The White Paper

- In June 2010 DOE Office of Science tasked a Working Group with producing a White Paper assessing accelerator and target technology for Accelerator-Driven Systems (ADS)

- The White Paper was intended to make a hard-nosed assessment, addressing
  - the technical requirements for ADS
  - the current status and readiness of accelerator and spallation target technology
  - the R&D necessary to meet the requirements

- ...and to answer two underlying questions:
  - Do the advances that have been made in Accelerator Technology in the last 10-15 years change the practicality of ADS for processing waste and generating electricity?
  - Is the technology to the point where a demonstration program is warranted?

S. Henderson, Thorium Energy Conference 2011
The White Paper

“Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production”


- Hamid Aït Abderrahim, SCK-CEN
- John Galambos, ORNL
- Yousry Gohar, ANL
- Stuart Henderson*, FNAL
- George Lawrence, LANL, retired
- Tom McManamy, ORNL
- Alex Mueller, CNRS-IN2P3

- Sergei Nagaitsev, FNAL
- Jerry Nolen, ANL
- Eric Pitcher*, LANL
- Bob Rimmer, TJNAF
- Richard Sheffield, LANL
- Mike Todosow, BNL

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S. Henderson, Thorium Energy Conference 2011
Accelerator Driven Systems

High-power, highly reliable proton accelerator
- ~1 GeV beam energy
- ~1 MW of beam power for demonstration
- Tens of MW beam power for Industrial-Scale System

Spallation neutron target system
- Provides external source of neutrons through spallation reaction on heavy metal target

Subcritical reactor
- Chain reaction sustained by external neutron source
- Can use fuel with large minor actinide content

S. Henderson, Thorium Energy Conference 2011
Applications of Accelerator Driven Systems Technology

- Accelerator Driven Systems may be employed to address several missions, including:
  - Transmuting selected isotopes present in nuclear waste (e.g., actinides, fission products) to reduce the burden these isotopes place on geologic repositories.
  - Generating electricity and/or process heat.
  - Producing fissile materials for subsequent use in critical or sub-critical systems by irradiating fertile elements.

S. Henderson, Thorium Energy Conference 2011
Finding

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.

S. Henderson, Thorium Energy Conference 2011
World-wide Efforts

- **Europe**
  - Ongoing program since 1990s on transmutation (EUROTRANS) and power production from thorium (Rubbia’s Energy Amplifier)
  - MYRRHA (SCK•CEN, Belgium) is leading development of first full-scale ADS system: 85 MW core driven by 2 MW accelerator

- **China**
  - Ambitious ADS Roadmap announced by Chinese Academy of Sciences to build an ADS Demo Facility by 2032 (1 GW core driven by 15 MW, 1.5 GeV accelerator)

- **India**
  - ADS plays key role in their 3-stage plan to develop sustainable Thorium fuel cycle

- **US**
  - An active program in the late 1990s, culminated in a Congressional Report outlining an ADS technology development Roadmap
  - Program terminated in 2003. There is no US ADS Program today

S. Henderson, Thorium Energy Conference 2011
Finding

Accelerator-driven sub-critical systems offer the potential for safely burning fuels which are difficult to incorporate in critical systems, for example fuel without uranium or thorium.
Advantages of ADS

• Greater flexibility with respect to Fuel Composition:
  - ADS are ideally suited to burning fuels which are problematic from the standpoint of critical reactor operation, namely, fuels that would degrade neutronic characteristics of the critical core to unacceptable levels due to small delayed neutron fractions and short neutron lifetimes, such as minor actinide fuel.
  - Additionally, ADS allows the use of non-fissile fuels (e.g. Th) without the incorporation of U or Pu into fresh fuel.

• Potentially enhanced safety:
  - External neutron source is eliminated when the beam is terminated.
Finding

Accelerator driven subcritical systems can be utilized to efficiently burn minor actinide waste.

S. Henderson, Thorium Energy Conference 2011
M. Cappiello, “The Potential Role of ADS in the U.S.”

The ADS is most efficient at Minor Actinide Transmutation

Pu Production Rate (grams / GWh)  MA Production Rate (grams / GWh)
Power Production

- A facility for transmutation of waste generates substantial power; process heat can be utilized to produce another form of energy (e.g., biofuels) or used to generate electrical power that far exceeds the that required to operate the accelerator.

- Many proposed ADS concepts for power production utilize thorium-based fuel to take advantage of some of its benefits, including:
  - greater natural abundance,
  - proliferation resistance, and
  - relative to U-based fuel, significantly reduced production of transuranics which are a major source of radiotoxicity and decay heat.

- An ADS system based on Th-fuel would not require incorporation of fissile material into fresh fuel, and could operate almost indefinitely in a closed fuel cycle.

- Expanded use of thorium-based fuels is actively pursued in some countries with large reserves of thorium, principally India, Norway and China. These programs are investigating whether ADS can speed up the deployment of the $^{233}$U-Th fuel cycle by breeding $^{233}$U, which does not exist in nature.

S. Henderson, Thorium Energy Conference 2011
Finding

Accelerator driven subcritical systems can be utilized to generate power from thorium-based fuels
Finding

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.
Range of Missions for Accelerator Driven Systems

Transmutation Demonstration and Experimentation
  • Accelerator sub-critical reactor coupling
  • ADS technology and components
  • M.A./Th fuel studies

Industrial-Scale Transmutation
  • Transmutation of M.A. or Am fuel
  • Convert process heat to another form of energy

Industrial-Scale Power Generation w/ Energy Storage
  • Deliver power to the grid
  • Burn MA (or Th) fuel
  • Incorporate energy storage to mitigate long interruptions

Industrial-Scale Power Generation w/o Energy Storage
  • Deliver power to the grid
  • Burn MA (or Th) fuel

Time, Beam-Trip Requirements, Accelerator Complexity, Cost

S. Henderson, Thorium Energy Conference 2011
ADS System Level Requirements

Accelerator and Target requirements are challenging

• High proton beam power
• Low beam loss to allow hands-on maintenance of the accelerator
• High wall-plug to beam power efficiency
• Accommodate high deposited power density (~1 MW/liter) in the target.
• Beam Trip Frequency: thermal stress and fatigue in reactor structural elements and fuel assembly sets stringent requirements on accelerator reliability
• High System Availability is required for a commercial system

S. Henderson, Thorium Energy Conference 2011
Accelerator Reliability

- More than any other requirement, the maximum allowable beam trip frequency has been the most problematic, and in many ways has been perceived as a “show-stopper”
- Conventional wisdom held that beam trips had to be limited to a few per year to avoid thermal stress and fatigue on the reactor structures, the target and fuel elements

Table 4. Main specifications for the proton beam. The listed requirements are for driving the technology-demonstrator XT-ADS compared to the industrial prototype EFIT.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>XT-ADS</th>
<th>EFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. beam intensity</td>
<td>2.5–4 mA</td>
<td>20 mA</td>
</tr>
<tr>
<td>Proton energy</td>
<td>600 MeV</td>
<td>800 MeV</td>
</tr>
<tr>
<td>Beam entry</td>
<td></td>
<td>Vertical from above</td>
</tr>
<tr>
<td>Allowed beam trips (&gt;1 sec)</td>
<td>&lt;5 per 3-month operation cycle</td>
<td>&lt;3 per year</td>
</tr>
<tr>
<td>Beam stability</td>
<td></td>
<td>Energy: ±1%, Intensity: ±2%, Size: ±10%</td>
</tr>
<tr>
<td>Beam time structure</td>
<td></td>
<td>CW, including zero-current periods (200 μs), repeated at low rate</td>
</tr>
</tbody>
</table>
Recent Developments Re: Beam Trip Requirements

• Three analyses based on transient response of reactor components using modern FEA methods are in good agreement: JAEA, MYRRHA and Argonne National Laboratory

• These new analyses result in ~2 order of magnitude relaxation of requirements for “short” trips and ~1 order of magnitude relaxation for “long” trips

• Updated Beam-Trip Rate requirements, while still very challenging, appear manageable with i) modern linac architecture, ii) appropriate redundancy and iii) utilization of reliability engineering principles

• More work is required to bring these components together with high reliability at > 10 times the beam power of today’s accelerators, but “getting from here to there” is achievable

S. Henderson, Thorium Energy Conference 2011
# Range of Parameters for ADS

<table>
<thead>
<tr>
<th></th>
<th>Transmutation Demonstration</th>
<th>Industrial Scale Transmutation</th>
<th>Industrial Scale Power Generation with Energy Storage</th>
<th>Industrial Scale Power Generation without Energy Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Power</strong></td>
<td>1-2 MW</td>
<td>10-75 MW</td>
<td>10-75 MW</td>
<td>10-75 MW</td>
</tr>
<tr>
<td><strong>Beam Energy</strong></td>
<td>0.5-3 GeV</td>
<td>1-2 GeV</td>
<td>1-2 GeV</td>
<td>1-2 GeV</td>
</tr>
<tr>
<td><strong>Beam Time Structure</strong></td>
<td>CW/pulsed (?)</td>
<td>CW</td>
<td>CW</td>
<td>CW</td>
</tr>
<tr>
<td><strong>Beam trips</strong></td>
<td>N/A</td>
<td>&lt; 25000/year</td>
<td>&lt;25000/year</td>
<td>&lt;25000/year</td>
</tr>
<tr>
<td><strong>(t &lt; 1 sec)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Beam trips</strong></td>
<td>&lt; 2500/year</td>
<td>&lt; 2500/year</td>
<td>&lt;2500/year</td>
<td>&lt;2500/year</td>
</tr>
<tr>
<td><strong>(1 &lt; t &lt; 10 sec)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Beam trips</strong></td>
<td>&lt; 2500/year</td>
<td>&lt; 2500/year</td>
<td>&lt;2500/year</td>
<td>&lt;2500/year</td>
</tr>
<tr>
<td><strong>(10 s &lt; t &lt; 5 min)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Beam trips</strong></td>
<td>&lt; 50/year</td>
<td>&lt; 50/year</td>
<td>&lt; 50/year</td>
<td>&lt; 3/year</td>
</tr>
<tr>
<td><strong>(t &gt; 5 min)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>&gt; 50%</td>
<td>&gt; 70%</td>
<td>&gt; 80%</td>
<td>&gt; 85%</td>
</tr>
</tbody>
</table>

S. Henderson, Thorium Energy Conference 2011
Finding

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.

S. Henderson, Thorium Energy Conference 2011
ADS-Relevant Technology Development of the Last 10-15 Years

- Modern, *MW-class high power proton accelerators* based on superconducting technology *exist and operate with acceptable beam loss rates* (Spallation Neutron Source)

- *Superconducting radiofrequency structures* have been built to cover a broad range of particle velocities (from $v/c=0.04$ to 1). Use of SRF offers potential for achieving high reliability

S. Henderson, Thorium Energy Conference 2011
Performance of SNS, a MW-class Proton Linear Accelerator

S. Henderson, Thorium Energy Conference 2011
Finding

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.

S. Henderson, Thorium Energy Conference 2011
ADS-Relevant Technology Development of the Last 10-15 Years

• High-power Injector technology has been built and *demonstrated ADS-level performance (100 MW equivalent) with beam* (Low-Energy Demonstration Accelerator at Los Alamos)

• Liquid-metal target systems have operated with MW proton beams (Pb-Bi loop - MegaPIE @ PSI, liquid Hg @ SNS)

• Key technologies relevant to ADS applications that existed only on paper ~15 years ago have since been developed and demonstrated
Finding

One of the most challenging technical aspects of any 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.
Finding

Spallation target technology has been demonstrated at the 1-MW level, sufficient to meet the “Transmutation Demonstration” mission.
Accelerator Technology Choices

• In the range of 5-10 MW, both cyclotron (at its limits) and linear accelerator technology are applicable. Perhaps FFAGs will be capable someday.

• For beam power in excess of ~10 MW, only SC RF linac technology appears to be practical.

• Various studies have concluded that SC RF technology has far greater beam power potential than cyclotron technology, and that it is the technology of choice for the > 10MW beam power required to drive GW-level subcritical cores.

• Further, SCRF has the capability for achieving very high reliability as it lends itself to implementing a robust independently-phased RF cavity system. It is that latter technology that has the potential for fault tolerance and rapid fault recovery, making use of built-in online spare cavities.

S. Henderson, Thorium Energy Conference 2011
Finding

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.

S. Henderson, Thorium Energy Conference 2011
Beam Trip Duration Experience

• It is instructive to look at the experience, but one must keep in mind that operating proton accelerators were not designed for low trip rates
Finding

Ten to one-hundred fold improvement 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.

S. Henderson, Thorium Energy Conference 2011
Finding

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

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.
Key technologies and issues for the Accelerator-Target system: many of the most challenging technical issues are inter-related.
# ADS Technology Readiness Assessment

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

Green: “ready”, Yellow: “may be ready, but demonstration or further analysis is required”, Red: “more development is required”.
Finding

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.

S. Henderson, Thorium Energy Conference 2011
Finding

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.

S. Henderson, Thorium Energy Conference 2011
Conclusions

• ADS requires challenging technology
• Tremendous developments in the last 10-15 years suggest that it is sufficiently well developed to meet the requirements of an ADS demonstration facility
• For *Industrial-Scale Systems* requiring tens of MW of beam power many of the key accelerator technologies have been demonstrated, but further development is required
• There is not an ADS R&D Program in the U.S. An ADS Research Program would be consistent with
  • the transmutation R&D needs articulated in the Nuclear Energy R&D Roadmap (2010), and
  • the broad RD&D priorities articulated in the MIT “Future of the Nuclear Fuel Cycle” Report (2010).
Timeline of US ADS Activities

• Since the early 1990’s, accelerator-driven systems have been proposed for addressing certain missions in advanced nuclear fuel cycles

• In 1995 the National Research Council issued a report on transmutation technologies (“The NRC Report”) which included an evaluation of one ADS concept for a ~100 MW accelerator to drive a thermal, molten salt subcritical core

• The NRC recognized the many complexities associated with this system, among them that much of the required high-power accelerator technology had yet to be demonstrated

• The NRC report was quite negative on accelerator applications in fuel cycles
### NRC Study (1996) Accelerator Parameters: Based on 1992 Normal-Conducting (coupled-cavity) Linac Design

<table>
<thead>
<tr>
<th></th>
<th>ATW-1</th>
<th>ATW-2</th>
<th>Present Day</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Energy [MeV]</strong></td>
<td>1600</td>
<td>800</td>
<td>1500</td>
</tr>
<tr>
<td><strong>Beam Power [MW]</strong></td>
<td>400</td>
<td>88</td>
<td>75</td>
</tr>
<tr>
<td><strong>Accelerating Gradient</strong></td>
<td>1 MV/m</td>
<td>1 MV/m</td>
<td>20 MV/m</td>
</tr>
<tr>
<td><strong>Linac Length</strong></td>
<td>1900 m</td>
<td>1000m</td>
<td>300 m</td>
</tr>
</tbody>
</table>
Timeline of US ADS Activities

• 1999: US Congress directed DOE to evaluate Accelerator Transmutation of Waste (ATW) concepts and prepare a “roadmap” to develop the technology
• 2000-2002, DOE sponsored the Advanced Accelerator Applications to investigate use of ADS in closed fuel cycles
• 2003: AAA program transitioned to the Advanced Fuel Cycle Initiative and DOE sponsored ADS research ceased (except for continuation of a few international collaborative efforts)
World-wide ADS research activities

• Meanwhile, outside the US, ADS R&D for both transmutation and power generation has not only continued but accelerated.

• 2001: European Technical Working Group evaluated the state of ADS technologies and recommended construction of an experimental ADS.


  “On the whole, the development status of accelerators is well advanced, and beam powers of up to 10 MW for cyclotrons and 100 MW for linacs now appear to be feasible. However, further development is required with respect to the beam losses and especially the beam trips to avoid fast temperature and mechanical stress transients in the reactor.”
Europe - EUROTRANS program

- "R&D efforts aiming at substantiating the potential of ADS and studying their role in innovative reactor and fuel cycle strategies that include systems for large-scale utilization and transmutation of minor actinides and long-lived fission products"

- Technology demonstration is gaining momentum with Belgium’s plans for MYRRHA, an 85-MW demonstration ADS at SCK•CEN

- Gov’t has committed to funding 40% of the construction cost and is investing 60 MEuro over the next 5 years to advance the design in preparation for construction start in 2015
Summary of World-wide ADS Activities

**Europe** - Energy Amplifier

- CERN Group (C. Rubbia)
- ThorEA – Thorium Energy Amplifier Association, UK: “Capturing thorium-fueled ADSR energy technology for Britain”

**India**

- Envision synergistic role of ADS within the larger Indian nuclear power program for electricity production, fertile-fissile conversion of Th, nuclear waste incineration
- Objectives of ADS R&D programme
  - Partitioning & Transmutation as part of advanced fuel cycles
  - Fissile material breeding ➔ thorium utilization
- Aggressively pursuing ADS technology, principally superconducting RF systems

S. Henderson, Thorium Energy Conference 2011
Summary of World-wide ADS Activities

Japan
- Japan Atomic Energy Agency (JAEA)
  - Sub-critical core design studies: 800 MWth Pb-Bi eutectic cooled ADS
  - TEF (Transmutation Experimental Facility) is being designed for deployment at J-PARC (Japan Proton Accelerator Research Complex)
- Experimental program on subcritical core-100 MeV proton beam coupling at Kyoto University

South Korea
- Studying ADS for transmutation of waste
- Design and construction of 1\textsuperscript{st} stage of a high-power proton accelerator at KAERI (KOMAC)
Summary of World-wide ADS Activities

China
• Recently announced technological development plans to reach industrial scale system in ~20 years

Ukraine, Russia, Belarus, Brazil
• Ongoing programs in accelerator-driven transmutation of waste and Th fuel utilization

There is no active U.S. Program in ADS technology

S. Henderson, Thorium Energy Conference 2011
(Stuart’s) Thoughts on Safety

ADS for Waste Transmutation

- Minor actinide destruction through transmutation is one mission that ADS are well suited to address.
- Unlike critical fast reactors which generally incorporate uranium or thorium in the fuel for safe operation, ADS can potentially operate on a pure MA feed stream, meaning a smaller number of ADS can be deployed to burn a fixed amount of minor actinides.
- ADS can recycle the MA multiple times until it is completely fissioned, such that the only actinide waste stream from these systems would derive from the recycling residuals, which could yield a significant reduction (by a factor of hundreds) in the amount of actinide waste per kW-hr of electricity generated, as compared to a once-through fuel cycle.
- Because accelerator driven systems do not require fuels containing uranium or thorium, they are more efficient at destroying MA waste.
Recent Beam Trip Duration Analyses

- There are three analyses based on transient response of reactor components using modern FEA methods: JAEA, MYRRHA and Argonne
- These analyses show relatively good agreement

![Four criteria depending on the beam trip duration T](image)

<table>
<thead>
<tr>
<th>Beam trip duration $T$</th>
<th>Acceptable Frequency</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 &lt; T &lt; 5$ sec.</td>
<td>$10^5 / 2$ year $10^6 / 40$ year (25,000 / y)</td>
<td>Beam window life time Fatigue failure of reactor structure</td>
</tr>
<tr>
<td>$5 &lt; T &lt; 10$ sec.</td>
<td>$10^5 / 40$ year (2,500 / y)</td>
<td>Fatigue failure of reactor structure</td>
</tr>
<tr>
<td>10 sec. $&lt; T &lt; 5$ min.</td>
<td>$10^4 / 40$ year (250 / y)</td>
<td>Fatigue failure of reactor structure</td>
</tr>
<tr>
<td>$T &gt; 5$ min.</td>
<td>Once a week (50 / y)</td>
<td>System availability</td>
</tr>
</tbody>
</table>

JAEA Analysis: H. Takei et. al., Proc. 5th OECD/NEA HPPA
## Accelerator Technology - Requirements

<table>
<thead>
<tr>
<th></th>
<th>Transmutation Demonstration (MYRRHA [5])</th>
<th>Industrial Scale Facility driving single subcritical core (EFIT [10])</th>
<th>Industrial Scale Facility driving multiple subcritical cores (ATW [11])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Beam Power [MW]</td>
<td>1.5</td>
<td>16</td>
<td>45</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>2.5</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Uncontrolled Beamloss</td>
<td>&lt; 1 W/m</td>
<td>&lt; 1 W/m</td>
<td>&lt; 1 W/m</td>
</tr>
<tr>
<td>Fractional beamloss at full energy (ppm/m)</td>
<td>&lt; 0.7</td>
<td>&lt; 0.06</td>
<td>&lt; 0.02</td>
</tr>
</tbody>
</table>
The Beam Power Landscape

- Average Beam Current (mA)
- Beam Energy (GeV)

Existing (SP)
Existing (LP)

Facilities:
- IPHI
- LEDA
- 10 MW
- 1 MW
- 100 kW
- PSI
- PEFP
- LANSCE
- MMF
- TRIUMF
- SNS
- ISIS
- JPARC
- PSR
- RCS
- TRIMF
- SNS
- JPARC
- MR
- AGS
- NUMI
- CNGS

S. Henderson, Thorium Energy Conference 2011
Accelerator Technology Choices

• Three technologies have demonstrated MW-level performance
  ▪ Cyclotron – PSI
  ▪ NC Linac – LANSCE
  ▪ SC Linac – SNS

• Alternative approaches to high power include
  ▪ Synchrotron technology
  ▪ Fixed-field alternating gradient (FFAG) technology
  ▪ Combining multiple beams (stacked cyclotron approach – P. McIntyre et. al.)
Front-End System Technology: Low-Energy Demonstration Accelerator (LEDA)

- Full power performance demonstrated for a limited operating period.
  - 20 hours at 100 mA CW
  - 110 hours at > 90 mA CW
- RMS beam emittances measured; reasonable agreement with simulation
- No long-term operations for reliability/availability evaluation.
- HPRF system performed well, but no long-term window tests.
SILHI: Source of Light Ions for High Intensity at CEA-Saclay

- An ECR-based injector (SILHI) was built and tested, extracting > 100 mA.
- The source was operated for ~1,000 hours to assess reliability and availability;

<table>
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<td>Duration (h)</td>
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<td>5.3</td>
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<td>97.9</td>
<td>99.96</td>
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</table>

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A Zoo of RF Structures for $\beta < 1$ Acceleration

Normal Conducting Structures

Superconducting Structures

$\beta=0$

0.05 0.1 0.25 0.5 0.8

$\beta=1$

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Beam Trip Duration Experience

- It is instructive to look at the experience, but one must keep in mind that operating proton accelerators were not designed for low trip rates

J. Galambos, HB2008, p. 489

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A cavity fault recovery scheme is developed to adjust downstream cavity setup, to accommodate upstream cavity changes:

- Uses a difference technique, with initial beam based measurements
- Successfully demonstrated and used at SNS
  - Could work in < 1 sec if needed

Final cavity phase found within 1 degree, output energy within 1 MeV

Turned on cavity 4a, reduced fields in 11 downstream cavities

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Courtesy J. Galambos
Target Systems- Requirements

- Maximize the number of neutrons *escaping* from the target per proton incident on it.
- Accommodate high deposited power density (~1 MW/liter).
- Relative to the subcritical core, contribute in an insignificant way to the dose received by workers and the public under design basis accident scenarios.
- Operate reliably for more than six months between target replacements.
- Be capable of being replaced within a reasonable (about one week) maintenance period.
Target Systems – Technology Choices

• Solid target options, which consist of a solid material in the form of rods, spheres, or plates to produce the neutrons, and coolant flowing between the elements for heat removal.

• Liquid target options where a flowing liquid metal (LM) acts both as the source of neutrons and the heat removal media.
Target Technology Design Issues

• Neutronics
  ▪ Maximizing the neutrons/proton emerging from the target
  ▪ trade-offs between engineering, materials, safety, operational, and cost considerations.

• Thermal Hydraulics
  ▪ Heat Removal from target and window
  ▪ Design considerations include material compatibility, safety, radiation damage, remote handling and required reliability.

• Safety
  ▪ Adequate cooling
  ▪ Maintaining structural integrity
  ▪ Manage/contain radioactive inventory
  ▪ Accommodate accelerator induced transients

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Target Technology Design Issues, cont’d

• Target Lifetime
  ▪ Limitations from radiation-induced degradation of mechanical properties
  ▪ Corrosion and erosion from coolant (oxygen control in LBE to avoid corrosion)

• Accelerator/Target Interface
  ▪ Beam profile control and measurement
  ▪ Equipment protection for off-normal events

• Maintenance and Remote Handling
State of the Art: Operating MW-class Target Systems

- Solid-target
  - SINQ at PSI (~1.2 MW “DC” beam)
- Liquid Hg
  - Spallation Neutron Source (1.1 MW pulsed)
  - Japan Proton Accelerator Research Complex (0.3 MW pulsed)
- Pb-Bi Eutectic target
  - MEGAPIE at PSI (0.8 MW)
- Spallation targets for ADS application well above 1 MW will likely use heavy liquid metal cooling to achieve compact designs.
  - The only example of lead or LBE cooling for high power is the Russian LBE submarine reactors which were designed for approximately 150 MW.

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