12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB364

Mu*STAR: A SYSTEM TO CONSUME SPENT NUCLEAR FUEL WHILE ECONOMICALLY GENERATING NUCLEAR POWER

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Abstract

Mu*STAR is a superconducting accelerator-driven, subcritical, molten-salt reactor designed to consume the spent nuclear fuel (SNF) from today's commercial fleet of light water reactors. In the process of doing so it will: 1) generate electricity in a cost-competitive manner, 2) significantly reduce the waste-stream volume per Gigawatt-hour generated, 3) greatly reduce the radio-toxic lifetime of the waste stream. As many states and countries now prohibit licensing of new nuclear plants until a national strategy has been established for the long-term disposal of their nuclear waste, Mu*STAR can be an important enabler for new nuclear facilities. This is especially important in the light of climate change, as nuclear energy is the only carbon-free technology for a base-load generation that is readily expandable.

Mu*STAR CONCEPT

Enormous advances in superconducting accelerators over the past two decades have enabled a transformational change in the way nuclear power is generated, which will prove to be disruptive to the entire industry by closing the fuel cycle and eliminating the need for uranium enrichment.

A Mu*STAR Nuclear Power Plant (NPP) uses a superconducting (SC) proton accelerator, derived from the technology of the Oak Ridge National Laboratory (ORNL) Spallation Neutron Source (SNS) Linac, to drive several subcritical small modular reactors (SMRs). Each SMR is a graphite moderated molten salt (MS) fueled reactor, like the one studied in the Molten Salt Reactor Experiment (MSRE) [1] but with an internal spallation target to generate source neutrons. These source neutrons initiate fission chains that die out, producing energy in a subcritical core. The MS core remains far below criticality (which depends on materials and geometry but not the beam), is always incapable of self-generated operation, and is immune to criticality accidents. The MS fuel in the core is continuously purged of volatile fission products (FPs) such that the offsite doses associated with the core volatile source term can be reduced by at least three orders of magnitude. We believe the combination of subcriticality and the small source term will deliver deployment flexibility and regulatory simplification to enable the US nuclear energy enterprise to have a real impact on greenhouse gas (GHG) emissions.

In our preferred electricity-producing configuration, up to 10 Mu*STAR modules would share a common accelerator source, producing a net power of over 2 GWe for the grid. Reliability of the single factory-built Linac is addressed by its modularity, internal redundancy, and an intermediate thermal energy storage system to coverdowntimes for module repairs or replacement. The levelized cost of electricity is reduced by staged next-of-a-kind SMR factory construction and secure underground economy-of-scale-operation. The first Mu*STAR NPP would start with a single SC Linac driving a single factory built SMR as a pilot plant on the site of an existing nuclear installation. With operational experience, SMR modules will be added along with Linac upgrades to split the beam to each SMR, on an RF bunch-by-bunch basis. This accelerator-driven, high-temperature Mu*STAR NPP design can be deployed for diverse missions including electric generation, used fuel disposition, process heat generation, hydrogen production, tritium production in support of future fusion systems, or any combination of these. The initial pilot plant is a natural place to develop these various applications, and explore upgrade paths for subsequent plants.

Figure 1 shows a simplified conceptual picture of a Mu*STAR Nuclear Power Plant that produces electrical energy by consuming spent nuclear fuel (SNF). SNF from LWR fuel assemblies are disassembled in the hot cell of the Fuel Processing Plant (red, top right) and the oxide fuel pellets are converted to fluoride salts that are added to the molten-salt eutectic (orange) in and around the graphite moderator (gray) of the core, scaled up from the graphite moderated design of the MSRE. A Superconducting RF Cavity Linear Proton Accelerator (red, top left) and beamline direct high energy protons onto a heavy metal spallation neutron target inside the core. A helium cover gas (green) removes volatile isotopes from the core, transfers them to the hot cell where they are removed from the helium by a cryogenic fractional distillation column and chemical processing; they are stored underground while they decay. The fuel salt never leaves the reactor vessel during operation; it is circulated using pumps located around the circumference, and via natural convection should pump power fail. In the case of station blackout that results in pump power loss, the accelerator will also be off.

There are several cost saving and safety features in this design: The reactor is near atmospheric pressure, so no pressure vessel is required. The source term for accidental radioactive release from the core is reduced by about a factor of a half a million by virtue of the continuous helium cover gas flow; the reactor containment is greatly simplified. Figure 2 shows a possible physical plant arrangement.

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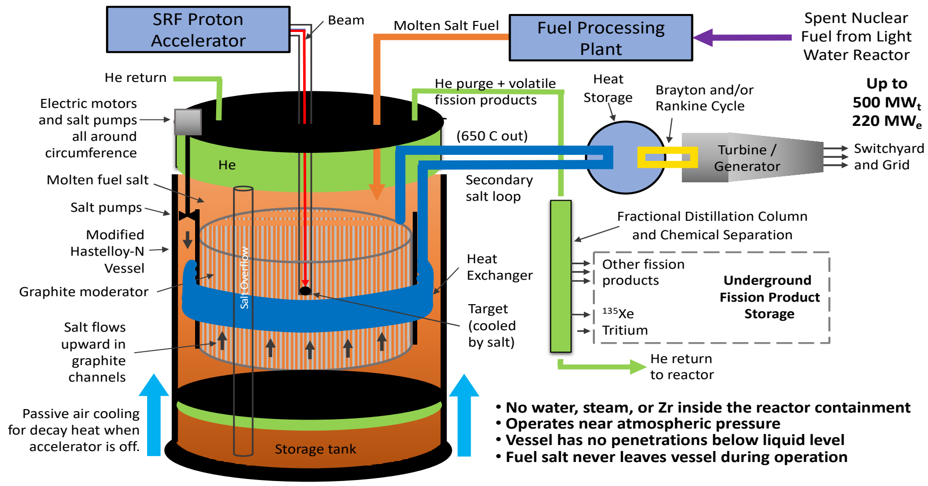

Figure 1: Concept of a single-SMR version of a Mu*STAR Nuclear Power Plant (NPP). The accelerator power is sufficient to allow the beam to be distributed and individually controlled to multiple Mu*STAR cores simultaneously.

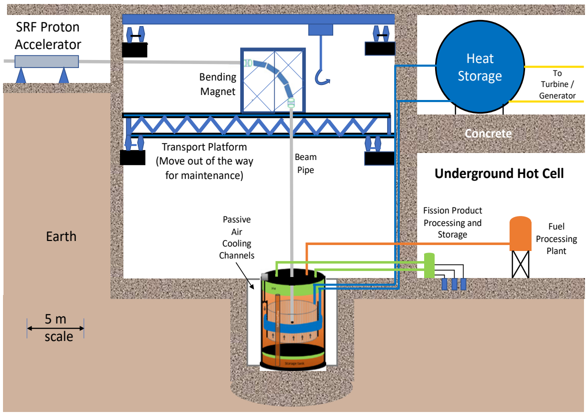

Figure 2: The underground placement of a Mu*STAR SMR, the proton accelerator, and the hot cell containing the fission product processing and storage with the fuel processing plant.

Mu*STAR SPENT FUEL CONCEPT

Figure 3 shows a conceptual picture of a Mu*STAR power plant built next to an existing or decommissioned LWR to take advantage of the site environmental impact studies, connection to the grid, and the stored SNF. There are approximately 65 existing US LWR sites and many others around the world, where the SNF could be converted to fluoride salt once and produce much more energy than LWR did, for many decades. This disruptive technology could mean not needing uranium mining, enrichment, fuel rod manufacture, SNF offsite transport, or a central nuclear waste repository. Our goal is to dispose of the SNF while generating cost competitive electricity, with extra benefits like useful isotopes and process heat. We will reduce the capital cost of all components by building them in factories with cost-saving inventions and will reduce operating costs with subcritical designs that are walk-away safe and underground secure.

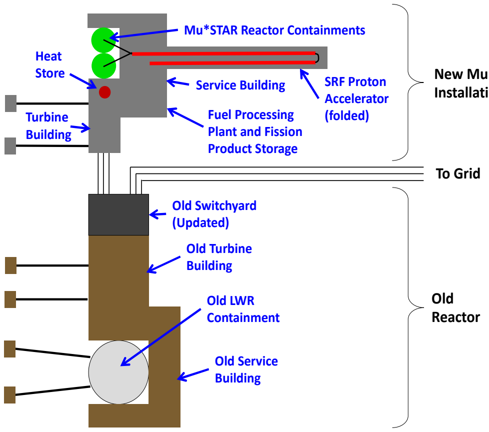

Figure 3: Building a two-core Mu*STAR nuclear power plant on an existing/decommissioned LWR site.

The Mu*STAR subcritical multiplier can be used to convert all the fissile energy and much of the fertile energy in LWR SNF to allow politically acceptable permanent onsite burial of a smaller and less radioactive amount of remaining material.

STEPS TO CLOSING THE FUEL CYCLE

Step 1: Convert SNF Into Fluoride Salts

The methods and costs for onsite conversion of SNF fuel assemblies to fluoride MS were examined in a Muons GAIN voucher grant with ORNL, INL, and SRNL [2]. Three different processes were considered. In examining our plans, our national lab partners in this grant observed that never separating the plutonium from the fission products made Mu*STAR technology more nuclear weapon proliferation resistant than any others they knew of. They also concluded that an onsite fuel conversion facility cost would be dominated by the cost of the required hot cell, which would cost at least $100 M with operating costs of about $10 M/y.

*Step 2: Burn Fluorinated SNF in Mu*STAR*

In this step we burn the fluorinated SNF to consume the remaining U-235 and the Pu-239 transmuted from U-238 for as long as commercially attractive (many decades). There will periodic interruptions to replace the spallation target and graphite as needed. Engineering studies are under way to determine the expected time between these interruptions and methods to minimize the downtimes to make the replacements. A 2010 study by Bowman *et al.* [3] implies that the 5% LWR burnup could reach 40% in a system much like Mu*STAR before the electricity demand to power the accelerator reaches 15% of reactor output. In this case, the energy-normalized SNF volume would be reduced by a factor of 7. The studies deserve to be repeated with modern codes and fewer approximations, as proposed here. However, an additional technique to selectively remove some fission products with high neutron absorption cross sections may allow mitigation if the approximations in the 2010 are shown to be too optimistic. In any case, the plutonium is never separated from the fission products in the MS, enhancing proliferation resistance.

Step 3: Remove Uranium from the MS

Experiments [4] at PNNL have shown that uranium can be removed from the MS without removing the plutonium from the fission products in the MS. In this step we remove the uranium, which has been depleted to be highly pure U-238; this stops the breeding of Pu-239 and reduces the SNF volume to be buried by about a factor of 2. The uranium can be stored separately, to be added into future fuel.

Step 4: Burn Remaining Pu-239 & Heavy Actinides

In a study [5] inspired by the year 2000 agreement between the US and Russia to each destroy 34 metric tons of weapons-grade plutonium, we compared

1. The US plan to form Mixed Oxide (MOX) fuel rods and burn them in LWRs.
2. The Russian plan to use their Fast Breeder Reactor.
3. A molten-salt ADSR similar to Mu*STAR.

It was concluded that the weapons grade Pu-239, as PuF_3 in the MS ADSR, can be completely and safely consumed leaving remnants that are useless for nuclear weapons. We take this as an indication that subcritical operation will allow the same destruction of the remaining plutonium in the MS after step 3, but the simulations need to be redone with the correct MS and fission products, as proposed here.

Step 5: Bury the Remaining Material

By Step 5, all the original SNF fissile elements have been consumed without uranium enrichment, up to 40% of the fertile U-238 has been consumed without plutonium separation from the fission products, the residual U-238 has been removed from the remnants, and the remaining Pu-239 consumed. The energy-normalized amount of SNF remnants have been reduced by as much as a factor of 14 and are mostly fission products with reduced radiotoxic lifetime and no weapons potential. We believe that it will be safe and politically acceptable to permanently bury the remnants on many of the available sites in the US.

CURRENT STUDIES

1. While the basic physics behind the design is understood, the expected performance of an engineered system must also be commercially viable. Towards this goal, we will complete design optimization using multi-physics simulations, costing, engineering feasibility, balance of plant considerations, regulations, financing options, and market context. The feed-back from this process will result in a down-selection of multiple options.
2. While the technology and cost of Megawatt-class accelerators are understood, there are no operating neutron-production targets appropriate for in-core operation cooled by the molten salt. We will combine neutronic, thermal-hydraulic, and structural analysis simulations to analyze and optimize the target design, including analysis of the chemical processes involving the target and the salt in a large neutron flux. We will use simulation results to prepare a targeting experiment at an existing beam facility to address targeting efficiency, longevity, and maintenance issues.
3. The ability to separate fission products and actinides from molten-salt systems has improved significantly over the past decade. Being able to do this at-temperature and in-containment would greatly improve the performance of both Mu*STAR, and any molten-salt critical reactor. In particular, the targeted removal of large neutron-capture fission products, without co-introducing the ability to separate U or Pu (to avoid proliferation concerns), would allow only fission product removal, as the system would continue to burn the heavy actinides while breeding Pu-239 from fertile U-238. This would greatly improve the overall performance of the system. We anticipate performing small-scale chemical experiments in this area.

REFERENCES

[1] P. N. Haubenreich and J. R. Engel, “Experience with the Molten-Salt Reactor Experiment”, *Nucl. Technol.*, vol. 8, pp. 118-136, 1970. `doi:10.13182/nt70-1`

[2] Muons, Inc., “Conversion of Light Water Reactor Spent Nuclear Fuel to Fluoride Salt Fuel”, GAIN award RFA-17-14589, 2017. `https://gain.inl.gov/SiteAssets/2017%20Voucher%20Abstracts/RFA-17-14589%2C%20Muons%2C%20Inc.pdf`

[3] C. D. Bowman *et al.*, “GEM*STAR: The Alternative Reactor Technology Comprising Graphite, Molten Salt, and Accelerators”, in *Handbook of Nuclear Engineering*, D. G. Cacuci, Ed. Boston, MA, USA: Springer, 2010.

[4] B. K. McNamara, A. M. Casella, R. D. Scheele, and A. E. Kozelisky, “Nitrogen Trifluoride-Based Fluoride-Volatility Separations Process: Initial Studies”, Pacific Northwest National Laboratory, Richland, WA, USA, Rep. FCR&D-SWF-2011-000390; PNNL-20775, Sep. 2011.

[5] R. P. Johnson, G. Flanagan, F. Marhauser, C. Bowman, and R. B. Vogelaar, “Disposition of Weapons-Grade Plutonium with GEM*STAR”, in *Proc. NAPAC'13*, Pasadena, CA, USA, Sep.-Oct. 2013, paper THPBA23, pp. 1277-1279.