ACCELERATOR-DRIVEN SUBCRITICAL SYSTEM FOR PROFITABLE DISPOSITION OF SURPLUS WEAPONS-GRADE PLUTONIUM AND ENERGY GENERATION

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Abstract

We discuss the GEM*STAR reactor concept, which addresses all historical reactor failures. This system includes a superconducting RF (SRF) proton accelerator, an internal spallation neutron target and high temperature molten salt fuel with continuous purging of volatile radioactive fission products such that the reactor contains less than a critical mass and almost a million times fewer volatile radioactive fission products than conventional reactors like those at Fukushima.. The GEM*STAR [1] reactor can, without redesign, burn spent nuclear fuel, natural uranium, thorium, or surplus weapons material. . It will operate without the need for a critical core, fuel enrichment, or reprocessing making it an excellent candidate for export. While conventional nuclear reactors are becoming more and more difficult to license and expensive to build, SRF technology development is on a steep learning curve and the simplicity implied by subcritical operation will lead to reductions in regulatory hurdles and construction complexity.

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 $k_{eff} \sim 0.99$. 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 generated 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.

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 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 [2] (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 $0.90 < k_{eff} < 0.98$, which can also be varied depending on operational requirements of a particular reactor and fuel.

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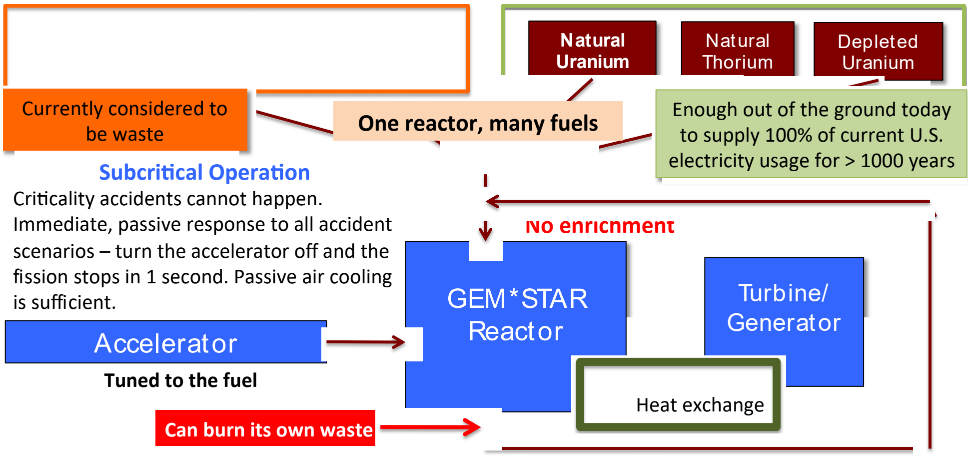


Criticality accidents cannot happen. Immediate, passive response to all accident scenarios – turn the accelerator off and the fission stops in 1 second. Passive air cooling is sufficient.

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.

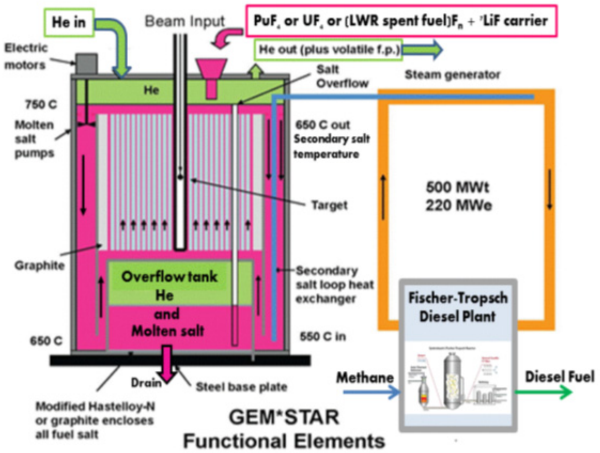
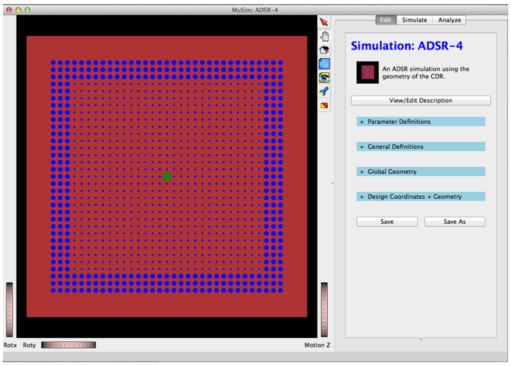


Figure 2: Cross-sectional view of GEM*STAR reactor driving an external diesel fuel generator.



Simulation: ADSR-4

An ADSR simulation using the geometry of the CDR.

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.

*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. 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.

A calculation of energy multiplier shown in Fig. 4 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 [3] and a reactor simulation in MCNP 6.1, then plotted vs. the proton beam energy. This was generated with the software tool MuSim, described below.

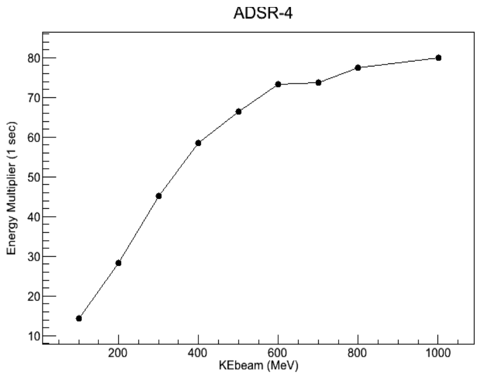


Figure 4: The energy multiplier as a function of incident beam energy. This is (total thermal energy) / (total beam energy).

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 [4] and simulated using FLUKA [5] and MCNPX [6] codes. Fig. 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%

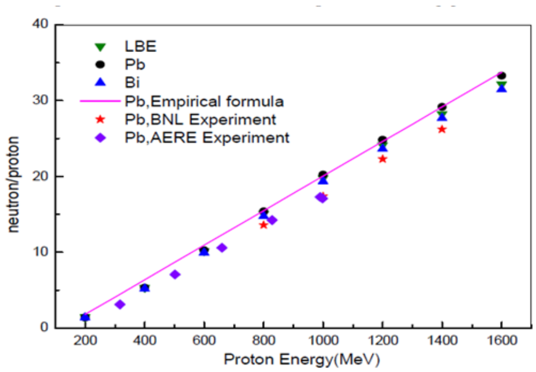


Figure 5: Neutron production per incident proton as a function of proton energy for targets 10 cm diameter by 60 cm long for data and FLUKA simulations [4].

to 90% more neutrons per proton than Pb or W, due to higher A and neutrons produced in fission reactions.

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. Fig. 6 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.

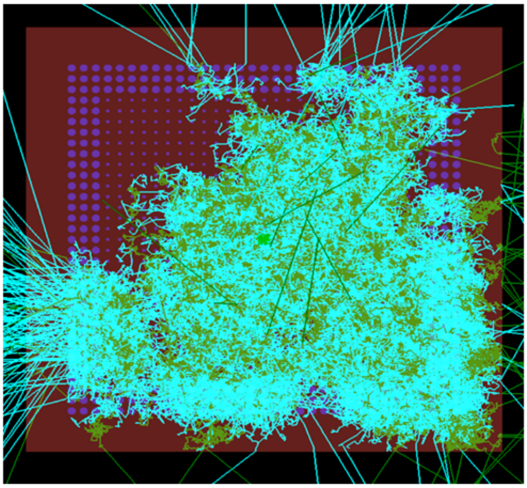


Figure 6: MuSim simulation of neutrons and gammas produced by a single 1 GeV proton on a U target in the GEM*STAR reactor. Neutron tracks are green and gamma tracks are cyan. Graphite elements are shown in brown and the molten fuel mixture of LiF and UF_4 in the tubes is shown in blue. The core is shown 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”). Fig. 7 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.

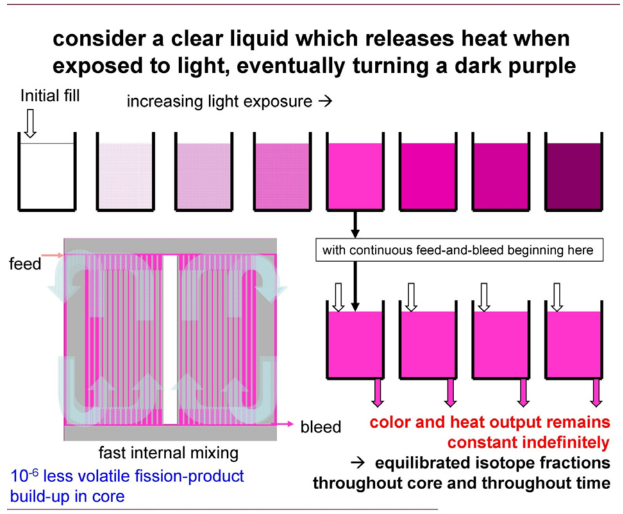


Figure 7: Description of approach to equilibrium operation in a “feed and bleed” system.

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 ^{135}Xe 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.

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