

Mu*STAR: AN ACCELERATOR-DRIVEN SUBCRITICAL MODULAR REACTOR

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Abstract

We present a conceptual design for a new modular, accelerator-driven subcritical reactor based on a molten salt. Mu*STAR is a reactor, that without re-design, can burn a variety of nuclear fuels, with the beam tuned to that fuel. We will discuss the elements of this system: the accelerator, the reactor, the spallation target, and the fractional distillation to separate volatile fission products. Our GAIN project with ORNL is successfully completed, with a design of the Fuel Processing Plant that will convert spent nuclear fuel into the molten-salt fuel for Mu*STAR.

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) done in the late 1960s [2]. 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.

Simulations described in the Handbook article indicated that spent nuclear fuel (SNF) from light water reactors (LWR) could be burned such that in five passes of 40 years each, about 7 times as much energy could be produced from the fuel as was generated by the LWR [1]. 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 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 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 [3]. 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. 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.

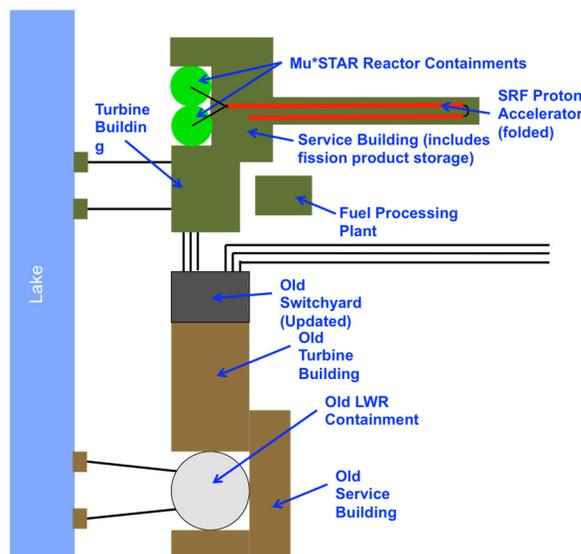


Figure 1: Mu*STAR installed at an old LWR site.

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.

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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 since $k_{\text{eff}} < 1$. Fission stops shortly after turning off the accelerator; no control rods are needed and passive air cooling is sufficient for the decay heat. 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 the 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 isotopic 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 its operations and maintenance plus the 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 an accelerator: SRF 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 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.

Other Application

The production of tritium and its decay product helium-3 are attractive possibilities for Mu*STAR. In particular, a first application of the Mu*STAR technology is a scaled-down demo system for tritium production solving a problem for the NNSA for domestic supply for national security needs. Preliminary models using MCNP5 and MCNP6 indicate that by using the natural lithium isotope ratio as the LiF component of the molten salt, one 500 MWt Mu*STAR unit could produce about 2.4 kg of tritium per year.

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.

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