

GEM*STAR ACCELERATOR-DRIVEN SUBCRITICAL SYSTEM FOR IMPROVED SAFETY, WASTE MANAGEMENT, AND PLUTONIUM DISPOSITION

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Abstract

The GEM*STAR system employs a high-power SRF proton accelerator with a spallation neutron target to provide a source of neutrons, and a molten salt/graphite core. This results in a lower cost, subcritical nuclear reactor design that has many attractive features, among which are the following. It eliminates the need for a critical core, fuel enrichment, or reprocessing. Fissionable fuel is dissolved in the high-temperature molten-salt fuel. The reactor cannot attain a critical mass and contains almost a million times fewer volatile radioactive fission products than conventional reactors like those at Fukushima.[‡] Volatile radioactive fission products are continuously purged. The GEM*STAR [1] reactor can, without redesign, burn spent nuclear fuel, natural uranium, thorium, or surplus weapons material. A first application is to burn up to 34 tons of excess weapons grade plutonium as an important step in nuclear disarmament under the 2000 Plutonium Management and Disposition Agreement, in which The U.S. and Russia each agreed to dispose of 34 tons of weapons-grade plutonium. The process heat generated by this W-Pu can be used for the Fischer-Tropsch conversion of natural gas and renewable carbon into 1.24 billion gallons of low-CO₂-footprint, drop-in synthetic diesel fuel per ton of W-Pu, for use by the DOD or for other purposes.

GEM*STAR SYSTEM

The Green Energy Multiplier*Subcritical Technology for Alternative Reactors (GEM*STAR) is a subcritical thermal-spectrum reactor operating with a molten salt fuel in a graphite matrix in a continuous flow mode, initially at $k_{\text{eff}} \sim 0.99$. Accelerator-produced neutrons supplement the fission neutrons. The beneficial combination of three reactor technologies (largely neglected since 1970) – molten salts, accelerator-produced neutrons, and the use of a graphite moderator – enable a versatile reactor that addresses multiple problems associated with conventional nuclear reactors and their fuel cycle: safety, nuclear proliferation, nuclear waste, limited fuel, and geologic storage. Unlike the several “Generation IV” reactor technologies, GEM*STAR mitigates or eliminates all of them.

The key point is that GEM*STAR operates in subcritical mode driven by an enormous neutron flux gener-

ated by a proton beam. This means that fission stops within 1 second after the proton beam is turned off, which is a passive response to essentially any accident scenario; without fission, passive air-cooling is sufficient. That flux also means that GEM*STAR can burn fuels no conventional reactor can use: spent nuclear fuel, natural uranium, natural thorium, its own output stream, and even depleted uranium. It burns these fuels without fuel reprocessing or uranium enrichment, greatly reducing proliferation concerns. This turns “waste” into fuel – enormous amounts of it: with a fleet of GEM*STAR reactors there is enough uranium *out of the ground today* to supply 100% of the current U.S. electricity usage for more than 1,000 years.

Accelerator-Driven Reactors

Cyclotrons and electrostatic accelerators played an essential role in the early development of nuclear technology. The first significant quantity of enriched ²⁵³U was produced from “Calutrons”, developed under E.O. Lawrence at Berkeley Laboratory. Later, in the early 1950s, Lawrence constructed much more powerful accelerators for neutron production to produce ²³⁹Pu from neutron capture on ²³⁸U - the “Mark I” of the material test accelerator (MTA). The MTA was a drift tube linear accelerator, designed for both high current and then-high energy, with a diameter of 19m and length of 27m, and reached unprecedented currents of 50 mA of deuterons at 10 MeV for an average power of 0.5 MW – 2 million times larger than that of the Berkeley cyclotrons. A larger version was planned, but discovery of abundant uranium deposits in New Mexico and Colorado, and the success of plutonium production in reactors at Oak Ridge and Hanford, ended the MTA initiative.

For 40 years, accelerator science was driven by basic, rather than applied, science. In the 1990s, Carlo Rubbia proposed an “Energy multiplier” [2], based on a proton cyclotron that produced neutrons to power a thorium-based reactor. Charles Bowman also proposed an accelerator-driven system for waste transmutation [3]. The multi-MW accelerators necessary seemed neither feasible nor practical until the development of superconducting RF. Today, beam power over 1 MW has been achieved at Oak Ridge National Laboratory (ORNL) and the European Spallation Source (ESS). The need for higher intensity beams for future accelerators is driving R&D for powerful proton sources that are increasingly cost effective.

One of the concerns for accelerator-driven subcritical reactor systems (ADSR) is that frequent accelerator trips would cause mechanical fatigue in reactor fuel rods.

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[‡] There is enough ²³⁹Pu to form a critical mass if it were Pu metal in a sphere, but chemically combined into PuF₄ it cannot achieve a critical mass.

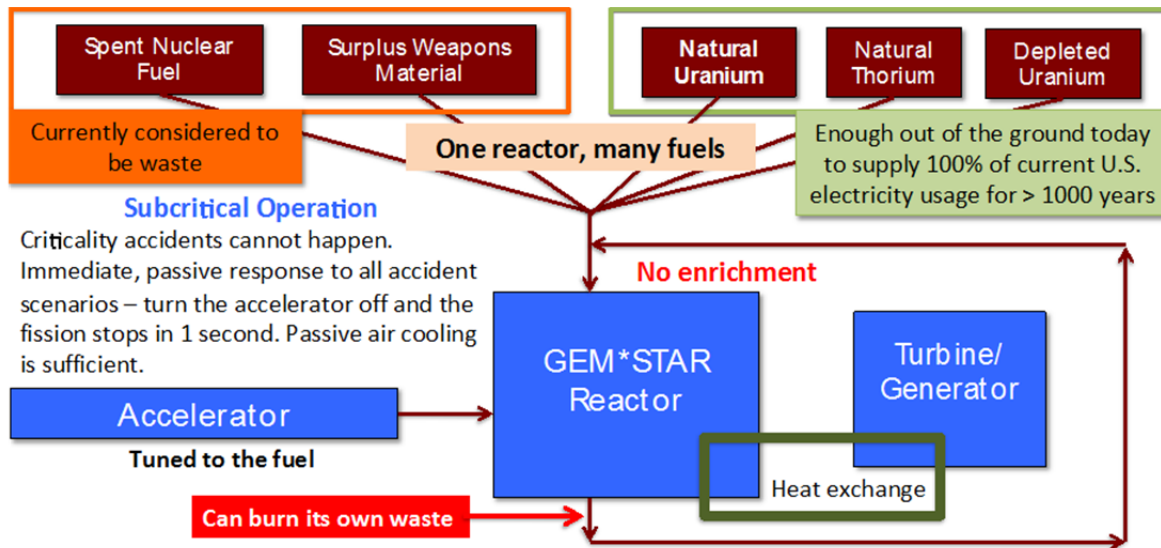


Figure 1: A conceptual schematic of the GEM*STAR reactor system. The molten salt reactor allows operation for many different types of fuel. The accelerator is tuned to optimize the reaction required by the fuel. Run in subcritical mode, the reactor stops within one second of turning off the accelerator. Passive air-cooling is then sufficient.

These concerns are eliminated by the use of molten-salt fuel and an accelerator design optimized for availability. The Molten Salt Reactor Experiment (MSRE) [4] ran at ORNL from 1964-1969. It was a critical reactor that demonstrated key aspects of using molten salt fuel with several different types of fuels. Interesting to note that it was routinely powered down for weekends, which no conventional reactor can do. The project was abandoned in 1970 when emphasis went to Fast Breeder Reactors (FBR).

In addition to new accelerator technology and a thorough study of the use of molten salts in reactors, new materials and new simulation techniques are now available for the design and construction of these new reactors and validation of their neutron economy.

The GEM*STAR Reactor

The main elements of the GEM*STAR system are a high-power proton accelerator with associated beam transport, the GEM*STAR reactor, and the ancillary facilities for utilizing the heat output for electricity generation and/or chemical processes. Many different fuels can be used with no reconfiguration of the reactor itself, including its own waste. A conceptual schematic of the elements is shown in Fig. 1.

The heart of the GEM*STAR system is the reactor, which consists of a graphite core matrix of tubular elements through which molten salt containing the fuel mixture circulates. As illustrated schematically in Fig. 2, pumps drive the molten salt down the periphery, up around the holding tank, and up through the graphite tubes, which act as the moderator, and back to the periphery. The molten salt level is maintained by an overflow pipe that returns the excess molten salt to the holding tank. A helium gas flow above the salt level is used to

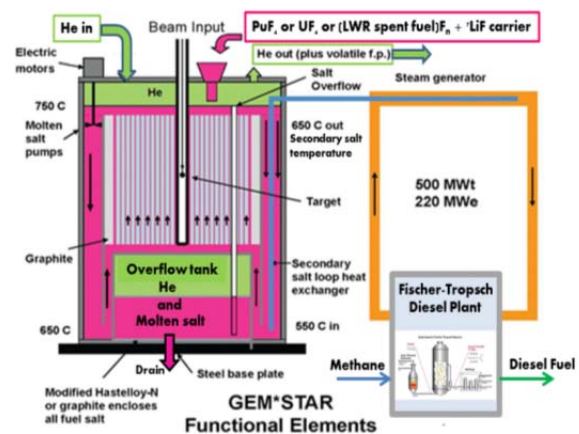


Figure 2: Cross-sectional view of GEM*STAR reactor driving an external diesel fuel generator

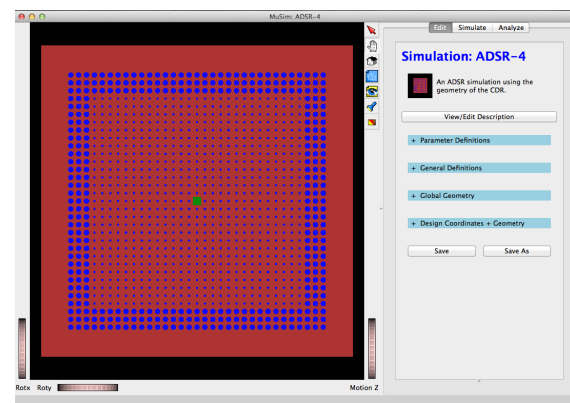


Figure 3: Screen shot of GEM*STAR reactor core from MuSim: the graphite carbon is red-brown, salt is blue, the spallation target (natural uranium) is green.

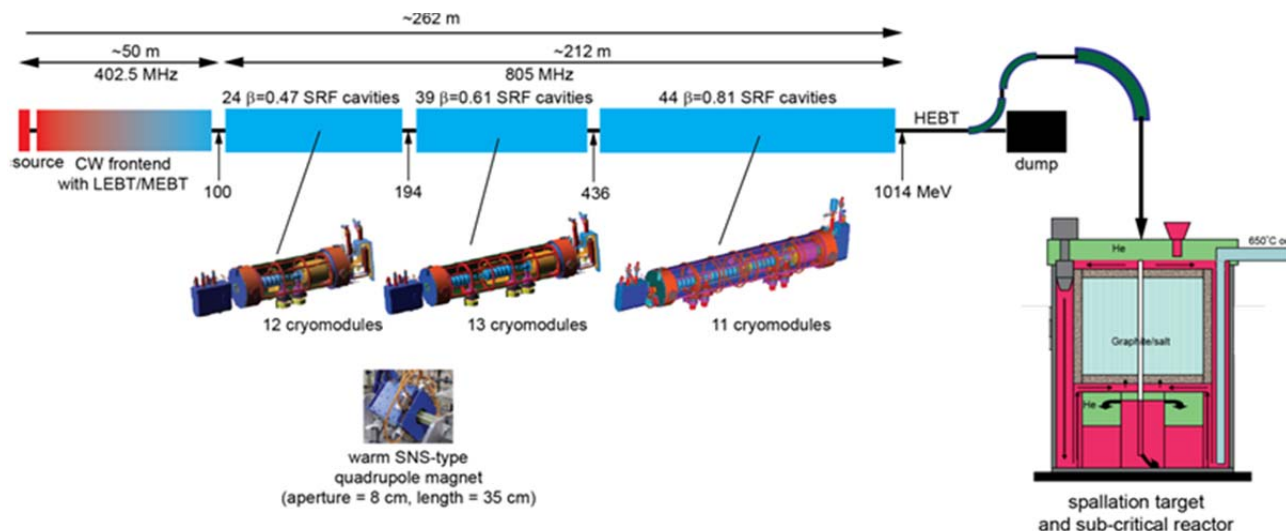


Figure 4: Configuration of a GEM*STAR reactor driven by a cost-reduced version of the ORNL SNS 1014 MeV proton accelerator (not to scale). HEBT denotes high energy beam transport. An accelerator of this type could support up to four GEM*STAR reactors in the plutonium disposition application.

purge the volatile products from the reactor core. No zircon or water is present, which avoids the risk of hydrogen explosions, seen in Fukushima. The molten salt mixture is shown in magenta, helium gas is shown in green; secondary flow loop tubes, shown in blue, carry process heat from the core to an external heat exchanger for use by the applications for generating diesel fuel. The reactor core is shown in Fig. 3, simulated with Muons, Inc. software, MuSim [5] (described below).

The fuel can be LiF salt mixed with fluorides of plutonium, natural uranium, and thorium, as well as fluoridated spent nuclear fuel rods and surplus weapons material, such as highly enriched ^{235}U and weapons-grade ^{239}Pu . The fuel preparation does not require MOX processing and encapsulation. Since the number of neutrons generated by the beam is independent of any particular fission chain reaction, a variety of fissile and fertile materials can be handled with one reactor design by varying the beam power. The reactor operates subcritically with $0.90 < k_{\text{eff}} < 0.98$, which can also be varied depending on operational requirements of a particular reactor.

The GEM*STAR Accelerator

The accelerator for the GEM*STAR system is a proton accelerator in the energy range from 600 MeV to 1 GeV. Figure 4 shows the GEM*STAR reactor as driven by a proton linac based on the ORNL SNS 1 GeV design. The ORNL SNS was designed to produce neutrons for a variety of research and application uses, not ADSR.

For a transmutation demonstration system the beam power required is 1 MW, which corresponds to a current of 1.6 mA at 600 MeV, or 1 mA at 1 GeV. For a transmutation demonstration, the requirement for beam trips of up to 5 minutes is <2500/year, and the accelerator availability requirement is >50%, which are considerably less stringent than for a commercial electric power, and are easily met. The GEM*STAR prototypes can also be designed for lower power, modular applications.

NEUTRON PRODUCTION

The production of neutrons by energetic proton beams depends on a number of parameters: beam energy, target material, target length, target diameter, etc. Neutron production has been measured experimentally [6] and simulated using FLUKA [7] and MCNPX [8] codes. Figure 5 shows experimental data, simulation results, and a (linear) empirical relation of neutron production in the range 200 MeV to 1600 MeV. Uranium targets produce about 60% to 90% more neutrons per proton than Pb or W, due to higher A and neutrons produced in fission reactions.

The energy multiplier shown in Fig. 6 takes into account the action of thermalized neutrons in energy multiplication and shows that proton beam energies as low as 600 MeV may suffice for ADSR operations. It is calculated using beam from G4beamline [9] and a reactor simulation in MCNP 6.1, then plotted vs. the proton beam energy. This was generated with the software tool MuSim, described next.

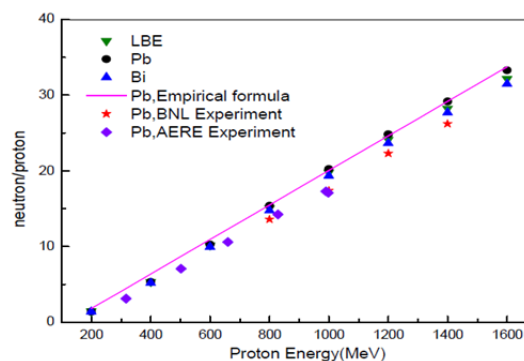


Figure 5: Neutron production per incident proton as a function of proton energy for targets 10 cm diameter by 60 cm long for data and FLUKA simulations [4].

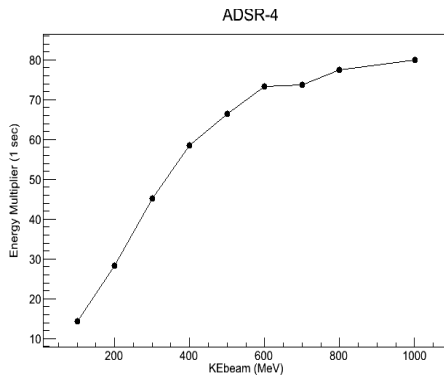


Figure 6: The energy multiplier as a function of incident beam energy. This is (total thermal energy) / (total beam energy).

MuSim Simulation of Neutron Production

MuSim is a new simulation tool developed by Muons, Inc. that facilitates MCNP6.1 and GEANT4 simulations by providing advanced visualization capabilities, flexibility and versatility. Figure 7 shows an example of a MuSim simulation for GEM*STAR. The neutrons are almost fully contained within the core, while some gammas escape. This includes all processes in the target and core, including fissions in the target and in the fuel.

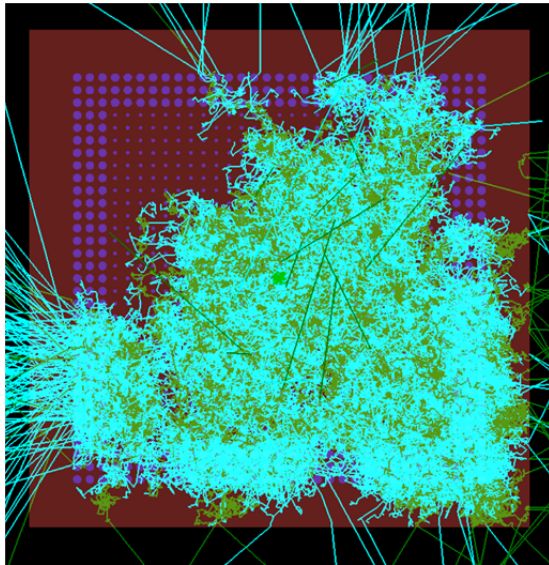


Figure 7: MuSim simulation of neutrons and gammas produced by a single 1 GeV proton on a U target in the GEM*STAR reactor. Neutron tracks are green and gamma tracks are cyan. Graphite elements are shown in brown and the molten fuel mixture of LiF and UF₄ in the tubes is shown in blue. The core is shown in 50% transparency to better visualize the tracks throughout the core. 20,000 tracks out of 585,000 are shown.

A key area of study will be the equilibrium operation of the molten salt reactor. Depending on the operation, the initial start up time can take years, but that can be considerably shortened by the appropriate initial starting composition and fuel management. GEM*STAR operates in a

simple equilibrium overflow system where the volume flow in equals volume flow out (“feed and bleed”). Figure 8 shows a graphical representation of this concept. The salt circulates by pumps and also moves slowly by natural convection; it is passively air-cooled in the event of a power outage.

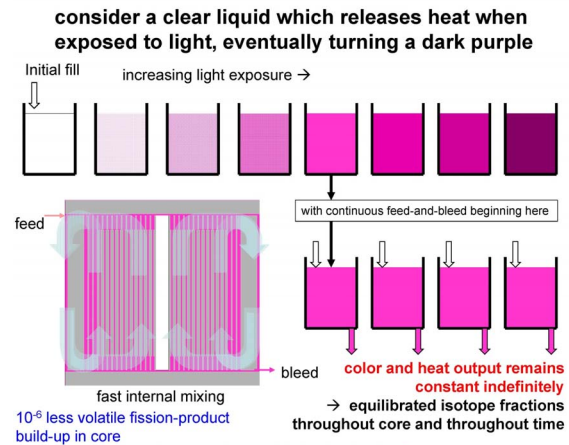


Figure 8: Description of approach to equilibrium operation in a “feed and bleed” system.

SAFETY AND OTHER BENEFITS

GEM*STAR provides many inherent safety and operational benefits, including:

- Sub-critical operation eliminates the need for control rods and considerably simplifies the safety analysis
- Passive response to essentially all accident scenarios
- Operation at atmospheric pressure eliminates the need for a pressure vessel
- Fuel in the form of fluoride salts that are mixed with the primary molten salt eliminates fabrication, installation, replacement and waste management needed for fuel rods or pellets
- Fuel is in a liquid form, which eliminates the need to fabricate and replace fuel rods.
- Fuel resides in the core until fully used, and additional fuel is introduced as needed.
- Volatile fission products are continually purged by the He flow to an external collection facility, eliminating issues with ¹³⁵Xe and avoiding major radiation leaks into the atmosphere during accident scenarios.
- Molten fluorides are chemically stable and impervious to radiation. The salts do not burn, explode, or decompose, even under high temperature and radiation. There are no rapid violent reactions with water or air.
- Coolant and fuel are inseparable, so any leak or movement of fuel will be intrinsically accompanied by a large amount of coolant. Molten fluorides have high volumetric heat capacity, which allows them to absorb large amounts of heat during transients.

GEM*STAR APPLICATIONS

Plutonium Disposition

This is attractive as a first application for GEM*STAR and an alternative for the U.S. W-Pu disposition program.

Transmutation of Reactor Wastes

GEM*STAR can burn the fissile materials remaining in spent fuel (SNF) rods and can transmute much of the long-lived fission products to isotopes with much shorter lifetimes, thus facilitating storage.

Production of Diesel Fuel

GEM*STAR process heat enables the Fischer-Tropsch process to synthesize methane into a more complex hydrocarbon called F-T wax. Catalytic conversion produces diesel fuel and other useful hydrocarbons. Contaminants in the methane are removed before entering the F-T reactor, so the resulting diesel fuel is a “clean” product.

Electric Power Generation

Generation of electricity by GEM*STAR is done in the same manner as in conventional power plants, except with a molten-salt heat exchanger. Due to the stringent requirements for accelerator beam trips and availability, electric power generation is not considered as an initial application.

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