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

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NAPAC 2016, Chicago.

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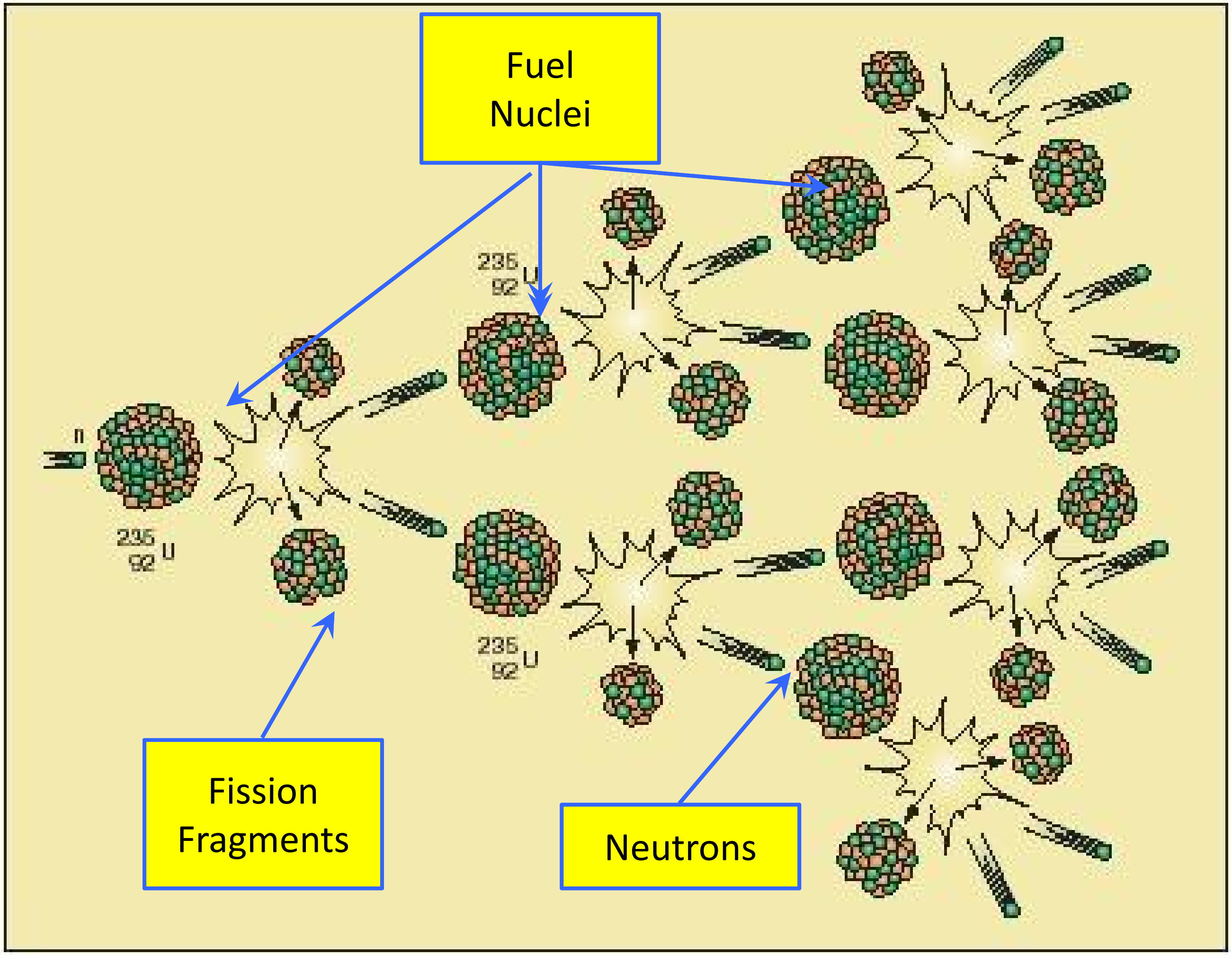
Accelerator Driven Subcritical Reactors

Introducing GEM*STAR – A Particularly Advantageous Example

- "Nuclear Reactors 101" – how they work for particle and accelerator physics.
- Subcritical operation – avoids many problems, and reduces expenses
- Why now? – answers to historical objections to ADSR
- GEM*STAR – specific example of ADSR
  - Passive safety
  - Burns all nuclear waste streams, *including its own*
  - Extracts multiple times more than of the 6% typically extracted in a Light Water Reactor from the spent nuclear fuel (94%)
  - Needs no isotope enrichment or reprocessing
- Summary

Nuclear Reactors 101
Fission Chain Reaction



http://www.scienceclarified.com

- Each fission yields:
  - 2-3 fragments
  - 2-3 neutrons
  - 1-3 gammas
  - Energy released ~ 200 MeV
- Some neutrons are lost, some are absorbed.
- Many fission products are radioactive – that is important.

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Criticality Factor

- A key parameter of a nuclear reactor is the *criticality factor:*

$$k = \frac{(\#\ \text{neutrons that induce new fissions})}{(\#\ \text{fissions that created them})}$$

- k depends on the fuel mixture, the geometry, and the probability of a neutron inducing fission vs. being absorbed.
- If **k>>1** the reaction grows without bound until something stops it (typically the system exploding violently). **Bomb.**
- If **k<1** the reaction stops, typically in less than 1 second. **Subcritical reactor.**
- All current reactors operate with **k=1**, maintained within about 1 part per million. **Critical reactor.** *

Neutron Moderation

- The neutrons emitted from a fission are *fast neutrons* with kinetic energies of 1-10 MeV.
- In a typical reactor fuel mixture, fast neutrons are more likely to be absorbed than to induce fission.
- That makes **k=1** difficult to achieve with **fast** neutrons.
- A *moderator* is used to slow the neutrons down to become *thermal neutrons* (< 1 eV), via elastic collisions.
- **Thermal neutrons** are much more likely to **induce fission**.
- Moderators have low A and low neutron absorption.
- Typical moderators: water, heavy water, and graphite.
- The geometry is important.

Delayed Neutrons

- Neutron-induced fission occurs within femtoseconds; neutron moderation and transport takes microseconds.
- That is too fast to be able to control the reaction.
- Fortunately, many fission products are radioactive, and some of them emit neutrons with a delay from milliseconds to minutes– typically 0.6–0.8% of the neutron flux.
- The reactor operating point is set to be **subcritical** for the fission neutrons alone, but **critical** when the delayed neutrons are included. *
- This is slow enough that control can be maintained.

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Cooling and Control

- The reactor must be maintained at k=1 to operate.
- *Control rods* are used, which are made of powerful neutron absorbers. With them fully inserted, k<<1.
- In operation, the control rods are partially withdrawn to set the operating point (where k=1).
- At the operating point, higher temperature will reduce k, while cooling down will increase it (combination of thermal expansion and moderation efficiency).
- Thus the reactor will automatically generate enough power to maintain its temperature – if you increase the cooling capacity it will increase power, etc.
- The control rods can be inserted at any time to shut down the reactor.

Fuel Handling

- As a reactor operates, some of the fissionable portion of its fuel is burned, and other fission fragments build up in the fuel rods.
- Some fission fragments are powerful neutron absorbers.
- So the control rods must be gradually withdrawn to maintain the operating point.
- Typically every 12-18 months, ¼-⅓ of the fuel rods are replaced. They still contain ~ 94% of their potential fissile material.
- The spent fuel rods are stored on-site, usually with water cooling to remove the decay heat from their residual radioactivity.
- That radioactivity remains for > 100,000 years.

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Nuclear Reactor 101 Summary

- Nuclear reactors depend on many details of nuclear physics. Fortunately that is now very well known.
- They must operate at k=1.000000 ± 0.000001. This is routine.
- But, the **downsides**:
  - Depend on ^{235}U, which is difficult to obtain and of limited supply on earth. Isotopic enrichment is required - intimately connected with concerns about **nuclear weapons proliferation**.
  - There are significant concerns about safety.
  - The U.S. has no acceptable plan for the handling of nuclear waste.
  - Subsidies for other "carbon free" (wind and solar) sources make it hard to compete.

Subcritical Operation

- Subcritical operation cannot sustain itself, so an **external source** of neutrons is required.
- The most appropriate source is a proton accelerator generating spallation neutrons:
  - 600-1000 MeV
  - 1-10 MW
- Appropriate k values: $0.97<k<0.99$.
- k closer to 1 gives more output power for a given beam power. That power ratio can range up to 200 or so.
- As fission stops when the accelerator is turned off (< 1 sec), this can provide safety and reduced regulatory financial burden.
- The neutron source permits operation even with large amounts of fission fragments and deeper burn for all possible fuels, especially important for W-Pu and SNF – **can burn waste**.

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Why now?
Answers to Historical Objections to ADSR

- Doubt that a multi-MW accelerator could be built.
- Belief that such an accelerator would be too expensive and inefficient to operate.

Superconducting accelerators answer both.
(ATW – accelerator too expensive)

- Expectation that frequent accelerator trips would cause mechanical fatigue in the **solid** reactor fuel rods.

Eliminated by using molten salt fuel, and by designing the accelerator for high availability.

- Doubt that the neutron economy would be viable.
  Addressed with modern materials and simulations.

- Possible new regulatory regime for new nuclear
  Legislation now working its way through Congress.

GEM*STAR

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

- Our long-range goal is to sell intrinsically safe and versatile nuclear reactors to address world energy needs.
- GEM*STAR is an Accelerator-Driven Subcritical Reactor designed to burn nuclear waste, natural uranium, depleted uranium, thorium, and excess weapons-grade plutonium.
- It uses a superconducting accelerator and molten salt fuel to achieve greatly improved safety, address the issues of nuclear waste, and be both economically and politically feasible.
- Note these technologies have already been demonstrated.
- We believe that even in an era of cheap natural gas that GEM*STAR will be economically attractive.

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 several different fuels.
- They routinely powered it down for weekends, something no conventional reactor could do.

From 1969 MSRE Report Abstract

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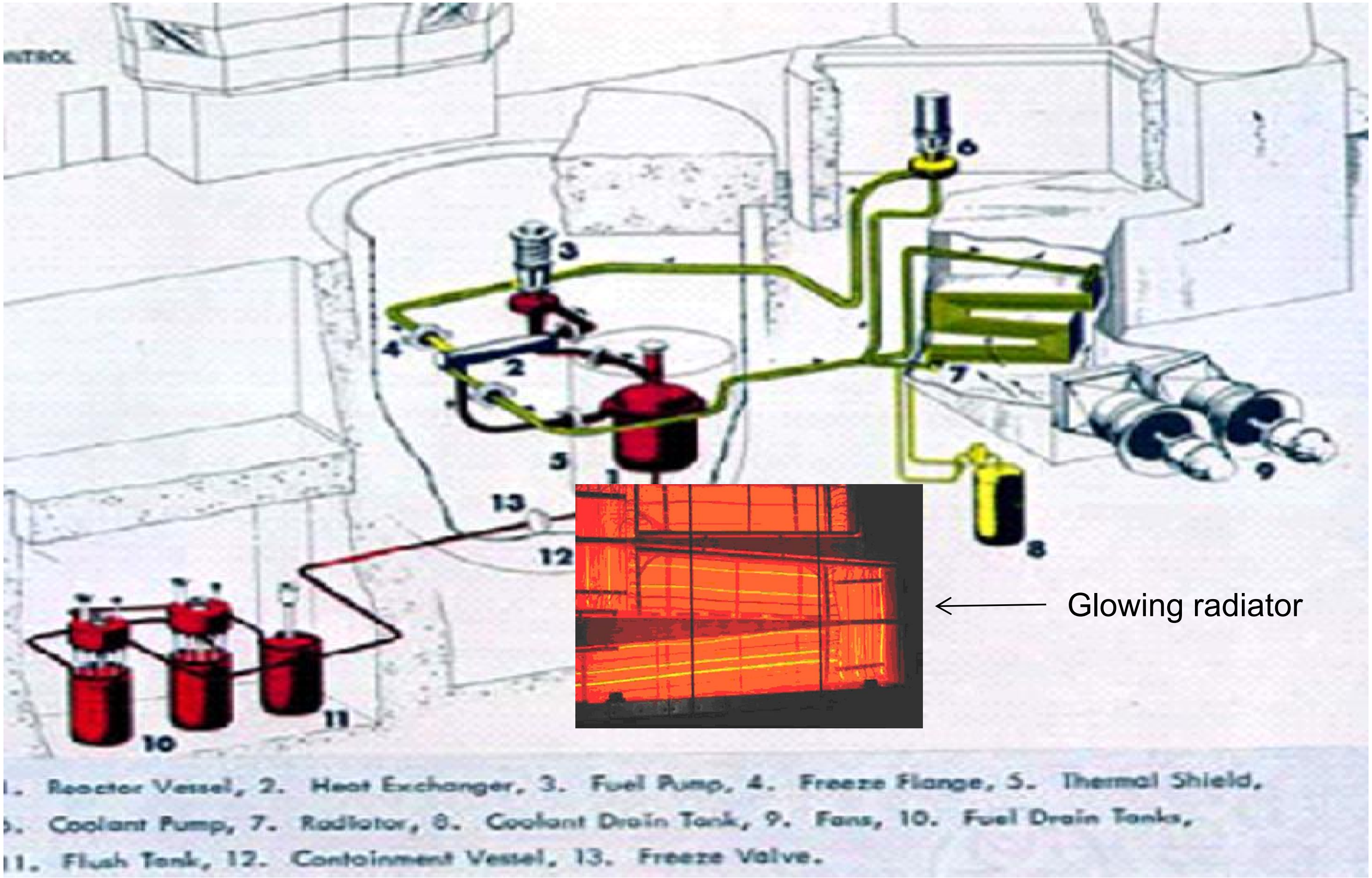
"The MSRE is an 8-MW(th) reactor in which molten fluoride salt at 1200°F (650 C) circulates through a core of graphite bars. Its purpose was to demonstrate the practicality of the key features of molten-salt power reactors.

<u>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.</u>

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

1965-69 ORNL Molten-Salt Reactor Experiment



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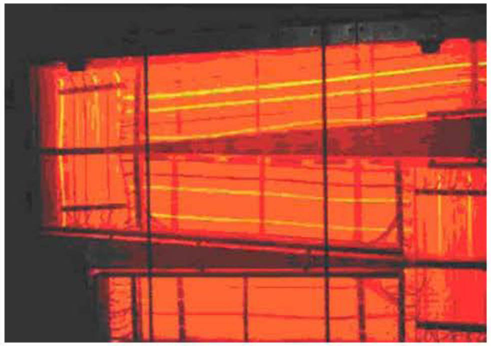
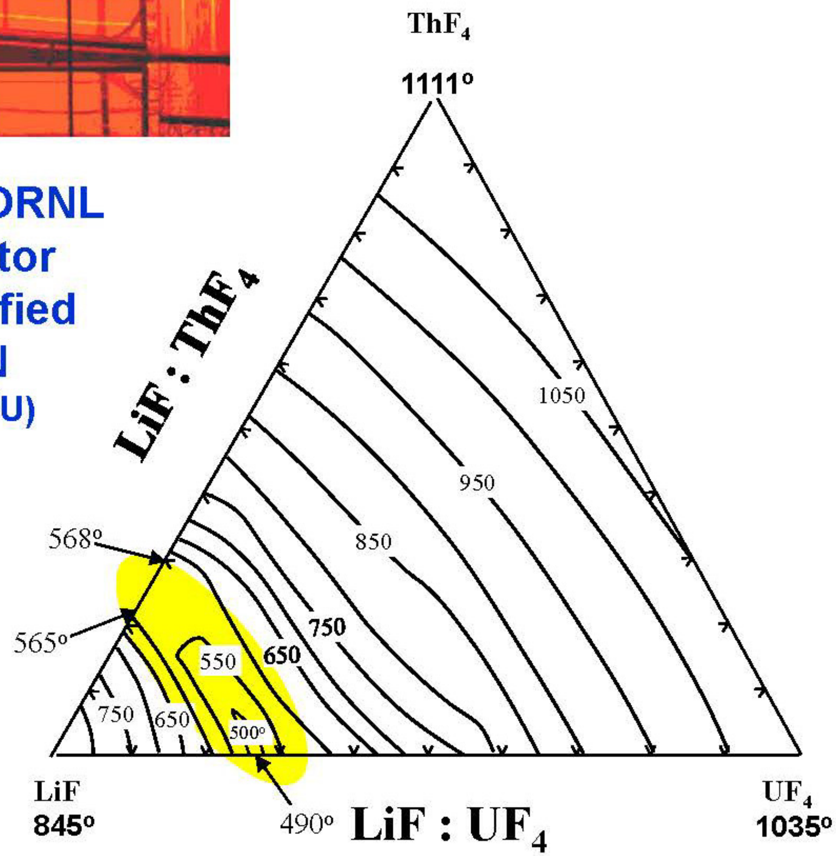
Molten Salt Eutectic Fuel



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



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

High boiling point → low vapor pressure

GEM STAR

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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:

1497 MHz Magnetron (for Jlab ERL)

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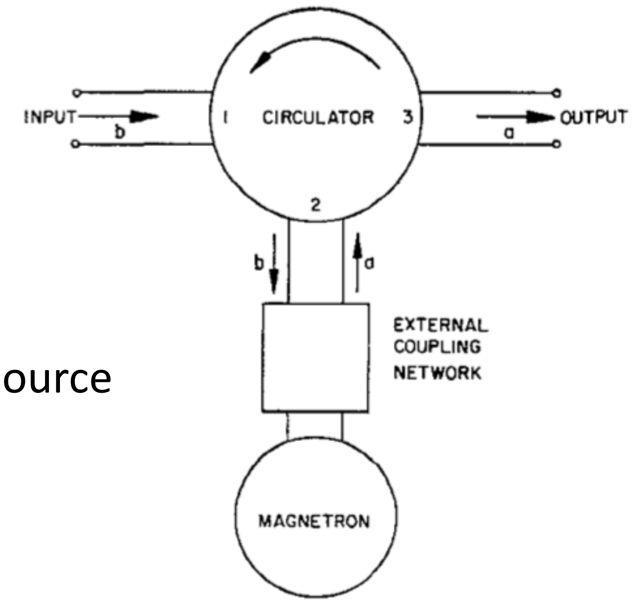
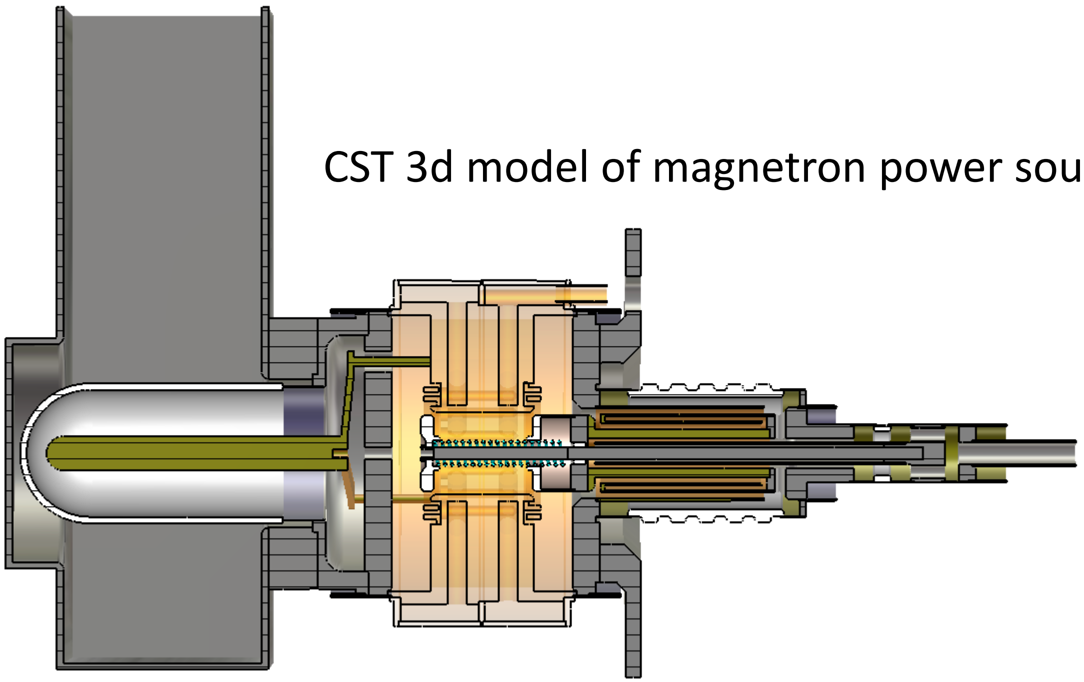
Klystrons at Jefferson Lab have an average life of 5 years. These could be replaced by magnetrons at 1/5 the cost!



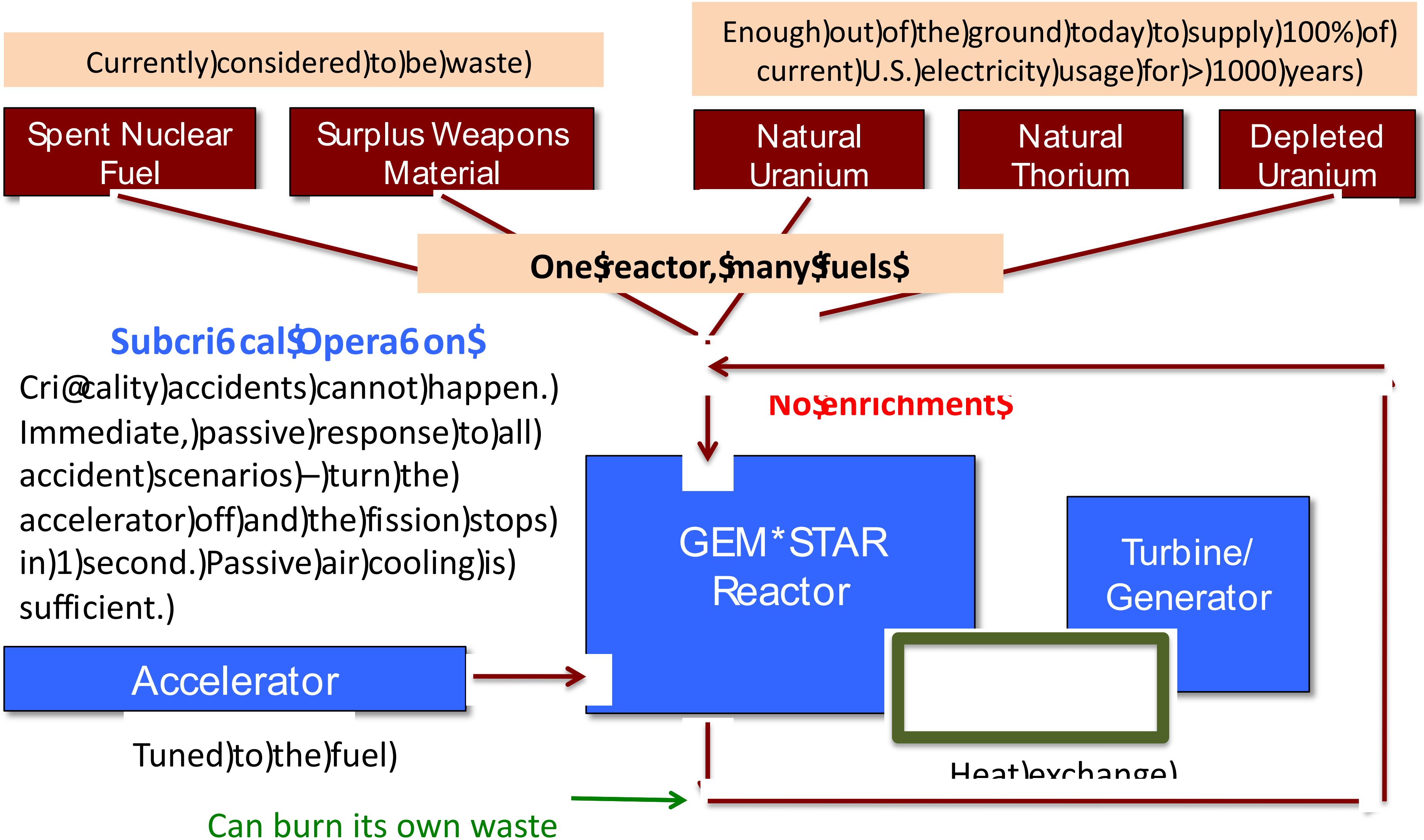
CST 3d model of magnetron power source



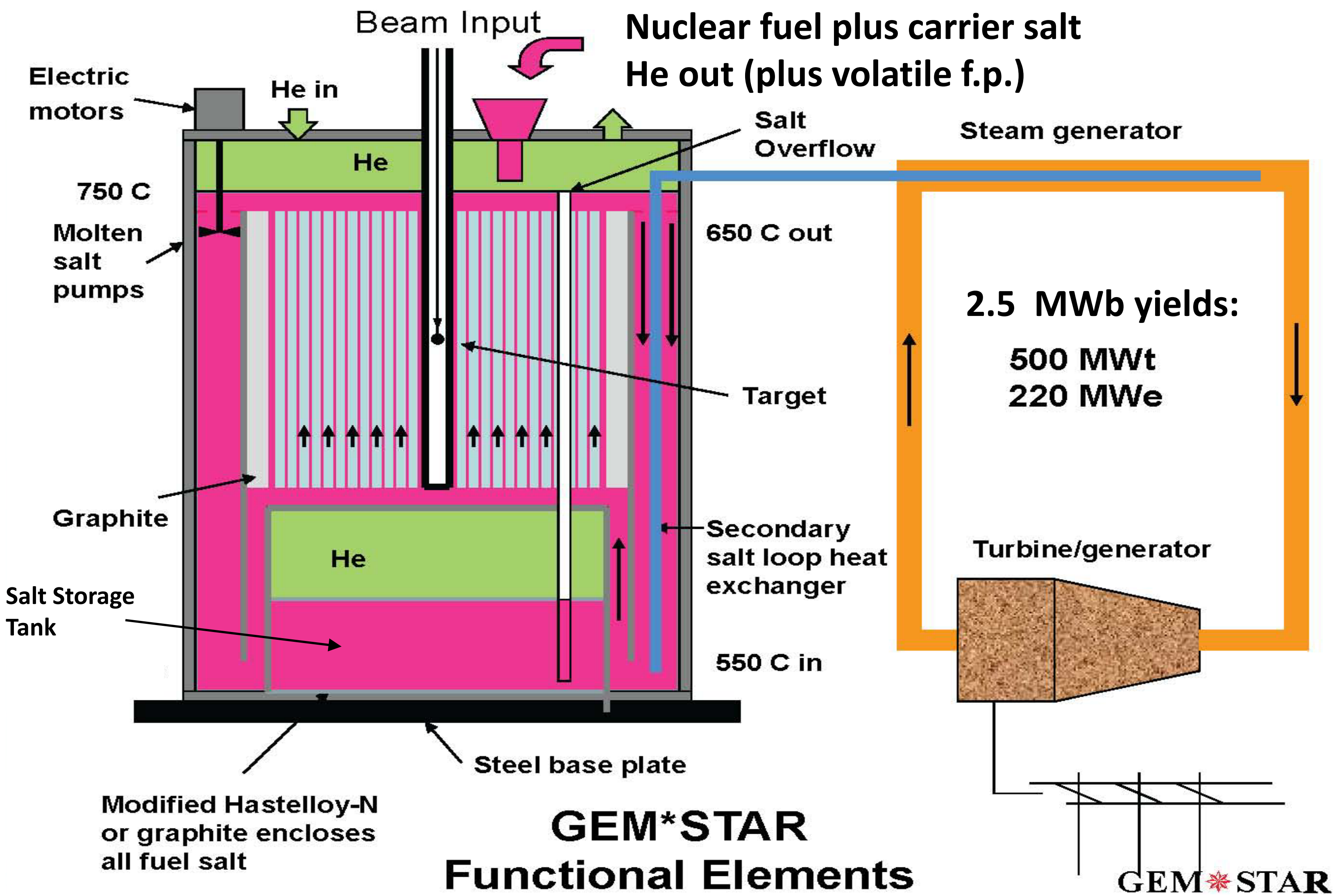
The Magnetron is is an **oscillator**, but with injection locking, becomes a reflection-type amplifier. Gain levels up to 30 dB have been achieved with efficiencies of 80%

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

GEM*STAR Concept



GEM*STAR



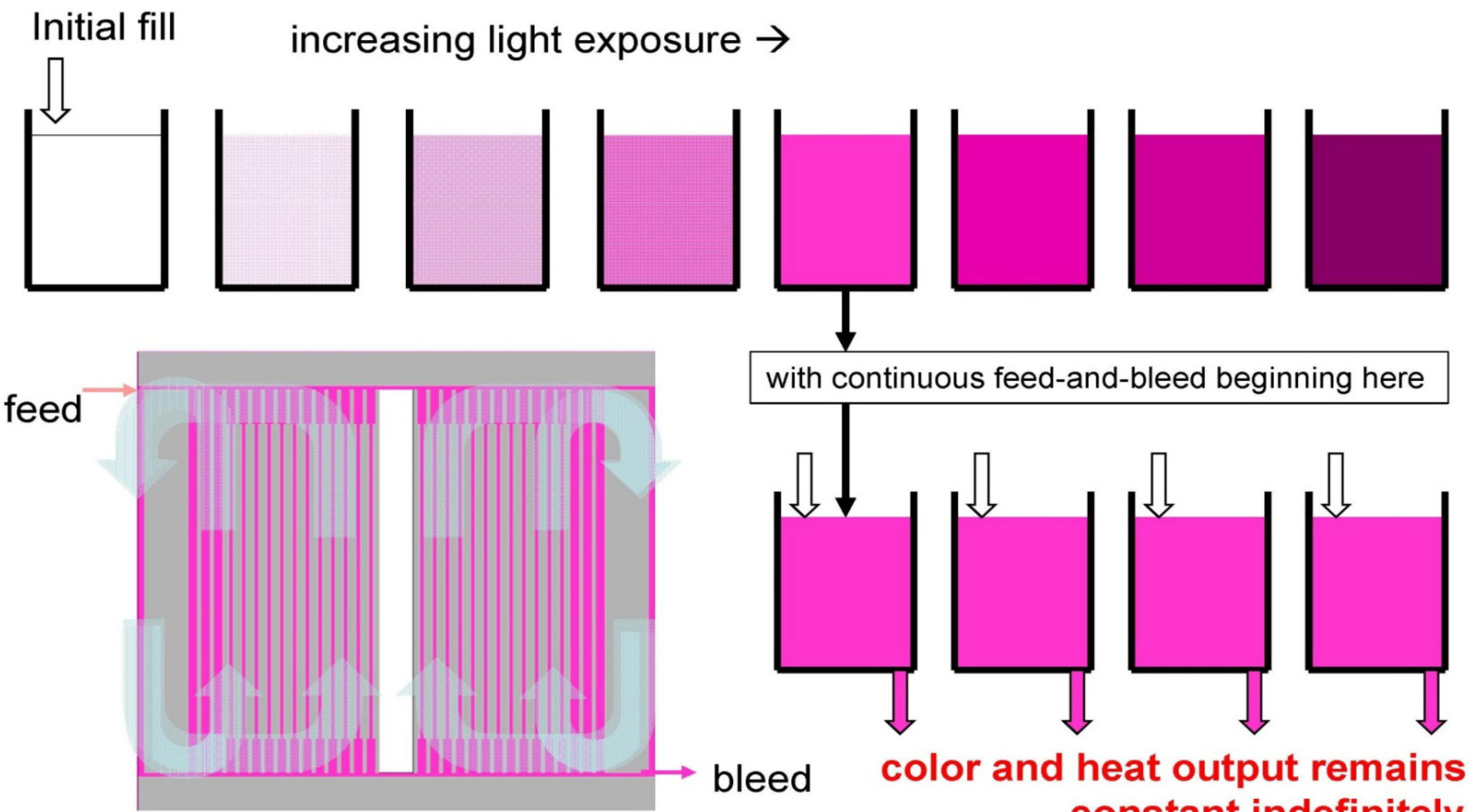
Beam Input
Nuclear fuel plus carrier salt
He out (plus volatile f.p.)
Electric motors
He in
He
Salt Overflow
Steam generator
750 C
Molten salt pumps
650 C out
2.5 MWb yields:
500 MWt
220 MWe
Target
Graphite
Secondary salt loop heat exchanger
He
Turbine/generator
Salt Storage Tank
550 C in
Steel base plate
Modified Hastelloy-N or graphite encloses all fuel salt
GEM*STAR
Functional Elements
GEM*STAR

GEM*STAR Advantages

- Proven 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.
  - Avoids possibility of release (total ~ a million times lower).
- 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

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



fast internal mixing

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

Holding tank ~ 25 x 10^{6} cm – long term capacity (no moderator, limited heat generation)

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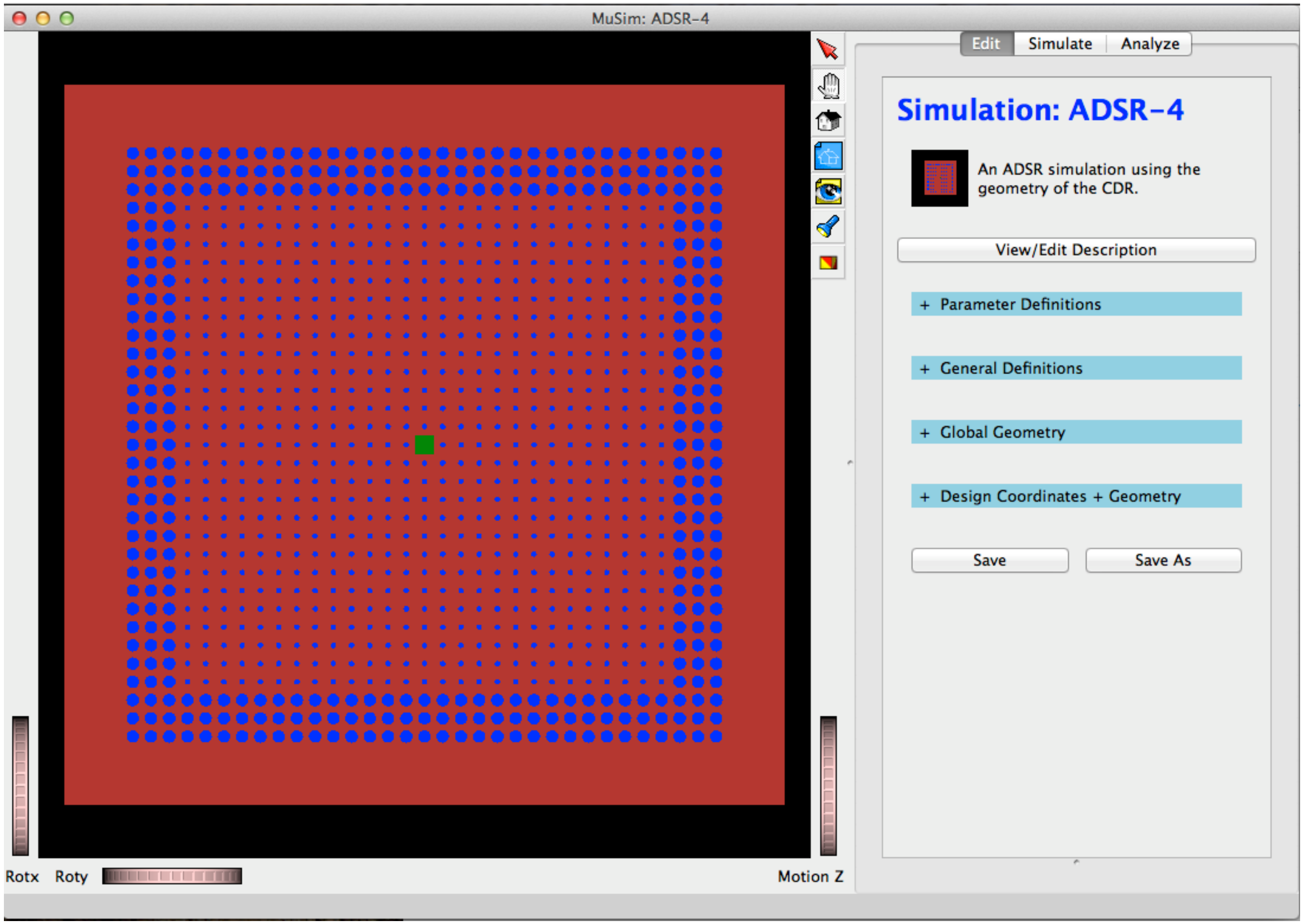
MuSim
Tom Roberts, Muons, Inc.

MuSim is a new and innovative graphical system that permits the user to construct, explore, optimize, analyze, and evaluate accelerator and particle-based systems efficiently and effectively. It is designed for both students and experienced physicists to use in dealing with the many modeling tools and their different description languages and data formats. It will be easy to use fast but less realistic codes to design and optimize a system, and then use slower but more realistic codes to evaluate its performance. **Graphical interfaces** are used throughout, making it easy to construct the system graphically, display the system with particle tracks, analyze results, and use on-screen controls to vary parameters and observe their effects in (near) real time. Such exploration is essential to give students insight into how systems behave, and is valuable to the experienced accelerator physicist. The use of **URL-based component libraries** will encourage collaboration among geographically diverse teams.

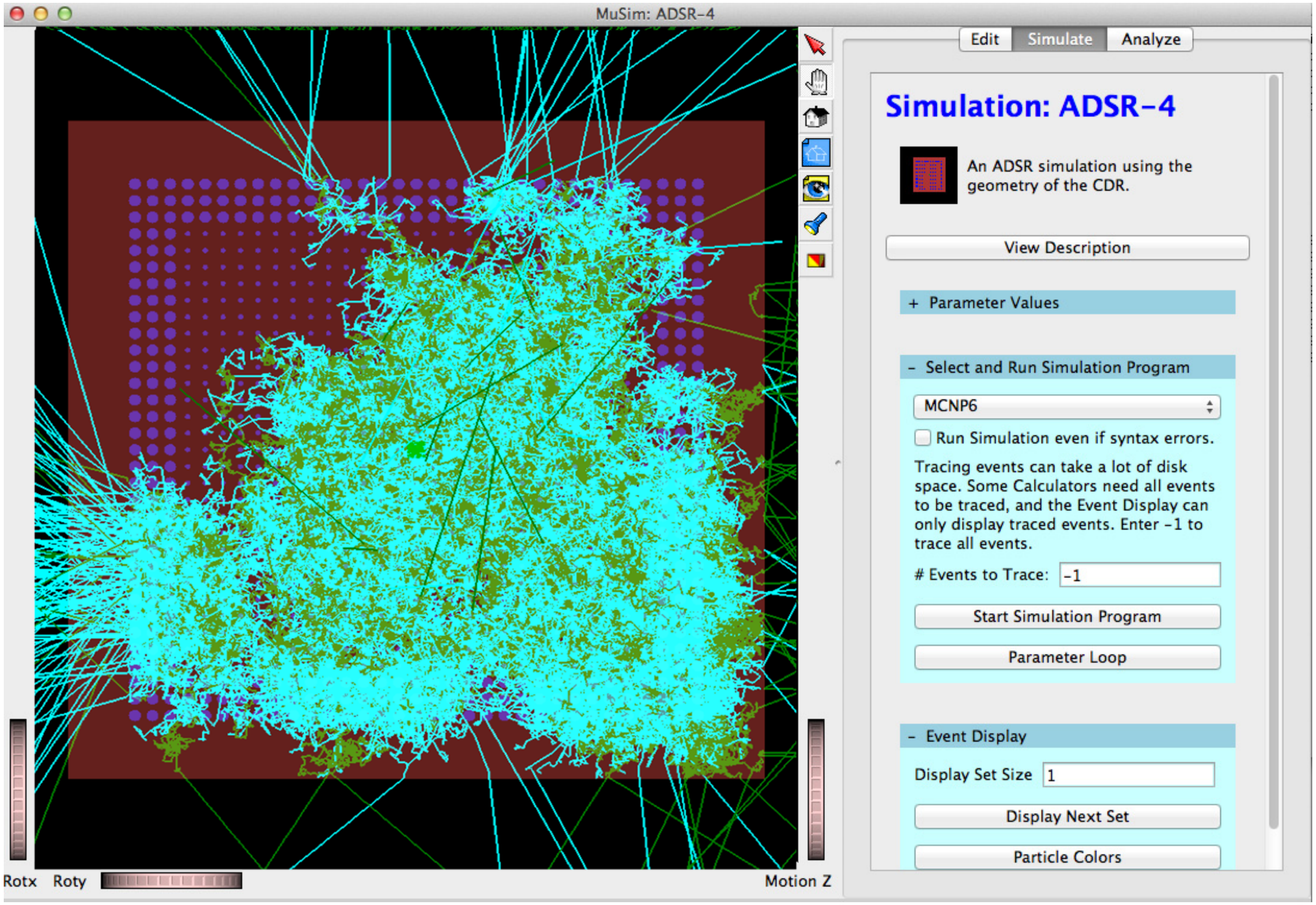
- Here is a movie that introduces MuSim by showing how to construct a Simple Proton Storage Ring in 20 minutes: http://musim.muonsinc.com

First MuSim Application - GEM*STAR



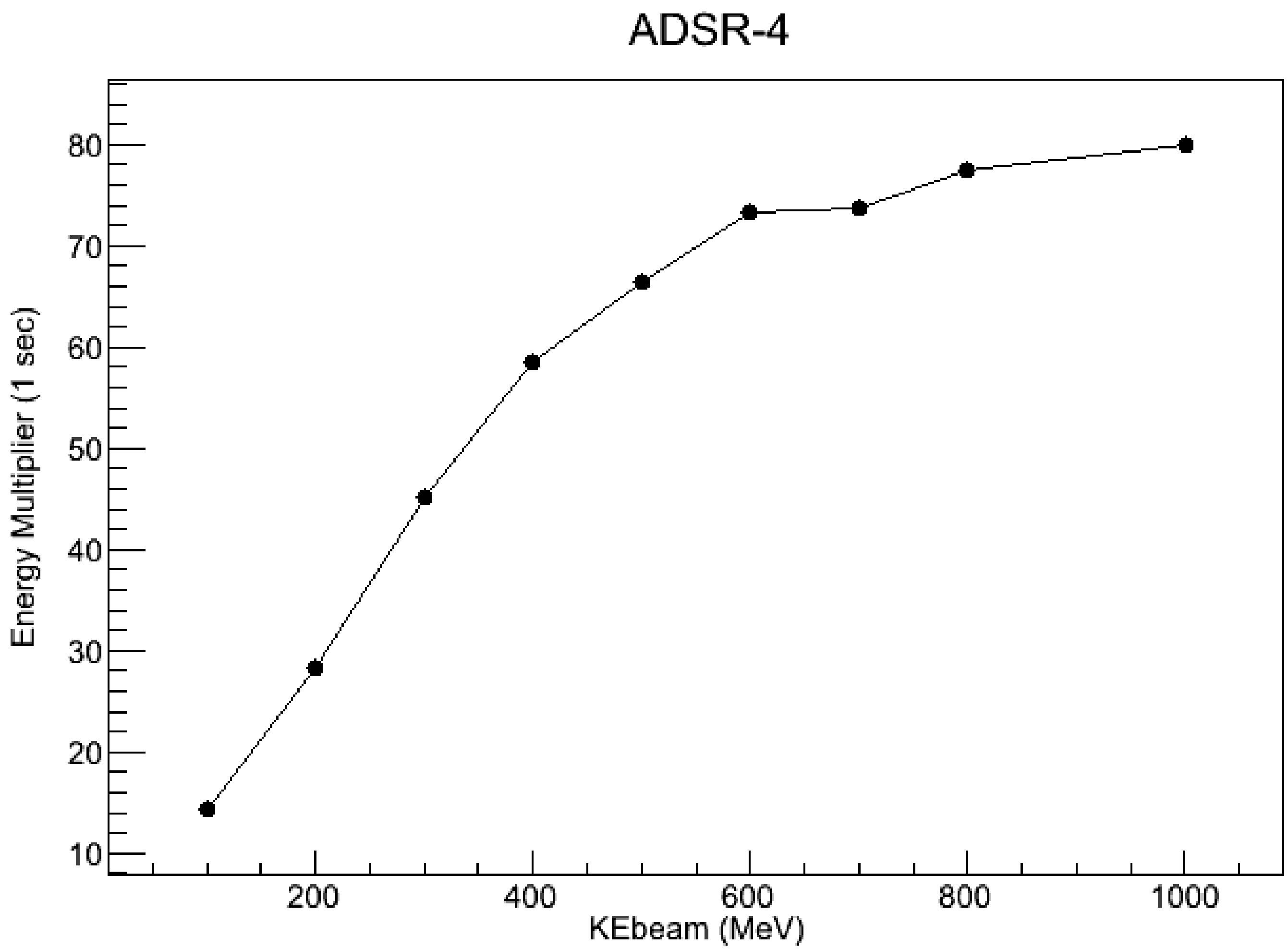
Screen shot of MuSim: carbon is brown, salt is blue, the spallation target (natural uranium) is green; the right side is an editing pane: ADSR-4 is the name of this simulation, and the blue headers are categories to specify the simulation that can be edited; Parameters are for parametrizing the simulation; 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.

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^-).

GEM*STAR
Energy Multiplier vs. Beam Energy



We can run much lower than 1 GeV energy ~ 600 MeV will be sufficient and be a significant cost saving on acceleration.

Target Considerations

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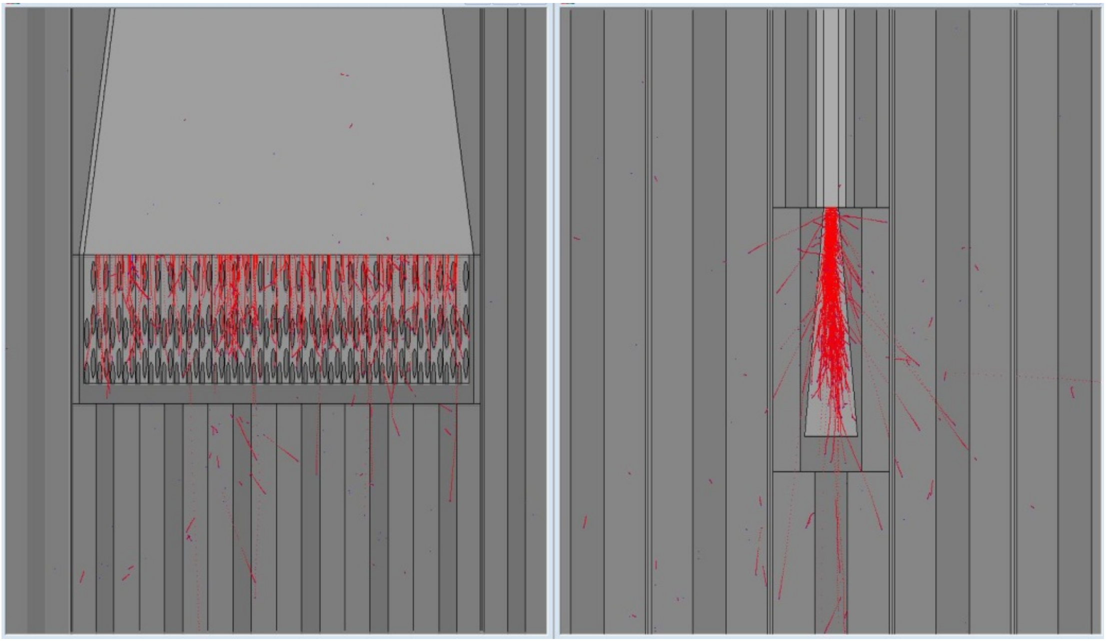

GEM*STAR Internal Target

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

- One thing it does particularly well is to dispose of surplus weapons-grade Plutonium.

    34 metric tons of surplus weapons-grade plutonium is slated to be destroyed by the 2000 U.S.-Russian Plutonium Management and Disposition Agreement.

- GEM*STAR destroys it 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 Pu.

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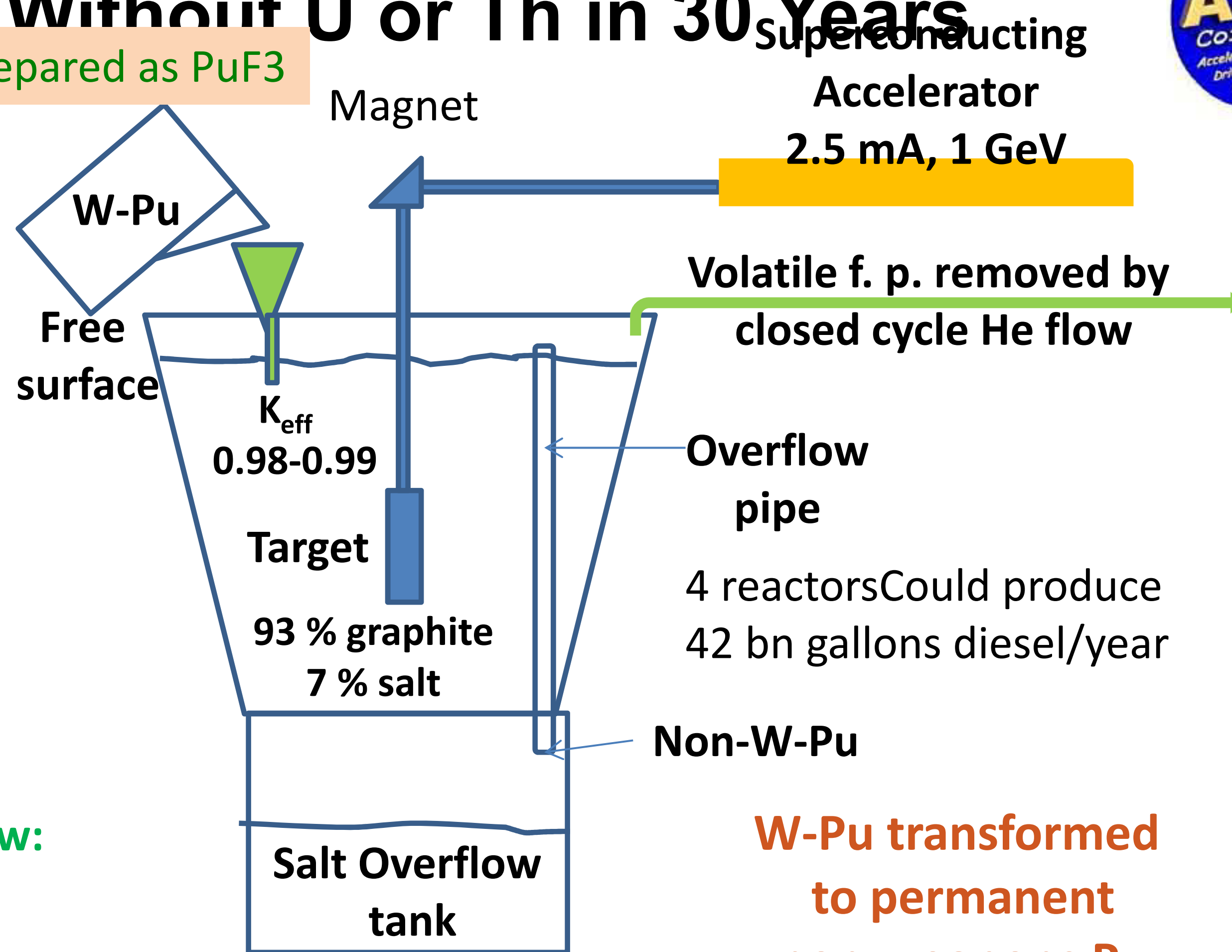
Four GEM*STAR Units Burn 34 Tonnes W-Pu Without U or Th in 30 Years

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

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

Prepared as PuF3



4 reactorsCould produce
42 bn gallons diesel/year

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

ADSR Small Modular Reactors

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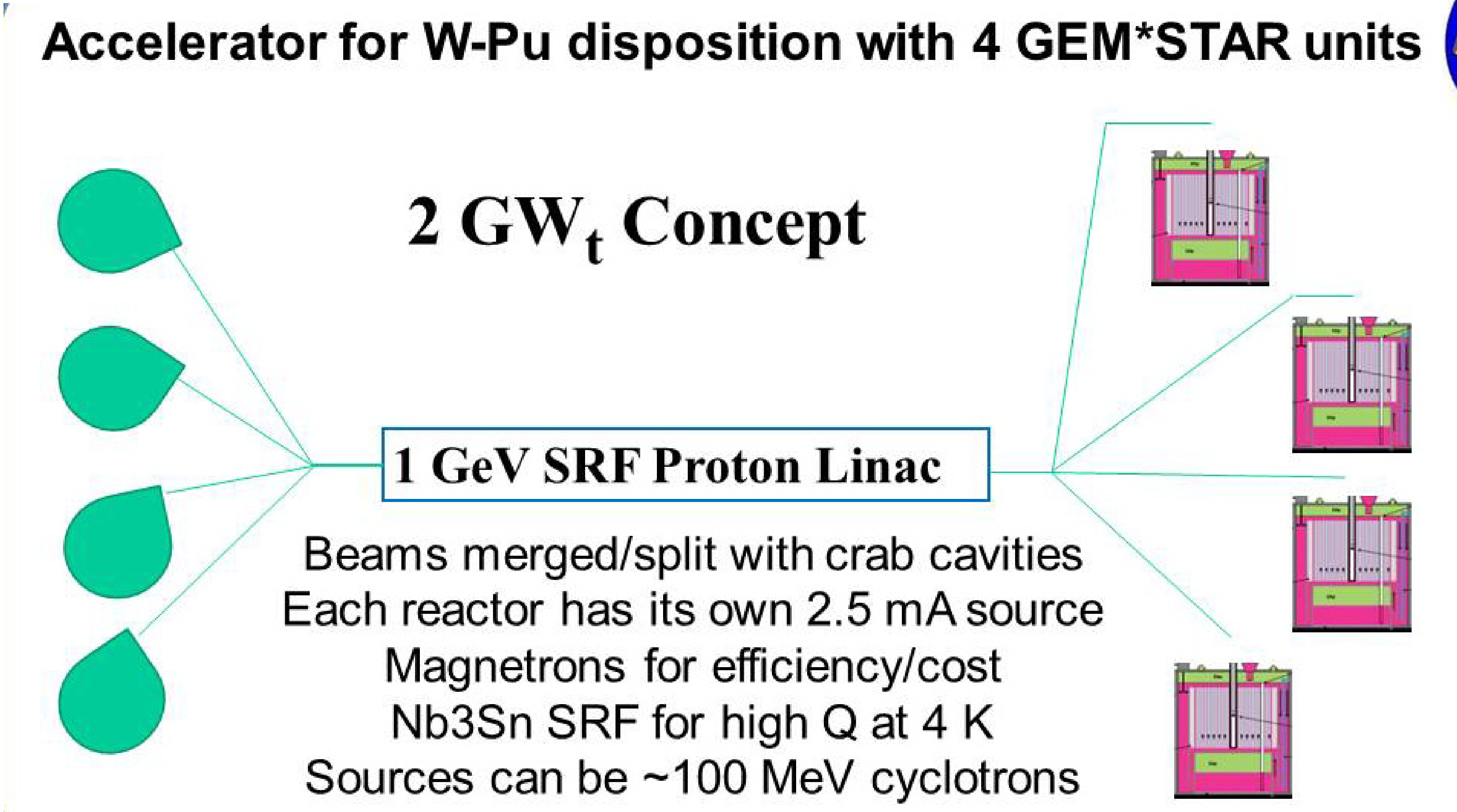

< 300 MWe for a "modular" reactor – the small size allows for convective cooling of the decay heat dwhen fission processes are terminated.

ADSR Small Modular Reactors

Conventional (large) LWR reactor:

- Too big to fund
- Too slow to construct
- Too expensive to make Nuclear electricity competive
- Don't get an economy of scale (higher specific costs ~ $(MW)^n$: BUT here n>1!
- Construction sites are poor places to learn!

So, small modular reactors (SMRs):

- Constructed in factories
- Production is coordinated and efficiency possible

Analysis: indicates optimum size of SMR (250 MWe < SMR < 450 MWe)

- Low end: personnel dominate
- High end: "specific" cost dominate

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What is sustainable?

- The world is already in an energy crisis, worsening rapidly as fossil fuels deplete and their devastating impact on climate change increases:

1 kWh by fossil fuel	1000 g	carbon emissions
1 kWh by gas	600 g	carbon emissions
1 kWh by solar	50-200 g	carbon emissions *
1 kWh by nuclear	4-110 g	carbon emissions *

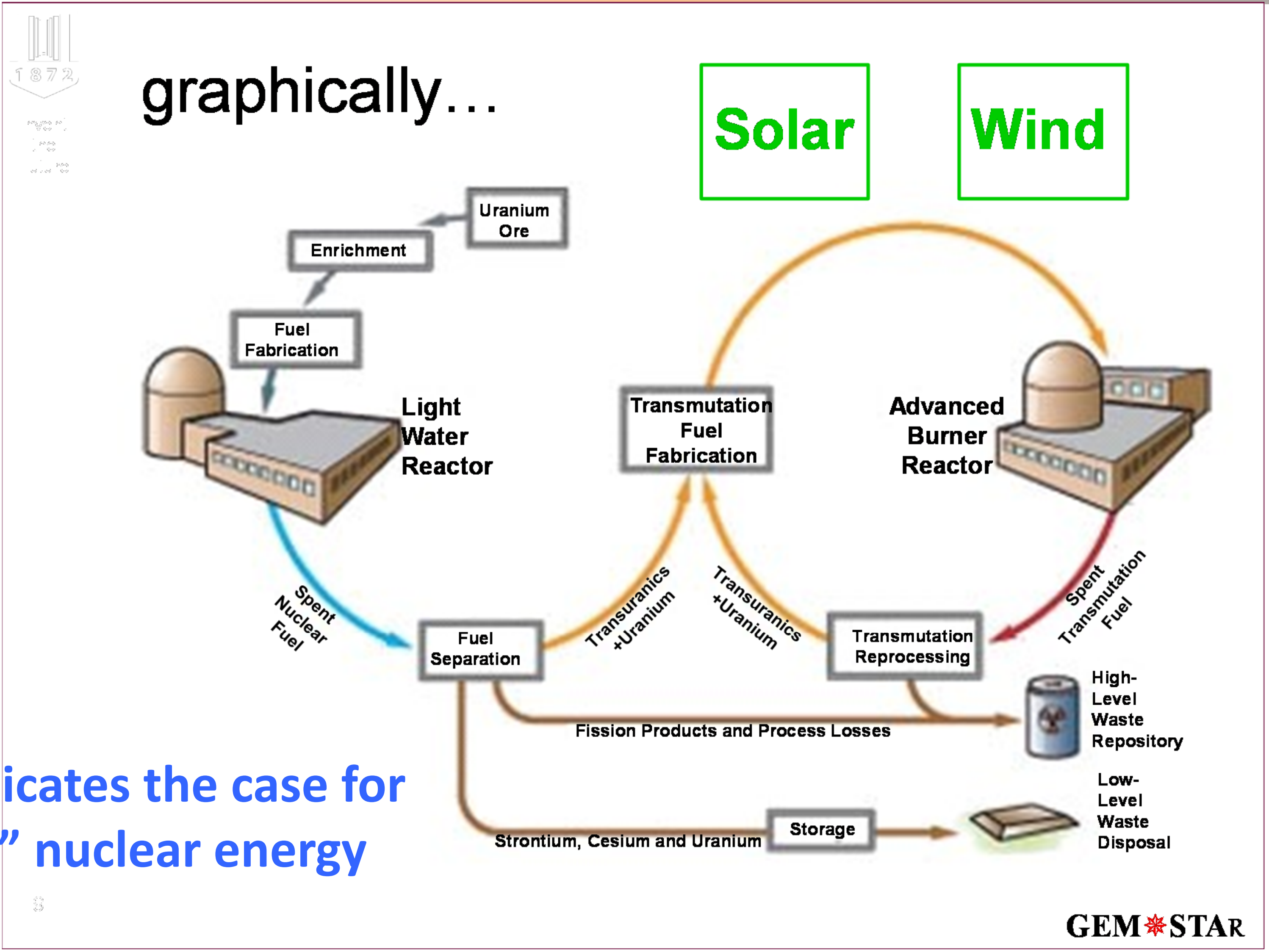
* Production processes

* Fuel reprocessing

- Nuclear power is the only *emission-free solution capable of producing the needed power levels* to meet rising demands. However, serious issues remain with current nuclear plants that must be solved or the cure will create new environmental hazards.
- Costs per kW hours: solar: $12/W nuclear: $6-7/W over lifetime of reactor

No long-term strategy for sustainable growth of nuclear power in the U.S.

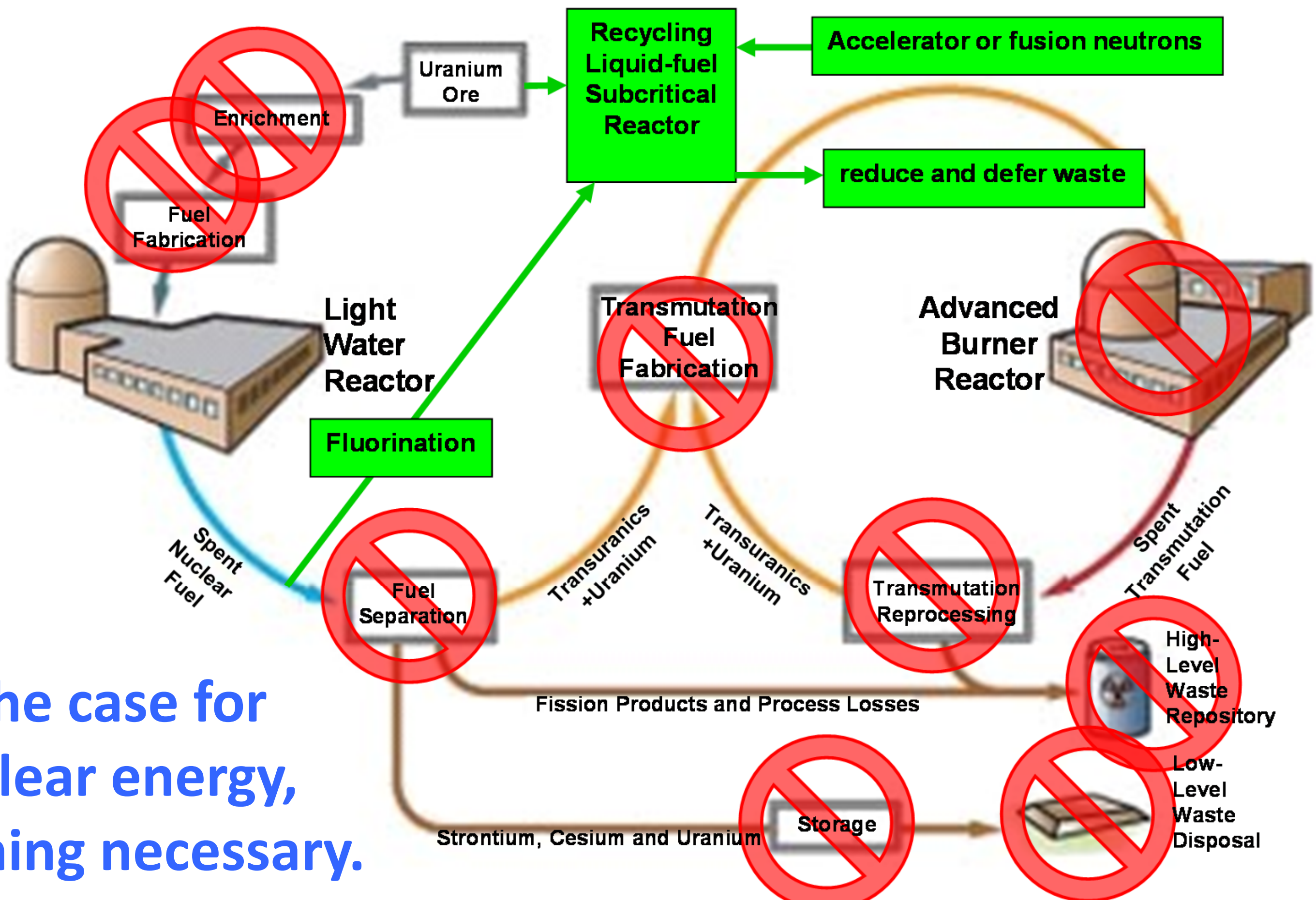
U. S. DOE's fuel cycle for nuclear compared with solar and wind



Complicates the case for "clean" nuclear energy

Fuel cycle for a GEM*STAR System

graphically…



Simplifies the case for “clean” nuclear energy, and no mining necessary.

GEM*STAR

Summary – GEM*STAR

- **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 is > two orders of magnitude smaller.
- **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.

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Political Talking Points

- Accelerator Driven Subcritical Reactors offer the promise to address the major problems associated with nuclear power – **both technical and political**.
- ADSR can be very flexible in fuel: spent nuclear fuel, natural uranium, depleted uranium, surplus weapons material, and thorium.
- Burning the waste from current reactors can potentially extend their lifetime and turn a huge **liability** into highly profitable use.
- Burning the spent nuclear fuel from the current fleet of nuclear reactors is vastly superior to throwing away its enormous internal energy and just piling it in a hole in the ground for 100,000 years.
- **With a fleet of systems like GEM*STAR there is 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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Future of Nuclear Energy

At the recent **White House Summit on Nuclear Energy** it was clear that nuclear energy is an important part of U.S. energy policy for the future.

That cannot happen without a sensible approach to the handling of nuclear waste#, which we don't have today.

ADSR is among the best approaches known.

Joint NRC-DOE Advanced Reactor Licensing Initiative

Major stumbling block for new technologies may soon be resolved with new legislation currently making its way through Congress.

E.g. Illinois has a moratorium on new nuclear facilities tied to a national policy on waste management.

BUT has passed legislation allowing transmutation facilities on **existing plant**s up to 150 MW .

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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)
    - **But now suspended for lack of US performance**
  - Navy adds nuclear power expertise, and location for demo
  - Solves Navy or Maersk long-range synthetic fuel need
  - <u>Turn $30B liability into $42B Profit (Congress/OMB</u>)

The Leaders

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

Rolland P. Johnson, Ph. D.
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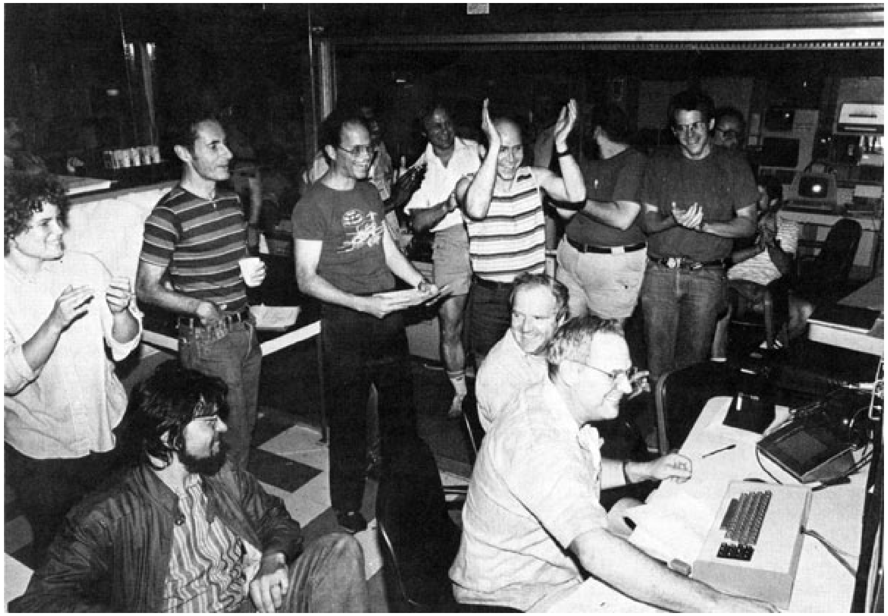
www.muonsinc.com



512 GeV at Fermilab

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

Charlie at LANL