21st CENTURY ADS In CONTEXT

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BROOKHAVEN NATIONAL LABORATORY
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Office of Science
U.S. DEPARTMENT OF ENERGY

Background

- Classic Accelerator-Driven System (ADS)
  - High power proton accelerator (E ~0.6 – 2 Gev; I = xmA $\rightarrow$ > 5 MW)
  - Heavy metal target (solid - tungsten, tantalum, U-238?; liquid – lead, mercury, LBE)
  - Spallation neutrons: En $\leq$ Ep; En(mean) = ~3 MeV
- Applications:
  - Discovery Science
  - Material irradiation
  - Production of fissile material
  - Transmutation of selected isotopes (actinides, fission products)
  - Energy production
- Some applications require a sub-critical blanket surrounding the spallation neutron target to achieve objectives/be feasible-attractive

ADS Applications/Issues/Challenges

- **Accelerator:**
  - **Most applications require a high power accelerator in the range 5 – tens of MW beam power**
  - **High reliability and CW operation desirable/essential**
- **Target/Window:**
  - **Must be able to handle high power densities**
  - **Materials and geometry should maximize leakage of neutrons for "productive" use**
  - **Reliability, Maintainability, Inspectability, and Maintainability (RAMI) considerations crucial**
- **Applications:**
  - **No "killer app" for ADS has been identified**
  - **Several potential roles have been identified with varying demands implied**
  - **For energy production or meaningful transmutation, sub-critical blanket is essential**

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Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production

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September 17, 2010

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Table 3: ADS technology readiness assessment. The color-coding is explained in the text.

		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance	Green	Green	Green
	Reliability	Yellow	Yellow	Red
Accelerating System	RF Structure Development and Performance	Green	Green	Green
	Linac Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
RF Plant	Performance	Green	Green	Green
	Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Red
Beam Delivery	Performance	Green	Green	Green
Target Systems	Performance	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
Instrumentation and Control	Performance	Green	Yellow	Yellow
Beam Dynamics	Emittance/halo growth/beamloss	Green	Yellow	Yellow
	Lattice design	Green	Yellow	Yellow
Reliability	Rapid SCL Fault Recovery	Yellow	Red	Red
	System Reliability Engineering Analysis	Yellow	Red	Red

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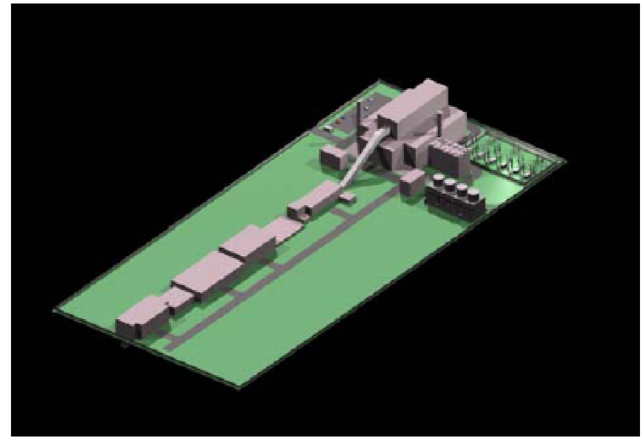
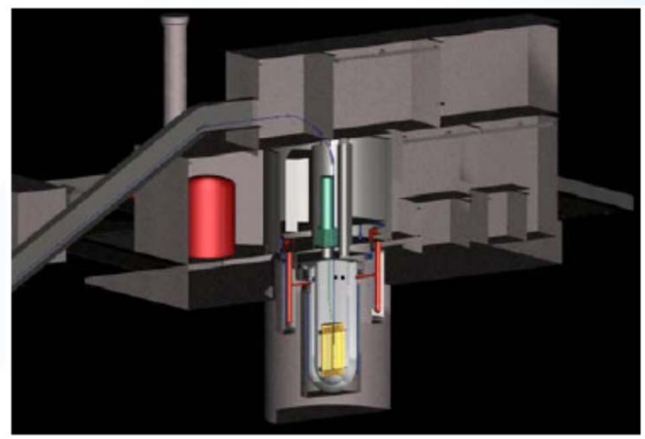
- **Considered accelerator and target - Sub-Critical Blanket was not addressed**
  - Essentially a reactor operating at keff < 1.0 → Therefore, subject to safety, safeguards and regulatory issues associated with reactors
  - Increased demands on stability for power production
  - Interface issues
- **Several "Findings" include:**
  - Finding #1: There are active programs in many countries, although not in the U.S., to develop, demonstrate and exploit accelerator-driven systems technology for nuclear waste transmutation and power generation (e.g., MYRRAH, SMART).
  - Finding #2: Accelerator-driven sub-critical systems offer the potential for safely burning fuels which are difficult to incorporate in critical systems, for example fuel without 238U or 232Th.
  - Finding #3: Accelerator driven subcritical systems can be utilized to efficiently burn minor actinide waste
  - Finding #7: For the tens of MW beam power required for most industrial-scale ADS concepts, superconducting linear accelerator technology has the greatest potential to deliver the required performance.
  - Finding #10: Ten to one-hundred fold improvements in long-duration beam trip rates relative to those achieved in routine operation of existing high power proton accelerators is necessary to meet industrial-scale ADS application requirements
- **SNS and MYRRHA have/will demonstrate key elements of advanced ADS**
- **Advances in circular accelerators warrant new look at their capabilities for ADS (cost, footprint, redundancy)**

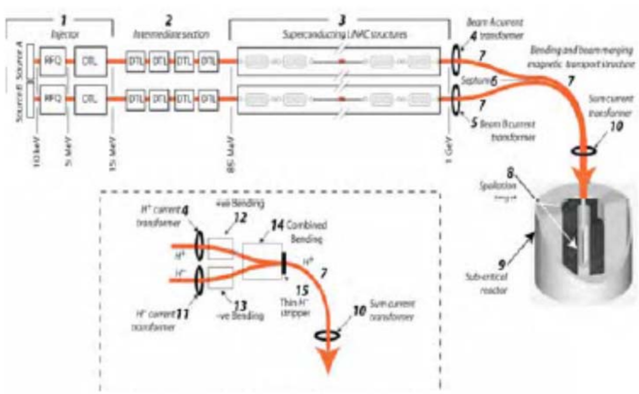
Example ADS for Power Generation

ADTR™ Parameters

Thermal Power (P_{th})	1500 MW_{th}
Electric Power (P_{el})	600 MW_{el}
Fuel	ThO_2 /PuO_2 84.5%/15.5% (first cycle)
Total fuel mass	59 tonne
Target fuel dwell time	8 – 10 years
Neutron multiplication coefficient (k_{eff})	0.995
Power density ρ	55 W/g oxide
Energetic Gain G	402 to 532
Coolant	natural lead
Spallation target	natural lead
Coolant temperature at core inlet	400˚C
Coolant temperature at core outlet	540˚C
Four off single loop lead to water/steam heat exchangers rated at 375 MW per unit	
Water temperature (feed to system steam generators)	340˚C
Steam temperature	450˚C
Steam pressure	183 bara
Coolant pumps	4 off axial flow
Sub-critical configuration, accelerator driven	

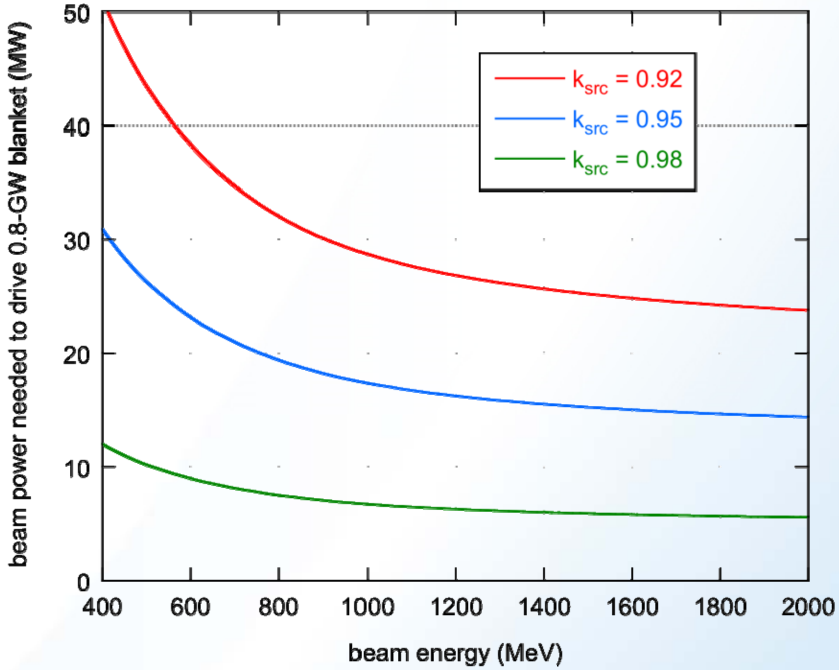




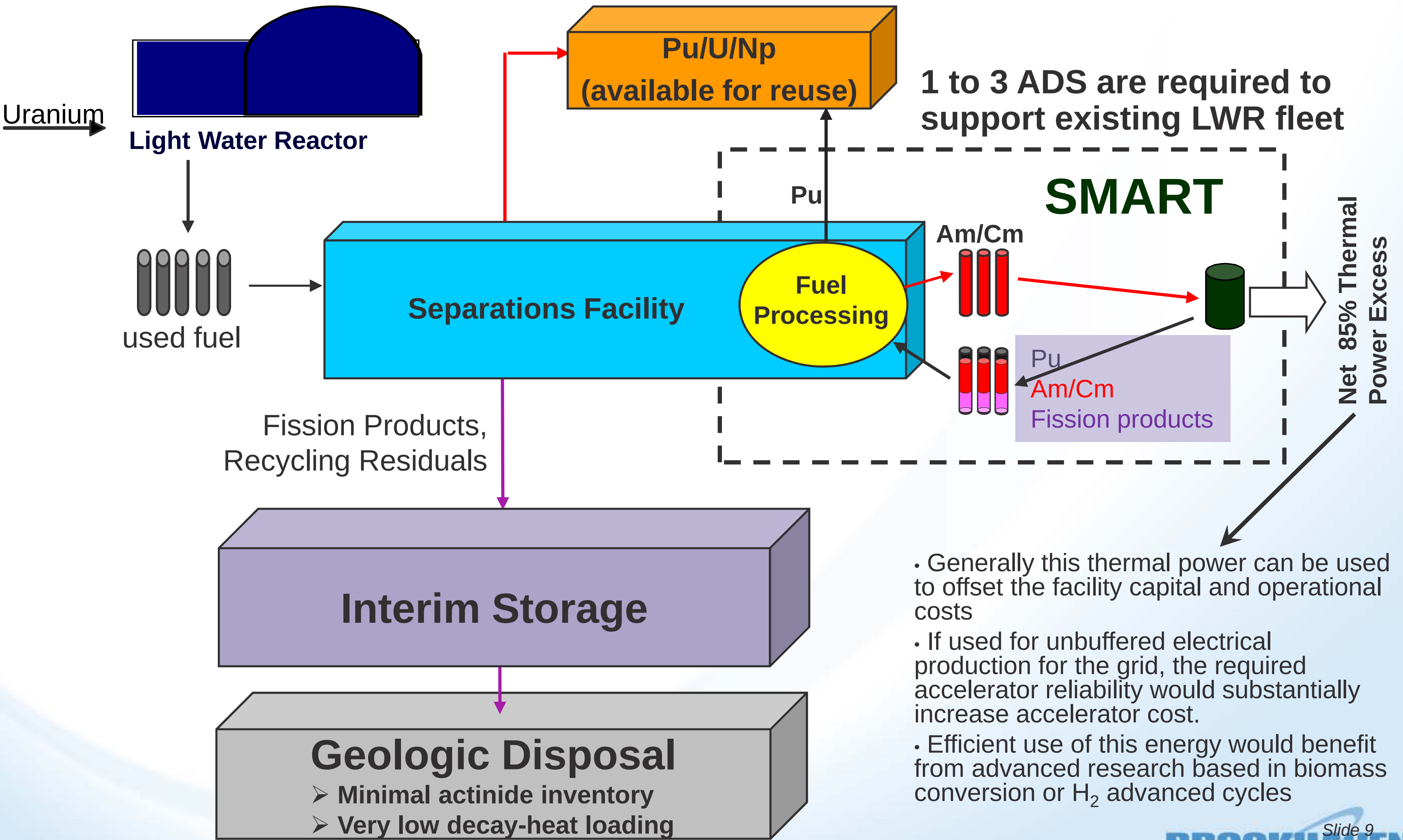


ADS Applications/Issues/Challenges

- Sub-Critical Blanket
  - Essentially a reactor operating at keff < 1.0 → Therefore, subject to safety, safeguards and regulatory issues associated with reactors
  - Optimal keff is trade-off with beam power → high keff requires lower beam power but start losing benefit of subcritical operation (i.e., when beam turns off, “reactor” shuts down → runaway transients are precluded)
  - Increased demands on stability and shape of proton beam on target
  - Accelerator must accommodate change in blanket keff with burnup to maintain near-constant power output

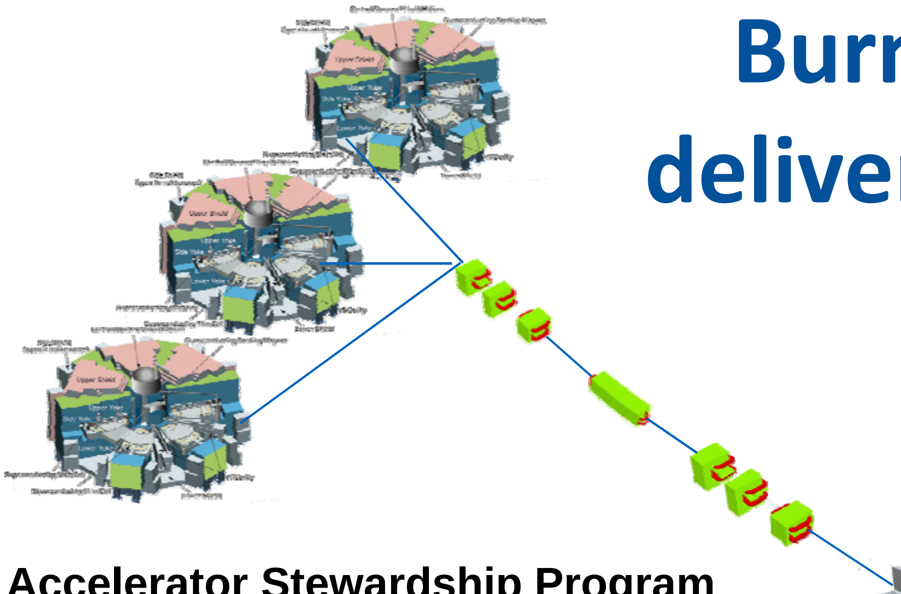


SMART: "Subcritical Minor Actinide Reduction Through Transmutation" Supports LWR Economy and Preserves U, Pu, & Np as a Future Energy Resource (LANL)



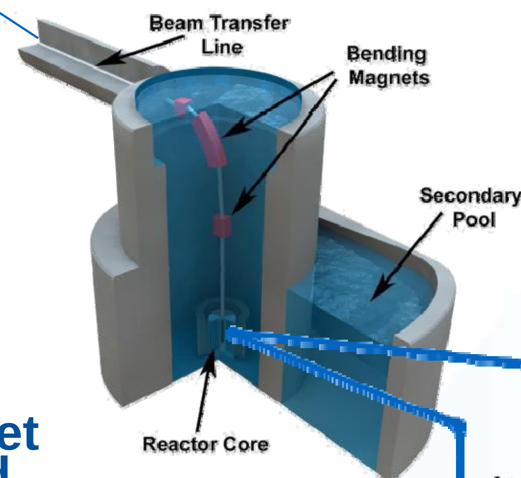
- Generally this thermal power can be used to offset the facility capital and operational costs
- If used for unbuffered electrical production for the grid, the required accelerator reliability would substantially increase accelerator cost.
- Efficient use of this energy would benefit from advanced research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

Burning nuclear waste while delivering carbon neutral energy

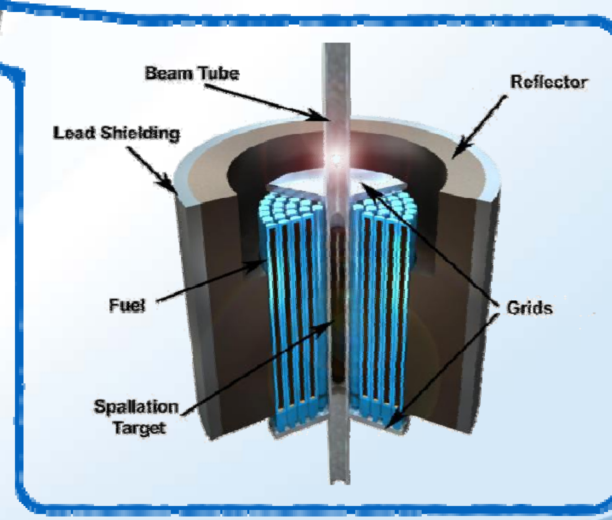


Accelerator Stewardship Program is seeking *new roles for accelerator science* in energy and environmental applications ***(Federal Register, 79, p 21910, April 18, 2014)***

- **Development of *sustainable nuclear fuel cycles* to manage radioactive waste and help meet growing global energy demand with low-carbon energy sources**
- **Burn higher actinides and long-lived fission products from LWR spent nuclear fuel**
- **ADS offers potentially greater flexibility (e.g. accommodating problematic materials; load-following capability)**

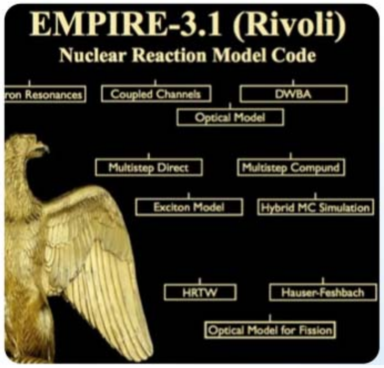


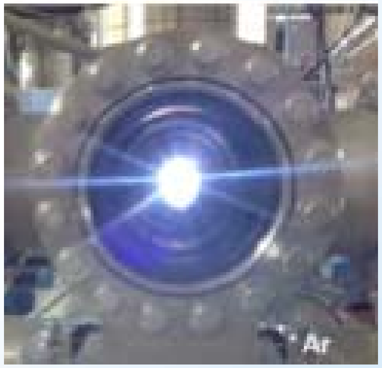
DOE-NE Evaluation & Screening of Fuel Cycle Options considered full spectrum of ADS applications: single-stage; front and back end ***(Wigeland, Taiwo, et al. Proc. Of ICAPP 2014)***

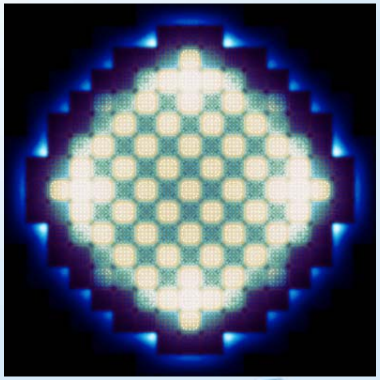


Inter-directorate BNL collaboration to develop a dual role hybrid accelerator driven system

- **Phase-1: Determine realistic boundary conditions; begin appraising system options**
  - **Envelope acceptable actinide & fission product loadings.**
  - **Begin assessing system options (liquid fueled blankets, cyclotron & FFAG, high power delivery system)**
  - **Develop activation & decay data to support design studies in project**
- **Phase-2: Appraise the detailed characteristics of the system**
  - **Continue assessing accelerator system options (cyclotron & FFAG, high power delivery system, plasma window)**
  - **Appraise reactor physics characteristics of system**
  - **Develop thermal neutron scattering evaluations for liquid blanket**
- **Phase-3: Systems integration and guide for R&D**
  - **System integration study focusing on safety, reliability, and cost effectiveness of hybrid system**
  - **Develop reactor and accelerator R&D roadmap**
  - **Identify basic science needs for future ADS efforts**







Backup

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Finding #1: There are active programs in many countries, although not in the U.S., to develop, demonstrate and exploit accelerator-driven systems technology for nuclear waste transmutation and power generation.

Finding #2: Accelerator-driven sub-critical systems offer the potential for safely burning fuels which are difficult to incorporate in critical systems, for example fuel without 238U or 232Th.

Finding #3: Accelerator driven subcritical systems can be utilized to efficiently burn minor actinide waste

Finding #4: Accelerator driven subcritical systems can be utilized to generate power from Thorium-based fuels

Finding #5: The missions for ADS technology lend themselves to a technology development, demonstration and deployment strategy in which successively complex missions build upon technical developments of the preceding mission.

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Finding #6: Recent detailed analyses of thermal transients in the subcritical core lead to beam trip requirements that are much less stringent than previously thought; while allowed trip rates for commercial power production remain at a few long interruptions per year, relevant permissible trip rates for the transmutation mission lie in the range of many thousands of trips per year with duration greater than one second.

Finding #7: For the tens of MW beam power required for most industrial-scale ADS concepts, superconducting linear accelerator technology has the greatest potential to deliver the required performance.

Finding #8: One of the most challenging technical aspects of the ADS accelerator system, the Front-End Injector, has demonstrated performance levels that meet the requirements for industrial-scale systems, although reliability at these levels has not yet been proven.

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Finding #9: Superconducting radio-frequency accelerating structures appropriate for the acceleration of tens of MW of beam power have been designed, built and tested; some structure types are in routinely operating accelerator facilities.

Finding #10: Ten to one-hundred fold improvements in long-duration beam trip rates relative to those achieved in routine operation of existing high power proton accelerators is necessary to meet industrial-scale ADS application requirements.

Finding #11: The technology available to accelerator designers and builders of today is substantially different from, and superior to, that which was utilized in early ADS studies, in particular in the design which was considered in the 1996 National Research Council report.

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Finding #12: Spallation target technology has been demonstrated at the 1-MW level, sufficient to meet the "Transmutation Demonstration" mission.

Finding #13: With appropriate scaling at each step along a technology demonstration path, there are no obstacles foreseen that would preclude the deployment of spallation targets at a power level (10 to 30 MW) needed to meet the application of ADS at an industrial scale.

Finding #14: Technology is sufficiently well developed to meet the requirements of an ADS demonstration facility; some development is required for demonstrating and increasing overall system reliability.

Finding #15: For *Industrial-Scale Transmutation* requiring tens of MW of beam power many of the key technologies have been demonstrated, including front-end systems and accelerating systems, but demonstration of other components, improved beam quality and halo control, and demonstration of highly-reliable sub-systems is required.