Mu*STAR Accelerator-Driven Subcritical Molten-Salt All-Purpose Nuclear Reactor

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/

512 GeV July 7 1983 Fermilab MCR

Superconducting magnet Energy Doubler became the Tevatron Pbar-P Collider.

Here I am with my commissioning team including a couple of BNL people you may know.

Muons, Inc.

BHAG: Big Hairy Audacious Goal,

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 at the Tevatron
2000 – Discovery of Quark-Gluon Plasma at RHIC
2010 – Large Hadron Collider
2014 – Discovery of Higgs Boson at the LHC

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

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

Muons, Inc.

Completed Muons, Inc. Projects

Year	Completed Projects	SBIR-STTR Funds	Research Partner	Phase III
2002	Company founded			
2002-5	High Pressure RF Cavity	$600,000	**IIT (Kaplan)**	$445,000
2003-7	Helical Cooling Channel	$850,000	**JLab (Derbenev)**	$3,100,000
2004-5	MANX demo experiment	$95,000	**FNAL (Yarba)**	$22,230
2004-7	Phase Ionization Cooling	$745,000	**JLab (Derbenev)**	
2004-7	H2Cryostat - HTS Magnets	$795,000	**FNAL (Yarba)**	$1,400,000
2005-8	Reverse Emittance Exch.	$850,000	**JLab (Derbenev)**	
2005-8	Capture, ph. Rotation	$850,000	**FNAL (Neuffer)**	$198,900
2006-9	G4BL Simulation Program	$850,000	**IIT (Kaplan)**	$8,732,479
2006-9	MANX 6D Cooling Demo	$850,000	**FNAL (Lamm)**	$495,630
2007-10	Stopping Muon Beams	$750,000	**FNAL (Ankenbrandt)**	$410,488
2007-10	HCC Magnets	$750,000	**FNAL (Zlobin)**	$255,000
2007-8	Compact, Tunable RF	$100,000	**FNAL (Popovic)**	$23,400
2008-9	Rugged RF Windows	$100,000	**JLab (Rimmer)**	
2008-9	H2-filled RF Cavities	$100,000	**FNAL (Yonehara)**	$23,400

More Completed Muons, Inc. Projects

Year	Projects In Progress	Funds	Research Partner
2008-12	Pulsed Quad RLAs (NFE)	$850,000	**JLab (Bogacz)**
2008-12	Fiber Optics for HTS (NFE)	$800,000	**NCSU (Schwartz)**
2008-13	RF Breakdown Studies	$850,000	**LBNL (Li) ANL (Gai)**
2009-12	HOM Absorbers	$850,000	**Cornell (Hoffstaetter)**
2009-13	Quasi Isochronous HCC	$850,000	**FNAL (Neuffer)**
2009-10	DC Gun Insulator	$100,000	**JLab (Poelker)**
2009-13	H-minus Sources	$850,000	**ORNL/SNS (Stockli)**
2009-13	Hi Power Coax Coupler	$850,000	**JLab (Rimmer)**
2009-10	Hi Field YBCO Magnets	$100,000	**NCSU (Schwartz)**
2009-13	Φ & f–locked Magnetrons	$850,000	**FNAL (Popovic)**
2010-11	ps detectors for MCDE	$100,000	**U Chicago (Frisch)**
2010-11	Crab Cavities	$100,000	**JLab (Rimmer)**
2010-11	MC detector bkgnds	$100,000	**NIU (Hedin)**
2010-13	Epicyclic PIC	$850,000	**JLab (Derbenev)**

More Completed Muons, Inc. Projects

2011-12	Adjustable Coax Coupler	$100,000	**ANL (Nassiri)**
2011-12	SAW Photoinjector	$100,000	**JLab (Poelker)**
2011-12	2-Stage Magnetron	$100,000	**FNAL (Yakovlev)**
2011-12	Efficient H-minus Source	$100,000	**FNAL (Bollinger)**
2011-12	Achromatic Low Beta	$100,000	**JLab (Derbenev)**
2011-14	FiberOptic Quench Detection	$1,100,000	**NCSU (Schwartz)**
2012-13	Ribbon e Beam Monitor	$100,000	**ORNL/SNS (Aleksandrov)**
2012-13	RF Photoinjector Cavity	$100,000	**JLab (Rimmer) LBL(Li)**
2014	Bi2212 30T Solenoid	$150,000	**FNAL(Shen)**
2011-14	FRIB Separator Magnet	$1,100,000	**BNL (Gupta)**
2011-14	HCC Engineering Design	$1,100,000	**FNAL (Yonehara)**
2012-15	S-Band RF Load	$1,100,000	**SLAC (Krasnykh)**
2012-15	Complete Cooling Channel	$1,100,000	**JLab (Derbenev)**
2013-19	High MTBF Magnetron	$1,150,000	**JLab(Wang)**
2014-16	H-minus source	$1,150,000	**ORNL/SNS (Stockli)**
2018-19	Mirascope Beam Profile Monitor	150,000	**FNAL (Thurman-Keup)**
2015-19	Gas-filled RF Beam Profile Monitor	1,150,000	**FNAL(Yonehara)**

Muons, Inc.

Contracts with National Labs

2009-10	Mono-E Photons	2 contracts w **PNNL**	$172,588
2009-10	Project-X and MC/NF	contract w **FNAL**	$260,000
2009-10	MCP and ps timers	contract w **ANL**	$108,338
2010	MAP - L2 mngr	2 contracts w **FNAL**	$55,739
2010	805 MHz RF Cavity	contract w **LANL**	$230,000
2012	MAP - L2 mngr	contract w **FNAL**	$40,000
2012	PX cooling for Mu2e	contract w **FNAL**	$75,490
2012	g-2	contract w **FNAL**	$40,160
2012	ACE3P 12 GeV Upgrade Studies	contract w **JLab**	$50,000
2013	MAP, L2, MASS, G4beamline	contract w **FNAL**	$115,000
2014	Parmela Simulations	contract w **Niowave**	$50,000
2014	MAP, L2, MASS, G4beamline	contract w **FNAL**	$125,000
2015	Mu2E MuSim Support	contract w **FNAL**	$230,000
2015	Magnetron power source feasibility	contract w **Toshiba**	$30,000
2017	RF Windows	contract w **Accuray**	$20,000
2018	H- Source for LANCE	contract with LANL	$20,000
	Explicit DOE/NE GAIN Grant for Mu*STAR		
2017-18	On-Site O2 to Fluoride conversion of LWR SNF	w ORNL, INL, SRNL	$500,000

Examples of SBIR-STTR Work Relevant to High Power SRF Accelerators for ADS

- RF Window and related technologies
- RF Window coax and waveguide designs
- RF Load material and related technologies
- Anti-Charging chemistry for Beam Loads
- Magnetron and related technologies
- Amplitude Modulated Magnetron designs
- Gun Inverted Insulator design
- Novel Crab cavity design
- Proton, Ion, and H- Sources
- High radiation environment Beam Profile Monitors

SRF Linacs need efficient microwave power

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

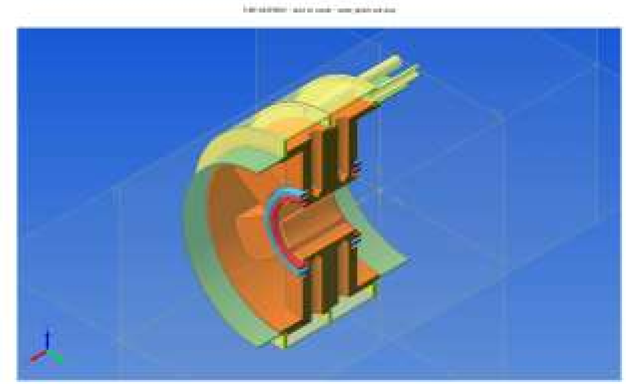
Replaces CEBAF klystrons

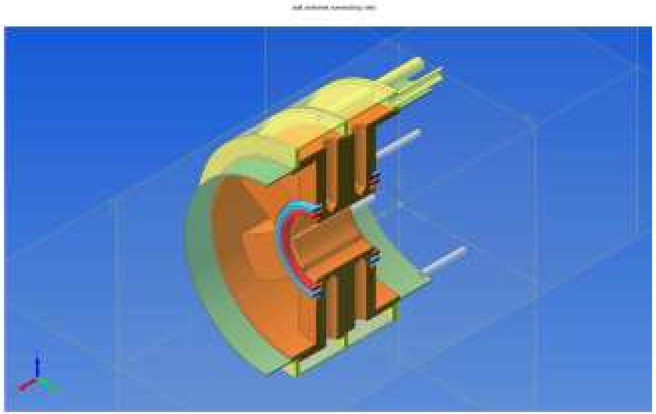
1497 MHz 4” D

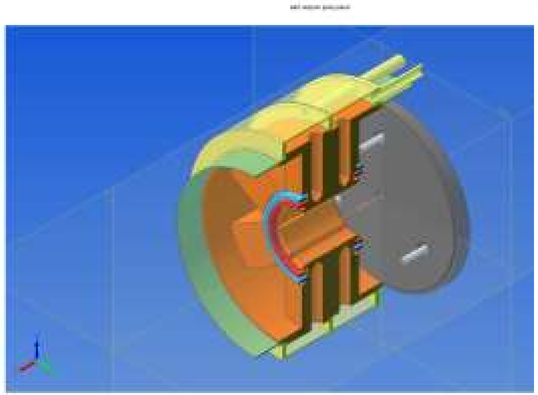
Replaces tetrodes for Mo99 production

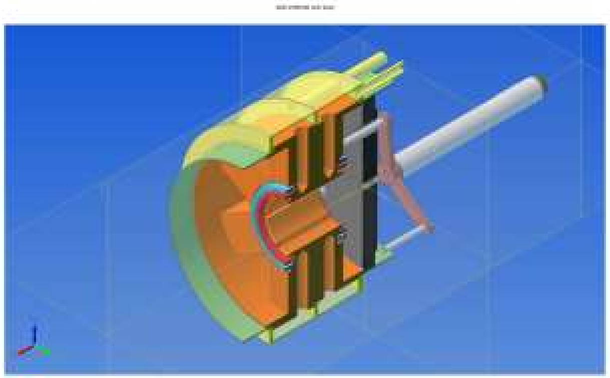
350 MHz 140 kW CW 10” D

Assembly of a Magnetron









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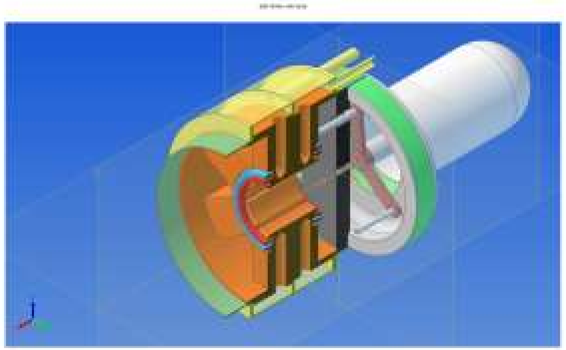
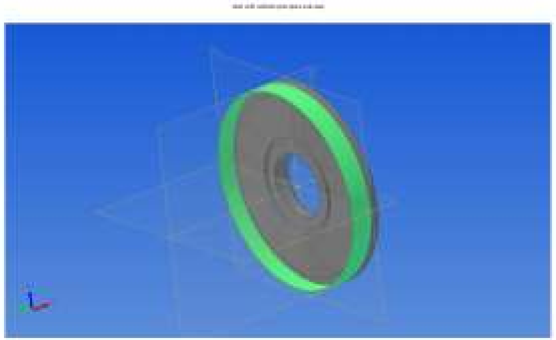
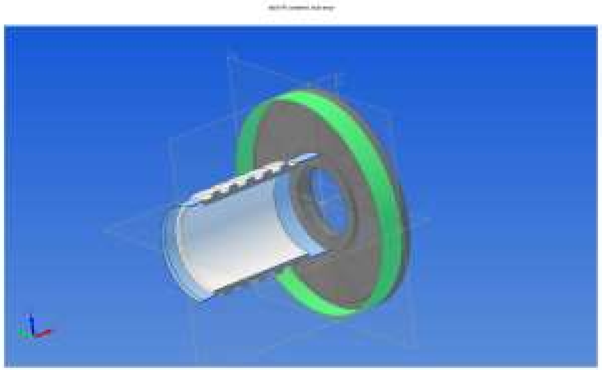
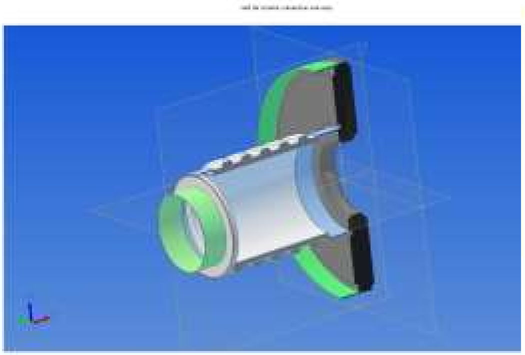
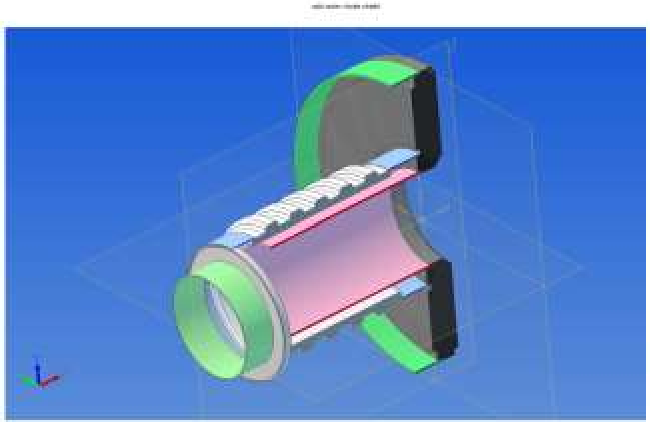
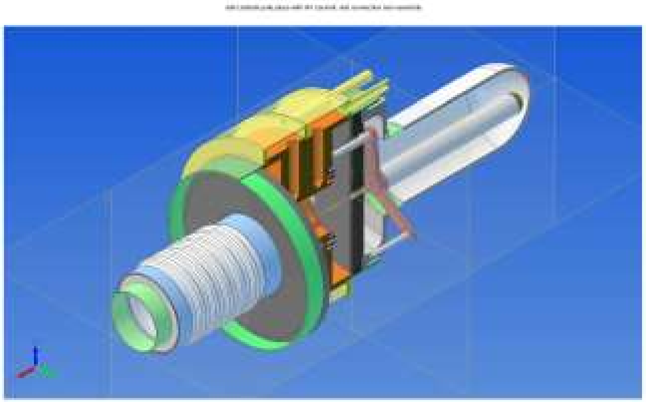




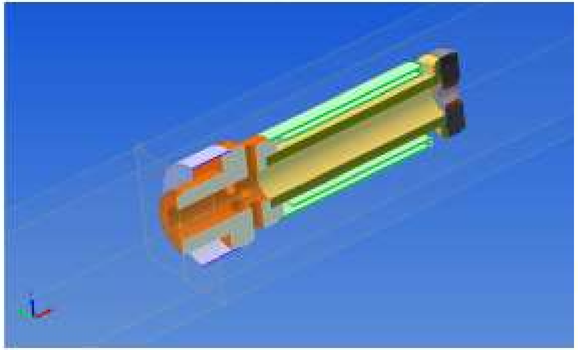


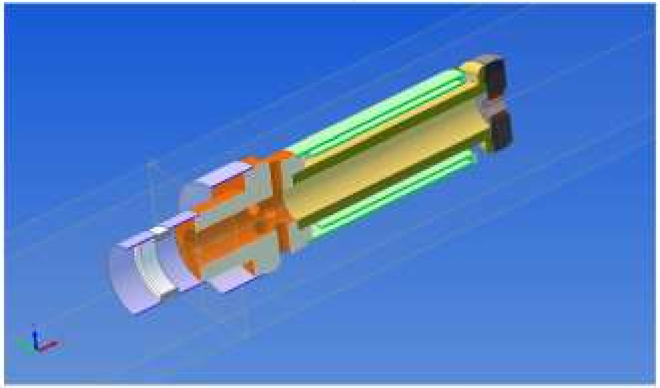


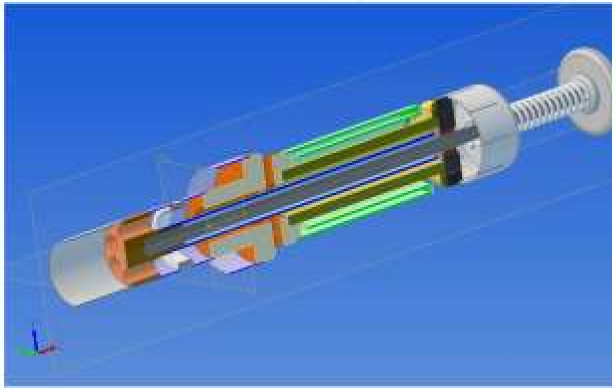


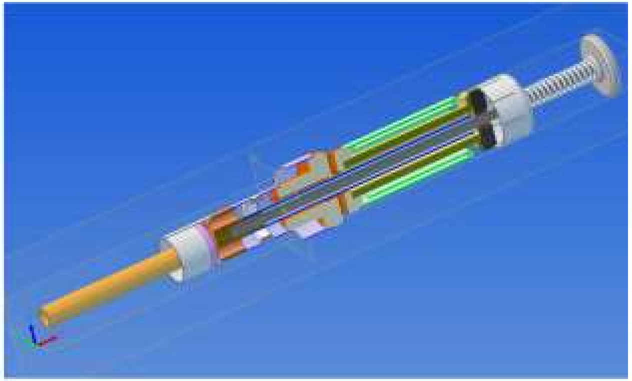


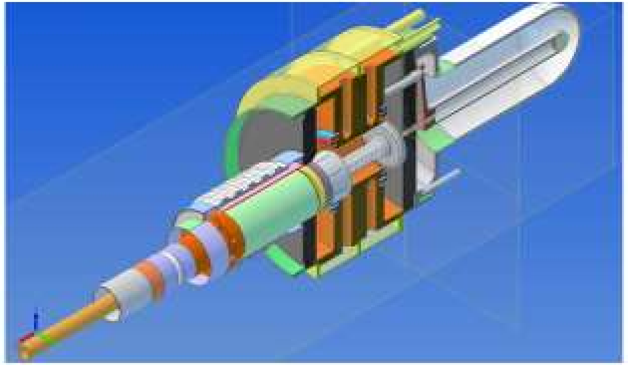
Assembly of a Magnetron (continued)



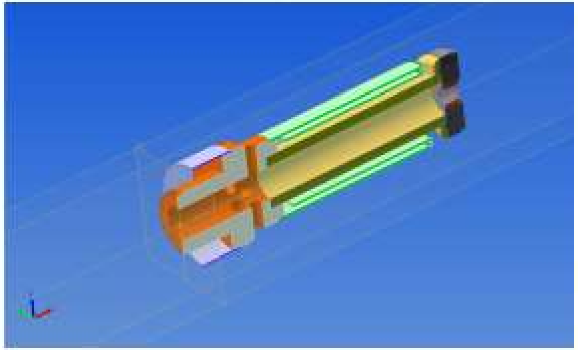


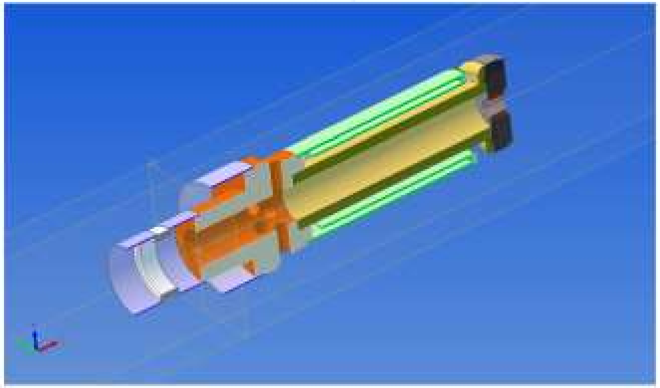


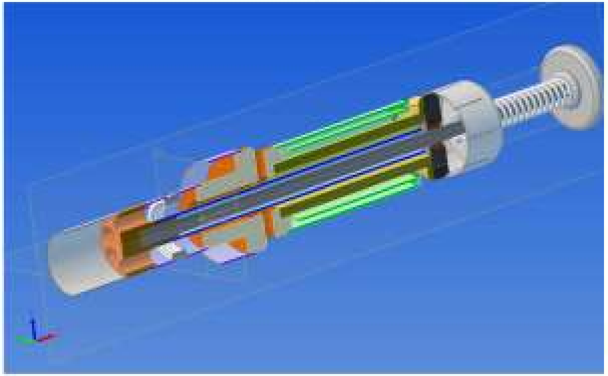


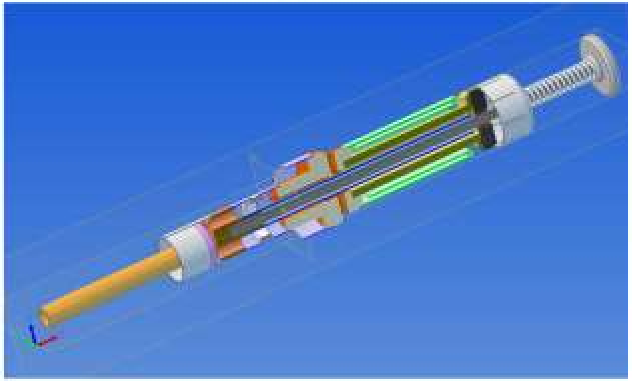


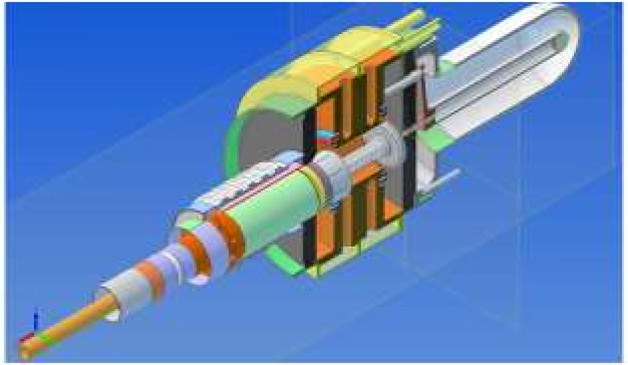
Assembly of a Magnetron (continued)











Magnetron Cathodes and RF Window

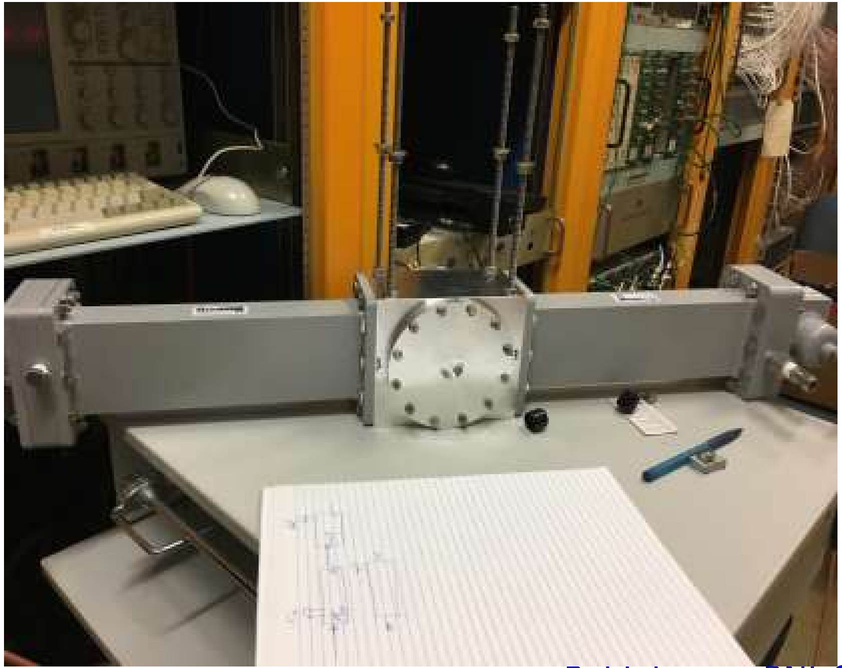
You may use kitchen microwave ovens to make popcorn. They are powered by magnetrons and the oven is an example of a (non-superconducting) RF cavity.

1497 MHz
Cathode Stalks

1497 MHz RF Window

ADS Need BPMs in High Radiation Areas

Katsuya Yonehara proposed a very robust and simple beam profile monitor based on pressurized RF cavities. The only things in the radiation area are aluminum waveguides and RF cavities filled with nitrogen gas.



- 2.4 GHz gas-filled RF resonator
- Pillbox cavity (TM011)
- Inner diameter 3.685±0.001”
- Length 3.000”
- RF body and wave guides are made of aluminum
- 1-mm thick beam window

Cavity is pressurized up to 2 atm

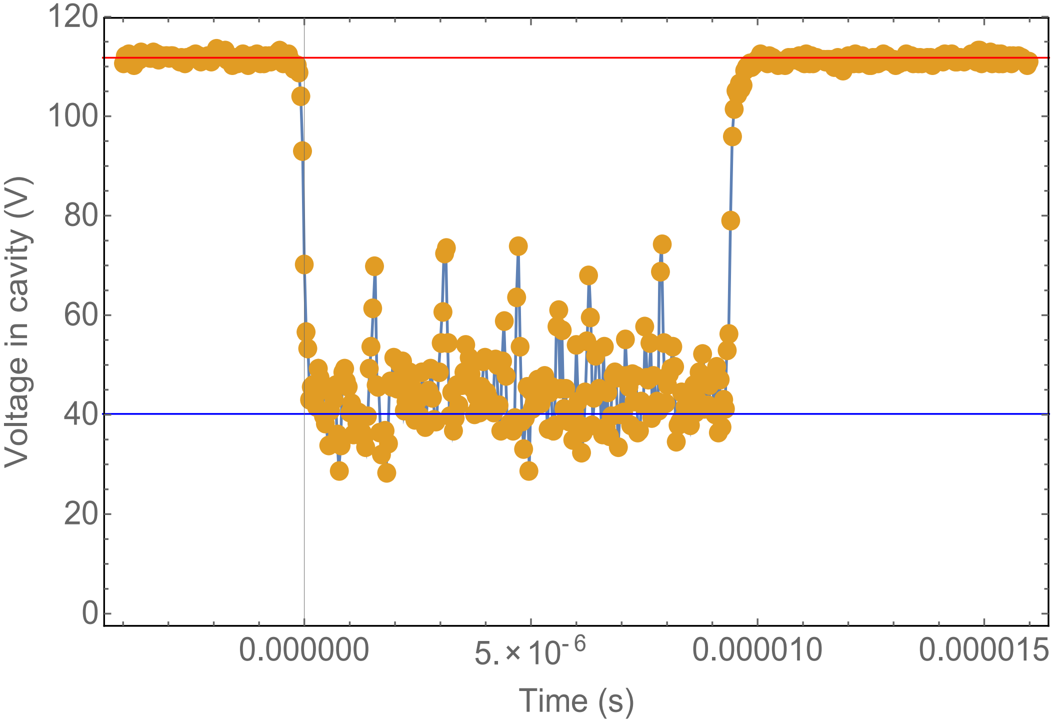
Beam tests show the idea works!
Will be used for LBNF and for Mu*STAR

An RF signal is sent through the waveguides and cavity as the 120 GeV, 4E12 Main Injector beam in 6 Booster batches goes through the cavity.

The signal is attenuated from 110 to 40 V as the beam induced plasma absorbs the RF energy.

The plasma production is proportional to the beam intensity.

Absolute calibration does not need beam.



Back to BHAG - A Critical Question

- **Criticality**. The normal operating condition of a reactor, in which **nuclear** fuel sustains a fission chain reaction. A reactor achieves **criticality** (and is said to be critical) when each fission event releases a sufficient number of neutrons to sustain an ongoing series of reactions.
- Subcritical reactor is not capable of sustained reactions
- In a subcritical ADS, each added neutron creates a fission chain that dies out
- The ADS is always subcritical – switching off the accelerator stops fissions
- DOE NNSA National Nuclear Security Agency responsible for Nuclear Weapons
  - NNSA $15B
  - SC $5B

Muons, Inc.

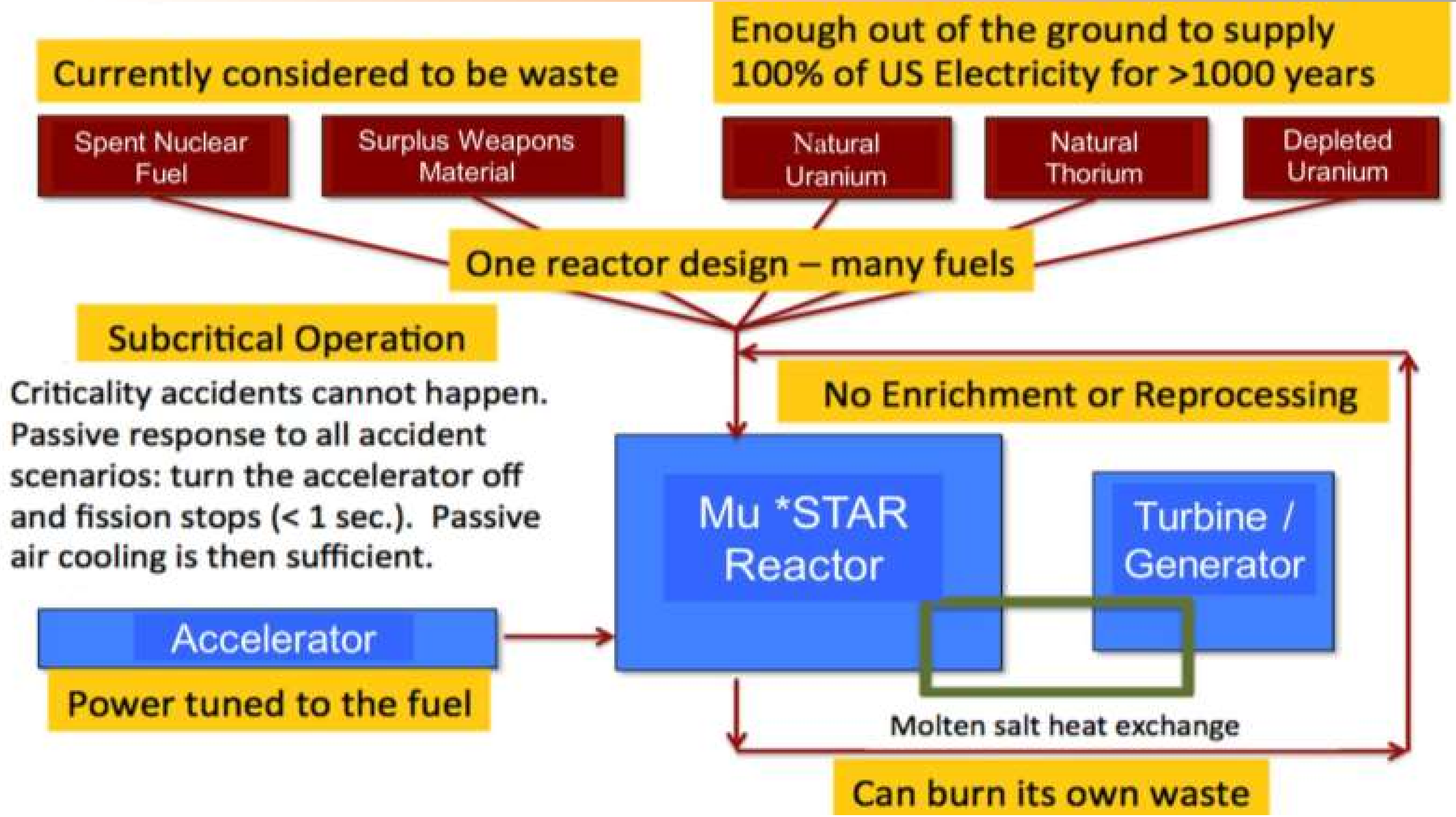
Back to BHAG - Why Molten Salt?

- Usual Nuclear Reactors use solid fuel
  - Small ceramic cylinders of UO_2 in long fuel rods
- If they are used in an ADS,
  - each time the beam trips off, fission stops
  - the cylinder experiences change in the temperature gradient-
    - hot in the center from fission to cooled edge
  - After hundreds of such trips of >few seconds,
  - mechanical fatigue is expected to cause the pellet to self-destruct

- So you need a perfect accelerator
  - SRF accelerators often have many short trips

- Molten Salt Fuel (a eutectic described later) is an end-run around this problem
  - (Other ADS projects use solid fuel)

Mu*STAR Concept: One Design, Many Uses



Currently considered to be waste

Enough out of the ground to supply 100% of US Electricity for >1000 years

One reactor design – many fuels

Subcritical Operation

Criticality accidents cannot happen. Passive response to all accident scenarios: turn the accelerator off and fission stops (< 1 sec.). Passive air cooling is then sufficient.

No Enrichment or Reprocessing

Power tuned to the fuel

Molten salt heat exchange

Can burn its own waste

New Technology, Old Technology

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    - First demo of scale and power needed
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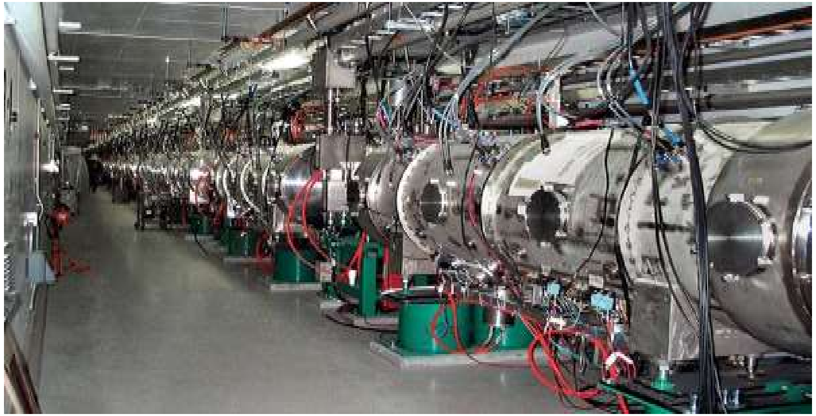
        - new approach to reactors(**1964-1969**)
- Merging these technologies allows
    - Eliminating enrichment and chemical reprocessing
    - Subcritical operation for safety and easier licensing
    - Deeper burns to extract more energy from fuel

Breakthrough Technology – Superconducting RF Linac

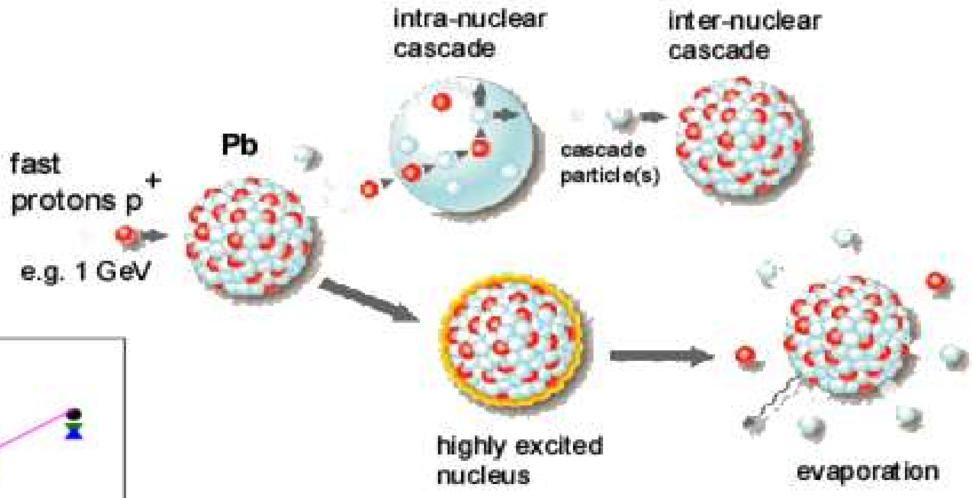
- Demonstrated at the ORNL Spallation* Neutron Source (SNS)
- Generates many neutrons to control reactor reactivity
- Powerful, efficient, affordable, reliable

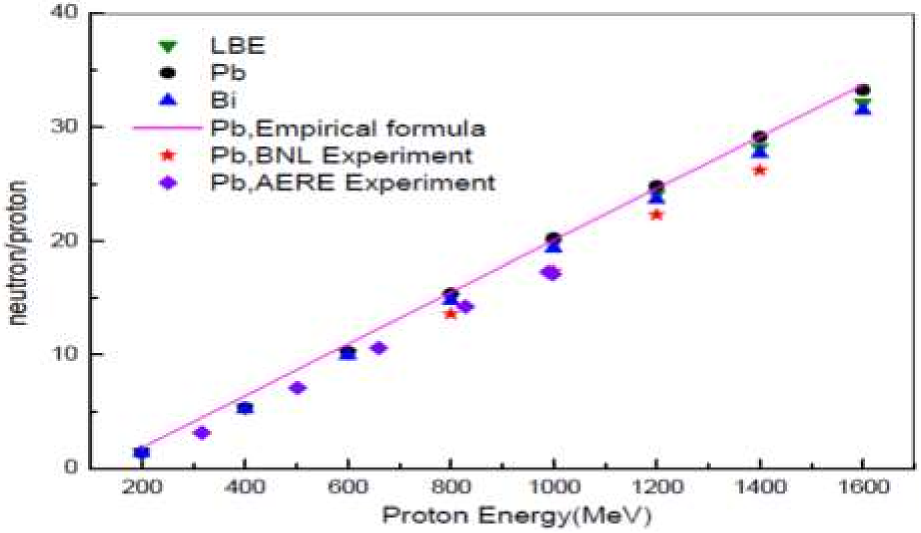
*1 p produces > 30 n

*Entry level niobium cavity delivered in 3 months (other options available).



Spallation requires Protons



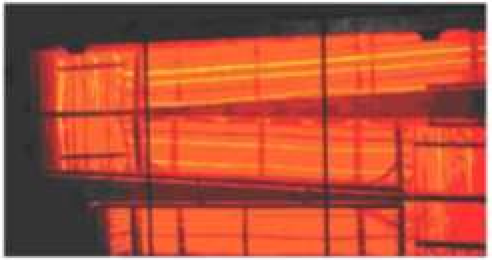


Target	600 MeV	800 MeV	1000 MeV
Fe	3.7	5.3	6.7
Pb	9.6	14.3	18.5
W	9.9	16.0	20.0
U	18.0	26.0	33.3

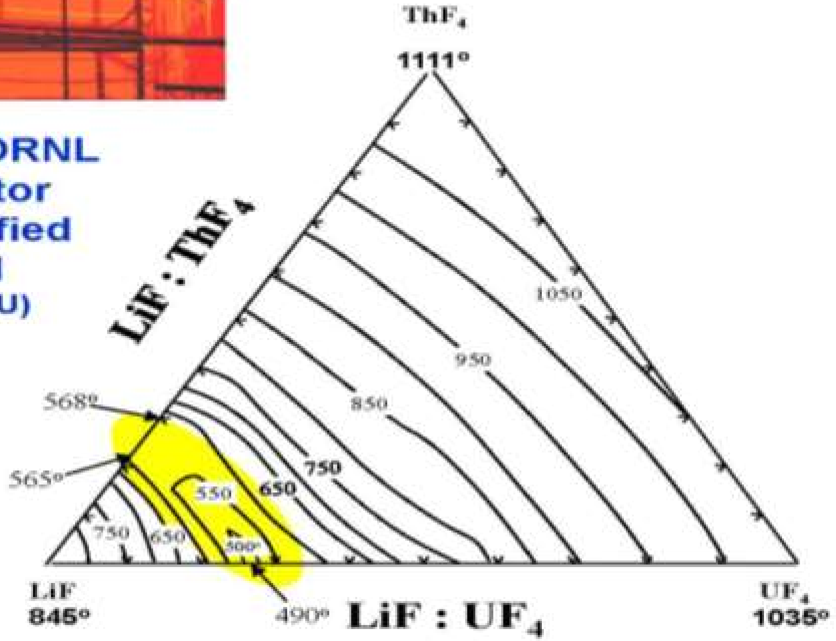
ORNL Molten Salt Reactor Experiment

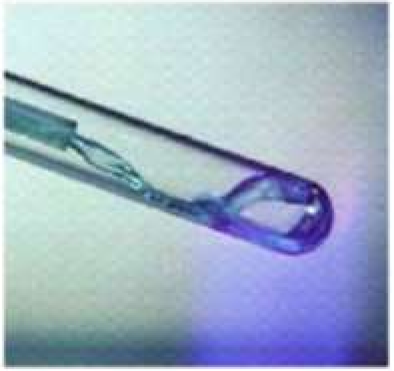
- Molten Salt Reactor Experiment operated at ORNL,1964-1969.
- Demonstrated the key aspects of using molten salt fuel.
- Critical reactor tested with three different fuels.
- Mu*STAR based on MSRE parameters-Temperature, graphite, Hastelloy-N
- Graphite MSRE core ¼ linear dimension of Mu*STAR, $4^3 =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

Molten Salt Eutectic Fuel



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



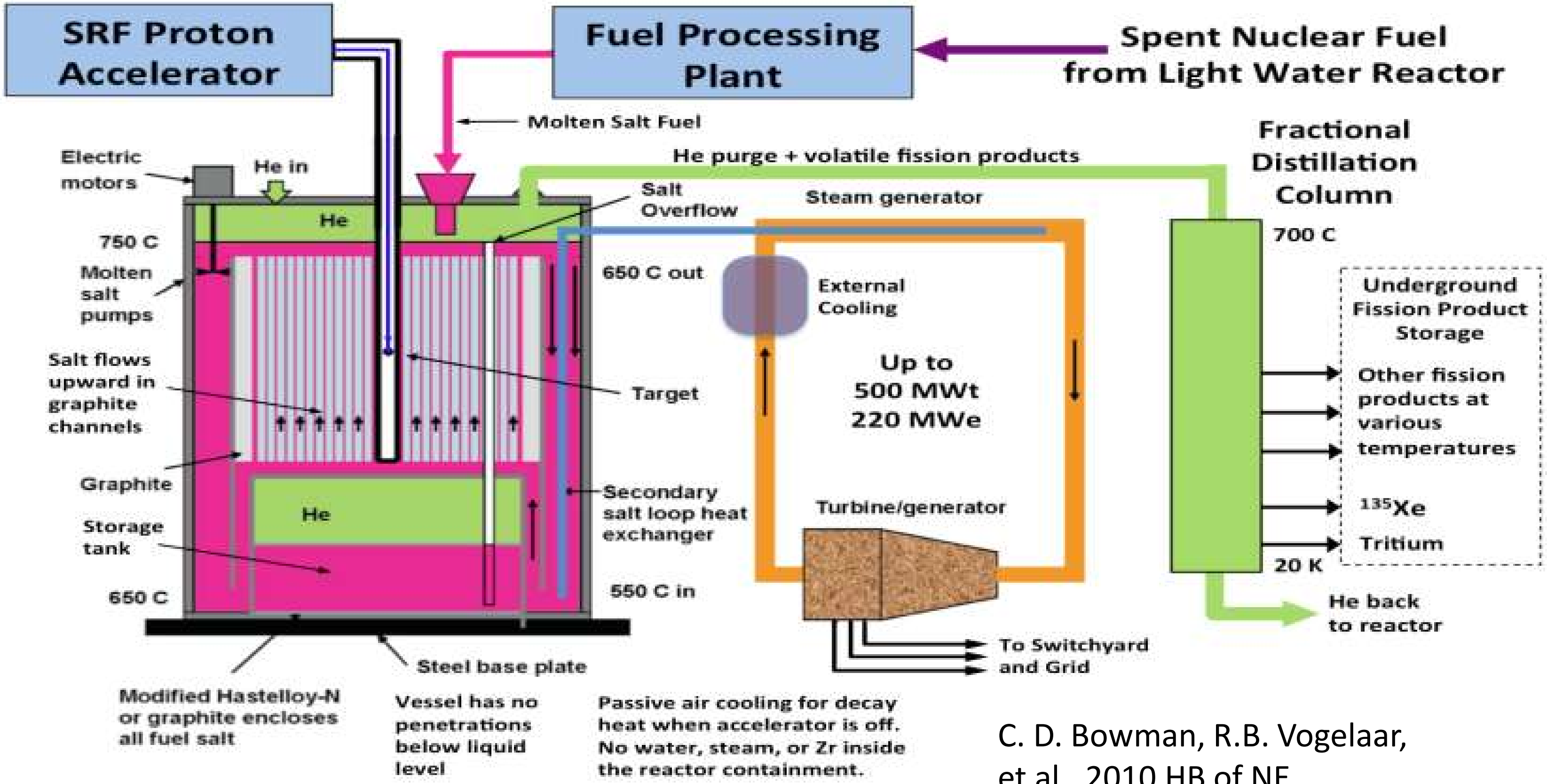


Uranium or Thorium fluorides form eutectic mixture with ^{7}LiF salt.

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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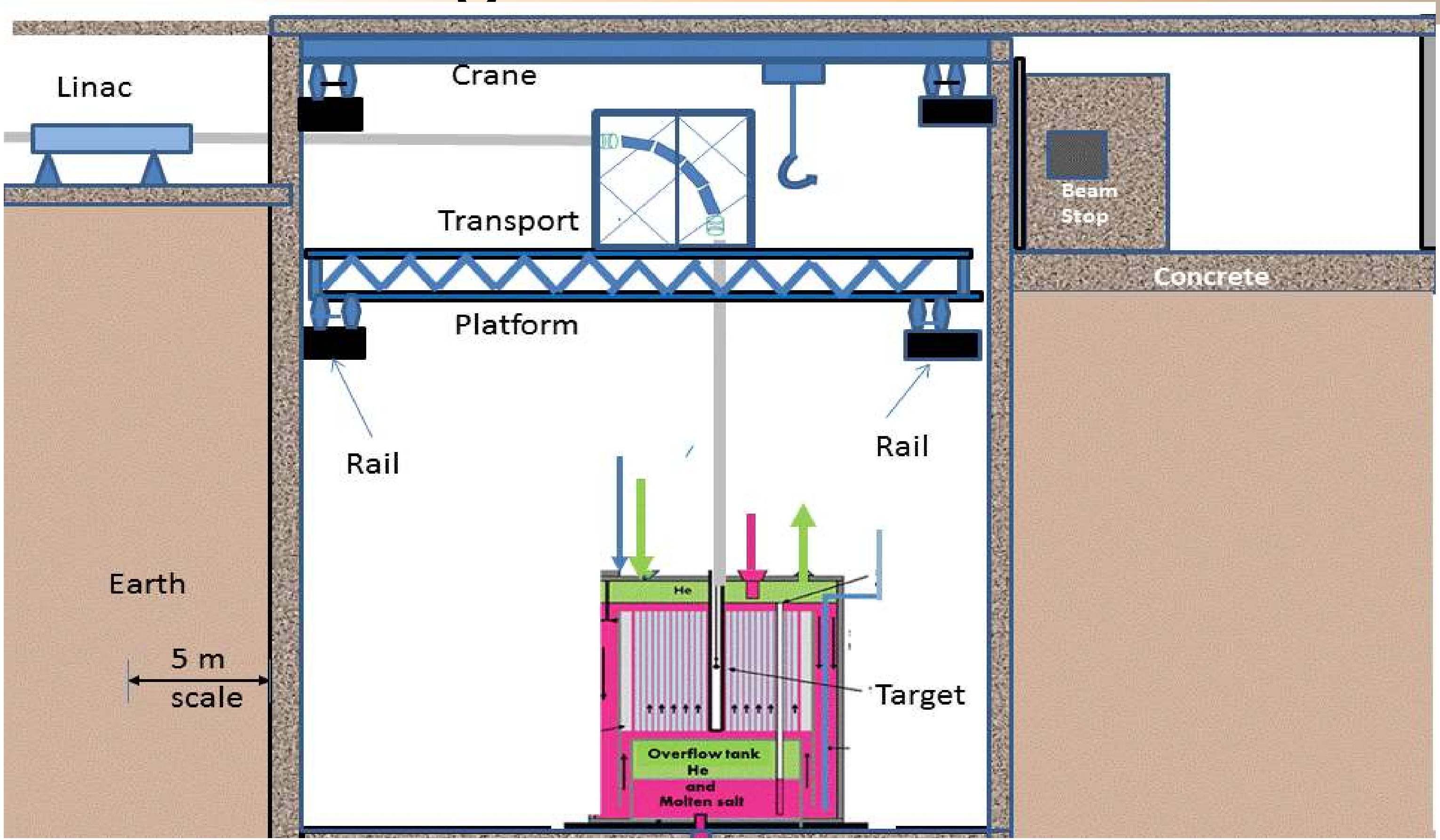
Underground Linac and Reactors



SRF Linacs Driving Subcritical MS Reactors
Why This Approach is Superior

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

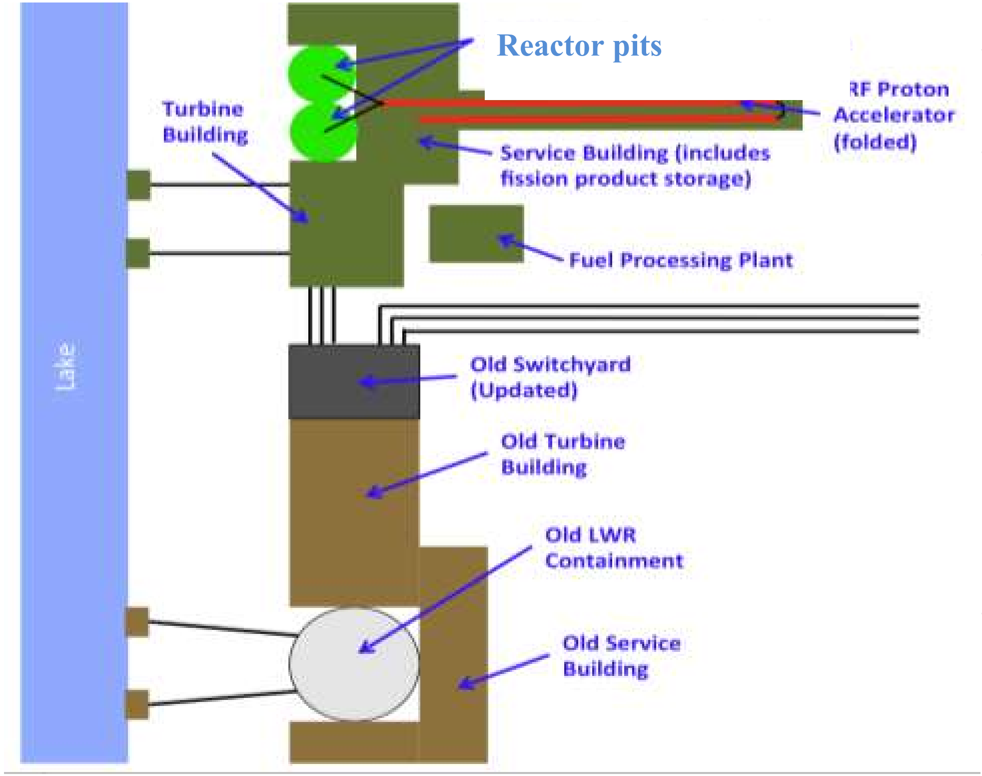
2 Examples of Deep Burn (compare to LWRs)

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

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

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 by burning Pu at SRS 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/

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)

Features 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 LiF 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 Pu
  - No enriched uranium needed (saves >$2B for US-owned plant)
- Pu burning easier with Mu*STAR
  - 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)
  - Accelerator and reactor components from National Labs

2nd Example of Deep Burn Advantage Comparing G*S W-Pu Burning to LWR

Hourly fill:

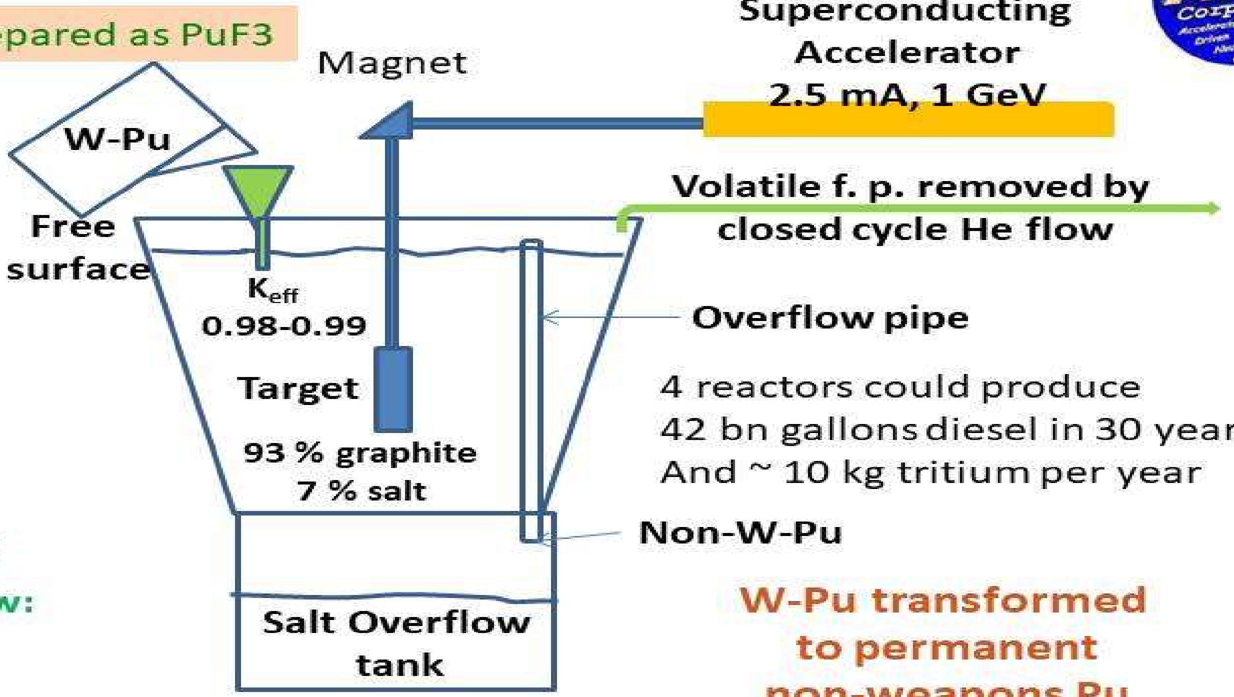
30 g W-Pu
as PuF_3 +
carrier salt

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

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



Superconducting Accelerator
2.5 mA, 1 GeV

Volatile f. p. removed by closed cycle He flow

4 reactors could produce
42 bn gallons diesel in 30 years
And ~ 10 kg tritium per year

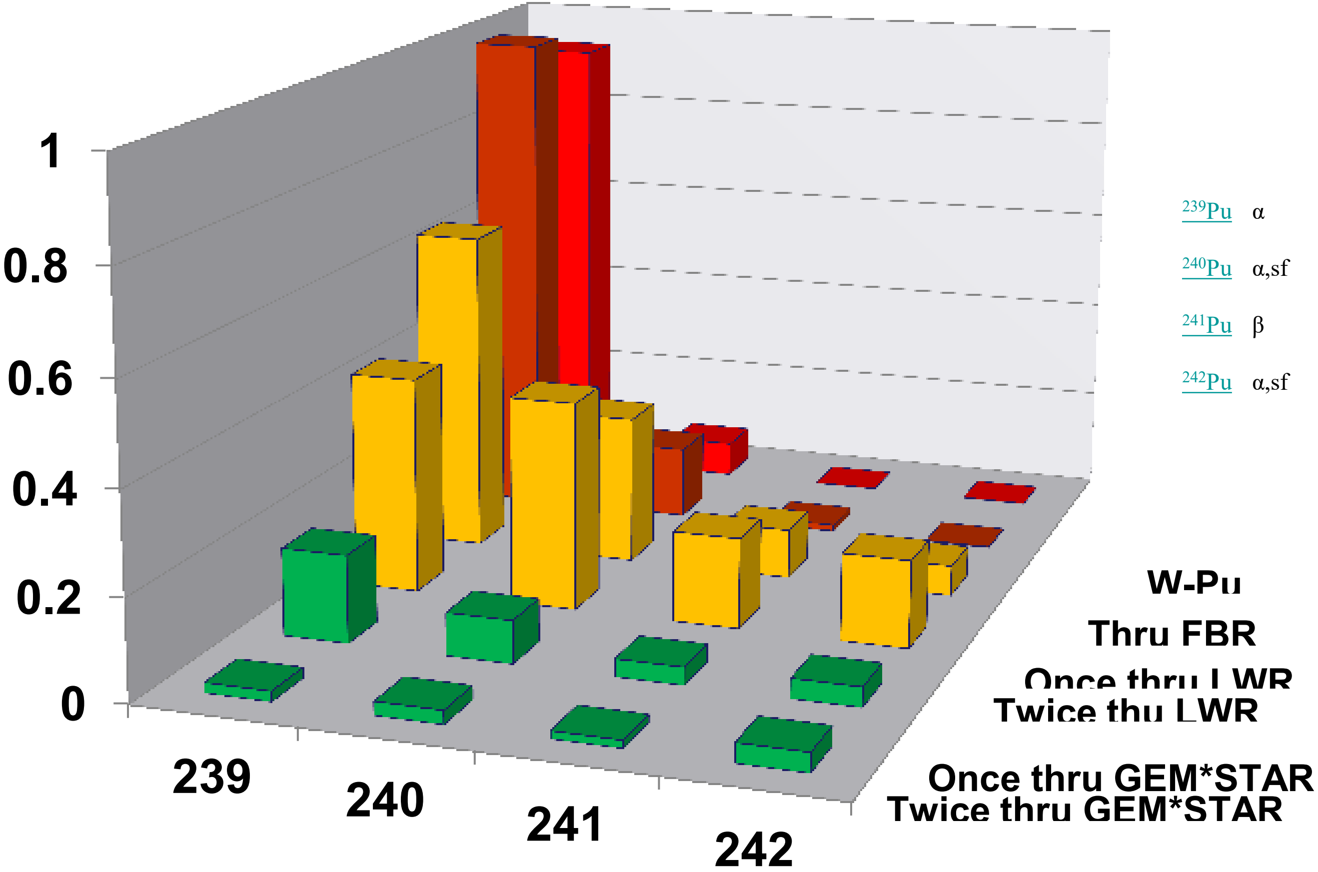
W-Pu transformed to permanent non-weapons Pu immediately upon adding and mixing

Fission power 500 MWt
for each GEM*STAR unit

Invent
the
Future

GEM*STAR
Consortium

FB BN800 MOX-LWR GEM*STAR



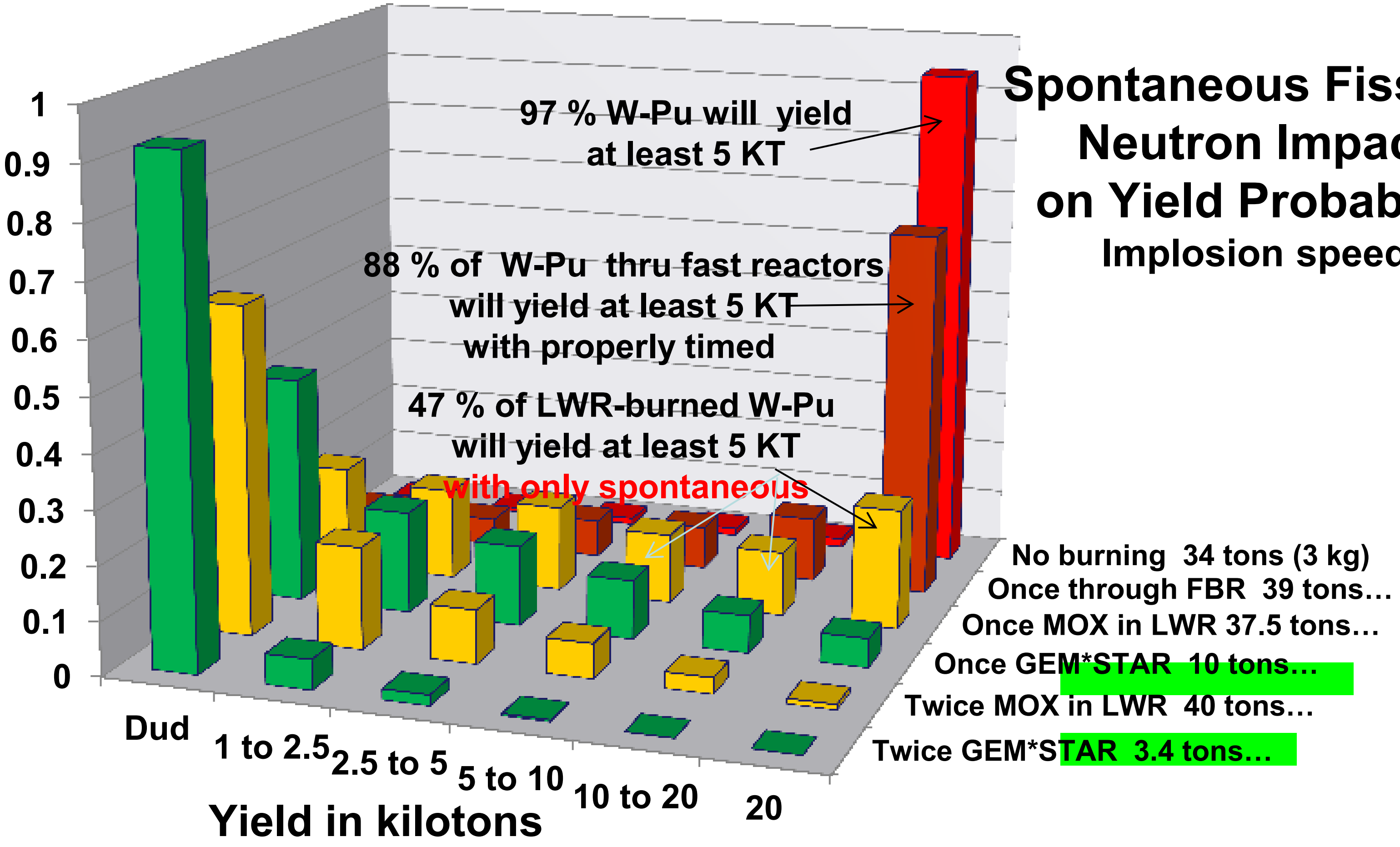
^{239}Pu	α	24,110 years
^{240}Pu	α,sf	6,561 years
^{241}Pu	β	14.325 years
^{242}Pu	α,sf	373,300 years

Invent
the
Future

GEM*STAR
Consortium

Spontaneous Fission Neutron Impact on Yield Probability

Implosion speed



97 % W-Pu will yield
at least 5 KT

88 % of W-Pu thru fast reactors
will yield at least 5 KT
with properly timed

47 % of LWR-burned W-Pu
will yield at least 5 KT
with only spontaneous

GEM*STAR

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 Preconceptual/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
<u>$800M </u>Pilot Plant large enough to make >2 kg/y of T	2.0 y	Methodology
$1,000M		

$985M of that Should be paid by NNSA

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.

Accelerator Driven System Conclusions

- Superconducting Accelerator Technology required for ADS has been demonstrated
  - and getting better fast
- The additional spallation target factor of 30 neutrons/proton is known
- The MSRE demonstrated the Molten-Salt technology needed for ADS
  - Operating subcritically (keff 0.98) each spallation neutron
  - Creates a chain of fissions that dies
  - Idea of Energy Amplifier
- The engineering to combine the accelerator, target, and MS reactor remain
- Converting and burning existing LWR SNF on site for cheap electricity is disruptive
  - See Big Hairy Audacious Goal to make electricity for less than from CH4
  - Using Mu*STAR burning LWR SNF
- Burning Pu is a new opportunity
- Making Tritium for the NNSA by burning Pu
  - Can enthuse the construction of a Mu*STAR pilot plant demo

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
    - e.g. 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 shouldl have a smaller regulatory burden for construction and operation
    - 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,...