PLENTIFUL ENERGY
The Story of the Integral Fast Reactor

International Symposium
Peaceful and Safer Use of Nuclear Power:
Role of Integral Fast Reactor

University of Tokyo
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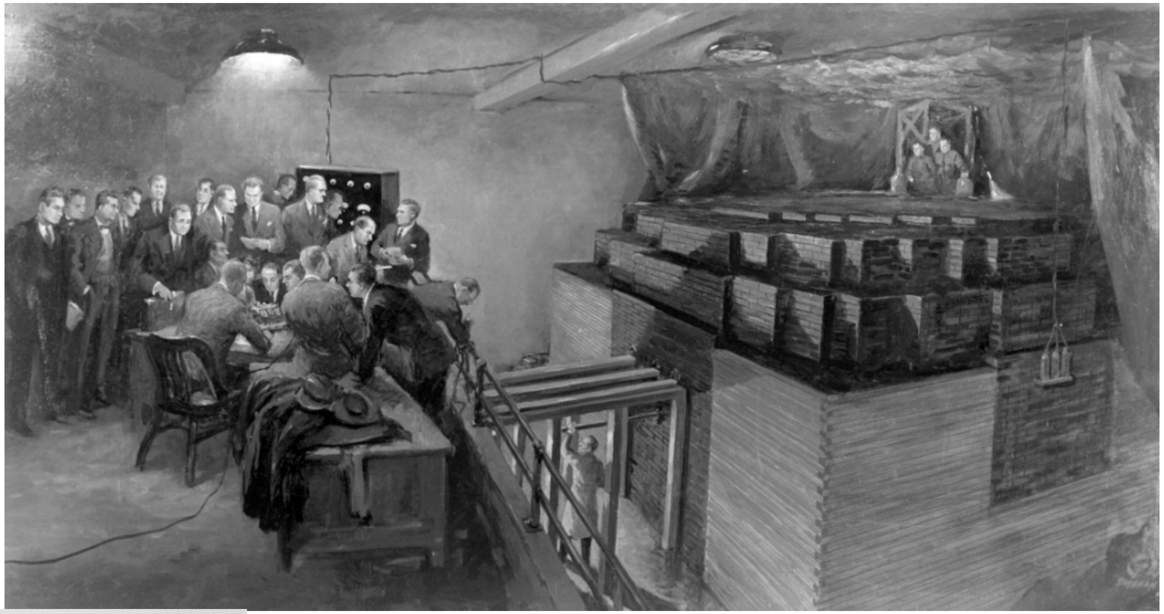
Chicago Pile-1 (CP-1): World's First Reactor

- Enrico Fermi and his team achieved the first controlled chain reaction in Chicago Pile-1 (CP-1): December 2, 1942.



- West stands of the Stagg Field of the University of Chicago was the site of Chicago Pile-1

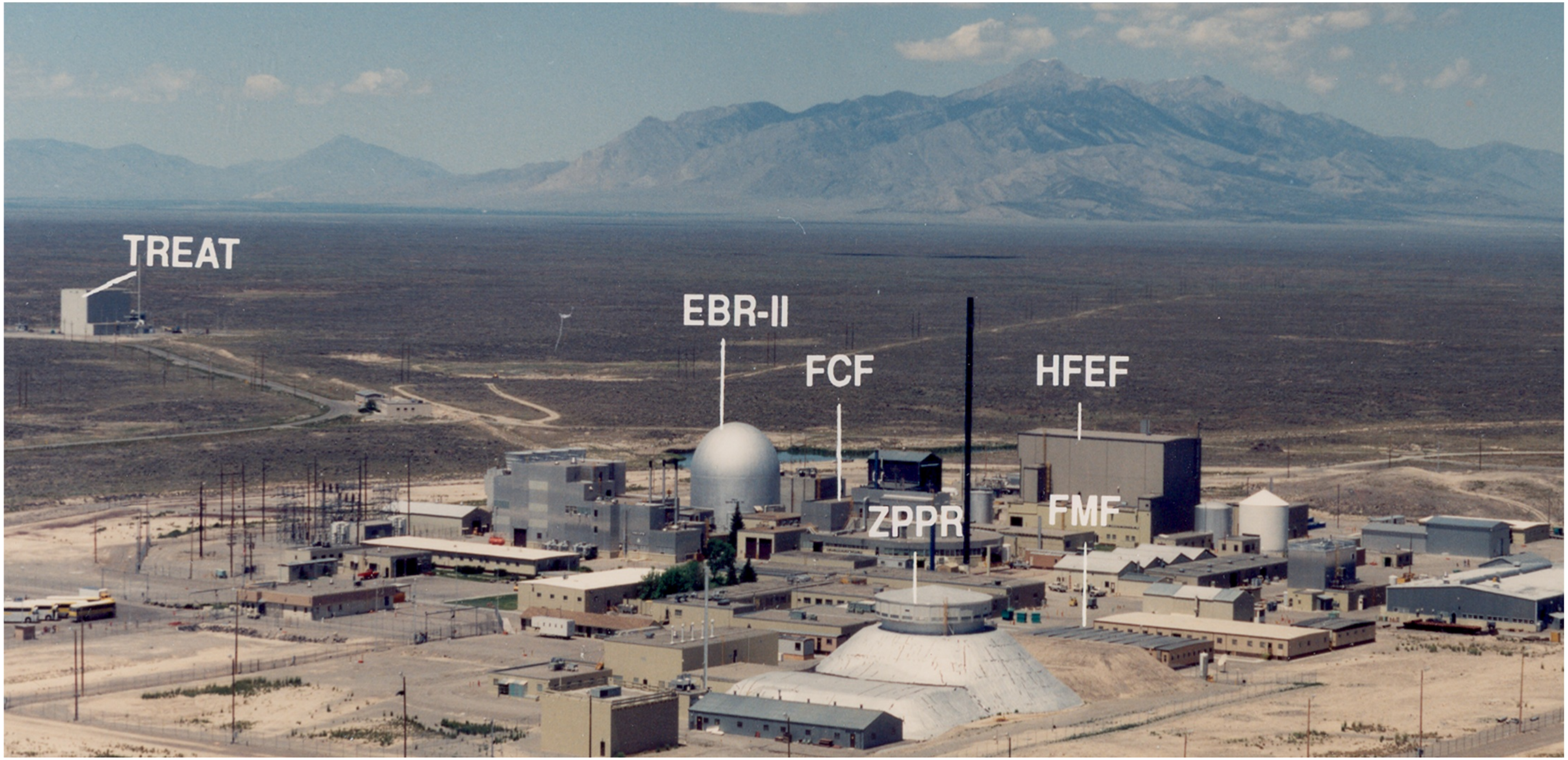
Experimental Breeder Reactor -I (EBR-I)

- Enrico Fermi first introduced the fast reactor idea in 1944 and CP-4 (renamed to EBR-I) was designed in 1946.

- EBR-I produced the first electricity from nuclear in 1951.
- EBR-I demonstrated the breeding principle in 1953.

Experimental Breeder Reactor-II (EBR-II)

- First pool-type fast reactor, started operation in 1964
- Fuel cycle closure demonstration during 1965-69



Argonne-West facilities, now merged into Idaho National Laboratory

Status of Fast Reactors in the 1970s

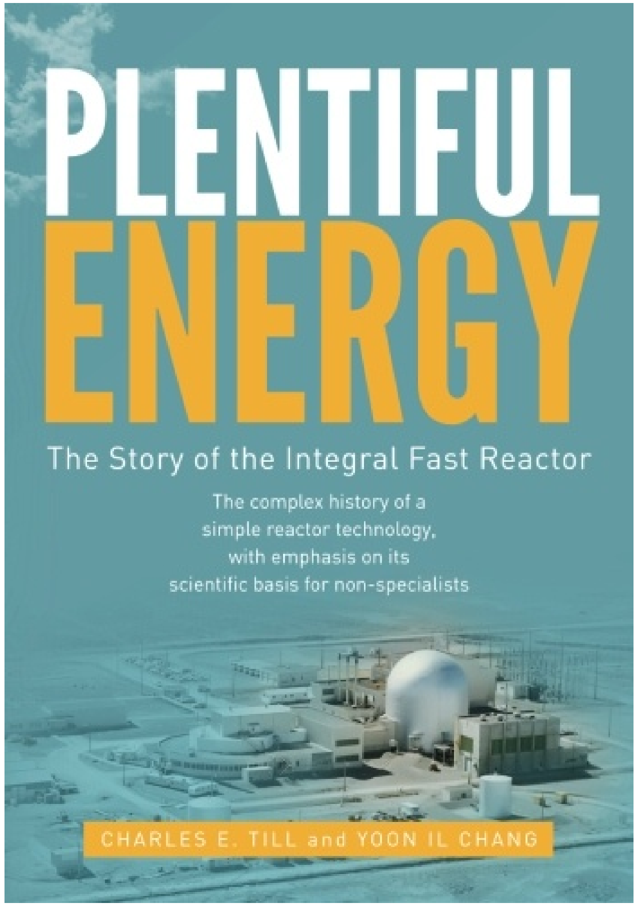
- Very strong fast reactor development programs were launched in the U.S., U.K., Russia, France, Germany, Italy, and Japan and much progress has been accumulated.
- In the U.S. alone, a large number of commercial fast reactors were envisioned by the year 2000 (LMFBR Programmatic Environmental Impact Statement).
- President Carter's nuclear policy statements in 1977:
  – Defer indefinitely U.S. commercial reprocessing and recycling of plutonium.
  – Restructure the U.S. breeder program to give greater priority to alternates to the plutonium breeder and to defer the introduction of a commercial breeder.

Recalibration Took Place

- The U.S. fast reactor development program came to a screeching halt in 1977 when President Carter announced the cancellation of the Clinch River Breeder Reactor project.
- This was a crisis situation. We had to come up with major technology innovations to overcome the roadblocks to further development of fast reactors:
  - A paradigm shift in safety design approach to prevent severe accidents: CRBR licensing was dominated by hypothetical core disruptive accident (HCDA), and the TMI-2 accident in 1979
  - Back-end fuel cycle was too complex and costly.
  - Proliferation concerns
  - Economics

Integral Fast Reactor Initiative

- Crisis (危機) also brings opportunities!
- Necessity is the mother of invention!
- The IFR was invented in a live-or-die situation.
- Key innovations are:
  - Metal fuel
  - Inherent safety
  - Economic pyroprocessing
  - Non-proliferarion
  - Waste management solution
- Details are described in “Plentiful Energy: The Story of the Integral Fast Reactor.”

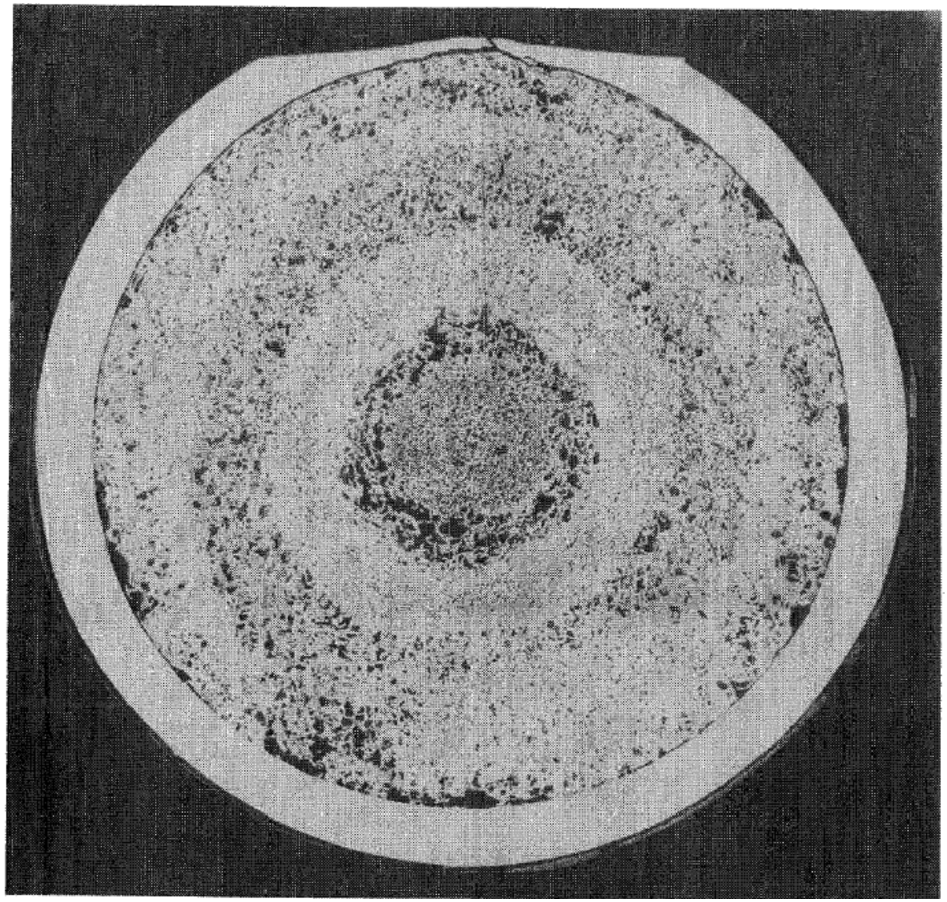


Metal Fuel Irradiation Performance

- Over 40,000 EBR-II Mark-II (75% smear density U-Fs) driver fuel pins have been successfully irradiated through early 1980's.
- When IFR Program was initiated in 1984, 10% Zr replaced 5% fissium, and a total of 16,800 U-Zr and 660 U-Pu-Zr fuel pins have been irradiated in the next 10 years. U-Pu-Zr fuel reached peak burnup of ~20% or 200,000 MWD/T.
- In addition, 7 full metal fuel assemblies have been irradiated in FFTF. Lead test achieved peak burnup of 16% or 160,000 MWD/T. One assembly contained U-Pu-Zr, which achieved peak burnup of 10% or 100,000 MWD/T.

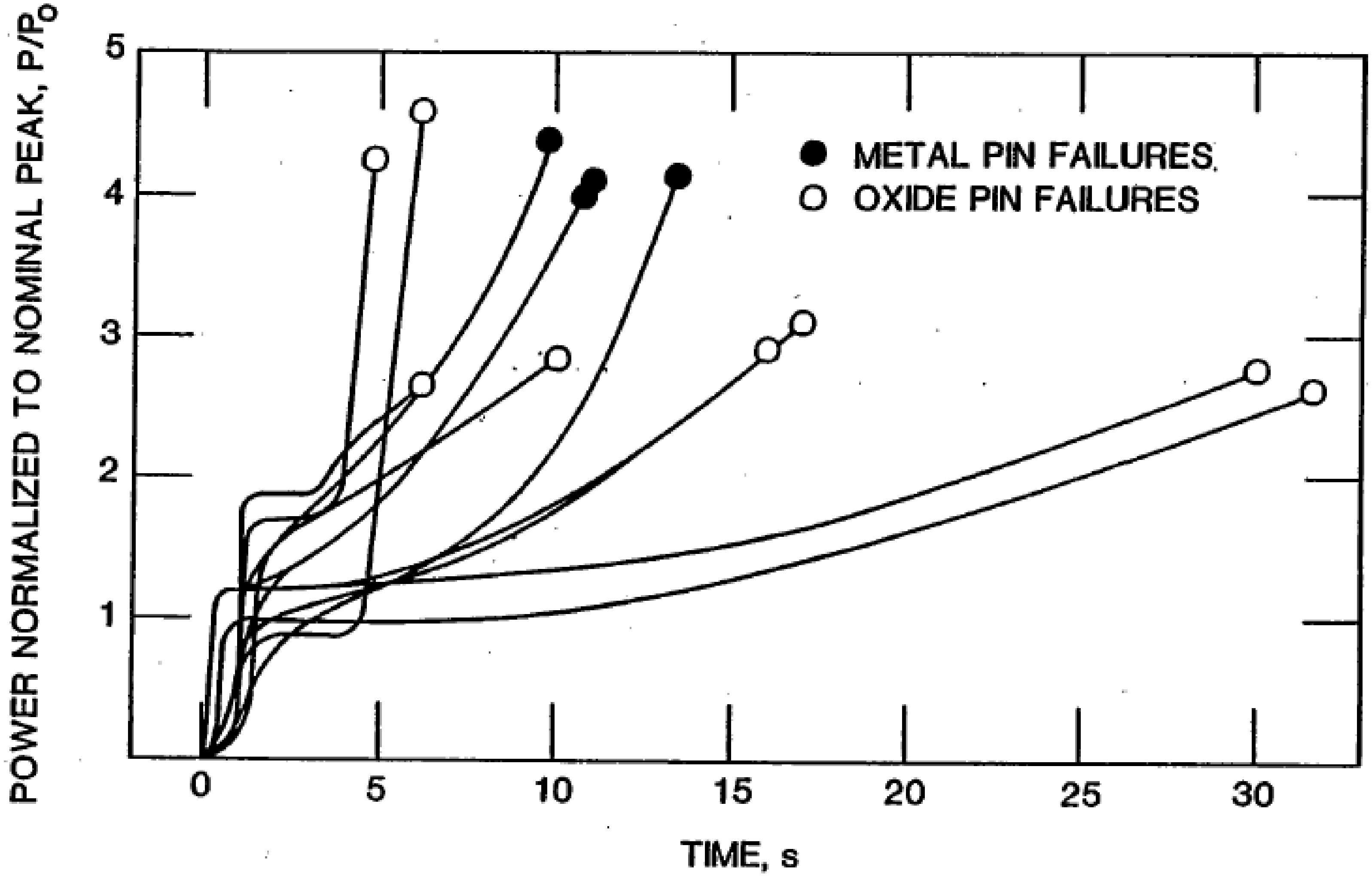
Run Beyond Cladding Breach Tests

9% burnup Oxide RBCB Test

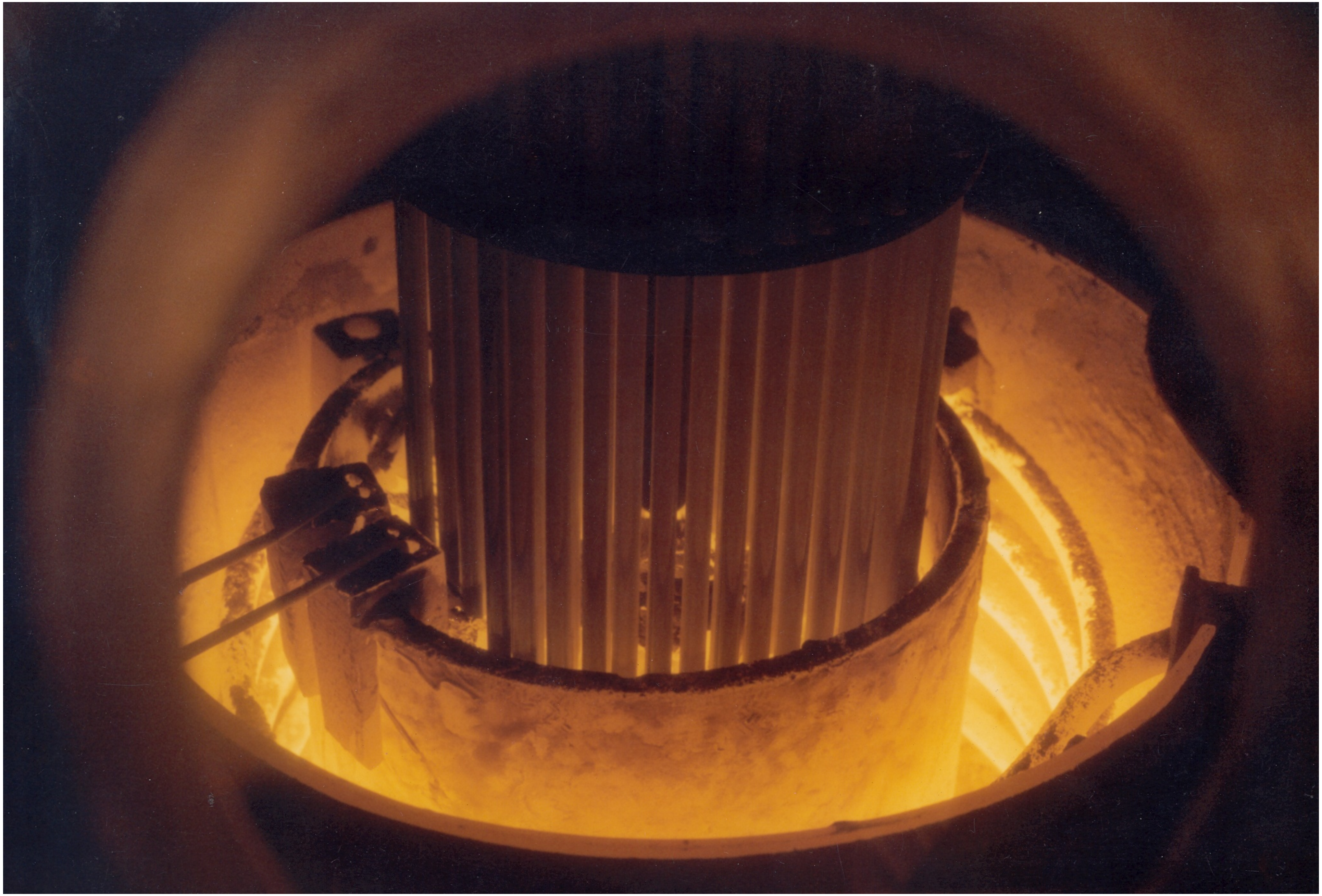


12% Burnup Metal RBCB Test
(Operated 169 days after breach)

Transient Overpower Failure Tests in TREAT

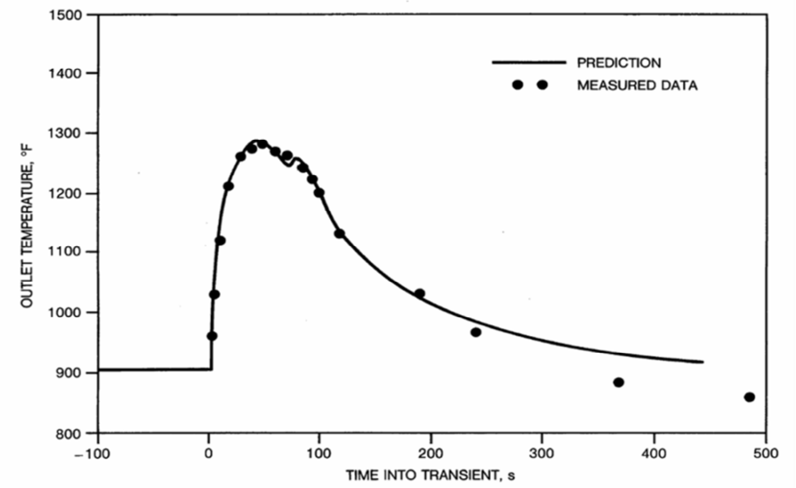


Very Simple Injection Casting Fabrication

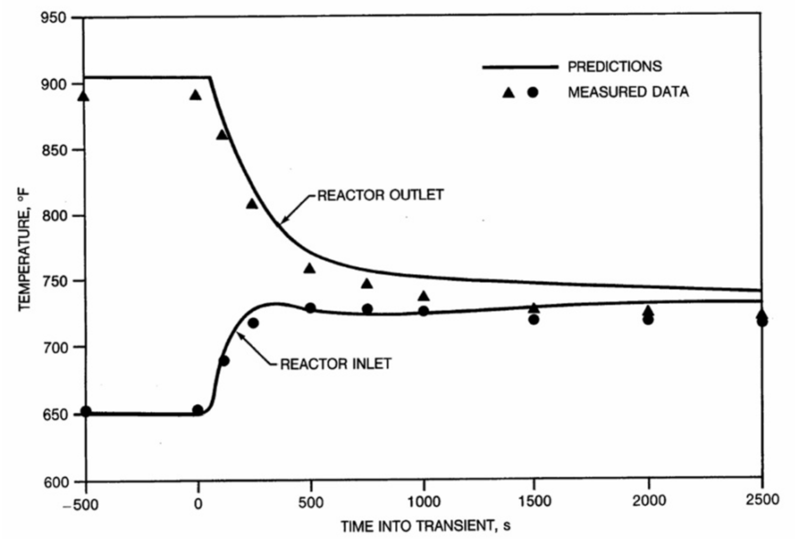


Inherent Safety Is Unique in IFR

- Inherent passive safety features were demonstrated in landmark tests conducted in April 1986 on EBR-II. The reactor shut itself down without operator actions nor safety systems for two most severe accident initiators:
  - Unprotected loss-of-flow at full power
  - Unprotected loss-of-heat-sink at full power



Unprotected Loss-of-flow Test

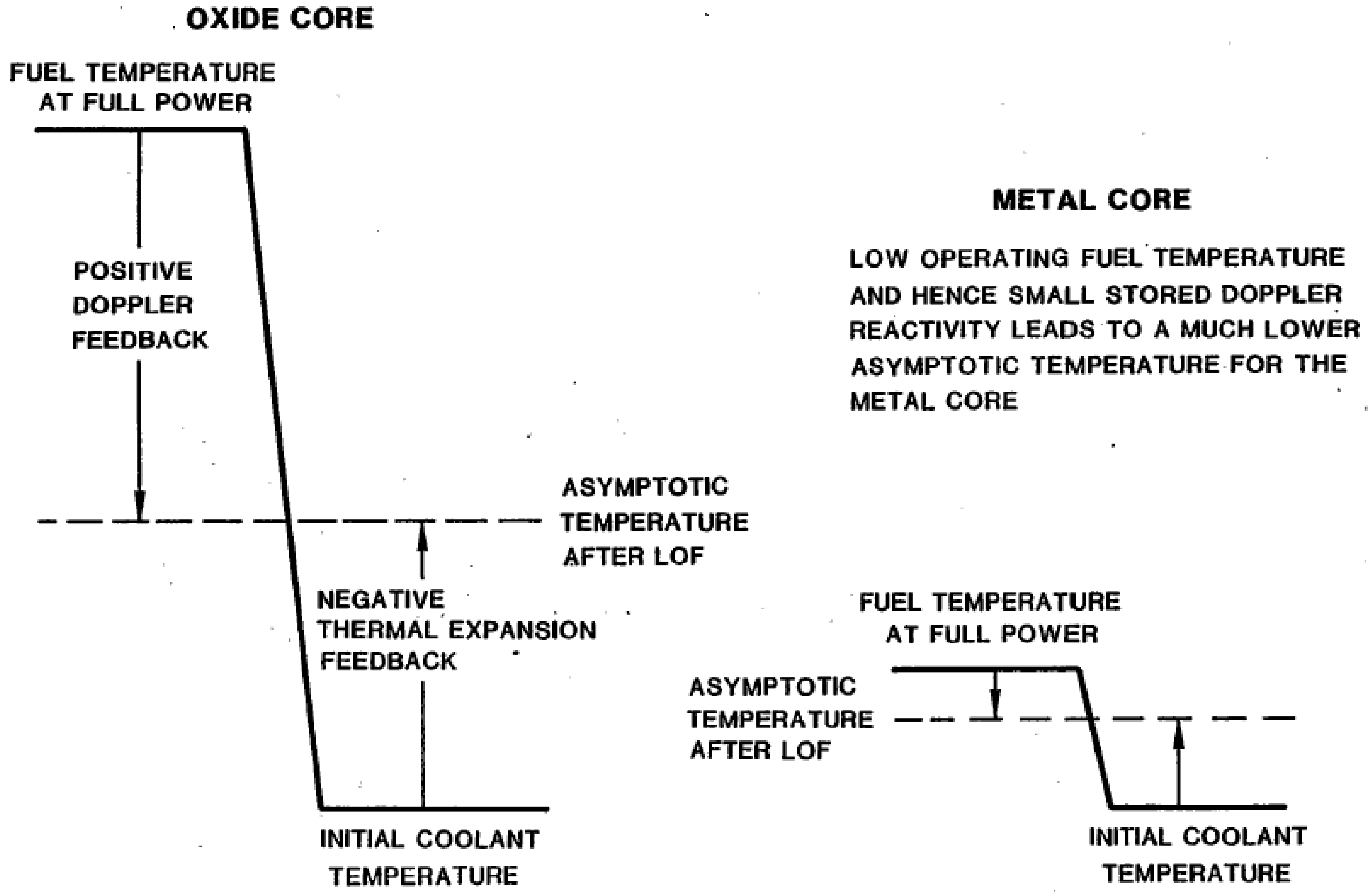


Unprotected Loss-of-heat-sink Test

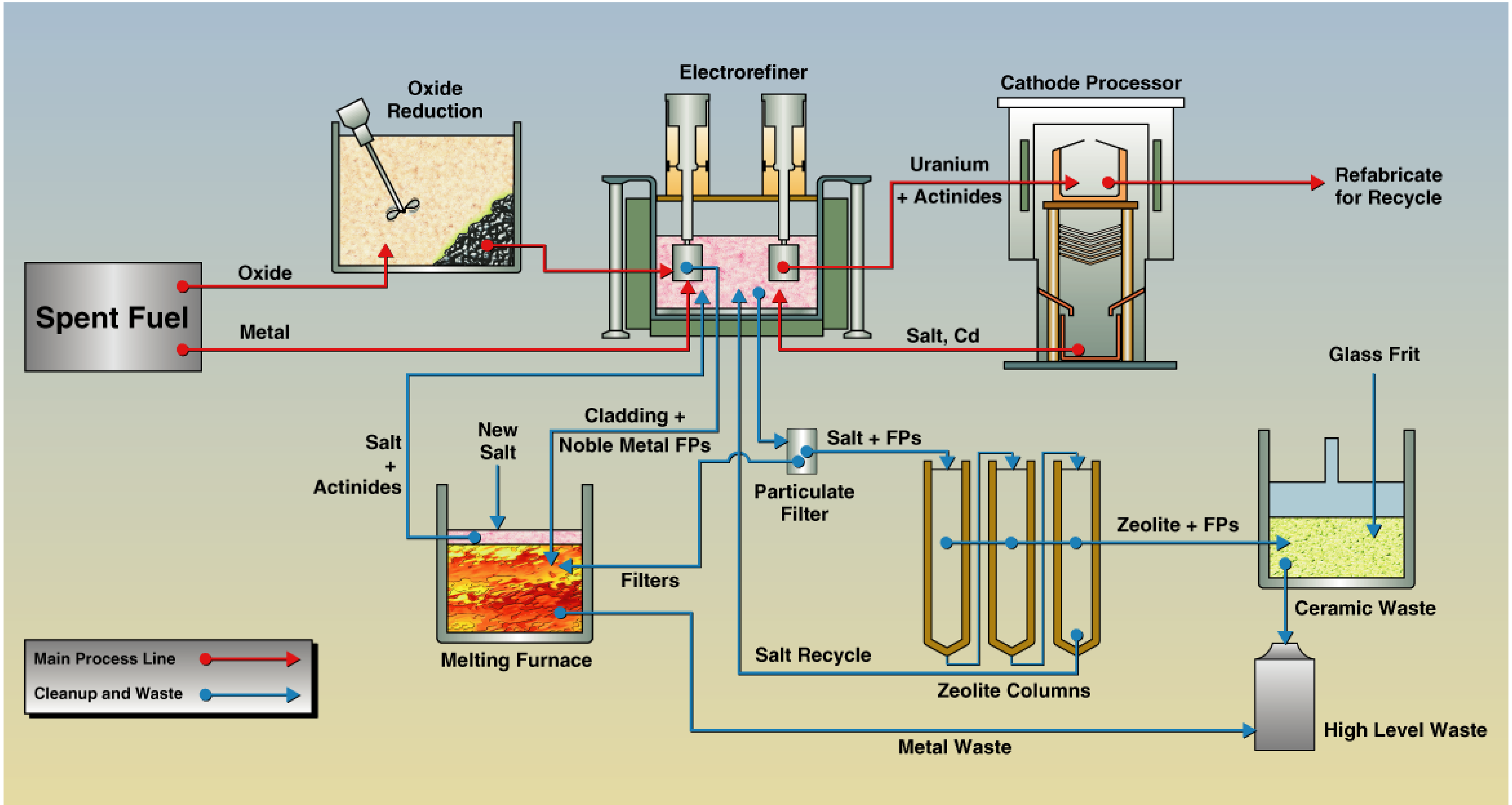
Key Contributors to Inherent Passive Safety

- 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 safety characteristics are unique to the IFR-type SFRs.

Schematic Comparison of Oxide and Metal Cores

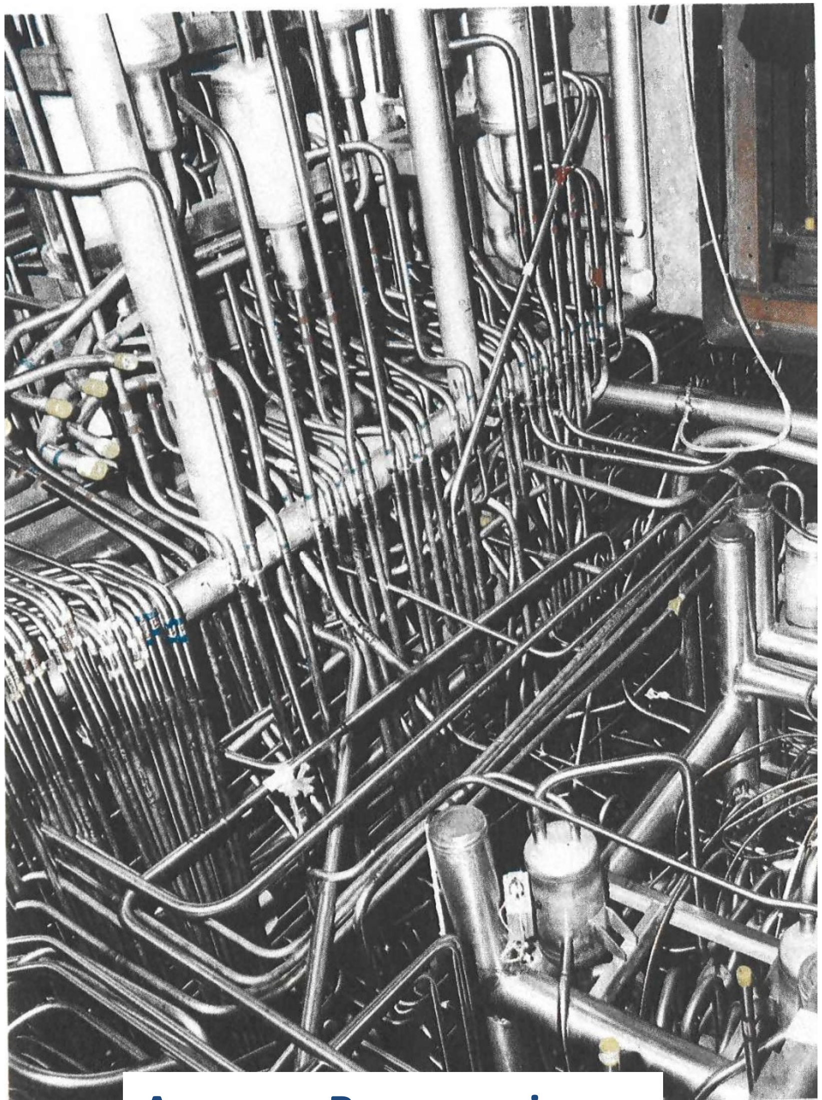


Pyroprocessing Flowsheet



Pyroprocessing provides economic fuel cycle closure and intrinsic proliferation resistance

Pyroprocessing



Aqueous Reprocessing

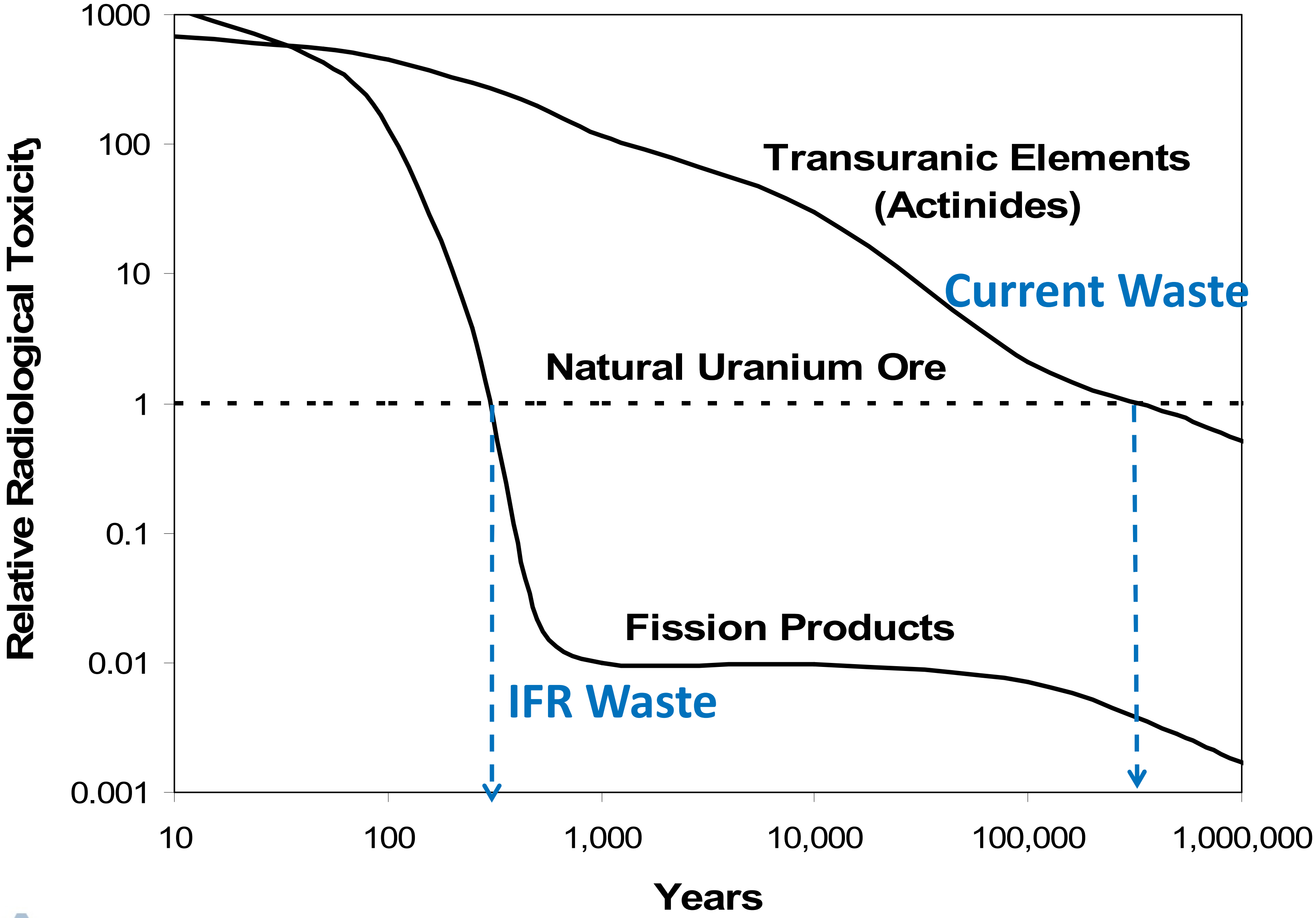
Capital Cost Comparison ($million)
Fuel Cycle Facility for 1400 MWe Fast Reactor

	Pyroprocessing	Aqueous Reprocessing
Size and Commodities		
Building Volume, ft^3	852,500	5,314,000
Volume of Process Cells, ft^3	41,260	424,300
High Density Concrete, cy	133	3,000
Normal Density Concrete, cy	7,970	35-40,000
Capital Cost, $million		
Facility and Construction	65.2	186.0
Equipment Systems	31.0	311.0
Contingencies	24.0	124.2
Total	120.2	621.2

Weapons Usability Comparison

	Weapon Grade Pu	Reactor Grade Pu	IFR Grade Actinide
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 rad r/hr at ½ m	0.2	0.2	200

Radiological Toxicity of LWR Spent Fuel



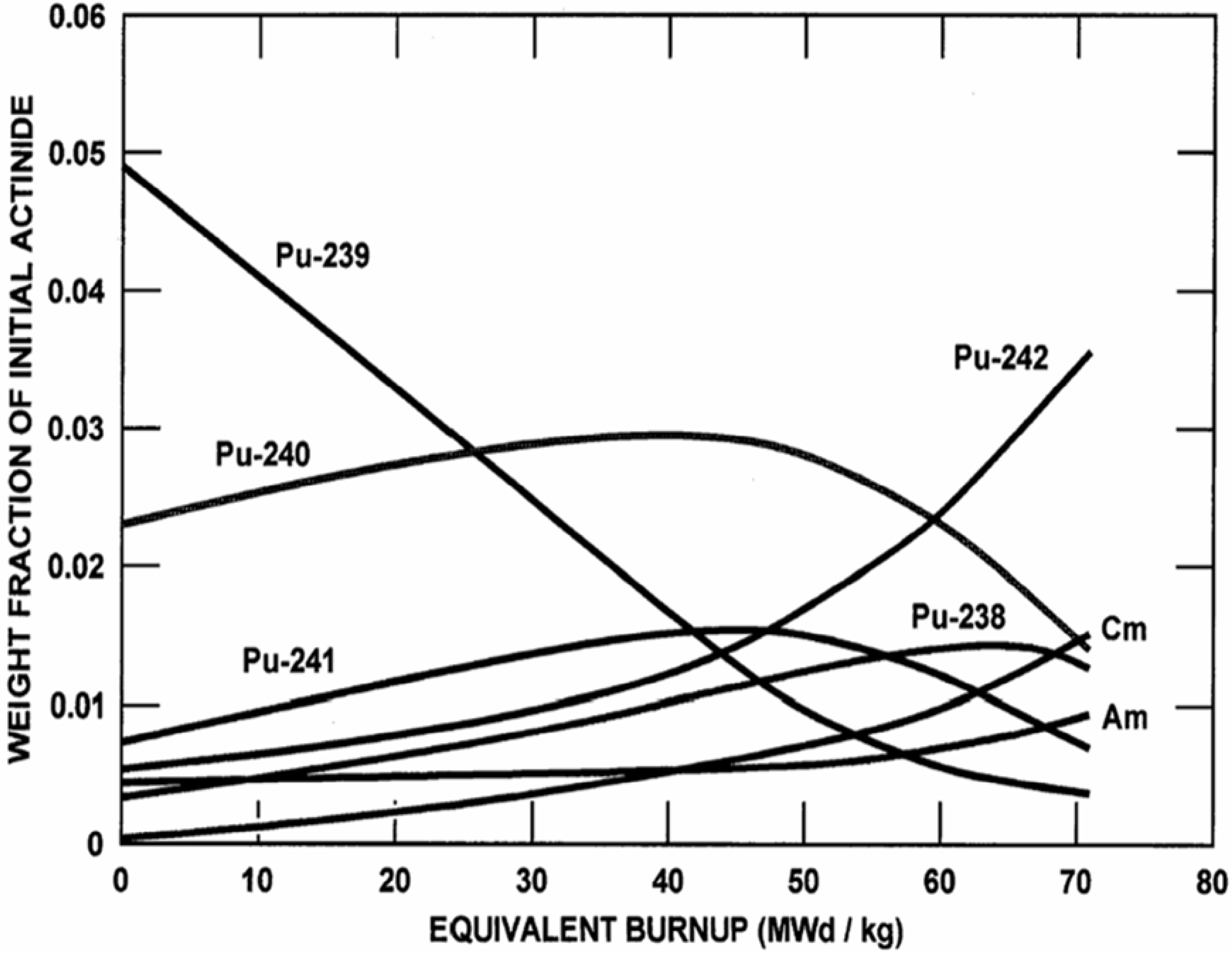
Actinide Burning

- Once actinides are removed from the waste streams disposed in the repository, the recovered products have to be burned (or transmuted) to achieve benefits of a shorter waste lifetime.
- LWR thermal spectrum is not effective in burning actinides.
- Only fast reactors can effectively burn actinides, at the same time generating energy.

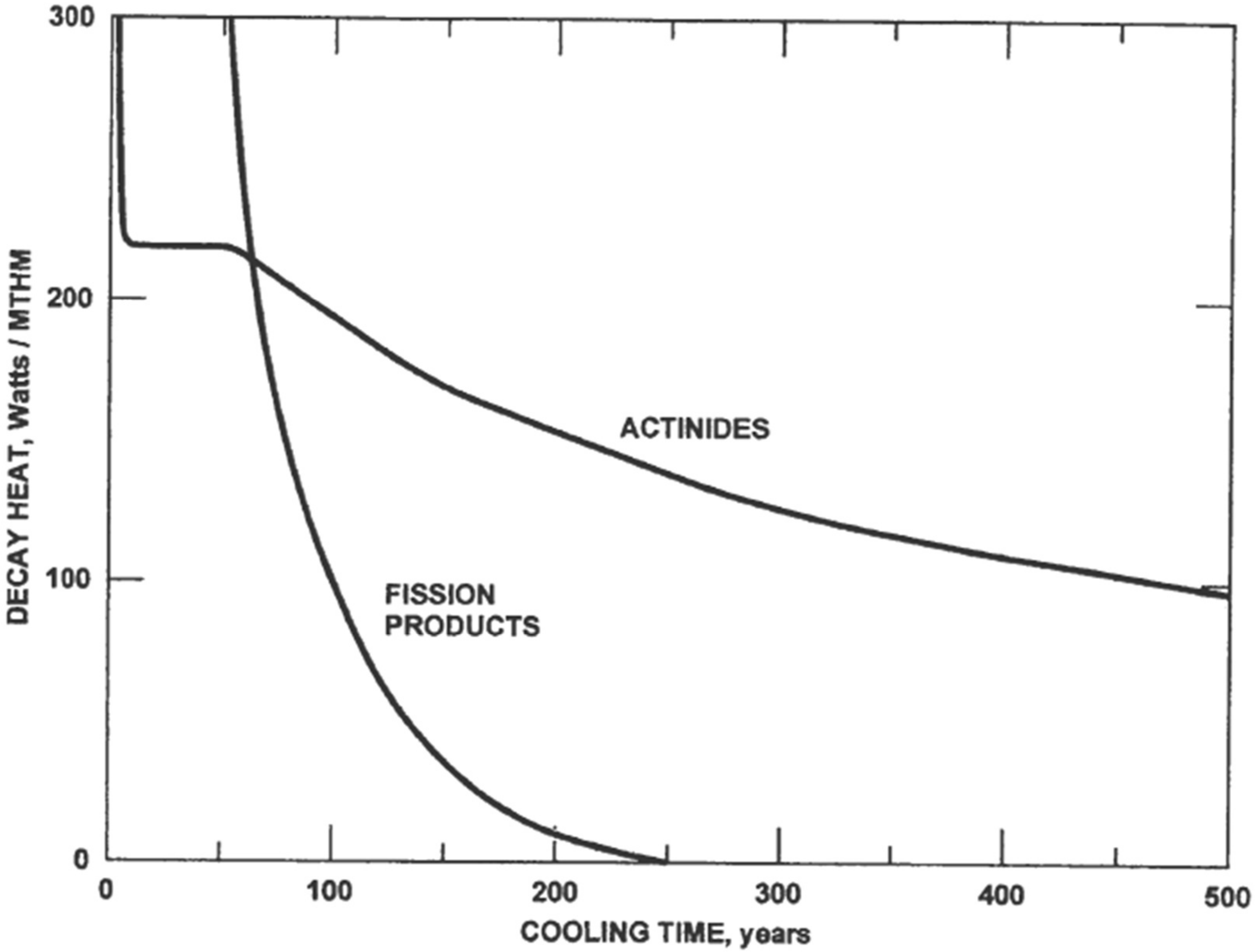
Transmutation Probabilities (in %)

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

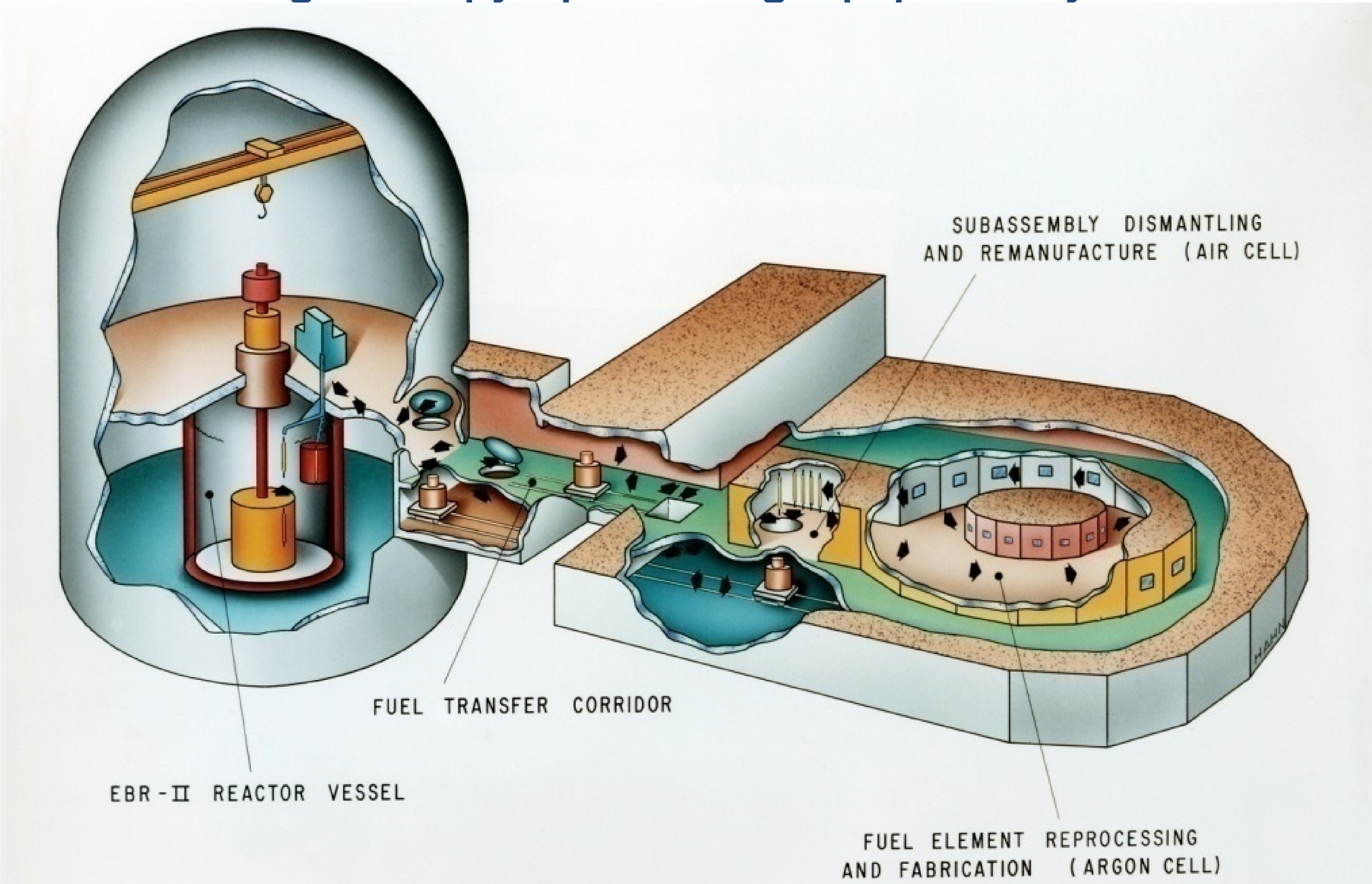
Evolution of Actinides in Thermal Spectrum (Pu recycle is typically limited to a single pass and cannot transmute minor actinides)



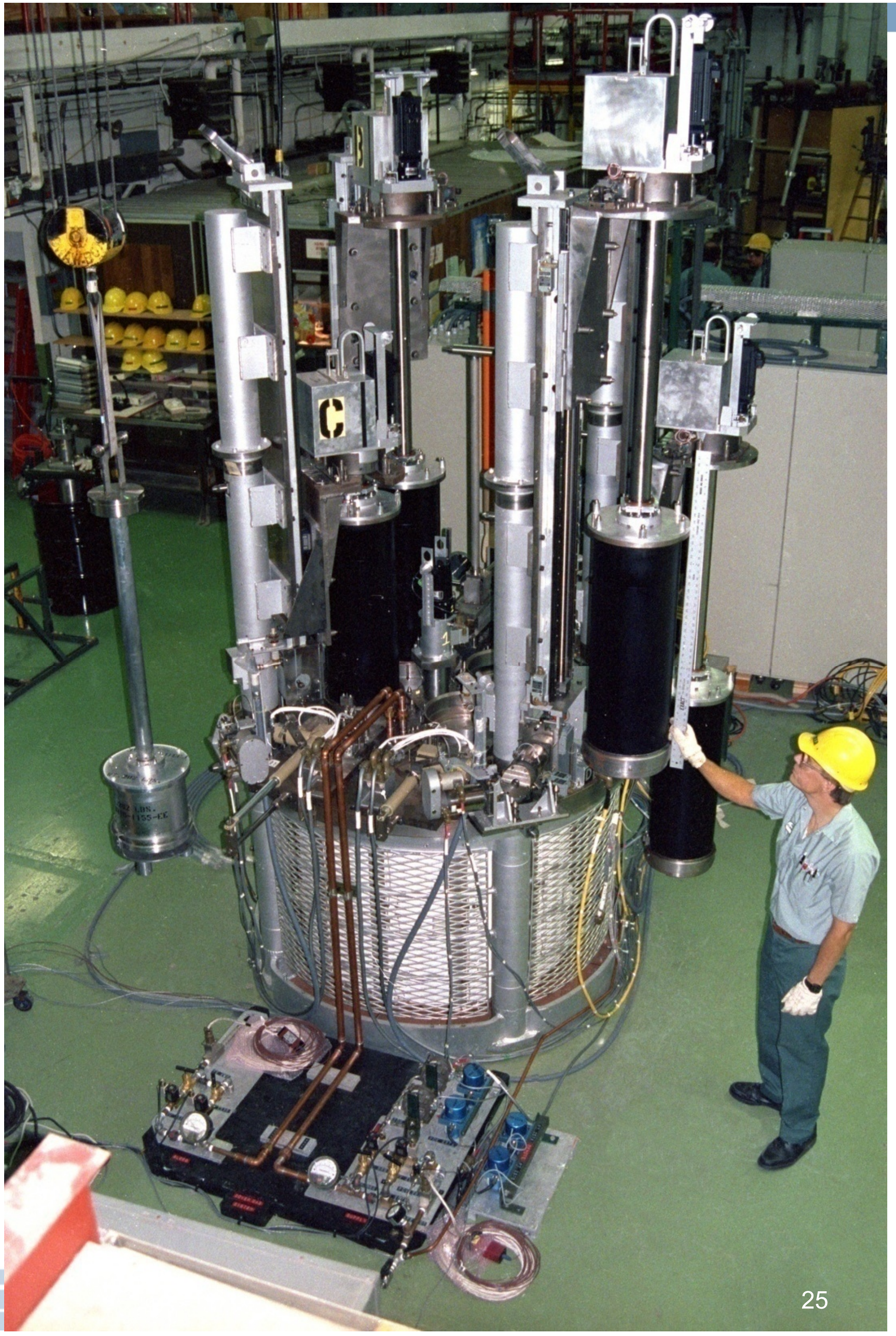
Spent Fuel Decay Heat as a Function of Time



The original EBR-II FCF was refurbished with electro-refining based pyroprocessing equipment systems



Electrorefiner



Joint Program on Pyroprocessing with Japan

- Drs. Hattori and Tokiwai, Central Research Institute of Electric Power industry (CRIEPI) visited ANL-W in July 1986 and arranged IFR Symposium at Keidanren Hall in January 1987.
- Joint Program with CRIEPI: $20 million cost sharing in July 1989.
- CRIEPI and Japan Atomic Power Company jointly representing Federation of Electric Power Companies (FEPC): Additional $20 million added in October 1992.
- Tokyo, Kansai, and Chubu Electric Power Companies: $6 million for LWR feasibility study signed in July 1992.
- PNC (predecessor of JAEA): $60 million cost sharing program agreed to in February 1994, but canceled by DOE.
- These joint programs ended when the IFR Program was terminated in October 1994.

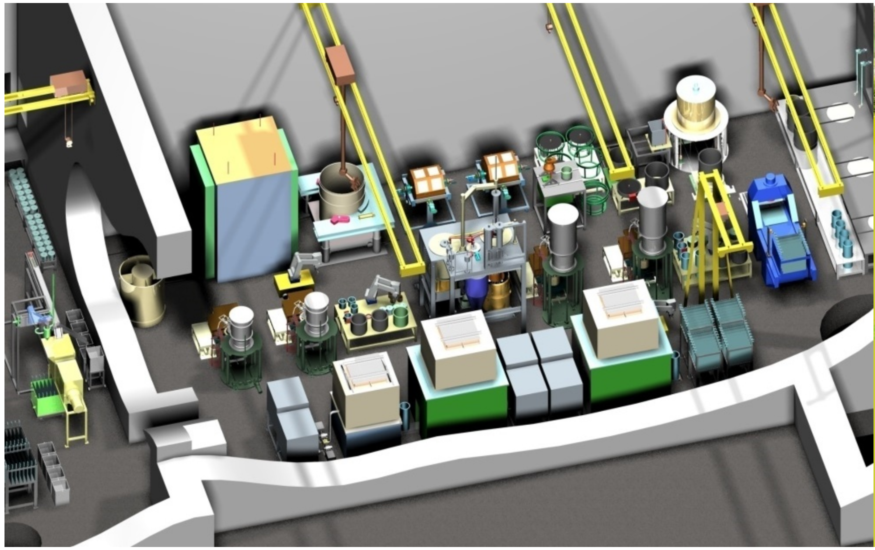
Signing Ceremony on July 7, 1989

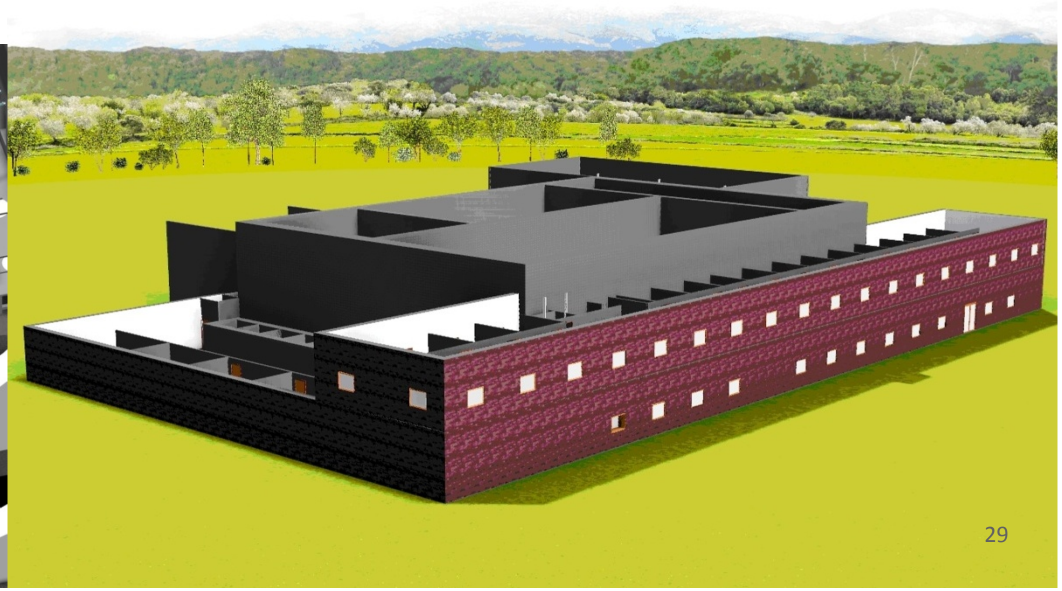
Pyroprocessing for LWR Spent Fuel

- Electrorefining has been demonstrated for fast reactor metal spent fuels.
- For LWR spent fuel application, oxide-to-metal reduction front-end step is required:
  - Electrolytic reduction process
- For economic viability, the electrorefining batch size and throughput rate has to be increased: this should be straightforward with planar electrode concept.
- A conceptual design for a 100 T/yr facility is currently being developed along with detailed flowsheet, equipment concepts and operational process models.

Pilot-scale (100 T/yr) Pyroprocessing Facility for LWR Spent Fuel

- Cooperative Research and Development Agreement (CRADA) is funded by Landmark Foundation to develop a conceptual design for the purpose of engineering details and capital and operating cost estimates.
- A 2-year effort through May 2015.
- If cost estimate is reasonable, a regional solution for spent fuel management can be envisioned.





Summary

- Near-term nuclear priorities should be placed on the current generation LWRs.
- IFR is a next-generation reactor concept:
  - Inexhaustible energy potential – essentially complete uranium utilization as compared to <1% in today's reactors.
  - Inherent passive safety – survives total station blackouts.
  - Economic and proliferation-resistant fuel cycle closure with pyroprocessing and simple fabrication.
  - Effective nuclear waste lifetime is reduced from ~300,000 years to ~300 years.
- Symbolic role for nuclear future!