Opportunities for Accelerators in Energy

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Outline

- **Paving the Way for Clean Energy - Helping Reduce the Nuclear Waste Stream**
  - **Spent Fuel Reduction**
  - **Thorium Reactors**
  - **ICF**
- **Tools for Future Energy Solutions - Materials Development For Fusion and Fission Systems**
  - **Materials Testing Needs**
    - **Fission**
    - **Fusion**
  - **Materials Testing Facilities**
    - **Triple beam**
    - **IFMIF**
    - **Spallation**
- **Energy-Related Spallation Neutron Science**

Disposal of Spent Nuclear Fuel is a Significant Impediment to the Use of Nuclear Reactors

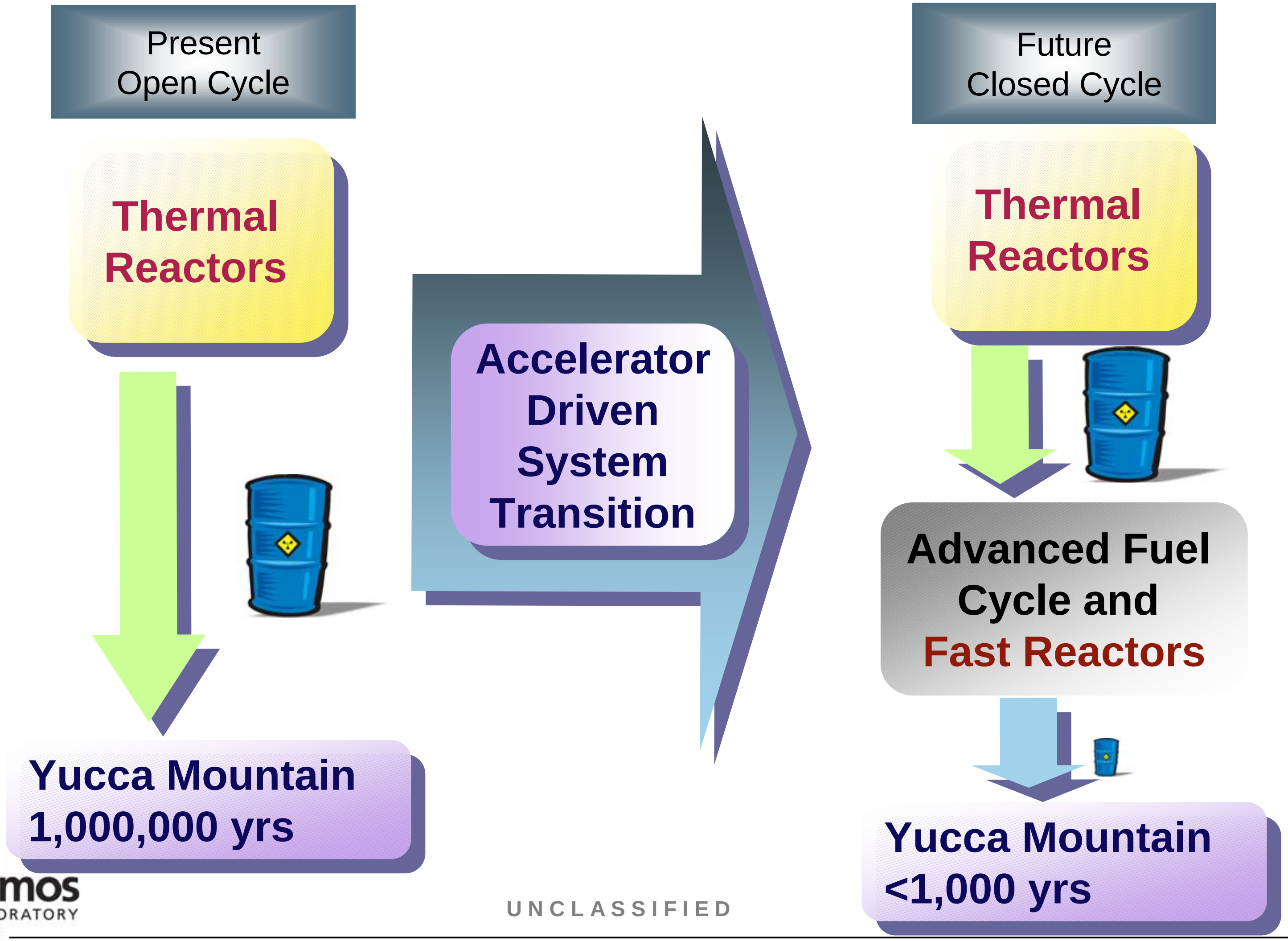
- In the United States, the roughly 100 operating reactors (which currently produce about 20% of the nation's electricity = more than 70% of the U.S. emission-free electricity) will create about 120,000 tons of such discharged or "spent" fuel over the course of their lifetimes.
- Sixty thousand tons of this spent fuel was destined for geologic disposal at the Yucca Mountain site in Nevada, along with another ~10,000 tons of defense waste.
- Worldwide, more than 250,000 tons of spent fuel from reactors currently operating will require disposal.

The Nuclear Fuel Cycle Appears Ideally Suited To Recycle

The potential exists to extract many times the energy while consuming problem “wastes” - but economics based only on fuel costs and concerns over material diversion favor the “Once-Through” or “Open” Cycle! However, large geologic repository costs (financial and political) have complicated nuclear technology implementation.

There must be better ways to utilize nuclear resources and reduce the waste problems….

The USA Needs To Transition From An Open To A Closed Nuclear Fuel Cycle



Present
Open Cycle

Thermal Reactors

Yucca Mountain
1,000,000 yrs

Accelerator Driven System Transition

Future
Closed Cycle

Thermal Reactors

Advanced Fuel Cycle and
Fast Reactors

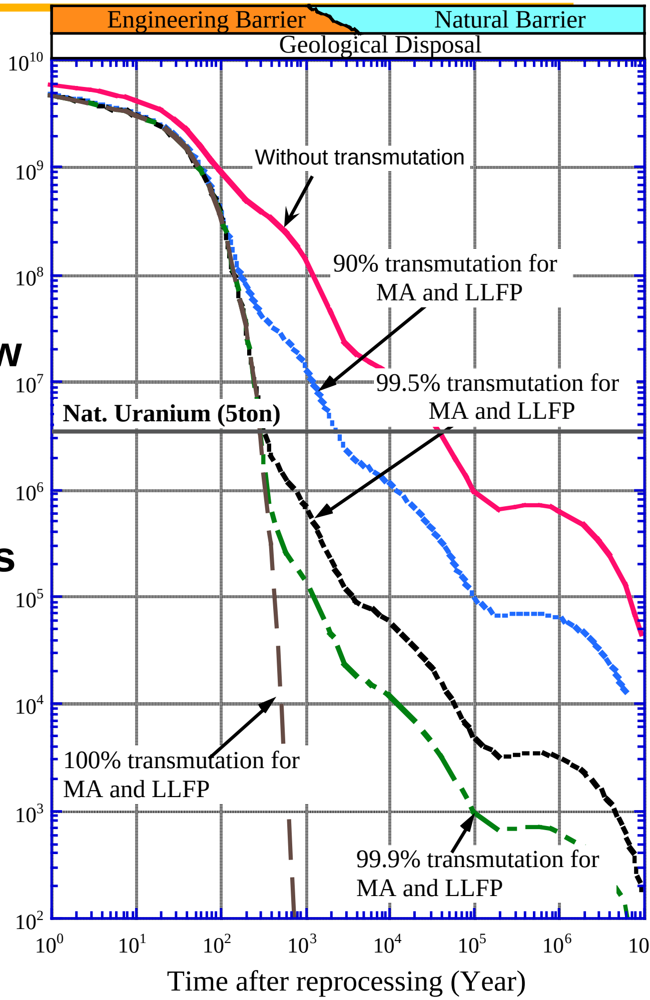
Yucca Mountain
<1,000 yrs

Transmutation Reduces Isolation Time-Frame to Within Engineered Barrier Limits

- **Unprocessed spent fuel contains materials that require isolation from environment for > 1,000 years**

  ➡ **Geologic Repository**

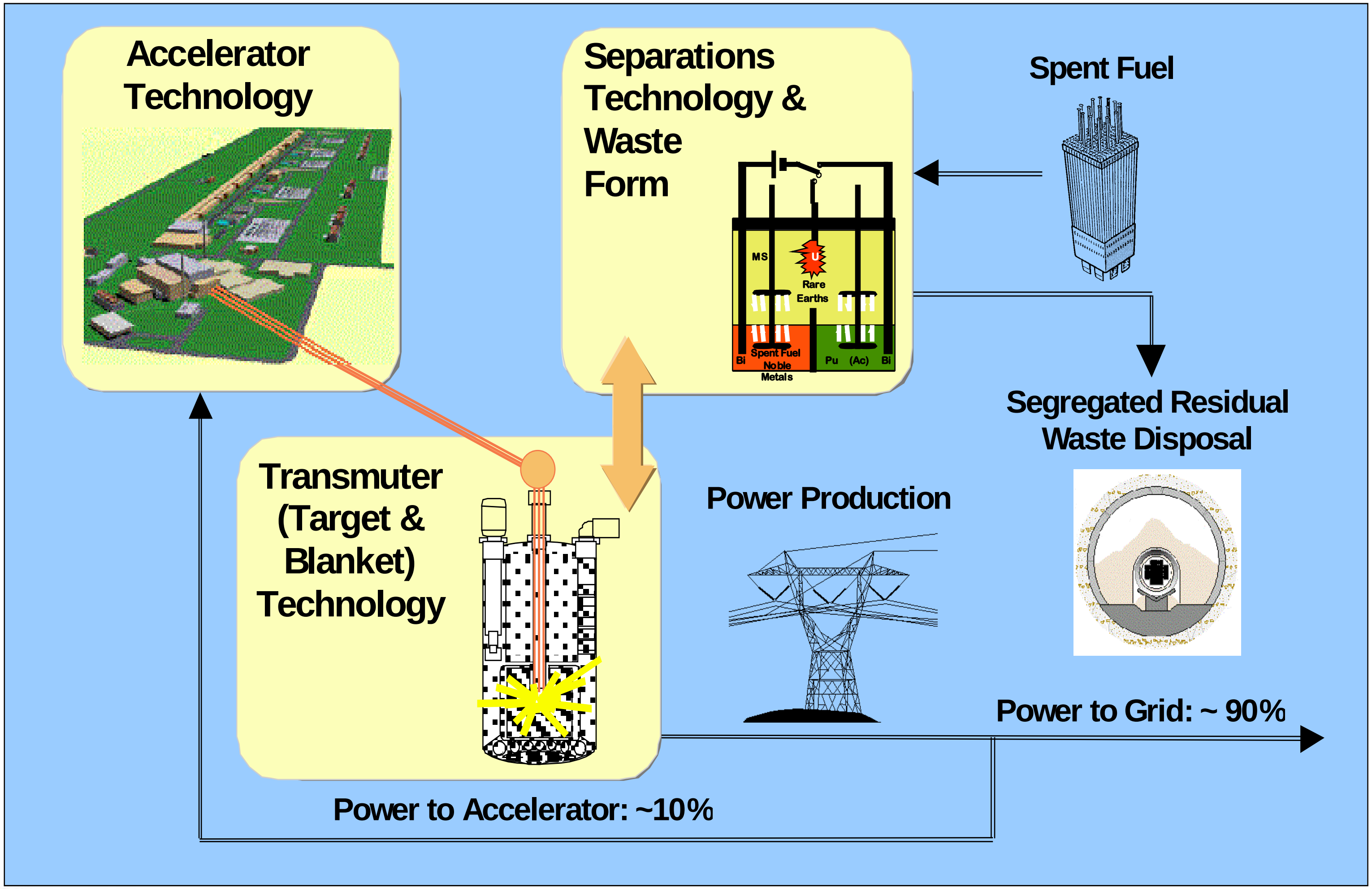
- **If Plutonium isotopes, Minor Actinides, Tc, and I are removed, requirements change:**
  - **Toxicity falls below natural uranium ore within a few centuries**
  - **Current man-made containers can provide more than 300 years of isolation**
  - **Geologic Strategy relies on geologic characteristics to isolate wastes after containers and barriers fail**
    - **Ground water transport a key issue; Climate change and populations shifts add uncertainty**
    - **Intrusions add further uncertainties**
- **Partitioning and transmutation can reduce isolation requirements within lifetimes of containers and barriers AND reduce incentives for intrusions**



LLFP: long-lived FP ($T_{1/2}$ >30years)

MA: minor actinide

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



Accelerator Technology

Separations Technology & Waste Form

Spent Fuel

Segregated Residual Waste Disposal

Transmuter (Target & Blanket) Technology

Power Production

Power to Grid: ~ 90%

Power to Accelerator: ~10%

Accelerator Driven System (ADS) Subcritical Operation Adds Flexibility

- Fission reactors have always operated “critical”; subcritical operation allows:
  - Driving systems with low fissile content (thorium or minor actinide) or high burden of non-fissile materials
  - Operating with fuel blends that could make critical systems unstable (Pu and minor actinide without uranium or thorium) *(Note: Addition of U to gain stability produces more Pu)*
  - Compensating for large uncertainties or burn-up reactivity swings
- The option to operate subcritical is especially useful for addressing fuel cycle issues and allows:
  - Jump-starting systems with insufficient fissile content
  - Supporting advanced fuel cycles by transmuting wastes
  - Closing-down fuel cycles with depleted fissile content

ADS Can Convert The Fraction Of Spent Fuel That Requires Ultra-long-term Isolation Into Materials That Are Primarily Stable Or Short-lived

The objectives include:

- Reducing isolation requirements to fit the lifetime of man-made containers and barriers.
- Reducing incentives and consequences of intrusions into repositories.
- Improving prospects for repositories and nuclear technologies.
- Improving fuel utilization.
- Making proliferation-resistant fuel streams.

Most likely: LWR waste will be the government's problem – this is consistent with a large ADS machine collocated with a government reprocessing facility.

Spallation Neutrons Can be Used to Drive a Subcritical Thorium Reactor

- Thorium (Th-232) is three to five times as abundant in the Earth's crust as uranium.
- An accelerator replaces the driver fuel, either U-235 or Pu-239, that is required for a critical thorium reactor.
- Spallation neutrons are directed to a subcritical reactor containing thorium, where the neutrons breed U-233 and promotes its fission.
- Thorium cycle is an on-going research effort, particularly in India.

A Subcritical Thorium Reactor Has Several Unique Characteristics

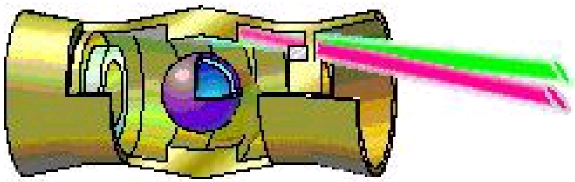
- The accelerator-driven fission reaction can readily be turned off and used either for power generation or destruction of actinides from the U/Pu fuel cycle.

- The use of thorium instead of uranium reduces the quantity of actinides that are produced.
  - Thorium cycle produces less plutonium than mainstream light-water reactors and what it does produce contains three times the proportion of plutonium-238, lending it proliferation resistance.

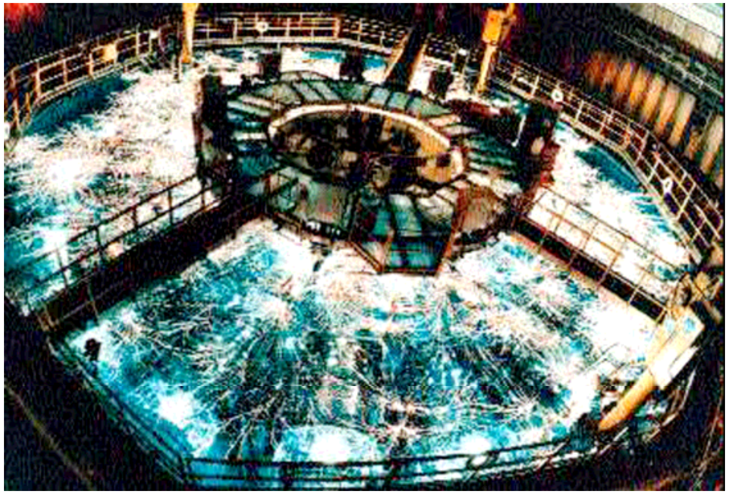
- Thorium cycle produces only half the amount of long-lived radioactive waste per unit of energy compared to mainstream light-water reactors.

An Alternative Inertial Confinement Fusion Drive Uses Induction Accelerators to Drive Heavy Ion Particle Beams

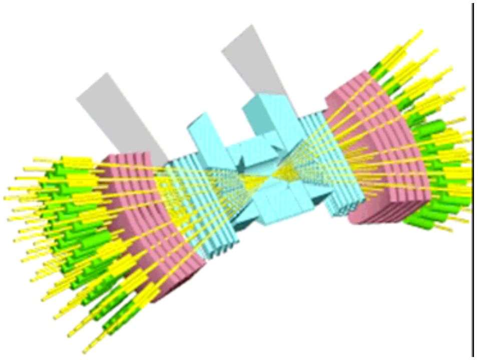
Virtual National Laboratory for Heavy-Ion Fusion (HIF-VNL) Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), and Princeton Plasma Physics Laboratory, is funded through the Office of Fusion Energy at the US Department of Energy



3-D drawing of a fusion target



Light Ion Fusion: The PBFA2 facility (Sandia National Laboratories, Albuquerque, NM) – ended in the early 90s



Heavy Ion Fusion: Pro-Engineer Model of HYLIFE-II Flibe pocket, cylindrical cross-jets, shielding, and final focus magnets.(Lawrence Livermore National Laboratories, Livermore, CA)

Induction linacs are typically less costly than RF linacs and more readily accelerate high-charge pulses

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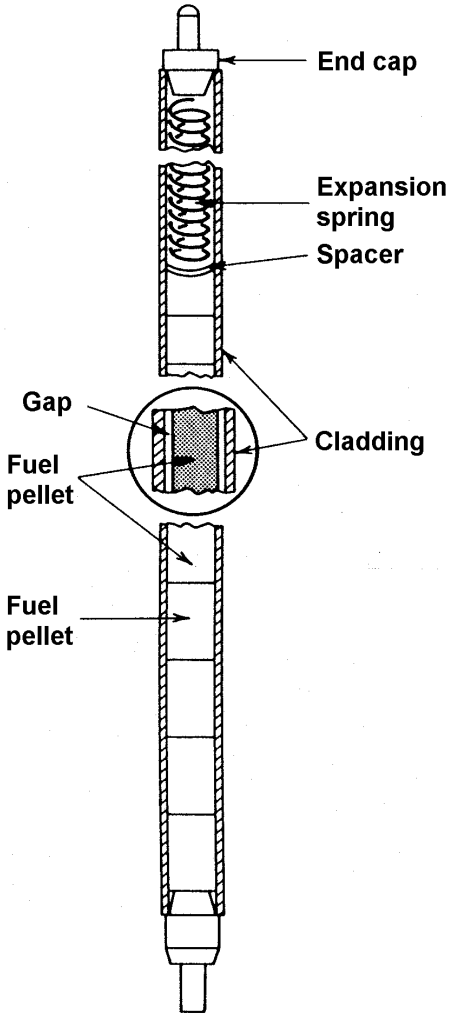
Licensing TRU-bearing Fuels For Fission Reactors Requires Proof Of Performance Of Nuclear Fuel And Cladding

- Transmutation fuels containing the transuranics (Np, Pu, Am, Cm) are now being developed for advanced reactor
- Qualification is a long process (~10 years or more)
- Irradiation testing in a prototypic environment is essential for fuel and cladding qualification
- Potential issues include
  - higher gas generation (especially He)
  - Need to achieve high burn-up (~20% or more)

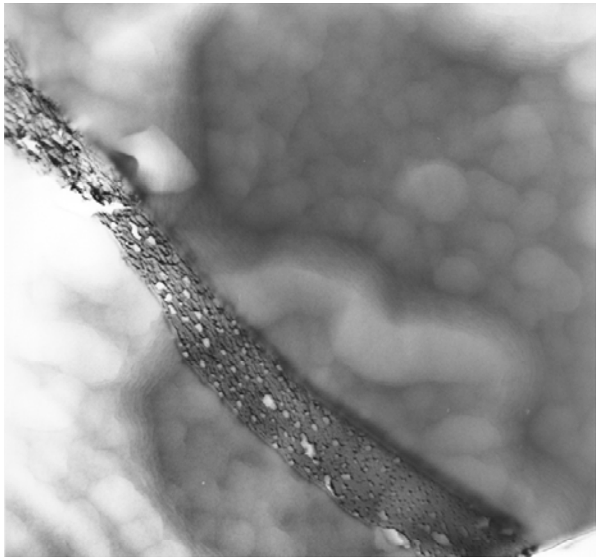
Irradiation testing in a thermal spectrum gives high fission rate but minimal clad damage, thereby missing any fuel-clad interaction failure mechanisms.



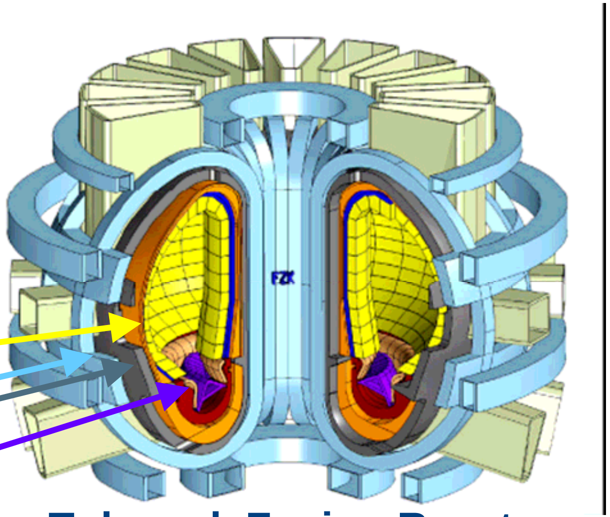
Development of Radiation Damage Resistant Materials Are Required For Fusion To Be Successful

Requirements for fusion materials:

- Low activation: shallow burial after 100 years desired, limits candidate elements
- Withstand fusion fluxes: maintain strength, ductility, structural integrity for 2 MW/m^2-s (10^{18} neutrons/m^2-s)
- Long lifetime: 5-10 years for full power operation with wall load of 2 MW/m^2; 1.5-3 x 10^{26} n/m2



He bubbles on grain boundaries can cause severe embrittlement at high temperatures



Tokamak Fusion Reactor

S. Zinkle, ORNL

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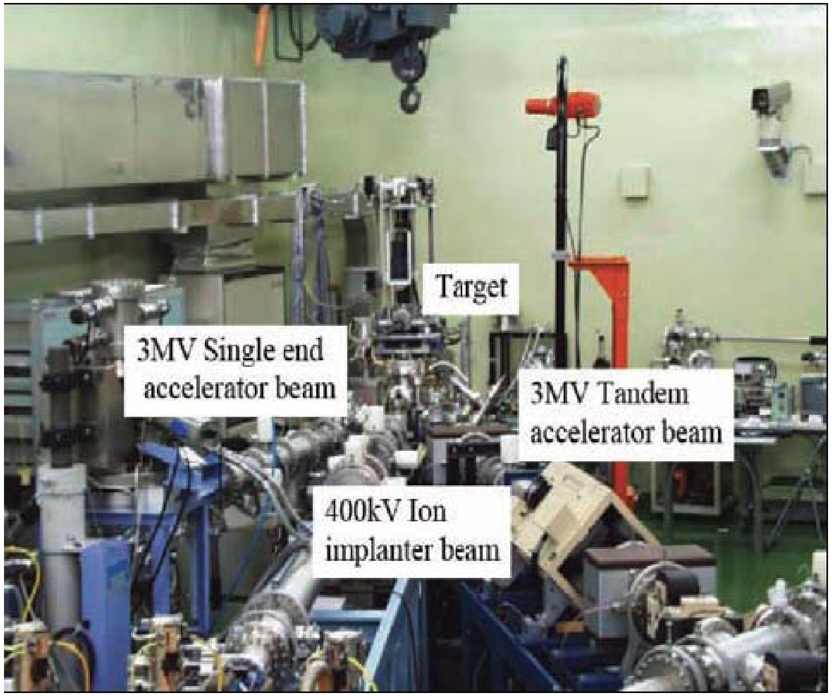
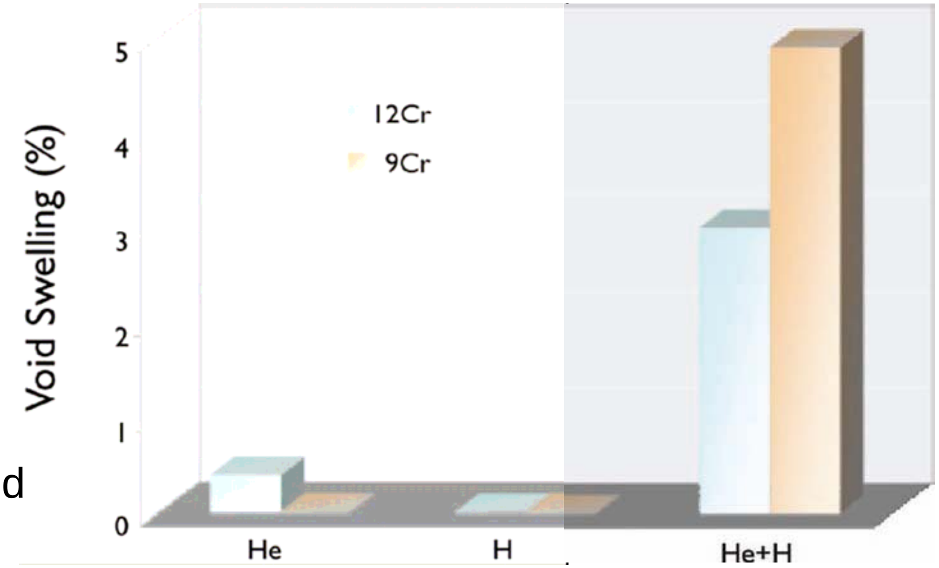
Triple Beam Ion Facilities Create High-radiation Damage Processes While Leaving Samples Nonradioactive



TIARA (Takasaki Ion Accelerators for Advanced Radiation Applications) triple beam facility.

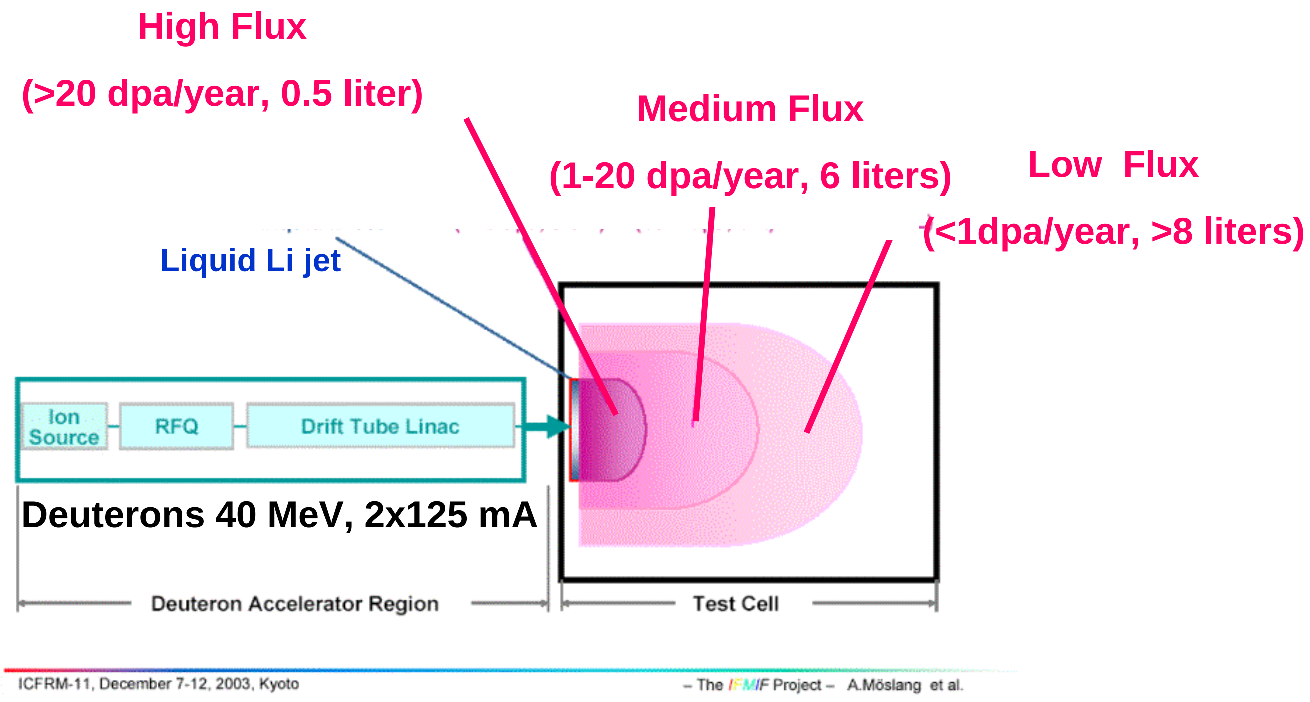
The synergistic effect of He and H was shown clearly in the triple ion ($Fe^{3+} + He^{+} + H^{+}$) irradiation of an FeCr steel. The facility consists of a 3-MV single-ended accelerator, a 3-MV tandem accelerator, and a 0.4-MV ion implanter.



The energy of the heavy ions is chosen to optimize penetration in bulk-like samples. The light ion energies are chosen so that the ions implant at the desired depths and intersect the displacement damage from the heavy ions.

Neutron Sources to Simulate 14 MeV Neutrons

- Fission Reactors (Materials Test Reactor, fast reactors – none in US)
- Spallation Targets
- International Fusion Materials Irradiation Facility (IFMIF)



High Flux

(>20 dpa/year, 0.5 liter)

Medium Flux

(1-20 dpa/year, 6 liters)

Low Flux

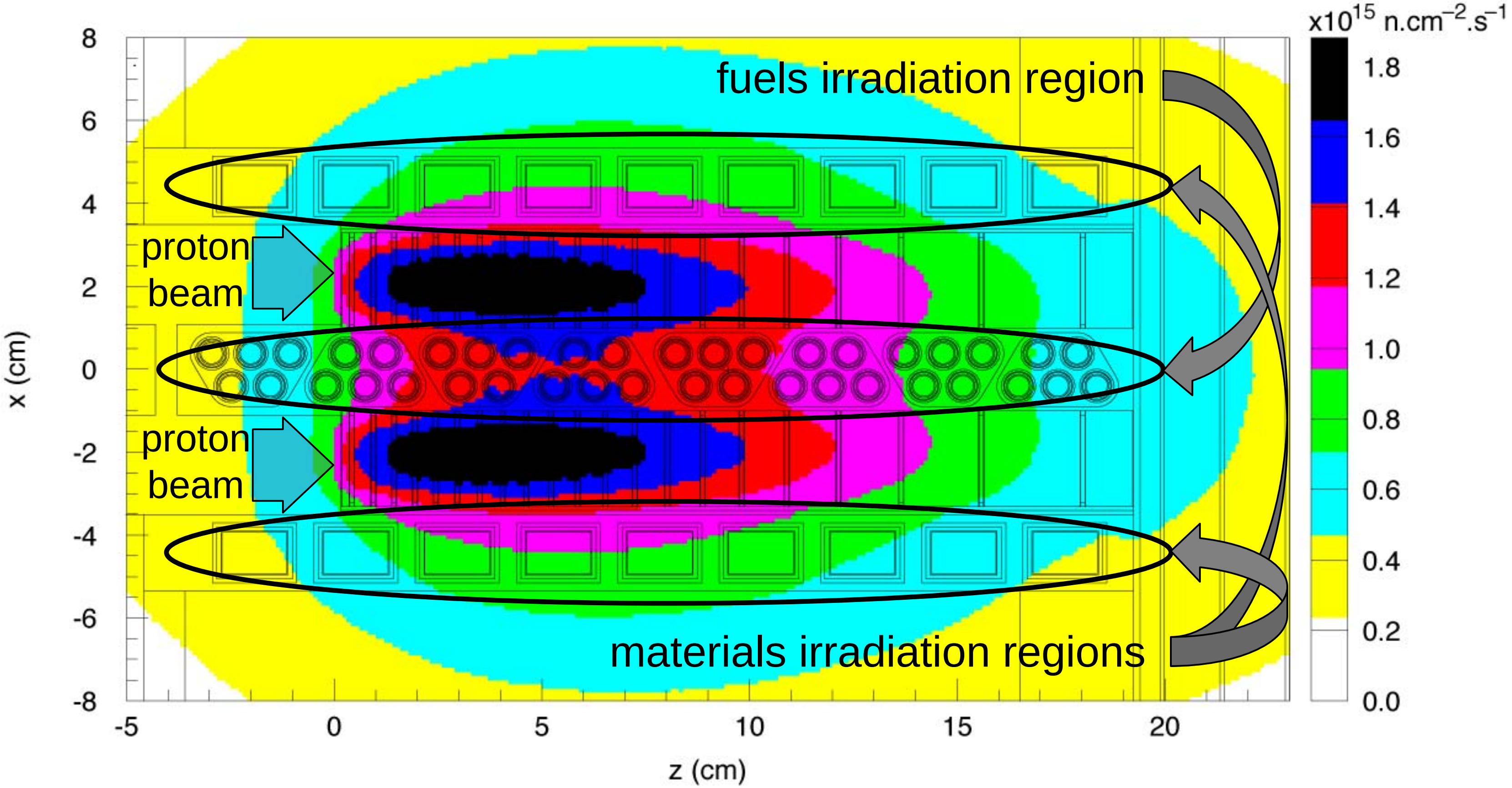
(<1dpa/year, >8 liters)

Liquid Li jet

Deuterons 40 MeV, 2x125 mA

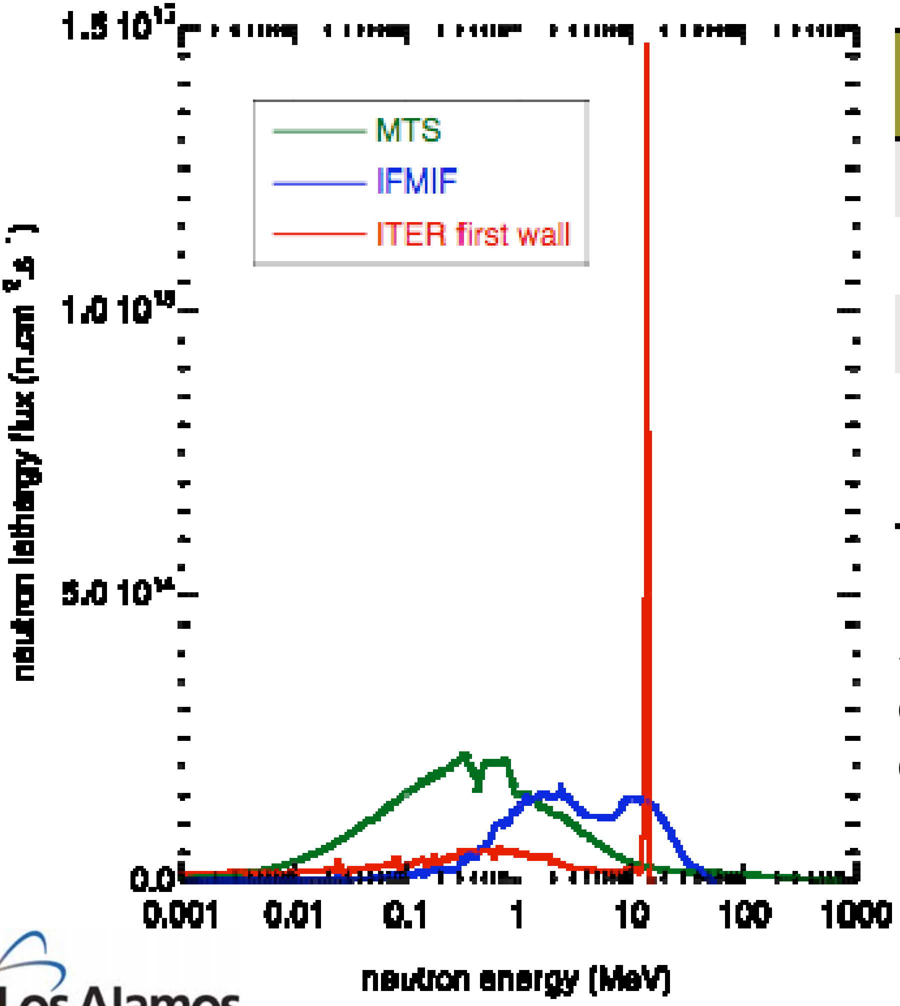
ICFRM-11, December 7-12, 2003, Kyoto – The IFMIF Project – A.Möslang et al.

A Spallation Source Produces An Intense Neutron Flux For Fast Reactor Fuels And Fission/Fusion Materials Irradiations



Though designed for fission irradiations, the neutron environment of the LANL MTS is well suited for fusion materials testing.

Though Fusion Reactors, Spallation Sources, And IFMIF Have Different Spectra, Materials Damage Is Similar



	MTS	IFMIF	Fusion Reactor
dpa/fpy	3-35	20-55	20-30
appm He/dpa	4-25	10-12	10-15
appm H/dpa	20-200	35-54	40-50
transmutations in Fe appm Mn/dpa	10	37	20-24

Spallation sources have higher recoil energies, but these ultimately yield sub-cascades similar to fusion first wall and IFMIF.

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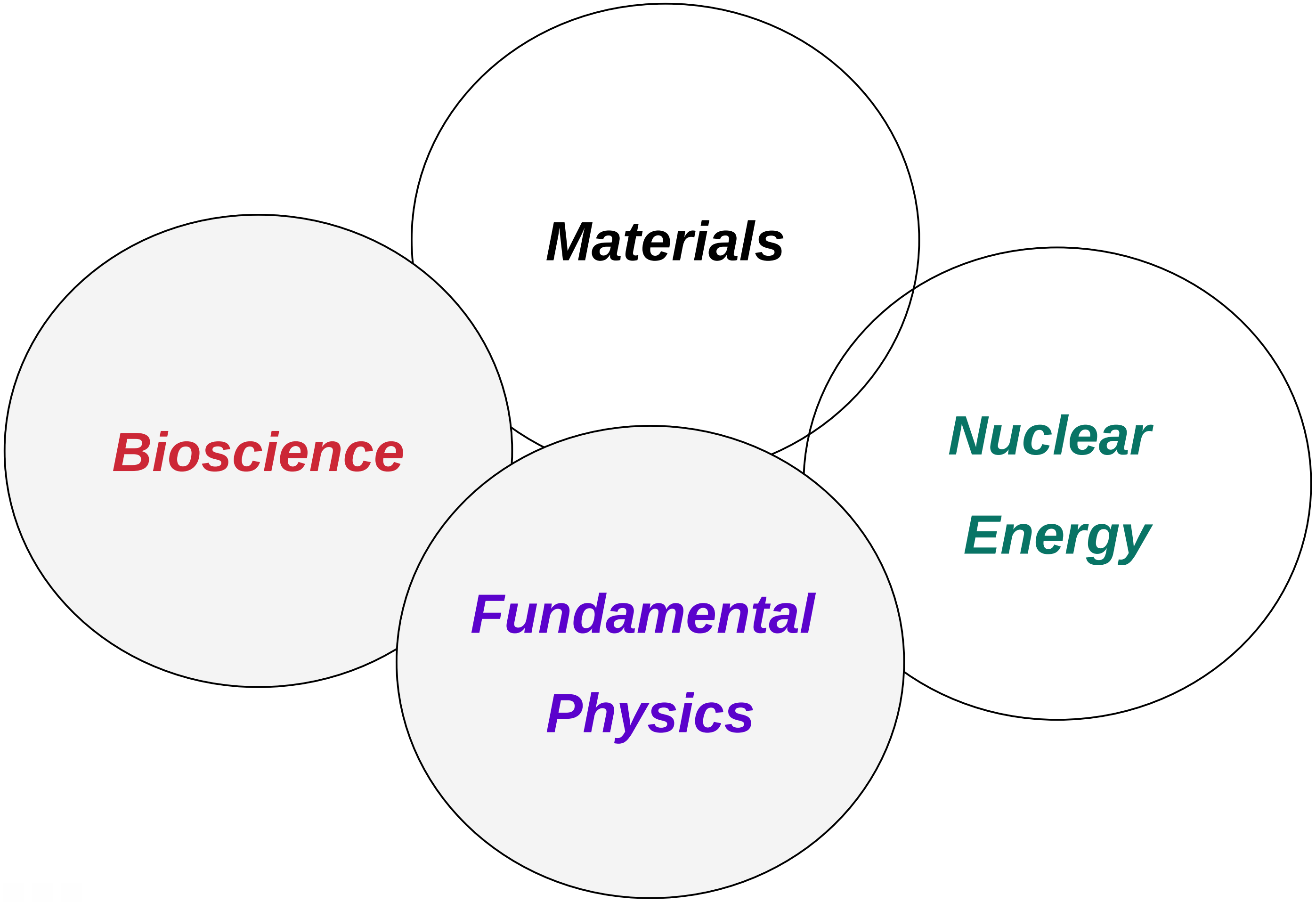
Spallation Sources, Such as the Lujan Center, WNR, and SNS, Enable a Broad Range of Significant Science Measurements



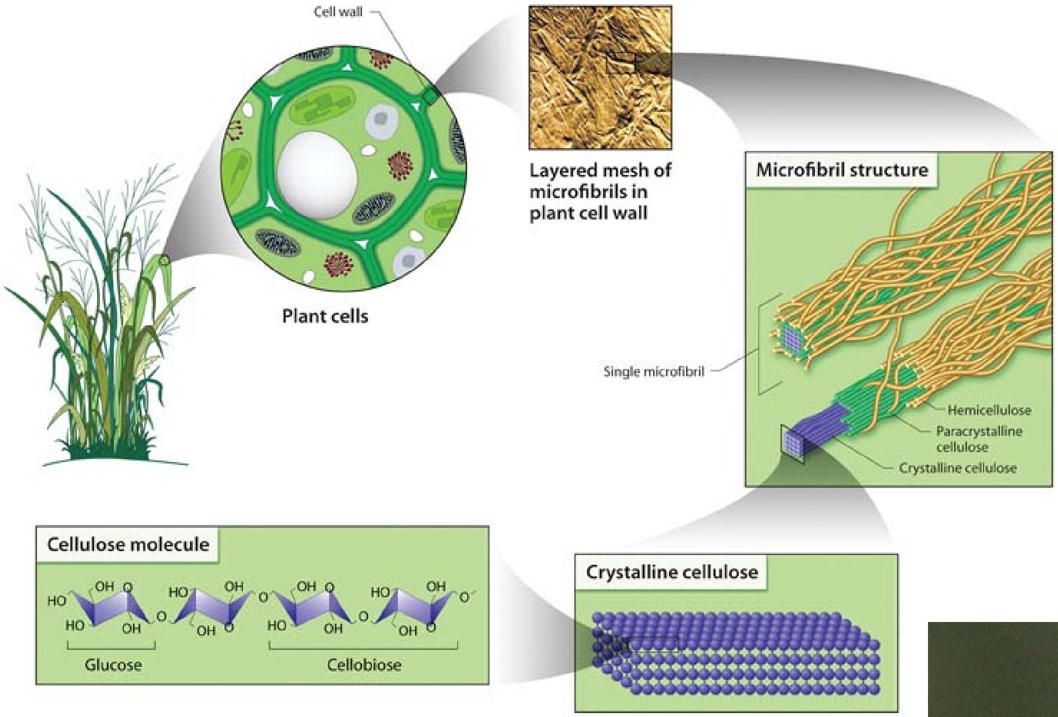
Materials

Bioscience

Nuclear Energy

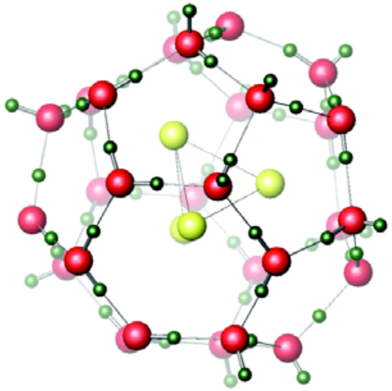
Fundamental Physics

Spallation Neutron Sources Play A Key Role In Research For Energy And The Environment



Biomass structure and conversion for 3rd generation biofuels

Hydrogen storage materials



Nuclear fuel cycle

Fundamental nuclear physics measurements needed for reactor design made at WNR facility:

- Capture and high-precision fission cross sections on actinides (Np, Pu, Am, Cm…)
- Gas production: (n,p), (n,α) reactions in structural materials

Conclusions

- **Accelerators are the tools for future carbon-free energy solutions.**
  - Manage spent LWR nuclear fuel during the transition to a Closed Fuel Cycle
  - Enable energy production from low fissile content fuels
  - Develop robust fusion and fission materials for advanced fuel cycles

- **Accelerator produced neutrons are tools for understanding the underlying science of next-generation energy systems.**
- **Research:**
  - High reliability, low fault accelerators
  - High efficiency, low-maintenance accelerator operations
  - Generation and matching of high-quality pulses for injection into induction linacs and addressing subsequent beam transport and focusing