Role of Decay Heat in Advanced Fuel Cycles

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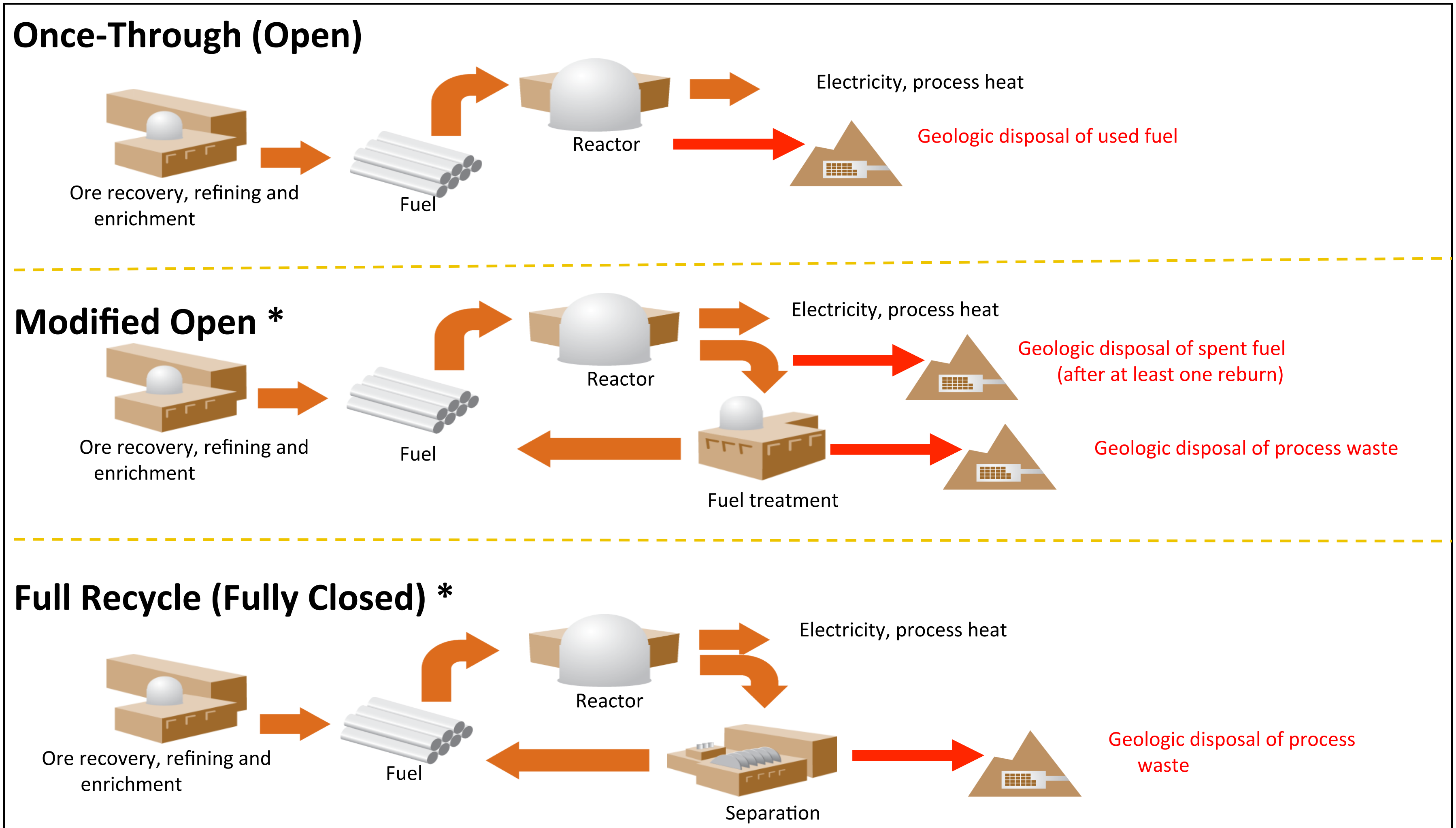
Outline

- Nuclear Fuel Cycle
  - Types of Nuclear Fuel Cycles
  - Performance Goals
  - Waste Management Issues

- Role of Decay Heat
  - Long-term: Design and Utilization of Disposal Space
  - Mid-term: Assurance of Adequate Cooling
  - Short-term: Reactor Safety Behavior

Potential Fuel Cycle Options

In the context of expanded nuclear generation, fuel cycle strategy becomes important!



*A specific fuel cycle strategy may include more than one fuel design, reactor design, or fuel treatment process.

Definitions of Three Fuel Cycle Categories

- **U.S. currently *utilizes* the <u>once-through fuel cycle</u> in its commercial nuclear power sector in which low enriched uranium (LEU) nuclear fuels are loaded into light-water reactors (LWRs) for purpose of power generation, and used nuclear fuel (UNF) removed following fuel utilization and stored prior to long-term disposal**
  - Plan is currently undefined; see Blue Ribbon Commission on America's Nuclear Future
- **Since advent of nuclear era, it has been anticipated that used fuel material could be processed and <u>fully recycled</u> with intent to better utilize nuclear fuel resources**
  - Recycling of nuclear fuel has been considered for managing nuclear waste within USDOE advanced nuclear fuel cycle program in last few years
- **A <u>modified open cycle</u> can be considered as a nuclear power approach in which fresh uranium, or thorium, or recovered fuel is used to generate power, and then is removed from the reactor with the back-end option of being stored in a repository or re-used at least once to generate additional power**
  - Modification or treatment of fuel between uses may be required
  - Used nuclear fuel is discarded at some point in the fuel cycle when further re-use is not desirable or possible

AFCI Program Objectives (from March 2005 Report to Congress)

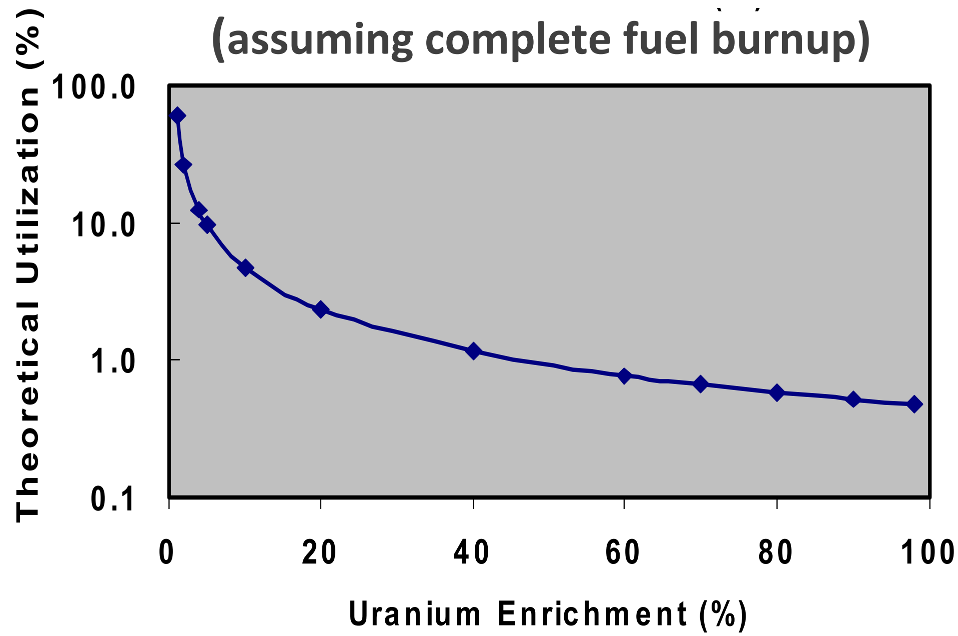
- **Reduce the long-term environment burden of nuclear energy through more efficient disposal of waste materials**
  - Remove transuranics (TRU) from waste
  - More efficient utilization of permanent disposal space
  - Significantly reduce released dose and radiotoxicity
- **Enhance energy security by extracting energy recoverable in spent fuel, avoiding uranium resource limitations**
  - Extend nuclear fuel supply
- **Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management**
  - Avoid disposal of weapons usable materials
  - Improve inherent barriers and safeguards
- **Continue competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system**

Resource Utilization

- **Natural uranium is significantly under-utilized by current and innovative advanced <u>once-through</u> nuclear systems**
  - LWR utilization less than 1%
  - Utilization in advanced once-through systems less than 2%

Theoretical Uranium Utilization

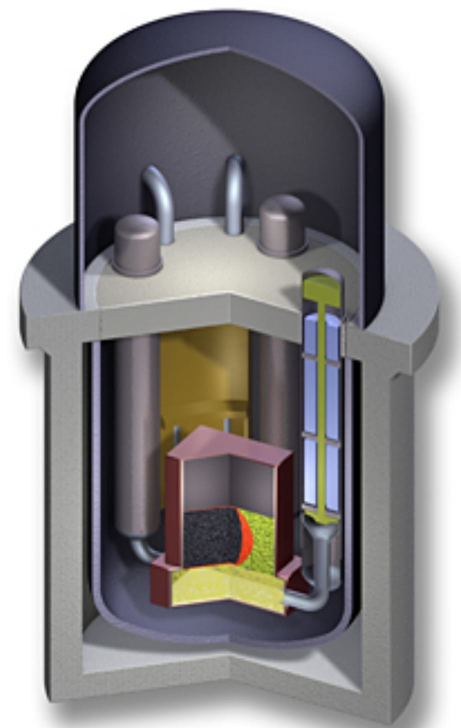
(assuming complete fuel burnup)



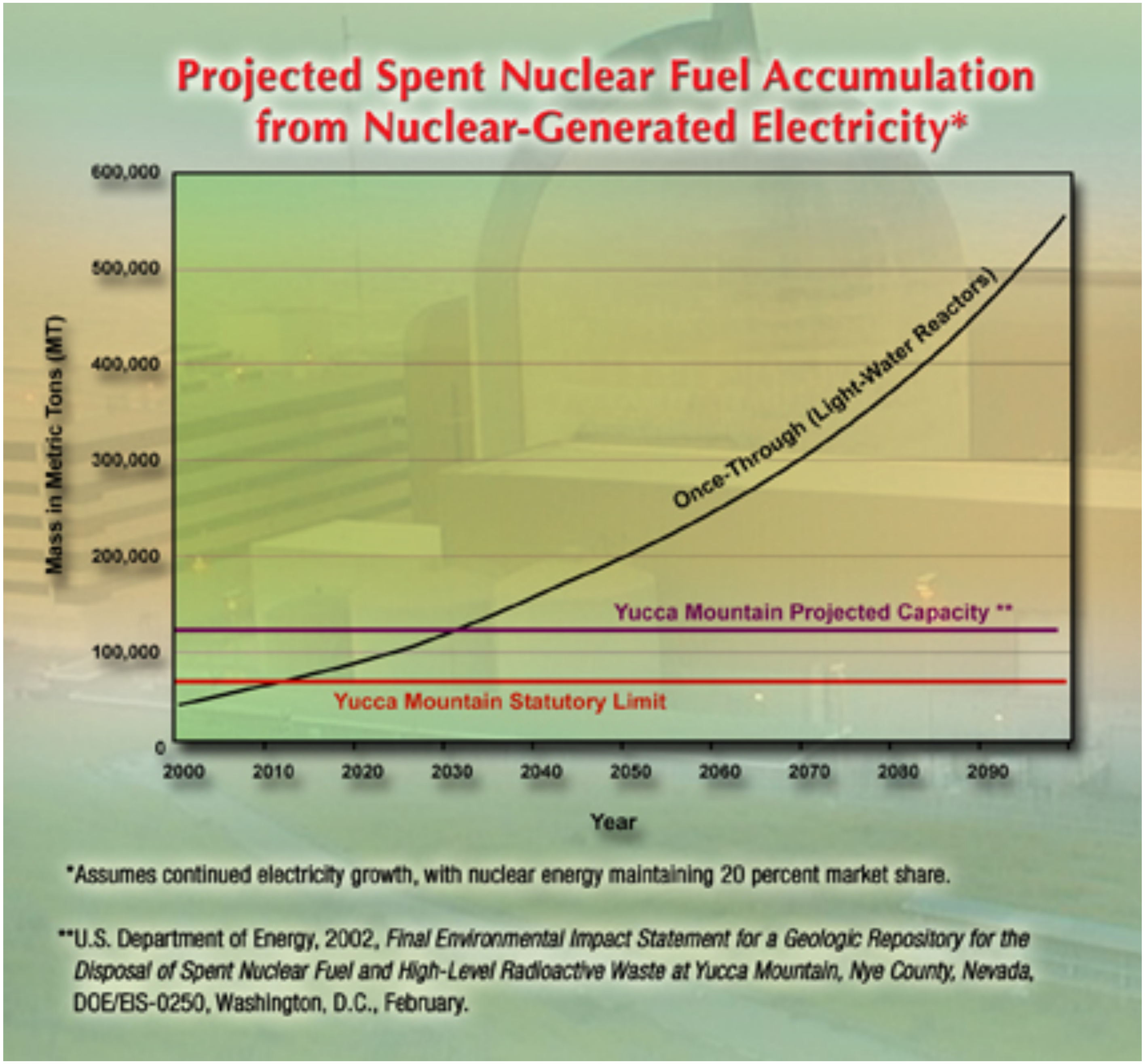
- **Any system that requires enriched uranium fuel will have low uranium utilization**
- **High uranium consumption is targeted**
  - 20-50% in modified open
  - >90% in full recycle
  - In both cases, requires consuming the depleted uranium tails

Fast Spectrum Breed and Burn Principles

- **Enriched U-235 (or Pu-239) starter core would be surrounded by a blanket of fertile fuel**
- **Enriched fuel would produce neutrons that generate power and convert fertile fuel to fissionable fuel**
- **Irradiated fertile fuel would replace enriched fuel after original U-235 (or Pu-239) is burned and new Pu-239 is formed**
- **Use of "Standard Breeders" exploit this physics in conjunction with reprocessing**
    - Complete U-238 conversion and fission, with the uranium utilization limited only by losses
- **Breed and Burn concepts promote conversion, but minimize reprocessing (modified open)**
    - Once fertile zone dominates, once-through uranium utilization at the fuel burnup limit



Travelling Wave Concept


Projected Spent Nuclear Fuel Accumulation from Nuclear-Generated Electricity*
Mass in Metric Tons (MT)
600,000
500,000
400,000
300,000
200,000
100,000
0
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year
Once-Through (Light-Water Reactors)
Yucca Mountain Projected Capacity **
Yucca Mountain Statutory Limit
*Assumes continued electricity growth, with nuclear energy maintaining 20 percent market share.
**U.S. Department of Energy, 2002, Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada, DOE/EIS-0250, Washington, D.C., February.

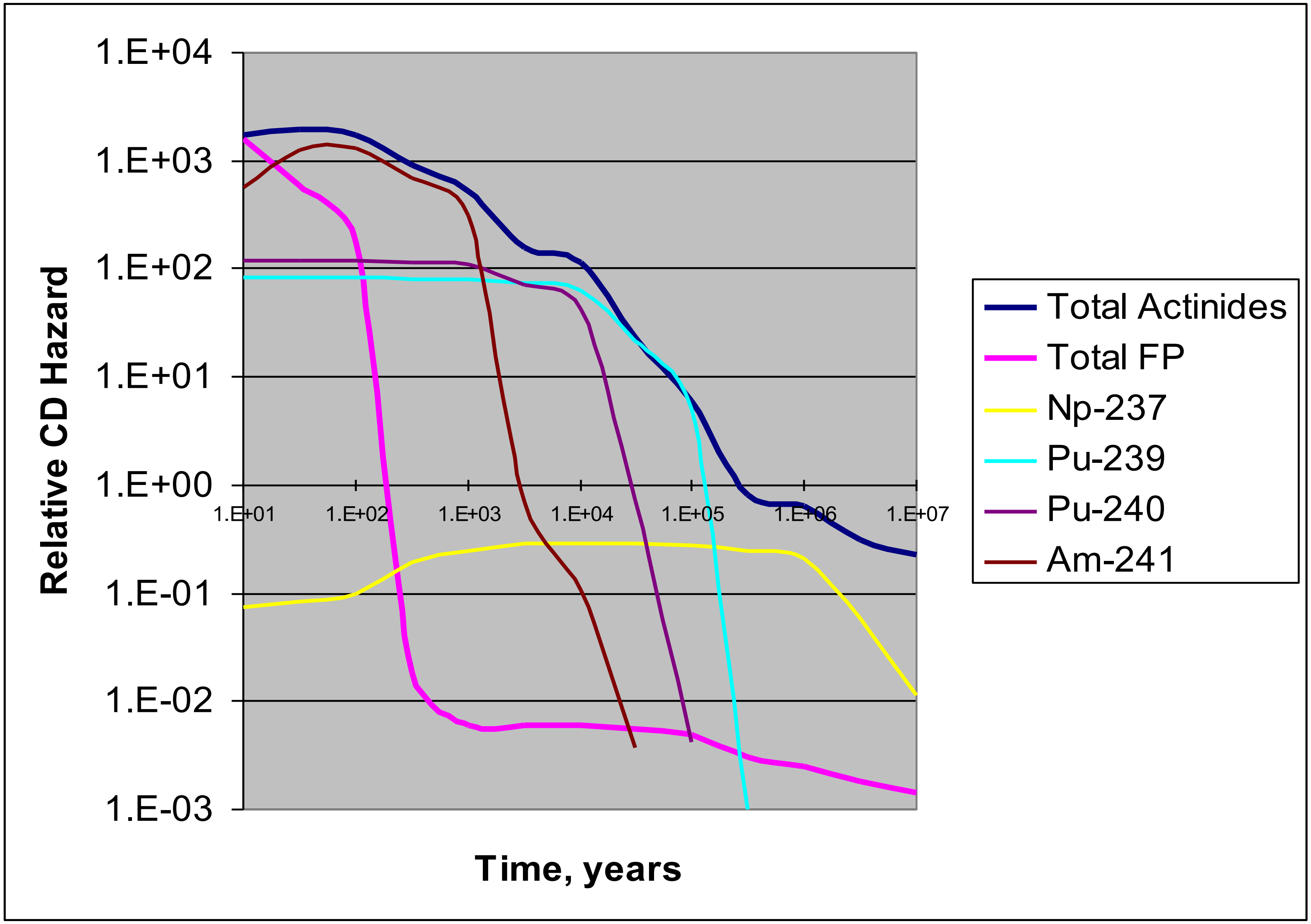
Waste Management Criteria and Benefits

- **Radiotoxicity quantifies the effect of exposure (hazard)**
  - Effectively assumes complete release and uptake

- **Repository environment will impact radiological risk**
  - ***Regulatory limit is based on released dose***
  - All material is contained for ~10,000 years
  - Plutonium moves slowly, fission products quickly
  - Maximum dose results from Np-237 in long-term

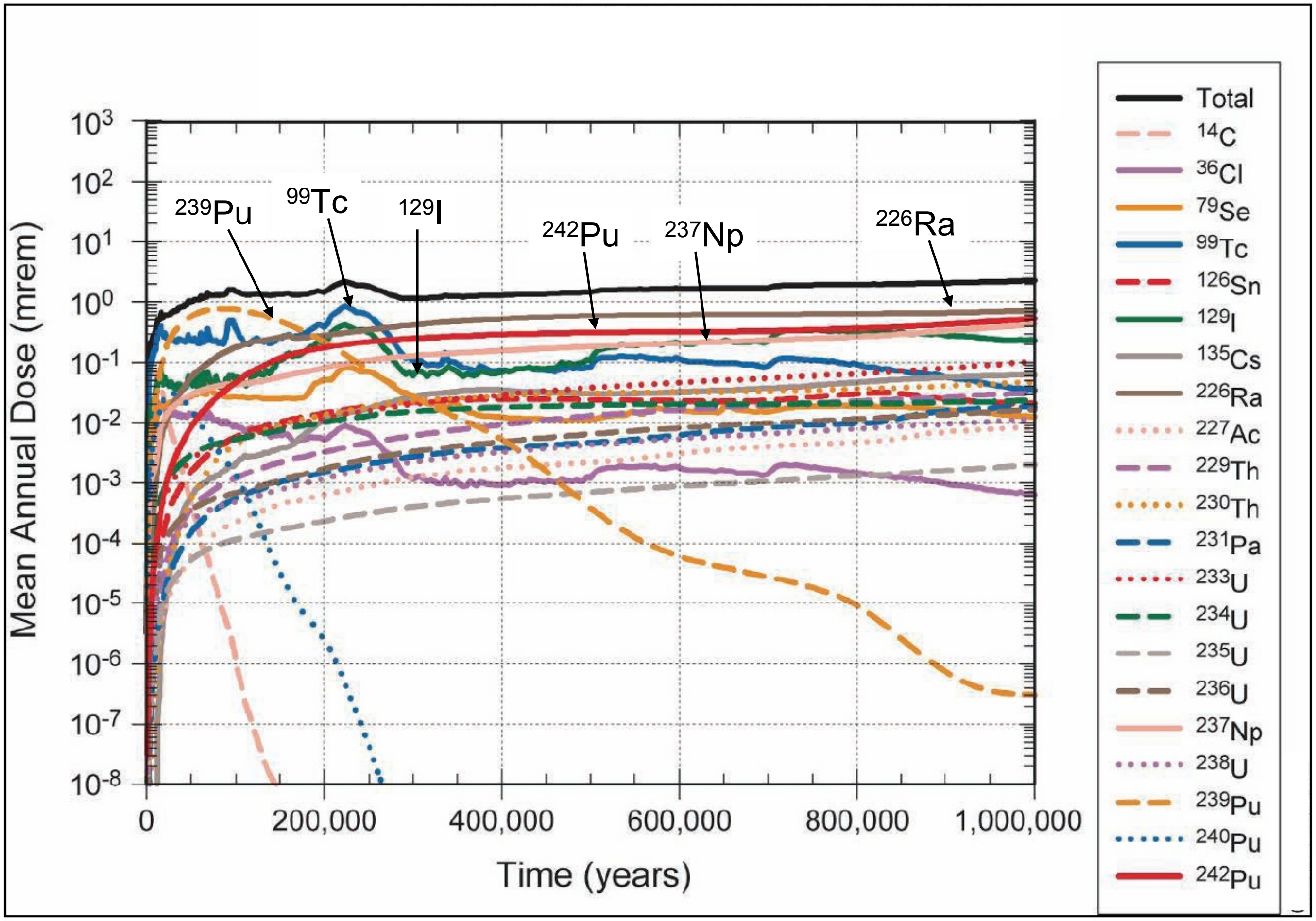
- **Repository design is typically constrained by thermal limits (heat load)**
  - For Yucca Mountain license application based on high-temperature operating mode (HTOM) of the cold repository, criteria were:
    - peak temperature below the local boiling point (96 ºC) at all times midway between adjacent drifts
    - peak temperature of the drift wall below 200 ºC at all time

Radiotoxicity of LWR Spent Fuel

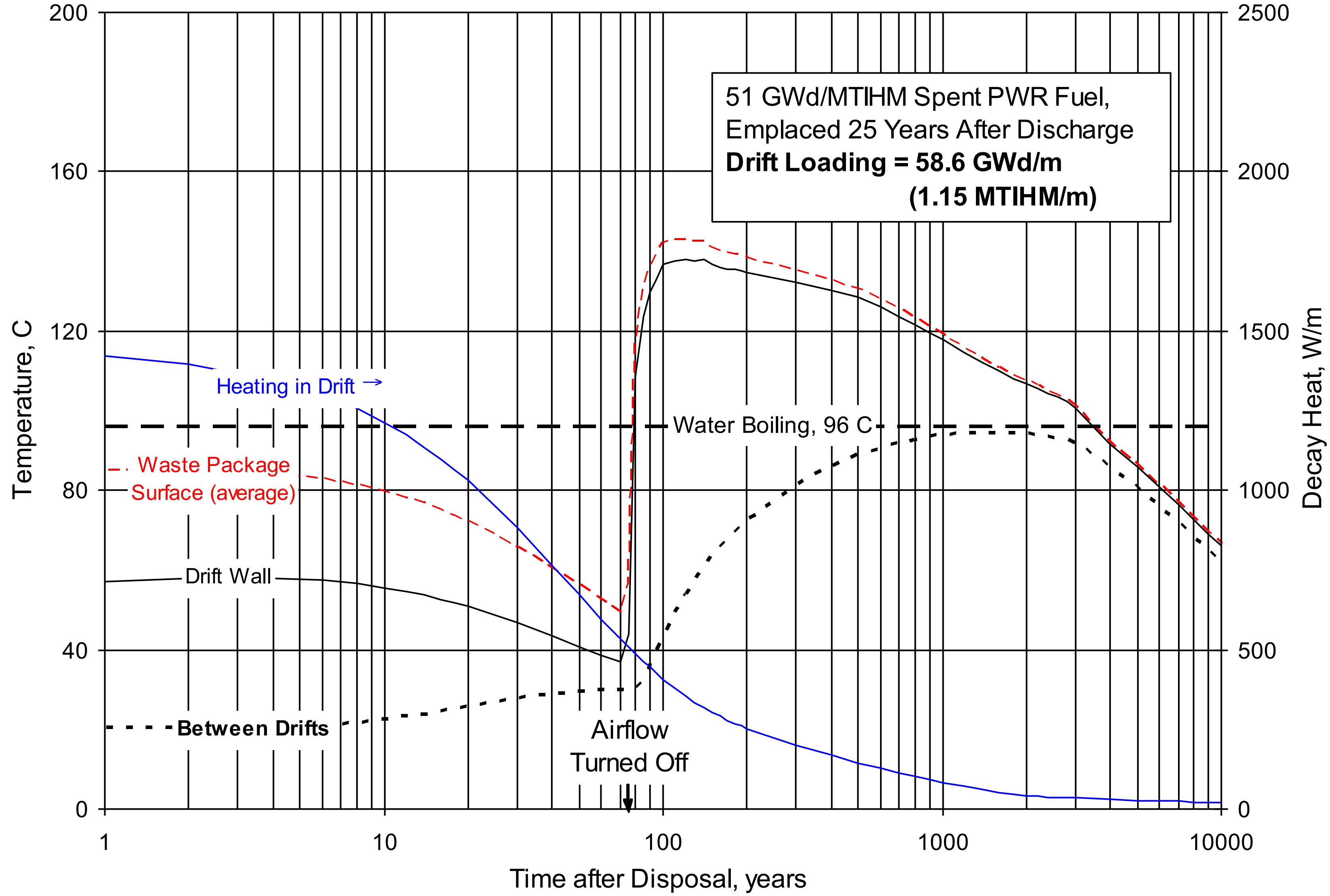


Repository Released Dose (YM Example)

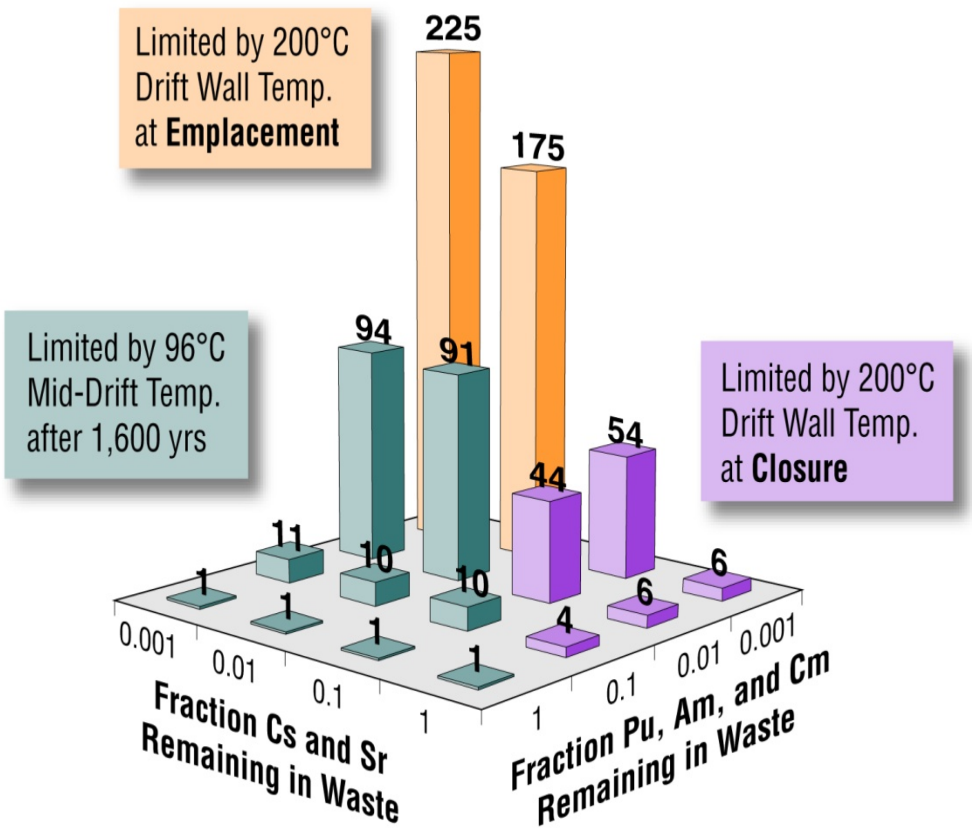
- **Radiotoxicity alone does not provide any indication of how a geologic repository may perform**
  - Different species are more mobile, depending on environment and barriers



Repository Thermal Response (YM Example)



Potential for Repository Drift Loading Increase

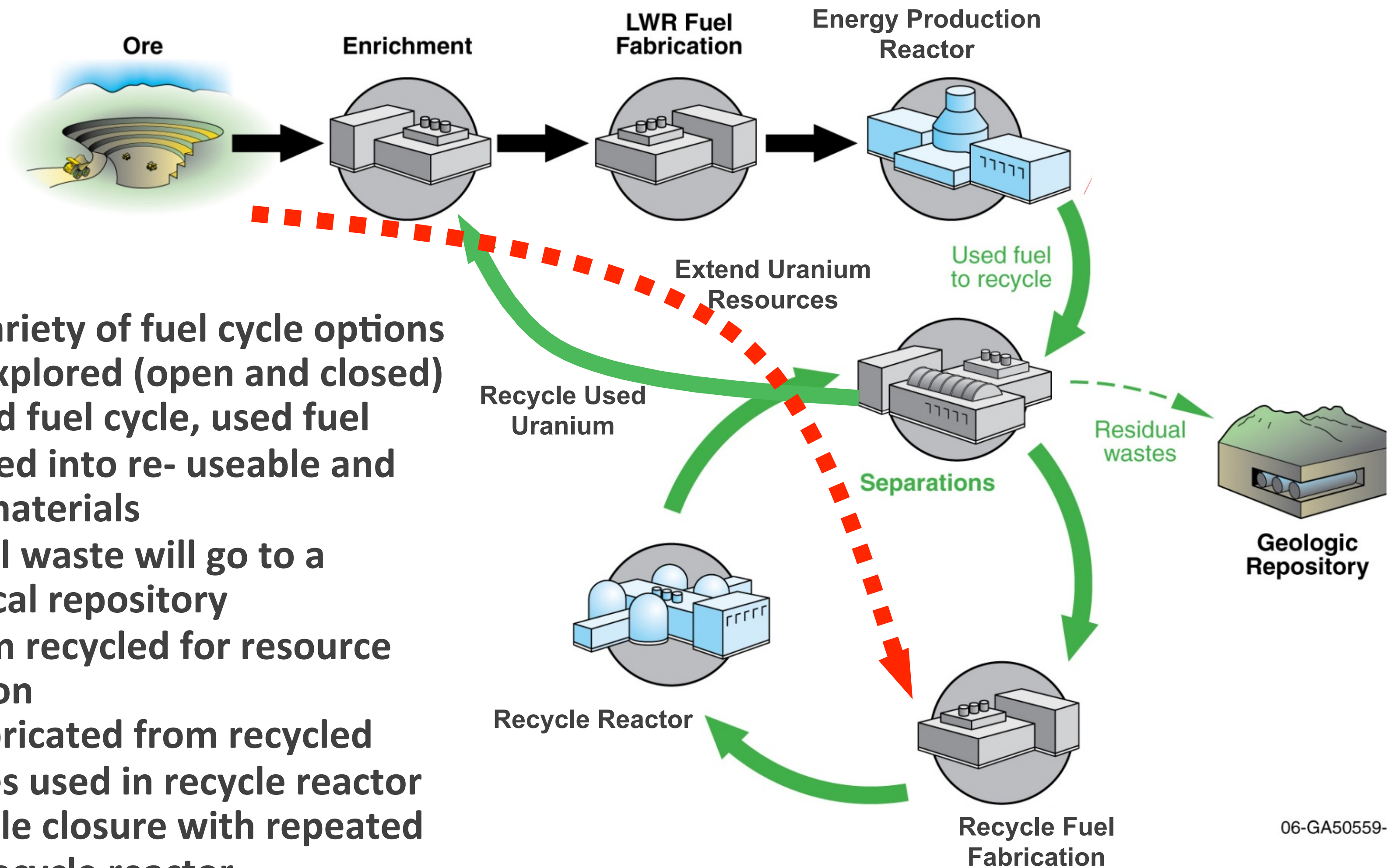


- **Separation of Pu & Am allow for denser loading of the repository**
  - up to a factor of 6 with 99.9% removal
- **Subsequent separation of Cs & Sr provides for much greater benefit**
  - up to a factor of 50 with 99.9% removal
- **Removal of Cm further increases the potential benefit (with Pu & Am)**
  - greater than a factor of 100 with 99.9% removal
- **Appropriate waste forms are needed to take advantage of this potential**

Transmutation Approach for Improved Waste Management

- **Long-term heat, radiotoxicity, and dose are all dominated by the Pu-241 to Am-241 to Np-237 decay chain**
- **Destruction of the transuranics (TRU) is targeted to eliminate the problematic isotopes**
- **Some form of separations is necessary to extract transuranic elements for consumption elsewhere**
- **The transuranic (TRU) inventory is reduced by fission**
  - Commonly referred to as 'actinide burning'
  - Transmutation by neutron irradiation
  - Additional fission products are produced
- **In the interim, the TRU inventory is contained in the fuel cycle**

Fuel Cycle R&D is considering fuel cycle options (e.g., closed fuel cycle with actinide management)



- Wide variety of fuel cycle options being explored (open and closed)
- In closed fuel cycle, used fuel separated into re- useable and waste materials
- Residual waste will go to a geological repository
- Uranium recycled for resource extension
- Fuel fabricated from recycled actinides used in recycle reactor
- Fuel cycle closure with repeated use in recycle reactor

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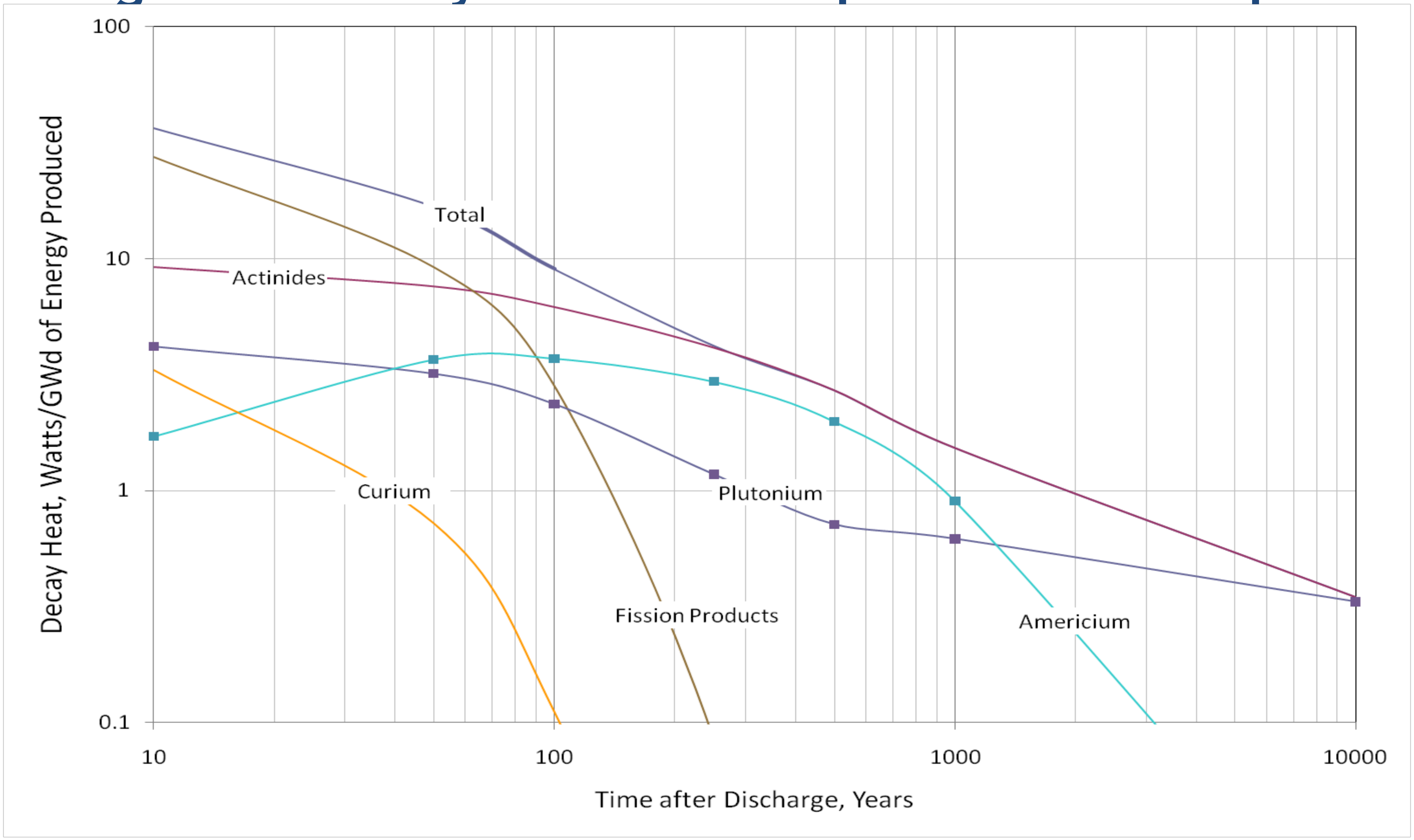
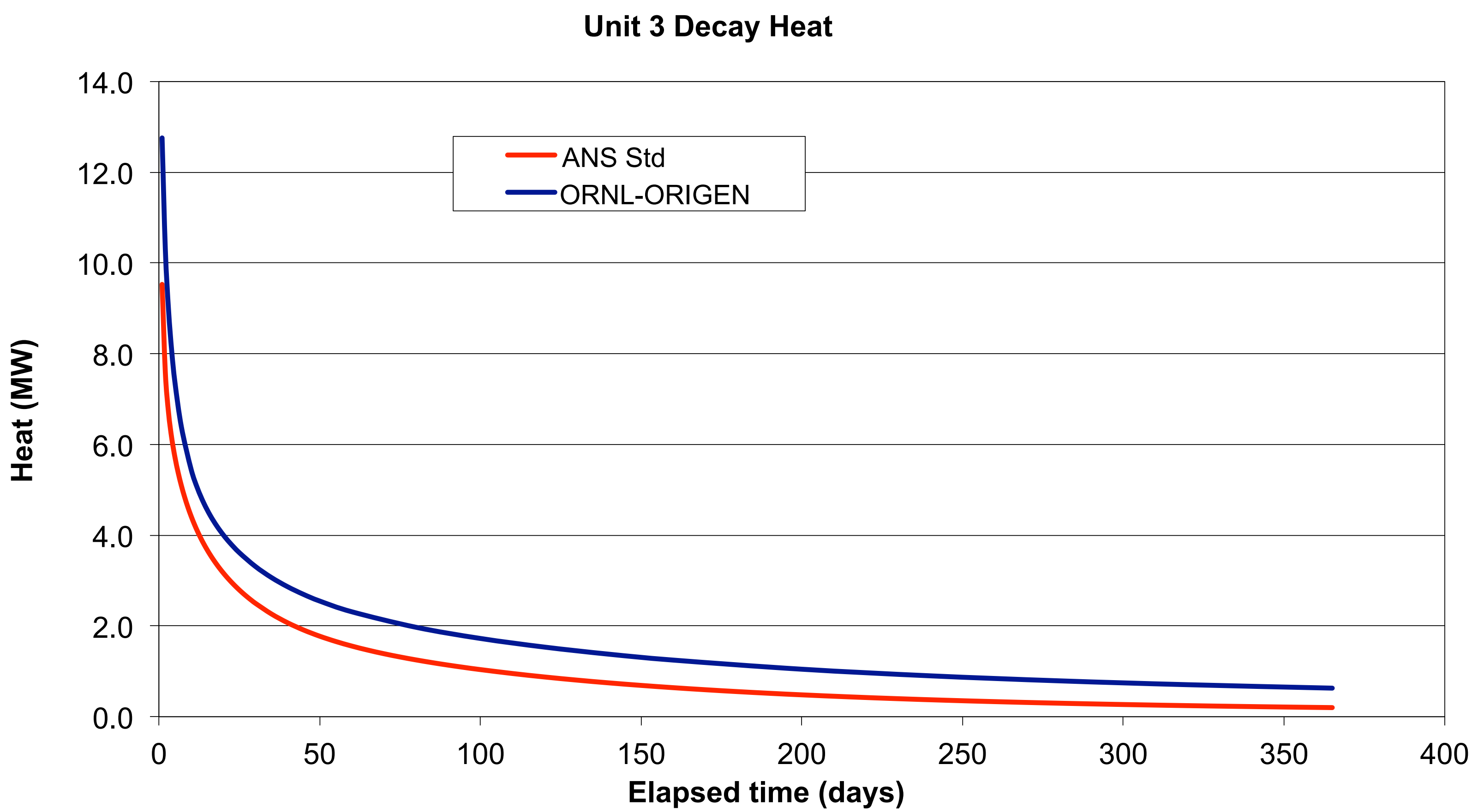
Long-Term Decay Heat – LWR Spent Fuel Example



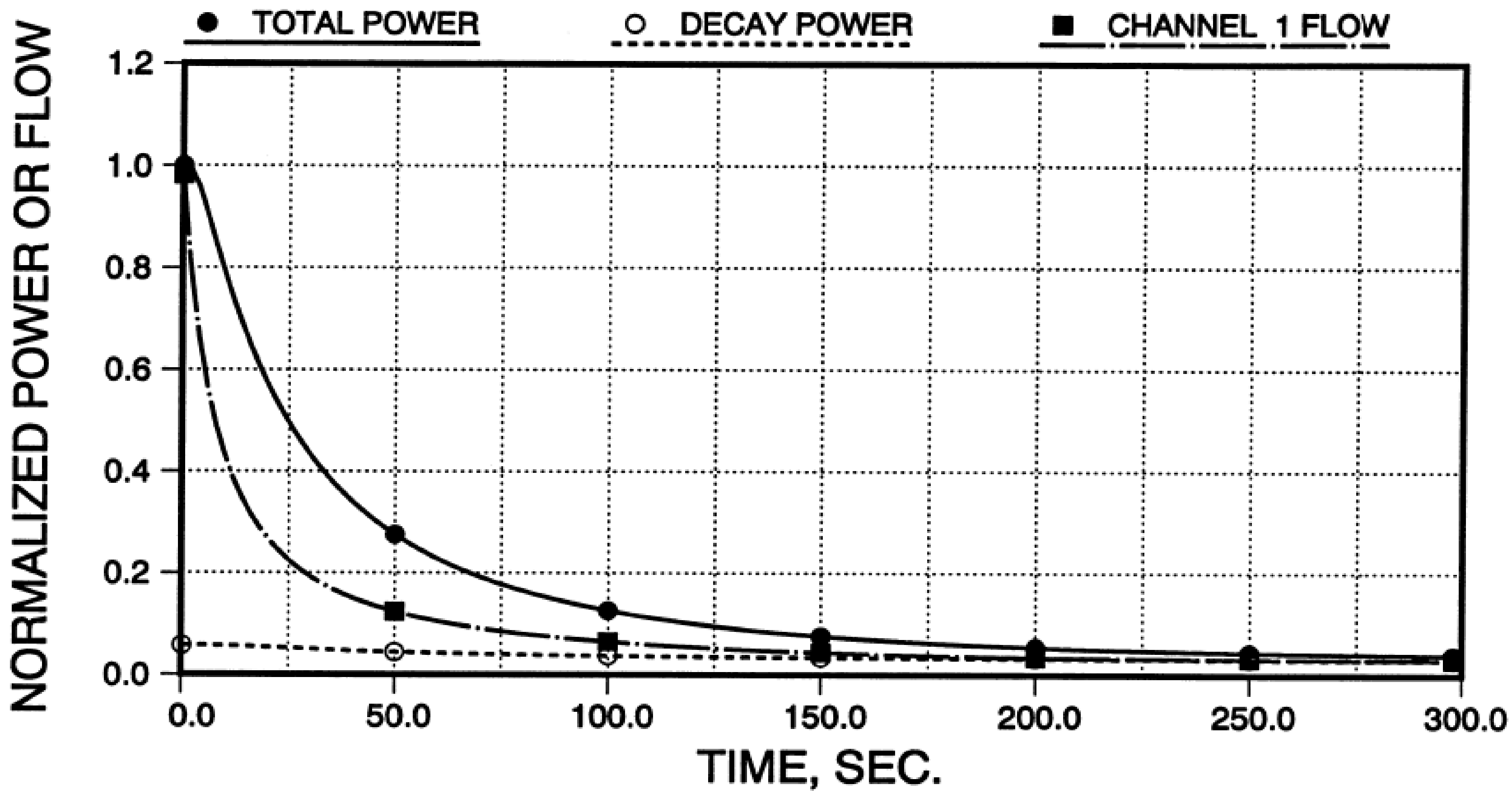
- **Actinides dominate the decay heat ~60 years after discharge**
  - Fission products important for decades – spent fuel storage
  - Actinides important for final disposal – as shown for repository space utilization

Mid-Term Decay Heat - Fukushima Example



- **Adequate cooling must be provided for decay heat removal**
  - Can be problematic for extended loss of power
- **Standard correlations show differences in decay power**

Short-Term Decay Heat - Reactor Transient Example



- **In modern designs, passive features introduced to remove decay power**
  - Loss of decay heat power fraction in standard operation
- **In transient conditions, both fission multiplication and decay power important**

Other Important Applications for Improved Fission Product Decay Data

- Transient behavior is also driven by delayed neutrons
  - Both magnitude and timing are important for reactor control

- Fission decay signatures may be useful for material detection
  - Unique gammas or other decay particles
  - Allow quick scanning for fissionable material content

- Isotopic production (e.g., medical applications) often require very short irradiation and recovery times
  - Short-term decay heat can dictate handling and target requirements