Advanced Reactors and Accelerators: Alternative Pathways for Tritium Production

WANDA

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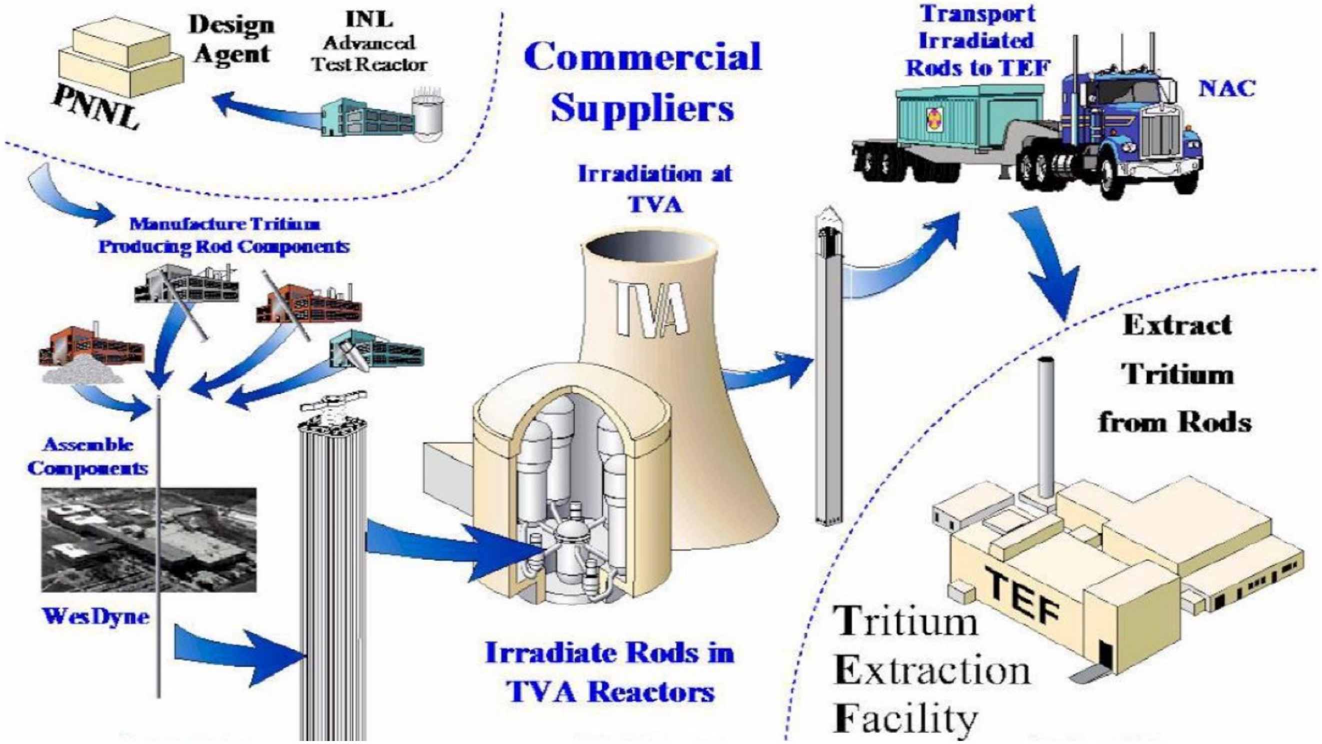
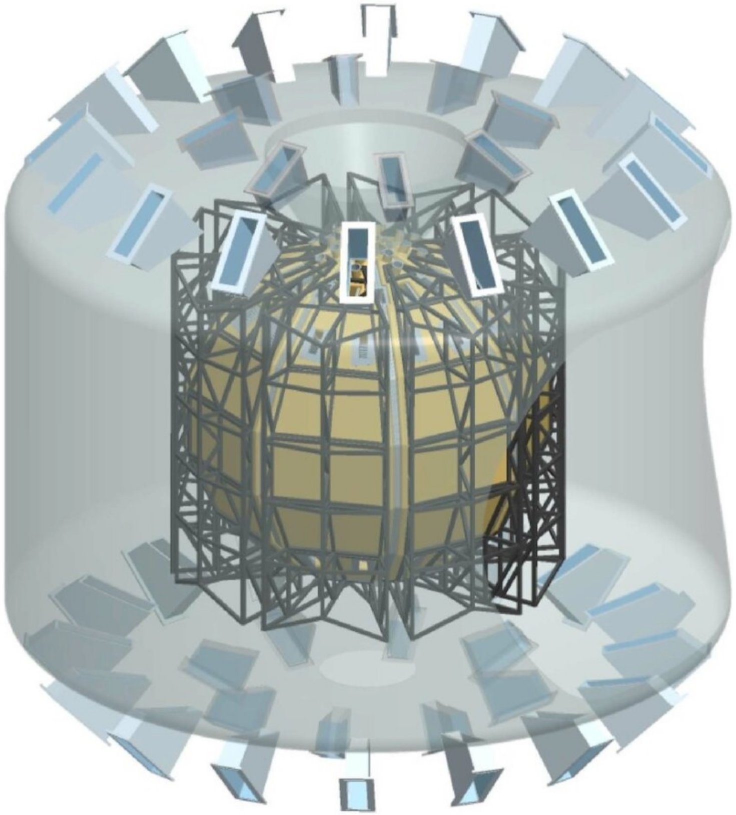
Traditional Pathways



- Tritium production and control will have large impacts for both the fusion energy lifecycle and nonproliferation applications.
- Tritium was traditionally bred in nuclear reactors using lithium encapsulated in TPBARs at TVA.

Tritium Production for Fusion Reactors

Inertial Confinement Fusion



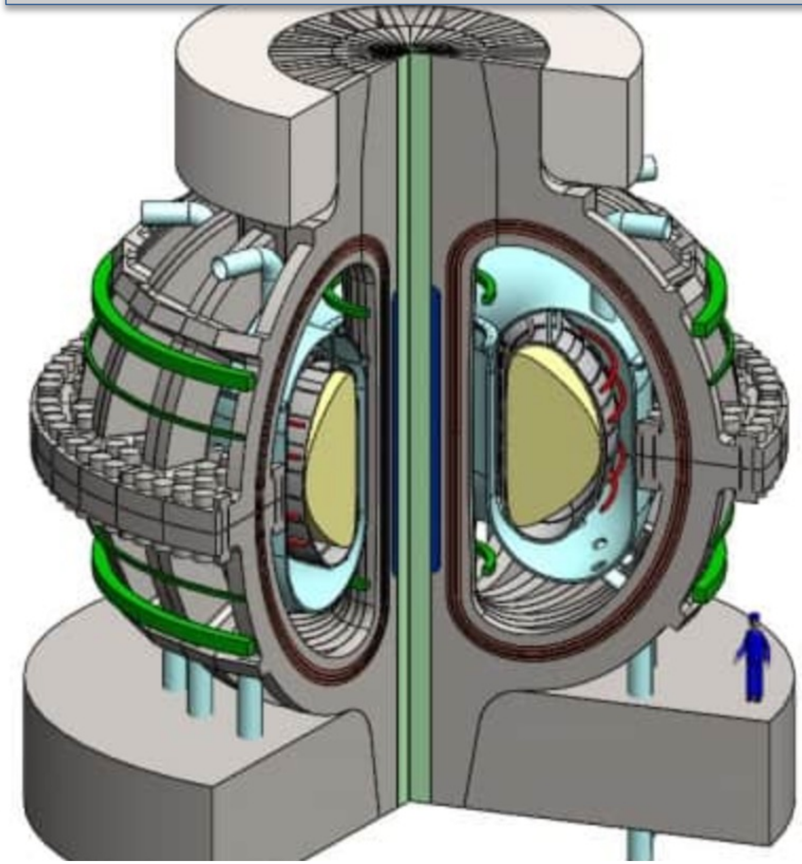
Latkowski, Jeffery F., et al. "Chamber design for the laser inertial fusion energy (LIFE) engine." *Fusion Science and Technology* 60.1 (2011): 54-60.

$^2H + {}^3H \rightarrow {}^4He + n(14\ \mathrm{MeV})$

$n + {}^6Li \rightarrow {}^4He + {}^3H$

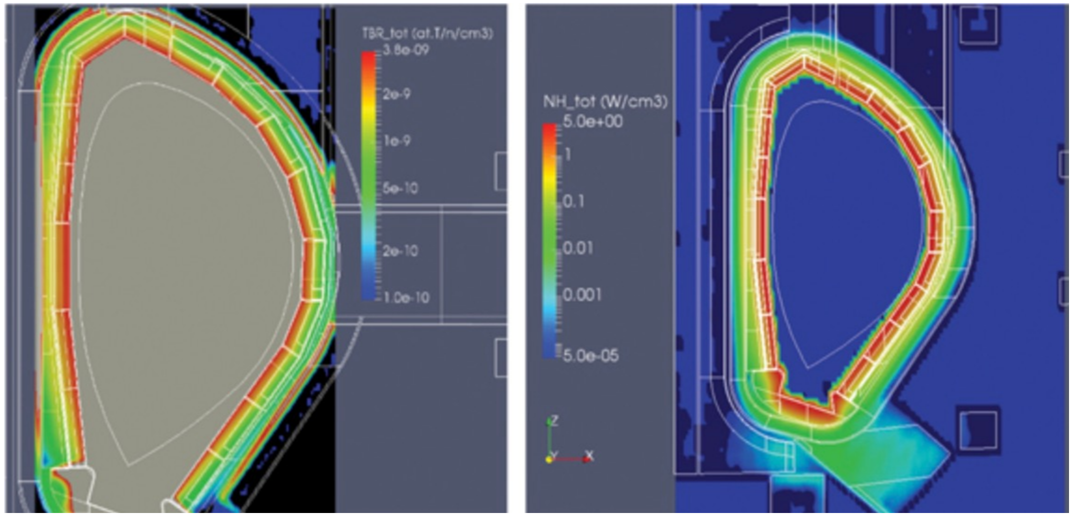
$n + {}^7Li \rightarrow {}^4He + {}^3H + n'$

Magnetic Confinement Fusion



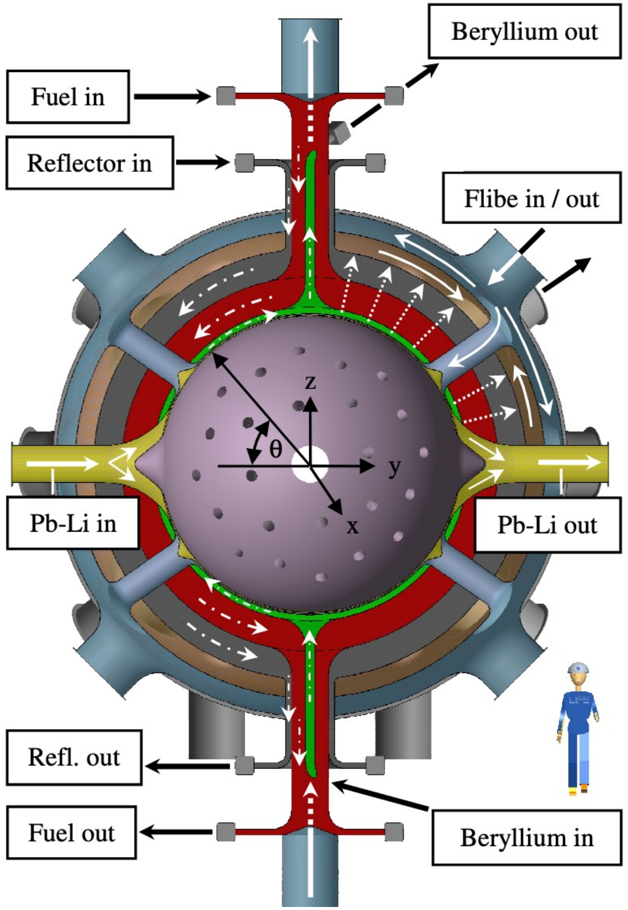
Segantin, S. et al. "Fusion Science and Technology." Fusion Science and Technology, 76,1 (January 2020): 45-52

Lithium Targets for Tritium Production for Fusion



D. Rapisarda *et al* 2021 *Nucl. Fusion* **61** 115001

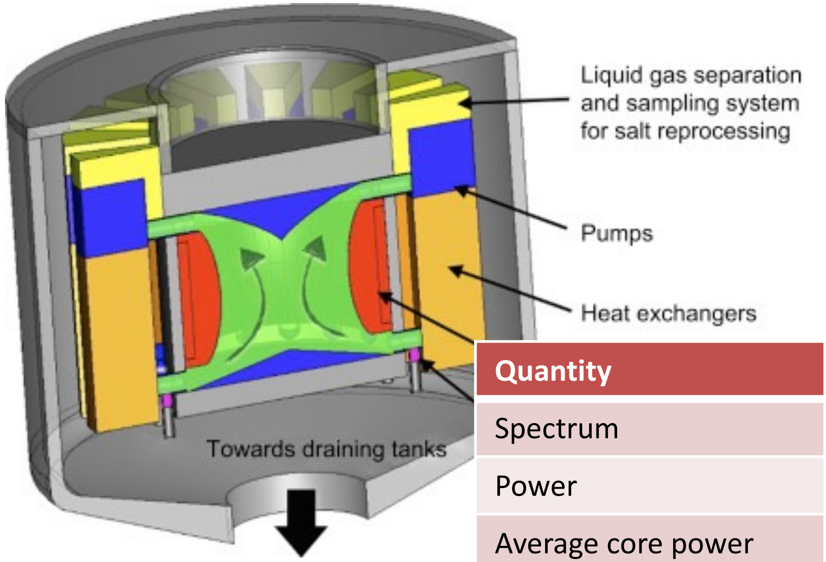
- In fusion reactors LiPb and FLiBe blankets are used to product tritium and transfer heat.
- Materials are selected for their ability to multiply neutrons and thermal-hydraulics properties.
- Unlike fission reactors the neutron economy is not essential to sustain reactions.



Abbott, Ryan P., et al. "Thermal and mechanical design aspects of the LIFE engine." *Fusion Science and Technology* 56.2 (2009): 618-624.

FLiBe Forms the Basis for Advanced Reactor Designs

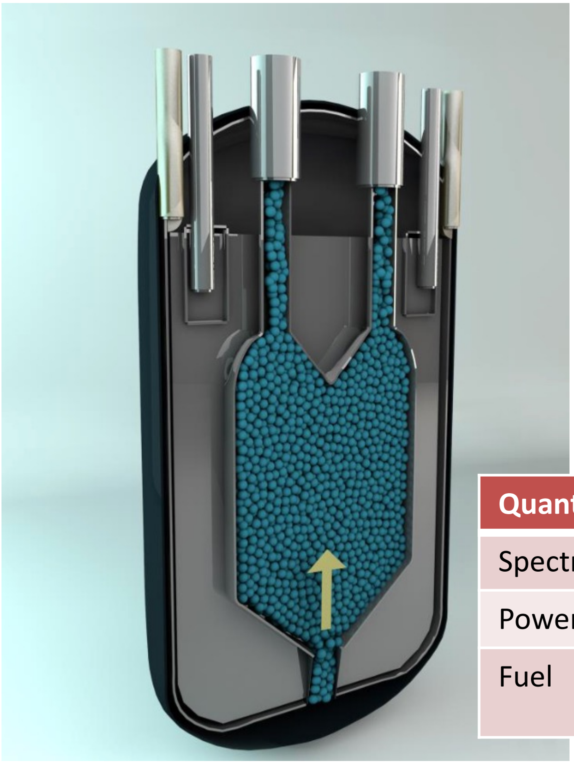
Molten Salt Reactors



Quantity	Value
Spectrum	Fast
Power	~3,000 MWth
Average core power density (per salt volume)	~350 MW/m3 (167 MW/m3)
Fuel	LiF-ThF$_4$-(^{233}U or ^{enr}U)F$_4$ or LiF-ThF$_4$-(Pu-MA)F$_3$ with 77.5 mol% LiF

Mauricio E. Tano,“Importance and Needs for Fission Product Yields in Molten Salt Reactor Chemistry and Corrosion Modeling”. Idaho National Laboratory. WANDA 2023

Fluoride-Salt-Cooled High-Temperature Reactors



Quantity	Value
Spectrum	Fast
Power	~300 MWth
Fuel	HALEU Triso-based fuels (annulus) Graphite core

Nadar Satvat “Nuclear data for Kairos Power’s Fluoride-salt cooled High Temperature Reactor (KP-FHR)” WANDA 2021

Reaction Channels for Advanced Reactors

- The neutron economy is directly proportional to the reactivity of these reactors.
- Detailed quantification of processes that absorb or produce neutrons is required for modeling reactor performance and tritium production.
- Nuclear data on ^{6}Li,^{7}Li,^{9}Be, and ^{19}F are essential, but have a different neutron energy distribution than a fusion reactor.

$$^{6}Li + n \rightarrow {}^{4}He + \boxed{^{3}H}$$

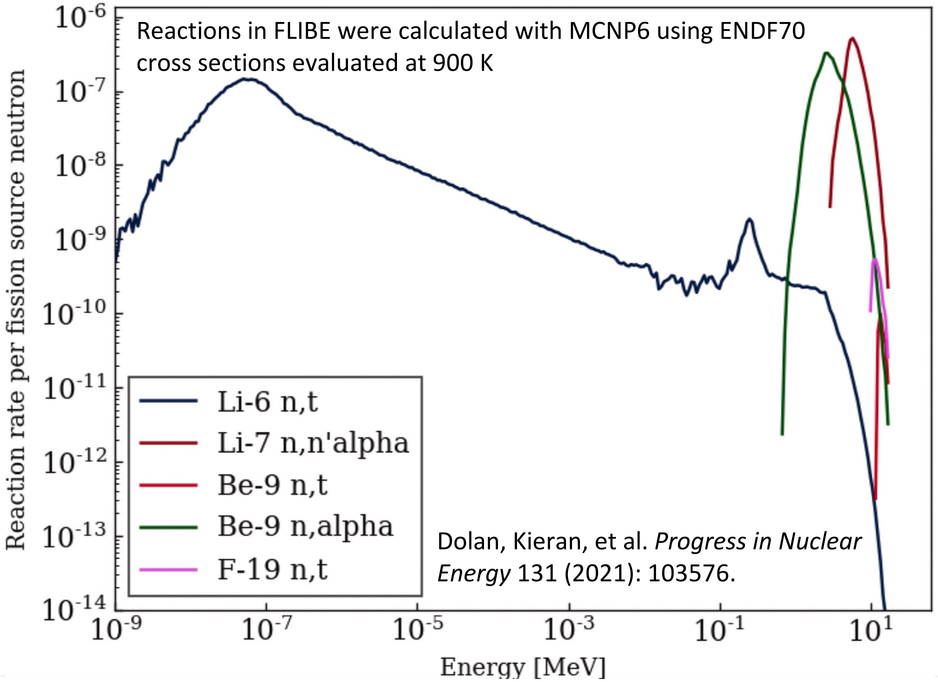
$$^{7}Li + n \rightarrow {}^{4}He + \boxed{^{3}H} + n'$$

$$^{9}Be + n \rightarrow {}^{7}Li + \boxed{^{3}H}$$

$$^{19}F + n \rightarrow {}^{17}O + \boxed{^{3}H}$$

$$^{9}Be + n \rightarrow {}^{6}He + {}^{4}He$$

$$^{6}He \rightarrow {}^{6}Li + \beta + \bar{\nu}_e \quad (\mathrm{t}_{1/2} = 0.8\ \mathrm{s})$$



Reactions in FLIBE were calculated with MCNP6 using ENDF70 cross sections evaluated at 900 K

Dolan, Kieran, et al. *Progress in Nuclear Energy* 131 (2021): 103576.

Tritium production from neutron capture on Boron-10

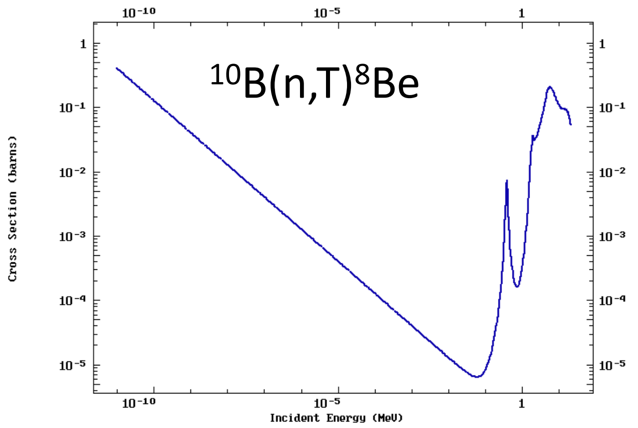
- Boron carbide is employed in Liquid Metal Fast Breeder Reactors (LMFBR).
- Boron is also used in control rods for criticality control.
- Boron is also being considered as the main component in neutron shielding systems for Fluoride-Salt Cooled High Temperature Reactors.
- In addition to products from the reactions, products can also decay to isotopes that produce Tritium.

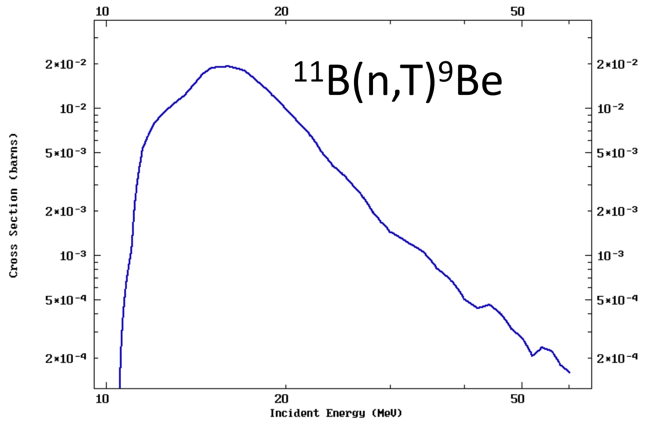
$$^{7}Li + n \rightarrow {}^{4}He + {}^{3}H + n'$$

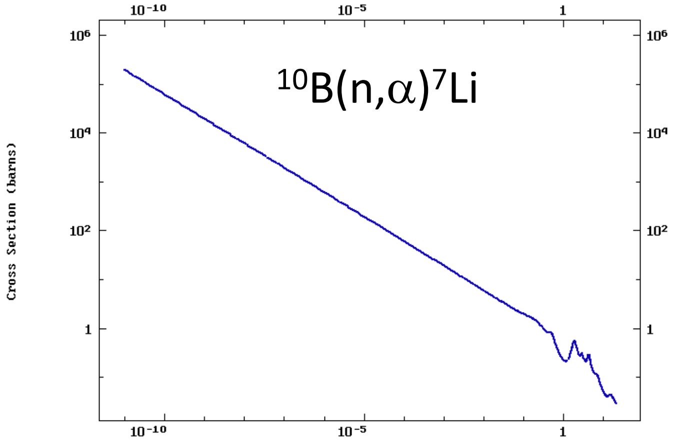
$$^{9}Be + n \rightarrow {}^{7}Li + {}^{3}H$$

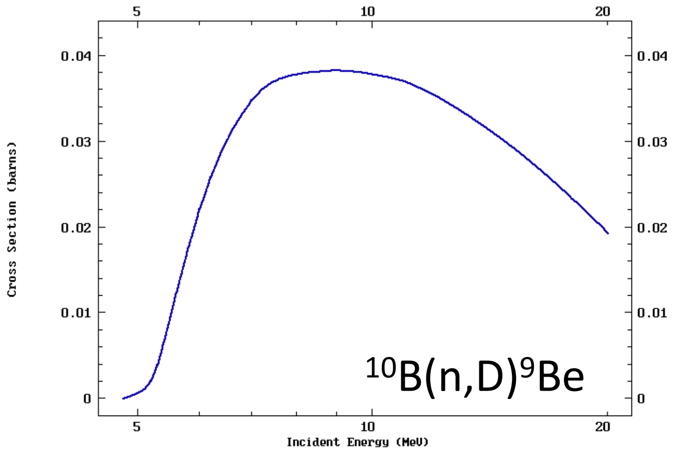
$$^{9}Be + n \rightarrow {}^{6}He + {}^{4}He$$

$$^{6}He \rightarrow {}^{6}Li + \beta + \bar{\nu}_e \quad (\mathrm{t}_{1/2} = 0.8\ \mathrm{s})$$


^{10}B(n,T)^{8}Be


^{11}B(n,T)^{9}Be

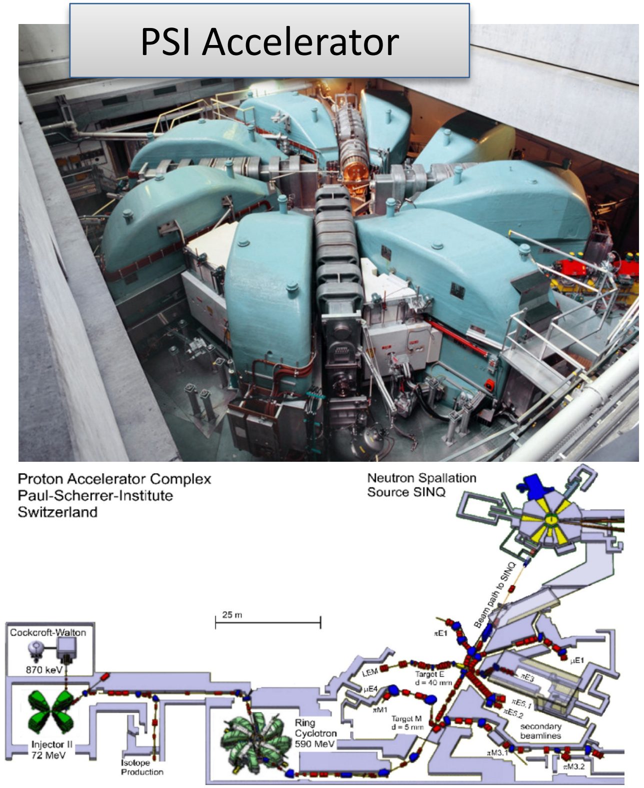

^{10}B(n,α)^{7}Li


^{10}B(n,D)^{9}Be

Accelerator Driven Systems

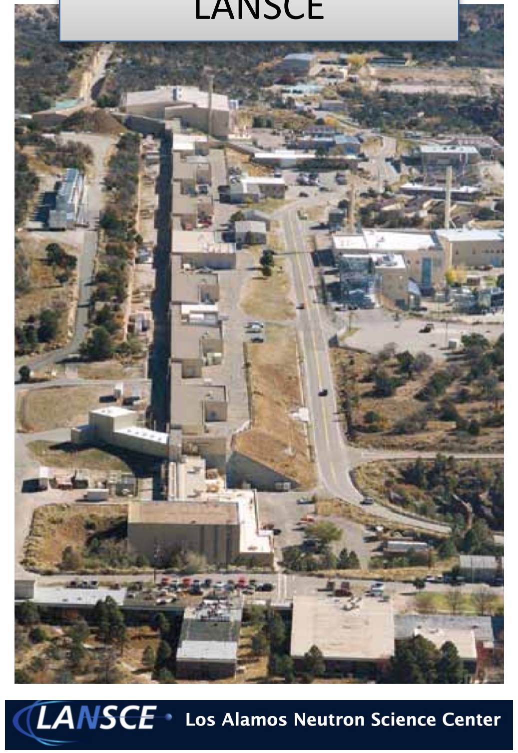
- Neutron capture drives tritium production.
- Other sources of tritium production under evaluation includes accelerator driven systems.
- Neutrons produced from accelerators require protons incident on spallation targets.

PSI Accelerator

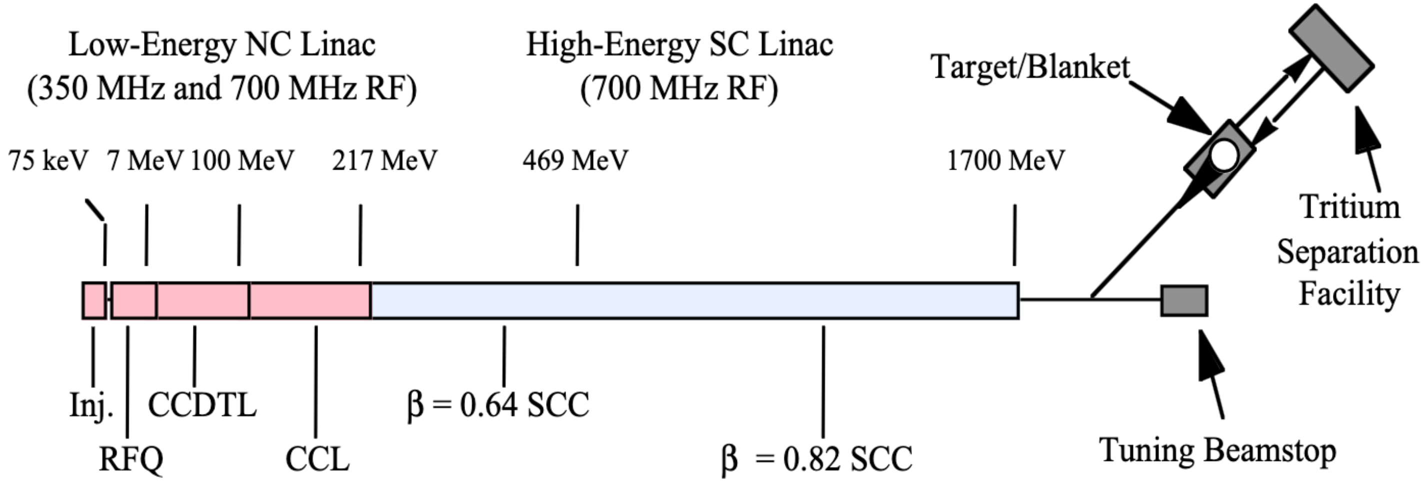


ORNL SNS

LANSCE



Accelerator Production of Tritium (ATP) Project



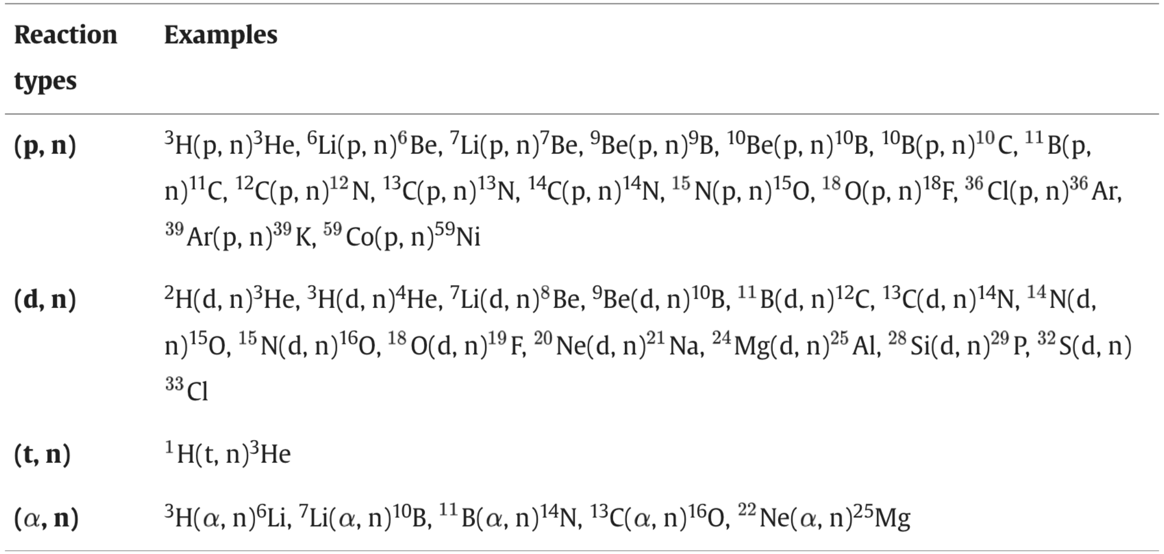
Accelerated Production of Tritium Plant Systems and Accelerator Architecture

Lisowski, Paul W. "The accelerator production of tritium project." *Proceedings of the 1997 Particle Accelerator Conference (Cat. No. 97CH36167)*. Vol. 3. IEEE, 1997.

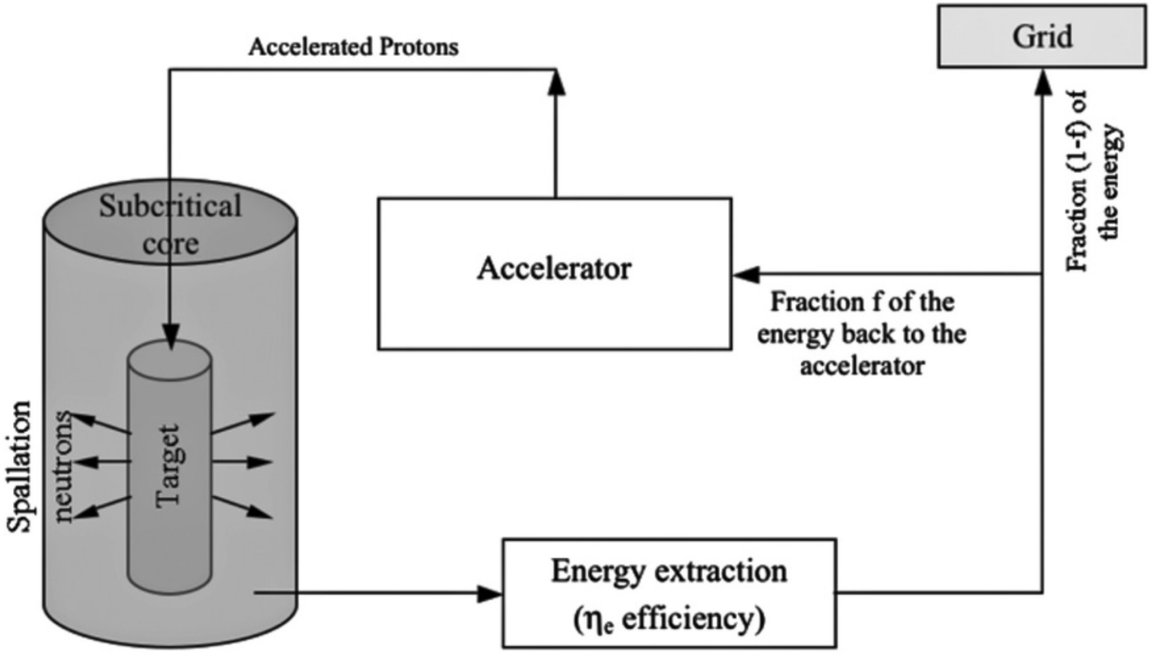
- The feasibility of tritium production using a linac accelerator was explored in the 90's.
- Tritium production was estimated to be ~7.4 kg per full power from ^{3}He gas targets.
- Reactor sources a have higher tritium output and lower cost.

Accelerator Driven Subcritical

- Numerous concepts for accelerator driven subcritical reactors have been proposed for energy production and breeding.
- Again, Li-based materials are of interest for tritium production as a direct target or as coolant.
- Nuclear data needs here are focused on the spallation targets for neutron production.



Reaction types	**Examples**
(p, n)	$^{3}H(p, n)^{3}He$, $^{6}Li(p, n)^{6}Be$, $^{7}Li(p, n)^{7}Be$, $^{9}Be(p, n)^{9}B$, $^{10}Be(p, n)^{10}B$, $^{10}B(p, n)^{10}C$, $^{11}B(p, n)^{11}C$, $^{12}C(p, n)^{12}N$, $^{13}C(p, n)^{13}N$, $^{14}C(p, n)^{14}N$, $^{15}N(p, n)^{15}O$, $^{18}O(p, n)^{18}F$, $^{36}Cl(p, n)^{36}Ar$, $^{39}Ar(p, n)^{39}K$, $^{59}Co(p, n)^{59}Ni$
(d, n)	$^{2}H(d, n)^{3}He$, $^{3}H(d, n)^{4}He$, $^{7}Li(d, n)^{8}Be$, $^{9}Be(d, n)^{10}B$, $^{11}B(d, n)^{12}C$, $^{13}C(d, n)^{14}N$, $^{14}N(d, n)^{15}O$, $^{15}N(d, n)^{16}O$, $^{18}O(d, n)^{19}F$, $^{20}Ne(d, n)^{21}Na$, $^{24}Mg(d, n)^{25}Al$, $^{28}Si(d, n)^{29}P$, $^{32}S(d, n)^{33}Cl$
(t, n)	$^{1}H(t, n)^{3}He$
(α, n)	$^{3}H(\alpha, n)^{6}Li$, $^{7}Li(\alpha, n)^{10}B$, $^{11}B(\alpha, n)^{14}N$, $^{13}C(\alpha, n)^{16}O$, $^{22}Ne(\alpha, n)^{25}Mg$



Ahmad, Ali, Benjamin A. Lindley, and Geoffrey T. Parks. "Accelerator-induced transients in accelerator driven subcritical reactors." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 696 (2012): 55-65.

Conclusion

- Tritium production is another consideration for nuclear data needs for advanced reactor.
- As both a neutron absorber and moderator, understanding tritium production in FLiBe requires a complete understanding of the neutron economy: poisons, burnups, fission products, etc.
- MSRs and FHRs come in various designs and nuclear data (and their uncertainties) plays a key role in their designs.
- Accelerator-based processes have been explored, but do not show maturity as of yet. However, accelerator driven subcritical reactors may be suitable for this application.

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