MuSTAR Superconducting Accelerator-Driven Subcritical UNF-Fueled Molten-Salt SMR NPPs

ABSTRACT

Muons, Inc. (MUONS) is developing a conceptual design for a Used Nuclear Fuel (UNF)-Fueled Muons Subcritical Technology Advanced Reactor (Mu*STAR) Nuclear Power Plant (NPP). It is based on a Multi-MW superconducting proton accelerator that drives several subcritical molten-salt (MS) small modular reactors (SMRs) that each contain an internal spallation neutron target. Two of the key system components of the Mu*STAR NPP, the accelerator and the Molten Salt SMR, have been demonstrated in principle at ORNL by the Spallation Neutron Source (SNS) and the Molten Salt Reactor Experiment (MSRE). Each MS reactor would be fueled with UNF that has been converted from oxides to fluorides. Three possible flowsheets to achieve this conversion are described in MUONS GAIN GRANT ORNL/TM-2018/989 [1] where none produces a plutonium stream.

After conversion to fluoride salts, the UNF is dissolved in the hot eutectic carrier salt of the reactor where decay chains started by neutrons from the internal accelerator driven spallation target transmute the actinides. Online processing of the circulating MS fuel within the subcritical reactor containment envelope continuously removes volatile radioisotopes, (lighter) neutron poisons, and useful materials while leaving (heavier) actinides in the MS to be transmuted to produce energy and to reduce the lifetime of remnants. Online processing methods include chemical (e.g. contactor) or mass separation (e.g. vortex) techniques or sparging, which has been shown to work with helium to remove volatile radioisotopes.

The combination of subcritical operation and low core inventory of volatile radioisotopes, which can each be guaranteed by design and continuous monitoring, ensures an extremely safe design that facilitates and expedites NPP licensing. This is a novel idea to use one high power linear accelerator to produce spallation neutrons in several MS reactors to transmute UNF for energy and reduction of remnant lifetime that is made possible by accelerator innovations. It has beneficial consequences for both the front and back ends of the fuel cycle as well as for <u>nonproliferation</u>, since <u>enriched uranium is not needed</u>, and <u>fissile materials never leave the MS</u>. At the front end of the fuel cycle, we use the remaining energy in UNF rather than uranium mining, enriching, and fuel fabrication. At the end of the fuel cycle, we transmute the actinides into energy and fission products that are mined for useful elements before being buried as 300 year lifetime waste. Materials accounting in this scheme will rely on continuous measurements of the isotopic content of the circulating fuel before and after the vortex separator as well as of isotopic content of the removed fission products. Computer models will be developed and benchmarked comparing the isotopic measurements to the energy produced.

This subcritical method is a new way to produce nuclear energy where fuel selection and reactor dynamics are not tied to maintaining criticality. Each spallation neutron generates a fission chain that dies out. Reactor power is proportional to proton beam power. Although the NPP can operate with many different nuclear fuels, Light Water Reactor (LWR) UNF is unusually good because the remaining Pu-239 and U-235 in it allows the reactor to start up and operate without enriched uranium and because the UNF is only slightly used (less than 5%), so there are fewer neutron poisons to overcome with additional spallation neutrons.

An Innovative Combination of Known Technologies

Muons, Inc. (Muons) is developing NPPs based on a powerful superconducting Linac driving subcritical molten salt fueled small modular reactors. The unique combination of subcritical operation and circulating liquid fuel that is accessible during operation enables economic transmutation of UNF, without reprocessing, to produce energy while destroying long lived actinides.

This allows MUONS to develop an affordable plan for UNF to provide US Energy Security by using the large and growing inventory of US UNF from LWRs. The bulleted list below is a summary of the important features of the conceptual design:

- Mu*STAR Concept based on ORNL Molten Salt Reactor Experiment (MSRE)
  - with an internal Molten Fuel Salt-cooled uranium or tungsten spallation target
  - The same fuel salts, graphite moderator, thermal spectrum as used by the MSRE
- ORNL SNS 1 GeV Linac is the basis for the >50 MW proton accelerator design
  - Use of MS fuel eliminates requirement on beam interruptions

- (Solid fuels experience thermal shock and destructive fatigue from beam interruptions)
- On-site conversion of UNF oxide rods to MS fluoride fuel without reprocessing
  - described in MUONS' GAIN Voucher Grant ORNL/TM-2018/989
  - found to be affordable and straightforward
  - but with large regulatory uncertainties in the cost of the hot cell
  - Over 65 potential US sites with onsite UNF storage for a Mu*STAR NPP
- Essential feature of MS fueled Cores is fuel access during operation (in confinement)
  - Volatile radioactive isotopes can be removed from core (low source term)
  - Vortex contactors/separators keep actinides in the fuel to be consumed
  - Neutron Poisons removed to allow deeper burns of the UNF
  - Technical challenge is to make separation devices that last in harsh environments
- NRC obstacles lower because of subcritical operation and insignificant source term
  - Subcriticality and radiotoxic inventory will be continuously monitored
- Intermediate MS heat storage covers maintenance and repair periods
  - Provides passive decay heat removal for Loss of Power Accidents
  - The high operating temperature is well suited for supercritical CO2 turbines
  - Small size of these turbines allows underground installation for enhanced physical security
- One Linac serves several Mu*STAR SMRs (e.g. 10 * 220 MWe = 2.2 GWe NPP)
  - Transverse-kicking RF cavities distribute beam bunch by bunch to SMRs
- Mu*STAR NPP approach allows true economy of scale to apply to SMRs
  - Add accelerator modules and factory built SMRs to get higher NPP power
  - Electricity sales start with the first module, grow with added Next of a Kind SMRs
  - MUONS is developing parameters for a proton beamline facility to develop its technology

An important feature of our concept is that all modules of the NPP are small enough to be built in factories, including superconducting accelerator cryomodules, Mu*STAR SMRs, and sCO2 turbines. Using several SMRs to improve economy of scale adds the opportunity to improve them constantly and forever, according to Deming [https://deming.org/explore/fourteen-points/]. From experiences with the Fermilab Tevatron, where we improved the power of the collider over the original design goal by a factor of 350 in 20 years, we know that better ideas come along, and it is important to be able to take advantage of them. Figure 1 shows where we start from.

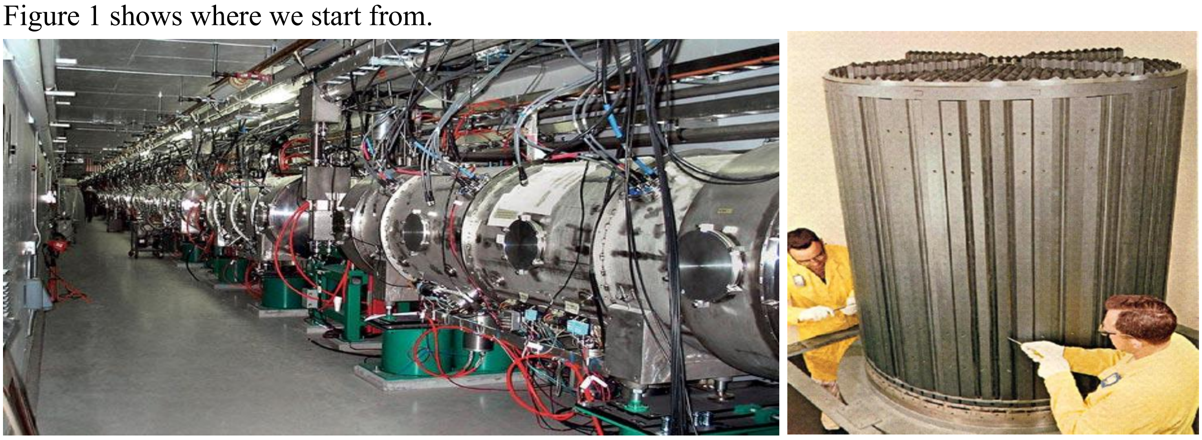

FIG 1: Conceptual building blocks of the Mu*STAR NPP. (Left) The ORNL SNS Linac tunnel showing the cryomodules that hold the 805 MHz superconducting cavities, (Right) The MSRE graphite moderator. The Mu*STAR SMR graphite moderator is larger by a factor of 4 in linear dimensions or 64 by volume, increasing the output power from 8 to 500 MWt = 220 MWe.

The ORNL SNS 6% duty factor Linac indicated on the top half of FIG 2 starts with a 65 keV H-minus Ion Source followed by a 2.5 MeV Radio Frequency Quadrupole, medium energy beam transport section, 87 MeV Drift Tube Linac (DTL), 186 MeV Coupled Cavity Linac (CCL), and the Super Conducting 1 GeV Linac. The DTL and CCL would be replaced by superconducting low beta structures for CW operation. One thousand turns of beam are injected into the Accumulator Ring every 60th of a second using charge exchange injection (invented and developed by Vadim Dudnikov of MUONS team) and then extracted in one turn onto a liquid mercury target to make the very intense neutron pulse that is used by experimenters. During these short beam pulses from the Linac, the instantaneous linac current is over 35 mA and shows no sign of instabilities; this is a good sign that a continuous beam of 50 mA is possible, corresponding to a 50 MW CW beam. For CW operation the accumulator ring is unnecessary, and the beam can be directed to multiple reactors by RF deflecting cavities.

Going from 1.4 MW pulsed SNS Linac to a 50 MW CW Linac for ADSR

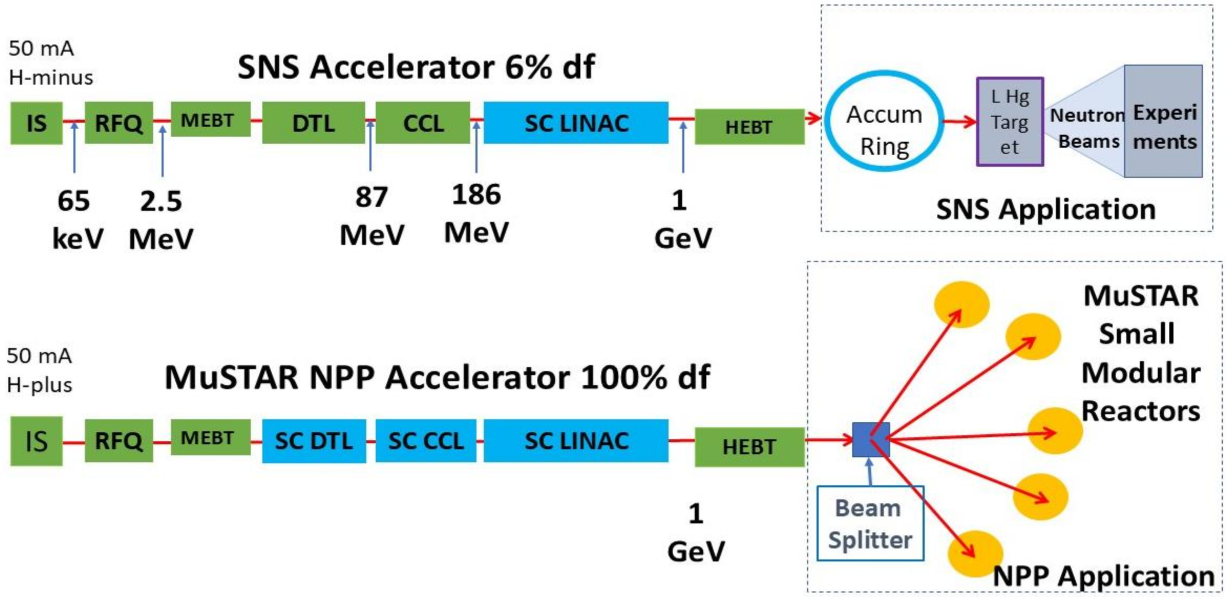

FIG 2: Comparison of the 6% duty factor operation of the ORNL SNS Linac that feeds a storage ring with the 100% duty factor Accelerator Driven Subcritical Nuclear Power Plant that is the subject of this proposal. The Mu*STAR NPP will require upgrading the DTL and CCL to be superconducting, replacing klystrons with less expensive and more efficient magnetrons, and developing the lossless beam splitter with SC RF cavities.

Experiments at the SNS Linac were done that showed that the small losses seen there were due to the H-minus ions losing an electron from intrabeam scattering. When protons were accelerated, losses were undetectably small. This is another indication that beam intensities above 50 mA will be possible with SC RF cavities. The SNS RFQ and DTL operate at 402.5 MHz and the CCL and SC Linac operate at 805 MHz. For our application it would be beneficial to have low cost, high efficiency magnetrons at those frequencies to drive superconducting linacs for UNF transmutation.

The niobium RF cavities of the SC Linac operate at 2 degrees above absolute zero where there is no electrical resistance. The RFQ, DTL, and CCL accelerating structures are made of copper and, because of resistive heating, are not well suited for the continuous beam that is needed for ADS applications. Upgrading these kinds of components to be superconducting has been accomplished at the Michigan State University Facility for Rare Isotope Beams (FRIB).

Figure 3 shows a diagram of the 6 m diameter Mu*STAR SMR. UNF is processed into molten-salt fuel by converting the oxide rods into fluoride salt and inserted into the reactor vessel. The SRF proton accelerator beam generates spallation neutrons that initiate fission chains in the graphite-moderated subcritical core. The circulating fuel salt exchanges heat with a secondary (non-radioactive) salt that carries it to a heat storage tank; from there it can be used to generate electricity (as shown), or for other applications of >600° C process heat. Volatile fission products are continuously removed and stored separately underground, greatly reducing the potential radioactive release in an accident. Internal processing to remove fission products from the MS fuel salt will be added, improving profitability and fuel utilization.

The US DOE has invested much effort in molten salt reactor development in the last 10 years. This can only help MUONS system that is based on the MSRE, an experiment that demonstrated in extraordinary detail that MS fueled reactors are practical even with the materials that were available in 1970.

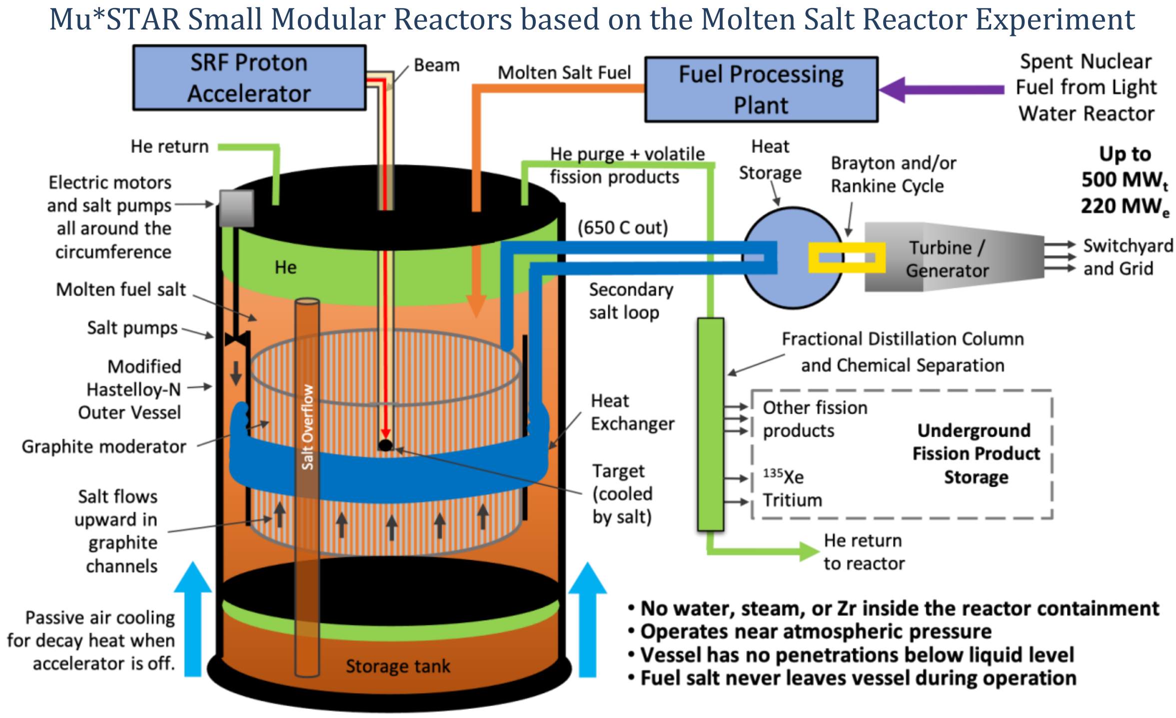

FIG 3: Block diagram for a single-reactor Mu*STAR nuclear power plant.

FIG 4 Shows a conceptual picture of the underground installation of one of the Mu*STAR SMRs. The hot cell serves 3 functions: conversion of UNF fuel rods from oxide to fluoride salts, fission product processing, and preparations for storage or burial of short lived radioisotopes. In the case of loss of power accidents, the decay heat of the reactor will rise to the heat storage tank through the unpowered pump by natural convection. The figure does not show the in-containment devices for removing the fission products from the circulating MS fuel. The idea is shown in FIG 5 which includes vortex separators

One 50 MW_b Linac can drive 10 SMRs like the one in FIG 3 using transverse-kicking superconducting RF cavities to feed each SMR on a beam bunch by bunch distribution. Each SMR will provide 220 MWe which requires 500 MW_t, which takes a beam of 500 $MW_t/100 = 5$ MW_b, with multiplication factor of 100, or 5 mA of 1 GeV protons. Ten SMRs require 50 MW_b or 100 MWe wall-plug power at 50% overall efficiency that is made possible by using 90% efficient magnetron power sources. In this case, the Linac uses 100/2200 = 4.5% of the electrical output power of the NPP.

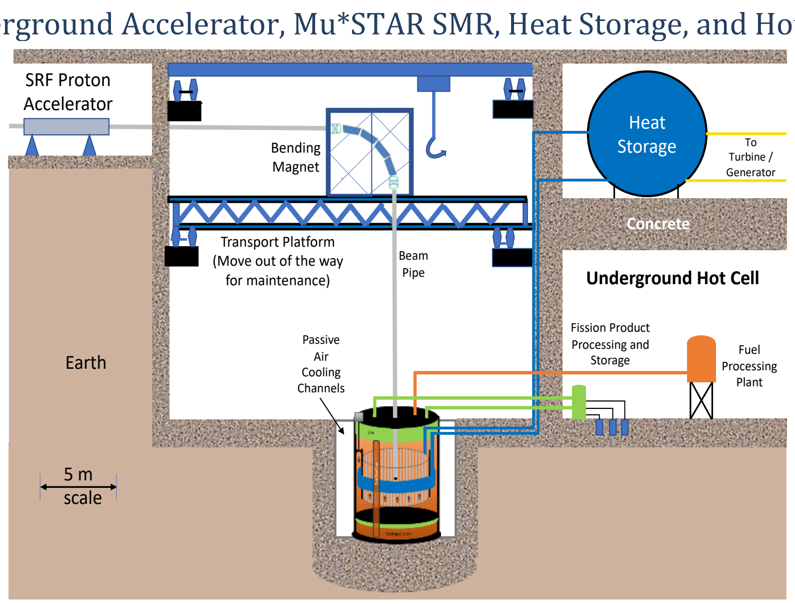

FIG 4: Concept of underground Mu*STAR SMR with beamline, MS Storage tank, and Hot Cell.

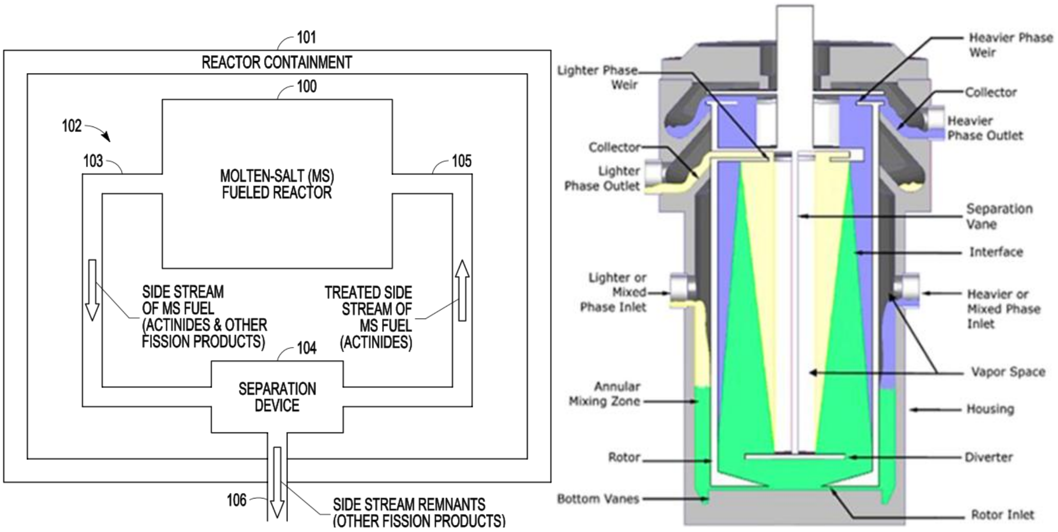

FIG 5: In-containment devices like vortex separators and contactors will remove lighter fission products while leaving heavier actinides in the fuel to be transmuted for energy and to reduce remnant lifetime.

Potential Impact

MUONS approach is like the "GEMSTAR-Green Energy Multiplier" of Charlie Bowman [patent/5160696], and "Energy Amplifier" of Carlo Rubbia [patent/5774514] in which a new subcritical way to make nuclear energy was described. Bowman identified the advantages of molten salt fuel as used by the MSRE. The PI of this proposal met Charlie Bowman and Bruce Vogelaar in 2010 after they had published their work describing GEM*STAR [1]. In these subcritical concepts, each spallation neutron generates a fission chain that dies out such that reactor power is proportional to proton beam power. An added feature is that fuel selection and reactor dynamics are not tied to maintaining criticality, allowing UNF to be consumed without having to be reprocessed or to have additional fissile material added to the fuel. Bowman and Vogelaar demonstrated in their 2010 Handbook of Nuclear Engineering paper using MCNP simulations that the neutron poisons in UNF that prohibited the further critical operation in a LWR could be overcome by spallation neutrons generated by a proton beam from a particle accelerator [2]. This was the key to MUONS GAIN VOUCHER GRANT project that showed that UNF could be economically turned into fuel for an ADS MS reactor just by converting all its isotopes from oxide to fluorides without separation of elements that could be proliferation concerns.

The factory-built SMR technology used in Mu*STAR NPPs invites the application of Deming's principles of total quality management. Unlike the present paradigm that forces nuclear reactors to be licensed and effectively unchangeable for decades, the use of subcriticality and negligible source term for accidental release of radiotoxic volatiles should allow flexible licensing to enable his fifth principle to allow nuclear reactor technology to improve forever. Deming's Fifth Total Quality Management Principle, "Improve constantly and forever the system of production and service, to improve quality and productivity, and thus constantly decrease costs," has been used by almost all successful technology companies since it was first adopted in the1950s by Japanese companies like Toyota and Sony that have since dominated their markets.

References

[1] PAUL TAYLOR, BARRY SPENCER, BILL DEL CUL, ALEX BRAATZ, STEPHEN WARMANN, ROBERT RABUN, JASON WILSON, TOM ROBERTS, "Mu*STAR ADSR Fuel Conversion Facility Evaluation and Cost Analysis", ORNL/TM-2018/989

[2] Charles D. Bowman, R. BRUCE VOGELAAR et al, "GEM*STAR: The Alternative Reactor Technology Comprising Graphite, Molten Salt, and Accelerators," Handbook of Nuclear Engineering, Springer Science+Business Media LLC (2010).