DESIGNING ACCELERATOR-DRIVEN EXPERIMENTS FOR ACCELERATOR-DRIVEN REACTORS

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Abstract

Muons, Inc., with its collaborators, to the best of our knowledge is the only one of the several reactor concept companies in the US that is concentrating on an accelerator-driven subcritical high-power reactor design. The major objection to such systems has been that short interruptions of beam of even a few seconds would turn off fission power long enough to induce temperature-gradient shocks and subsequent fatigue of solid fuel elements. Mu*STAR solves this problem by using a molten-salt fuel. Mu*STAR is a reactor design that not only includes a particle accelerator as an integral part, but has several innovative features that make it a compelling solution to many problems. We note that the ADSR concepts being pursued by the Chinese Academy of Science (ADANES) and the Belgians (MYRRHA) are based on traditional solid fuel elements and require exceptional stability from their accelerator.

INTRODUCTION

The Mu*STAR Accelerator-Driven System includes a 500 MW 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 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 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. 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.

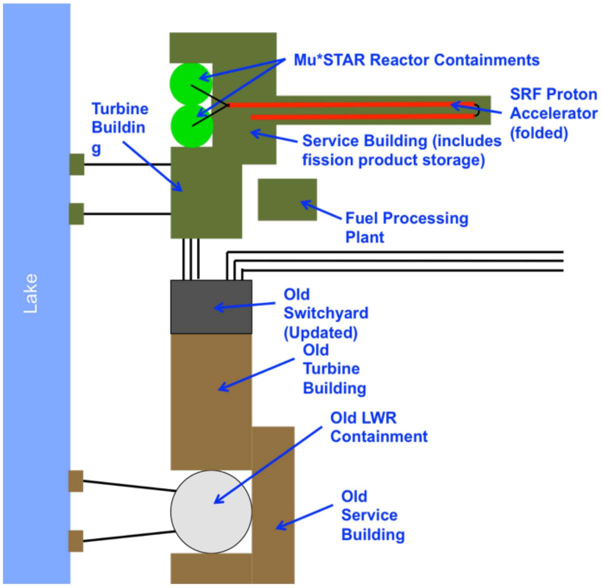

Figure 1: Mu*STAR installed at an old LWR site.

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

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with neutron poisons reduction, and reduction of reactor-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 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 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.

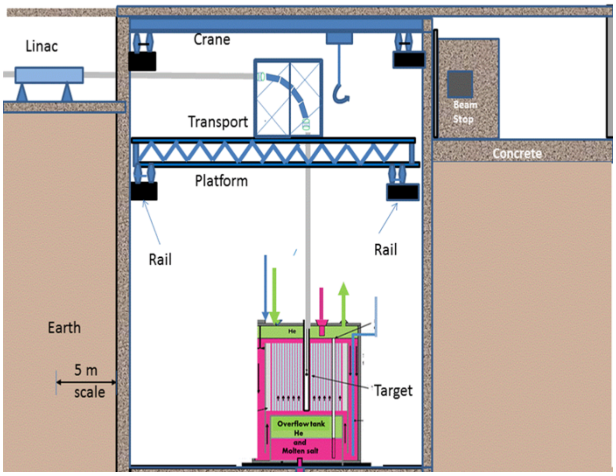

Figure 2: Underground placement of Linac and Reactor.

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

The Mu*STAR system, including the MSRE-like 500 MW core is shown in Figure 3. 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. This is and the safety features of the Mu*STAR system are discussed in Refs. [4, 5].

DESIGNING EXPERIMENTS FOR ACCELERATOR-DRIVEN REACTORS

Data are needed about accelerator-driven spallation-neutron targets feeding moderated reactor cores, specifically using the moderators of interest to accelerator-driven reactors. Especially lacking are measurements of the neutron energy spectra that such a combination of target and moderator produces that are needed to verify and optimize the choices of materials and geometries for thermal-spectrum molten salt cores. For example, the accelerator-driven spectrum has many more fast and high-energy neutrons than conventional reactors, extending beyond 500 MeV. A major interest is the rate of moderation of fast and high-energy neutrons becoming thermal neutrons that have higher probabilities of inducing fissions. Understanding and verifying the moderation of the higher-energy neutrons

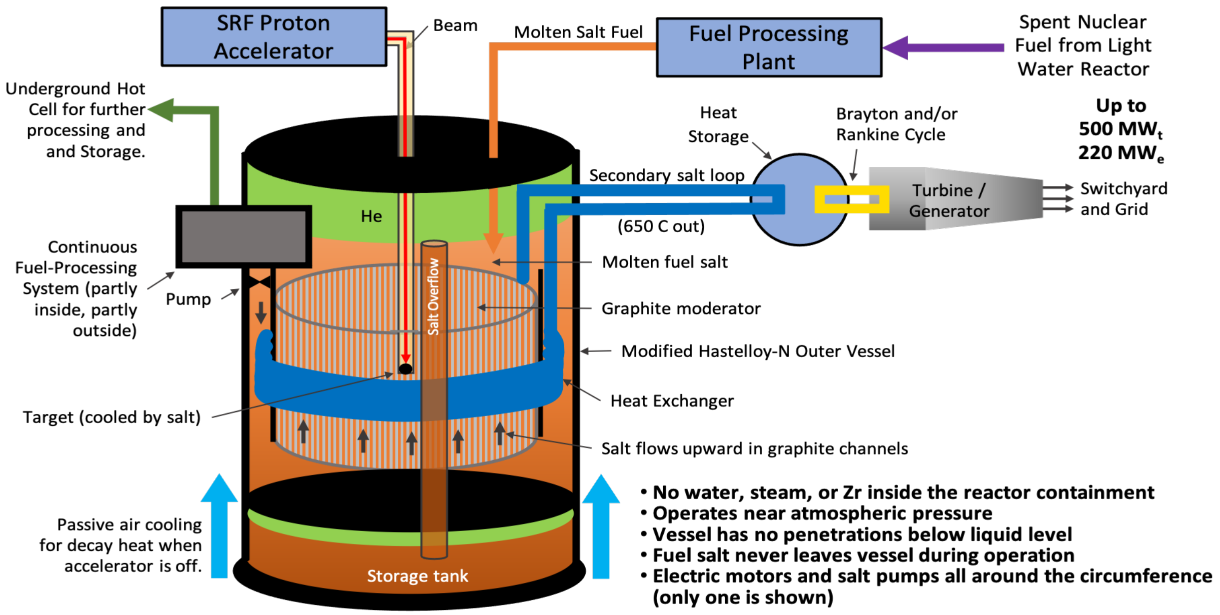

Figure 3: Conceptual diagram of the Mu*STAR system, comprised of a 1 GeV, 2.5 MW SRF proton linac, a 500 MW graphite moderated reactor with internal solid metal spallation neutron target, a molten-salt fuel preparation plant, and collection system for volatile radioisotopes. The reactor power can be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

is also important since they have a greater ability to damage the moderator damage the moderator and other reactor components such as heat exchangers. Variations in the spectrum and flux a function of moderator depth can be modeled by various simulation programs, but much of the spectrum is above the energy where accurate tables are used, so programs like MCNP use less accurate nuclear-physics models. Experimentally validating those models is an important aspect of ensuring that future ADSR systems will operate as designed.

The Spallation Neutron Source at ORNL has unique capabilities that are well-suited to perform such experimental measurements. In particular there are multiple existing 1 GeV proton beamlines that can range in power from a few Watts to over a Megawatt. This project will explore the feasibility and design of utilizing their low-power proton beams in new experiments involving spallation targets and moderators, using single-neutron counting to measure spectra and fluxes. This will use existing beamlines in enclosures that have never had experiments before, so careful integration with SNS facilities and operation is essential, which can only be done by collaborating with SNS personnel. The following tasks have been identified:

Task 1: Survey of available beamlines;

Task 2: Enumerate the types of experiments desired, including spallation targets, moderator materials, basic geometry, and detectors. It might also include considering the use of materials to simulate salts and fuels inside the moderator, and potentially actual fuels such as natural uranium. This includes planning how to use the experimental results to validate the simulation programs used for designing nuclear reactors and systems.

Task 3: Survey available neutron detectors around the lab, and potentially at other labs. This includes enumerating and assessing their capabilities and requirements (power, electronics, data acquisition, etc.), and their applicability to the experiments of Task 2.

Task 4: From the previous tasks and select an initial experiment to design, then proceed with the experimental design within the funding and schedule constraints. This should include minor variations in materials and geometry, and will be as detailed as necessary.

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