Mu*STAR: A Modular Accelerator-Driven Subcritical Reactor Design

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Muons, Inc. - http://muonsinc.com/
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What is Muons, Inc.?

- Founded 2002, subsidiaries - MuPlus, MuSTAR - by Scientists from US National Labs – original mission to design a **Muon Collider**
- NEW tools and technology for particle accelerators
- Funded by DOE contracts and SBIR-STTR grants • total of ~$30M
- 9 US university and 11 national lab research partners • Broad, diverse and cutting edge scientific network • We are embedded in both worlds
- Supported 18 post-docs and 6 Ph.D. students
- Muons, Inc. software product **G4beamline** widely used in particle physics, **MuSim** being developed for more general use.
- Mu*STAR accelerator-driven molten-salt nuclear reactors • Major focus of our companies
Mu*STAR: Superconducting RF Linac Driving Molten-Salt Graphite-Moderated Subcritical Modular Reactors

- **Superconducting RF proton Linac**
  - ORNL SNS demo (1.4 MW, SC Linac proton beam)
  - Scales to 25 MW, 1 GeV, $800M$ (ANL Design)
  - Improved by Muons, Inc. inventions

- **Molten-Salt Graphite-Moderated**
  - ORNL MSRE 1965-69, 8 MWt demo
  - Add internal SNS target
  - Virtues described by Bowman, Vogelaar, et al., HBofNE 2010 [1]

- **Subcritical**
  - Additional neutrons by SC technology and spallation

- **Modular Reactors**
  - Built in factories ($<500MWt$)
Why isn’t this already being done?

• **Economics:**
  – Used fuel is not a liability to the operating companies
  – By law, it is the responsibility of the U.S. government
  – The government **pays** the operating companies to store it

  **They have no incentive to deal with the used fuel.**

• **Technology:**
  – The Department of Energy did a study in the 1990s that concluded ADSR is not viable because the accelerator is barely feasible and far too expensive
  – Today that no longer holds:

  **Superconducting Accelerators are now far more efficient and enormously less costly than the study considered.**
What is Sustainable?

https://energy.utexas.edu/news/nuclear-and-wind-power-estimated-have-lowest-levelized-co2-emissions

Costs per kW hours:
- solar: $12/W
- nuclear: $6-7/W - over lifetime of reactor

Mu*STAR minus fuel mining and reprocessing ~ 4g

No long-term strategy for sustainable growth of nuclear power in the U.S.
• 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 $\frac{1}{4}$ linear dimension of Mu*STAR, $4^3 = 64$ times Power
Example: 350 MHz, 140 kW DC Magnetron

- Muons, Inc. Invents Accelerator Technology
  - Magnetrons up to 90% efficient
  - Prototype for Niowave to make Mo-99 – replaces 30 kW tetrode
  - $2/W vs $10/W for klystrons

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Superconducting RF Linacs

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
Much higher neutron Amplification
1 p produces > 30 n

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Universal Reactor Concept

Nuclear Power Reinvented by Mu*STAR

- Currently considered to be waste
  - Spent Nuclear Fuel
  - Surplus Weapons Material
- Enough out of the ground today to supply 100% of current U.S. electricity usage for > 1000 years
  - Natural Uranium
  - Natural Thorium
  - Depleted Uranium

One reactor, many fuels

Subcritical Operation
Immediate, passive response to all accident scenarios: turn the accelerator off and fission stops within 1 second; passive air cooling is then sufficient. Mu*STAR is walk-away safe.

No Enrichment or Reprocessing

Mu*STAR Reactor

Accelerator
- Tuned to the fuel

Turbine/Generator

Heat exchange
- Can burn its own waste for ~ 200 years
SNF Burning Concept

**Fuel Processing Plant**
- Spent Nuclear Fuel from Light Water Reactor
- Oxides -> Flourides – GAIN award
- Fractional Distillation Column
- Up to 500 MWt 220 MWe
- Underneath Fission Product Storage
- 135Xe
- Tritium
- He back to reactor

**SRF Proton Accelerator**
- Electric motors
- 750 C
- Molten salt pumps
- Salt flows upward in graphite channels
- Graphite
- Storage tank
- Steel base plate
- Modified Hastelloy-N or graphite encloses all fuel salt
- Vessel has no penetrations below liquid level
- Passive air cooling for decay heat when accelerator is off. No water, steam, or Zr inside the reactor containment.

**Reactor concept from C. D. Bowman, R.B. Vogelaar, et al., 2010 HB of NE**

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SRF Linacs Driving Subcritical MS Reactors
Why This Approach is Superior

Deepest Burn – Unique to SC Linac & MS Reactors
• Driven by Superconducting RF Linacs
  • Newest technology for highest proton power (>25 MW)
• Molten Fluoride Salt Fuel Reactor (MSRE experience)
  • Accommodates short beam interruptions
  • Avoids issues of solid fuel rods
• 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 (NRC – NOT a reactor, many licensing and import controls issues are avoided)
• Fission turned off by switching the accelerator off
• Continuous removal of volatile radioisotopes
• Versatile reactor design accommodates many fuels
• Decouples nuclear energy from nuclear weapons
Mu*STAR Features

Additional Features/Advantages

• Tested technology put together in a new way
• The reactor operates underground at atmospheric pressure
  • no pressure vessel - eliminates many accident scenarios
• Volatile fission products are continuously removed
  • reactor contains almost a million times less than in a LWR
• No fuel rods/Zircaloy
  • no mechanical fatigue of UO$_2$ fuel rods from accelerator trips
• No critical mass is ever present, and cannot form
  • freeze plug as in all MS designs
• No chemical reprocessing or isotopic enrichment is needed
  • more proliferation resistant than other technologies
• Burns SNF, W-Pu, U233, natural uranium, thorium
  • without redesign –accelerator parameters match fuel
• Passive response to most accident scenarios
  • turn off the accelerator – passive air cooling is then sufficient
Mu*STAR SNF Concept

• 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
  • Fuel for their utility
  • Lots of jobs, economic stability
• Goal – electricity for less than gas

Build Mu*s at 60 existing LWR sites

Muons, Inc.
Underground Linac and Reactors
Mu*STAR

Using MuSim MCNP6 single event display

green=neutron, cyan=gamma, brown=graphite, purple=molten-salt fuel.
This single 1 GeV proton generated 402,138 tracks (not counting e⁻).

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Cummings/Muons, Inc. ADSR
We can run much lower than 1 GeV energy ~ 600 MeV will be sufficient and be a significant cost saving on acceleration.
Burning used nuclear fuel (UNF) in Mu*STAR - neutron poisons build up in the fuel, reducing its reactivity and requiring increased accelerator power to maintain a constant thermal output. Identify the elements that are most responsible for reducing the reactivity, so we can concentrate on removing them.
Deep Burn Example #1
New Economics for SNF

- Convert LWR SNF into molten fluoride salt fuel
- Muons New DOE GAIN Award (with ORNL, SRNL, INL)
  - Gateway for Accelerated Innovation in Nuclear (GAIN)
- Example in Handbook of NE (Bowman et al) - Burns the M-S fuel for 200 years
  - In 5 passes in successive reactor units (fuel moved by He pressure)
  - Without chemical reprocessing
  - Only increasing the accelerator power each pass
  - 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
Deep Burn Example #2
Making Tritium for the NNSA

The Vision –
-Mu*STARs at 60 US LWR sites
  burning their existing stored SNF
  for >200 years

How to get there?
Need to build a demo system

Get the NNSA to pay for it
Solve their problems
Save them money
NNSA Makes Tritium Now

- Tritium Production Burnable Absorbing Rods (TPBARS)
- 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 Mu*STAR module
  - Essentially a Mu*STAR pilot plant (~$1B)
Mu*Star solution for Tritium at SRS

- Tritium contained in reactor, not TPBARs (saves $)
- Uses natural Li-6 component of the LF MS eutectic (saves $)
- Excess Pu at SRS as fuel (saves $)
- Pu burning easier
  - Subcritical operation
- Built on Savannah River Site (fewer uncertainties)
  - Some accelerator and reactor components from National Labs

- Simulations already show 2.4 kg/y of tritium
  - with 2.5 MW, 1 GeV proton beam
  - on an internal depleted uranium target burning 200kg/y of Pu
Conclusions

• **Mu*STAR is a solution to NE SNF problem**
  – Gets 7 times energy w/o reprocessing
  – Extends life of present reactor sites
  – Defers SNF transport/burial indefinitely

• **Mu*STAR pilot/demo funding**
  – Can solve tritium supply security for NNSA
  – Saves NNSA construction and operation costs
Screen shot of MuSim: carbon is brown, salt is blue, the spallation target (natural uranium) is green; the right side is an editing pane: ADSR-4 is the name of this simulation, and the blue headers are categories to specify the simulation that can be edited; Parameters are for parametrizing the simulation; Definitions define general things like materials; GlobalGeometry includes all objects, solids, sources, and detectors (except objects placed via design coordinates); DesignCoordinates are for a beamline and define its centerline for placing objects.
Mu*Star solution for Tritium at SRS

• Tritium contained in reactor not TPBARs (saves $)
  – Removed continuously at low partial pressure
  – Reduced embrittlement and escape potential
• Uses natural Li-6 component of the LF MS eutectic
  – Upgrade of Y-12 enrichment plant not needed (saves $)
• Excess Pu at SRS as fuel
  – Environmental Management (EM) operates SRS
    • wants to get rid of many tons of it
  – No enriched uranium needed (saves >$2B)
• Pu burning easier
  – Subcritical operation overcomes PuF3 solubility limitations
  – Pu has fewer delayed neutrons than U235
  – U238 Doppler broadening not available or needed
• Built on Savannah River Site (fewer uncertainties)
  – Some accelerator and reactor components from National Labs

• Simulations already show 2.4 kg/y of tritium
  – with 2.5 MW, 1 GeV proton beam
  – on an internal depleted uranium target burning 200kg/y of Pu