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# USA Plans/progress on SRF Linacs Driving GEM*STAR Subcritical Reactors for Profitable Disposition of Spent Nuclear Fuel and Surplus Weapons Materials

Rolland Johnson

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

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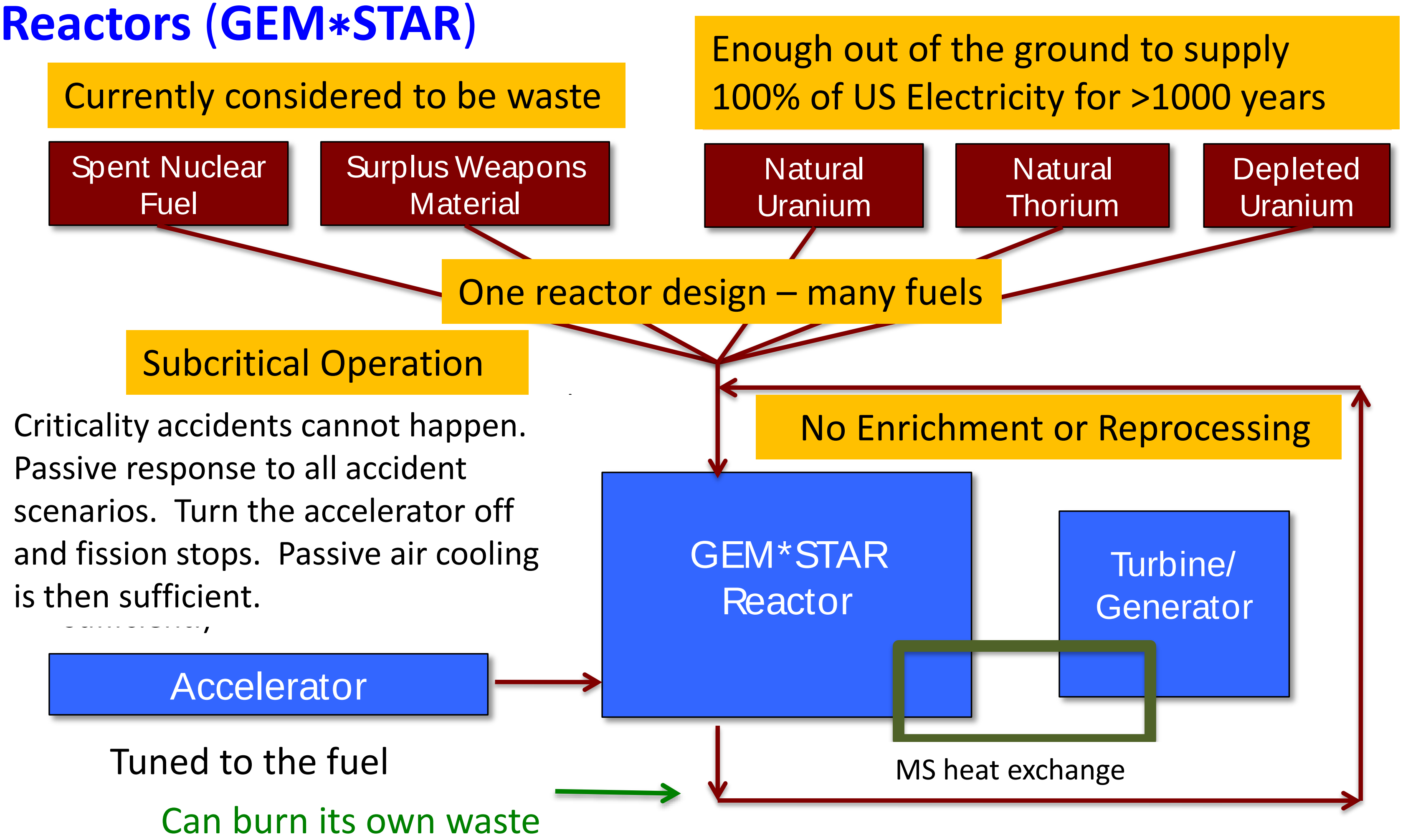
CERN-EuCard2 Workshop

# USA Prospects for Nuclear Energy

- Nuclear Energy to Produce Electricity <u>Not Needed</u>
  - Natural Gas is plentiful and inexpensive (fracking)
    - Lower $CO_2$/W than Coal
  - Subsidies for Wind and Solar, but not Nuclear
    - Utilities required to take solar energy when sun shines
    - Power companies required to use least expensive source
  - Low $CO_2$ production has not led to economic advantage
    - Not likely to change with present US government
  - Utilities are losing money even on paid-for reactors
    - Some states (NY, IL) are intervening to prevent closures
- Attractive Nuclear Options in USA near term are
  - Reducing wastes from LWRs
  - Disposing of surplus weapons materials
    - For process heat – e.g. $CH_4 + C \rightarrow$ green diesel fuel

# GEM*STAR Concept

## Green Energy Multiplier∗Subcritical Technology for Alternative Reactors (GEM∗STAR)



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# New Accelerator Technology Enables ADSR

OAK RIDGE, Tenn., Sep. 28, 2009 — The Department of Energy's 1 GeV Spallation Neutron Source (SNS), breaks the one-megawatt barrier! Operating at <10% duty factor, this corresponds to >10 MW at CW. Based on Superconducting RF Cavities, available from U.S. Industry:

# 1497 MHz Magnetron (for Jlab ERL)

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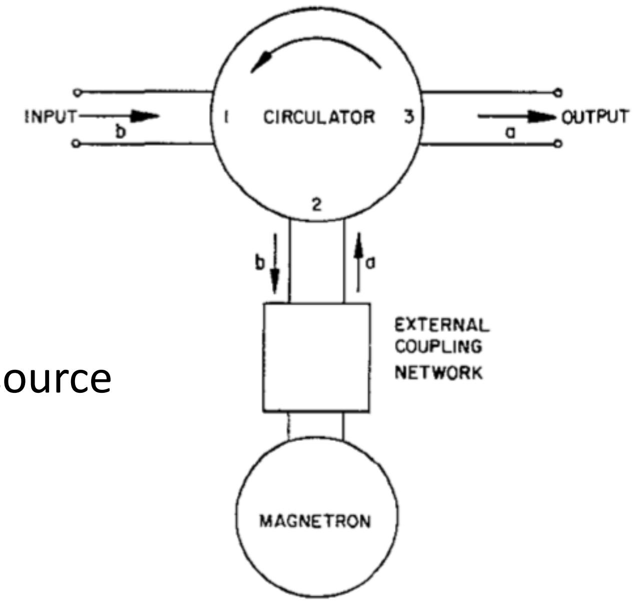
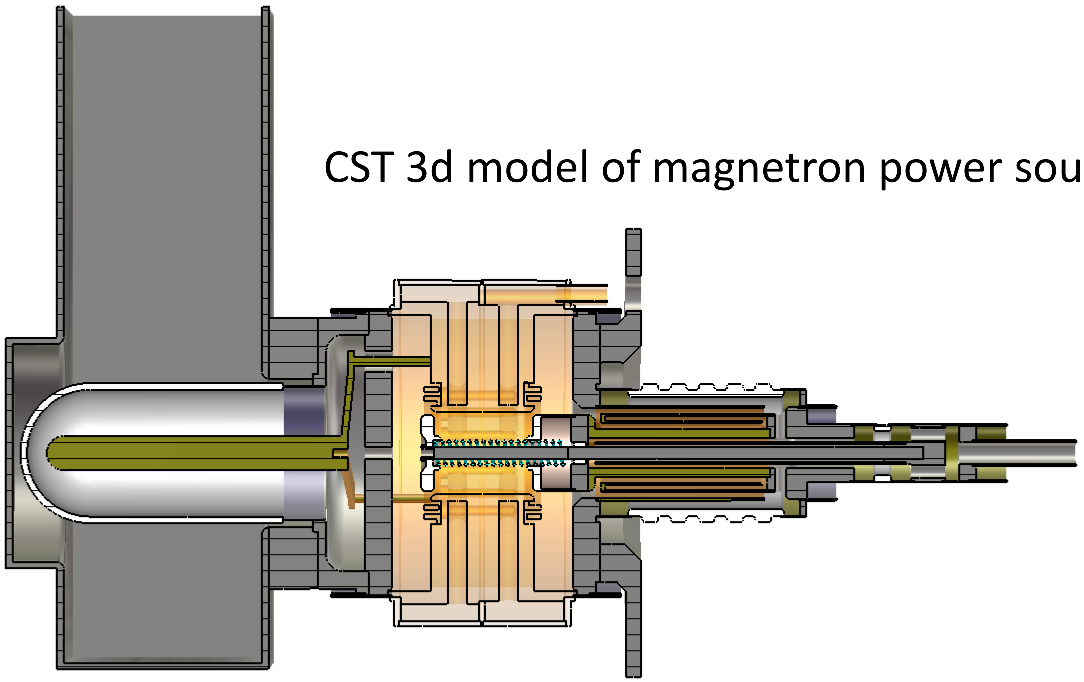
Klystrons at Jefferson Lab have an average life of 5 years. These could be replaced by magnetrons at 1/5 the cost!




CST 3d model of magnetron power source



The Magnetron is is an **oscillator**, but with injection locking, becomes a reflection-type amplifier. Gain levels up to 30 dB have been achieved with efficiencies of 80%

**Muons, Inc. is currently building a 350 MHz CW 120 kW magnetron for SRF linacs.**

# 350 MHz CW 140 kW Magnetron

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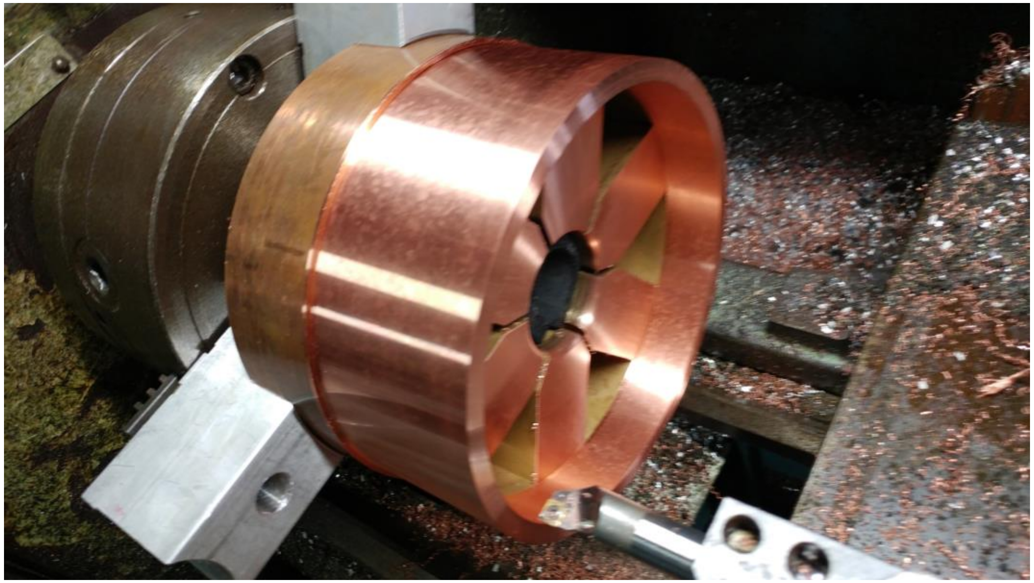
Magnetron is a good RF source for SRF
Inexpensive (<$2/W vs $5 to $10/W for klystron or IOT)

Efficient (~85% vs 50-60% for klystron or IOT)
Frequency and phase stabilization are an issue for accelerators

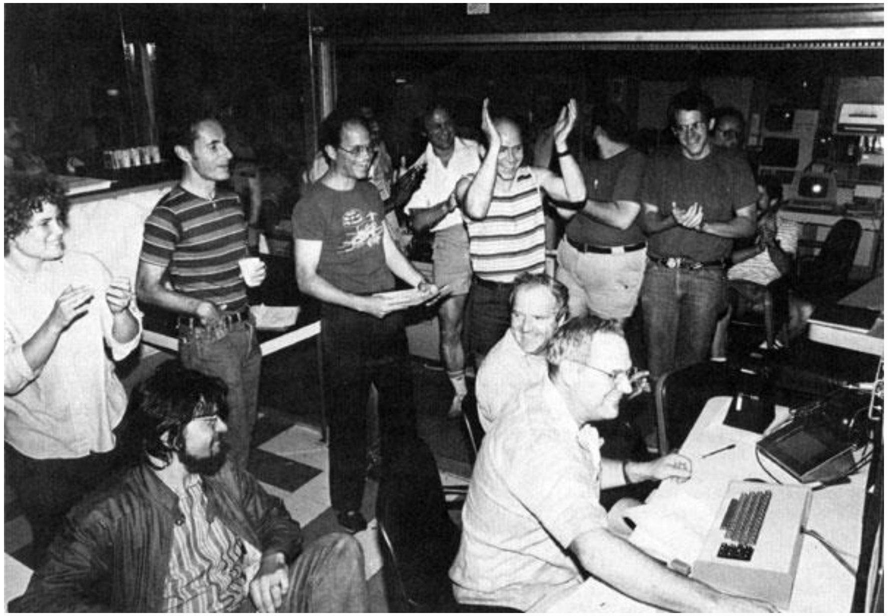
Muons, Inc. has several magnetron projects underway that are relevant to ADS
350 MHz CW 120 kW for radioisotopes
650 MHz for medical applications
1497 MHz for CEBAF klystron replacement



# Some History

**Combining Subcritical System and Accelerator Technologies**
**First Customers can be: NNSA and DOD**

**Rolland P. Johnson, Ph. D.**
**President , Muons Inc.**
**[www.muonsinc.com](http://www.muonsinc.com)**



512 GeV at Fermilab

**Charles D. Bowman, Ph. D.**
**President ADNA Corporation**
***Accelerator-Driven Neutron Applications***

Charlie at LANL

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# Superconducting RF Linacs Driving GEM*STAR Subcritical Reactors

## Outline

- Breakthrough Technological Advance – Superconducting RF (SRF)
  - Demonstrated at the ORNL Spallation Neutron Source (SNS)
  - Powerful, efficient, affordable, reliable
  - Capabilities and economies on steep growth curves
- Molten-salt fueled GEM*STAR subcritical reactor
  - Well-matched to SRF Accelerators
  - Based on ORNL MSRE with several new ideas
  - Precludes all previous nuclear energy accidents
  - Deeper burn of any fissile or fertile fuels – <u>W-Pu example</u>
  - Needs no isotope enrichment or chemical reprocessing
- Combination leads to new solutions
  - Profitable, effective disposition of SNF and weapons materials
- Possible path to start of construction of a pilot plant in <5 years

*Muon*

# GEM*STAR

**Combining Accelerator Technology with Molten Salt Reactor Technology**

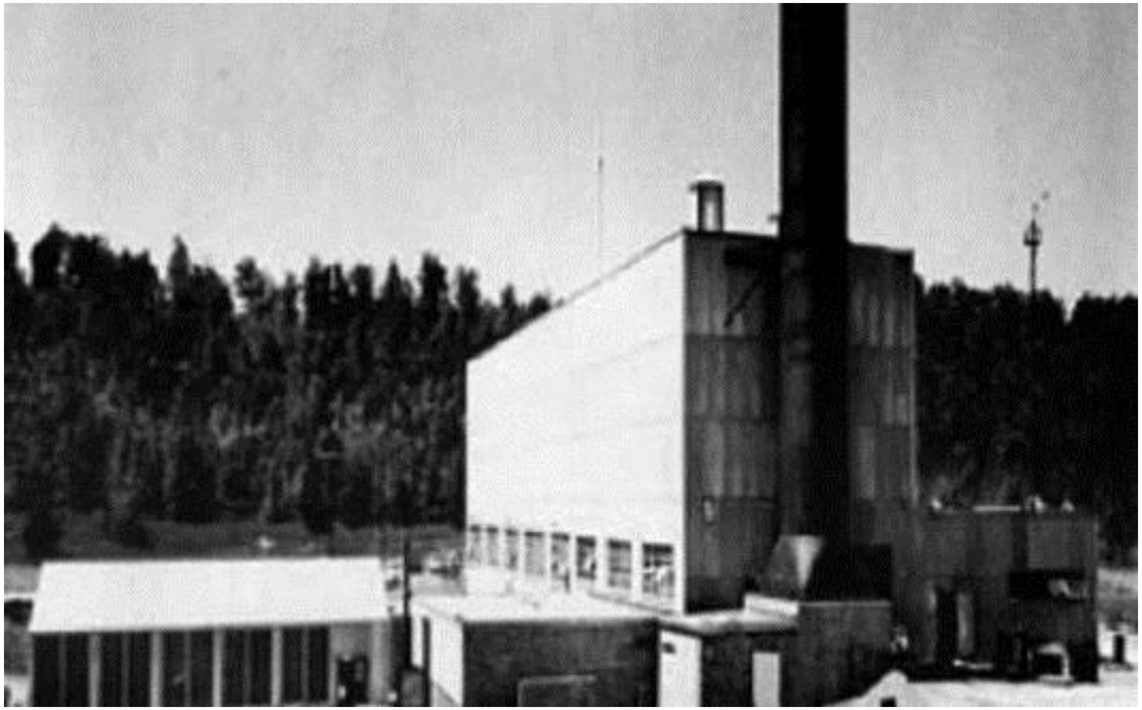
Green Energy Multiplier-Subcritical Technology for Advanced Reactors was first described in the 2010 Handbook of Nuclear Engineering:

Charles D. Bowman, R. Bruce Vogelaar, Edward G. Bilpuch, Calvin R. Howell, Anton P. Tonchev, Werner Tornow, R.L. Walter, “GEM*STAR: The Alternative Reactor Technology Comprising Graphite, Molten Salt, and Accelerators,” Handbook of Nuclear Engineering, Springer Science+Business Media LLC (2010).

**Prof. Bruce Vogelaar and his Virginia Tech Team, including Prof. Alireza Haghighat, have continued to contribute to GEM*STAR since this 2010 article.**

**I will say more later about their work on the internal target design and the simulations describing the approach to equilibrium in the feed and bleed scheme invented by Charlie Bowman.**

# ORNL Molten Salt Reactor



- The Molten Salt Reactor Experiment operated at ORNL,1964-1969.
- It demonstrated the key aspects of using molten salt fuel.
- It was a critical reactor tested with three different fuels.
- They routinely powered it down for weekends, something no conventional reactor could do.

# Molten Salt Eutectic Fuel

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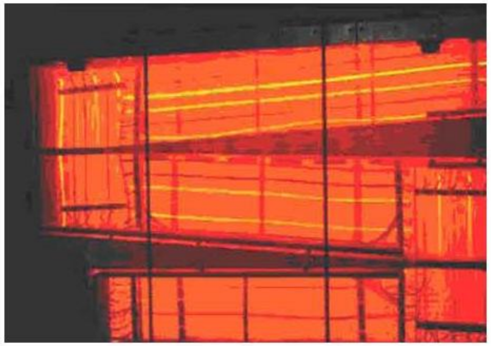
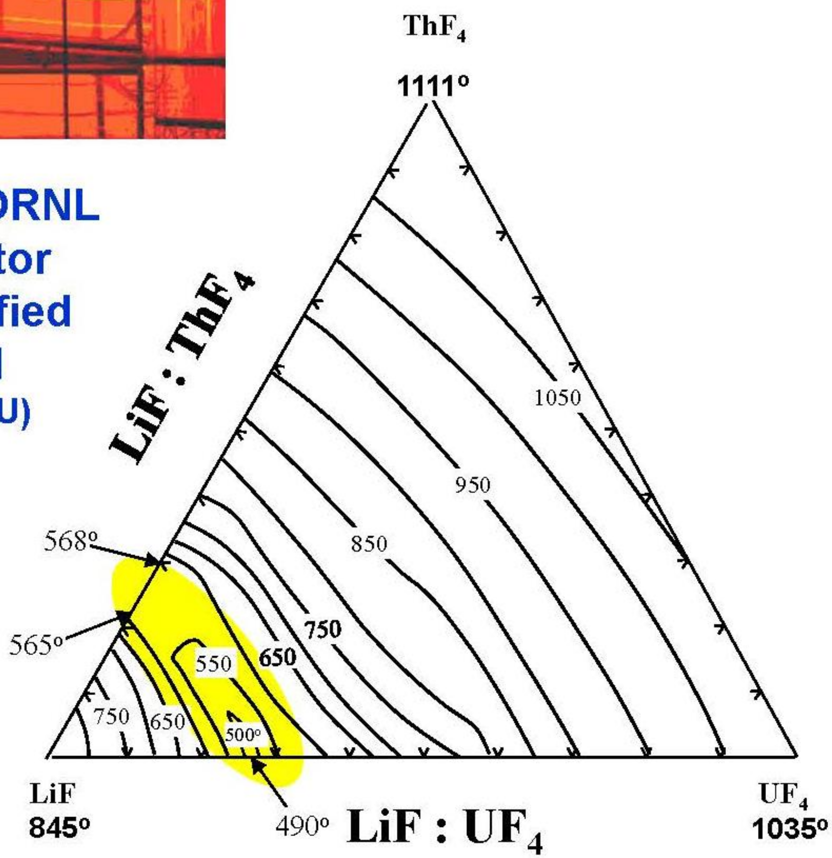
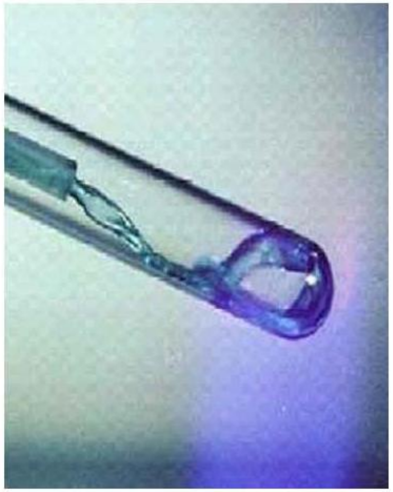


**Proven in ORNL MSRE reactor using Modified Hastelloy-N**
($^{235}U$, $^{239}Pu$, $^{233}U$)



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

High boiling point → low vapor pressure

GEM*STAR

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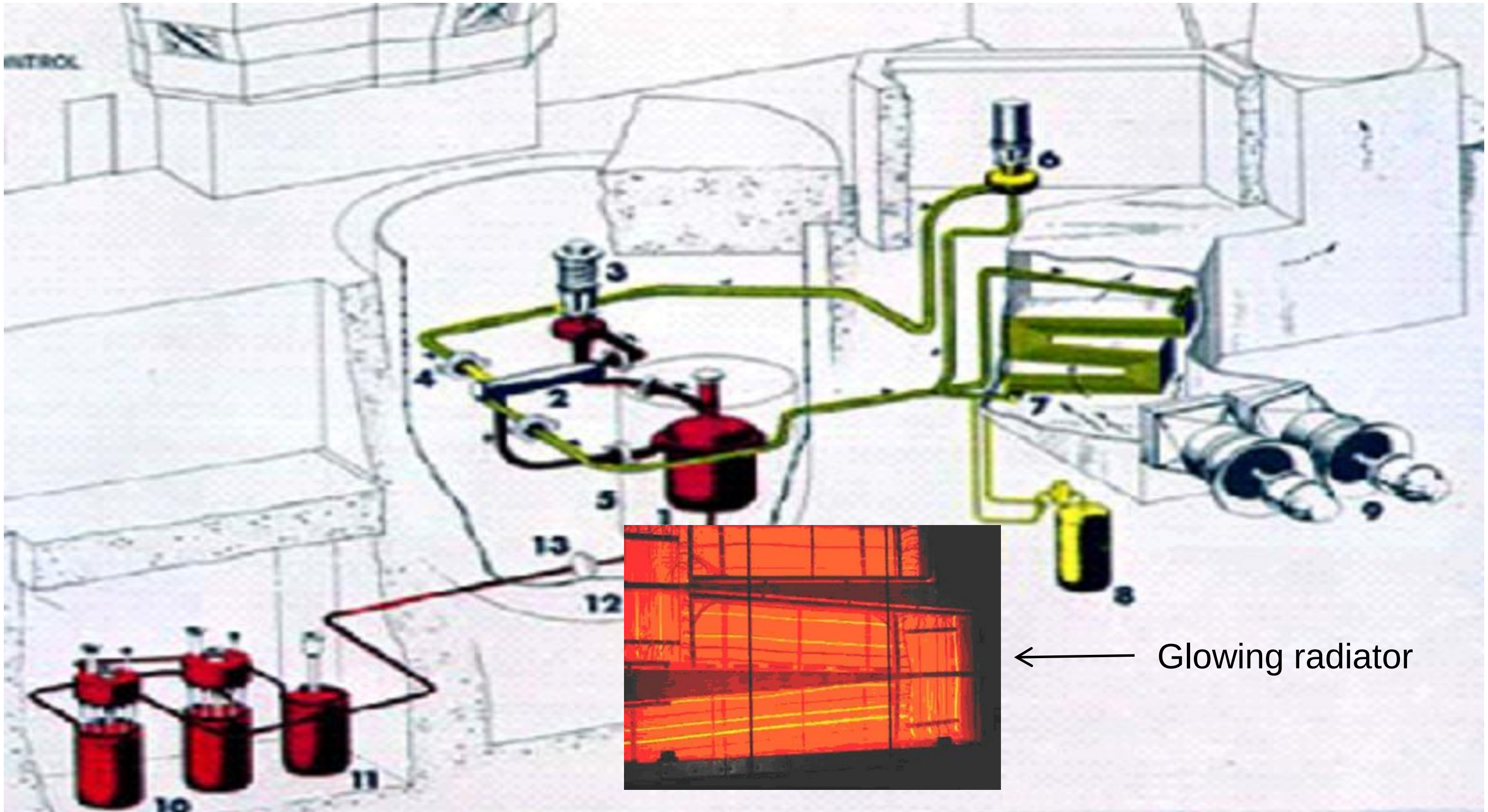
# 1965-69 ORNL Molten-Salt Reactor Experiment




1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

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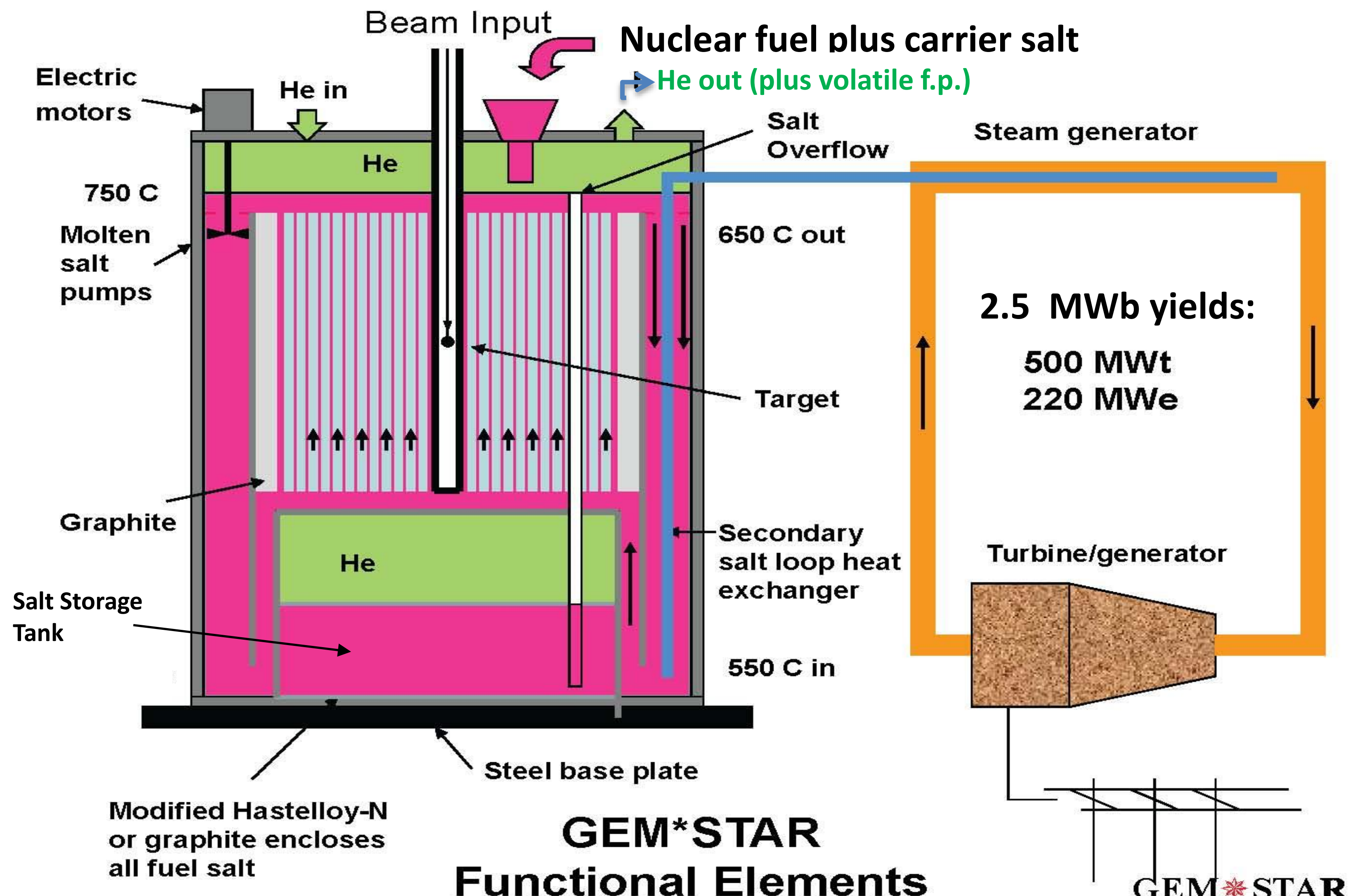
# GEM*STAR




No penetrations below level of fuel

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# Some GEM*STAR Advantages

- Tested technology put together in a new way.
- The reactor operates at atmospheric pressure.
  - No pressure vessel.
  - Major design simplification, and eliminates many accident scenarios.
- Volatile fission products are continuously removed.
  - Reactor contains almost a million times less than in a LWR.
- No fuel rods.
  - No Zircaloy that can instigate a hydrogen explosion (Fukishima).
  - No mechanical fatigue of $UO_2$ fuel rods from accelerator trips
- No critical mass is ever present, and cannot form.
- No reprocessing or isotopic enrichment is needed.
  - More proliferation resistant than other technologies.
- Burns SNF, W-Pu, U233, natural uranium, thorium, without redesign
- Passive response to most accident scenarios: turn off the accelerator – passive air cooling is then sufficient.

# Neutron Fluence Equilibrium

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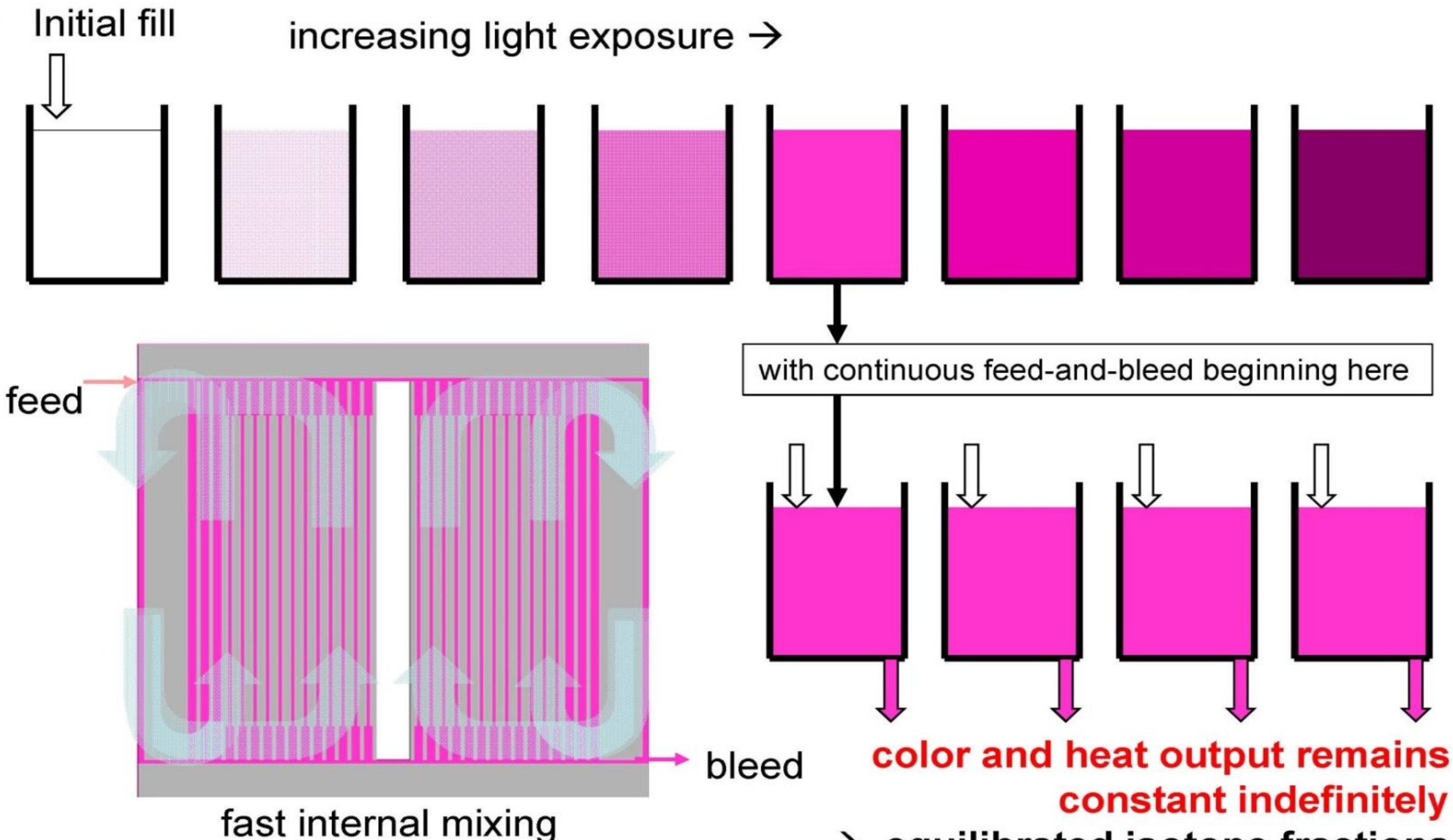
**consider a clear liquid which releases heat when exposed to light, eventually turning a dark purple**



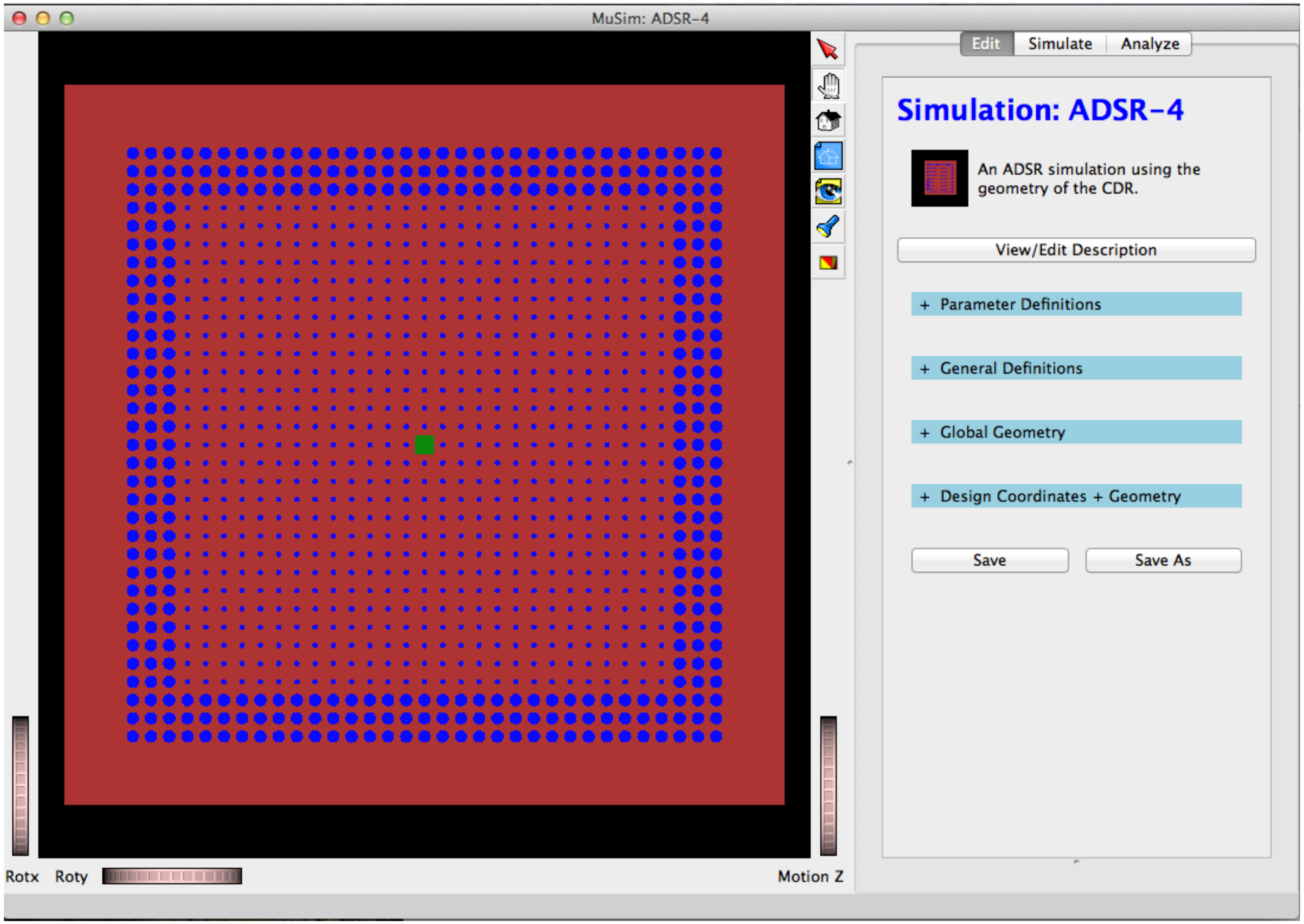

$10^{-6}$ less volatile fission-product build-up in core

color and heat output remains constant indefinitely

→ equilibrated isotope fractions throughout core and throughout time

**Feed-Bleed concept patented by Charlie Bowman**

# First MuSim Application -GEM*STAR




Screen shot of MuSim: carbon is red, 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.

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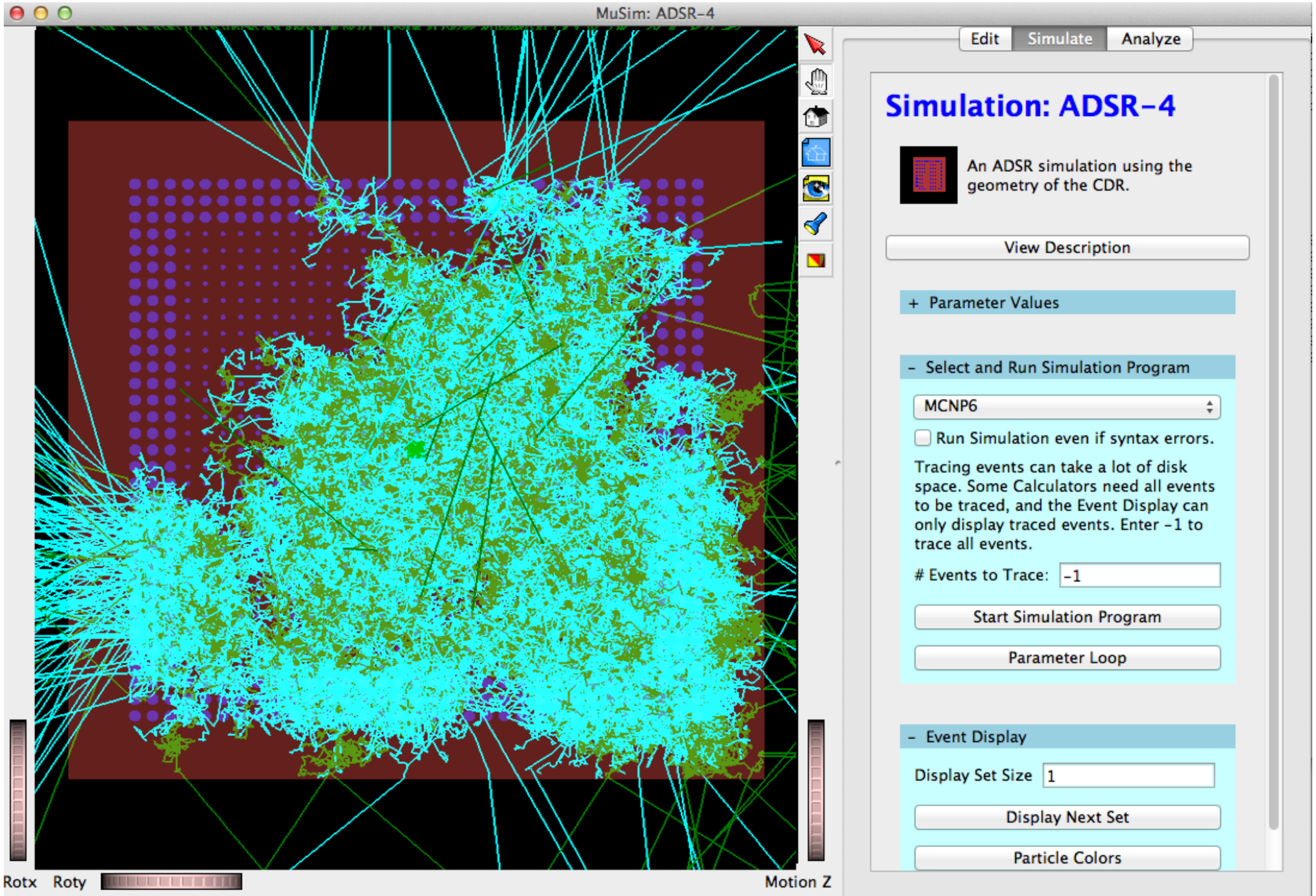
# GEM*STAR
## Using MuSim MCNP6 single event display




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

# Target Considerations

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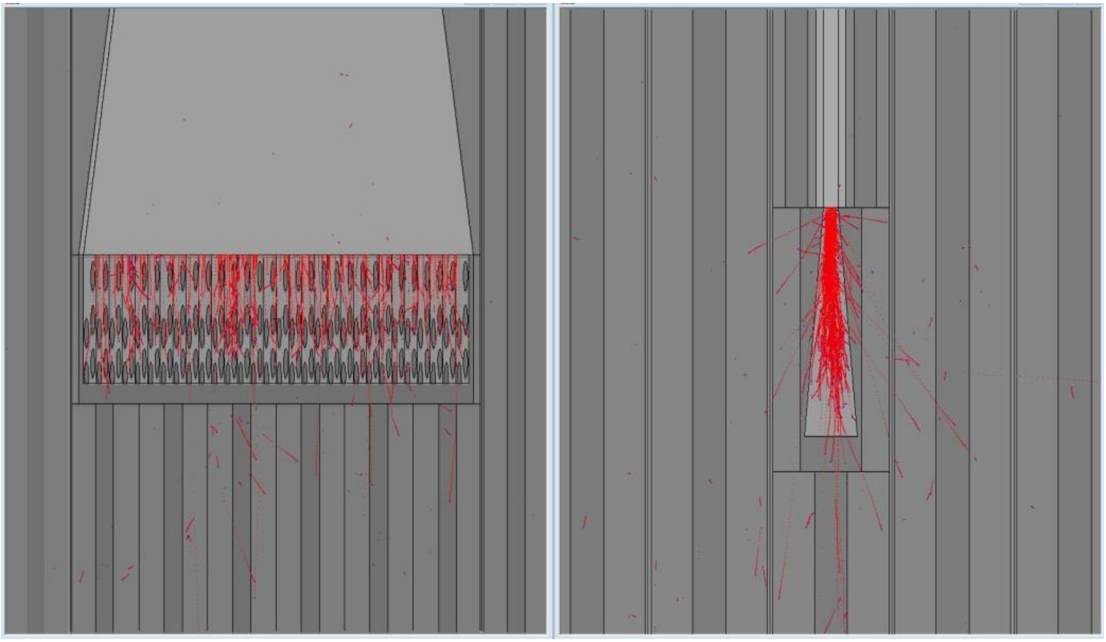

GEM*STAR Internal Target

**Work of Bruce Vogelaar of Virginia Tech (co-author of GEM*STAR article in HB of NE)**

- diffuse (or multiple) beam spots
- molten salt used for heat removal
- high neutron yield from uranium
    (but minimize target fission)
- spent target fluorinated and used as fuel
- minimize impact on local reactivity – neutrons produced isotropically, many react within the target

# GEM*STAR W-Pu Disposal

- Dispose of surplus weapons-grade Plutonium.

  34 metric tons of surplus weapons-grade plutonium
  to be destroyed by the 2000 U.S.-Russian Pu Agreement.

- GEM*STAR destroys it more completely than other approaches.
- Pu fed continuously into the reactor and immediately rendered not weapons-grade (even before burning is complete).
- Despite current events, there is still desire to dispose of Pu.
- Fischer-Tropsch process converts natural gas and renewable carbon
  - Into 42 Billion gallons of green diesel fuel for the DOD over 30 years at production cost of ~$1.5/gallon.

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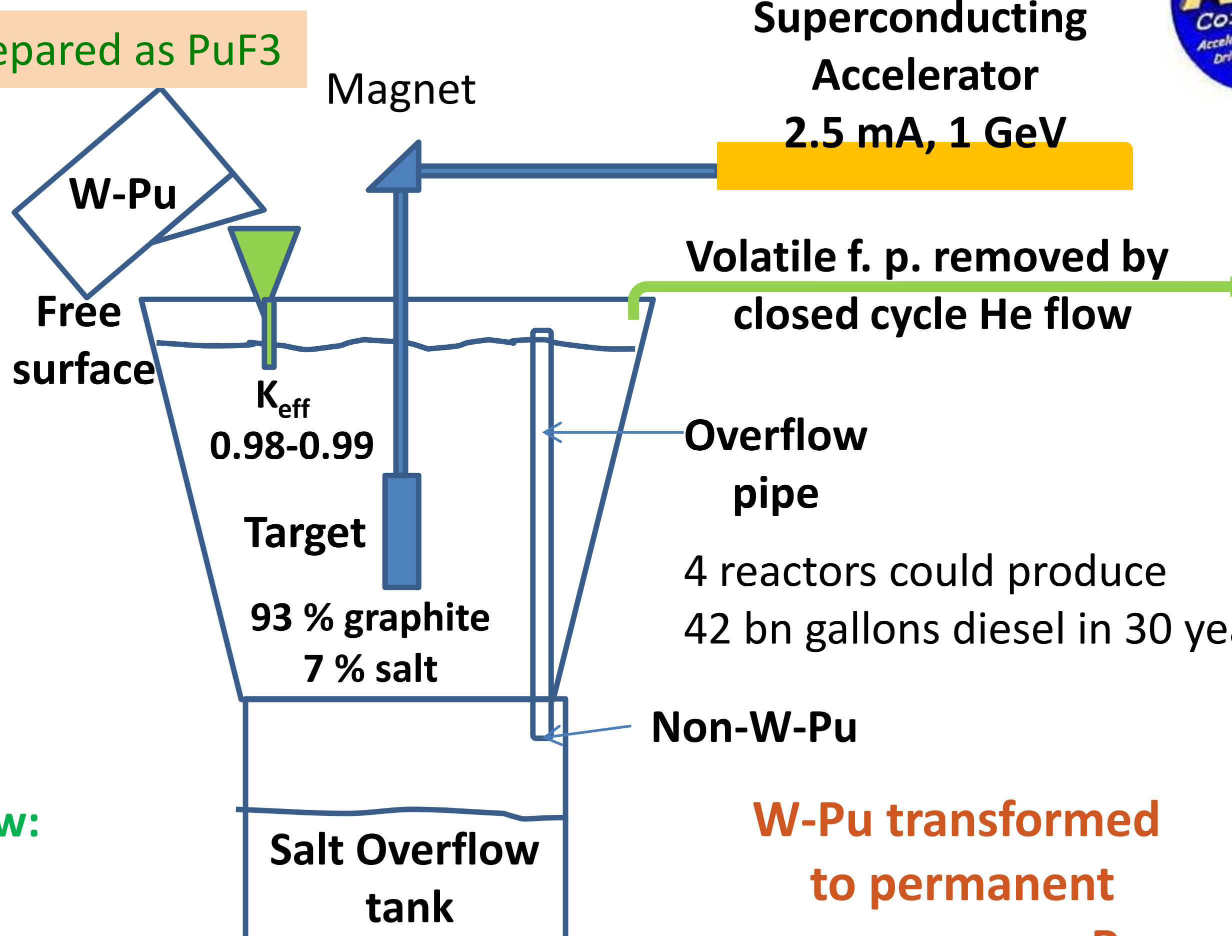
# Four GEM*STAR Units Burn 34 Tonnes of W-Pu in 30 Years

**Hourly fill:**
**30 g W-Pu as $PuF_3$ + carrier salt**

**Inflow W-Pu:**
**93 % $^{239}Pu$**
**7 % $^{240}Pu$**




4 reactors could produce
42 bn gallons diesel in 30 years

**Hourly overflow:**
**7.5 g as $PuF_3$ + carrier salt + 22.5 g of fission product**

**Non-weapons Pu Outflow:**
**52.4 % $^{239}Pu$**
**25.4 % $^{240}Pu$**
**10.6 % $^{241}Pu$**
**11.7 % $^{242}Pu$**

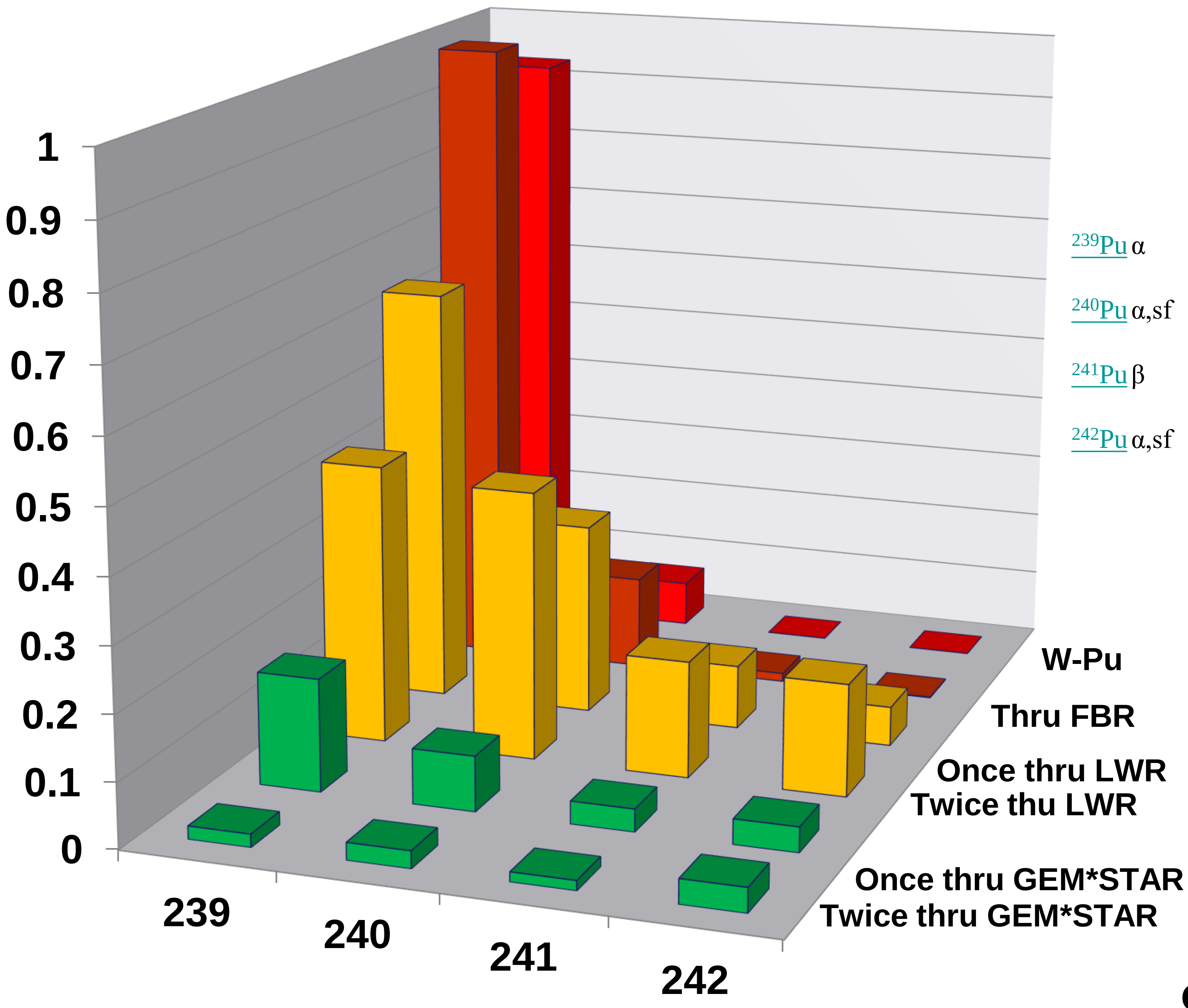
**Fission power 500 MWt for each GEM*STAR unit**

**W-Pu transformed to permanent non-weapons Pu immediately upon adding and mixing**

Invent
the
Future

GEM*STAR Consortium

# FB BN800 MOX-LWR GEM*STAR



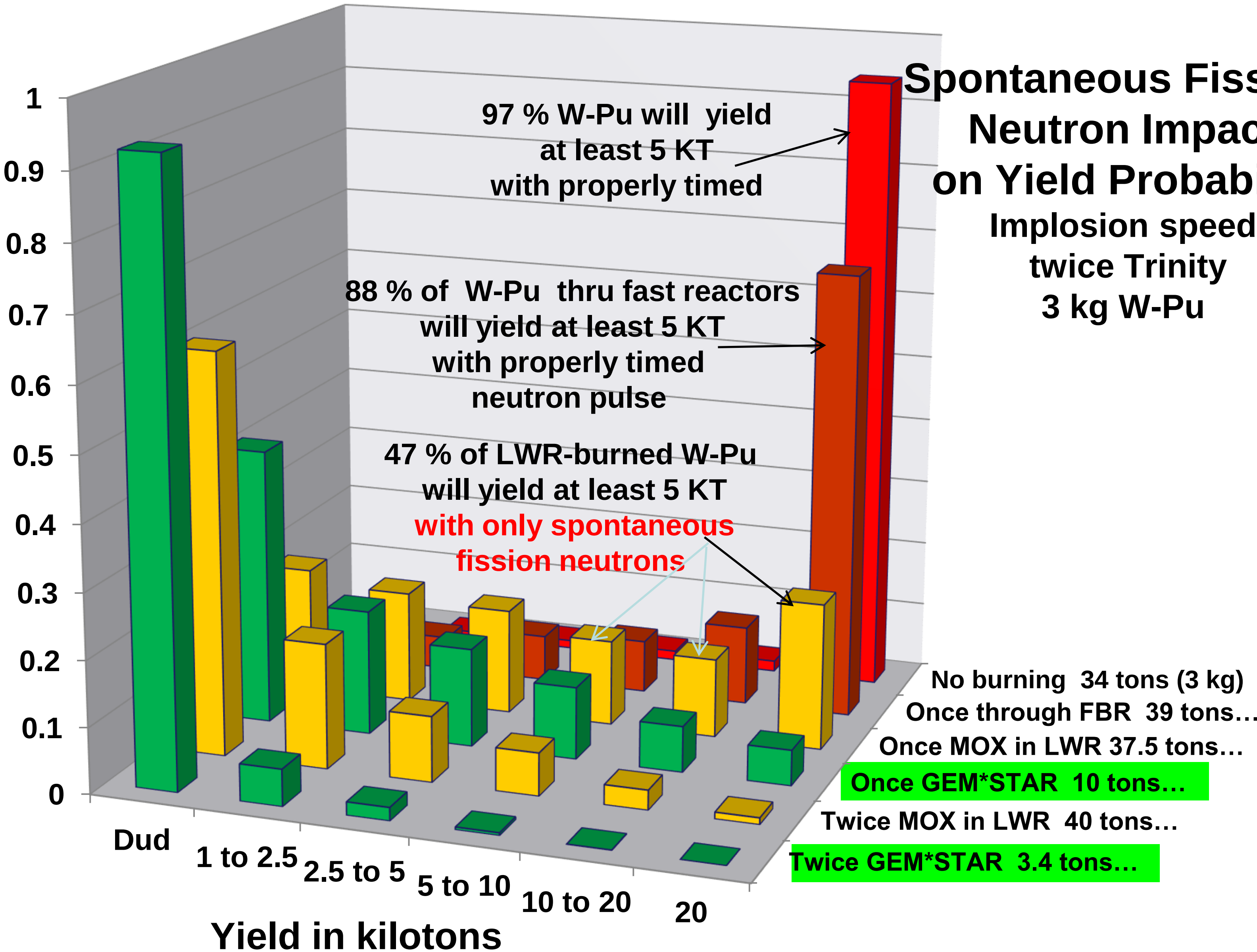

| | | |
|---|---|---|
| $^{239}$Pu | α | 24,110 years |
| $^{240}$Pu | α,sf | 6,561 years |
| $^{241}$Pu | β | 14.325 years |
| $^{242}$Pu | α,sf | 373,300 years |



GEM*STAR

# Spontaneous Fission Neutron Impact on Yield Probability

Implosion speed
twice Trinity
3 kg W-Pu



# ADSR Small Modular Reactors

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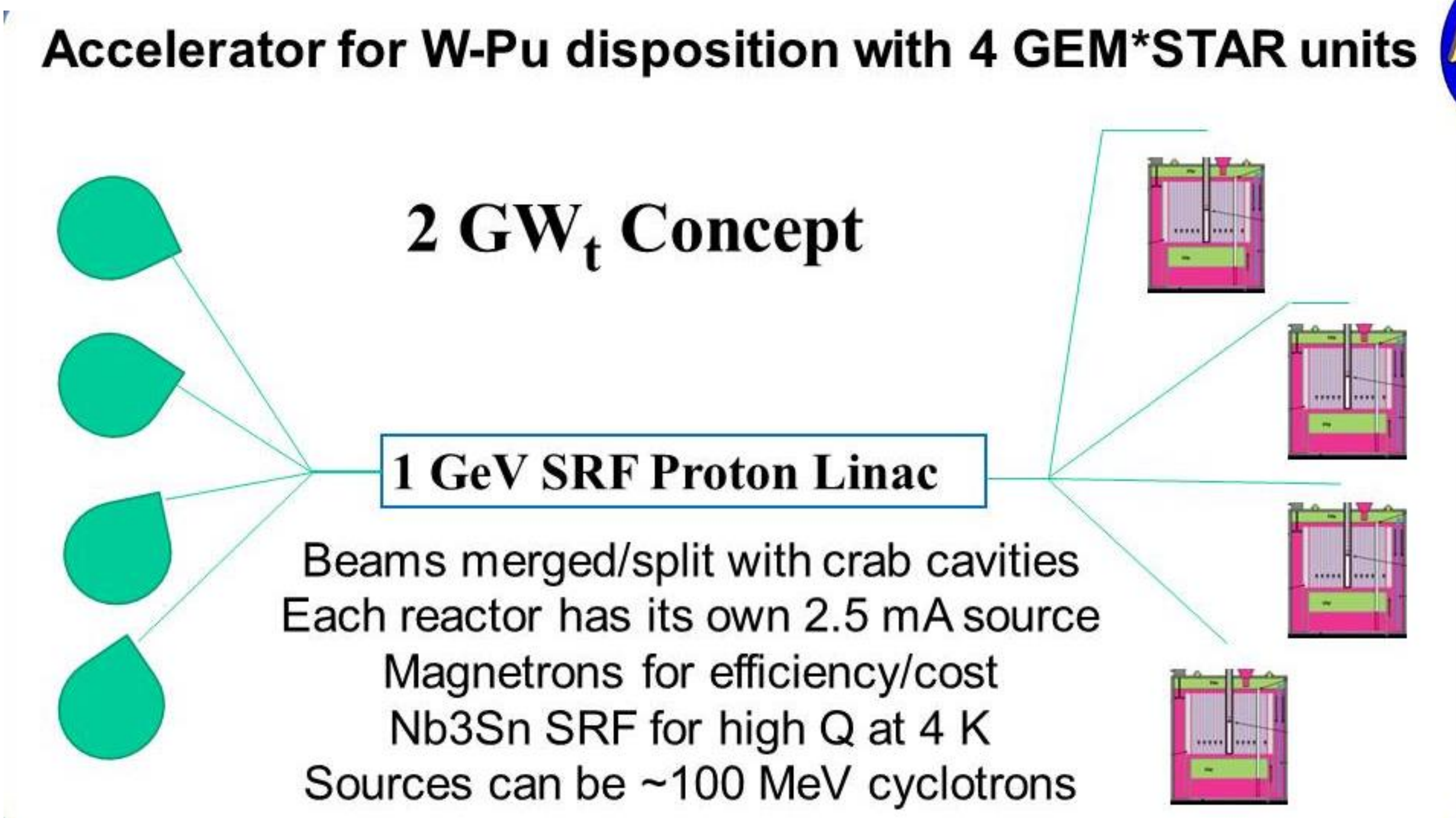


**< 300 MWe for a "modular" reactor – the small size allows for convective cooling of the decay heat when fission processes are terminated.**

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# GEM*STAR Advantages

- **Safety:**
  - Fission stops when the accelerator is turned off.
  - Without fission, passive air cooling is sufficient.
  - Passive response to most accident scenarios.
  - Design avoids all historical reactor accident scenarios involving radioactive release.
- **Waste Management:**
  - Burns all nuclear waste streams, *including its own.*
  - Ultimate waste stream can be two orders of magnitude less than LWR SNF.
- **Efficiency:**
  - Extracts most of the 94% energy left in spent nuclear fuel.
- **Proliferation Resistance:**
  - Needs neither isotopic enrichment nor reprocessing.
  - Waste stream is never useful to build weapons.

✧ **Enough uranium *out of the ground today* to supply the current U.S. electrical power usage for more than 1,000 years.**

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# 2015 Submision to DOE/NE

Muons, Inc. and partners competed for DOE-NE $50M, 5y grant – not granted
Now looking for the next opportunity for similar DOE grant

| Partners | year 1 | Primary Role | Point of Contact |
|---|---|---|---|
| Muons/ADNA | 2.6 | Project direction, integration | Dr. Rolland Johnson |
| | | Scientific oversight, Fischer-Tropsch | Dr. Charles Bowman |
| Niowave, Inc. | 1.0 | Commercial Accelerator Manufacturer | Dr. Terry Grimm |
| Newport News Shipbuilding | 0.5 | Commercial Manufacturer of Nuclear Reactors (for Aircraft Carriers and Subs) | Mr. Phillip Mills<br>Mr. Neil Moravek |
| ORNL | 2.0 | Reactor Design | Dr. Lou Qualls |
| | | Accelerator Operations (SNS) | Dr. John Galambos |
| TJNAF | 0.4 | Accelerator Design | Dr. Andrew Hutton |
| VT | 0.5 | Reactor Design, Simulations | Prof. Alireza Haghighat |
| | | Internal Target Design | Prof. R. Bruce Vogelaar |
| GWU | 0.5 | Policy Issues, Systems Integration | Prof. Andrei Afanasev |
| | | Simulations, Material Studies | Prof. Philippe Bardet |

# Summary – GEM*STAR & SRF Linacs

- multipurpose reactor design
  - internal spallation neutron target
  - high temperature molten-salt fuel
  - feed-bleed innovation
  - continuous purging of volatile radioactive fission products
  - burns SNF, natural uranium, thorium, or surplus weapons material
  - burns its own spent fuel
- subcriticality, versatility, and intrinsic safety features imply
  - less expensive to build, license, and operate than conventional reactors.
  - especially effective to dispose of nuclear weapons materials & SNF
- SRF Linacs - powerful, reliable, affordable, and efficient
  - steep learning curve with new developments
  - e.g. magnetron power sources and cavity construction techniques
- Goal - pilot plant demo of a GEM*STAR subcritical molten-salt fueled nuclear reactor driven by a superconducting RF proton linac
  - Burn SNF
  - Burn W-Pu

# Backup Slides

# G*S ADSR Advantages - Safety

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**Safety Aspects Reduce Regulatory Burden**

- Never requires a critical mass
  - Fission is stopped by turning off the accelerator
  - Mechanical control rods are not needed
  - Understanding subcriticality increases nuclear power acceptance
- No stored large volatile fission product inventory inside the reactor
  - Volatile FPs continuously removed and stored underground
  - Radioactive volatile FP inventory inside the reactor is reduced
  - by almost a factor of a million compared to LWRs
  - Reduces Defense in Depth problem
- Passive recovery from a loss of power or loss of coolant accident
  - Accelerator shuts down to stop fission
  - Simple modular reactor design limited to 500 MWt
  - Convective air cooling of heat from radioactive decay
- Internal heat exchange from molten salt fuel to molten salt coolant
  - Non-volatile FPs remain inside the reactor core or lower reservoir
- Freeze plug drains fuel into lower reservoir if temperature too high
  - In case of operator errors
  - Nothing is destroyed - Operation resumed by refilling from the lower chamber
- Operation at atmospheric pressure – no pressure vessel
- Neither fuel enrichment nor chemical reprocessing is required
- Operation above the annealing temperature of graphite
- Accelerator and reactors are below ground level

# G*S ADSR Advantages - Economics

**Economics**

- Fuel in the form of molten fluoride salts eliminates fabrication, installation, replacement and waste management needed for fuel rods
- Complexity of the reactor is reduced by adding a complex, but well tested, accelerator
  - Superconducting RF accelerators are on a steep development curve, and will only get simpler, shorter, more powerful, more efficient, and less expensive with time
- One accelerator can feed several GEM*STAR reactors, each with its independent proton source
  - Accelerator is itself modular and can be repaired quickly and safely
  - Operation history at SNS and CEBAF shows good reliability
  - Capital costs for a multi-MW proton accelerator reduced drastically in last 20 years (factor of 80) due to Superconducting RF (SRF).
  - Wall power (MWw) to beam power (MWb) efficiency is much improved relative to previous copper structures – can be around 80% with magnetron power sources.
  - 25 MWb, 1 GeV accelerator designed at ANL with DOE costed at ~$800M – can feed up to 10 GEM*STAR SMRs (2.2GWe for W-Pu).

# G*S ADSR Advantages - Operations

**Operations**

- Liquid fuel moved by He pressure; no radiation exposure to humans
  - allows graphite and spallation target replacement
- Operates at atmospheric pressure - No pressure vessel
- Low vapor pressure molten salt
- No fuel enrichment required
- No chemical reprocessing required
- Feed/bleed concept allows for continuous operation
  - No need to replace or move fuel pins

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# G*S Advantages W-Pu Disposition

**Pilot Plant to Dispose of W-Pu**

- Economy of GEM*STAR W-Pu disposition is compelling
- Burned W-Pu never useful for weapons
- Burned W-Pu never decays back to weapons useful material
- Conversion to non-W-Pu immediately upon entry into the reactor
- Pu 239 inventory can be reduced from 34 tons to 0.2 tons if desired
- Also converts Commercial Pu (C-Pu) to non-weapons-useful material
- Fission energy converted to diesel and sold as green fuel to DOD
  - for profit compared to MOX plan which has >$30B expense
- No conversion to MOX; conversion of Pu metal or $PuO_2$ to $PuF_3$