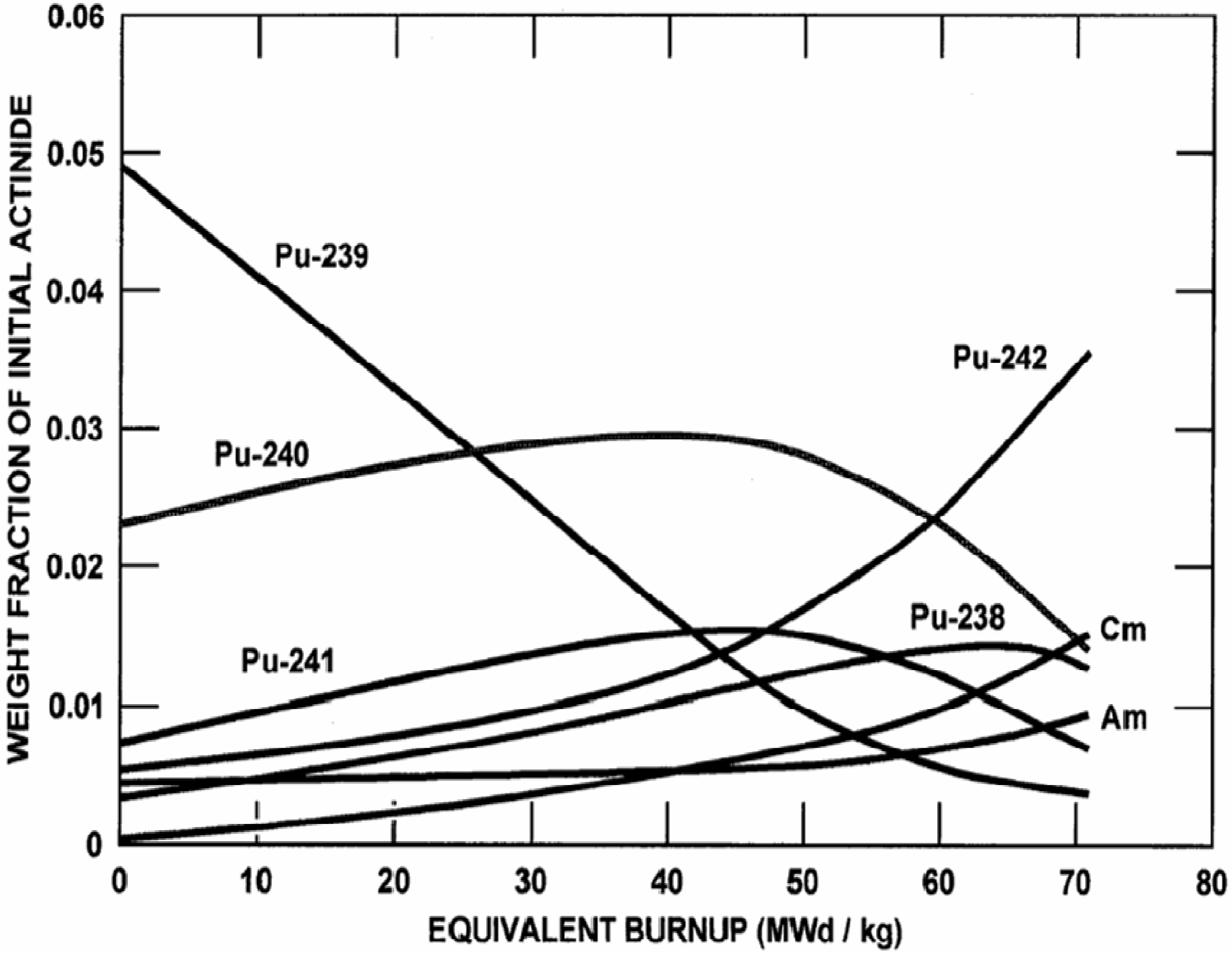
Intrinsic Reactivity Constraint



Transmutation Probabilities (in %)

Isotope	Thermal	Fast
Np-237	3	27
Pu-238	7	70
PU-239	63	85
Pu-240	1	55
Pu-241	75	87
Pu-242	1	53
Am-241	1	21
Am-242m	75	94
Am-243	1	23
Cm-242	1	10
Cm-243	78	94
Cm-244	4	33

Evolution of Actinides in Thermal Spectrum



Waste Management Implications

- The ability to burn actinides in fast reactors should be viewed as a bonus rather than an imperative.
- The IFR fuel cycle based on pyroprocessing provides key advantages:
  - All actinides are recovered together and easily recycled.
  - Revolutionary improvements in economics.
  - Intrinsic proliferation-resistance.

Status of Sodium-cooled Fast Reactor

- Over a dozen reactors have successfully operated:
  - U.S.: EBR-1, EBR-II, Fermi-1 and FFTF
  - France: Rapsodie, Phenix and SuperPhenix
  - U.K.: DFR and PFR
  - Germany: KNK-II
  - Japan: Joyo and Monju
  - Russia:BR-5/10, BOR-60, BN-350 and BN-600
- However, commercialization efforts have been stalled around the world in the last 20 years or so.

Worldwide Fast Reactor Experience

U.S.	EBR-I	1/0.2	1951-63
	EBR-II	62.5/20	1964-94
	Fermi-1	200/61	1965-72
	FFTF	400	1980-92
Russia	BR-5/10	8	1958-02
	BOR-60	60/12	1969-
	BN-350	1000/150	1973-99
	BN-600	1470/600	1980-
France	Rapsodie	40	1967-83
	Phenix	563/250	1974-
	SuperPhenix	3000/1240	1985-97
Japan	Joyo	140	1978-
	Monju	714/300	1993-
UK	DFR	72/15	1963-77
	PFR	600/270	1976-94
Germany	KNK-II	58/21	1972-91
India	FBTR	42.5/12	1985-

Current Fast Reactor Construction Projects

- Russia resumed the construction of BN-800, scheduled to be on-line in 2012.
- India is constructing a 500 MWe Prototype Fast Breeder Reactor (PFBR), to be on-line in 2010. Subsequently four more units of the same size are planned in two sites by 2020.
- China is constructing 65 MWth/20 MWe China Experimental Fast Reactor, to be on-line in 2009. Follow-on 800 MWe prototype FBR planned ~2020.
- Both China and India envision rapidly growing demand for nuclear and consider fast breeder reactors to be essential part of their future energy mix.