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# Mu*STAR: SUPERCONDUCTING ACCELERATOR DRIVEN SUBCRITICAL MOLTEN SALT NUCLEAR POWER PLANTS

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*Abstract*

The Mu*STAR Nuclear Power Plant (NPP) is a transformational and disruptive concept using advances in superconducting accelerator technology to consume the fertile content in spent nuclear fuel (SNF) from light water reactors (LWRs) and to eliminate need for uranium enrichment. One linac drives multiple Mu*STAR Small Modular Reactors (SMR) using subcritical molten salt fueled reactors with an internal spallation neutron target. Neutrons initiate fission chains that die out in the subcritical core. That means intrinsic immunity to criticality accidents. This new way to make nuclear energy employs continuous online removal of all fission products from molten salt fuel volatiles removed by helium purge gas. This reduces chance of accidental release. Non-volatiles removed by vortex separators, allowing complete burning of SNF.

## INTRODUCTION

The Mu*STAR Accelerator-Driven System includes a 500 MWt subcritical, graphite-moderated, thermal-spectrum, molten-salt fueled, reactor design that was described in the Handbook of Nuclear Engineering in 2010 [1]. The reactor parameters are larger by a factor of 4 in linear dimension than the ORNL 8 MWt Molten Salt Reactor Experiment (MSRE) [2] done in the late 1960s. The reactor operates subcritically, with additional neutrons generated by an internal spallation target that is driven by a superconducting RF (SRF) linear proton accelerator, similar to that in the ORNL Spallation Neutron Source (SNS). Unlike the SNS, the target is not subjected to shock from the beam, which in Mu*STAR is rastered over the face of a solid uranium target that is cooled by molten salt fuel. Muons, Inc. and its collaborators have simulated engineering solutions to combine the accelerator and reactor with an internal uranium spallation target that is cooled by the MS fuel.

In 2017, Muons, Inc. was awarded a GAIN voucher award [3] with ORNL, INL, and SRNL to design and cost a facility to convert LWR SNF into molten salt (MS) fluoride fuel suitable for use in Mu*STAR. Our expectations are that such a facility will be relatively small and inexpensive enough to consider building one at each of the existing reactor sites in the US and abroad wherever SNF is stored.

## CONCEPTS AND INNOVATIONS

Our concept is to install Mu*STAR accelerator-driven subcritical systems at existing light-water reactor (LWR) sites, transform the LWR spent nuclear fuel (SNF) using on-site technology developed under our GAIN award into molten salt fuel, and to burn it to produce electricity for at least 200 years. The concept is shown in Fig. 1. The additional neutron flux provided by the accelerator permits a much deeper burn such that several times more energy can be produced from the SNF than was generated by the LWR. The limit is reached when the accelerator cannot economically overcome the neutron absorption by fission products. Schemes for reducing those products are described below. This innovative and disruptive concept eliminates the need for uranium mining, fuel enrichment, fuel rod manufacture, SNF off-site storage and transport, and encourages local communities to consider consent-based storage of SNF combined with continued operation of their power utility using Mu*STAR when their LWR is retired.

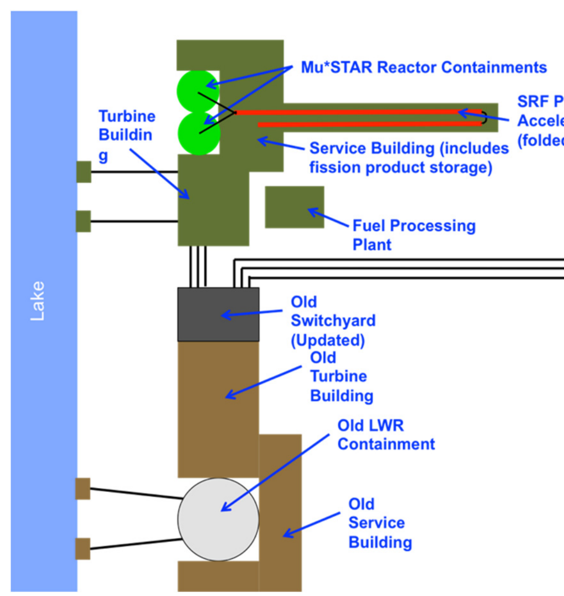


Figure 1: Mu*STAR installed at an old LWR site.

Leaving the SNF on the site where it was produced solves many problems that have long confounded the US government that is legally required to eventually take title to the SNF.

Two important consequences of the Mu*STAR are: 1) the conversion of the SNF to MS does not require fission products to be removed by chemical reprocessing and 2) the accelerator neutrons allow a deeper burn to extract as much as seven times as much energy from the SNF than was extracted by the LWR. Normalized to the energy produced, the amount and toxicity of the SNF will be reduced by more than a factor of 7 over the course of a few centuries of operation.

The reactor design since its inception has been concerned with development of self-cleaning technologies that simultaneously recover valuable nuclear materials along with neutron poisons reduction, and reduction of reactor-

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life threatening, dose-related injury. Later in this article we will describe Muons, Inc. current proposal to develop a hybrid volatility/solvent extraction technology for the separation and recovery of fission and activation products (FPs/APs) from LWR SNF. We find this technology mutually attractive for high throughput recovery of (Ac's) that will be transmuted for their energy content in responsible next-generation molten salt technologies

## TECHNICAL DESCRIPTION

Mu*STAR is a graphite-moderated, thermal-spectrum, molten-salt-fueled reactor that uses an external accelerator to generate neutrons from an internal spallation target. Mu*STAR can be operated with many fuels, without redesign, for process heat and/or for electricity generation. The active reactor volume is 93% graphite and 7% molten salt eutectic fuel; this fuel is the subject of our recent GAIN award, and has a melting point near 500° C.

The graphite moderator, molten-salt fuels, reactor materials, and operating parameters that are proposed for Mu*STAR are meant to be similar to those tested in the ORNL MSRE. The SRF Linac and reactors are underground as shown in Fig. 2.

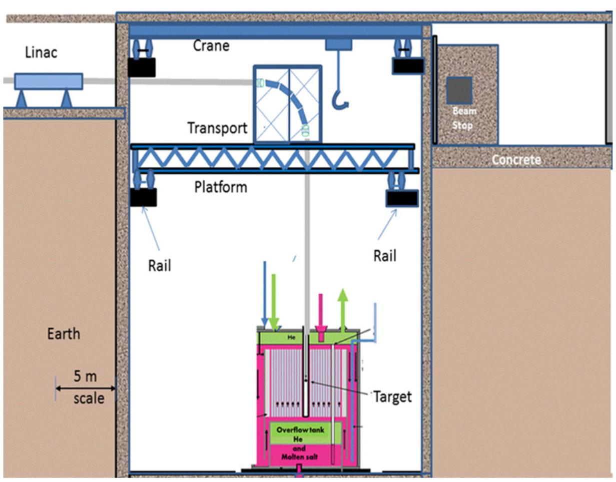


Figure 2: Underground placement of linac and reactor.

Helium flows over the surface of the hot salt to remove volatile isotopes and carry them to a hot cell where they are separated out chemically and/or cryogenically with a fractional distillation column, and then safely stored underground while they decay. This reduces the inventory of volatile isotopes in the reactor by a factor of almost a million compared to reactors like those at Fukushima. This also permits continuous harvesting of valuable isotopes such as tritium and Xe-133 as well as unwanted isotopes like iodine-131 and Xe-135.

Under steady state operation, the MS fuel is fed in at the same rate that it flows out through the salt overflow tube into the storage tank located below the reactor core. In this situation, the reactor would burn around 25 g of fissionable material (U-235 and Pu-239) per hour for around 40 years. At that time, the fuel in the storage tank could be pumped by helium pressure into a second reactor to operate with a higher power beam for another 40-year cycle. After a total of 5 such 40-year cycles, it would take more than 15% of the electricity produced by the reactor to drive the accelerator and fuel could be reprocessed or put into long-term storage.

There are solutions for the interface between the accelerator and the internal target that involve proprietary intellectual property. The spallation neutron target is much less difficult than that used at the ORNL Spallation Neutron Source in that the beam in that facility is required to be pulsed at extremely high power and tightly focused such that shock phenomena quickly destroy any simple solid metal target. In the case of Mu*STAR, the beam can be diffuse or rastered on the target and the 700° C MS fuel can be used to cool the target

## CONTINUOUS REMOVAL OF FISSION PRODUCTS

For all future generation molten salt reactor (MSR) types, neutron poisons build-up progressively conflicts with the extended operation of the reactor. Radiolysis of the fuel salt contributes to an evolution of corrosion mechanisms that are time, salt, and reactor type dependent. Moreover, radiolytic embrittlement of functional reactor parts is life-threatening to extended operations. The first line of offense is to rid the fuel salt of FP gases: Xe, Kr, $T_2$, by use of a continuous helium purge that purges them through the heat exchanger and out of the salt. Other FPs, such as I, Tc, Mo, Nb, Te, Se, Sb, Ru, require a bit more persuasion than their simple purging, but nevertheless, are efficiently expelled by use of fluorinating reagents. Consequently, continuous removal and ultra-high purity recovery of members of this class of FPs can be envisioned at some duty cycle appropriate to management of their radiolytic burden.

The Mu*STAR system, including the MSRE-like 500 MWt core is shown in Fig. 3. A brief summary of the processes necessary to take SNF from encased uranium oxides to molten salt fuel and to deal with the FPs and activation products (AP)s is below:

1. The LWR UNF requires conversion to fluoride form followed by dissolution in a fluoride MS.
2. Batch transfer to subsequent processing steps is thus done by liquid transfer. This reduces hold up, confines FP dose to the batch processing apparatus, and consequently is inherently more proliferation resistant than powder transfer and alternate manipulations.
3. Processing loads (e.g., 1-ton UNF/day) would be reduced quickly to ~0.05-ton FP's/AP's/day by volatility recovery of total uranium as volatile $UF_6$.
4. Simultaneous volatility removal/recovery of valuable, $^{3}H$, $^{3}He$, U, $^{99}Mo$, Ru, Rh, etc.
5. Solvent extraction (SX), using liquid bismuth, of lanthanides (Ln's) as potential critical materials.
6. Selective liquid bismuth SX of (Ac's) for reactor consumption.
7. Selective extraction of Cs, Ba, Sr for thermal power.

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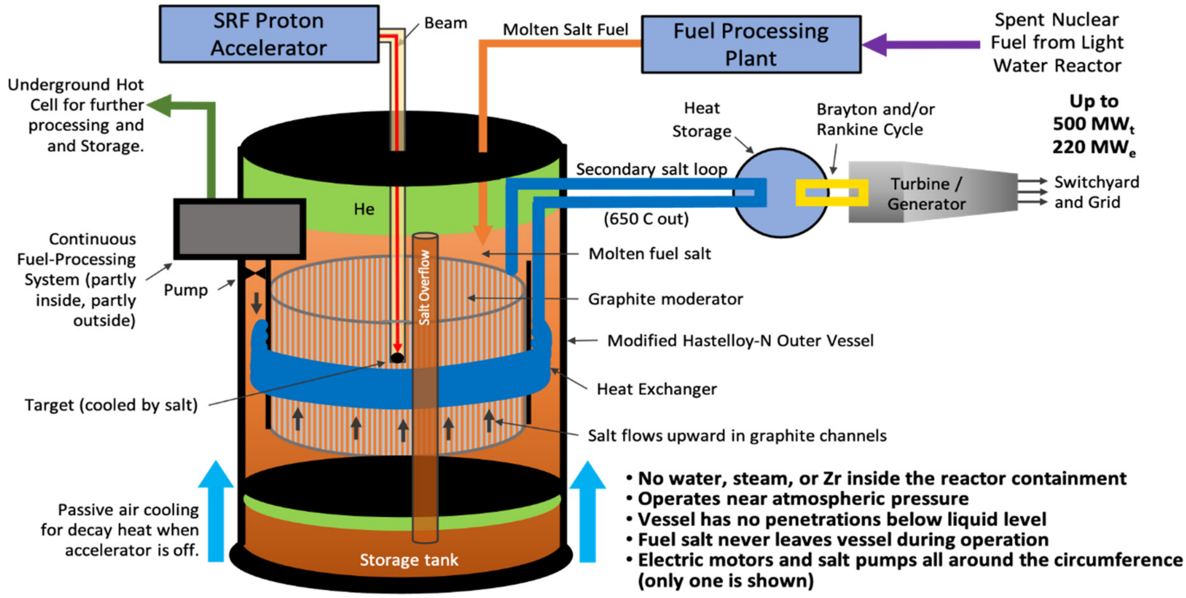


Figure 3: Conceptual diagram of the Mu*STAR system, comprised of a 1 GeV, 2.5 MW SRF proton linac, a 500 MWt graphite moderated reactor with internal solid metal spallation neutron target, a molten-salt fuel preparation plant, and collection system for volatile radioisotopes. The reactor power can be used for process heat or electricity generation

To enable this vision Muons, Inc. proposes that the fuel-salt be slip-streamed from the reactor in ~1 l batches and processed through a series of unit activities: fluorination, followed by liquid metal extractions or vapor phase extractions. In addition to valuable nuclear materials recovery, the concept results in a proliferation resistant stream of plutonium (Pu) and transuranics (TRUs) fuel stock for future consumption. Currently, an MSR technology that holistically consumes Pu/TRUs fuel stocks, breeds these fuel stocks and reprocesses the fuel in a continuous manner does not exist. Indeed, most MSR current designs promise to simply add to existing Pu and TRU inventories!

## SAFETY

The inherent safety features of the Muons, Inc. Mu*STAR system have been discussed elsewhere [4]. The additional benefits of our continuous FP removal proposal:

- Continuously removing fission products (FP) eliminates most neutron poisons, keeping fuel reactivity high throughout the lifetime of the fuel and reactor.
- Such continuous fuel processing requires a liquid-fueled reactor.
- Works best with a subcritical reactor, which can be thousands of times more tolerant of reactivity variations than a conventional critical reactor.
- Essentially only fission products are removed; the actinides remain inside the reactor core where ultimately they are fissioned by the enormous neutron flux.
- Estimates and simulations imply that essentially all actinides can be destroyed, leaving a final waste stream that is radiotoxic for just a few hundred years.

The last two features in particular make this system proliferation resistant and provide a sensible, efficient and profitable solution to the disposal of nuclear waste.

## CONCLUSION

The promise of the Muons, Inc. Mu*STAR reactor design is a fully automated, eco-centric power plant having virtually no Pu/TRU output, facile continuous recovery of valuable nuclear materials and likely recovery of high purity of output gases. The processing concept as proposed begins with recovery of the energy content locked in LWR SNF and transmits this fledgling information as generally applicable to several next generation MS reactor types.

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