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US Companies Pursuing ADS Techniques

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

Initial focus is on using natural uranium fuel and high-temperature molten-salt as the working fluid to produce synthetic transport fuel via the Fischer-Tropsch process.

Rolland P. Johnson, Ph. D.
President Mu*Star Inc.
www.muonsinc.com

Initial focus is on using SNF co-located at a nuclear plant to extract additional energy, then finally burn-down remaining actinides (after removing Uranium), and potentially have sufficiently reduced radiation remaining to allow local underground disposal – thus closing the fuel cycle.

major collaborative ARDP R&D proposal is under review

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The US is actually behind … global ADS research and development

SRF - US product!

Japan: ADS experiment Japan began in March 2009 at the Kyoto University Research Reactor Institute (KURRI), utilizing the Kyoto University Critical Assembly (KUCA). The experiment irradiates a high-energy proton beam (100 MeV) from the accelerator on to a heavy metal target set within the critical assembly, after which the neutrons produced by spallation are bombarded into a subcritical fuel core.

India: The Indian Atomic Energy Commission is designing a 200 MWe PHWR accelerator-driven system (ADS) fuelled by natural uranium and thorium. Ultimately there is a fully-thorium core with in situ breeding and burning of thorium. Achieves a high burnup of thorium – about 100 GWd/t. A 30 MW accelerator would be required to run it. India is also pursuing an electron neutron source for potential ADS applications.

Belgium: The Belgian Nuclear Research Centre (SCK.CEN) is building MYRRHA (Multipurpose Hybrid Research Reactor for High-tech Applications) research reactor at Mol. It will be a 57 MWt ADS, consisting of a proton accelerator delivering a 600 MeV, 2.5 mA (or 350 MeV, 5 mA) proton beam to a liquid lead-bismuth (Pb-Bi) spallation target that in turn couples to a Pb-Bi cooled, subcritical fast nuclear core.

Sweden: The Swedish are constructing the European Spallation Source (ESS) facility in Lund. The research facility will feature the world's most powerful neutron source. The ESS will be used for material research and life sciences. The facility set to be fully operational by 2025.

China: In March 2016 a strategic cooperation agreement to develop accelerator-driven advanced nuclear energy systems was signed between China General Nuclear (CGN) and the Chinese Academy of Sciences (CAS). It will include a 2 MWe accelerator-driven sub-critical liquid fuel prototype designed to demonstrate the thorium cycle as well as its Venus II ADS for transforming long-lived radioactive waste into short-lived waste.

Closing The Fuel Cycle - Burning and Burying SNF

Rol Johnson for the Mu*STAR ARDP ARC-20 Collaboration:

Companies:	Labs:	Universities:
Burns & McDonnell	**BNL**	**Texas A&M**
Deep Isolation	**JLab**	**VCU**
Muons	**ORNL**	**Virginia Tech**
	PNNL	

30 creative key individuals
Workforce Development w PDs & Students

GOAL – Demo NPP Conceptual Design Report in 3 years

1st Demo using existing accelerator by 2028

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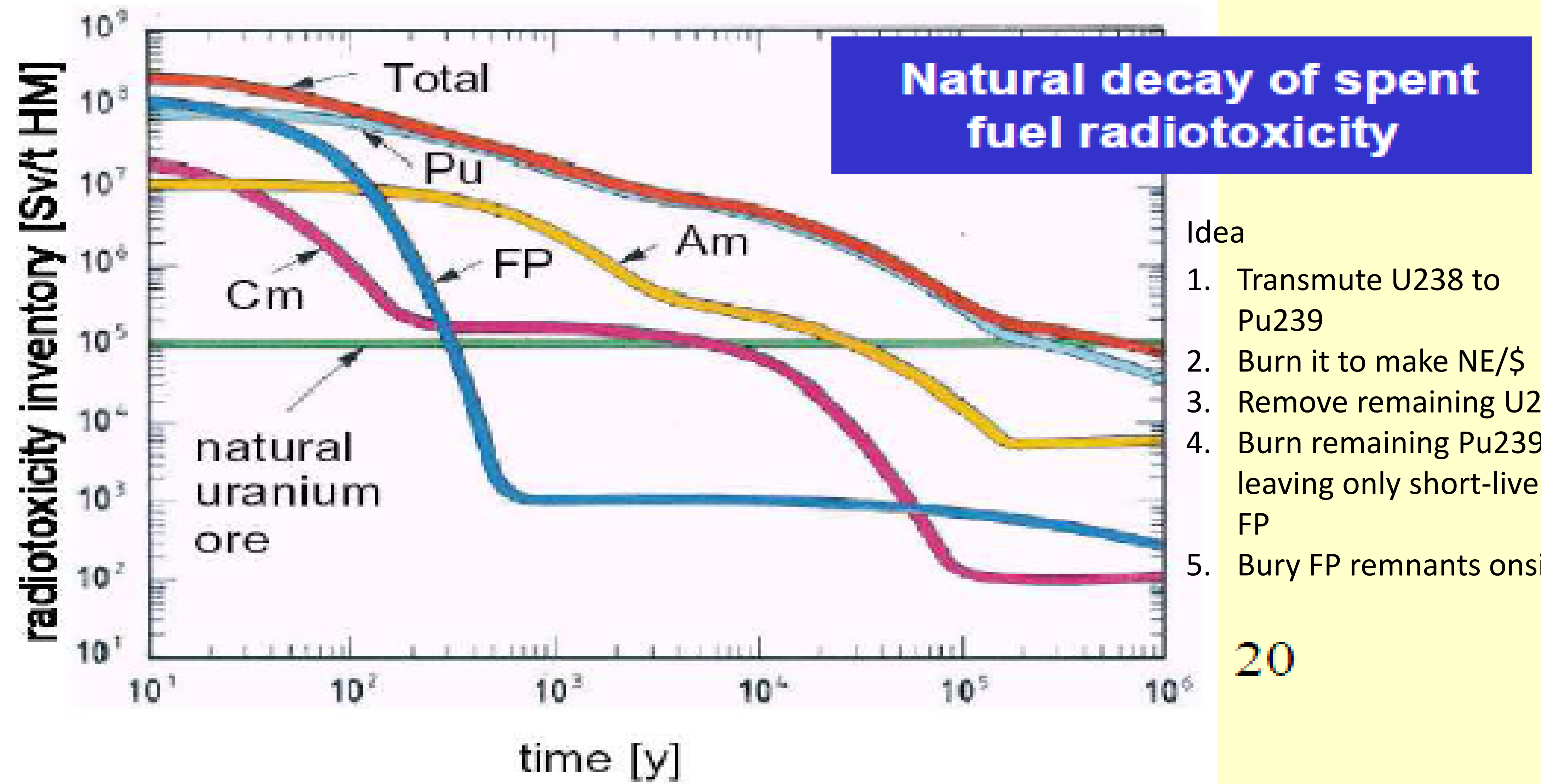
Closing The Fuel Cycle - Burning and Burying SNF

Mu*STAR (Muons Subcritical Technology Advanced Reactor)

Superconducting Accelerator-Driven
Subcritical
Molten Salt Fueled
Graphite Moderated
Thermal Spectrum
Reactor
To burn Spent Nuclear Fuel (SNF) from Light Water Reactors (LWR)
(a technical solution to a political problem)

Muons, Inc. Closing The Fuel Cycle – Motivation and Idea



Idea

1. Transmute U238 to Pu239
2. Burn it to make NE/$
3. Remove remaining U238
4. Burn remaining Pu239, leaving only short-lived FP
5. Bury FP remnants onsite

20

Not your grandfather's nuclear reactor I

"Why an expensive accelerator instead of a control rod?"

The accelerator allows subcritical operation

1) larger safety margins (e.g. k_{eff} control 10^{-2} vs 10^{-6} in LWR)

– reduce regulation, construction, operation costs

2) breaks restrictive link between maintaining criticality and fuel selection and reactor dynamics

– Allows low reactivity fuels like SNF (U enrichment not needed)

– Allows very reactive fuels like Pu-239 (MOX not needed)

Not your grandfather's nuclear reactor II

"Does the accelerator drive the reactor to criticality?"

- The reactor always operates subcritically
  - Incapable of self-sustained operation
    - (NRC comment "not a nuclear reactor")
  - Depends on fuel, moderator, geometry
- The accelerator makes spallation neutrons that initiate fission chains that die out in the MS fuel

$$P_{t\ reactor}/P_{accelerator\ beam} \sim 200$$

$$2.5\ MW_{beam} \text{ -> } 500\ MW_t \quad \text{or} \quad 5\ MW_e \text{ -> } 200\ MW_e$$

New Technology + Old Technology

- New - Superconducting Proton Accelerators (2009 ORNL SNS) with needed energy and power

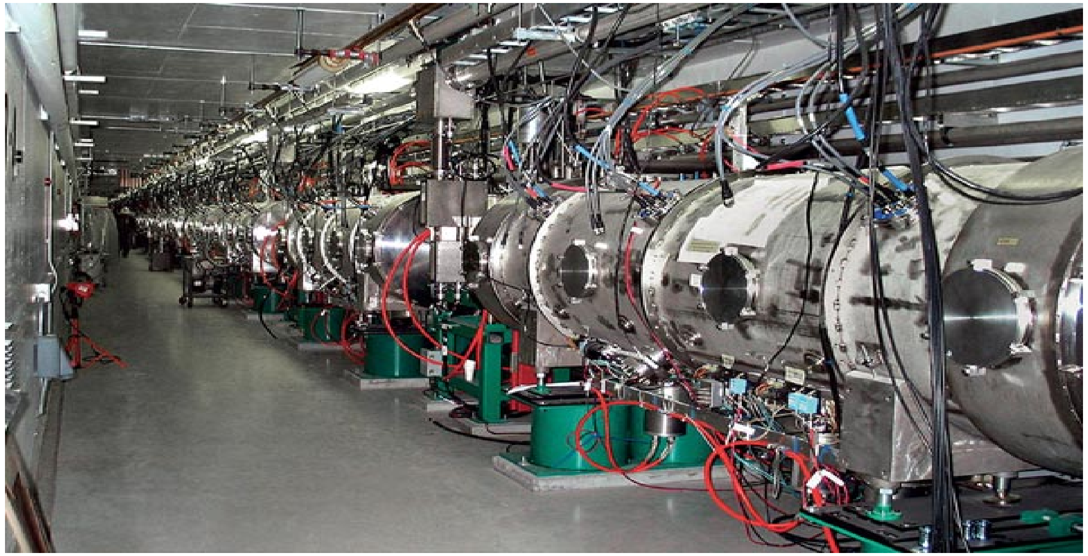
(

- Old - Molten-Salt Graphite-Moderated Reactor (1965-1969 ORNL MSRE)
- Merging these technologies allows
  - Eliminating enrichment and chemical reprocessing
  - Large safety margins for easier licensing & reduced costs
  - Deeper burns to extract more energy from fuel
  - <u>Closing the nuclear fuel cycle</u>

Breakthrough Technology – Superconducting Linacs

- ORNL Spallation* Neutron Source (SNS) operating since 2009
- FOAK SC p Linac cost ~ \$800M, 1 GeV protons, 1.4 MW_b, 6% df
- CW for ADSR can get >20 MW_b for less cost, higher efficiency
- One Linac can drive several Mu*STAR cores

*1 p produces > 30 n



ORNL Molten Salt Reactor Experiment

- Mu*STAR based on MSRE parameters-Temperature, graphite, Hastelloy-N
- Graphite MSRE core ¼ linear dimension of Mu*STAR, 4^3 = 64 times Power
- (TRE Mu*STAR SBIR)

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Molten Salt Reactor Experiment Report

Mu*STAR MS is a Lithium Fluoride based eutectic that melts around 500 C.

The MSRE operated using U-235, U-233, or Pu-239 as UF_4 or PuF_3 in the eutectic salt

https://en.wikipedia.org/wiki/Molten-Salt_Reactor_Experiment

"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."

Haubenreich and Engel, 1970 NUCLEAR APPLICATIONS AND TECHNOLOGY

Mu*STAR SMR Concept

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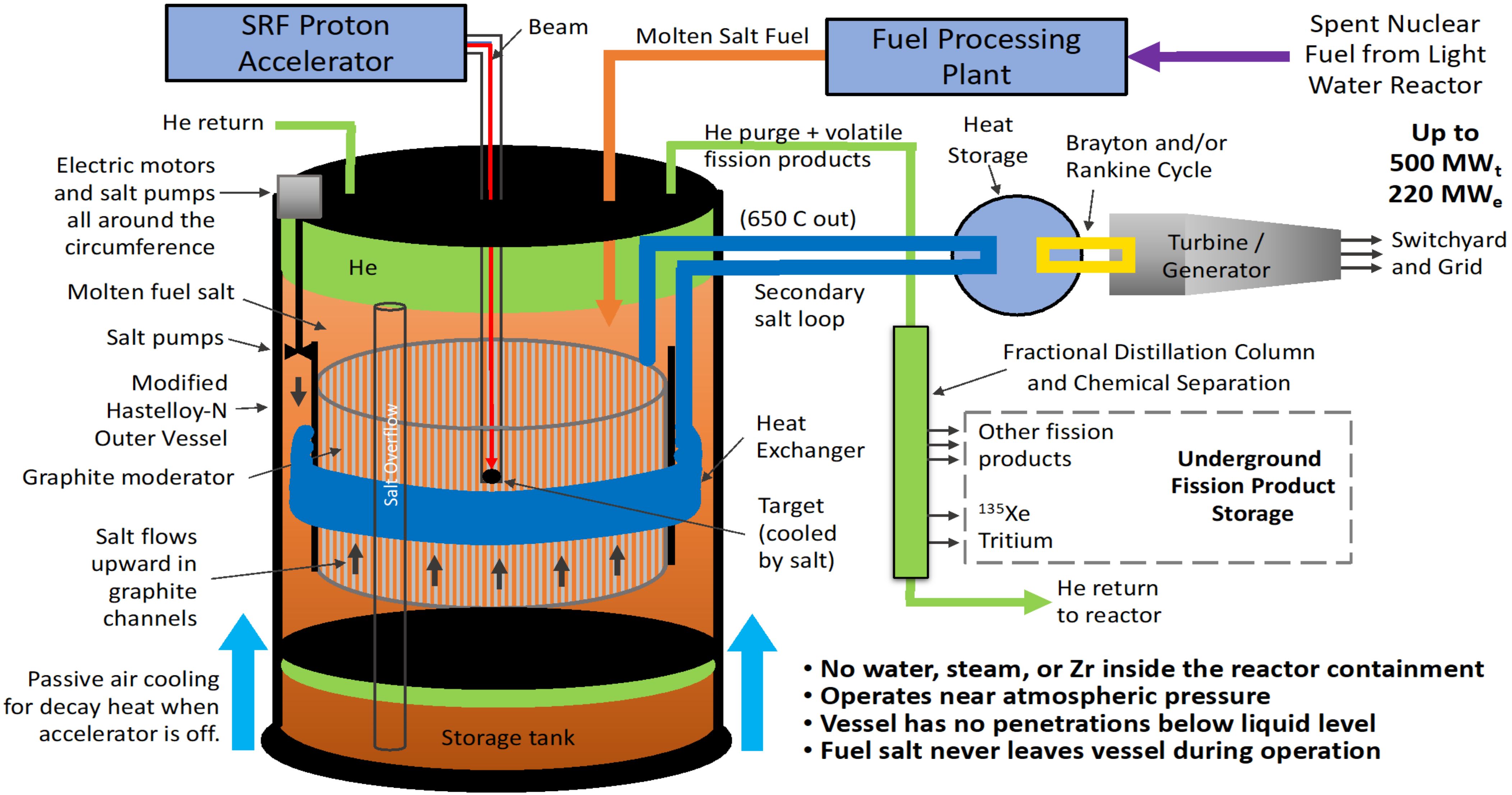
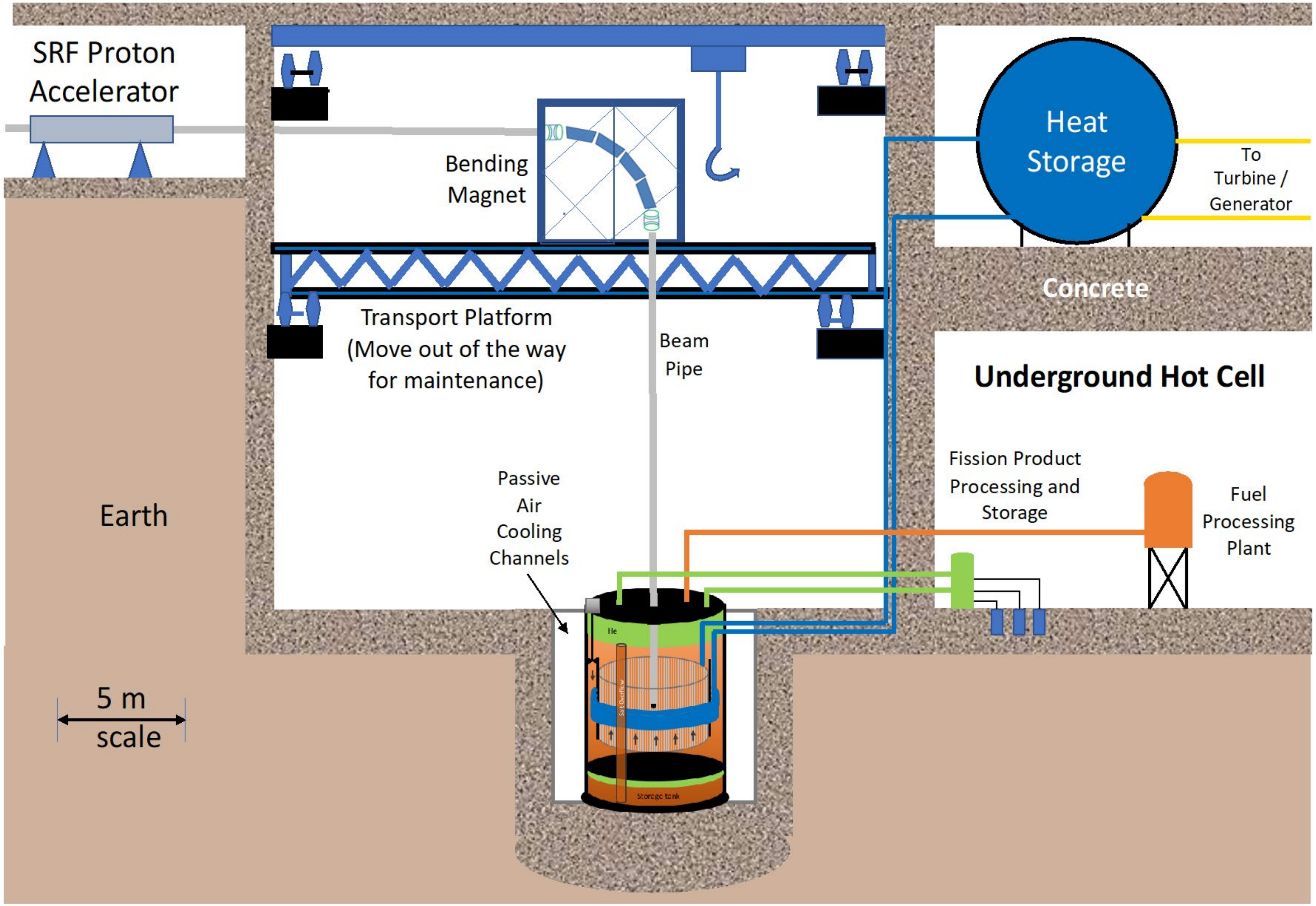


- **No water, steam, or Zr inside the reactor containment**
- **Operates near atmospheric pressure**
- **Vessel has no penetrations below liquid level**
- **Fuel salt never leaves vessel during operation**

No penetrations below level of fuel

Underground Linac and Cores



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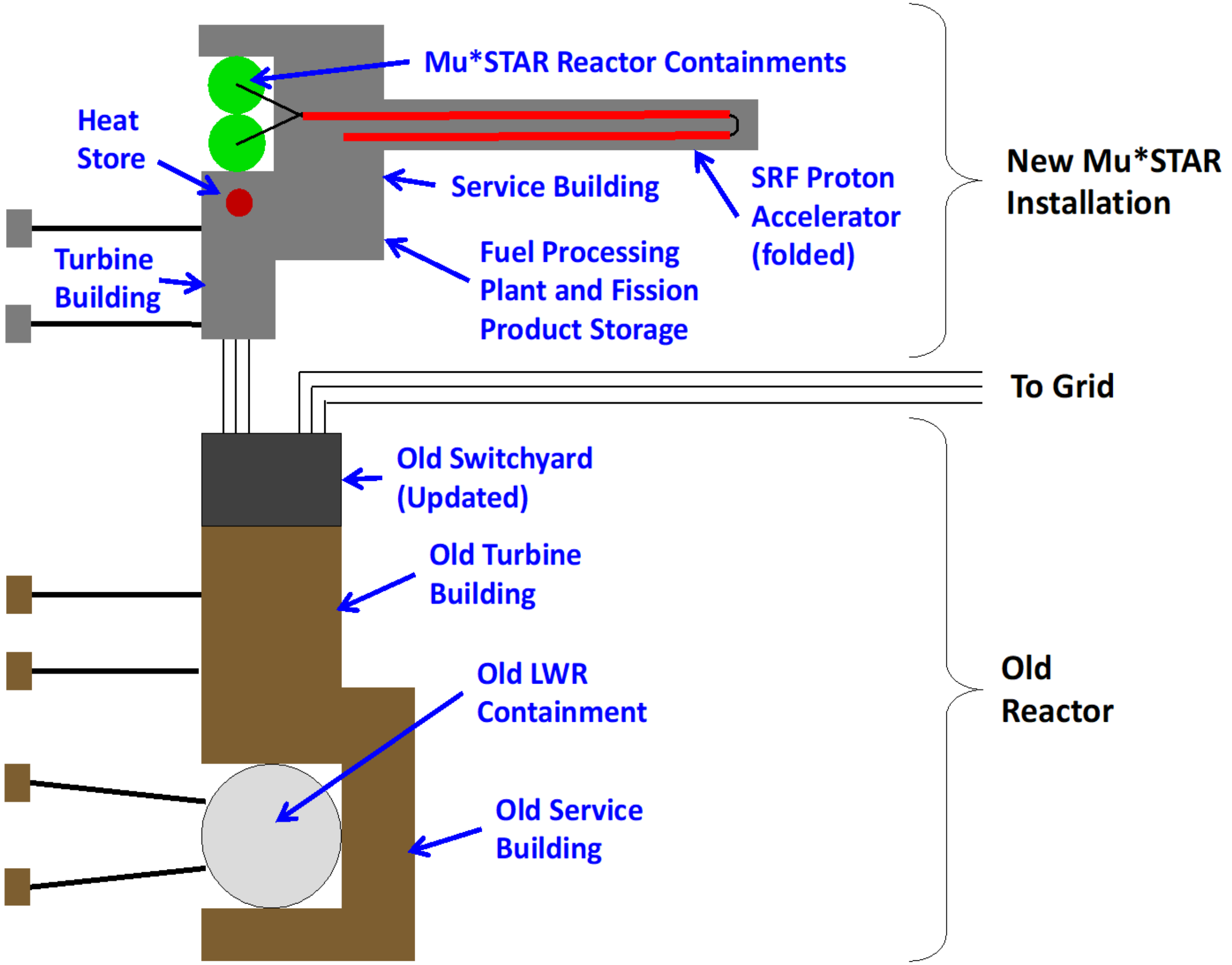
Mu*STAR Spent Nuclear Fuel Concept



ores

- Build Mu*STAR at >65 existing US LWR sites
- Convert SNF to fluoride MS fuel once
- Produce much more energy than LWR did
- Disruptive Technology
  - No U mining, enrichment, rods
  - No SNF transport
  - No central repository, Onsite burial
- Goal - cost competitive electricity
  - Capital cost – built in factories, site vetted
  - Operating – underground, remote opn
- CLOSE NUCLEAR FUEL CYCLE

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Mu*STAR Steps to Close the Fuel Cycle

1) Convert SNF into fluorides Onsite
2) Burn converted SNF in Mu*STAR SMRs
   1) burn all U-235
   2) transmute U-238 to Pu-239 and burn it
   3) increase P_{beam} to overcome neutron absorption by f.p.
3) Remove Uranium from MS
   1) Stop transmuting U-238
   2) Pu stays in MS with f.p. (no chemical separation of Pu)
4) Burn the remaining Pu-239 and long-lived actinides
5) Bury SNF remnants Onsite (deepisolation.com)

Step 1: Convert SNF into fluoride salts.

Methods and costs for onsite conversion of SNF fuel assemblies to fluoride MS were examined in Muons GAIN grant with ORNL, INL, and SRNL.

Concluded hot cell cost dominates >~$100M + $10M/y

Observed that Plutonium never separated from f.p.

PAUL TAYLOR, BARRY SPENCER, BILL DEL CUL, ALEX BRAATZ, STEPHEN WARMANN, ROBERT RABUN, JASON WILSON, TOM ROBERTS, “Mu*STAR ADSR Fuel Conversion Facility Evaluation and Cost Analysis”, ORNL/TM-2018/989

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Step 2: Burn fluorinated SNF in Mu*STAR

- Consume U-235 and Pu-239 transmuted from U-238
  - 2010 Study implies 5% LWR burnup could reach 40% when electricity demand reaches 15% of reactor output
  - Energy normalized SNF volume reduced by factor of 7
  - May require removal of some f.p.

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).

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Step 3: Remove Uranium from the MS

- Remove the very depleted uranium from the MS
  - Reduces SNF volume to be buried by ~2
  - Stops Pu-239 breeding
  - Leaves plutonium in MS with fission products

BK MCNAMARA, AM CASELLA, RD SCHEELE, & AE KOZELISKY, Nitrogen Trifluoride-Based Fluoride-Volatility Separations Process: Initial Studies Prepared for U.S. DOE Modified Open Cycle, PNNL September 2011FCR&D-SWF-2011-000390 PNNL-20775

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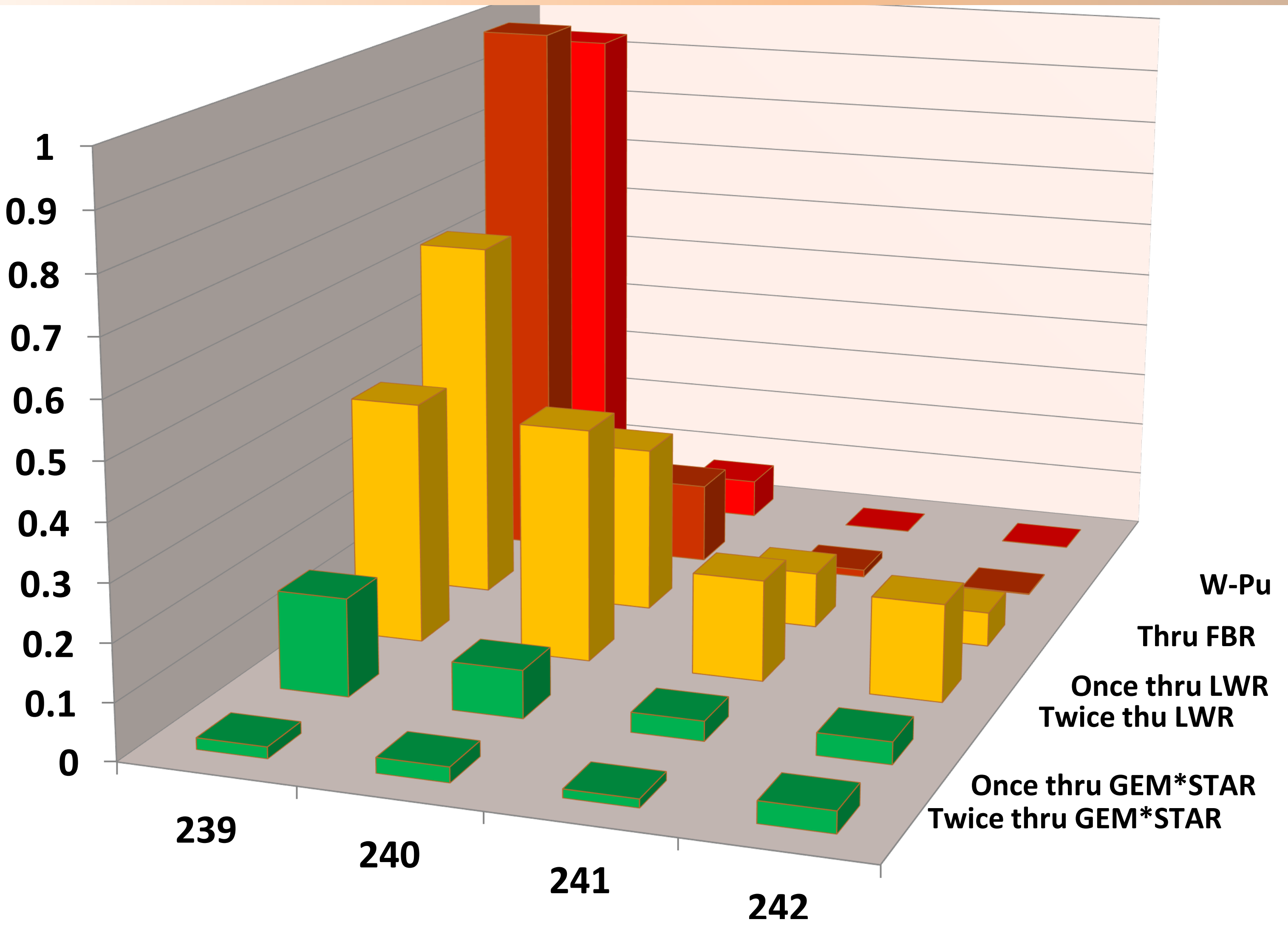
Step 4: Burn remaining Pu-239 & heavy actinides

- W-G Pu disposition method study compared
  - US Mixed Oxide (MOX) in LWRs
  - Russia Fast Breeder Reactor
  - MS ADSR like Mu*STAR
- Concluded Pu-239 as PuF_3 in MS ADSR
  - can be completely consumed
  - leaving remnants that are useless for nuclear weapons

R.P. JOHNSON, G. FLANAGAN, F. MARHAUSER, C. D. BOWMAN, R. B. VOGELAAR, "Disposition of Weapons-Grade Plutonium with GEM*STAR", http://accelconf.web.cern.ch/AccelConf/PAC2013/papers/thpba23.pdf

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

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Mu*STAR SNF Treatment Results

- SNF fissile elements consumed (no U enrichment)
- Up to 40% of fertile U-238 consumed (Pu stays in FP)
- Unused U-238 removed (not included in remnants to be buried)
- Remaining Pu-239 consumed (nonproliferation benefits)
- SNF Remnants Permanently Buried Onsite
    - Energy-normalized SNF volume reduced
    - Greatly reduced radiotoxic lifetime (mostly f.p.)
    - No weapons potential
    - Politically acceptable

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Summary/Conclusion

- Superconducting Linear Accelerators
  - Demonstrated by ORNL SNS (since 2009)
  - Energy, Power, Reliability to drive
- Mu*STAR Subcritical SMRs
  - Based on ORNL MSRE (1960s)
  - Internal Spallation Neutron Target
- New subcritical way to make NE
  - Fuel selection and reactor dynamics not tied to maintaining criticality
  - Each spallation neutron generates a fission chain that dies out
  - Reactor power proportional to proton beam power
- Burn SNF
  - Reduce to fission products buried onsite
  - Cost-competitive electricity, isotopes, process heat
- Enables all nuclear reactors that produce SNF
  - By Closing the Nuclear Fuel Cycle