ACCELERATOR-DRIVEN SUBCRITICAL REACTORS FOR WEAPONS-GRADE PLUTONIUM DISPOSITION AND ENERGY GENERATION

Robert Abrams, on behalf of the

Muons, Inc. ADSR collaboration

OUTLINE

1. **About Muons, Inc.**
2. **Current status of nuclear power in U.S.**
3. **Benefits of coupling an accelerator with a nuclear reactor**
4. **Accelerators as neutron sources**
5. **Molten salt reactors**
6. **The GEM*STAR ADSR concept**
7. **One application: Disposition of W-Pu**
8. **Summary and outlook**

ABOUT MUONS, INC.

- Private company founded in 2002 by Rolland Johnson, with SBIR grants to support fundamental research on muon cooling and to promote development of a muon collider.
- Along the way Muons, Inc. has partnered with National Labs and Universities to further develop and innovate in these areas (see www.muonsinc.com):
  - Innovative muon cooling channels and associated superconducting magnet technologies
  - RF components: power sources (magnetrons), pressurized RF cavities, superconducting RF cavities
  - Ion sources
  - Beamline design software (G4beamline)
  - Generalized simulation software (MuSim)
  - Quasi-monochromatic gamma sources
  - Microtron-based gamma sources for security scanning
  - Innovative hadron beam monitors
  - Fast time-of flight detectors
  - Participation in experiments (MICE, Mu2e)
  - Development of ADSR and related applications and technologies

STATUS OF NUCLEAR POWER IN THE U.S.

Present Situation

- **U.S. has ~100 light water reactors (LWRs) that generate ~20% of electricity**
- **Aging nuclear reactors (LWRs) are being retired**
- **Issues with light water reactors (LWRs)**
  - **Fuel rods need replacement after burning ~5% of fissionable material**
  - **Accumulation and storage of spent nuclear fuel and fission products (nuclear waste)**
  - **Complexity and cost of replacing retired LWRs with new LWRs**
  - **LWRs operate near criticality (k=1.000000 ± 0.000001)**
  - **Risks of H_2 production in water-cooled reactors (Fukushima)**
- **Benefits of nuclear power**
  - **Very low carbon by-products**
  - **Safety and reliability record is good and can be improved**
  - **Needed to meet increasing future energy needs**

Future Trends and Progress

- ***Renewed interest in new types of advanced reactors (Next Gen), e.g.***
  - ***Small modular reactors***
  - ***Molten salt reactors with thorium or other fuels***
  - ***Liquid metal and gas cooled fast reactors***
  - ***Accelerator-driven sub-critical reactors***
- ***U.S. NRC is streamlining regulatory and licensing procedures***
- ***Private sources as well as DOE are funding new initiatives***

WHY COUPLE AN ACCELERATOR WITH A NUCLEAR REACTOR?

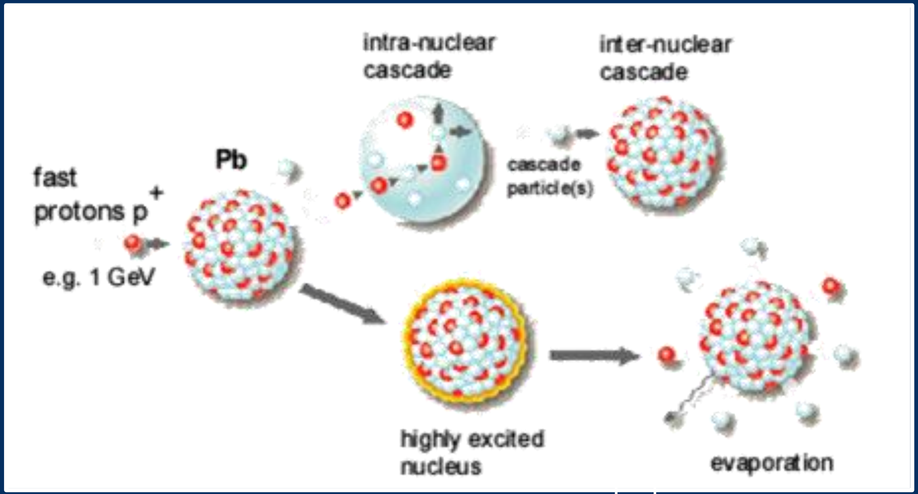
Features of Accelerator-driven reactors

- Proton accelerators produce large fluxes of neutrons by spallation processes, e.g. SNS and ESS
- The accelerator-generated neutrons enable the reactor to operate with lower amounts fissionable material in the core than conventional reactors, i.e. sub-critical operation (k = ~0.98)
- The accelerator beam can be varied to meet operating conditions
- The accelerator beam can be shut off to turn off the reactor
- Accelerator technologies, especially superconducting linacs, are rapidly improving, costs are declining

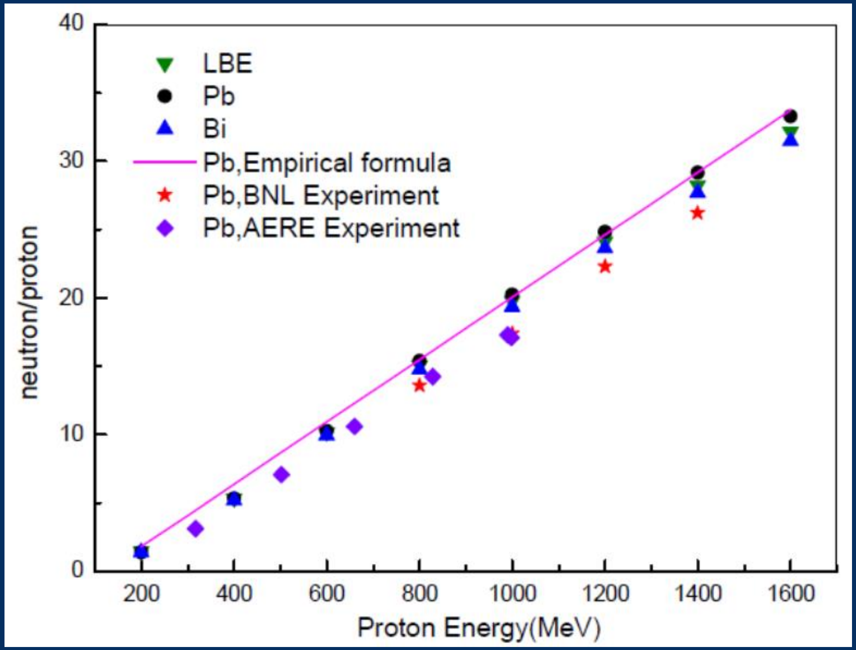
We at Muons, Inc. are furthering plans to use an accelerator with a molten salt reactor

PRODUCTION OF NEUTRONS BY ACCELERATORS

Spallation process

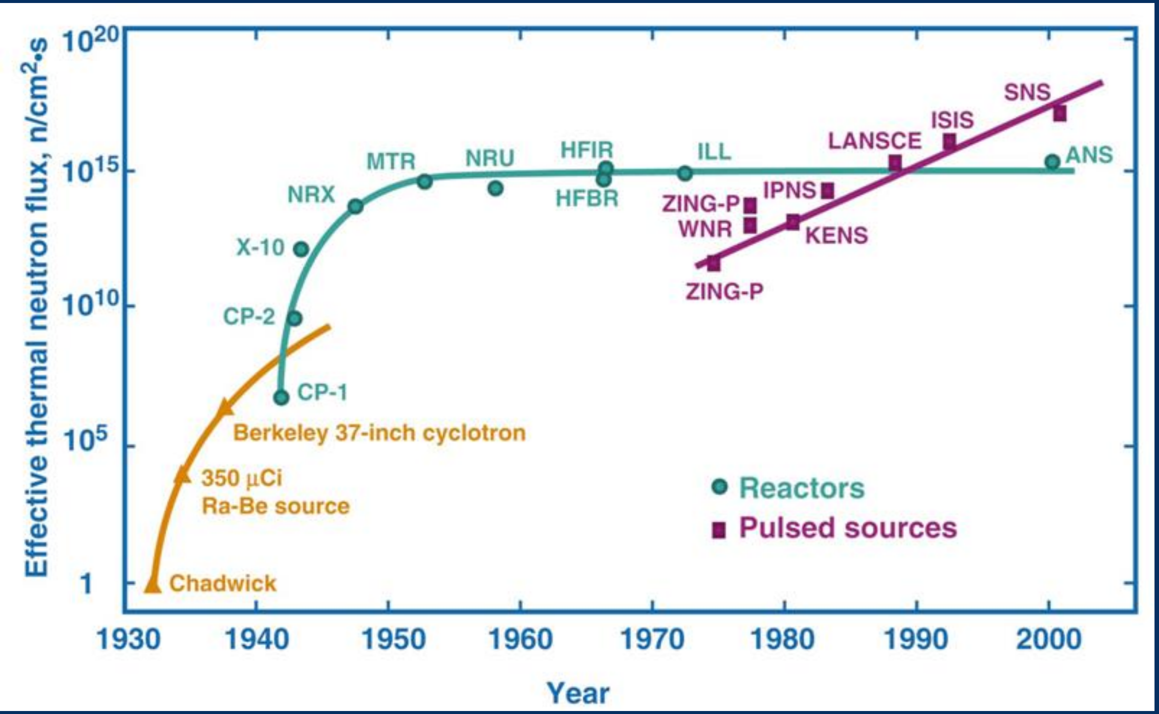


Neutrons per proton



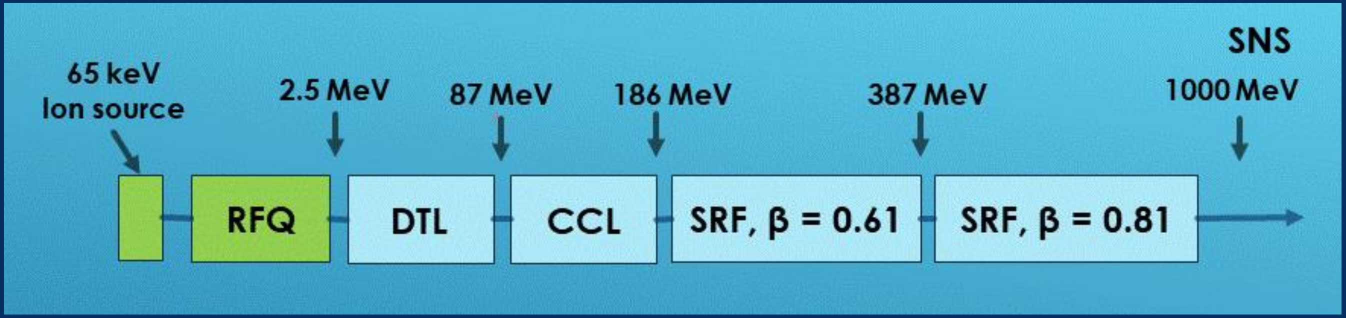
Target	600 MeV	800 MeV	1000 MeV
Fe	3.7	5.3	6.7
Pb	9.6	14.3	18.5
W	9.9	16.0	20.0
U	18.0	26.0	33.3

NEUTRON FLUXES FROM REACTORS AND ACCELERATORS



ORNL SNS: 1 GeV, 1 mA,1 MW p beam with 10% duty factor produces: ~6 E16 protons/s and ~2 E18 n/s

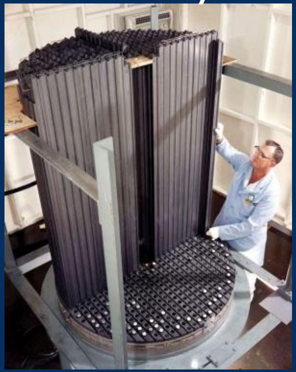
A CW SNS-type accelerator (~100% duty factor) produces ~10x < i > of pulsed accelerators, 10x fluxes of SNS, enough for several reactors



MOLTEN SALT REACTOR EXPERIMENT (MSRE):

Successfully built and operated at ORNL in 1964-69

MSRE Graphite core assembly

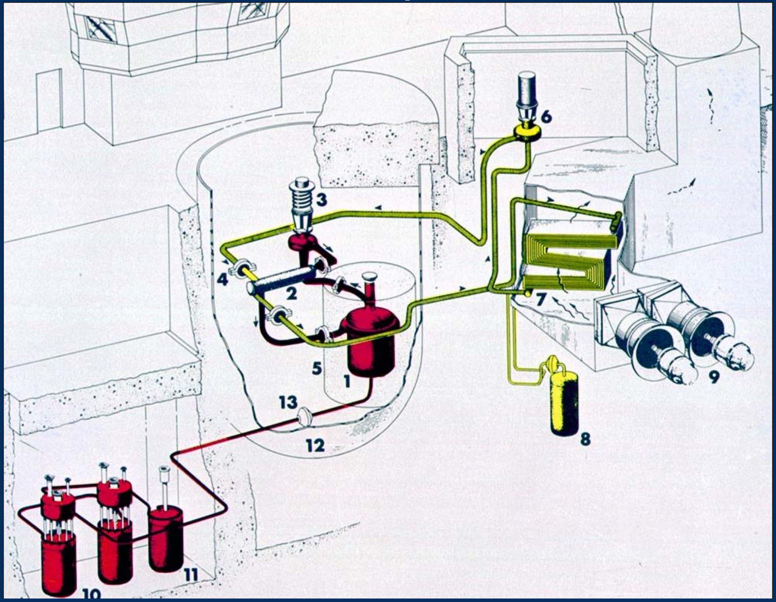


Molten salt

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

High boiling point → low vapor pressure

MSRE System



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 tank
11. Flush tank
12. Containment vessel,
13. Freeze valve

Began as Aircraft nuclear propulsion program (ARE) with a MSR, followed by MSRE

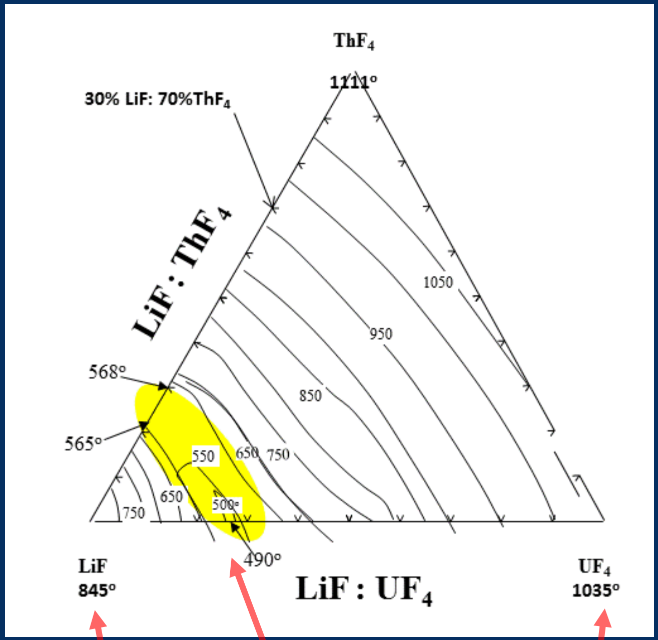
- MSRE Design began: 1960
- Construction began: 1962
- First went critical 1965
- Phase 1 Full power (8 MW_t), operated 6 mos: May, 1968
- Phase 2 100 kW operation with U233: 1967
- All objectives were met
- Feasibility and design studies of 1000 kW MSBR (breeder reactor) were completed

ORNL tried unsuccessfully to obtain funding to build the MSBR

The legacy of MSRE is a wealth of information about the chemistry, metallurgy, and engineering of molten salt reactors

MOLTEN SALT PROPERTIES

Example: Ternary mixture of LiF, UF_4, and ThF_4
- Binary mixtures along sides
- Yellow highlights eutectic region (Lowest melting point for mixtures)



Purely LiF:
m.p. is 845°C

Eutectic mixture: 73% LiF and 27% UF_4: m.p. is 490°C

Purely UF_4:
melting point is 1035°C

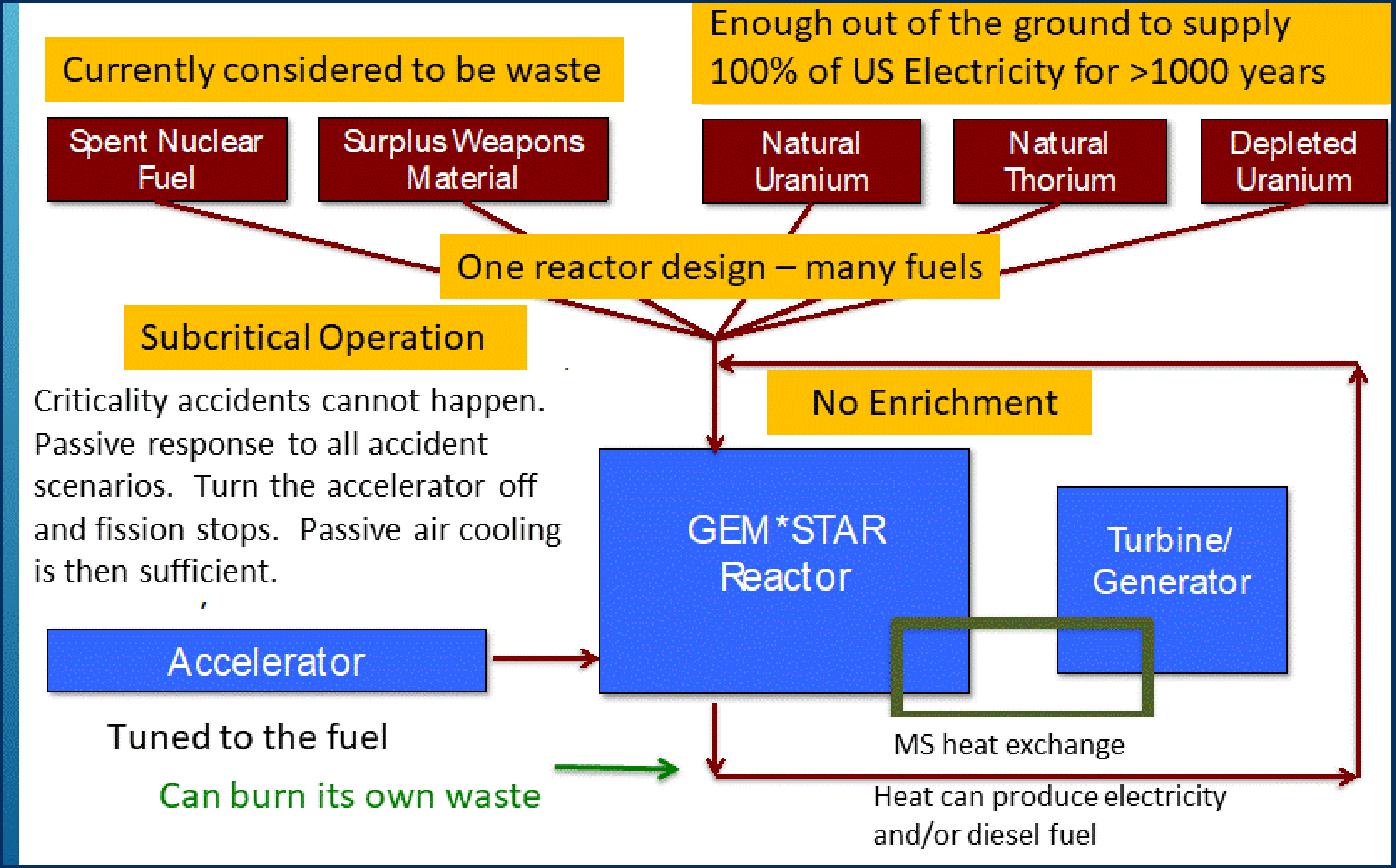
A typical operating temperature is ~650°C - 750°C

- Low vapor pressure
- Low viscosity
- High boiling point
- High heat capacity

Various carrier fluoride salts:
- Li F
- LiF and BeF2 (FLiBe)
- LiF, NaF, KF (FLiNaK)

Fuel fluoride salts:
- UF_4 (U-233, U-235, U-238)
- ThF_4
- PuF_3 (Pu-239, Pu-240)
- Mixtures of fuel salts

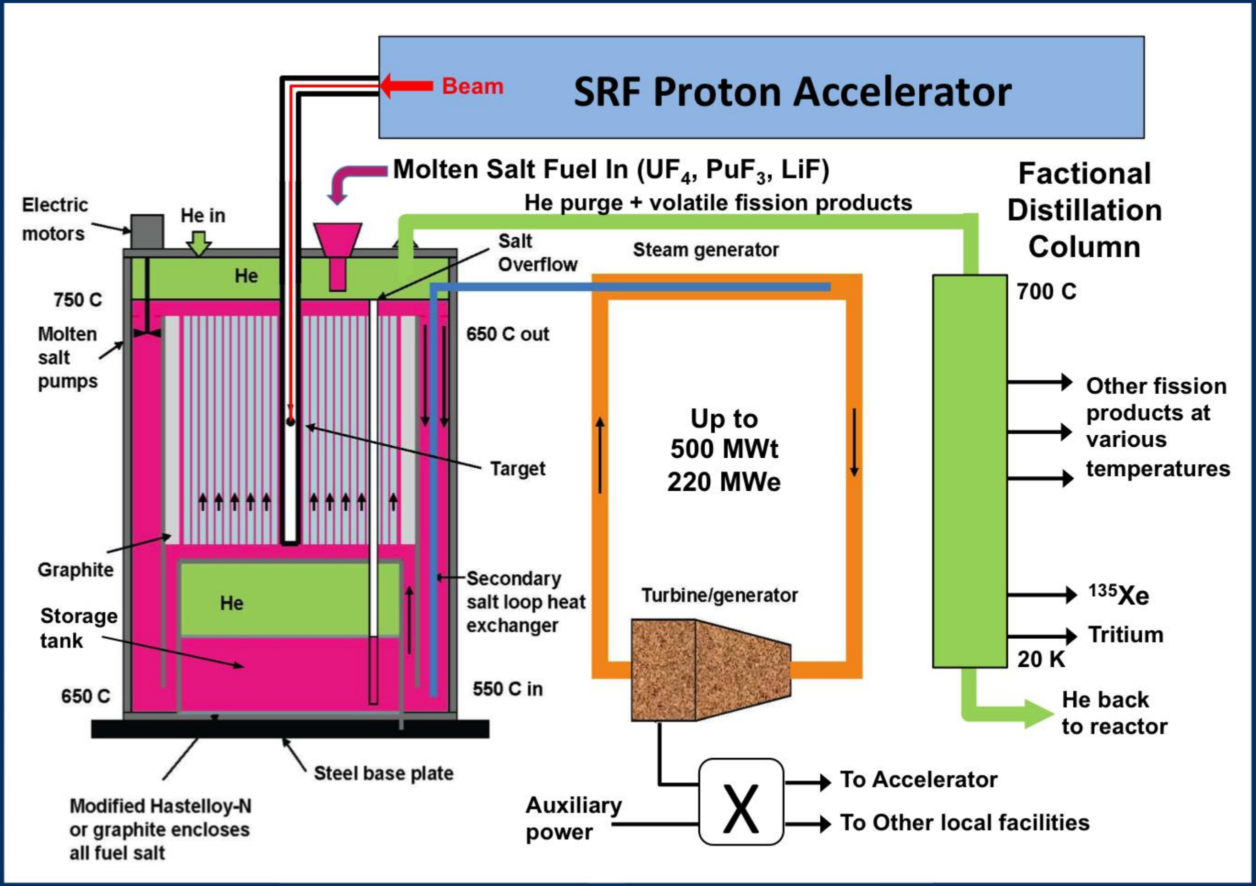
GEM*STAR: GREEN ENERGY MULTIPLIER-SUBCRITICAL TECHNOLOGY FOR ADVANCED REACTORS: FEATURES



Originated by C. Bowman (LANL and ADNA Corp.)

Concept published in 2010 Handbook of Nuclear Engineering: , "GEM*STAR: The Alternative Reactor Technology Comprising Graphite, Molten Salt, and Accelerators", Charles D. Bowman, R. Bruce Vogelaar, Edward G. Bilpuch, Calvin R. Howell, Anton P. Tonchev, Werner Tornow, R.L. Walter

GEM*STAR ADSR REACTOR



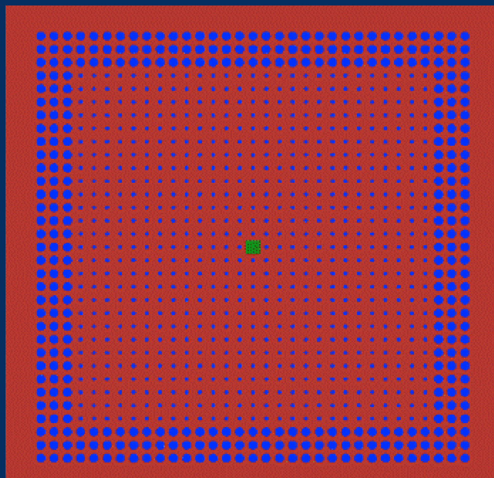
Muons, Inc. has been awarded a DOE GAIN* grant for ORNL to assist in conversion of LWR SNF to fluorides for GEM*STAR and to provide computer resources to Muons, Inc.

* Gateway for Accelerated Innovation in Nuclear (GAIN)

- Molten salt flows through channels in graphite core
- He gas removes volatile fission products
- Can burn multiple fuels
- Inherent safety features

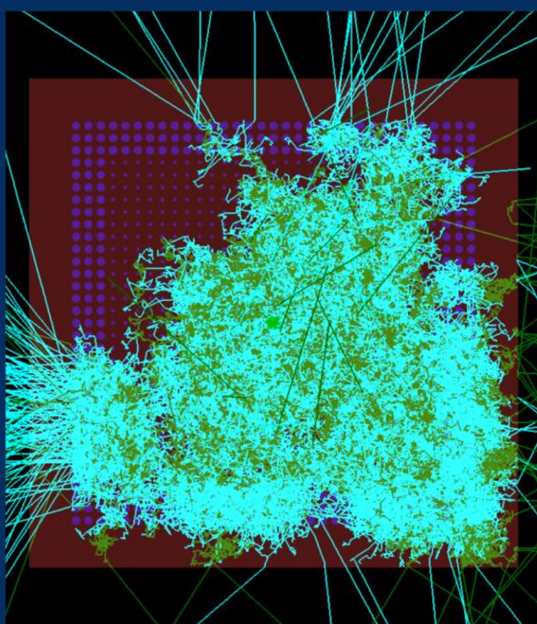
MUONS, INC SIMULATIONS OF GEM*STAR

Section through core center



Configuration: Graphite shown in brown
Molten salt in purple
Beam shown in green

Muons, Inc. has developed a simulation package (MuSim) that utilizes advanced nuclear codes such as MCNP6 and provides simplified user access and user-friendly graphical interfaces

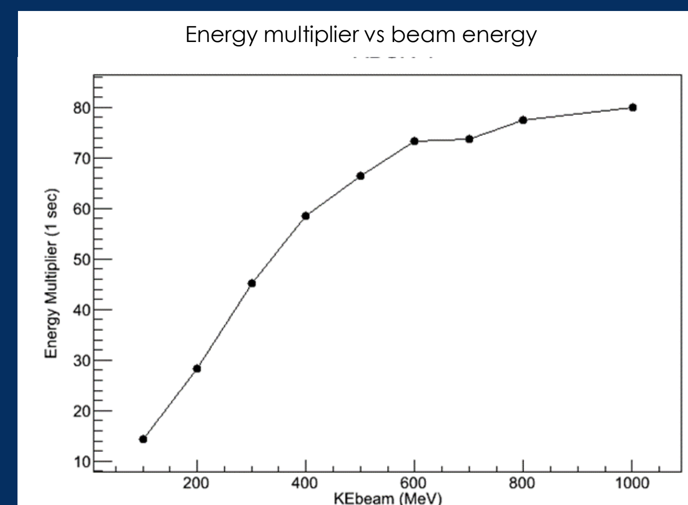


Simulation: Single 1 GeV proton striking U target in GEM*STAR

- 402,138 tracks (not counting e⁻)
  - green=neutron
  - cyan=gamma
- brown=graphite
- purple=molten-salt fuel

Graphite moderates initial (~ MeV) neutrons to thermal energies

Optimal beam energy ~ 600-800 MeV



A GEM*STAR APPLICATION: DISPOSAL OF WEAPONS-GRADE PLUTONIUM (W-Pu)

U.S.-Russian Plutonium Management and Disposition Agreement (1998-2011): Destroy 34 metric tons of surplus weapons-grade plutonium each by Russia and by U.S.*

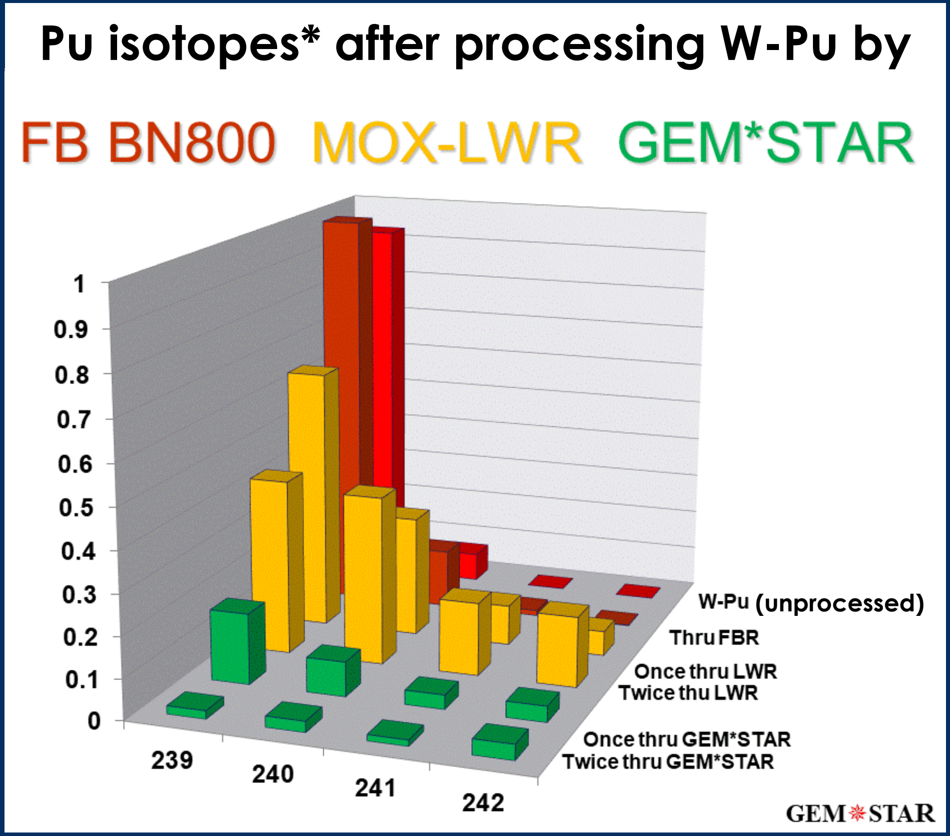
- Russia plans to burn the W-Pu as fuel in fast reactors
- U.S. plan is to mix oxides of W-Pu with oxides of depleted U and encase the mixed oxides (MOX) in glass pellets for use as fuel in LWRs
- In 2015 the MOX plant construction was put on hold due to cost overruns, and alternatives are being sought.

GEM*STAR can destroy W-Pu more completely than other approaches.

The Pu is fed continuously into the reactor, and is immediately rendered not-weapons-grade (even before burning is complete)

*Despite current events, there is still desire to dispose of W-Pu.

PLUTONIUM DISPOSITION COMPARISONS

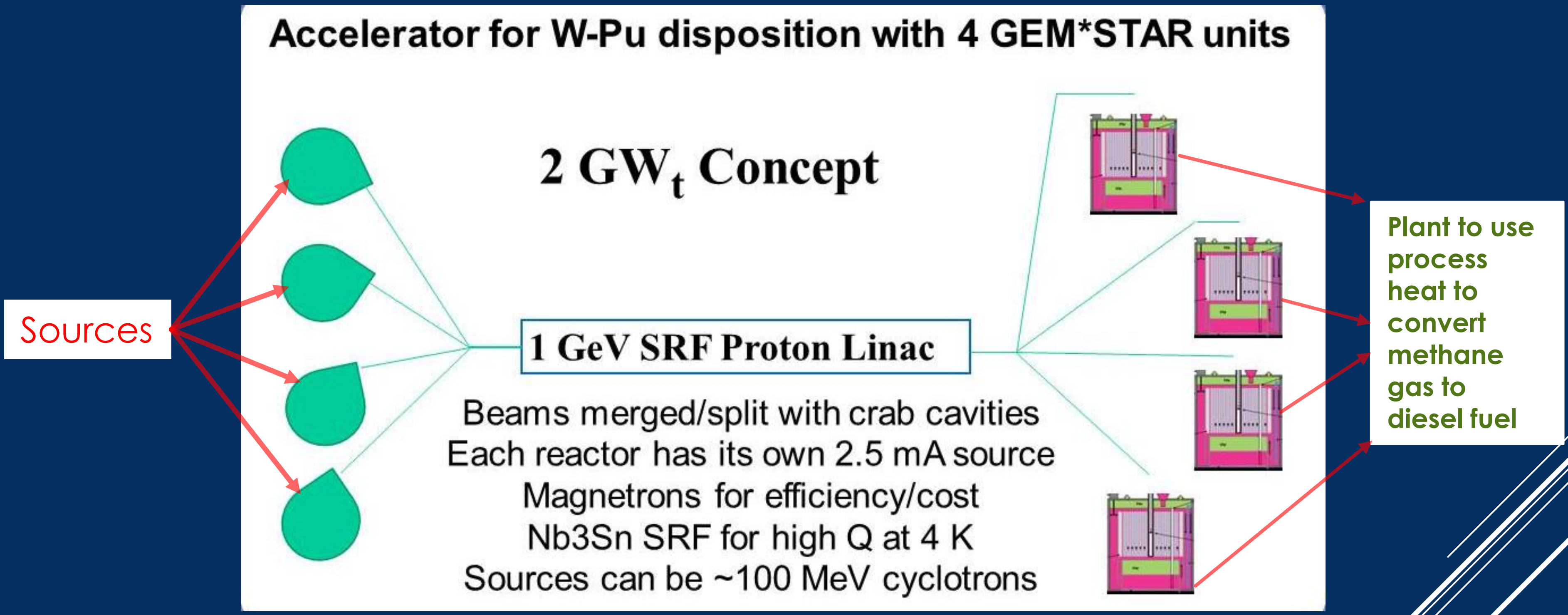


* Based in part on C. Bowman et al, Ann. Rev. Nucl. Sci. 48: 505

- Normalized to (Sum of W-Pu isotopes =1)
- Pu-239 is fissionable isotope
- Fast breeder (FB) reactor increases Pu239!
- MOX-LWR reduces Pu239 by ~40% per pass
- GEM*STAR reduces Pu239 by ~85% per pass

GEM*STAR eliminates more Pu239 than either LWR or fast breeder (FB)

CONCEPT OF PROPOSED SYSTEM



GEM*STAR TECHNOLOGY READINESS ASSESSMENT:

Ready For Engineering, No New Research Needed

Table 1: Component Technology Readiness

Component	Level	Comment / Example
Accelerator – 1 MW	9	SNS at ORNL
Accelerator – 10 MW	7	SNS is a "prototype": 1 MW with < 10% duty factor
Molten-Salt Reactor	6	Molten Salt Reactor Experiment at ORNL
Spallation Target	6	Other designs (in many places) are level 9
Fischer-Tropsch	9	Numerous operational plants e.g. SASOL in South Africa
MS Heat transfer to F-T	4	Prototype at BCLF Corp. (C. D. Bowman)

DOE's Technology Readiness Scorecard (Levels 1 – 9):

1. Basic principles observed and reported.
2. Technology concept 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 mission operations.

PARTNERS WHO HAVE EXPRESSED INTEREST IN TEAMING UP WITH MUONS, INC. FOR GEM*STAR W-PU DISPOSITION

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

SUMMARY AND OUTLOOK

- **Support for Gen 4 reactors is growing in the nuclear industry and in the DOE.**
- **The GEM*STAR system is a candidate for Gen 4**
- **GEM*STAR can without redesign will burn spent nuclear fuel, natural uranium, thorium, or surplus weapons material.**
- **The GEM*STAR reactor operates in subcritical mode, with inherent safety features, will be less expensive to build and to operate than conventional reactors.**
- **SRF linacs meet requirements for power, reliability and efficiency for ADSR, and are advancing rapidly with new developments in magnetron power sources, cryostats, and cavity construction techniques that will make SRF systems even more powerful and cost-effective.**
- **Muons, Inc. invites you to consider joining our team and our quest. Contact rol@muonsinc.com if interested.**

BACKUP SLIDES

Muons, Inc.

GEM*STAR SAFETY FEATURES

- 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 in this mitigation technique
  - Operation is 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

GEM*STAR ECONOMICS FEATURES

- 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 acceptable reliability
    - Capital costs for a multi-MW proton accelerator reduced drastically in last 20 years.
    - Wall power (MWw) to beam power (MWb) efficiency with Superconducting RF (SRF) is much improved relative to previous copper structures – will be >50%.
    - 25 MWb, 1 GeV accelerator designed at ANL with DOE costed at ~$800M – can feed up to 10 GEM*STAR SMRs

GEM*STAR OPERATIONAL FEATURES

- Liquid fuel moved by pumps and 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 chemical reprocessing required - No fuel enrichment required
- Feed/bleed concept allows for continuous operation
  - No need to replace or move fuel pins

GEM*STAR W-Pu DISPOSAL PROCESS