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ABSTRACT - GEM*STAR: Accelerator-Driven Subcritical-System for Improved Safety, Waste Management, and Plutonium Disposition

The successful operation of high-power superconducting radio-frequency particle accelerators at two US national laboratories allows us to consider a new kind of nuclear reactor that operates without the need for a critical core, fuel enrichment, or reprocessing. We consider a multipurpose reactor design that takes advantage of this new accelerator capability that includes an internal spallation neutron target and high-temperature molten-salt fuel with continuous purging of volatile radioactive fission products. The reactor contains less than a critical mass and a million times fewer volatile radioactive fission products than conventional reactors like those at Fukushima. These and other safety features will help to generate public enthusiasm for this new CO2-free and weapons proliferation-resistant technology. We describe GEM*STAR [1], a reactor that without redesign will burn spent nuclear fuel, natural uranium, thorium, or surplus weapons material. A first application is to burn 34 tonnes of excess weapons grade plutonium as an important step in nuclear disarmament under the 2000 Plutonium Management and Disposition Agreement [2]. The process heat generated by this W-Pu can be used for the Fischer-Tropsch conversion of natural gas and renewable carbon into 42 billion gallons of low-CO2-footprint, drop-in, synthetic diesel fuel for the DOD at less than $2/g, to turn a $30B US government liability into a $40B profit. The Savannah River MOX plant could supply PuF3 salt for a GEM*STAR demonstration plant to be built at that site.

[1] 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).

[2] http://www.state.gov/r/pa/prs/ps/2010/04/140097.htm

US Industry can take nuclear waste or excess plutonium and produce energy from it

- Molten-salt Reactor Experiment (MSRE) 1965-1969
  - continuous purging of volatile radioactive elements – no zircaloy
- Accelerator-Driven Subcritical Reactors (ADSR)

  reactor concept uses molten salt fuel (e.g. UF_4 ,ThF_4, or PuF_3)
  - GEM*STAR
    - Avoids nuclear weapon proliferation concern of reprocessing for 200 years
- The next step is a prototype ADSR to inspire industry
- Inexpensive natural gas changes things in the US
  - New Nuclear Power cannot compete with 4.5 c/kW-h from natural gas
  - ADSR process heat can make synthetic diesel out of natural gas and carbon
- GEM*STAR technology can
  - Turn excess weapons-grade plutonium into process heat,
  - with remnants useless for weapons,
  - to provide the DOD with inexpensive, green diesel fuel

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Outline - GEM*STAR: Accelerator-Driven Subcritical-System for Improved Safety, Waste Management, and Plutonium Disposition

- **Green Energy Multiplier*Subcritical Technology Alternative Reactor**
  - graphite-moderated, thermal spectrum, accelerator driven
  - GEM*STAR - based on ORNL Molten Salt Reactor Experiment 1965-1969
  - SRF accelerator power recently demonstrated at ORNL SNS and JLab CEBAF
  - Need to merge 3 known technologies: Accelerator, MS Reactor, F-T diesel prod.
- **Public safety and public perception**
  - Safety: subcritical, low volatile Fission Product (FP) inventory
  - Security: no enrichment or reprocessing
  - 1st Application burns weapons-grade Pu (also a Security feature) w/o NRC
- **Costs versus benefits**
  - SNS SRF accelerator with 4 GEM*STAR SMRs and F-T diesel costs ~$3B
  - burns SNF, W-Pu, natural uranium, thorium, without redesign
  - no enrichment, no reprocessing, less complex reactor - reduces costs!
- **Impact of a successful W-Pu Disposition demo**
  - Large profits from process heat for F-T diesel: 34 T W-Pu => 42B g =~$42B
  - Proliferation-resistant, exportable technology
  - Burning SNF enables/extends conventional LWRs

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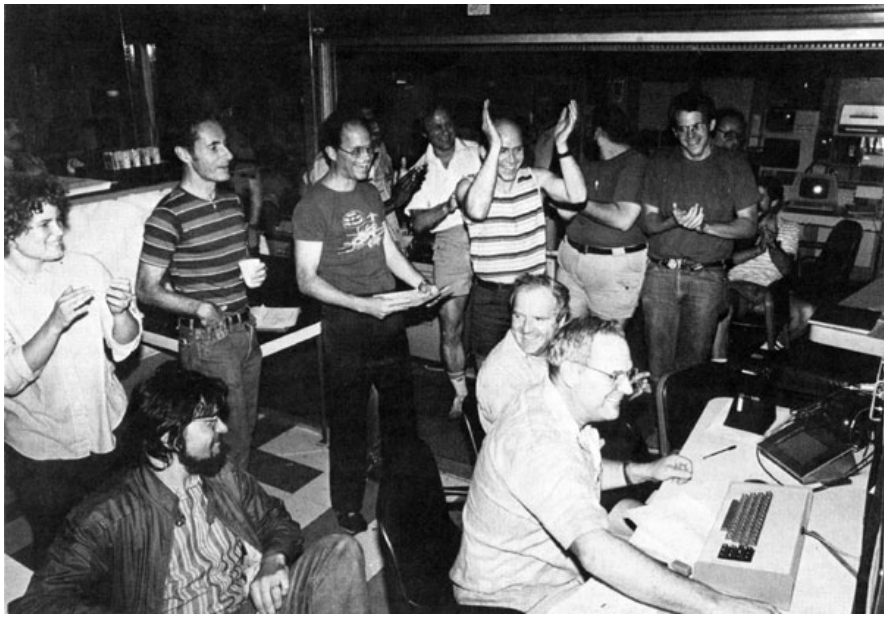
GEM*STAR

Generating Intrinsically Safe Power
Combining Subcritical System and Accelerator Technologies
First Customers can be: NNSA and DOD

Rolland P. Johnson, Ph. D.
President , Muons Inc.
www.muonsinc.com

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



512 GeV at Fermilab

Charlie at LANL

Charles D. Bowman (from CV) of ADNA Corp.

Ph. D. in Neutron Physics, 1961 — Duke University
M..A Neutron Physics, 1958 — Duke University
B.S. in Physics, Magna cum Laude, 1956 — Virginia Tech

1997 - Present — President, ADNA Corporation
1999 - French Atomic Energy Commission (CEA)
1996 - Los Alamos National Laboratory
- Associate Division Leader for Basic Research
- Construction Project Manager for LANSCE
- Project Leader for the Los Alamos ADTT program
- Led Project 17 of the ISTC, ~500 Russian scientists ADTT program

1982 - (NIST) National Bureau of Standards
1968 - Oak Ridge National Laboratory
1972 - Lawrence Livermore National Laboratory

1969 Honored as a Fellow of the American Physical Society (recommended by Teller)
1978 Admitted to the Senior Executive Service (civil equivalent to General/Admiral)
1982 Awarded the U. S. Department of Commerce Silver Medal
1984 Appointed Construction Project Manager for the LANSCE Experimental Halls
1990 Patent awarded; "Apparatus for Nuclear Transmutation and Power Production Using an Intense Accelerator-Generated Thermal Neutron Flux"
1991 Honored as a Fellow of the Los Alamos National Laboratory
2001 Patent Awarded; "Apparatus for Transmutation of Nuclear Reactor Waste"

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MUONS, INC.
Batavia, IL & Newport News, VA

- **STAFF OF CREATIVE, EXPERIENCED PHYSICISTS AND ENGINEERS**
  - Founded 2002 - by R. Johnson (10y LBNL, 17y FNAL, 3y Maxwell, 5y Jlab, 12 MI)
  - Infrastructure and partners at 9 National Labs and 8 universities
- **PARTICLE ACCELERATOR R & D**
  - Muon Collider, ~$10B atom smasher to follow the LHC
    - Muon beam cooling – Helical Cooling Channel, High Pressure RF
  - Superconducting RF accelerators
    - magnetron RF power sources, power couplers, HOM dampers
  - Superconducting radiation-tolerant, extreme high-field magnets
  - Designs and Simulations
    - G4beamline (GEANT4), CST, ACE3P, MuSim (MCNP6)
  - Special devices for unique applications
  - Supported 7 post-docs, 7 subgrant postdocs, 4 Ph.D. Students
- **FUNDED AT ~$3.5M/Y REVENUE**
  - SBIR-STTR grants – 50 Phase I, 25 Phase II, (~$23,000,000 total in 12 y) first w IIT
  - DOE Laboratory contracts – PNNL, LANL, Fermilab, JLab
  - Contracts with industries – Niowave, Lockheed Martin

Neutrons! Needed to cause fission

Operating at or above criticality in a traditional reactor generates the needed extra neutrons

Or

High-power proton accelerators can break apart large nuclei to generate the extra neutrons, 1 proton => 30 neutrons

Superconducting RF (SRF) accelerators,

CEBAF at JLab

Spallation Neutron Source at ORNL

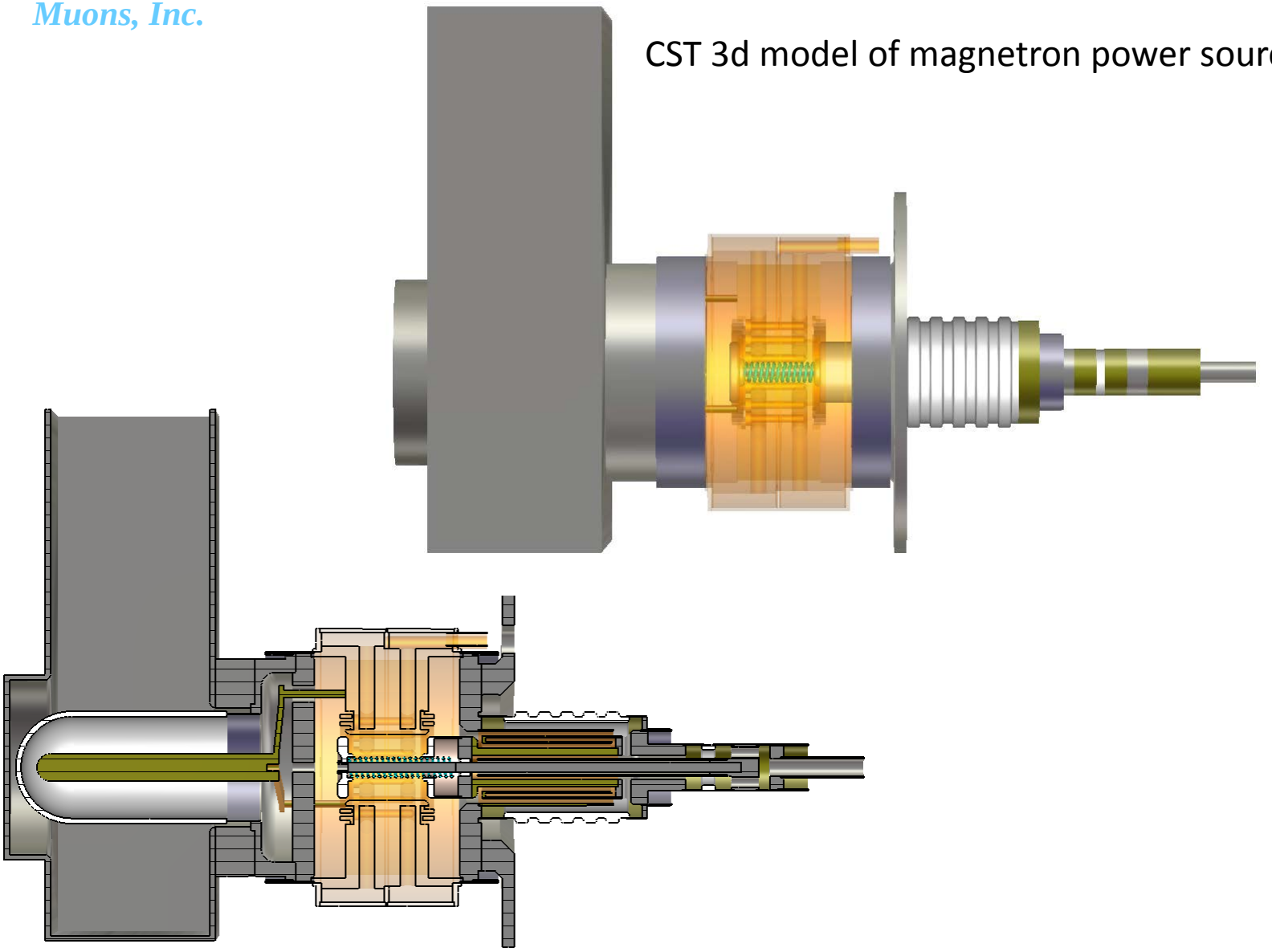
have demonstrated the required technology

However, we are improving this technology by developing a magnetron power source that will be less expensive and more wall-power efficient than klystrons or IOTs! See assy drawings of a 350 MHz Magnetron we are building:
CW, 120 kw, 90% efficient, tube itself ~$20k

New Accelerator Technology Enables GEM*STAR

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:

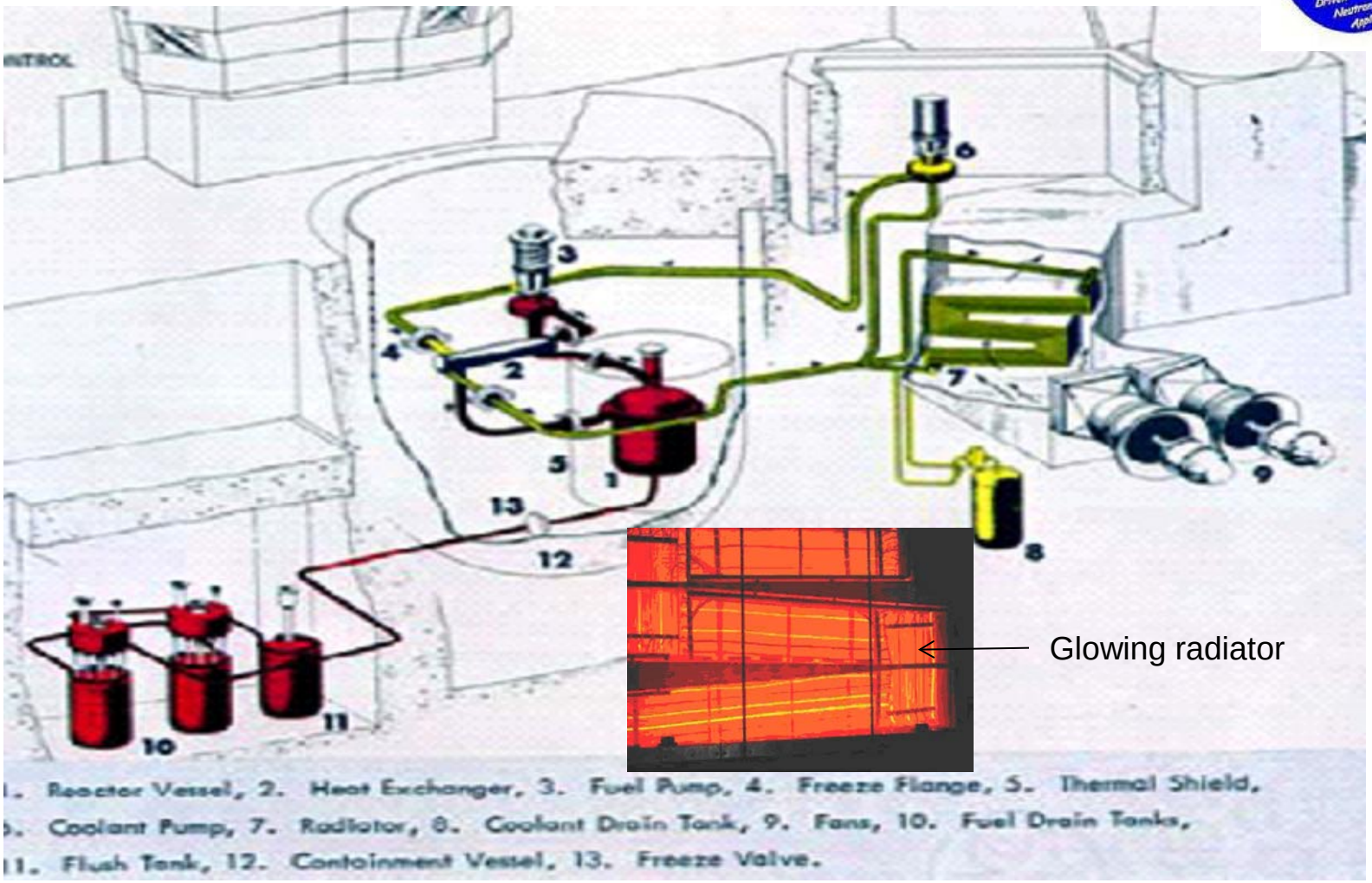
CST 3d model of magnetron power source



- An intrinsic safety problem for conventional reactors is enclosed solid fuel.
- a natural solution is to use molten-salt fuel
- that is also well suited to accelerator-driven subcritical reactors.
  - A major difficulty is fatigue of UO_2 fuel in rods caused by accelerator trips – no such problem for molten salt fuel
- The technology of molten-salt fuel was developed in the 1960s in the Molten-Salt Reactor Experiment (MSRE) at ORNL.
  - Use of molten salt fuel was later abandoned
    - not enough Pu-239 for bombs?
    - President Nixon?
      (See MSRE on wikipedia for nice summary)

1965-69 ORNL Molten-Salt Reactor Experiment

1965-69 ORNL Molten-Salt Reactor Experiment



From 1969 MSRE Report Abstract

"The MSRE is an 8-MW(th) reactor in which molten fluoride salt at 1200°F (650 C) circulates through a core of graphite bars. Its purpose was to demonstrate the practicality of the key features of molten-salt power reactors.

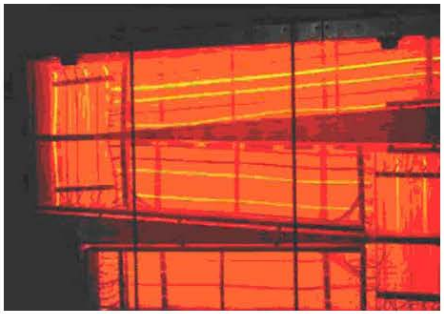
The MSRE has shown that salt handling in an operating reactor is quite practical, the salt chemistry is well behaved, there is practically no corrosion, the nuclear characteristics are very close to predictions, and the system is dynamically stable. Containment of fission products has been excellent and maintenance of radioactive components has been accomplished without unreasonable delay and with very little radiation exposure.

The successful operation of the MSRE is an achievement that should strengthen confidence in the practicality of the molten-salt reactor concept."

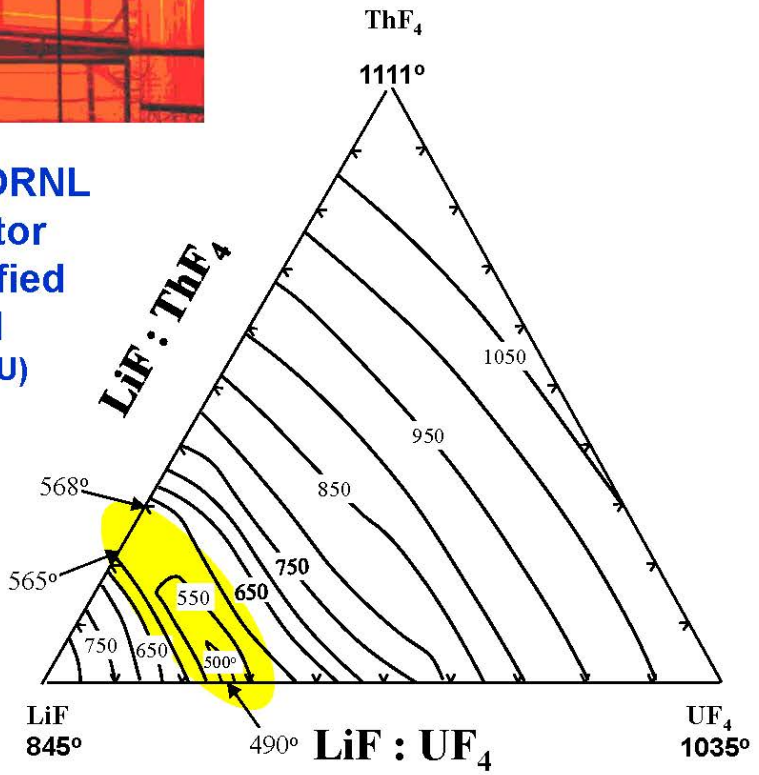
Invent the Future

ADNA & GEM*STAR Consortium

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

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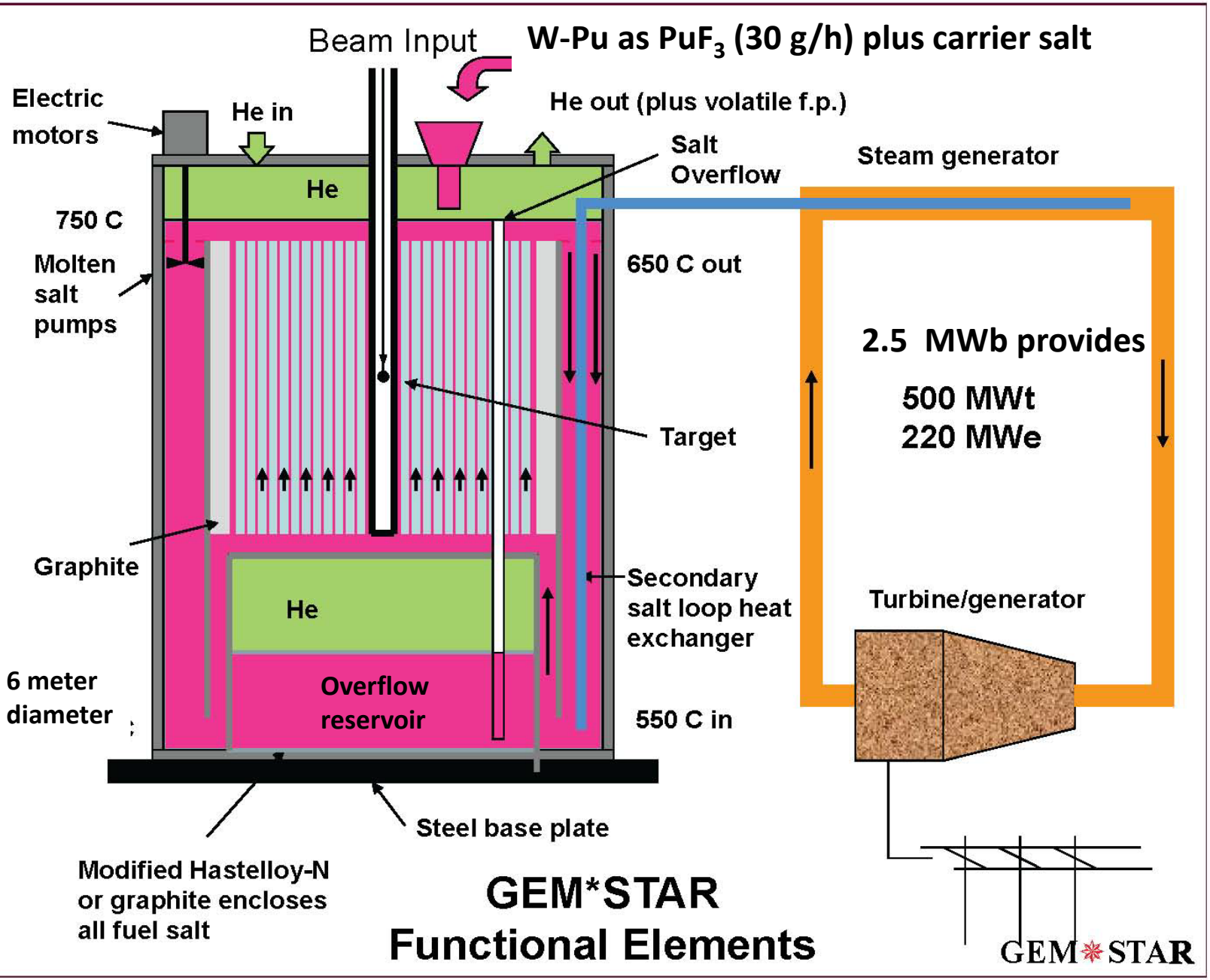
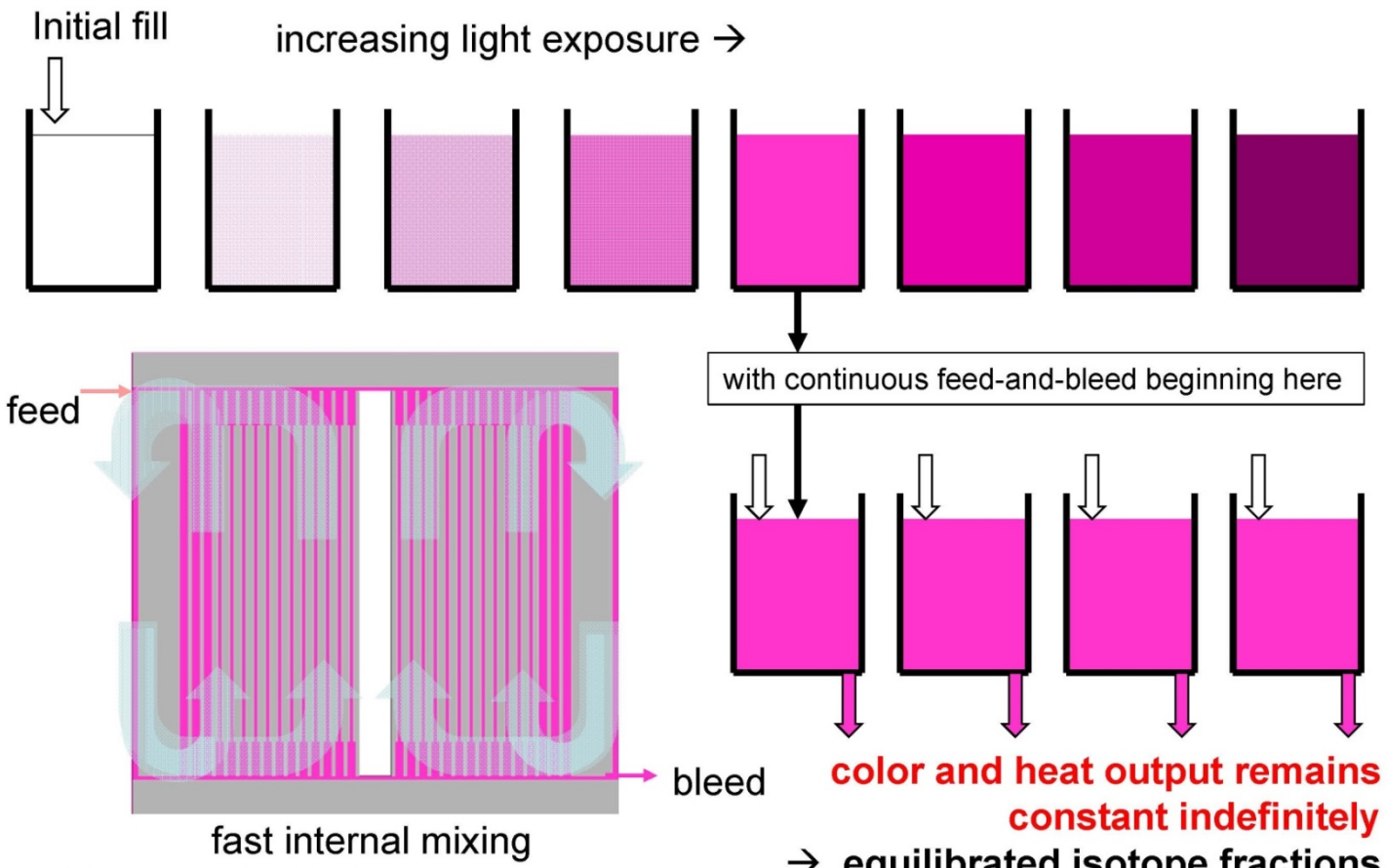

Beam Input
W-Pu as PuF_3 (30 g/h) plus carrier salt
Electric motors
He in
He out (plus volatile f.p.)
Salt Overflow
Steam generator
He
750 C
Molten salt pumps
650 C out
2.5 MWb provides
500 MWt
220 MWe
Target
Graphite
Secondary salt loop heat exchanger
Turbine/generator
He
6 meter diameter
Overflow reservoir
550 C in
Steel base plate
Modified Hastelloy-N or graphite encloses all fuel salt
GEM*STAR Functional Elements
GEM*STAR

Invent the Future

ADNA & GEM*STAR Consortium

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



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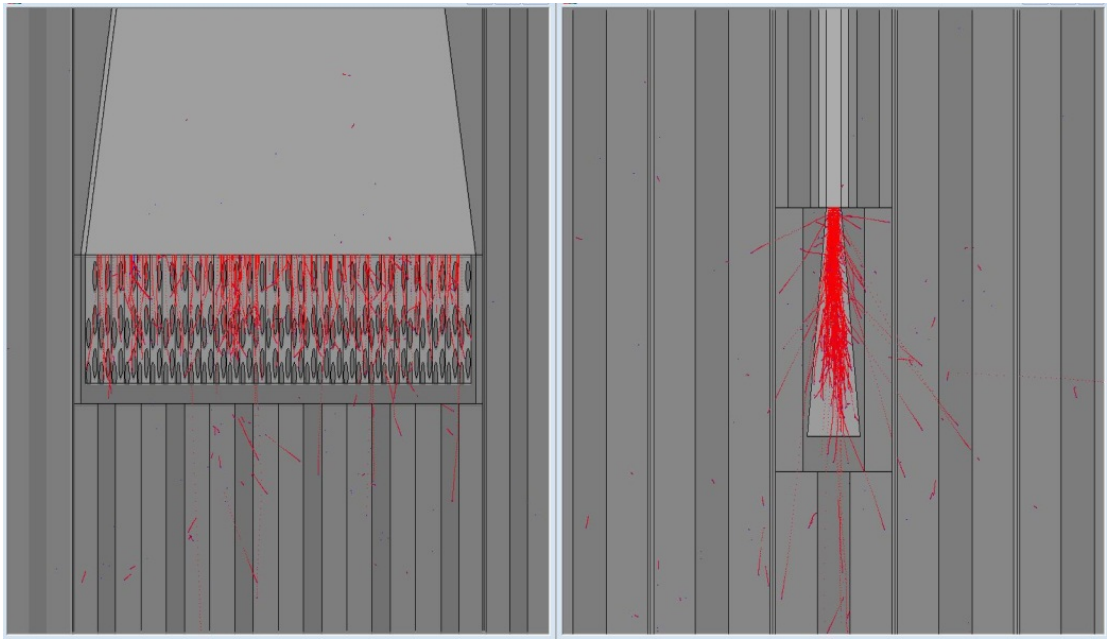
Target Considerations



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

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G4beamline User Survey, September 2014
Tom Roberts, Muons, Inc.

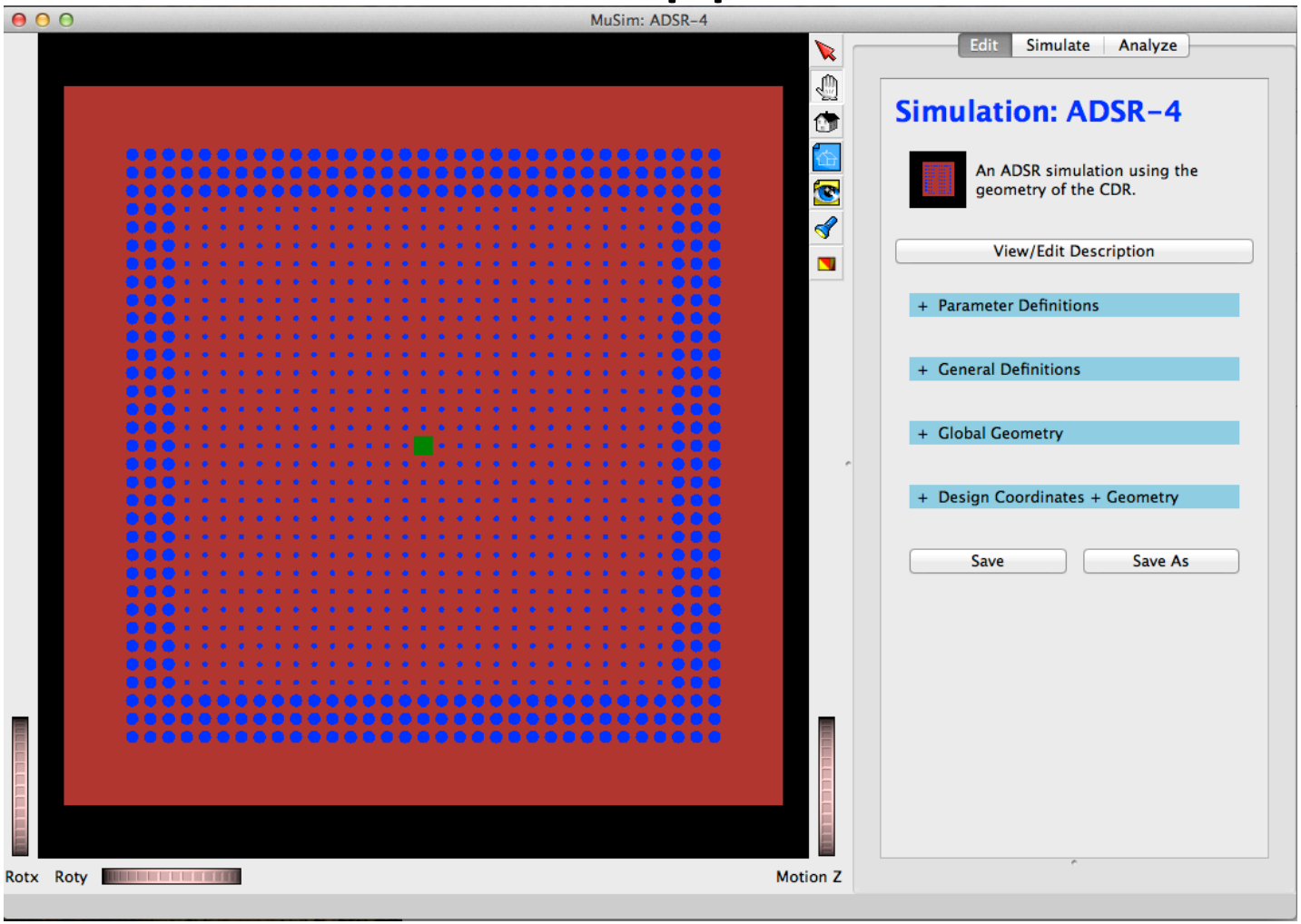
In February 2013 a survey was added to the g4beamline.muonsinc.com download page. It asked users to make a broad-brush estimate of how much time they have spent using G4beamline, including all design and analysis for which G4beamline was an essential tool. Between then and September 2014, G4beamline was downloaded 920 times, and users have self-reported 87 FTE-years of usage.

	Jan. 2013	Oct. 2013	Sept. 2014
Total estimated non-SBIR usage	40 FTE-years	57 FTE-years	87 FTE-years
Average time using G4beamline	3.1 years	2.1 years	1.4 years

Estimating an FTE-year to cost $200k, this represents at least $17 Million in investment by the G4beamline user community. Multiple downloads by a single person have been removed, as have spam and other junk records; all of the people reporting usage > 1 FTE-year are known to me. As only 20% of the downloads provided data, this is clearly an underestimate. The decrease in the second row shows the user community is growing.

For an encore, Tom is creating Muonsinc Simulation (MuSim) interface to MCNP6

First MuSim Application -GEM*STAR



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.

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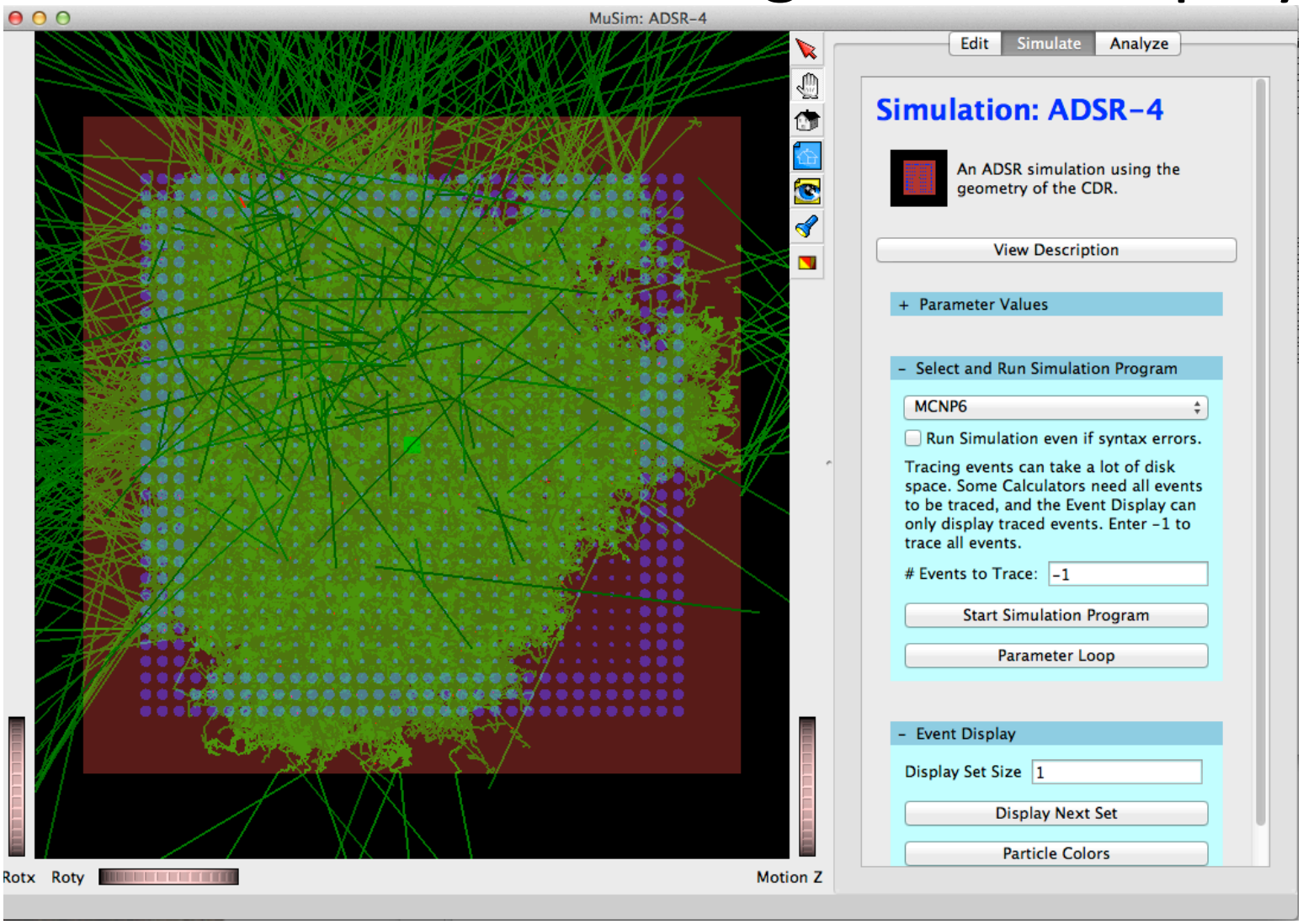
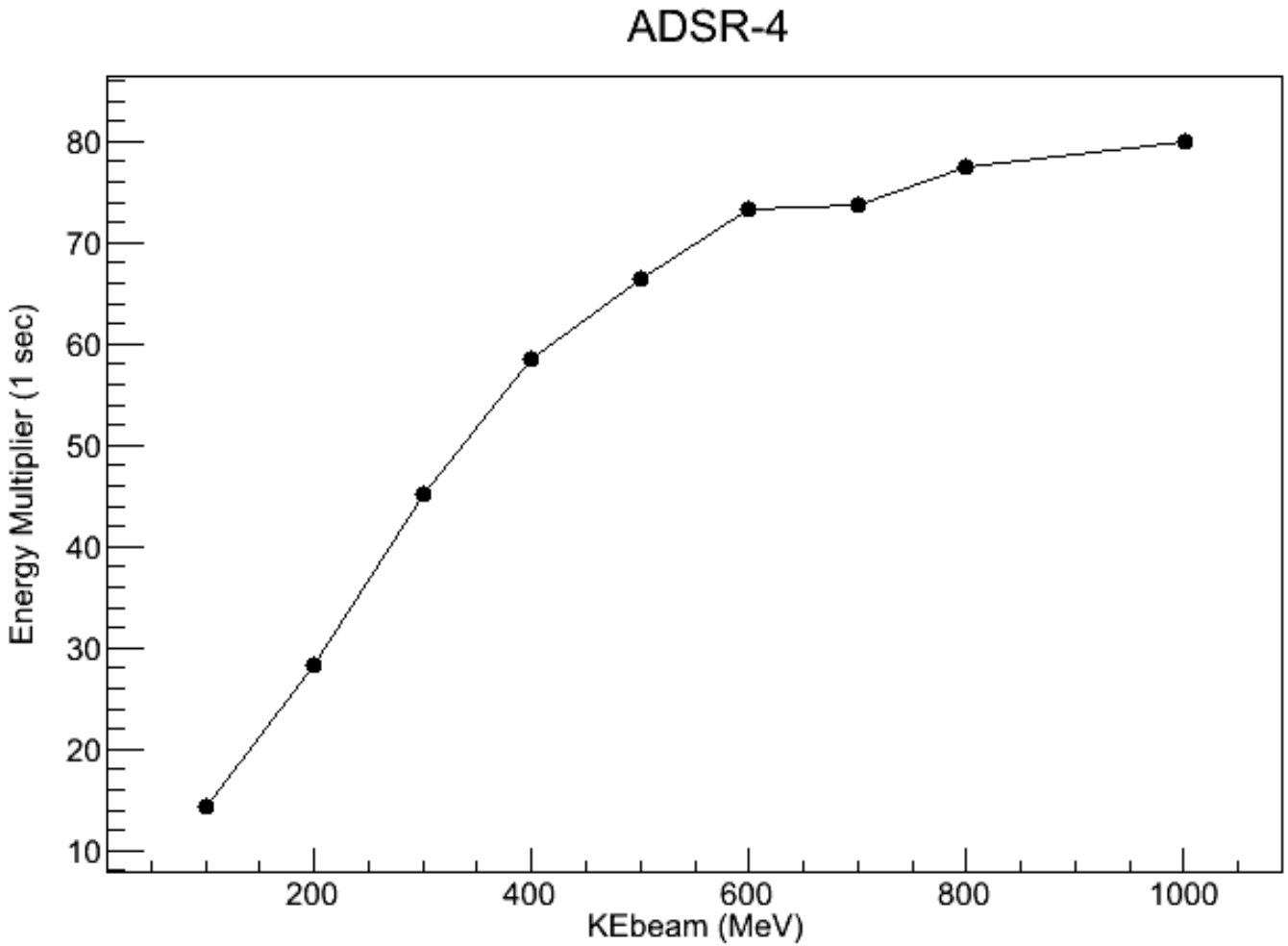
MuSim MCNP6 single event display



Here is a single event, green=neutron, darkgreen=gamma. This single proton generated 402,138 tracks (not counting e- < 0.5MeV). I used a "transparency slider" to make the solids mostly transparent, so tracks inside them can be seen. This makes the solids darker, because the black background show through; tracks inside them affect their color.

Optimum Beam Energy



Is W-Pu a Killer Application?

34 metric tons of excess weapons-grade plutonium slated to be destroyed by the troubled 2000 U.S.-Russian Plutonium Management and Disposition Agreement (PMDA)[2]

GEM*STAR allows a better solution than either MOX (US) or BR (Russia)

<7% Pu240 vs >19%

Here we do some handwaving to explain how a Pu bomb works and what weapons grade refers to:

Four GEM*STAR Units Burn 34 Tonnes W-Pu Without U or Th in 30 Years

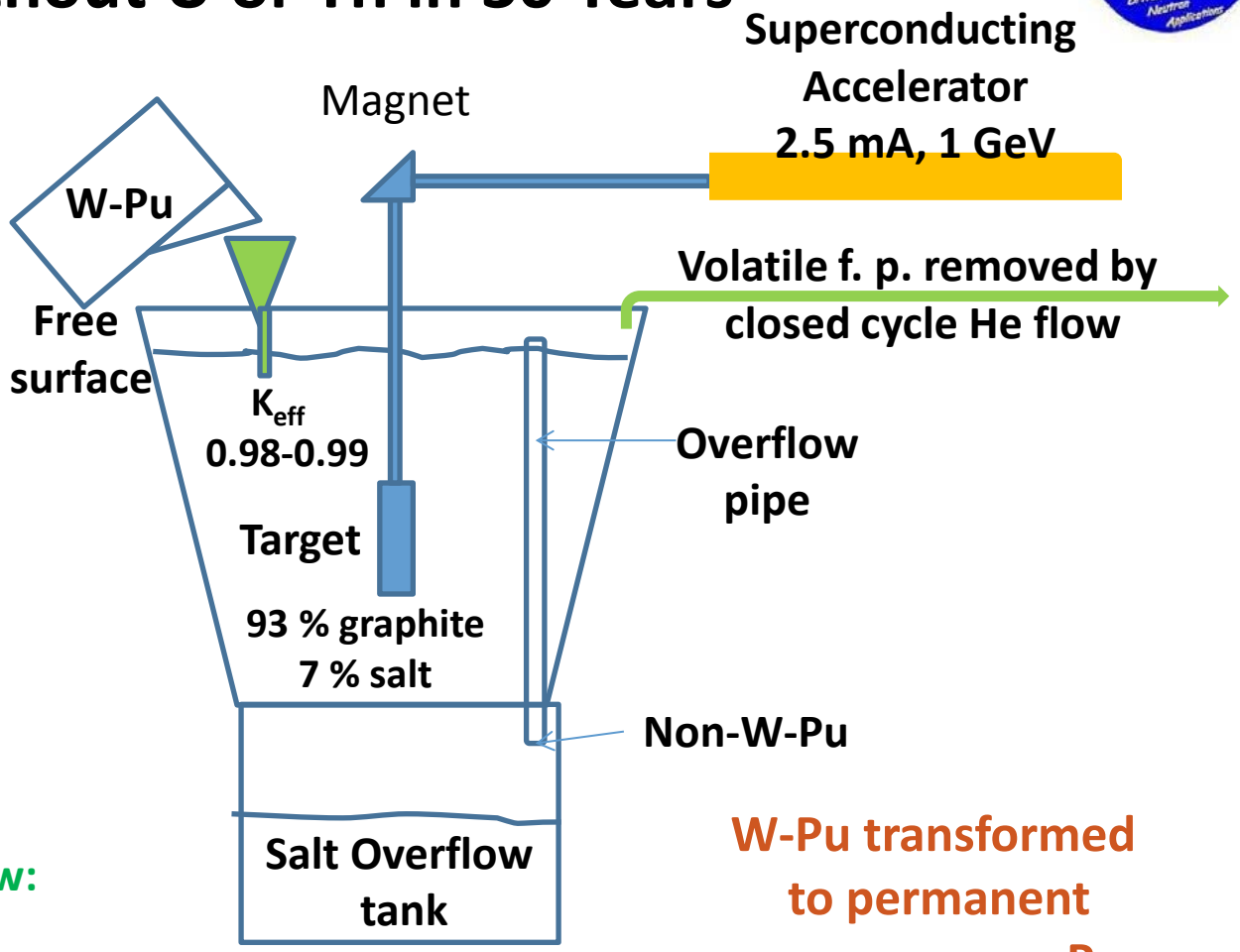
Hourly fill:

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

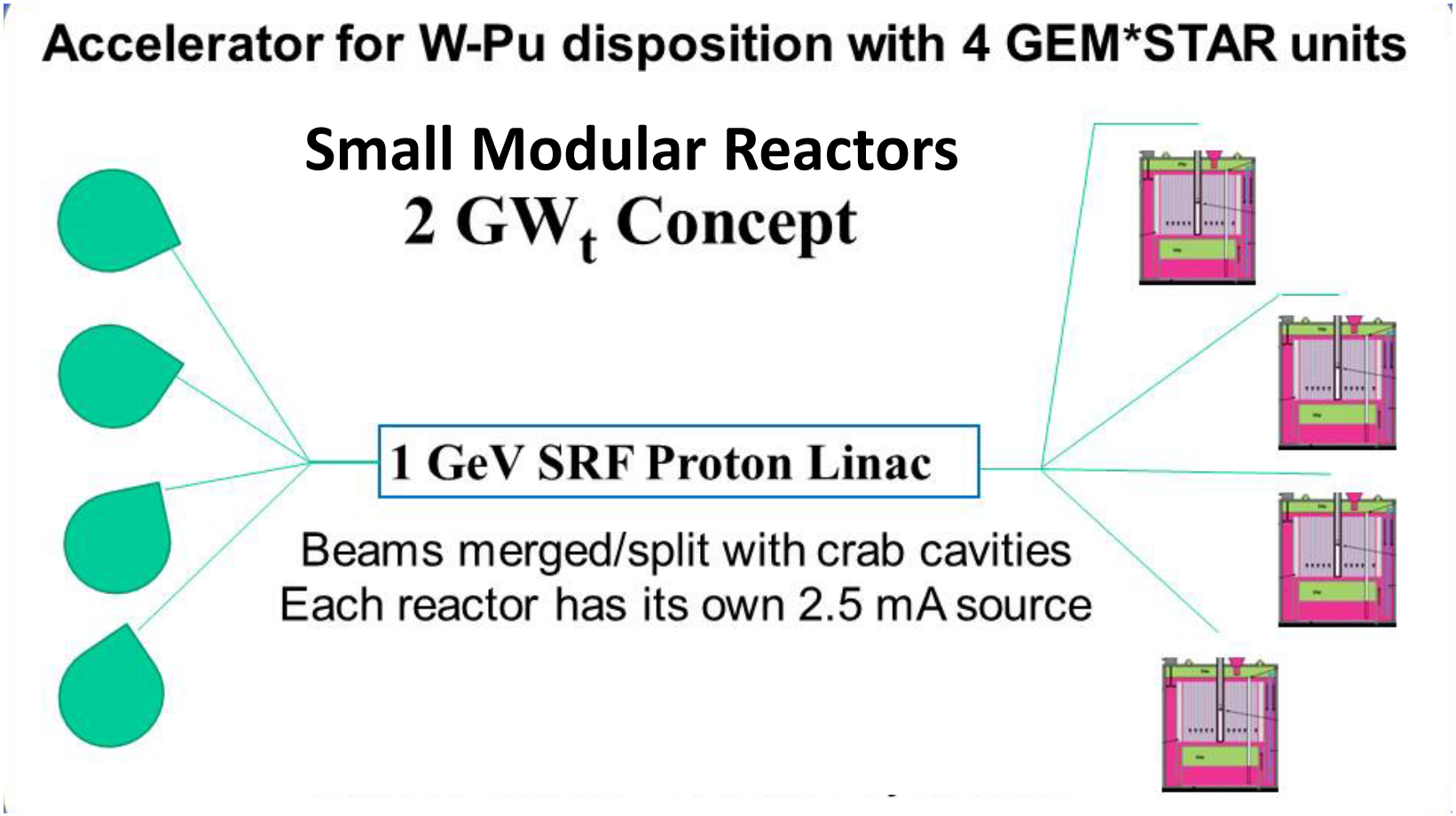
Fission power 500 MWt for each GEM*STAR unit

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

Accelerators for the First GEM*STAR Application: W-Pu Disposal

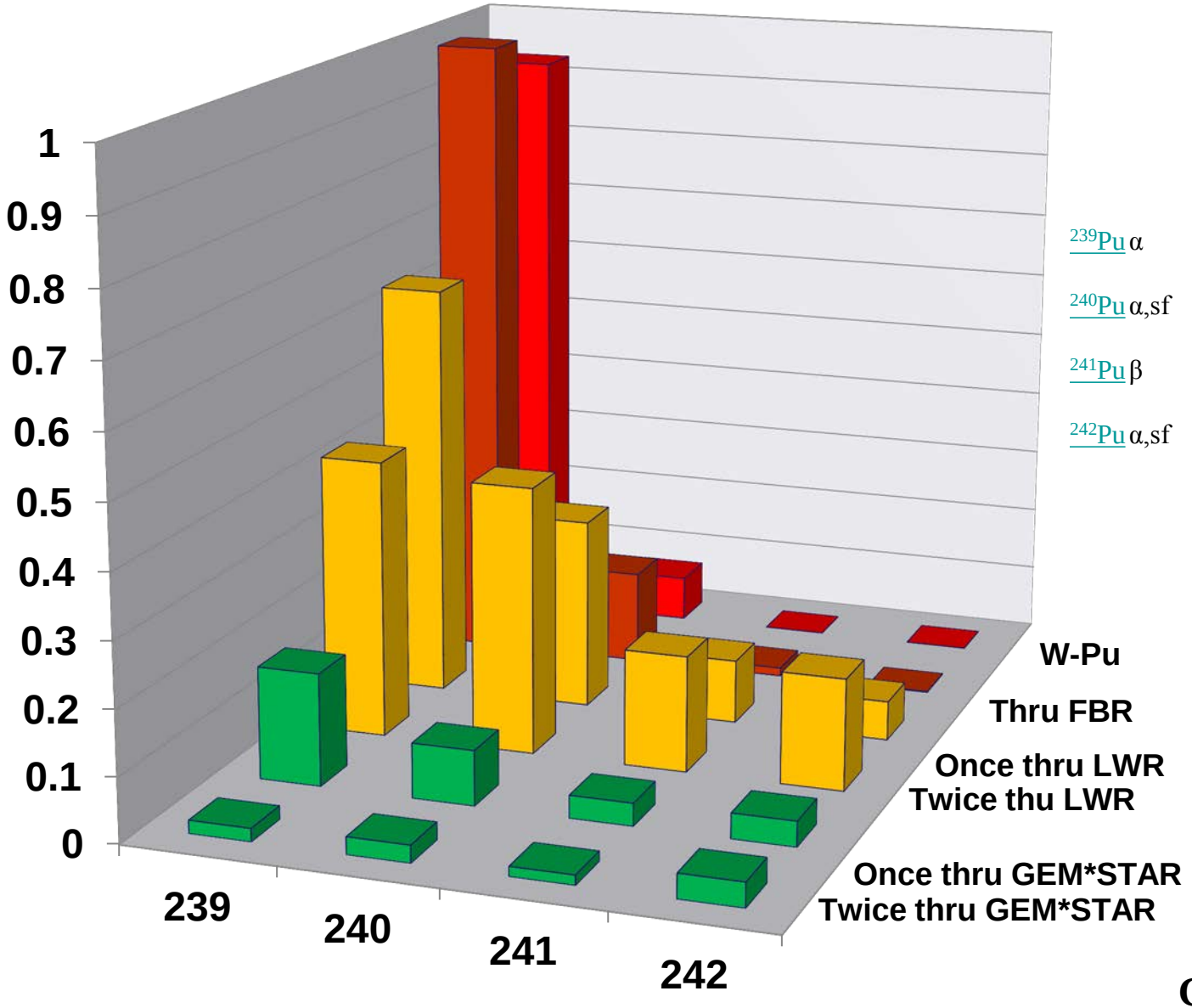
R. P. Johnson, G. Flanagan, F. Marhauser and C. D. Bowman, R. B. Vogelaar
Muons, Inc., Batavia, IL USA, *ADNA, Los Alamos, NM USA*

Accelerator for W-Pu disposition with 4 GEM*STAR units



<300 MWe follows from requiring that each reactor contain less than a critical mass and recover passively from a power or coolant loss accident

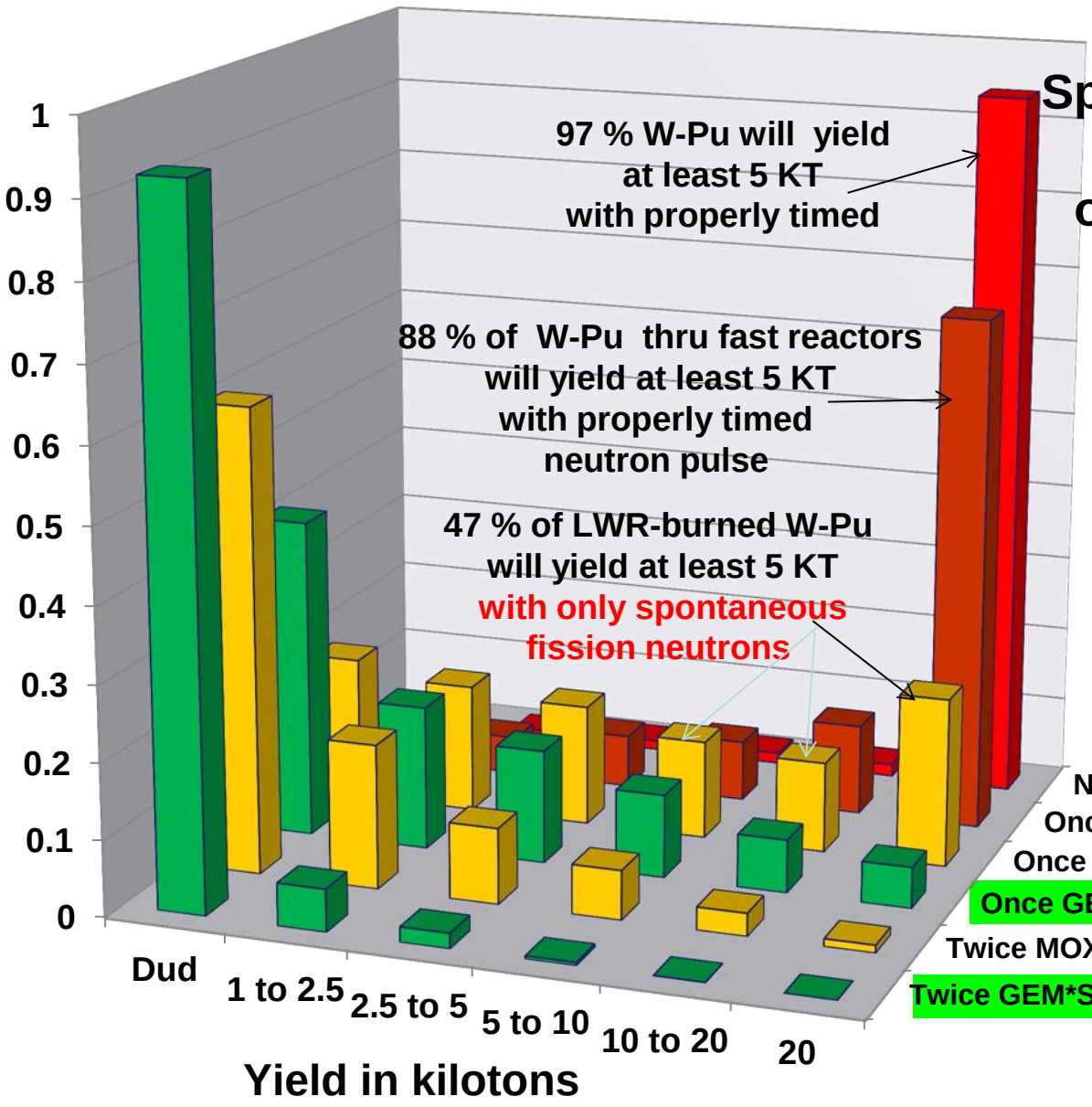
FB BN800 MOX-LWR GEM*STAR



^{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

Spontaneous Fission Neutron Impact on Yield Probability

Implosion speed twice Trinity
3 kg W-Pu



No burning 34 tons (3 kg)
Once through FBR 39 tons…
Once MOX in LWR 37.5 tons…
Once GEM*STAR 10 tons…
Twice MOX in LWR 40 tons…
Twice GEM*STAR 3.4 tons…

http://www.nuclearfaq.ca/cnf_sectionF.htm#x2

Benefits of GEM*STAR

- Never requires a critical mass so no control rods
- Never contains large volatile fission product inventory as in LWRs
- No reprocessing or enrichment required
- No pressure vessel
- Passive recovery from loss of coolant or loss of power accidents
- Higher actinides effectively destroyed with thermal neutron spectrum
- Molten salt fuel tested to be effective, practical, less demanding than pins

Eliminating problems avoids the need for Defense in Depth

Benefits of GEM*STAR for W-Pu

- Burned W-Pu never useful for weapons
- No conversion to MOX; simple conversion of Pu metal and PuO_2 to PuF_3
- Fission energy converted to diesel and sold as green fuel to DOD

Benefits of GEM*STAR for SNF

- SNF burned without need for reprocessing (separation of elements)
- Simple conversion of oxides to fluorides
- Fission energy converted to green diesel and/or efficient electricity (650C)
- 200 year fuel cycle,
  - 7 times original LWR energy output
  - 85% of higher actinides destroyed

A Perfect Storm of Opportunities?

- US Plan to use MOX plant and LWRs not working
  - SRS Plant overspent: $2B -> $5B -> asking for $2B more,
  - No LWR ready to accept W-Pu MOX fuel =>
  - Obama MOX budget on hold while alternatives examined
- Eliminate W-Pu (State Department-DOE/NNSA)
  - Opportunity for Lavrov and Kerry to extend cooperation
  - 2000 Plutonium Management and Disposition Agreement
    - (DOE Secretary Moniz was major proponent of PMDA)
  - Navy adds nuclear power expertise, and location for demo
  - Solves Navy or Maersk long-range synthetic fuel need
  - Turn $30B liability into $42B Profit (Congress/OMB)

Muons, Inc.

Summary - GEM*STAR: Accelerator-Driven Subcritical System for Improved Safety, Waste Management, and Plutonium Disposition

ADNA Corporation
Accelerator Driven Neutron Applications

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  - Proliferation-resistant, exportable technology
  - Burning SNF enables/extends conventional LWRs