Burning LWR SNF On-Site With Mu*STAR Accelerator-Driven Molten-Salt Systems

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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.

As the reactor operates subritically, additional neutrons are generated by an internal spallation target that is driven by a superconducting RF (SRF) linear proton accelerator that is a similar to 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.

Simulations described in the Handbook article [1] indicated that spent nuclear fuel (SNF) from light water reactors (LWR) could be burned such that in five passes of 40 years each, about seven times as much energy could be produced from the fuel as was generated by the LWR. Once the oxide-based fuel rods are converted to molten fluoride fuel, no further processing of the fuel is needed since the neutron absorption by the accumulated fission products can be overcome by increasing the beam power for each successive 40 year pass.

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 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.

CONCEPT 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. See the concept in Figure 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. 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.

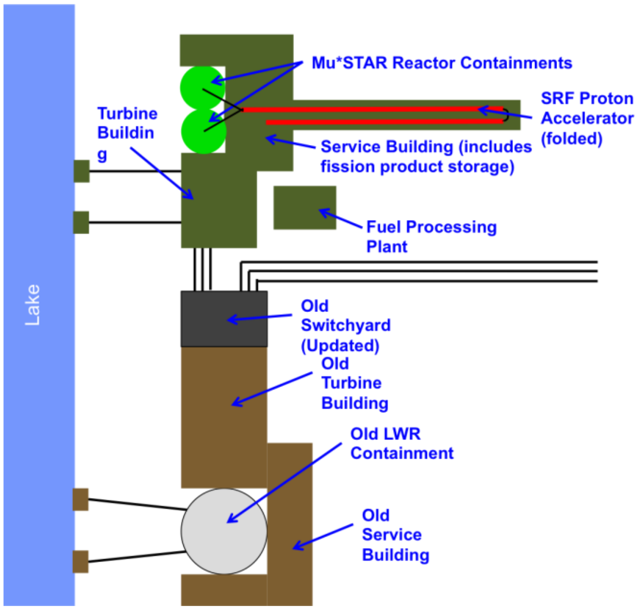


Figure 1: Mu*STAR installed at an old LWR site using a folded proton Linac and two reactor modules.

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.

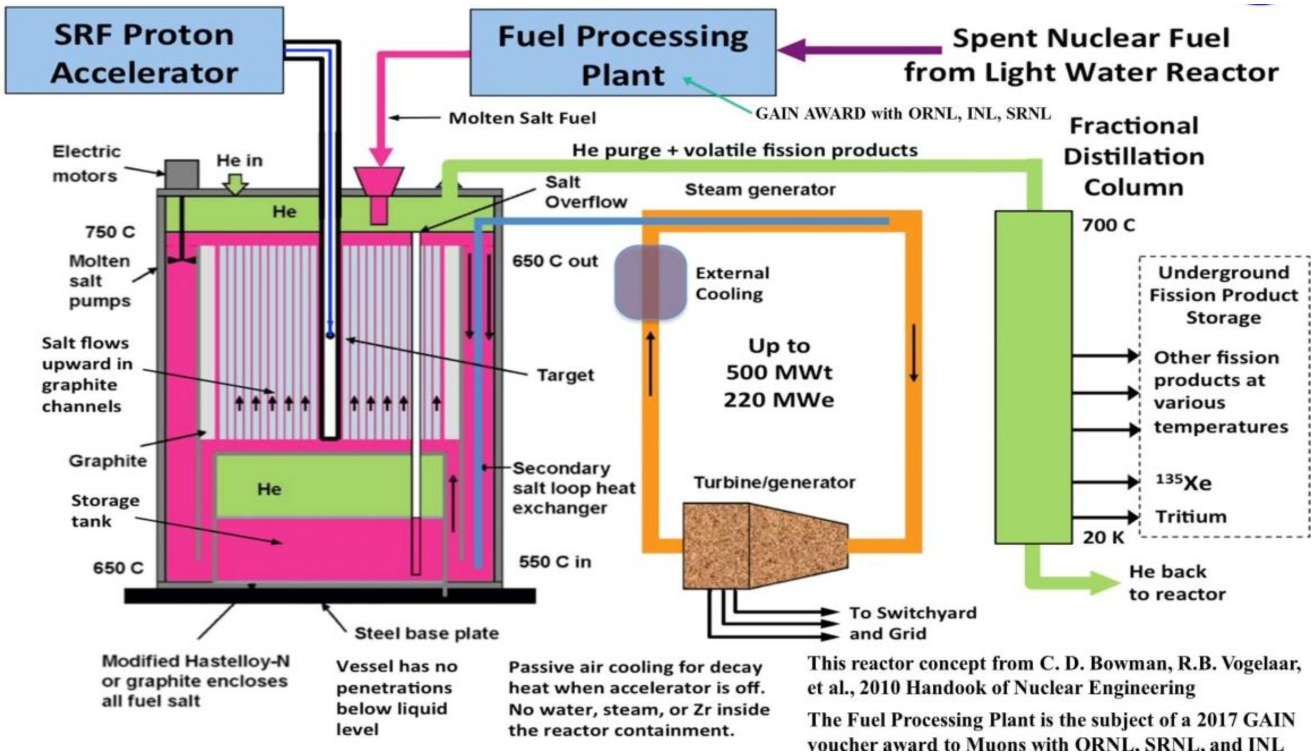
Mu*STAR can achieve low overnight construction cost, and short onsite-construction time, because it will be pre-built in a factory and assembled on-site. Mu*STAR is inherently walkaway safe, and needs no backup power or active cooling once the accelerator is turned off. The system recycles its own waste for centuries (with appropriate module replacements, and increasing accelerator power each cycle). It needs no isotopic enhancement or chemical reprocessing, so it is highly resistant to nuclear proliferation. As Mu*STAR can operate above 700ºC, it can be a highly economical and emission-free source of process heat.

Mu*STAR is based on proven technologies that are combined in a new way. The molten-salt reactor was tested at ORNL in the 1960s; powerful and affordable superconducting RF linacs have been demonstrated at many locations including the ORNL Spallation Neutron Source. 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.

Unlike the usual critical reactors, we use a superconducting linear accelerator beam on an internal spallation target to generate an additional neutron flux that overcomes the absorption of neutrons by the fission products in the subcritical reactor. Two important consequences 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.

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.



This reactor concept from C. D. Bowman, R.B. Vogelaar, et al., 2010 Handook of Nuclear Engineering

The Fuel Processing Plant is the subject of a 2017 GAIN voucher award to Muons with ORNL, SRNL, and INL

Figure 2: Conceptual diagram of the Mu*STAR system, comprising of a 1 GeV, 2.5 MWb 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.

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. Figure 3 is a photograph of the graphite core of the 8 MWt MSRE, which is about a factor of 4 in linear dimension smaller than the 500 MWt core in figure 2.

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 Xenon-133 as well as unwanted isotopes like Iodine-131 and Xenon-135.

Figure 3: Graphite core of the MSRE.

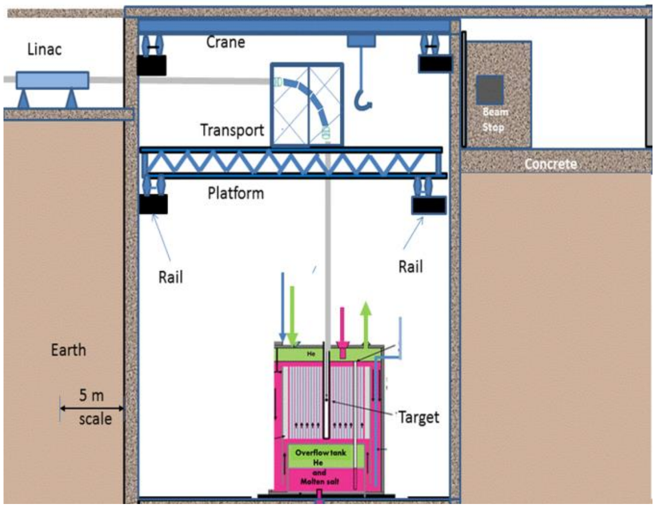


Figure 4: Underground placement of Linac and Reactor

The SRF Linac and reactors are underground as shown in Fig. 4. By using transverse-bending RF cavities, beams can be merged at the beginning of the Linac and split at the end of the Linac. Thus, one Linac can serve several reactors, where each reactor has its own independently-controlled proton source.

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.

FEATURES AND ADVANTAGES

Safety: Mu*STAR is walk-away safe. It never operates critically, $k_{eff} < 1$. Fission essentially stops after turning off the accelerator; no control rods are needed. Passive air cooling is sufficient for the decay heat when the accelerator is turned off. No large volatile fission product inventory is stored inside the reactor as in LWRs; volatile fission products are removed as they are produced and stored separately underground. There is passive recovery from a loss of power accident or loss of coolant accident. The reactor operates at atmospheric pressure. Neither fuel enrichment nor radio-chemical fuel reprocessing is required. The accelerator and reactors are below ground level. The fuel never leaves the reactor vessel except when it is transferred to another Mu*STAR reactor. There are no penetrations below the level of the liquid fuel. These features imply the avoidance of the most serious consequences encountered during every one of the historical reactor accidents, all of which involved solid fuel or other components not present in Mu*STAR.

Operations: Volatile radioactive isotopes are continuously removed from the reactor to an underground separation facility. Liquid fuel is moved between chambers in ther reactor vessel by He pressure without radiation exposure to humans; fuel can be drained and refilled to allow graphite and spallation target replacement. The reactor operates at atmospheric pressure with low vapor pressure molten salt fuel; no pressure vessel is needed. No istotopic enrichment or radio-chemical reprocessing is required. No fuel rods to be moved or replaced. The feed/bleed concept allows for continuous operation. At operating temperature, the molten salt flows freely, being only slightly more viscous than water.

Requiring an accelerator adds accelerator operations and maintenance and spallation target replacement and storage. In return for that extra burden, one gets excellent load following capability and subcritical operation to simplify regulatory requirements (the reactor does not require a critical mass of anything, under any conditions). At some point, the accelerator operation will be turn-key and the volume of the intermediate heat-exchanger salt large enough to provide electricity for long enough to change out any failed component of the accelerator.

Economics: Molten salt fuel eliminates fabrication, installation, replacement and waste management needed for fuel rods or pellets, replacing them with simpler procedures, The complexity of the reactor is reduced by adding a well-tested, accelerator. Superconducting RF accelerators are already proven as the best method to produce high-energy, high-quality particle beams, and will continue to get simpler, smaller, more powerful, more efficient, and less expensive. One accelerator can feed several Mu*STAR reactors. The accelerator is itself modular, truck transportable, and can be repaired quickly and safely. Operation history at SNS and CEBAF shows good reliability. Capital costs for a multi-MW proton accelerator have been reduced drastically in the past 20 years. Wall power to beam power efficiency with superconducting RF (SRF) is much improved compared to previous copper structures and can be greater than 50%. Mu*STAR can be configured to simultaneously generate valuable radioisotopes such as tritium, whose economic value can be comparable to that of the power generated.

WORK IN PROGRESS

Defence in Depth: Fission product transport, separation, and storage outside the core may cause mishaps, leakages, or other potential accidents. A defense-in-depth approach to retain fission products, including tritium, and prevent or mitigate their release is being developed.

Materials Challenges/Opportunities: In the almost 60 years since the materials of the MSRE were chosen, considerable work has been done to address materials challenges. New materials with acceptable corrosion-solubility behavior are being considered and experimental tests in molten salts and neutron radiation felds are being designed.

Molten Salt Handling: The MSRE operated with a system of heaters to prevent freezing during normal operation, transients, and during extended downtime. The challenge to do the same with a volume of fuel that is 64 times larger is being addressed.

MS Pumps and Heat Exchangers: Our desire to keep the non-volatile fission products contained in the reactor vessel means that the MS pumps and heat exchangers must also be inside the vessel. We are considering pumps that are driven by motors outside of the vessel and new heat exchanger materials with corrosion resistance and appropriate thermal properties.

Conversion to MS fuel from SNF fuel: This is the subject of the GAIN grant discussed above. It seems likely that the output of the Fuel Processing Plant in Fig. 2 will be granular room-temperature salt that can be added to the reactor as needed.

Risk Management: Muons, Inc. has started to work with INL to develop Probablistic Risk Analysis tools that can be adapted to new reactor concepts. Our first application to test this capablity will be for Mu*STAR. We believe this will be an important contibution to licensing.

Partners: We are seeking a strong commercial lead and partners for design, construction, operation, and dealing with .the regulatory scope of the project.

CONCLUSIONS

Building Mu*STAR reactors at existing LWR sites allows a new view of closing the fuel cycle. The SNF created on site stays on site and is used to provide electricity for centuries. No more SNF is generated and, normalized to the energy produced, the volume and toxicity of the fuel is reduced by almost an order of magnitude. For those centuries, no fuel needs to be brought into the site and no SNF needs to be removed from the site. There are more avenues to explore regarding the attractiveness of new reactors sharing the site with or replacing existing LWR reactors. For example, will regulatory hurdles be easier for an existing site? Will utilities and communities see what is proposed here as the best option? Will shared infrastructure components like storage ponds, buildings, and connections to the grid lead to cost savings?

REFERENCES

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