ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPMP048

Mu*STAR: A MODULAR ACCELERATOR-DRIVEN SUBCRITICAL REACTOR DESIGN

Rolland P. Johnson†, Robert Abrams, Mary Anne Clare Cummings, J. D. Lobo, Milorad Popovic, Thomas J. Roberts, Muons, Inc., Batavia, IL, USA

Abstract

Mu*STAR is an accelerator-driven molten-salt subcritical reactor based on recent superconducting RF technological breakthroughs that allow a highly efficient and powerful proton accelerator to drive a spallation target inside a graphite-moderated, thermal-spectrum reactor. The additional spallation neutrons can be used to overcome the absorption of neutrons by fission products to allow a deeper burn than is possible with critical reactor designs. Simulations have shown that as much as seven times the energy that was extracted from used fuel from light water reactors can be produced by this method before the accelerator demands significant power from the reactor. Once the fuel rods have been converted from oxide ceramics to fluoride salts, in a process that is proliferation resistant (not chemical reprocessing), the fuel can be burned for centuries without increasing its volume while reducing its radio-toxicity. Our 2017 GAIN voucher grant supported studies by ORNL, SRNL, and INL to design and cost a Fuel Processing Plant to convert used nuclear fuel into the molten-salt fuel for Mu*STAR. Based on those studies, it seems possible to build Mu*STAR systems on existing sites where used fuel is stored, convert it to fluoride salts, and use it to provide affordable carbon-free electricity for centuries.

INTRODUCTION

It is well-known that less than 6% of the uranium in fuel rods has been converted to energy when they are removed at the end of their useful life from light water reactors (LWR). To get more energy out of the fuel, the normal procedure is to chemically reprocess the fuel rods to eliminate the fission products and reform the rods with the recovered unburned uranium, which implies another round in a LWR to extract another 6% of the energy. This process involves handling radioactive materials and the second 6% is more expensive than digging up more uranium, enriching it, and making new fuel rods. This latter "once-through" is the preferred method for utility operators for this reason and because the US government agreed to be responsible for the used fuel. This has turned out to be a large problem because it has proven impossible to find a politically acceptable repository for the used fuel.

The Mu*STAR Accelerator-Driven System includes a 500 $MW_{thermal}$ 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 MW_t Molten Salt Reactor Experiment (MSRE) [2] of 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 moved to different positions, i.e. "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 used nuclear fuel (UNF) 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. 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 UNF into molten salt (MS) fluoride fuel suitable for use in Mu*STAR. The results of the study are contained in an ORNL technical report [3]. The major cost of the facility is the hot cell that is necessary to allow the solid fuel assemblies to be opened and converted to fluorides. A possible cost savings is to use the same hot cell for the fuel conversion as is used for the fractional distillation method described below that treats the helium purge gas that flows over the Mu*STAR core to remove unwanted or valuable volatile isotopes. Such a facility may be relatively small and inexpensive enough to consider building one at each of the existing reactor sites in the US and abroad wherever UNF 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 used nuclear fuel (UNF) 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 additional neutron flux provided by the accelerator permits a much deeper burn such that several times more energy can be produced from the UNF 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, UNF off-site storage and transport, and encourages local communities to consider consent-based storage of UNF combined with continued operation of their power utility using Mu*STAR when their LWR is retired.

†rol@muonsinc.com

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPMP048

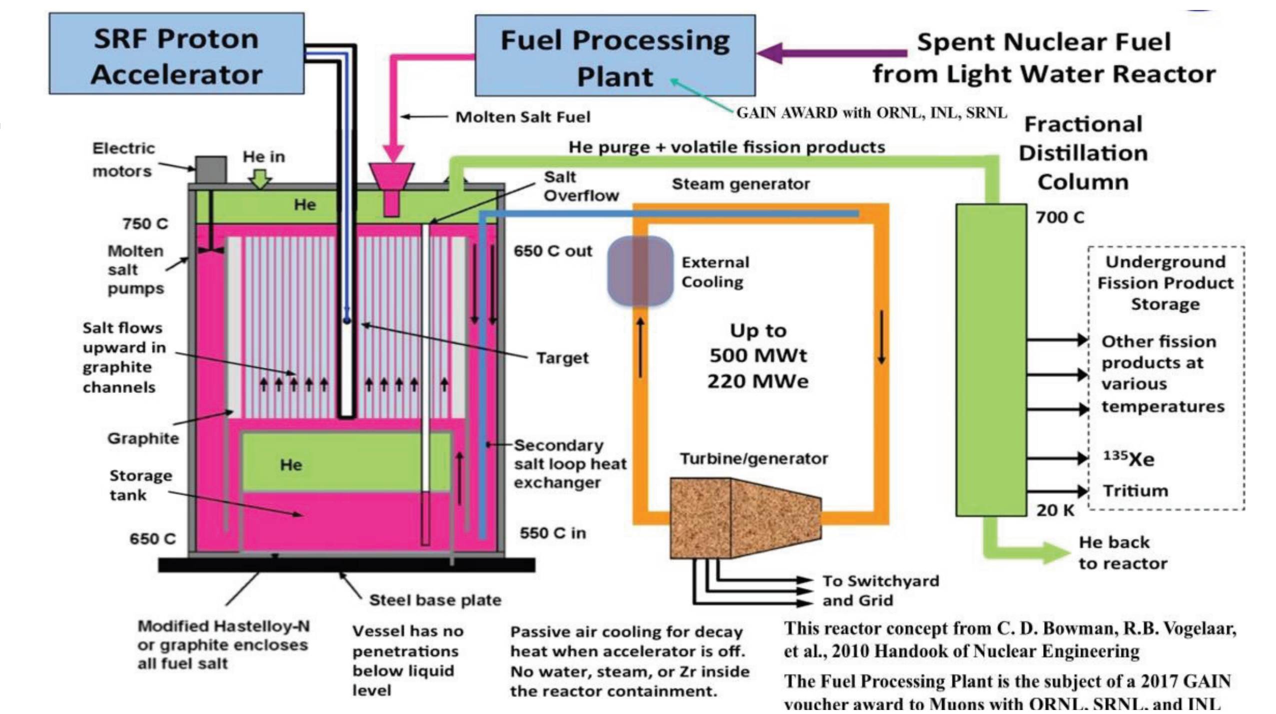

Figure 1: Conceptual diagram of the Mu*STAR system, comprised of a 1 GeV, 2.5 MW SRF proton Linac, a 500 MWt graphite moderated reactor with internal solid metal spallation neutron target, a molten-salt fuel preparation plant, and collection system for volatile radioisotopes. The reactor power can be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

Leaving the UNF on the site where it was produced solves many problems that have long confounded the US government that is legally required to own the UNF.

Important consequences of the Mu*STAR design include: 1) the conversion of the UNF to Molten Salt 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 UNF than was extracted by the LWR. Normalized to the energy produced, the amount and radiotoxicity of the UNF will be reduced by more than a factor of 7 over the course of a few centuries of operation.

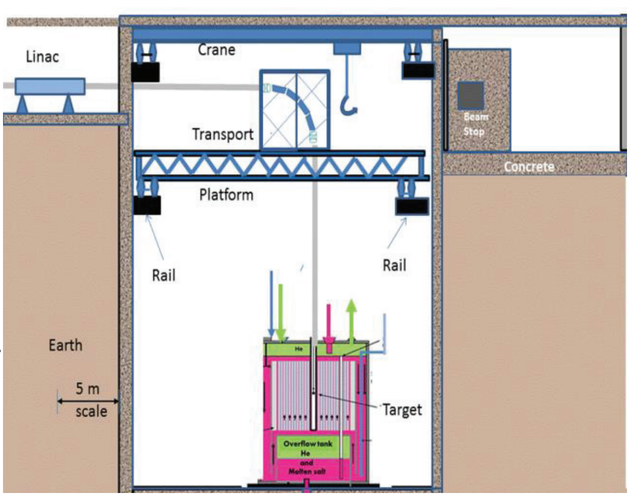

Figure 2: Underground placement of Linac and Reactor.

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 system, including the MSRE-like 500 MWt core is shown in Fig. 1. The SRF Linac and reactors are underground as shown in Fig. 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 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

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPMP048

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; the fuel could be reprocessed or put into long-term storage with reduced radiotoxicity.

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 molten salt fuel can be used to cool the target.

FEATURES AND ADVANTAGES

Safety

Mu*STAR is "walk-away" safe. It never operates critically since $k_{eff} < 1$. 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 radiochemical 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 istotopic enrichment or radio-chemical reprocessing is required. No fuel rods to be moved or replaced. The feed/bleed concept descrbed in the Nuclear Engineering Handbook 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 contain 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, each of which is modular in that it is small enough to be built in factories and below 300 MWe to fit the Small Modular Reactor (SMR) definition. 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, or to generate process heat**.**

CONCLUSIONS

Building Mu*STAR reactors at existing LWR sites allows a new view of closing the fuel cycle. The UNF created on site stays on site and is used to provide electricity for centuries. No more UNF is generated and, normalized to the energy produced, the volume and radiotoxicity 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 UNF 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.

REFERENCES

[1] 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", in Dan Gabriel Cacuci (ed.), Handbook of Nuclear Engineering, © Springer Science+Business Media LLC, p2841. https://link.springer.com/referenceworkentry/10.1007/978-0-387-98149-9_24

[2] Paul N. Haubenreich and J. R. Engel "Experience with the Molten-Salt Reactor Experiment" Oak Ridge National Laboratory, Oak Ridge, Tennessee, Nuclear Applications & Technology Vol. 8 February 1970. http://thmfgrcs.homestead.com/NAT_MSREexperience.pdf

[3] Paul Taylor *et al.*, "Mu*STAR ADSR Fuel Conversion Facility Evaluation and Cost Analysis." ORNL/TM-2018/989, February 2019.https://info.ornl.gov/sites/publications/Files/Pub117081.pdf