Utilization of Accelerators for Transmutation and Energy Production

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Outline

- **Case for an increase in the use of nuclear power and the main concerns**
- Used fuel management – a major impediment to increasing nuclear power usage
- Path to increasing the public acceptance of used nuclear fuel – solving the americium problem
- Accelerator driven systems
- Thorium reactor

Nuclear Power Is The Best Present Choice For Emission-Free Power

- **A 1 GW electric nuclear power plant without recycling used nuclear fuel produces 20 tons, mostly U-238, (~2m^3) of used fuel per year with no significant airborne emissions.**
- **For comparison, a 1 GW electric coal-fired plant burns 3,400,000 tons of coal per year and produces:**
  - copious quantities of emissions (some are now scrubbed*, scrubbed plants tend to use "dirtier" and has more Hg):
    - CO_2 (7,400,000 tons)
    - SO_2, NO_x (20,000 tons each)*
    - Hg vapor (250 lbs)
    - Radon
  - 340,000 tons of solid waste:
    - 27 tons of radioactive material, mostly U-238 and Th-232
    - toxic compounds of arsenic, copper, barium, cadmium, chromium, lead, mercury, nickel, and thallium
- **Nuclear power in the U.S. has the highest operating availability, > 90%, of all the present electric power sources.**
  - For comparison, geothermal is 75%, coal with 73%, wind is 27%, and solar is 19%.
  - Availability determines the base grid support required, either through stored power or alternative power sources, to make up for times of low production.

The Perceived Risk of Nuclear Plants, Including the Three Mile Island (TMI-2) Accident, is Usually Greatly Overestimated

Occupation	mrem/yr
DOE and site workers (radiological work activities)	44
Medical personnel (patient diagnosis/treatment)	70
Grand Central Station, NY workers (building materials)	120
Nuclear power plant workers (radiological work activities)	700
Airline flight crew members (cosmic radiation)	1000

Background	
Living within 50 mi of nuclear plant (due to plant emissions)	0.009
Living within 50 mi of a typical coal plant (mostly radon)	0.03
Radioactive emission of the NM 4-Corners coal plant (mostly radon)	1-4
Average US background (natural:255, internal:40, manmade: 66)	361
Grand Central Station (mostly radon)	600
Northeast/Northwest Washington State (diff. due mostly to radon)	1700/240
Kerala and Madras States in India, 140K people (½ thorium, ½ radon)	500-2700

Maximum calculated possible total exposure to public due to TMI-2 100 mrem

Nuclear Power Addresses Key U.S. National Security Issues

- In the United States, the 104 operating nuclear reactors:
  - Currently produce about 20% of the U.S.'s electricity.
  - Provides greater than 70% of U.S.'s emission-free electricity.
- The fuel for nuclear reactors is sufficient for at least the next 100 years.
- The fuel comes from politically stable countries.

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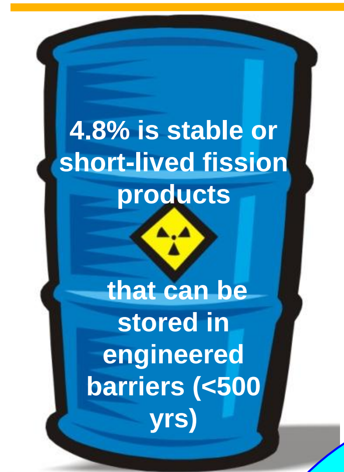
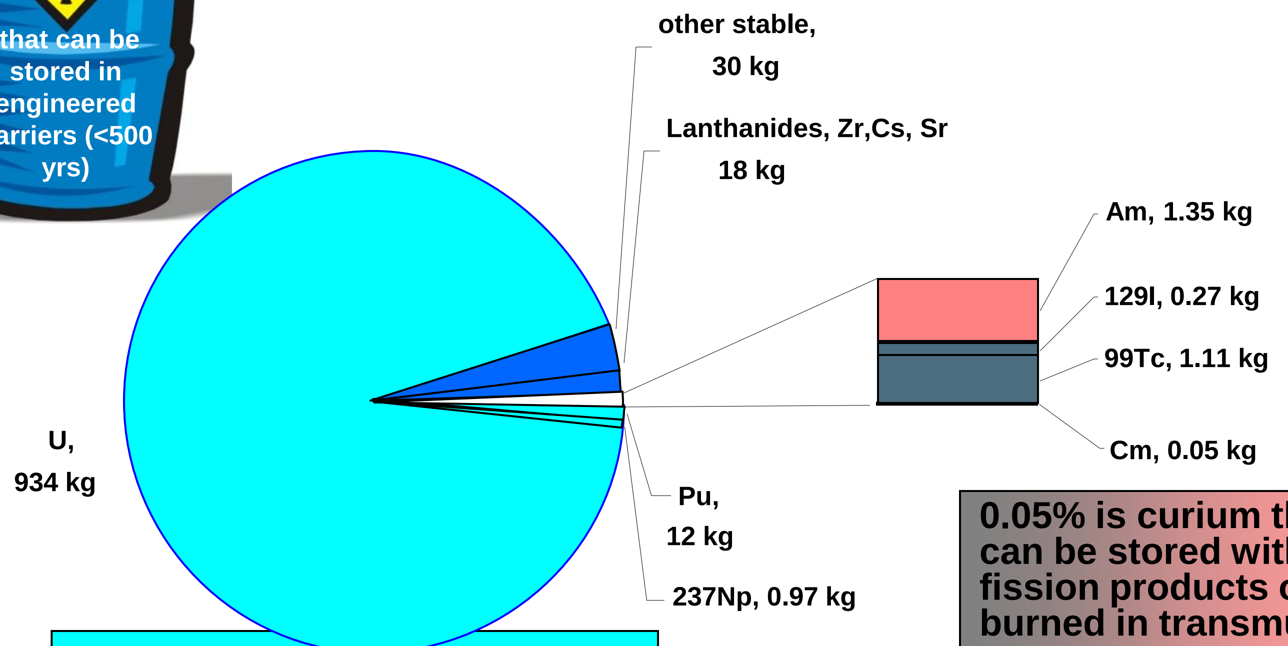
92% of Used Nuclear Fuel is U238 That Carries The Same Health Concerns Of Any Heavy Metal



0.14% is long-lived iodine and technetium (mobile) that can immobilized in glass and stored in a small geologic repository along with the residual waste processing stream



0.14% is americium that can be fissioned in a fast neutron spectrum

0.05% is curium that can be stored with fission products or burned in transmuter

95% can be stored as a future fuel source

High-Burn PWR 50 GW/Mt, 25-year cooling per MT of initial fuel

Goal is to Eliminate Nuclear Waste Stream Components That Significantly Affect Disposal: ½-lives of > 500 Years

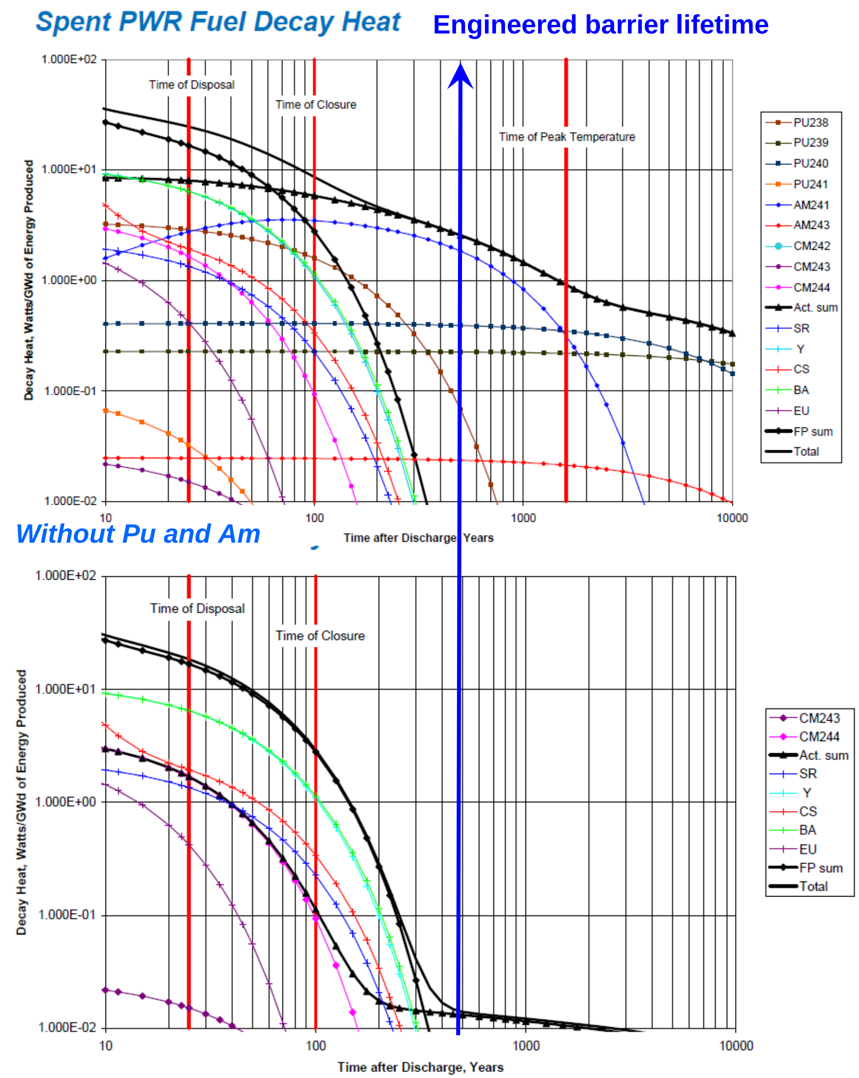
Actinides				Half life	Fission products			
^{244}Cm	**^{241}Pu**	^{250}Cf	**^{243}Cm**	**10–30 y**	**^{137}Cs**	**^{90}Sr**	^{85}Kr	
^{232}U		**^{238}Pu**		**69–90 y**			**^{151}Sm**	
	^{249}Cf	^{242}Am		**141–351 y**	No fission product has $t_{1/2}$ between 100 to 2×10^5 years			
	^{241}Am		^{251}Cf	**431–898 y**				
^{240}Pu	^{229}Th	^{246}Cm	**^{243}Am**	**5–7 Ky**				
	^{245}Cm	^{250}Cm	**^{239}Pu**	**8–24 Ky**				
	^{233}U	^{230}Th	^{231}Pa	**32–160 Ky**				
		^{234}U		**211–290 Ky**	**^{99}Tc**		**^{126}Sn**	**^{79}Se**
^{248}Cm		**^{242}Pu**		**340–373 Ky**	Long-lived fission products			
	^{237}Np			**1–2 My**	**^{93}Zr**	**^{135}Cs**		
^{236}U			^{247}Cm	**6–23 My**		**^{107}Pd**	**^{129}I**	
^{244}Pu				**80 My**	>7%	>5%	>1%	>.1%
^{232}Th		**^{238}U**	**^{235}U**	**0.7–12By**	fission product yield			

Isotopes present in 40 yr used fuel at > 0.0001% are in bold

The Decay Heat Poses Many Difficult-to-Answer Issues for Engineered and Geologic Barrier Performance and so Significantly Impacts Licensing

- **Thermohydrologic (e.g evaporation/condensation)**
- **Thermomechanical (e.g. fracturing)**
- **Thermochemical (e.g. radionuclide solubility, enhanced barrier corrosion)**
- **Thermobiological (e. g. bacterially enhanced barrier breakdown).**

Partitioning and transmutation can reduce isolation requirements to fit within lifetimes of engineered containers and barriers AND reduce incentives for intrusions



Wigeland 2006

Decay Heat Significantly Impacted the Yucca Mountain Repository Design

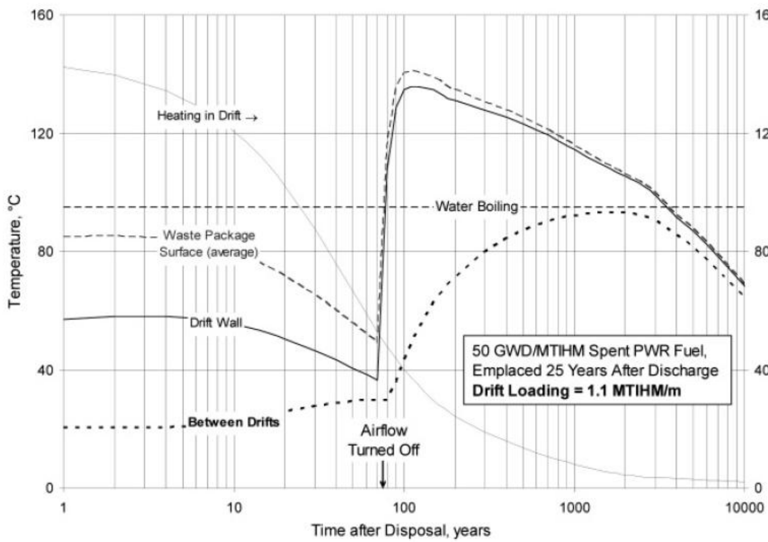


Fig. 3. Transient thermal response of a repository at Yucca Mountain for reference loading conditions of spent PWR of forced ventilation.

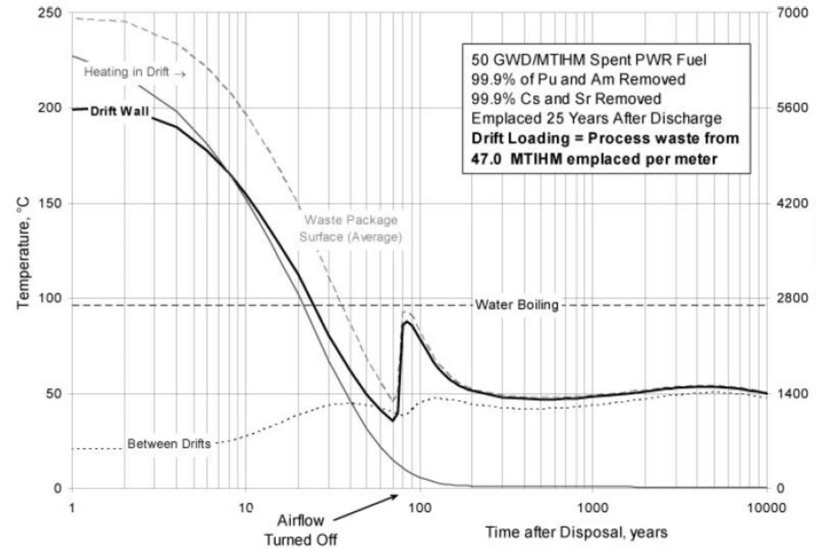
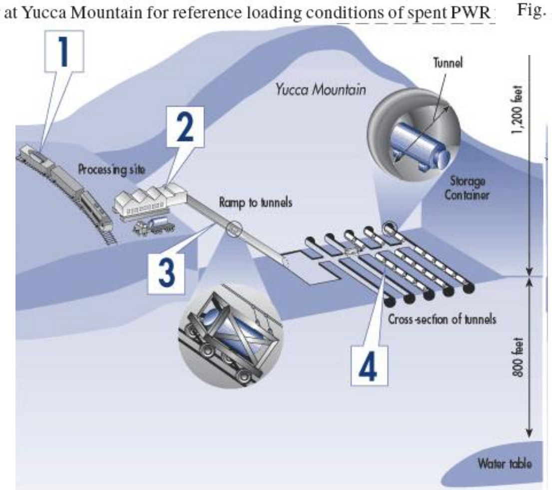


Fig. 5. Transient thermal response of a repository at Yucca Mountain with plutonium and americium removal and subsequent removal of cesium and strontium from spent PWR fuel with increased drift loading.

Wigeland, Nuclear Technology Vol. 154, p95, April 2006



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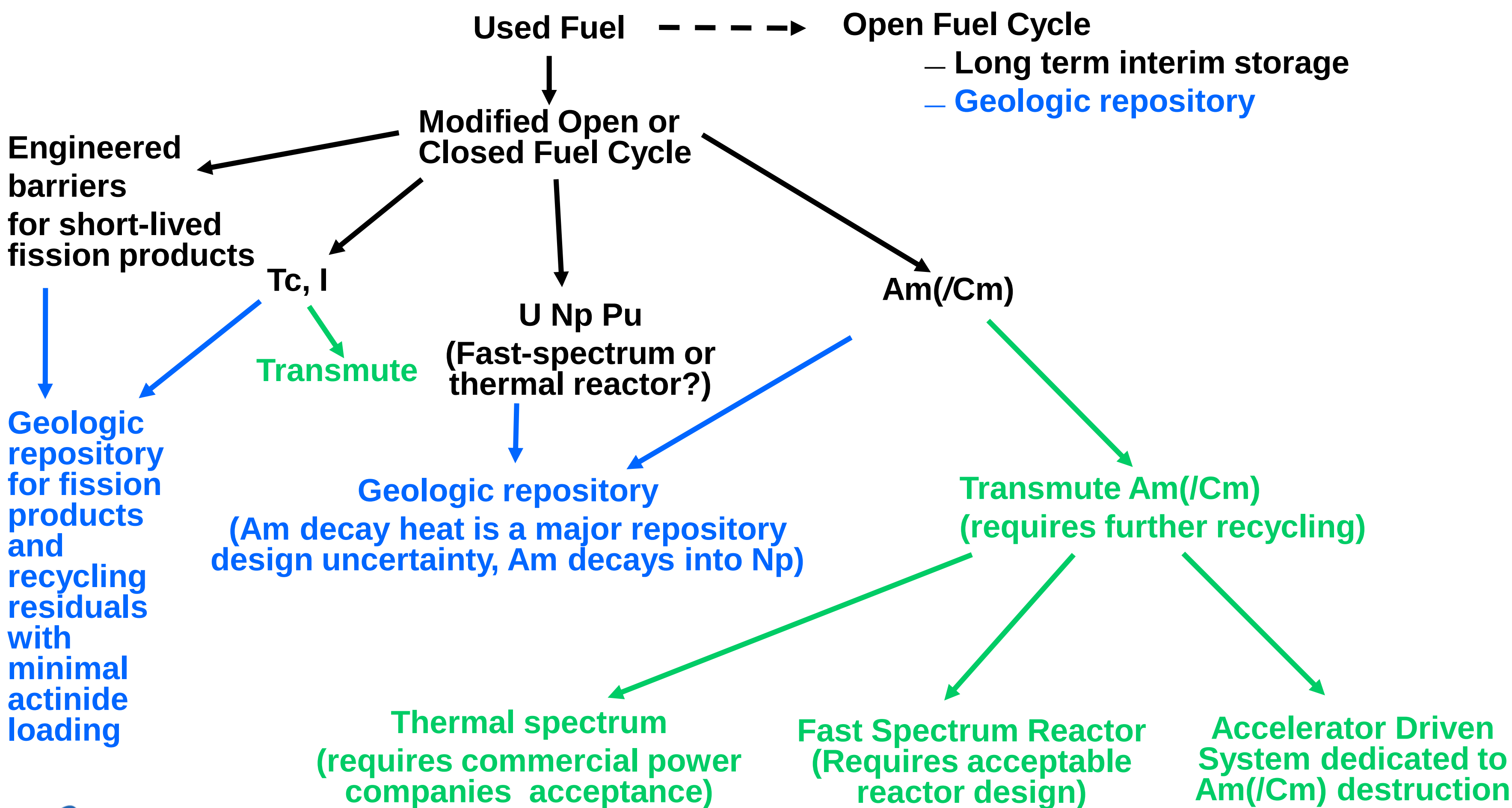
Fuel Deposition Options That Directly Address the Am Issue



In Lieu of a Closed Cycle, An Ideal Cycle Minimizes the Waste Stream Requiring Geologic Disposal:

- Separating the Pu-U-Np from the used fuel and immediately burn or store as a future resource.
- Transmute the isotopes that produce significant decay heat and have half-lives that exceed man-made container lifetime.
- Either transmute or immobilize the remaining isotopes that have a half-lives exceeding man-made container lifetime.
- Developing licensable disposal paths for the remaining waste streams that minimizes reliance on geologic barriers.

Questions/Issues: What about the long-lived fission products Tc-99 and I-129?

- **Option 1: Transmute.**
  - As opposed to fast neutron spectrum required for Am, the Tc neutron capture cross-section has 6000 and 1750 barn resonances at 5.6 to 20.3 eV, respectively, with a full-width of ~5%. The average cross-section is 0.5 barn and 9 barn for thermal and fast neutron spectra, respectively.
  - Research at JOYO focused on Tc burning indicated it may be possible to design specially moderated areas in a fast spectrum system that have relatively high Tc burn-up (burn 25% of the Tc loading per year).
- **Option 2: Dispose in repository.**
  - Unlike Am-241 decay, Tc-99 and I-129 do not generate significant repository heat load.
  - Several possible stable structures are being studied for Tc:
    - Synthetic garnet has a large cation-variance acceptance and so the crystal structure is stable with Tc-99 decay. Garnets are stable under the extremes that occur in the mantle – room temperature to 1200 C, 40 kbar pressures, and 3 billion year lifetimes. It is estimated that garnets could be Tc doped to 5-10%.
    - Incorporate the Tc into highly corrosion resistant metal alloys. Initial estimates indicate that in Alloy22 only 1% will leach into the environment over the Tc radioactive half-life.
  - I-129 can be vitrified and would have very low mobility in a salt repository

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Why Am Destruction by Accelerator Based Transmutation?

- **Accelerator-driven systems have a higher support ratio than fast reactors**
  - Fast reactors, unlike an ADS, need U-238 in the fuel to operate safely (increases delayed neutron fraction), which breeds Pu-239 and minor actinides
  - Accelerator-driven systems can probably operate on a pure Am feed stream in the equilibrium cycle
- **For example, the current US LWR fleet:**
  - Generates about 3 MT/yr Am after 40 yrs cooling (~1 MT/yr after 7 years)
  - Burning 3 MT/yr Am generates 8 GW of fission heat (about 3% of US nuclear fleet size)
  - After 40 year cooling, three high-powered accelerators can burn the Am generated by the current US fleet ; after 7 year cooling only 1 system is required

The Main Advantage of an Accelerator Driven System is Subcritical Operation

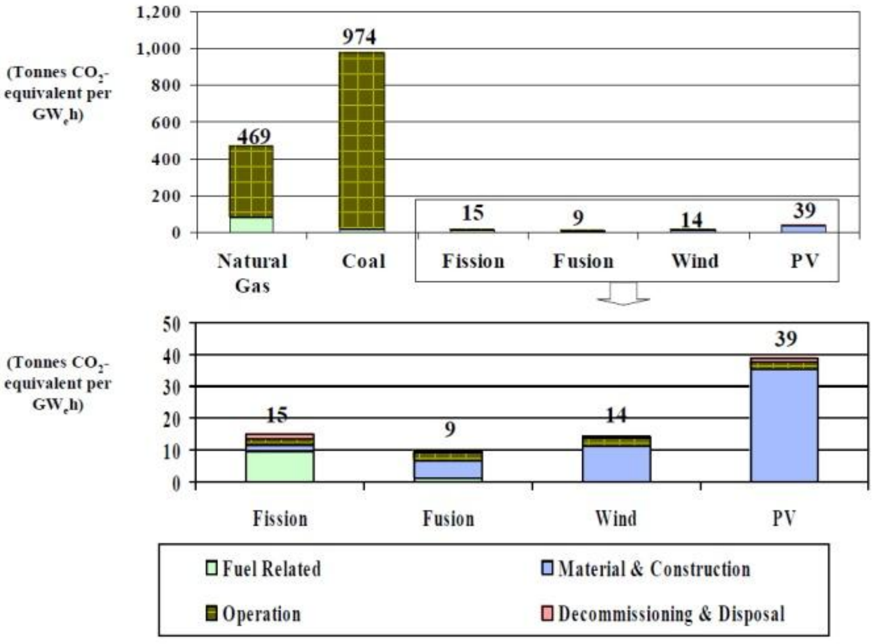
- **Subcritical capability adds fuel flexibility**
  - Can drive systems with low fissile content (Th or M.A.) or high burden of non-fissile materials
  - Can operate with fuel blends that could make critical systems unstable that could make critical systems operate in an unsafe regime, i.e. avoid prompt critical abnormal accident and leads to bounded rather than exponential power density responses to reactivity changes. (Pu and M.A. wo/ U or Th - *Note: Addition of U to gain stability produces more Pu)*
- **Can compensate for large uncertainties or burn up reactivity swings**
- **Option to operate subcritical is useful for addressing fuel cycle issues**
  - Can support advanced fuel cycles by transmuting wastes
  - Can close-down cycles with depleted fissile content
  - Can jump-start systems with insufficient fissile content

How does an ADS system cost to mitigate waste compare to a large geologic repository and what about reprocessing concerns?

- Based on studies in Europe and Japan, revenue generated by using excess thermal energy can be used substantially offset the total operating and capital cost.

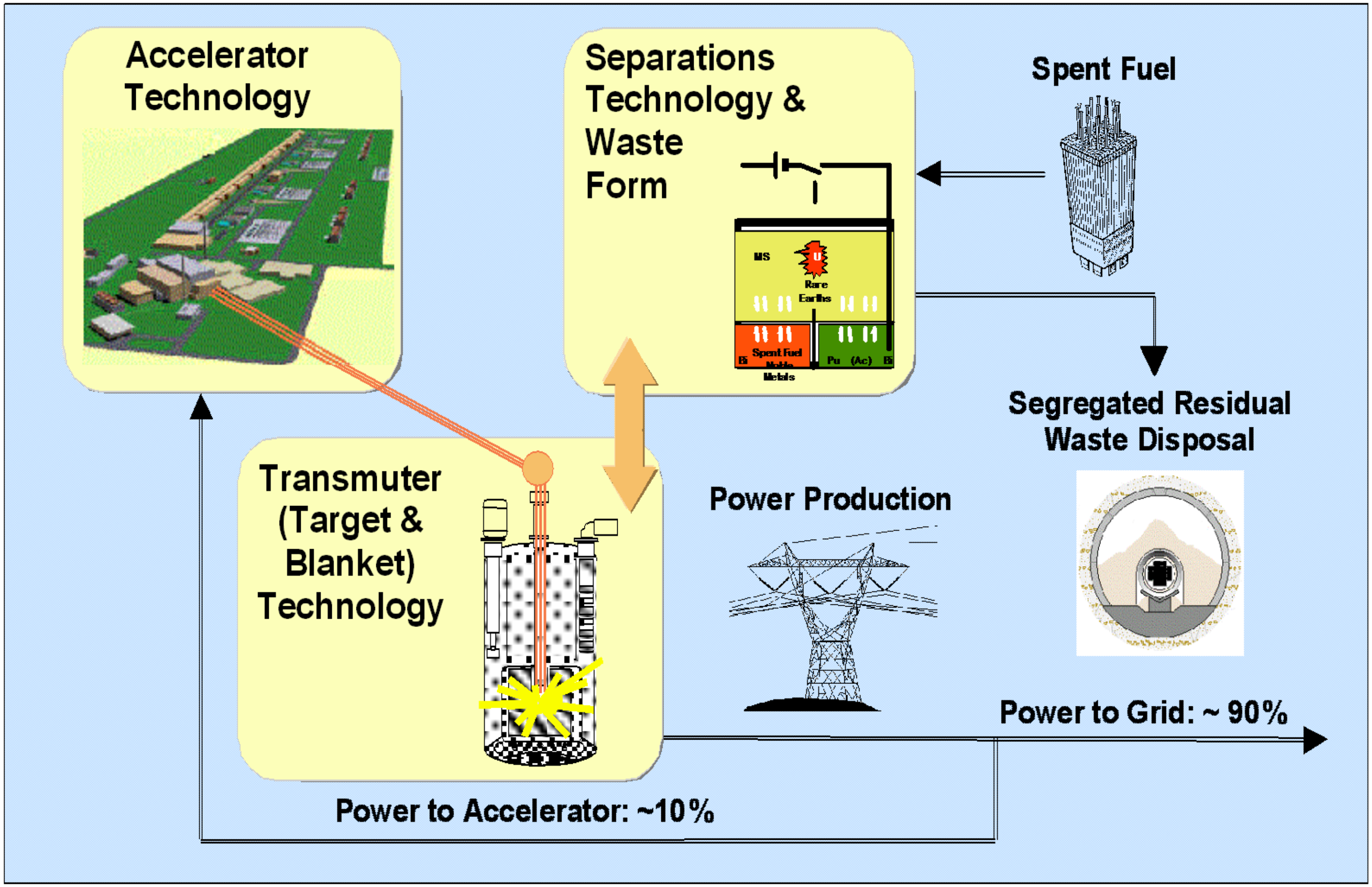
- We are reviewing simplified reprocessing technologies that have a minimal secondary waste stream, similar to a DUPIC approach.

- As with any closed of modified open fuel cycle, reuse of fissile material in used LWR fuel significantly reduces mining thus reducing the environmental impact (costs) and the largest component to the CO_2 footprint of nuclear power.



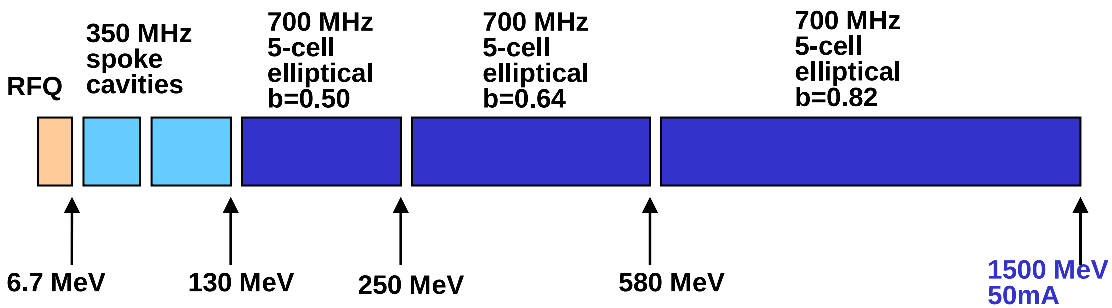
*Coal, Fission, Fusion, and Wind analysis by S.White.[37]

Accelerator-Based Transmutation Includes Four Major Technology Elements: Accelerators, Transmuters, and Separations, Fuels and Waste Forms



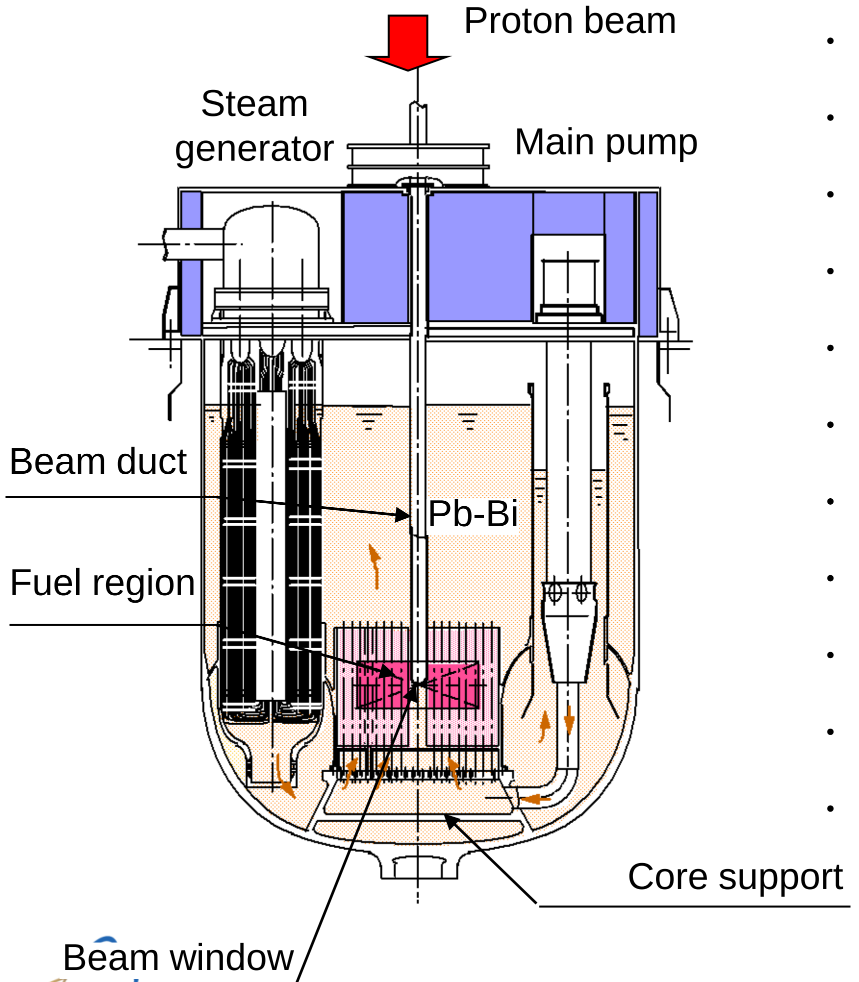
Our ADS LINAC design is Based on Our APT Work

- The RFQ will be normal conducting.
- The low-beta structures can be ¼ wave and ½ wave SC resonators.
- The high-beta structures can be elliptical.



Possible design based on the Accelerator Production of Tritium LINAC design.

High Intensity Proton Accelerator Project in JAERI/Tokai: Preliminary Design of the Reactor



- Proton beam : 1.5GeV 22 – 30 MW
- Spallation target : Pb-Bi
- Coolant : Pb-Bi
- Subcriticality : $k_{eff} = 0.95$
- Thermal output : 800 MWt
- Core height : 1000 mm
- Core diameter : 2440 mm
- MA initial inventory : 2.5 tonnes
- Fuel composition : (40%Pu + 60%MA) Mono-nitride
- Transmutation rate : 10%MA / Year (10 units of LWR)
- Burn-up reactivity swing : +1.8% $\Delta k/k$

A Subcritical System Requires An External Neutron Source, The Choice Will Be Made On Safety And Cost Effectiveness

- Each system will have its own unique safety basis considerations, but any system that has large quantities of fissionable material will have to meet reactor class safety regulations and will be evaluated against conventional reactors (and their 50 years of operational experience). The further the design is from existing reactor designs, the more design and testing that will be required.
- Any system with large reactivity swings will have the neutron source operate at low power for a significant period of the time, thus the resources used to enable operation at higher powers are inefficiently used.
- Any system with a k_{eff} close to 1 (neutron multiplication = $k_{eff}/\{1-k_{eff}\}$) significantly reduces the fraction of total neutrons provided by the source
  - **significantly reduces the cost of the neutron source relative to overall system cost.**
  - **since cost will certainly be a big factor then the implication is that a sub-critical system will be viewed as a reactor first and the neutron source viewed as an appendage - but with a large (and negative from a conventional reactor engineer) design impact**

Past Issues with ADS Technology Effectively Eliminated an ADS System as a Component of US Fuel Cycle

- **Concerns about faults/trips by reactor designers**
  - Effect of transients on materials
  - Effect of transients on fuels
  - Quality of electrical power delivered to the grid
  - Periodic maintenance

- **1996 National Research Council study in the U.S. was negative – Research and politics has negating most of the reports conclusions**

Concern About Faults And Trips Still Exist But Beam Interruptions Appear to be Manageable

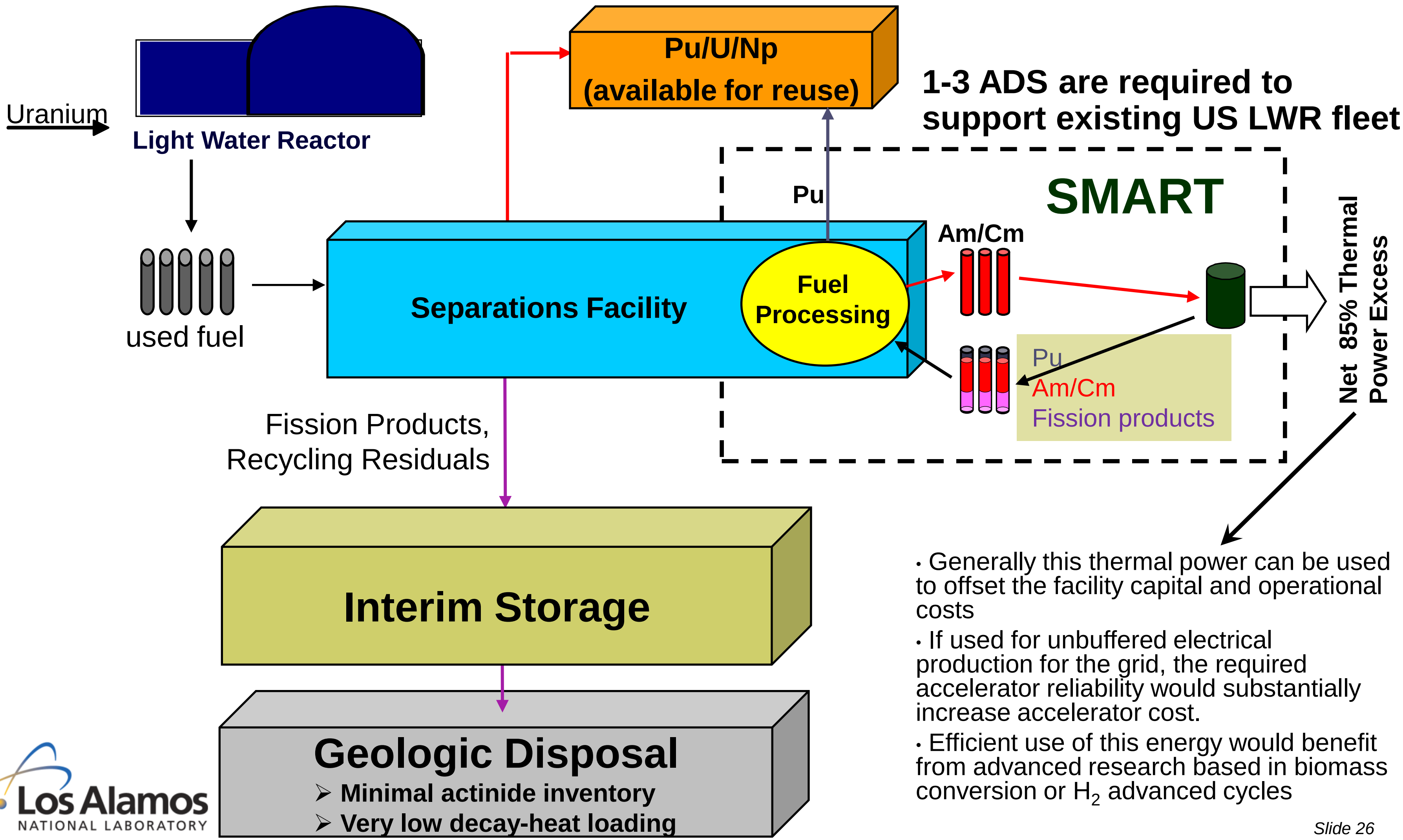
- **A JAEA study considered an 800 MWth subcritical reactor driven by a 30 MW proton beam. The analysis, considering thermal shock and cycling on the beam window, reactor vessel, inner barrel and turbine system gave allowable beam interruptions of:**
  - 25,000/yr for < 5 seconds,
  - 2500/yr for greater than 5 and less than 10 seconds,
  - 250/yr for greater than 10 seconds and less than 5 minutes, and
  - 50/yr for greater than 5 minutes.
- **A recent MYRRHA study gave similar results (with a factor of 10 safety margin):**
  - 2500 trips/year for greater than 1 second and less than 10 seconds,
  - 2500 trips/year between 10 seconds and 5 minutes, and
  - less than 25/year for greater than 5 minutes..
- **A U.S. study performed in 2001 gave:**
  - no limit on trips less than 0.3 seconds,
  - 1000 trips/year for longer than 0.3 seconds but shorter than 100 seconds, and
  - 30 trips/year for longer than 100 seconds.

Why Not Burn Pu, Np in an ADS System?

- The remaining actinides that pose an issue for a geologic repository are Np and Pu.
  - To burn the yearly LWR production of just the Np in a sub-critical transmuter would require the addition of two more full-scale accelerator system, and
  - more than 5 to 7x as many systems to burn the Pu.
  - If the government is responsible for handling the used fuel stream then burning other actinides will substantially increase the government role, i.e. costs.
    - System studies are needed to verify that non-ADS systems may be optimal for this application, but existing LWRs or new reactors (Gen IV, deep burn concepts) may be attractive options for burning the Pu and Np.

- U, Np, and Pu recovered from used once-through LWR fuel should not require remote handling.

SMART: "Subcritical Minor Actinide Reduction Through Transmutation" Supports LWR Economy and Preserves U, Pu, & Np as a Future Energy Resource

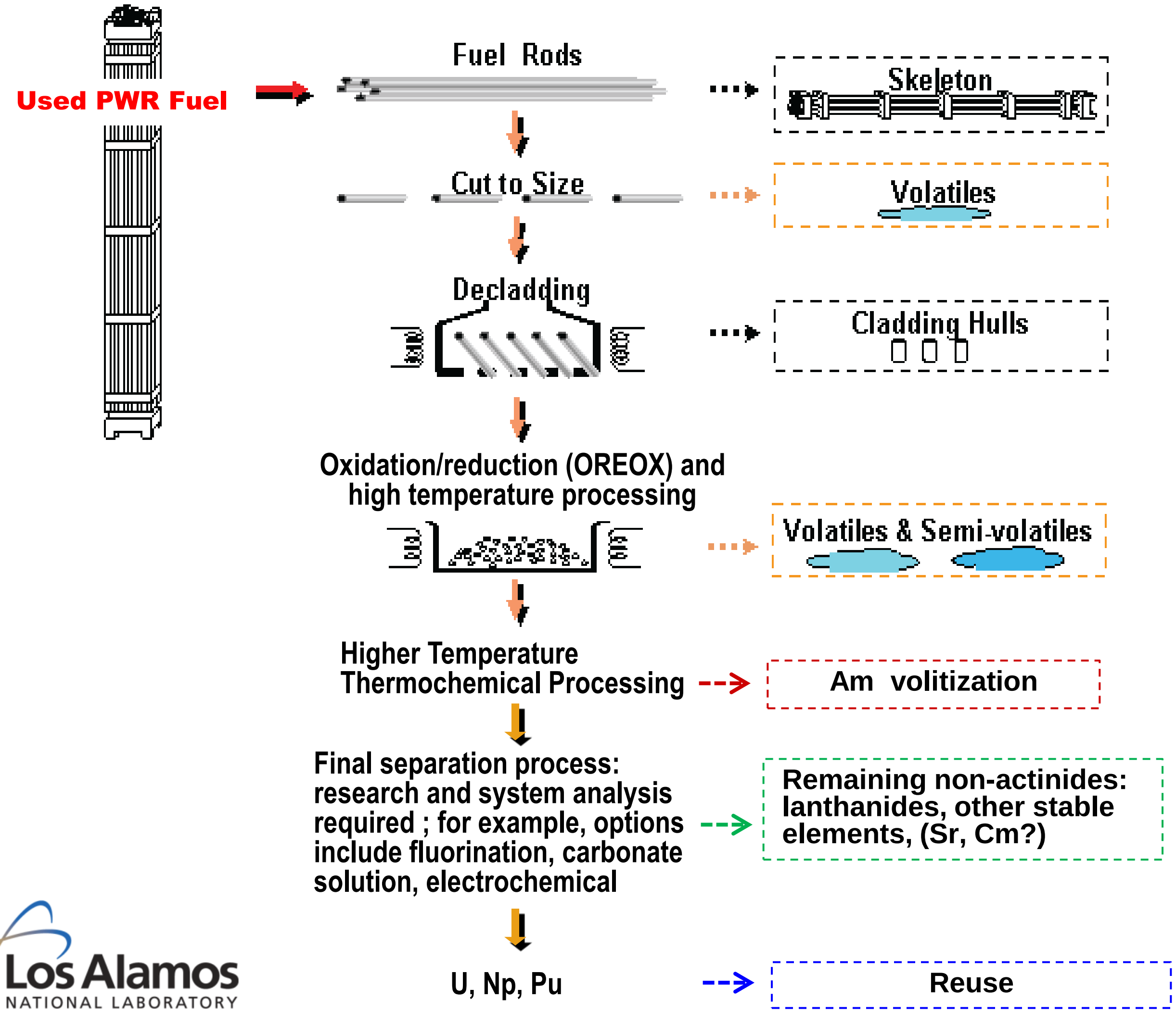


- Generally this thermal power can be used to offset the facility capital and operational costs
- If used for unbuffered electrical production for the grid, the required accelerator reliability would substantially increase accelerator cost.
- Efficient use of this energy would benefit from advanced research based in biomass conversion or H_2 advanced cycles

Power Production Adds Cost, But This Additional Cost is Much Less Than Its Revenue

- *Electricity to the grid*
- *Electricity to storage (pump water or such)*
- *Hydrogen production*
- *Conversion of biomass to hydrocarbon fuel*

We Are Reviewing Alternatives To Conventional Partitioning Strategies; For Example,



From Korean work with surrogate fuel forms:

Elements	OREOX %	Sintering Temps %	Total %
H	100	-	100
Kr	100	-	100
I	40	60	100
Ru	2	-	2
Cs	0	99	99
Tc	10	90*	100
Cd	-	100	100
Se	10	90	100
Sb	-	100	100
Rb	0	99	99
Te	10	90	100
C	100	-	100
Ag	10	-	100

*Tc removal between 90% and 100% for temperatures between 900 and 1250 C, Westphal

Design Issues for ADS Systems

- **Multiplying assembly design**
  - Neutronics analysis
  - Thermal-hydraulic analysis
  - Safety analysis
  - Fuels
  - Structural materials
- **Coolant technologies (i.e. - lead-bismuth-eutectic, etc.)**
  - Corrosion studies / oxygen control
  - Erosion studies
  - Safety assessment / polonium release
- **Spallation target technologies**
  - Window vs. windowless targets
  - Target material and coolant options beyond LBE
- **Accelerator systems**
  - High-power accelerator design
  - Impact of beam trips on fuel and clad performance
  - Reliability-Availability-Maintainability-Inspectability (RAMI) assessments

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Why Thorium with ADS?

- **An alternative approach to a conventional reactor is to use an external source of neutrons to drive a sub-critical reactor loaded with a fertile fuel such as thorium, i.e. a fuel which cannot support a self-sustaining chain-reaction.**
  - A conventional nuclear reactor is the controlled fission chain reaction of fissile isotopes, such as U-235 and Pu-239. The chain reaction depends on having a surplus of neutrons to keep it going. To fission a fissile isotope requires one neutron and produces 2 to 3 neutrons.
- **Thorium is a potentially valuable energy source since it is about three to four times as abundant in the earth's crust as uranium and is a widely distributed natural resource, which is readily accessible in many countries.**
  - The American Nuclear Society has endorsed continued research and development of the use of thorium as a fertile fuel material for nuclear reactors.

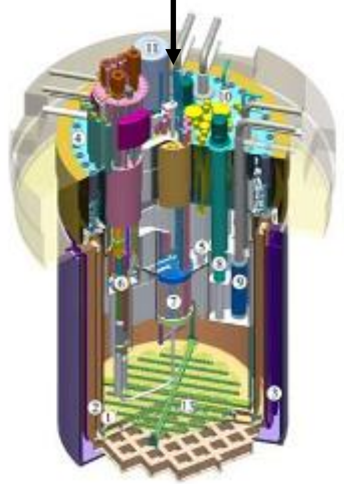
A Thorium Reactor Has Several Positive Attributes

- **The thorium cycle produces only half the amount of long-lived radioactive waste per unit of energy compared to mainstream light-water reactors.**
  - The use of thorium instead of uranium reduces the quantity of actinides that are produced.
- **The thorium cycle produces less plutonium than mainstream light-water.**
- **The thorium cycle coproduces a highly radioactive isotope, uranium-232, which provides a high radiation barrier to discourage theft and proliferation of used fuel**
- **Several countries, notably India, would profit from technology that utilizes their vast thorium resources.**

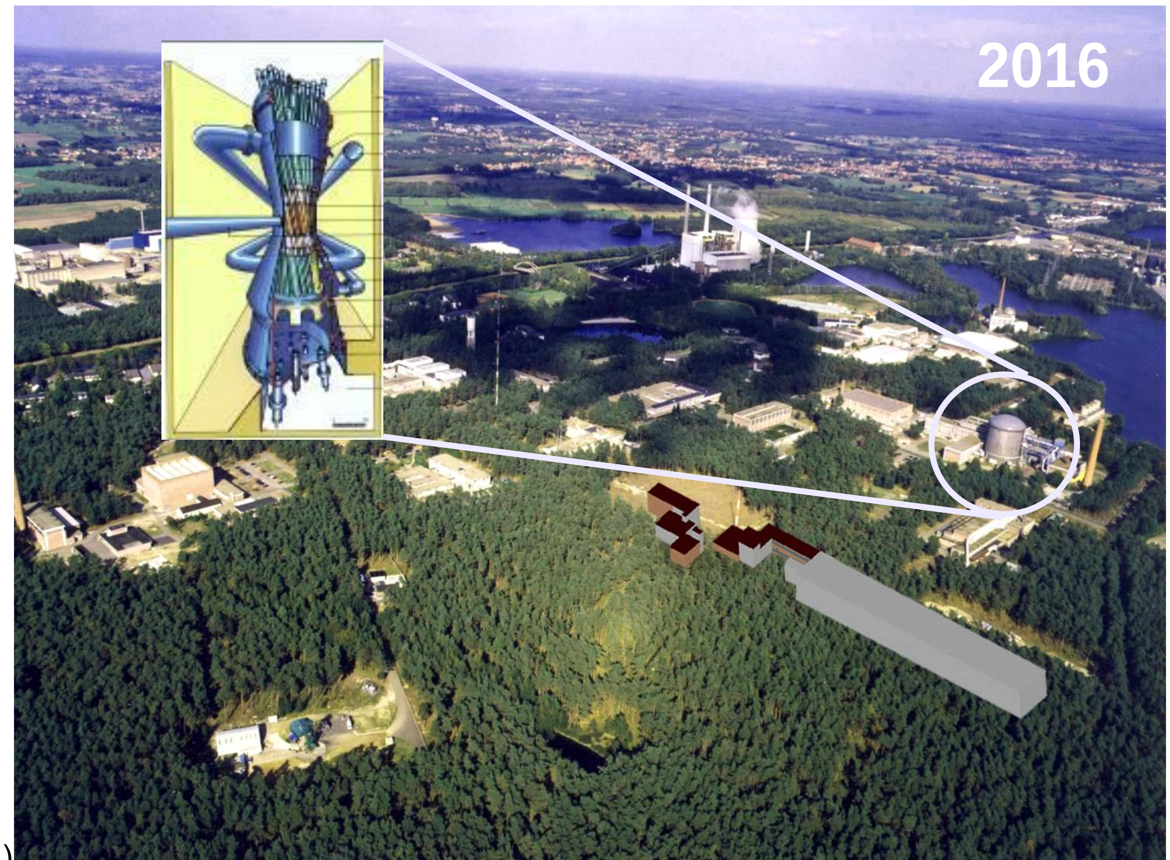
MYRRHA = accelerator + reactor to replace BR2

Protons accelerator

multidisciplinary



Research tool



MYRRHA is to be:

- A flexible neutron irradiation testing facility as successor of the SCK•CEN MTR BR2 (100 MW)
- A flexible fast spectrum testing facility in Europe for Gen.IV and Fusion
- A full step ADS demo facility and P&T testing facility
- A technological prototype as test bench for LFR Gen.IV
- An attractive tool for education and training of young scientists and engineers
- A medical radioisotope production facility
- Fundamental research facility at the accelerator

MYRRHA components: Spallation target

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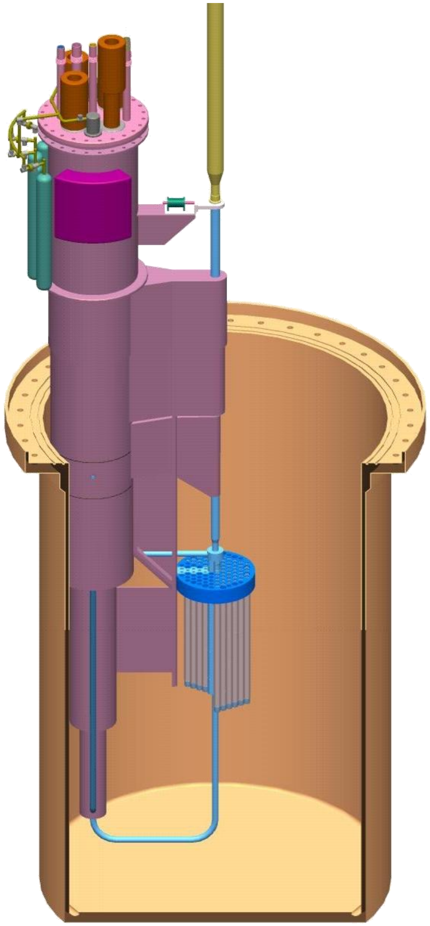

- **Tasks**
  - **Produce 10^{17} neutrons/s to feed subcritical core @ k_{eff}=0.95**
  - **Accept megawatt proton beam**
    - **600 MeV, 2.5-3 mA ⇒ ≈1-1.2 MW heat**
    - **300 mm penetration depth**
    - **Pb-Bi eutectic as target material**
  - **Fit into central hole in core**
    - **compact target**
    - **windowless (beam density)**
    - **Off-axis geometry**
  - **Match MYRRHA purpose as experimental irradiation machine**
    - **flexible remote handling**
  - **Survive (lifetime)**

Conclusions

- Nuclear energy is a safe, cost-effective, emission-free power source.
- Disposal of used nuclear fuel is still a major hindrance in nuclear power acceptance.
- Accelerator-driven transmutation addresses repository licensing issues and so can help diminish used fuel disposal as an issue in the expansion of nuclear power.
- Accelerator-driven systems with thorium reactors provide an alternative power plant that produces less radioactive waste and opens up more reactor fuel options.