For most Americans, it is difficult to imagine the need for energy, clean air, or clean water. However, in many parts of the world, people have little energy available to them, and in many others, the air and water are polluted. Energy is a driving force behind modern living and the need for energy is growing. Figure 1 shows the consumption of energy in the United States over the course of its history by resource [1]. The United States benefits from a diverse set of energy sources but remains predominantly reliant on fossil fuels for electricity and transportation, while emission-free energy sources such as nuclear and renewables provide smaller but significant amounts. The transportation sector is powered mostly by petroleum, which is the largest single source of energy consumed. The U.S., and other developed nations, are looking beyond fossil fuels. Emerging nations want to expand their energy consumption. New clean energy options are needed.

When I began studying nuclear engineering in 1982, I had it in my mind that the concepts of nuclear physics and engineering were old and settled science. They were not. Einstein published his famous equation in 1905. It was a mathematical novelty of mass and energy equivalence, but at the time, no one understood that mass could actually be converted into energy for useful purposes. The atom was thought to be indestructible. The great nuclear experimentalist Ernest Rutherford, who discovered the nucleus but could not break it, is quoted as saying, “The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from transformation of these atoms is talking moonshine.” The accuracy of that statement is disputed, but the implication was clear; based on what we knew then, nuclear disintegration would not amount to a useful energy source. That sentiment was reported in September 1933.

Enrico Fermi produced fission in laboratory experiments in 1934, but not until Lise Meitner and her nephew Otto Robert Frisch worked it out during a winter hike in 1938 did we understand that the ~1/5 of a proton mass lost during a uranium fission was the physical embodiment of Einstein’s relationship [3]. The conversion of a small amount of mass results in an incredible amount of released energy. The possibility of establishing chain fission reactions was soon postulated, and the first successful demonstration of self-sustaining nuclear fission was performed at the University of Chicago in 1942. The Chicago Pile demonstrated that it was possible to get controlled, sustained energy from a properly designed reactor. From that demonstration, the first reactor designed for continuous operation was constructed at what is now the Oak Ridge National Laboratory (ORNL) in East Tennessee. The X-10 Graphite Reactor Experiment, shown in Figure 2, took only nine months to build and became operational in November 1943. It was a solid fuel reactor into which individual fuel pellets were loaded into ~1260 channels running horizontally through a fixed graphite matrix. The graphite held the fuel in place and provided the neutron moderation, the slowing of neutrons to increase their likelihood of producing a fission, as part of what is called a thermal neutron spectrum. Neutron moderation is needed for criticality in this design.

This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).
The reactor operated at a maximum power level of approximately 4-MW and air was pulled into the front of the channels to cool the fuel and graphite. In over 20 years of operation, the basic principles of reactor physics were confirmed, and the first production of usable quantities of medical isotopes and transuranic materials occurred. The Graphite Reactor operated until 1963. Today, it is a National Historic Landmark you can tour if you visit ORNL.

During the X-10 Reactor’s operational life, hundreds of reactor concepts of various shapes and sizes were conceived and dozens were constructed and operated. One of those concepts was the molten salt reactor (MSR) and approximately 60 variants of them were considered to one degree or another within the United States alone.

A salt reactor is any reactor that uses molten salt within the core to a significant degree as a fuel carrier or coolant. Concepts that use solid fuels are typically cooled by fluoride-based salts and are referred to as fluoride high-temperature reactors (FHRs). Concepts that include fueled liquid salts as part of the primary system fluid are generally referred to as molten salt reactors. MSRs were the subject of a great deal of concentrated research beginning in the 1940s and extending into the 1970s. The pioneers of the technology, R.C. Briant and Alvin Weinberg, described the potential for the concept in 1957 [2]. By this time, a high-temperature molten salt reactor, the Aircraft Reactor Experiment (ARE), had already been demonstrated and projections of sound economic performance were already being made. By 1960, enough was known to begin building and operating MSRs to evaluate their potential for commercial operation. The first of these reactors, the Molten Salt Reactor Experiment (MSRE), began critical operations in 1965.

ORNL began discussing the use of molten salts as a reactor fuel and coolant around 1950. The basic MSR features are shown in Figure 3. As the liquid fuel enters the reactor vessel, it assumes a critical configuration and the salt is heated by fission. A pump moves the salt through a heat exchanger and the heat is transferred to and removed by a second heat transfer loop to be used as a heat source or converted to electricity. In this example, the salt can be transferred to a drain tank for processing or safe storage as needed, but not all concepts utilize drain tanks. Because the boiling temperatures of salts are very high, MSRs operate at a low pressure and have a wide temperature margin to coolant boiling. This allows for the use of thinner-walled components and reduces the chances of over-pressure events.

ORNL successfully demonstrated the key features of operational stability, reliability, and flexibility in the mid to late 1960s with the MSRE, shown in Figure 4. The reactor vessel, pump, and heat exchanger can be seen on one level in addition to a series of salt drain tanks below. The MSRE operated at approximately 7.4-MW, but it is physically much smaller than the X-10 Reactor, as can be seen in Figure 5, which shows the reactor vessel prior to installation. As the fueled salt enters the vessel, it flows into and through vertical coolant channels in the internal core structure, shown in Figure 6. The core structure is also the graphite moderator necessary for criticality in this design. If the salt is not in the vessel, it will not be in a critical configuration. In the MSRE, the salt is passed through a single heat exchanger by a single pump and heat is removed and dissipated by a second heat transport system. Larger MSR concepts use multiple pumps and heat exchangers, but overall, MSRs are simple devices.

Currently, three predominant salt reactor technology options are under consideration for early commercial deployment:

1. liquid-fueled fluoride-salt thermal-spectrum systems derived directly from the MSRE experience,
2. fluoride-salt high-temperature reactor (FHR) concepts using MSRE-derived salts to cool a solid fuel form, and
3. liquid-fueled chloride-salt fast-spectrum reactors.

Each option follows from the historic MSR program, but differ in salt and material selections, neutron energy spectrums, and business strategies. The fast spectrum reactor concepts do not use internal core structure for neutron moderation and can have very high power densities. Both thermal and fast MSRs can consume long-lived wastes that would otherwise require disposal and they can extend the available energy of nuclear fuels through breeding. An excellent review of fast spectrum molten salt reactor options is available [4].
**Elevation View of Reactor and Fuel Drain Cells**

![Diagram of Reactor and Fuel Drain Cells](image)

Figure 3: Simplified Molten Salt Reactor system featuring a reactor vessel, pumps, heat exchangers, and drain tank. (ORNL-DWG-68-4190a)

**FIGURE 4 KEY**

1. Reactor Vessel  
2. Heat Exchanger  
3. Fuel Pump  
4. Freeze Flange  
5. Thermal Shield  
6. Coolant Pump  
7. Radiator  
8. Coolant Drain Tank  
9. Fans  
10. Drain Tanks  
11. Flush Tank  
12. Containment Vessel  
13. Freeze Valve

Figure 4: The Molten Salt Reactor Experiment. (ORNL-LR-DWG-63-1209R)
MSRE’s success was built on a substantial foundation of scientific and engineering effort pursued at scale for 15 years prior to initial operation. The extensive science and technology achievements are captured in some one-thousand technical reports. Successful reactors were built and operated in just a few years and with modest funding. Material combinations worked well enough for short-term demonstrations, and salt-handling processes proved adequate for protecting personnel, equipment, and the environment.

MSRE had over 13,000 hours of full-power reactor operation, and in one operational run it operated for six months without interruption—quite remarkable for a first-of-a-kind reactor demonstration. The MSRE was the first in a series of four reactors that were planned to achieve commercial deployment:

1. The Molten Salt Reactor Experiment (MSRE) was a 10-MW proof of concept reactor with limited fuel processing.
2. The Molten Salt Demonstration Reactor (MSDR) was to be a larger (750-MW) reactor concept to show that the operation observed in the MSRE scaled up to representative commercial reactors, but without the added complexity of significant fuel processing.
3. The Molten Salt Breeder Experiment (MSBE) was a 150-MW concept that was to demonstrate the full suite of fuel processing needed to operate a closed uranium-thorium fuel cycle in a molten salt reactor.
4. The Molten Salt Breeder Reactor (MSBR) was envisioned as a commercial prototype in which the full capability demonstrated in the MSDR and the MSBE were brought together into a single system.

Progress toward salt reactor commercialization is again occurring. Developers are maturing their designs, developing and demonstrating technology, and gathering data needed for licensing. Because of their attractive safety features and by using modern design and modeling tools, it is anticipated that new plants can be modeled with sufficient accuracy to directly support licensing and operation of commercial prototype plants, helping to significantly reduce both the time and cost to market.

**Why MSRs and why now?**

The direction chosen for the nuclear industry in the late 1950s led to the development of light water reactors (LWRs) for commercial deployment. The sodium fast reactor system was intended to work in concert with LWRs to close the fuel cycle and to increase utilization of what was then thought to be a much smaller supply of uranium. Over one hundred commercial LWRs were constructed and operated in the United States, and they have provided safe, reliable, clean electricity for decades. Worldwide, 400-450 commercial reactors have been operational at any one time since the mid-1980s. However, projected increases in electricity demand in the 1960s and 1970s largely did not materialize and significantly more uranium resources were discovered. Fewer LWRs were built than planned and commercial fast reactors were not extensively deployed. Commercial nuclear power is still in its early phases and its potential has yet to be fully realized.

It is challenging for existing reactors to compete in today’s U.S. energy market. Natural gas prices are historically low and renewable energy options are often subsidized through clean energy production credits. The market does not currently monetize the reliability, stability, and reduced emissions of nuclear plants. Cost is certainly an important metric for a robust energy strategy, but it is not the only one. Diversity, availability, environmental impact, and the ability to achieve energy independence are also important national considerations. Nuclear energy in general can help with all of these issues and MSRs can potentially offer improved economic performance.

The higher temperatures of salt reactors allow for improved power conversion efficiencies and the lower pressures can help reduce the cost of reactor components. Emerging advanced manufacturing methods, plant standardization (for a given developer), the use of factory construction methods, and plant automation may also be important parts of successful economic performance. Salt reactors are also fueled during operation, which allows them to be online a higher percentage of the time. Online fueling also limits the amount of fuel in the system to only that needed, which reduces the number of possible accident scenarios and their potential consequences. As a simple system that operates at low pressures with a limited fuel inventory, salt reactors are attractive from both a safety and economic perspective. Salt reactors can be large, like current LWRs, or they can be small and modular. They can use a range of fuels, even within the same design, and they can be used to consume fuels discharged from other reactors. They can also operate as breeders, allowing for increased resource utilization. Salt reactors have the flexibility to adapt to many aspects of a modern energy market.

**The need for more clean energy**

The modern world requires electricity. As societies increase their levels of electrification (think cars, computers, automation, and communications), and as developing countries look to replace existing fossil-based systems with cleaner energy options, new energy options are needed. Approximately 450 commercial reactors produce approximately 10 percent of the world’s electricity and about 1/3 of the low-carbon electricity. Coal and natural gas currently supply approximately 60 percent of the world’s electricity. Renewables such as hydro, solar, biomass, and wind produce approximately 23 percent of the total electricity [5]. Solar power and other renewables...
have come a long way and they continue to make excellent progress, but today, we cannot run energy-intensive economies on renewable energy alone. To maintain the current level of clean energy production, we will eventually need to replace the existing reactor fleet. To expand clean energy production to the point of replacing fossil fuels, we would have to increase generation many times over its current capacity. The key to success will be to identify and develop the best technologies and to use them together. It will be most effective to combine the foundational base of clean nuclear energy with the opportunistic clean energy of renewables, and we are working to do just that within the integrated energy programs sponsored by the U.S. Department of Energy [6]. Working together, we can get there.

The next phase of nuclear power

The MSR Program was officially terminated in 1976. There simply did not seem to be a need for another nuclear reactor technology at that time. I studied nuclear engineering at the University of Tennessee, about 30 miles from ORNL. Dr. Tom Kerlin, South Carolina Beta '58, was one of my professors. He worked with Syd Ball on the MSRE and they published papers about its stability and control that are still used today [7]. I learned about MSRs as a student and later as a colleague to people like Syd and Uri Gat at ORNL. New interest arose in FHRs and MSRs through the efforts of national laboratory and university programs led by new champions such as David Williams, Charles Forsberg, Per Peterson, Nevada Alpha '82, and David Holcomb, and by independent efforts from others, such as Kirk Sorenson, and David LeBlanc, who gave an excellent technical review of the technology in 2010 that I encourage you to read [8]. Through these initial efforts, and now with the combined efforts of hundreds of others around the world, we are working on a second opportunity to develop MSRs.

A major difference in the new MSR development effort is that industry is leading the way. Worldwide, more than ten private companies have active MSR or FHR designs under development using private investment. The first demonstration salt reactors since the MSRE are expected in the U.S. within five years, and commercial plants are planned before the 2030s, in time to help replace the clean energy lost as the existing fleet begins to age out. Another significant difference is that the pressing need for abundant clean energy is more widely recognized.

Clean energy means more than just having clean air and water. It means the possibility of a stable, sustainable future for everyone. It seems unlikely that society can expand, modernize, reduce poverty, and be sustained without the clean energy that can be provided by fission and (someday) fusion energy. The nuclear industry continues to maintain its impressive safety record, address waste concerns, and be vigilant about weapons proliferation. It is also working to becoming more innovative, cost competitive, and flexible. MSRs are promising candidates to address these issues and emerge as a new clean energy option.

MSRs are demonstrated technology, they are flexible in design and purpose, they can be used to help close the nuclear fuel cycle, and they allow for effective utilization of the vast uranium and thorium resources. They may also significantly improve nuclear energy economics. Yes, they are a little different; but it’s time to try something new (even if it’s old).

Louis Qualls, Ph.D., is the national technical director for molten salt reactors for the U.S. Department of Energy’s Office of Nuclear Energy and also serves as the reactor technology integration lead for the Oak Ridge National Laboratory Reactor and Nuclear Systems Division. In these roles, he works with the DOE to support industry efforts to develop and deploy commercial molten salt reactors. Lou has been a researcher at ORNL since 1988, working on a wide range of nuclear projects, including fusion energy, nuclear space power systems, and advanced fission reactor concepts. He holds a Ph.D. in nuclear engineering from the University of Tennessee, Knoxville.
Figure 6: The MSRE core internal structure, assembled from individual extruded graphite components to form coolant channels on the perimeter of each piece. (ORNL Photo 70797)

From the Editors: Tau Beta Pi does not advocate the use of one energy source over another. Information in the article is attributed to the author and the references provided below.

References


