Used Nuclear Fuel for On-Ramping the Fusion Economy with Kilogram Quantities of Commercial Tritium

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High-Level Project Scope

- A multi-mission Accelerator Driven System + [sub-critical] Molten Salt Assembly (ADS+MSA) facility for a reliable source of domestic, commercial tritium.
  - Tritium production and energy recovery by burning fuel [owned by the federal government (U or Pu) in a sub-critical configuration.
  - Federal agencies (like ARPA-E) have shown interest in civilian applications (nuclear waste transmutation) and restarted funding efforts.

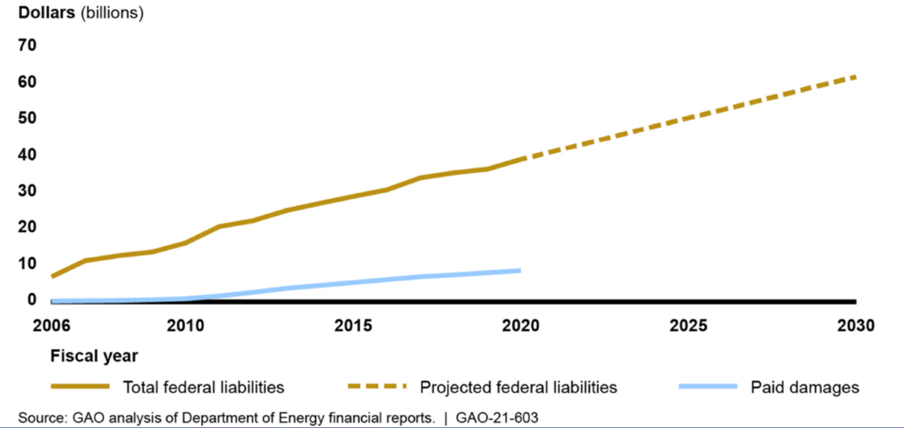
- What we don't want to do:
  - Provide excess power to wider grid.
    - Avoid competition with local utilities.
    - Can still use the excess power for an on-site grid (or for energy intensive processes (H_2 production).
  - Have regulatory entanglements.
    - Sub-critical system == no Nuclear Regulator Commission (NRC) license?
  - Make radioisotopes?
    - Not at this time, due to additional cost and licensing relative to the mission.

- Department of Energy (DOE) has more flexibility and experience in operating this sort of facility.
  - A centralized tritium production facility will decrease fusion plant complexity, cost, and reduce proliferation concerns.

Financial and and Legal Considerations

- As of 09/2024, the federal government has paid out $11.1 billion (~$400M) / year in damages to nuclear utilities.
  - Total liabilities as of 2024: $37.6-$44.5B (increase of ~$3.5B from 2023, does not include money already paid out).

- Consolidated Interim Storage Facility (CISF).
  - With Yucca Mountain off-limits for it's use as a long-term, geologic storage facility, temporary options are being considered.
  - Yucca Mountain was licensed for ~70,000 MT of Used Nuclear Fuel (UNF).
    - Currently there are ~100,000 MT of UNF around the country at generator site.
    - We would now need 2 Yucca Mountain's to handle our current UNF that is stored at reactor sites and the UNF increases by 2000 MT/yr.



Projected federal liabilities (penalties) that are paid to utilities to store UNF. Government Accountability Office, "Commercial Spent Nuclear Fuel" 2021.

LANL's Interest In This Effort

- LANL has historically been a lead institution in using high-powered accelerators for important applications related to our nuclear deterrent and stockpile stewardship.

- This history leads to a unique wealth of institutional knowledge related to large, accelerator applications projects and the new technology areas we need to develop for our system.

- Projects directly related to our current effort:
  - Accelerator Transmutation of Waste (ATW).
  - Accelerator Production of Tritium (APT).
  - Matter Radiation Interactions in Extremes (MaRIE) and the Materials Test Station (MTS).
  - Drift-tube linac for the Spallation Neutron Source (SNS).

Accelerator Capability, Technology and Operations

- We are leveraging the technologies and knowledge-base that were put together over 30+ years at LANL.
  - Low-Energy Demonstration Accelerator (LEDA)
    - 100% duty factor (cw) Radio Frequency Quadrupole (RFQ).
    - Accelerated proton beam from 7.5 keV → 6.7 MeV, to 100 mA of beam current.
    - 8 m in length.
    - ~$300 million (adjusted for inflation) for engineering design and demonstration.
- New design would require:
  - 100% duty factor (cw), ~20 mA beam current.
    - This kind of beam current (5-20 mA) is used in similar RFQs for cancer treatment (2.5 MeV beam).
    - Not quite commercial, off-the-shelf technology…but getting there.
      - Advances made during the original APT (and other LANL accelerator projects) contributed to the development of the current generation of accelerator technology.
      - Like many discoveries emanating from the Manhattan Project, the commercial and (life-saving) value may not be known for decades.

Tritium

- Total tritium inventory on the planet is ~25 +/- 14 kg [1].
  - Only ~4 kgs is natural (i.e., from cosmogenic sources).
  - ~20 kgs from atmospheric nuclear weapons tests (peaked in early 1960s, decreasing ever since) and from nuclear power plants.
- US atmospheric nuclear tests are not coming back.
  - 1963 Test Ban Treaty (signed, ratified, and entered in to force in 1963). Banned nuclear testing in the atmosphere, underwater, and in space.
- Each 5-year delay in International Thermonuclear Experimental Reactor (ITER) D-T operations == 24.6% decrease in pre-existing global commercial tritium inventory.
- There will be a severe tritium resource shortage for larger DEMO and Inertial Fusion Energy plants.

https://postalmuseum.si.edu/object/npm_1980.2493.5161

[1] P.E. Oms, et al., "Inventory and distribution of tritium in the oceans in 2016”.

Current US Domestic Tritium Production for Civilian Use

Current International Tritium Production for Civilian Use

- Most commercial tritium is produced in critical reactors with a heavy water (D_2O) moderator and coolant.
- Canada:
  - CANada Deuterium Uranium (CANDU) reactors.
    - Producing ~100 grams ^3H/yr/600 MW.
    - ~1.5 kgs annually extracted from Canadian Reactor Fleet at the Darlington Tritium Removal Facility.
- CANDU technology was exported to several countries that won't export tritium:
  - Argentina.
  - China.
  - India.
  - Pakistan.
  - Romania (with a planned tritium extraction facility at Cernavoda).
  - South Korea (Wolsong Tritium Extraction Facility).

https://natural-resources.canada.ca/energy-sources/nuclear-energy-uranium/canadian-nuclear-energy-technology

https://energyeducation.ca/encyclopedia/CANDU_reactor

https://www.iter.org/mag/8/tritium-changing-lead-gold

https://cna.ca/reactors-and-smrs/how-a-nuclear-reactorworks/

- There will barely be enough commercial tritium to fuel ITER.
  - Each 5-year delay in ITER D-T operations == 24.6% decrease in pre-existing global commercial tritium inventory.
  - Planned D-T DEMO reactors will need 10s of kgs ^3H at startup.

Tritium and Commercial Fusion Development

- Fusion economy is projected to be multi-trillion $ beyond 2050 [1].
- Current commercial costs for tritium are ~$33 million / kg.
  - A 1- 2 GW_{th} D-T fusion energy plant will require 56-112 kg of ^3H/full-power-year.
    - What will the cost be of ^3H operations at a commercial fusion power plant?
  - If a fusion plant costs the same as a fission plant ($20 billion to build) tritium capabilities > $2 billion / plant.

- Regulatory Changes:
  - Nuclear Regulatory Commission (NRC) decision to regulate fusion reactors under 10 CFR Part 30 (“byproduct utilization facilities”), does not imply regulations won’t change.
    - Legal risk: Atomic Energy Act can be amended at any time to change definitions.

− Our proposed facility would operate under DOE O 420.2D, Safety of Accelerator Facilities and other related statutes.

[1] https://www.cnbc.com/2025/03/16/the-us-is-falling-behind-china-in-nuclear-fusion-needed-to-power-ai.html.

Tritium Production Rates for an ADS+MSA With Actinide Fuel

- First principles calculation:
  - Consumption rate for actinides > 1.0 g/MW/day.
    - At 1 GW_{th} > 1.0 kg/day.

- Tritium production rate at 1 $GW_{th:}$ > 1.5 kg ^3H/year.

- Tritium Breeding Ratio (TBR) in fusion power plants ~ 1.1-1.2.
    - ADS+MSA TBR > 20 tritons/neutron.

- Scalable solution: Each additional MSA (or MW_{th}) increases your tritium production rate.

Advantages to the Accelerator Driven Sub-Critical Molten Salt Assembly (ADS+MSA) Concept

- Performance:
  - Energy recovery while burning UNF.
    - Net-energy out to run accelerator, other local facilities, and energy intensive industrial processes.
  - Sub-critical operation allows greater flexibility in fuel and fuel-forms that are difficult (or impossible) for typical critical reactors.
- Non-Proliferation:
  - Final product is proliferation resistant. Actinides are locked up in the salt, making recovery difficult.
    - ^{6}Li (and ^{3}H) are accountable nuclear materials. ^{6}Li hasn't been produced in the US since 1963.
    - Beryllium compounds are hard to deal.
    - It is easier to prevent [or ascertain] material diversion and safeguard one/few government-owned facilities vs. many fusion plants.
- Government-owned Fuel Assets:
  - Low-Enriched Uranium (LEU, ~5% enriched U-235, > 90,000 MT) owned by DOE (UNF at civilian reactor sites).
  - Pu (> 7 MT) owned by DOE/NNSA.
  - Highly-Enriched Uranium (HEU, > ?? MT) owned by DOD (spent fuel).
- Burn <u>metric tons (MT) of actinides (U/Pu/Am) and produces kg quantities of tritium</u>, annually.
  - No dependence on enriched uranium supply.

Summary

- Energy transitions are costly.
  - Nuclear power plants provide the solution for a growing, 21st century technological economy that needs reliable baseload power.
  - An expansion in nuclear fission power plants (capacity factors > 0.90, technology available now, inherently carbon-free), with fusion power coming in the following decades.
  - Recent Presidential Executive Orders are changing the nuclear power landscape.

- Our proposed ADS+MSA concept can be used in a commercial tritium mission for on-ramping the fusion economy.
  - DOE has the experience to operate this facility.
  - DOE can engage with industry on a cost recovery scheme for its commercial tritium product.
  - Fusion companies can reduce their exposure to the (known and unknown) risks and other costs ($100s M → $B+) associated with tritium breeding, processing, recovery, storage.
  - A centralized tritium production facility will decrease fusion plant complexity, cost, and reduce proliferation concerns.

- Sub-critical system can burn government-owned fuels not possible in critical reactors.
  - Tritium Breeding Ratios for an ADS Using U/Pu Fuel are > 20 tritons/neutron using current technology.