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SRF Linacs Driving Subcritical MS Reactors vision: Burning LWR SNF On 65 US Sites path to vision: Burning Pu at SRNL

Rolland Johnson

Muons, Inc. - http://muonsinc.com/

BHAG: Big Hairy Audacious Goal,

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from"Built to Last: Successful Habits of Visionary Companies"

by Jim Collins and Jerry Porras (2004)

Bob Wilson's BHAG: make superconducting magnets so powerful and efficient that they make possible new kinds of accelerators and colliders to study the smallest things in the universe.

1970s – SC magnet conductor developed
major spin-off – SC magnets for MRI
1982 – SC Energy Doubler/Accelerator
1985 – Tevatron proton-antiproton collider
1995 – Discovery of the Top Quark
2010 – Large Hadron Collider
2014 – Discovery of Higgs Boson

Our Big Hairy Audacious Goal:

To make SRF accelerators so powerful and efficient that they make enough neutrons to produce nuclear energy for electricity or process heat at less cost than from wind, solar, or natural gas, without weapons proliferation legacies of enrichment and chemical reprocessing, by burning unwanted nuclear materials.

New Technology, Old Technology

- Superconducting Radio Frequency Accelerators
  - First demo of scale and power needed
    - Oak Ridge National Lab Spallation Neutron Source
    - Achieves 1 MW power **Sept 28 2009** -1.4 MW now
    - 6% duty factor implies more than 20 MW CW possible
- Molten-Salt Graphite-Moderated Reactor
  - ORNL Molten Salt Reactor Experiment (MSRE)
    - new approach to reactors(**1964-1969**)
- Merging these technologies allows
  - Eliminating enrichment and chemical reprocessing
  - Subcritical operation for safety and easier licensing
  - Deeper burns to extract more energy from fuel

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What is Muons, Inc.?

- Muons, Inc.
  - Founded 2002, subsidiaries - MuPlus, Mu*STAR
    - by Scientists from US National Labs
  - Funded by DOE contracts and SBIR-STTR grants
    - total of ~$30M
  - Tools and technology for particle accelerators
  - 8 US university and 11 national lab research partners
    - extraordinary people work with us
  - Supported 18 post-docs and 7 Ph.D. students
  - accelerator-driven molten-salt nuclear reactors
    - Major focus of our companies

SRF Linacs need efficient microwave power

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Muons, Inc. is developing power sources for Superconducting Radio Frequency Linacs under SBIR-STTR awards and contracts. First tests of two magnetrons underway now. Magnetrons up to 90% efficient vs klystrons 50%. Capital cost 1/5 of klystrons

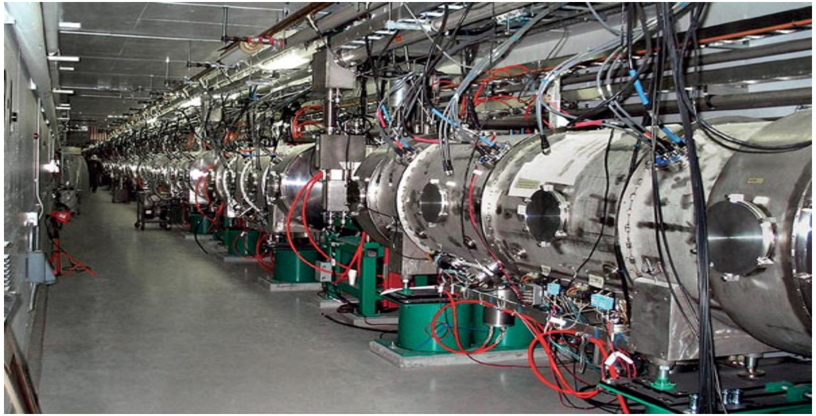
Magnetron cathodes and rf window

You may use kitchen microwave ovens to make popcorn. They are powered by magnetrons and the oven is an example of a (non-superconducting) RF cavity.

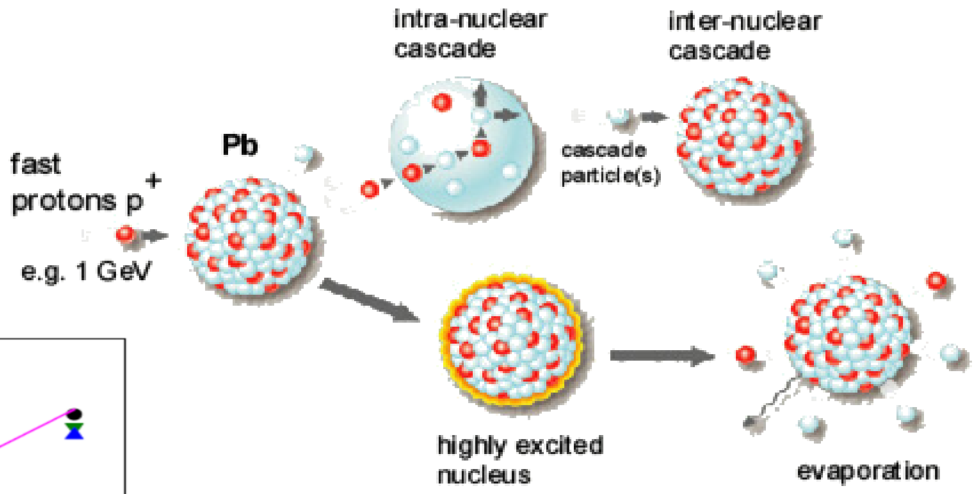
Breakthrough Technology – Superconducting RF Linac

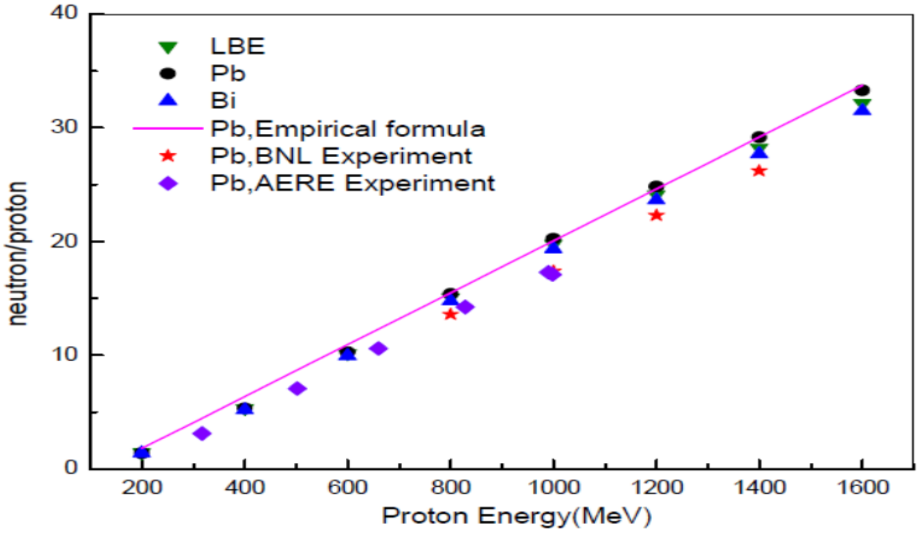
- Demonstrated at the ORNL Spallation* Neutron Source (SNS)
- Generates many neutrons to control reactor reactivity
- Powerful, efficient, affordable, reliable

*1 p produces > 30 n



Spallation requires Protons





Target	600 MeV	800 MeV	1000 MeV
Fe	3.7	5.3	6.7
Pb	9.6	14.3	18.5
W	9.9	16.0	20.0
U	18.0	26.0	33.3

ORNL Molten Salt Reactor Experiment

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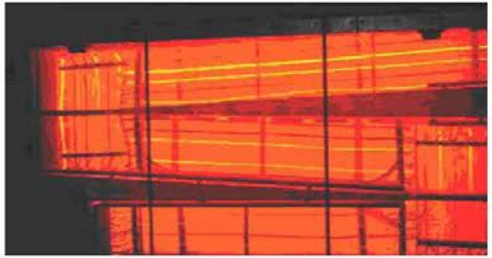
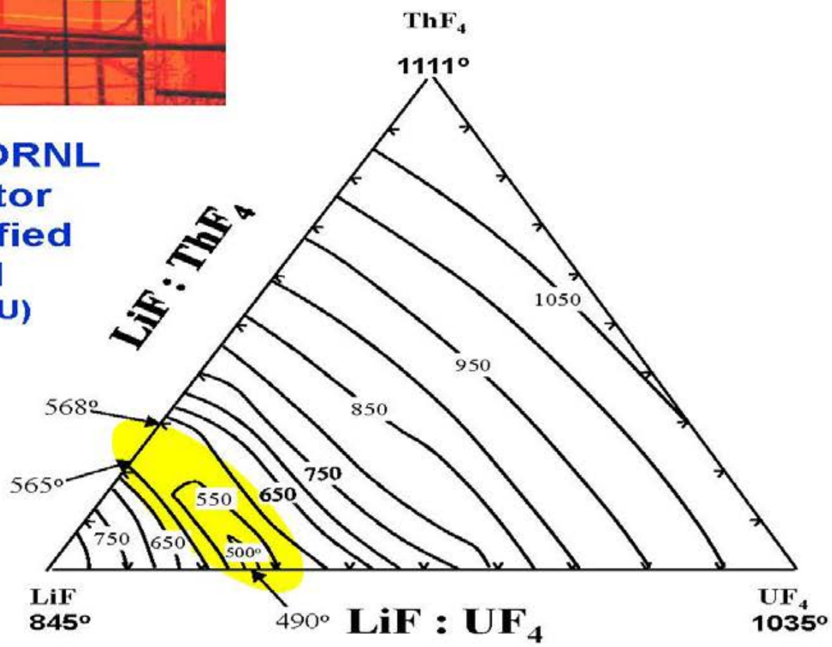
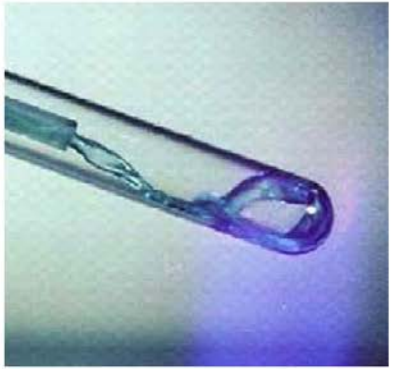
- Molten Salt Reactor Experiment operated at ORNL,1964-1969.
- Demonstrated the key aspects of using molten salt fuel.
- Critical reactor tested with three different fuels.
- Mu*STAR based on MSRE parameters-Temperature, graphite, Hastelloy-N
- Graphite MSRE core ¼ linear dimension of Mu*STAR, 4^3 = 64 times Power

Molten Salt Eutectic Fuel



Proven in ORNL MSRE reactor using Modified Hastelloy-N
(^{235}U, ^{239}Pu, ^{233}U)



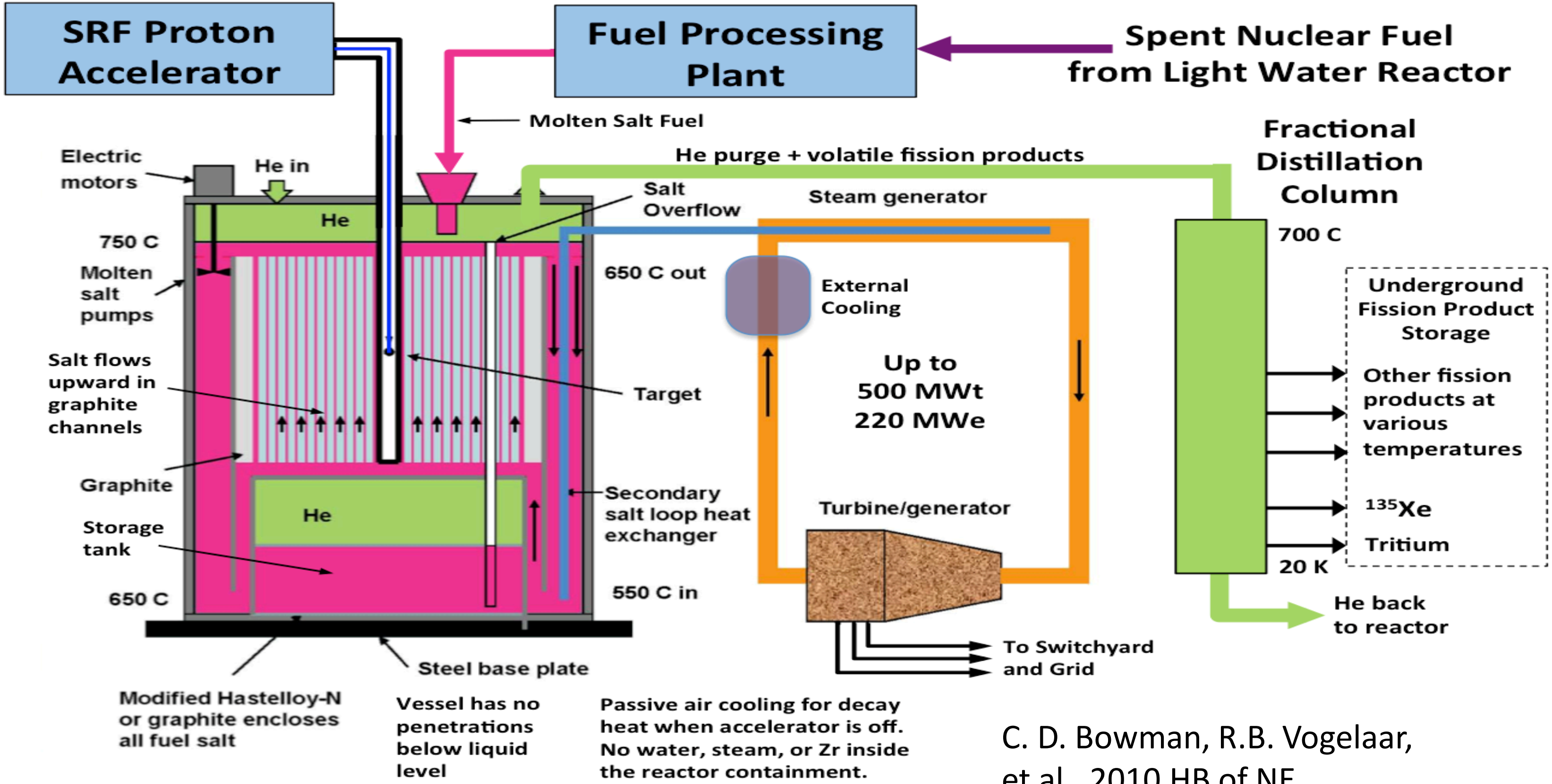


Uranium or Thorium fluorides form eutectic mixture with ^7LiF salt.

High boiling point → low vapor pressure

GEM*STAR

Reactor Concept



C. D. Bowman, R.B. Vogelaar, et al., 2010 HB of NE

No penetrations below level of fuel

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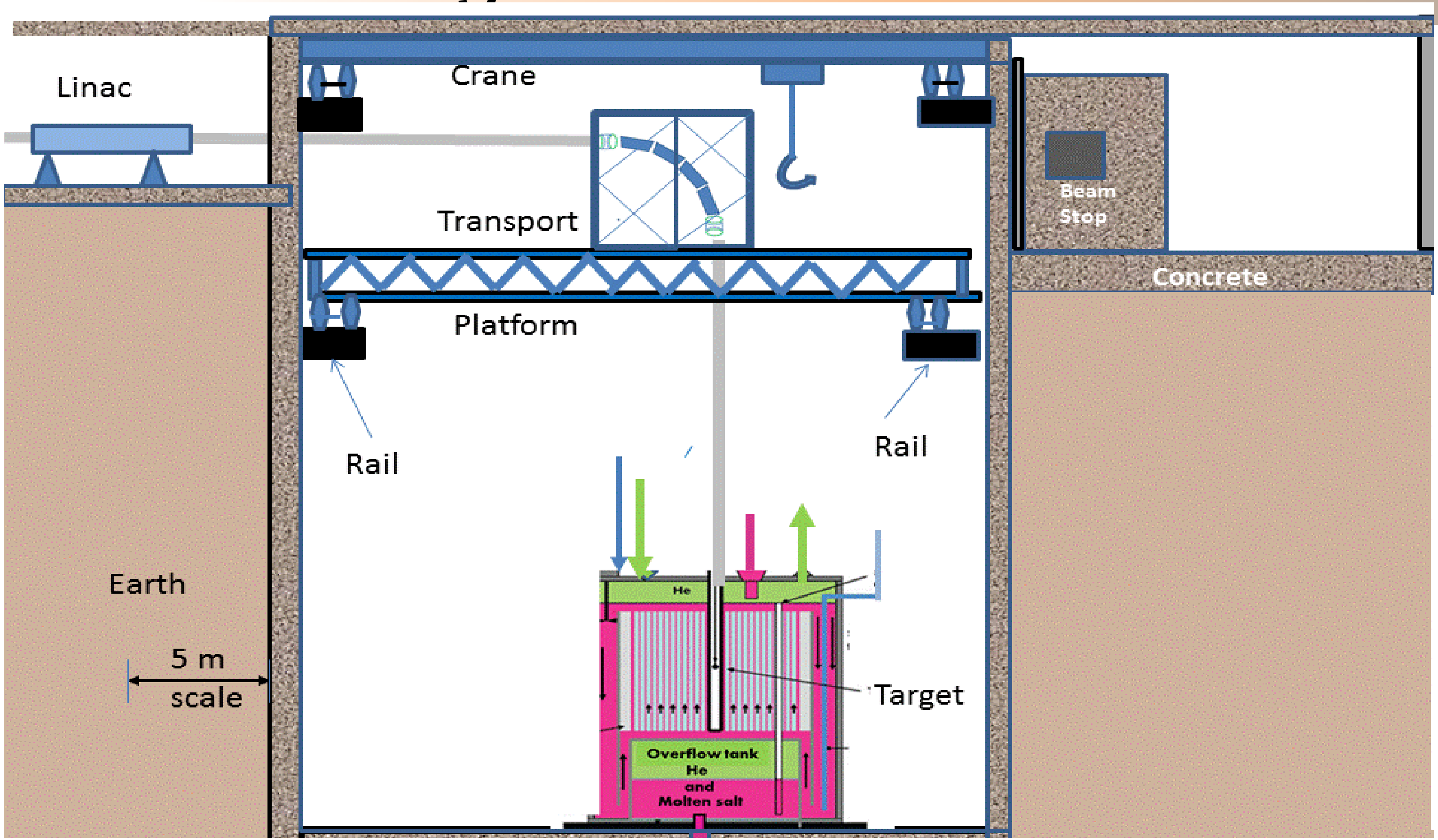
Underground Linac and Reactors



SRF Linacs Driving Subcritical MS Reactors
Why This Approach is Superior

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Deepest Burn – Unique to SC Linac & Mu*S

- Driven by Superconducting RF Linacs
  - Newest technology for highest proton power (>25 MW)
- Molten Fluoride Salt Fuel Reactor (MSRE experience)
  - Accommodates short beam interruptions
- Internal Spallation target
  - Amplifies neutron flux by factor of >30
- Graphite moderated thermal neutron spectrum
  - Less sensitivity to fission products

New Features

- Subcritical - defense in depth by controlling fuel reactivity
  - Fission turned off by switching the accelerator off
- Continuous removal of volatile radioisotopes
- Versatile reactor design accommodates many fuels

2 Examples of Deep Burn (compare to LWRs)

- Burning SNF on LWR sites for energy security, clean-up
- Burning Pu for tritium needed for weapon security, clean-up

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Deep Burn Example #1
New Economics for SNF

- Convert LWR SNF into molten fluoride salt fuel for Mu*STAR
  - Muons New DOE GAIN Award (with ORNL, SRNL, INL)
    - Gateway for Accelerated Innovation in Nuclear (GAIN)
    - https://info.ornl.gov/sites/publications/Files/Pub117081.pdf

- Burn the M-S fuel for 200 years
  - Without chemical reprocessing
  - Only increasing the accelerator power
  - Until it takes 15% of the reactor power to run the accelerator

- Extract 7 times the energy as was generated by the original LWR
  - Energy normalized waste reduced by more than a factor of 7
  - Toxicity reduced – higher actinides burned

- SNF becomes a valuable commodity

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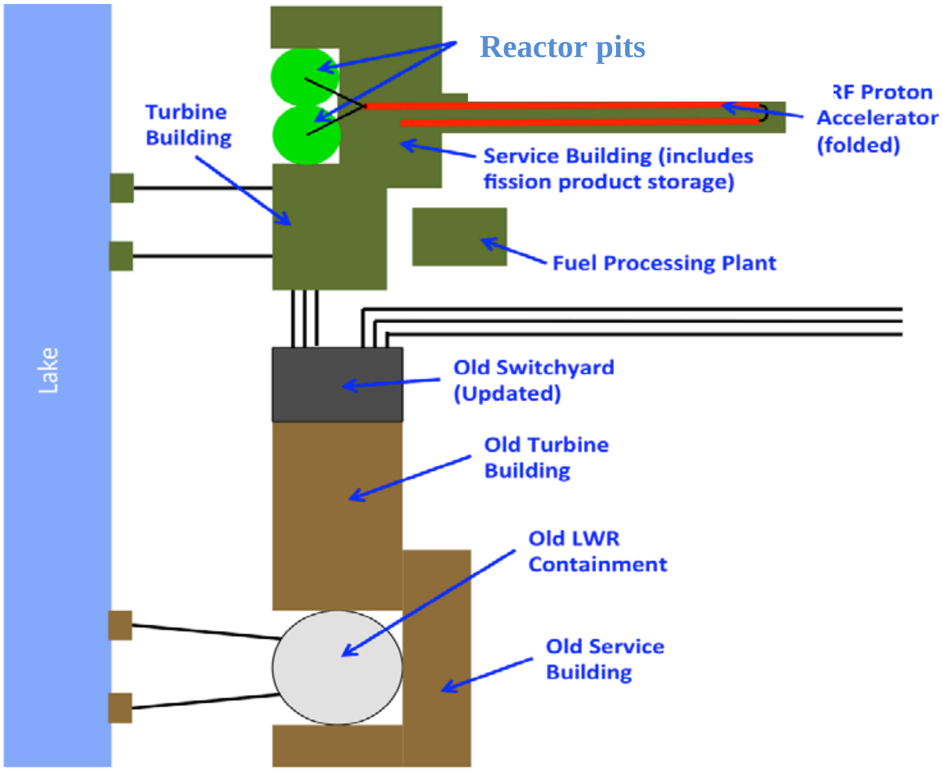
Mu*STAR SNF Concept



- Build Mu*STAR at 65 existing LWR sites
- Convert SNF to fluoride MS fuel once
  - GAIN award with ORNL, SRNL, INL
- Burn to get 7 times as much energy
  - For 200 years
- Disruptive Technology
  - No uranium mining
  - No fuel enrichment
  - No fuel rod manufacture
  - No new SNF
  - No SNF transport
  - No SNF remote storage
- Consent based storage of SNF
  - Community support
  - Same amount of SNF as now
  - Lots of jobs, economic stability
- Goal – electricity for less than from gas

Deep Burn Example 2
Making Tritium for the NNSA

The Vision –
-Mu*STARs at 65 US and many foreign LWR sites
burning their existing stored SNF
for >200 years

How to get there?
Need to build a Mu*STAR demo system

Get the NNSA to pay for it to make tritium by burning Pu
Solve their problems
-need 2.8 kg/y tritium starting in 2025
Save the US taxpayer money
-now $300,000,000 kg

NNSA Makes Tritium Now

- Tritium Producing Burnable Absorbing Rods (TPBARs)
- Rods contain enriched Li-6
- Take the place of fuel rods in the TVA Watts Bar reactor
  - $n + {}^{6}_{3}Li \rightarrow {}^{4}_{2}He\ (2.05\ MeV) + {}^{3}_{1}T\ (2.7\ MeV)$
- Removed after 18 months
- Sent to SRNL to recover the tritium
- Stored in metal hydride beds

- Difficulties –
- described in NNSA's 2018 Nuclear Stockpile Stewardship and Management Plan (SSMP) https://fas.org/blogs/security/2017/11/ssmp2017/

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Difficulties, Uncertainties, Expenses

- National security function on commercial site
  - Subject to local, state, EPA, NRC regulation
  - Number of TPBARs limited – e.g. tritium in cooling water
  - NNSA pays TVA to use Watts-Bar ($?)
- Reactor fuel must be of national origin
  - Need US owned, US sited uranium enrichment facility (>$2B)
- ORNL (Y-12) Li-6 enrichment facility obsolete ($?)
- 2.8 kg/y of tritium needed after 2025
  - Weapon decommissioning ends
  - Additional reactor(s) needed
    - to be upgraded and certified for TPBARs ($?)

- Mu*STAR solves all these problems and saves money
  - Scaled back accelerator and only one μ*S module can make >2.4 kg/y of T
  - Essentially a μ*S pilot plant (~$1B)

Technology Readiness Levels

1 Basic principles observed and reported.
2 Technology concept and/or application formulated.
3 Analytical and experimental critical function and/or characteristic proof of concept.
4 Component and/or breadboard validation in a laboratory environment.
5 Component and/or breadboard validation in a relevant environment.
6 System/subsystem model or prototype demonstration in a relevant environment.
7 System prototype demonstration in an operational environment.
8 Actual system completed and qualified through test and demonstration.
9 Actual system proven through successful mission operations.

Mu*STAR Components Technology Readiness

Component	Readiness Level	Comment / Example
Accelerator – 1 MW	9	SNS at ORNL
Accelerator – 10 MW	7	SNS is a “prototype”: 1 MW with 6% duty factor
Molten-Salt Reactor	6	Molten Salt Reactor Experiment at ORNL
Spallation Target	6	Other designs (in many places) are level 9
LWR SNF to MSF	6	2017-18 Muons GAIN Voucher Subject. Known techniques, but cost optimization required.

Estimates of Costs

$ 15M System Study	1.5 y	Using National Labs
$ 35M Conceptual Design	1.5 Y	and following DOE
$150M Technical Design	2.0 y	Critical Decision
$800M Pilot Plant large enough to make >2 kg/y of T	2.0 y	Methodology

NRC confirmed that subcritical operation means Mu*STAR is not a nuclear reactor and should be exempt from many regulatory expenses and uncertainties.

NRC approval not required for Pilot Plant on DOE/NNSA site.

Outro (questions)

- How can Mu*STAR be cheaper than wind, solar, or ng with free or cheap fuel?
  - Because our fuel (e. g. SNF or Pu) is cheaper than free
    - We will be paid to dispose of it
  - May be more environmentally cost effective and attractive than Wind, Solar, or NG
    - Considering birds, toxic waste, and greenhouse gases
- Isn't nuclear too expensive?
  - Subcritical means Mu*STAR does not fall under NRC rules for nuclear reactors
    - It will have a smaller regulatory burden
    - As an SMR it will be built in factories
    - Reducing source term means smaller evacuation zone footprint
- Aren't superconducting accelerators too expensive and spallation targets difficult?
  - Research requirements are more demanding than needed for Mu*STAR
  - SC RF technology is on the front end of a steep learning curve
    - magnetrons, Nb3Sn, cryocoolers,…