

ACCELERATORS FOR SUBCRITICAL MOLTEN-SALT REACTORS*

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Abstract

Accelerator parameters for subcritical reactors that have been considered in recent studies [1] have primarily been based on using solid nuclear fuel much like that used in all operating critical reactors as well as the thorium-burning accelerator-driven energy amplifier [2] proposed by Rubbia et al. An attractive alternative reactor design that used molten salts was experimentally studied at ORNL in the 1960s, where a critical molten salt reactor was successfully operated using enriched U235 or U233 tetrafluoride fuels [3]. These experiments give confidence that an accelerator-driven subcritical molten salt reactor will work as well or better than conventional reactors, having better efficiency due to their higher operating temperature, having the inherent safety of subcritical operation, and having constant purging of volatile radioactive elements to eliminate their accumulation and potential accidental release in dangerous amounts. Moreover, the requirements to drive a molten salt reactor can be considerably relaxed compared to a solid fuel reactor, especially regarding accelerator reliability and spallation neutron targetry, to the point that much of the required technology exists today.

INTRODUCTION

Energy, Safety, Waste

The US nuclear power industry provides about 20% of the nation's electricity, in spite of the fact that no new reactors have been built in the US in decades. Public perceptions regarding possible nuclear accidents, weapons proliferation, terrorist activities, and the mounting stockpile of waste from conventional reactors have made the growth of this industry difficult. However, even the general public is coming to realize that nuclear power could be an effective mitigation to the greenhouse gas emissions related to climate change. Accelerator Driven Subcritical Reactors (ADSR) have the potential to address the concerns of the public in all respects, from intrinsic safety from subcritical operation, discouraging proliferation and terrorists, to burning the waste from conventional reactors.

Extra Neutrons

The only materials that exist in the world in significant quantity that are capable of a sustained nuclear reaction are U235, found as 0.7% of natural uranium, and Pu239, which has been created in U235-based reactors. A critical mass of either of these isotopes will create enough

neutrons so that a chain reaction will continue.

Other materials such as naturally occurring thorium, nuclear waste from conventional reactors, or natural uranium can also be used to produce energy if additional neutrons can be added.

The two known methods to add neutrons use 1) fast breeders reactors or 2) particle accelerators similar to those developed for basic physics research. While the development of fast breeder reactors has been on hold in the USA because of nuclear weapon proliferation concerns, particle accelerator technology has reached the point where spallation neutrons can be produced in sufficient quantity for practical ADSR uses.

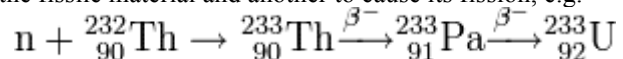
ACCELERATORS FOR ADSR

Solid Fuel ADSR

ADSR that have been examined the most implicitly rely on the general features of existing critical reactors like the light water reactors (LWR) that make up about 85% of the US nuclear power industry. In these reactors, long metallic tubes (zirconium alloy) enclose small cylinders of solid uranium or plutonium oxide ceramic. Moderators to slow the neutrons can be inserted between the tubes or rods to control the reaction rates while water circulates between the rods to transfer the heat to steam turbines.

One safety concern with these fuel rods is that they contain radioactive materials such as ¹³¹I and ⁸⁵Kr that can be accumulated over time and suddenly released if a rod gets too hot or catches fire.

To turn such a reactor into one driven by a particle accelerator, a beam of protons is directed to a spallation neutron target to cause neutrons to enter the fuel to produce power as long as the neutron flux is adequate. Two neutrons are needed for each fission, one to breed the fissile material and another to cause its fission, e.g.



Similar reactions can convert and eliminate materials such as are found in spent fuel rods to generate energy.

The efficiency for producing spallation neutrons increases with proton energy almost linearly up to about 900 MeV, where it remains high and relatively constant up to several GeV. The minimum beam power for ADSR to be economically attractive is thought to be 10 MW.

A recent study [1] of "Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production" was supportive of the idea that accelerator technology was capable of providing proton beams appropriate for ADSR, but pointed out that certain R&D was needed. For example, the applicability of superconducting RF (SRF) linacs for solid fuel ADSR

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depends on the sensitivity of the fuel rods to interruptions of neutron flux. In this case, large temperature gradients caused by abrupt changes in the nuclear reaction rate would stress the ceramic fuel cylinders, eventually leading to fatigue and possible damage to the fuel rod.

The study concluded that the number of allowable accelerator trips per year was more than had earlier been estimated, but still would require accelerators which were orders of magnitude less likely to have trips lasting more than a few seconds than present-day machines. For longer interruptions of some hours or fractions of an hour, there was the belief that there would be additional costs associated with increased accelerator reliability or redundancy and that this should be a subject of R&D along with other unknowns, such as beam losses that could lead to unacceptable levels of induced radiation in accelerator structures.

Molten-Salt Fuel ADSR

The features of a molten-salt reactor are displayed in Fig. 1, which shows the ADNA GEM*STAR conceptual design [4]. The molten-salt fuel mixture (e.g. UF₄, ThF₄, LiF) is held in a graphite-reflector, Hastelloy-N container which also contains the heat exchanger (non-radioactive) liquid salt. Beams of energetic protons hit targets to cause spallation neutrons to enter the fuel mixture. Volatile radioactive by-products are constantly purged by a flow of helium gas.

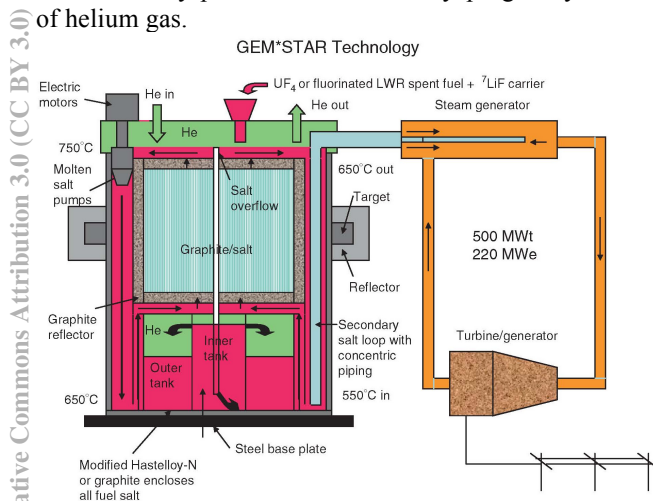


Figure 1: Conceptual design of the ADNA Green Energy Multiplier - Subcritical-technology, Thermal-spectrum, Accelerator-driven, Recycling reactor (GEM*STAR) molten salt reactor. A significant inherent safety feature is the helium purging of volatile radioactive by-products, which are not built up as in the fuel rods of conventional reactors; the constant purging practically eliminates the possibility of unintended release of radioactive elements.

This helium purging feature practically eliminates the possibility of accidental releases of radioactivity that is a well-known problem of technologies that employ fuel rods that must contain years of built-up radioactive volatile elements. In the molten-salt case, the usual containment vessel may not be required.

The heat exchanger salt includes a large-volume reservoir to reduce sensitivity to accelerator beam interruptions to the point that power output from the turbine/generator can continue even for accelerator down times of several hours. The fuel itself, being liquid, is insensitive to shorter accelerator interruptions that are troublesome for solid fuels because of fatigue.

The practicality of the molten-salt concept was demonstrated in an experiment at ORNL in the 1960s:

MOLTEN-SALT REACTOR EXPERIMENT

1969 MSRE Report Abstract [3]

“The MSRE is an 8-MW(th) reactor in which molten fluoride salt at 1200°F circulates through a core of graphite bars. Its purpose was to demonstrate the practicality of the key features of molten-salt power reactors.

Operation with ²³⁵U (33% enrichment) in the fuel salt began in June 1965, and by March 1968 nuclear operation amounted to 9,000 equivalent full-power hours. The goal of demonstrating reliability had been attained - over the last 15 months of ²³⁵U operation the reactor had been critical 80% of the time. At the end of a 6-month run which climaxed this demonstration, the reactor was shut down and the 0.9 mole% uranium in the fuel was stripped very efficiently in an on-site fluorination facility. Uranium-233 was then added to the carrier salt, making the MSRE the world's first reactor to be fueled with this fissile material. Nuclear operation was resumed in October 1968, and over 2,500 equivalent full-power hours have now been produced with ²³⁵U.

The MSRE has shown that salt handling in an operating reactor is quite practical, the salt chemistry is well behaved, there is practically no corrosion, the nuclear characteristics are very close to predictions, and the system is dynamically stable. Containment of fission products has been excellent and maintenance of radioactive components has been accomplished without unreasonable delay and with very little radiation exposure.

The successful operation of the MSRE is an achievement that should strengthen confidence in the practicality of the molten-salt reactor concept.”

It remains to recapture the expertise that was demonstrated more than 40 years ago and to extend it based on technology that has been developed since then.

SRF-BASED ACCELERATOR

Superconducting RF Linac

The most popular accelerator contenders for ADSR applications that have the potential to provide 10 MW, 1 GeV continuous proton beams include cyclotrons and fixed-field alternating synchrotrons as well as SRF linacs. While SRF linacs are likely to be the most expensive due to their complexity and component costs, they are the

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most likely to achieve the required energy and power parameters. This can be seen by extrapolating the 1.4 MW performance of the SNS pulsed H⁻ linac with its 6% duty factor to CW operation, where the Jefferson Lab CEBAF machine is a model for CW SRF technology.

One uncertainty in this extrapolation is the requirement of loss rates in the linac, which should be kept below 1 W/m to avoid levels of induced residual radioactivity in the linac components that would make hands-on maintenance difficult.

As previously discussed [5], the easiest and surest way to achieve higher beam power with an SRF linac is to increase its energy. Beta = v/c = 1 SRF structures are the most efficient and have built-in redundancy. Nuclear shower sizes that are required to match to the dimensions of a reactor are only logarithmically dependent on the incident proton energy.

Economies of scale will eventually be important for ADSR, since in many markets, the issue will be cost per kw-h in comparison with other power sources, including conventional reactors and fossil fuel power stations. The natural maximum size of a molten-salt reactor such as GEM*STAR as shown in Figure 1 implies that a multiple-GW power station may have one or two dozen reactors that need 10 MW each for operation. Perhaps more if deeper burns are desired. The present design of the first phase of the (~1\$B) Project-X proton driver is for a 5 to 10 ma H-minus source (limited to 1 ma average) that will operate CW at 3 GeV. Its design could eventually be upgraded to handle a 100 ma proton source for 300 MW to feed 30 molten-salt reactors.

The upgrade would require only slightly more cryogenic infrastructure but would need higher-power RF sources and couplers, added redundancy, efficient beam splitting and distribution schemes based on the same transverse-kicking RF used at CEBAF, and highly efficient and fast trip recovery and beam loss protection techniques. These additional requirements could be met with an enthusiastic R&D program that could be an additional goal of Project-X to augment its HEP importance. Such an ambitious goal would complement the development of a national power grid with sufficient capability to handle very large power stations.

However, to get started and to develop confidence that there are no surprises, it is possible to use a smaller energy and beam power, perhaps as little as 500 MeV at 2.5 MW. Very little development effort for reliability may be needed for the first stage because of the intrinsic insensitivity of the molten-salt fuel to short-term interruptions and because of the buffering provided by the large volume molten-salt heat exchanger to cover longer interruptions.

Spallation Target for ADSR

The SNS spallation neutron target and other high-power targets under development [6] are expensive and complex in part because the heat produced is large and difficult to remove from the relatively small interaction region where the beam is absorbed, and also because the

beam is pulsed, which adds shock to the problem. For ADSR, the beam is CW, relatively diffuse, and the target and molten-salt fuel can share the same volume inside the reactor. In this latter case, the heat from the target can be handled naturally by the heat exchange salt and some of the power used by the accelerator can be recovered.

CONCLUSIONS AND OUTLOOK

For a multi-GW ADSR power station, the accelerator costs, both capital and operating, will be small relative to the revenue stream. Nevertheless, the operational parameters are far from being developed to industrial standards, and a demonstration accelerator-driven subcritical molten-salt reactor is an essential first step. Relative to the costs of research accelerators, the initial step is large. However, relative to industrial power generation, the initial investment to develop accelerators for the next generation of nuclear reactors can be relatively modest.

ADSR using molten-salt fuel has impressive advantages: 1) ability to burn any number of materials including conventional reactor waste, excess plutonium from weapons, and very abundant thorium; 2) exceptional safety advantages including subcriticality to eliminate Chernobyl disasters, 3) no build-up of volatile radioactive elements to eliminate 3-Mile Island problems; 4) no storage of solid nuclear waste that can catch fire.

The Fukushima problems may generate more interest in new techniques for nuclear power. The advantages of an accelerator driven subcritical molten-salt reactor are clear. The accelerator community has an opportunity to play an important role in developing this concept for the health and prosperity of the world.

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