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

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Abstract

Operation of high-power SRF particle accelerators at two US national laboratories allows us to consider a less-expensive nuclear reactor that operates without the need for a critical core, fuel enrichment, or reprocessing. A multipurpose reactor design that takes advantage of this new accelerator capability includes an internal spallation neutron target and high-temperature molten-salt fuel with continuous purging of volatile radioactive fission products. 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. We describe GEMSTAR[1] , a reactor that without redesign will burn spent nuclear fuel, natural uranium, thorium, or surplus weapons material. A first application is to burn 34 tonnes of excess weapons grade plutonium as an important step in nuclear disarmament under the 2000 Plutonium Management and Disposition Agreement. The process heat generated by this W-Pu can be used for the Fischer-Tropsch conversion of natural gas and renewable carbon into 42 billion gallons of low-CO2-footprint, drop-in, synthetic diesel fuel for the DOD.

GEM*STAR SYSTEM

The main elements of the GEM*STAR system are a particle accelerator and associated beam transport, the GEM*STAR reactor, and the ancillary facilities for utilizing the heat output for electricity generation and/or chemical processes. A block diagram of the elements is shown in Fig. 1.

*The GEM*STAR Reactor*

The heart of the GEM*STAR system[1,2] 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.

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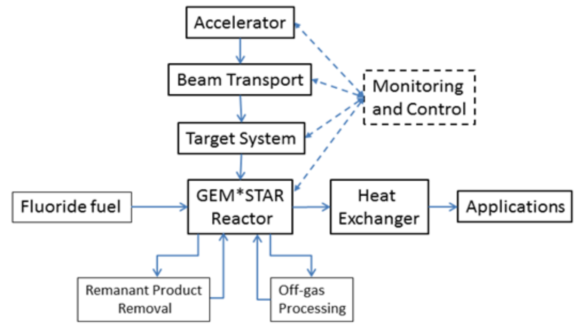

Figure 1: Block diagram showing major elements of the GEM*STAR system.

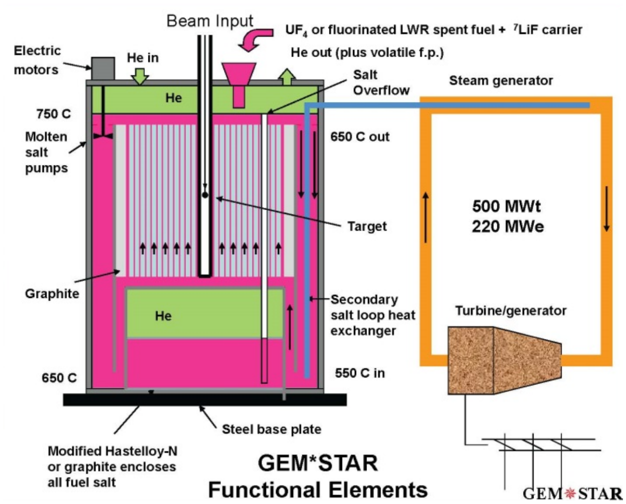

Figure 2: Cross-sectional view of GEM*STAR reactor driving an external generator.

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. LiF salt, mixed with fluorides of plutonium, natural uranium, and thorium can be used as fuel mixtures, as well as spent nuclear fuel rods and surplus weapons material. The fuel preparation does not require MOX processing and encapsulation. Since the number of neutrons generated is independent of any particular fission chain reaction, a variety of fissile or fertile materials can be handled with one reactor design. The reactor operates in a subcritical mode, at $k_{eff} \approx 0.98$.

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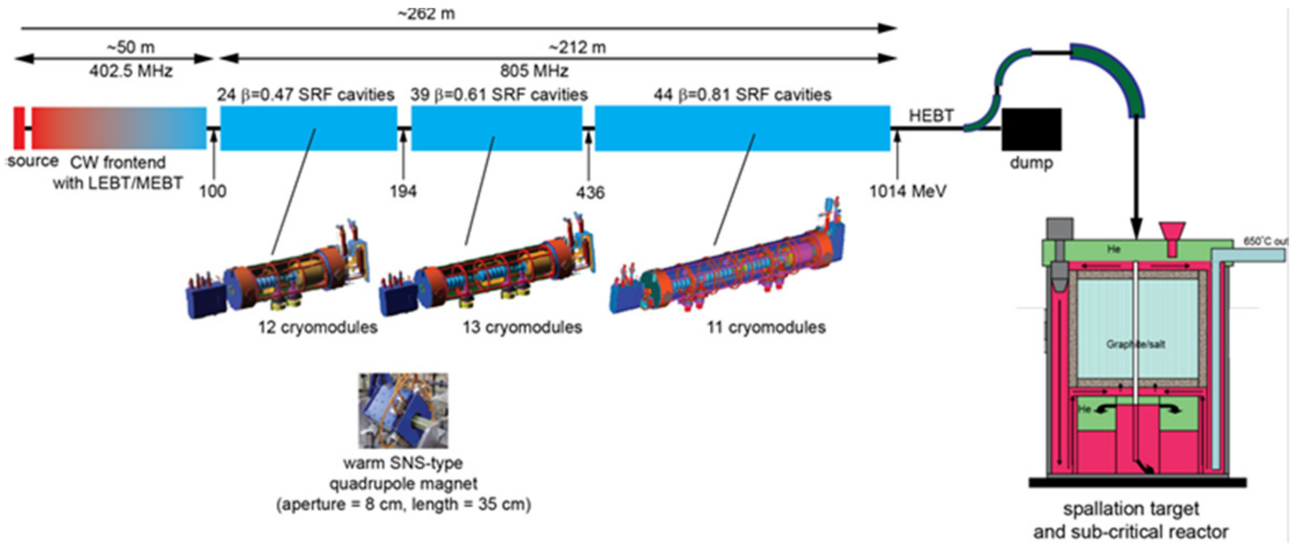

Figure 3: Configuration of a GEM*STAR reactor driven by a cost-reduced version of the ORNL SNS 1014 MeV proton accelerator (not to scale). HEBT denotes high energy beam transport (HEBT). An accelerator of this type could support up to four GEM*STAR reactors in the plutonium disposition application.

*The GEM*STAR Accelerators*

The accelerator envisaged for the GEM*STAR system is a proton accelerator in the energy range from 600 MeV to 1 GeV. Fig. 3 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.

NEUTRON PRODUCTION

The production of neutrons by energetic proton beams depends on a number of parameters: beam energy, target material, target length, target diameter. Neutron production has been measured experimentally [3] and simulated using FLUKA[4] and MCNPX [5] codes. Fig 4 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 neutron energy spectrum from 600 MeV protons is lower than the spectra at 800 or 1000 MeV, which tends toimprove the yield of thermalized neutrons at 600 MeV.placed above tables.

Fig. 5 shows a plot of a slightly different variable, energy multiplier, which takes into account the action of thermalized neutrons in energy multiplication. It shows that proton beam energies as low as 600 MeV may suffice for ADSR operations.

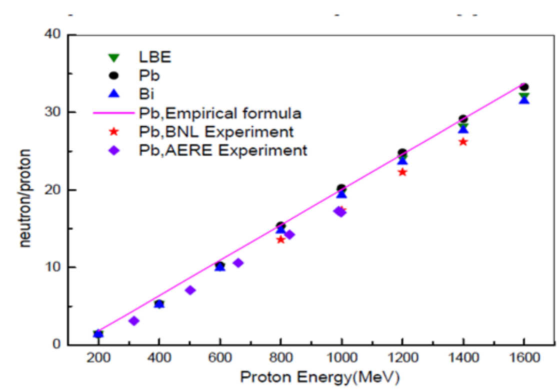

Figure 4: Neutron production per incident proton as a function of proton energy for targets 10 cm diameter by 60 cm long for data and FLUKA simulations [4].

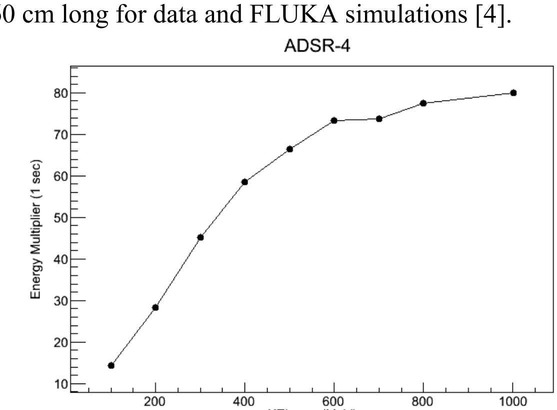

Figure 5: The energy multiplier is calculated using beam from G4beamline[6] and reactor simulation in MCNP 6.1, then plotted vs. the proton beam energy. This was generated with the software tool MuSim, described below.

MuSim Simulation of Neutron Production

MuSim [7] is a new simulation tool developed by Muons, Inc. that facilitates MCNPX and GEANT4 simula-

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tions and provides advanced visualization capabilities, flexibility and versatility. Fig. 6 shows an example of a MuSim simulation for GEM*STAR. Approximately 20,000 tracks out of 585,000 are shown. The neutrons are fully contained within the core, while a number of gammas escape. The neutrons result from all processes in the target and core, including fissions in the target and in the UF_4 in the fuel.

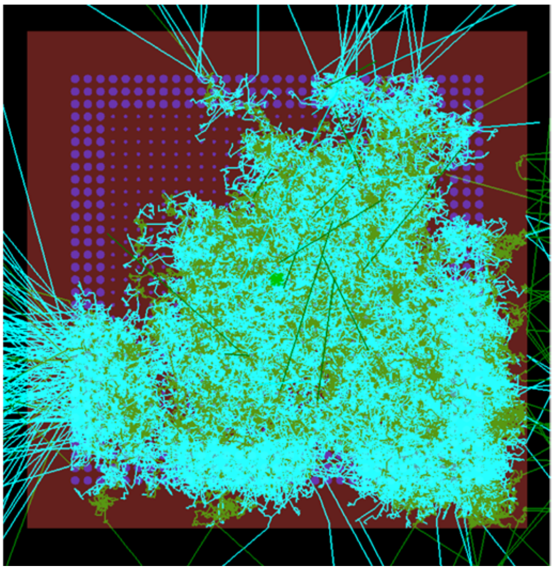

Figure 6: MuSim simulation of neutrons and gammas produced by a single 1 GeV proton on a U target in the GEM*STAR reactor. Neutron tracks are green and gamma tracks are cyan. Graphite elements are shown in brown and the molten fuel mixture of LiF and UF_4 in the tubes is shown in blue. The core is shown in 50% transparency to better visualize the tracks throughout the core.

SAFETY AND OTHER BENEFITS

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

- Sub-critical operation with less than a critical mass of fuel eliminates the need for control rods
- 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 or transmuted, and additional fuel is introduced as needed.
- Volatile fission products are purged by the He flow to an external collection facility.
- Molten fluorides are chemically stable and impervious to radiation. The salts do not burn, explode, or decompose, even under high temperature and radition. There are no rapid violent reactions with water and 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, this 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 GEM*STAR can transmute the long-lived fission products to isotopes with much shorter lifetimes, thus facilitating storage.

Production of Diesel Fuel

GEM*STAR process heat enables the F-T 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. Due to the more stringent requirements for accelerator beam trips and availability, electric power generation is not considered as an initial application.

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