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 GEM*STAR1, 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 Agreement2. 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 is the reactor [1, 2], 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. The accelerator beam strikes a target in the reactor to produce neutrons to control the fission rate in the reactor and maintain sub-critical operation.

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

Figure 2: Cross-sectional view of GEM*STAR reactor.

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 $k_{enr} \approx 0.98$.

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2 http://www.state.gov/r/pa/prs/ps/2010/04/140097.htm

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The GEM*STAR Accelerator

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

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 application.

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. Figure 4 shows experimental data, simulation results, and a (linear) empirical relation of neutron production in the range 200 MeV to 1600 MeV. Table 1 shows neutron production for various target materials in the energy range 600 MeV to 1000 MeV. Uranium targets produce about 60% to 90% more neutrons per proton than Pb or W, due 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 to improve the yield of thermalized neutrons at 600 MeV.

Table 1: Neutrons/proton for Various Targets and Beam Energies from MCNPX [adapted from 5]

<table>
<thead>
<tr>
<th>Target</th>
<th>600 MeV</th>
<th>800 MeV</th>
<th>1000 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>3.7</td>
<td>5.3</td>
<td>6.7</td>
</tr>
<tr>
<td>Pb</td>
<td>9.6</td>
<td>14.3</td>
<td>18.5</td>
</tr>
<tr>
<td>W</td>
<td>9.9</td>
<td>16.0</td>
<td>20.0</td>
</tr>
<tr>
<td>U</td>
<td>18.0</td>
<td>26.0</td>
<td>33.3</td>
</tr>
</tbody>
</table>

MuSim Simulation of Neutron Production

MuSim [6] is a new simulation tool developed by Muons, Inc. that facilitates MCNPX and GEANT4 simulations and provides advanced visualization capabilities, flexibility and versatility. Figure 5 shows an example of a MuSim simulation for GEM*STAR.
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 radiation. 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.

REFERENCES


