Creating The Ultimate Reactor

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Several next-generation nuclear reactor designs hold the promise of almost completely solving the worst concerns about nuclear energy. There is still a long way to go, however, before we see the “ultimate reactor” in operation.
IN RECENT YEARS EXPERTS AND NON-EXPERTS ALIKE HAVE looked enthusiastically at nuclear power as a possible solution to the intractable problems posed by climate change and continued fossil-fuel dependence. There are good reasons for such optimism. If the world were to invest only one-half as much as France did during the last half of the twentieth century in nuclear power plant construction, about one-third of global carbon emissions would be eliminated.[1] Of course, aggressive new nuclear development would bring with it some downsides. For instance, a fairly robust worldwide nuclear growth scenario probably would create 1 million more tons of spent nuclear reactor fuel.[2] Finding ways and places to dispose of this waste would not be easy. Some experts believe that a renewed commitment to reprocessing, which removes uranium and plutonium from spent fuel for reuse in power reactors, could do the trick, but reprocessing itself raises significant proliferation issues, among other seemingly insurmountable challenges.

In an attempt to offer my own solution to the shortcomings of the conventional nuclear fuel cycle, I propose using something I have dubbed the “Ultimate Reactor System.” Although it is hypothetical, the Ultimate Reactor System allows us to define exactly what attributes are required to make nuclear energy a sustainable energy source for the planet. The system's requirements would be absolute: no uranium mining, no uranium enrichment, no reprocessing of spent fuel, and no troublesome long-lived nuclear waste products.

The ultimate reactor would have perfect fuel utilization—meaning that any uranium or other heavy metal fuel entering the reactor would ultimately undergo fission—and that demand for new uranium mining would be nil. Fuel for this reactor should be *only* natural or depleted uranium, possibly thorium, and/or spent nuclear fuel. Outputs would be electricity and/or hydrogen, waste heat, and fission products in need of disposal such as cesium 137 and strontium 90 (these fission products tend to have shorter half lives, hopefully making the waste problem much less politically contentious).[3] There would always be some waste heat, which is required by the laws of thermodynamics, but it would contribute much less to climate change than what is released by burning fossil fuels.[4]

Over the years, several proposed designs have attempted to achieve some, if not all, of these benchmarks—most notably, the Integral Fast Reactor, the Molten Salt Reactor, and the newer and less-known Traveling Wave Reactor. The first two systems were mothballed because of high projected development costs and unanswered technical questions. But it should be noted that if they had been further developed, they may have significantly reduced waste generation and reduced proliferation risks. Each of these three proposed systems offers clues and lessons about how such a perfect reactor might be achieved.

A history of the Integral Fast Reactor. While fast reactors have long held the promise of functioning as the ultimate nuclear system, they have had a difficult history. Both small and large fast reactor prototypes have been built in several countries, but in declining number over the past decades. In fact, there is a growing conviction that such reactors will never be economically competitive with conventional light water reactors, unless a radically new design becomes available. The most widely used fast reactor fuel cycle in the world is the breeder model, where the reactor makes or “breeds” its own fuel. But it still requires external fuel reprocessing and the stockpiling of plutonium for later use, disqualifying it from my ultimate reactor system because of the proliferation problems it creates.

To address some of the breeder reactor's shortcomings, U.S. researchers at Idaho National Laboratory began designing the concept of the Integral Fast Reactor in the mid-1980s. The Idaho lab has extensive experience with many of the components needed to build a prototype Integral Fast Reactor, because of years of operating the Experimental Breeder Reactor II. The program developed many innovative and interesting ideas that could be implemented in a future prototype, but it was never well funded. The program was terminated in

1994 by President Bill Clinton when oil prices were low and concerns about climate change were not widespread.

How it works. The Integral Fast Reactor was intended to combine the entire fast reactor fuel cycle into one facility, including reprocessing and fuel fabrication. It required metal fuel elements made from uranium, plutonium, and other isotopes that are harvested from the spent fuel of conventional nuclear reactors (and also from excess weapons plutonium). Further supplies of fuel would be produced by reprocessing the reactor's own spent fuel. The emphasis of the reactor design was on completely burning all long-lived radioisotopes; and due to this, it would appear to meet some of my objectives of the ultimate reactor.

This reactor concept could overcome some proliferation objections by providing technical barriers to diverting highly radioactive “transuranic” material—elements with atomic numbers higher than uranium such as neptunium, americium, curium, plutonium, etc. The recycling of this material is via a reprocessing technology that cannot remove many of the highly radioactive fission products from the fuel. Thus, the reprocessed product is dubbed “self-protecting” as a result of the high-gamma radiation emitted from it. The chemistry involved further cannot produce a plutonium product that is not at least 25 percent contaminated with uranium; the plutonium is always mixed with isotopes that provide substantial decay heat and neutron radioactivity. The process must also be conducted in a heavily shielded, argon gas-filled room, where humans could not enter without rapidly receiving a lethal dose of radiation. All access would be via robot.

What could be used in an ultimate reactor system. The Integral Fast Reactor offers the chance to burn all plutonium, americium, curium, and neptunium from spent nuclear fuel, greatly reducing the complexity of nuclear waste disposal. And because everything is based at a single site, no plutonium would leave the confines of the reactor building, thereby addressing proliferation threats. Because the system continually recycles all of its fuel, using only a small additional stream of uranium as an input, mining requirements would be greatly reduced. This has always been one of the great potential advantages of fast reactors, a reduction in uranium mining and consequently reduced environmental damage per unit of electricity output.

What doesn't work and needs more research. First and foremost, the biggest drawback of this reactor design was cost. The upfront reprocessing of commercial reactor spent fuel to fabricate the initial fuel feedstock and the need to continuously remake the fuel guaranteed that the Integral Fast Reactor would always be more expensive than a conventional reactor per unit of electricity output, Most fuels to date have either been made strictly of uranium or uranium/plutonium mixtures. It is uncertain if the novel fuel in the reactor would have the excellent safety characteristics of conventional nuclear fuel. even if the reactor itself cost the same to build. Only if the construction costs of this new reactor could be made lower than a conventional nuclear plant would this technology ever be competitive. Additionally, an extensive fuel-research program would be required to lower fuel-related reprocessing and fabrication costs.

The reactor fuel's mixture of radioactive isotopes presents a new unknown to nuclear engineers and safety specialists. Most fuels to date have either been made strictly of uranium or uranium/plutonium mixtures. It is uncertain if the novel fuel in the reactor would have the excellent safety characteristics of conventional nuclear fuel. Moreover, much of the chemistry that would be required for the reactor to work effectively as an ultimate reactor system has not been demonstrated. For instance, a research effort would be needed to keep the reactor's structural and cladding material from becoming contaminated with neptunium, americium, curium, and plutonium; otherwise, another waste stream requiring a geological repository would need to be created. Also, small gaseous and liquid releases to the environment from the chemical processing facilities within the Integral Fast Reactor would be unavoidable—a potential source of public consternation even if there is not much firm science supporting the belief that such releases have negative health impacts.

A history of the Molten Salt Reactor. Alvin Weinberg, the first director of Oak Ridge National Laboratory in Tennessee, and some other early nuclear physicists were enamored with this fluid-fueled reactor design. When configured as a Molten Salt Breeder Reactor, it offered the potential for 100 percent fuel utilization and integrated fuel processing, and it could potentially be made to burn spent fuel without external reprocessing or the fabrication of fuel rods. It also could use plentiful thorium 232 as a fuel, which is about three times as abundant as uranium in the Earth's crust and waste streams could be about two to three times less radioactive.

By the early 1970s, the molten salt reactor program at Oak Ridge had produced several concept designs and even a small prototype was built.[5] Because of the potential benefits of a thorium-based fuel cycle, but due to potential proliferation concerns surrounding the weapons-usable uranium 233 isotope produced as part of it, a second molten salt reactor dubbed the Denatured Molten Salt Reactor was designed in 1980; yet, it was never built due to cost and technical concerns.[6]

The molten salt reactor program was finally scrapped by the early 1980s because the technical challenges were considered to be too large and liquid-metal cooled fast breeder reactors showed more economic promise. Although a decision was made to cancel the program, molten salt reactors still have advocates and there are still some small research programs around the world.

How it works. In a Molten Salt Breeder Reactor, the nuclear fuel is in the form of a fluoride salt dissolved in a molten salt carrier, the composition of which may be one-half lithium fluoride and one-half beryllium fluoride. The molten salt flows through circular cross-section channels bored directly into a graphite moderator (slowing neutrons to encourage fission) in the core. The nuclear reactions occur while the fuel is in the presence of the moderator. Next, the fuel flows to a heat exchanger to transfer its heat energy to a secondary coolant that eventually drives turbines and generates electricity. It can be fueled by non-fissile thorium, which absorbs neutrons in the reactor and decays to protactinium 233, which then decays in a few days to uranium 233, a usable nuclear fuel. In the reactor, uranium 233 absorbs a neutron and fissions, producing either two or three additional neutrons that go on to continue the nuclear reaction and keep the reactor functioning.

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The design of the more proliferation-resistant Denatured Molten Salt Reactor required continuous fueling with both thorium and low-enriched uranium and required minimal fuel processing (only xenon and krypton gases were removed). No fissile material was recovered. The uranium in the reactor was not weapons usable, due to the continuous addition of uranium 238 and the fact that neither protactinium nor uranium 233 was to be stored outside the reactor. A feed consisting of a mix of thorium and spent commercial fuel could alternatively be burned in the Denatured Molten Salt Reactor, making it a viable candidate for my ultimate reactor.

What could be used in an ultimate reactor system. The reactor's liquid fuel makes this system passively safe against power spikes caused by sudden changes in operating conditions, such as loss of a coolant pump, or the blockage of a coolant channel. In fact, the reactor is so stable that control rods may be unnecessary, save for shut down purposes. Additionally, as the fuel fissions and its composition changes during the lifetime of the system, it will not cause the reactor to become unstable, a significant problem in fast reactors.

Molten salt reactors also have the potential to *fully* recycle conventional light water reactor fuel. Here's how it would work: First, entire spent fuel assemblies from light water reactors, consisting of stainless steel and zirconium-clad uranium oxide fuel interspersed with plutonium, would be lowered into a bath of molten lithium fluoride salt. Then pure fluorine gas would be bubbled through the liquid at high pressure, burning all of the metals (including uranium and plutonium) into fluoride forms that would then be soluble in molten salt. Finally, an electrochemical process would remove fission products and structural remnants such as radioactive iron, nickel, and zirconium for permanent disposal. The remaining liquid salt would be fed into the molten salt reactor as fuel, making reprocessing and fuel fabrication unnecessary.[7]

The ability of the reactor design to use thorium-based fuel is also a major benefit and a reason why it still has supporters. The reason is clear—known U.S. thorium reserves are enormous and single-handedly could supply fuel for the world's entire nuclear capacity for the next 2,000 years! A thorium-burning reactor, if engineering practicalities were overcome, could continue to provide replacement nuclear electricity for retiring light water reactors without generating any significant transuranic waste stream of its own. This presumes, however, that at the end of the roughly 60-year service life of the reactor, the molten fuel would be transferred to a new molten salt reactor for continued use. The system has many qualities that would make it a good candidate for an ultimate reactor system.

What doesn't work and needs more research. Although the reactor sounds great, there are some negatives. Fission products that are produced continuously in the fuel must be removed or else they will act as a “fission poison” and shut down the reactor. Hence, a chemical processing system for the fuel salt must be continuously operating as fuel flows into and out of the reactor—both a technical challenge and a proliferation concern. Another problem is that the reactor may not produce enough uranium 233, which is necessary to produce enough fast neutrons that can then fission more atoms. To solve this problem, the original Molten Salt Breeder Reactor design included processes to continuously recover and store protactinium outside the reactor core, which would decay to uranium 233 over a few days and then be returned to the core to keep the reaction going. But again, this presents both a technological challenge and a proliferation concern since it produces a pure stream of weapons-usable uranium.

The Denatured Molten Salt Reactor, designed to deal with some of these proliferation concerns, was hamstrung by its own problems. A complete nuclear accounting of this reactor design shows that the process would be inefficient. The main reason is that the relative proportion of spent fuel in the feedstock must be small, necessitating many more such reactors than traditional fast reactors to burn up the entire existing inventory of spent nuclear fuel. To completely burn the entire accumulated U.S. spent fuel stockpile (which is projected to equal 1 million tons in 50 years) would take a fleet of such reactors a century.

There are some technical obstacles to be overcome as well. The graphite moderator in the core would last only a few years, so the system would regularly have to be shut down completely for core replacement. As such, a viable method of reprocessing and reuse of radioactive graphite would have to be found. Furthermore, some aspects of molten salt chemistry are not well known. For instance, it is suspected that plutonium can precipitate out of molten salt, creating a potential safety issue if too much plutonium were to agglomerate in one location in the reactor's piping and create a hot spot. To further understand phenomena such as these, a long, involved, and costly experimental program would have to be carried out. Such a research program would suffer from the same proliferation concerns as other research involving separated nuclear materials. Lastly, the molten salt itself is of concern because when exposed to radiation inside the core, it produces large quantities of radioactive tritium. Making matters worse, no one has found a way to remove and store kilogram quantities of tritium in a completely safe fashion without leakage to the environment. It seems that another salt (or an entirely different fluid) should be found to address this issue.

> The Traveling Wave Reactor has some great features, including no reprocessing, almost no enrichment, and up to 50 percent fuel utilization—a dramatic improvement over existing reactors.

A history of the Traveling Wave Reactor. This reactor design was originally proposed at a 1958 International Atomic Energy Agency meeting, where it caught the attention of Edward Teller.[8] It remained otherwise unnoticed, however, for much of the latter half of the twentieth century. In the past few years, it has attracted support and venture capital from Intellectual Ventures, funded by former Microsoft executives including Bill Gates. The company conducting the research is Terrapower, and its principle idea is for a reactor that burns its initial fuel load for up to 60 years without refueling. The basic idea has had several incarnations in its history. For several years, Teller promoted a traveling wave reactor based on thorium fuel and slow-moving “thermal” neutrons similar to conventional reactors. The Terrapower concept is a uranium-fueled fast neutron reactor design.

How it works. The current iteration of the Traveling Wave Reactor is a uranium-fueled fast reactor started by inserting a small piece of 10-percent enriched uranium fuel at one end of the otherwise depleted or natural uranium metal-filled core.[9] The reaction starts locally at that end. Uranium 238 is transmuted inside the reactor to plutonium 239 for further burning. The reaction (transmutation followed by fission) proceeds along the several meter-length core, taking decades to first convert and then burn from one end to the other. At all times after the initial startup, the mixture of isotopes in the core is not weapons usable, and the system contains no subsystems or processes that can remove weapons-usable material. There is almost no enrichment and there is no reprocessing at all during the lifetime of the reactor.[10]

What could be used in an ultimate reactor system. The Traveling Wave Reactor has some great features, including no reprocessing, almost no enrichment, and up to 50 percent fuel utilization—a dramatic improvement over existing reactors. These reactors are able to produce carbon-free and mining-free electricity and generate very tiny waste streams for many decades making them viable candidates for my ultimate reactor. The environmental footprint of such a system would be almost zero, when compared to other energy systems producing the same amount of power.

What doesn't work and needs more research. The reactor would be liquid-sodium cooled—which has been prone to leaks and fires during operation and maintenance. In fact, many of the shutdowns and problems at fast reactors throughout their history have been caused by problems with liquid-sodium coolant. It might be possible to use a pool filled with sodium in which the reactor would be immersed. This has proven to be more reliable than other configurations that use meters upon meters of intricate piping and other mechanical features that are vulnerable to wear, tear, and leaks. Alternatively, another coolant could be found.

Also the reactor cannot burn spent fuel, unless the fuel is first reprocessed and made into metal. There is also no firm plan for the burning or transmuting of the end-of-life fuel residue in the core, although there are some concepts under discussion. To take the Terrapower system to the point where it functions like an ultimate reactor would require a second generation of Terrapower reactors that would use the first generation's core residue as fuel along with a stream of spent fuel from conventional commercial power reactors.

There are also several technical questions about this design that are familiar ones to the reactor research community. Most important is how the fuel and structural material would be affected after decades or irradiation inside the reactor core. The exposure of materials to radiation is measured by displacements per atom. When a fast moving neutron strikes an atom in a metal it often knocks the atom out of place in the metal's molecular lattice. Roughly speaking, this would be called 1 displacement per atom. As conceived, the Traveling Wave Reactor shall inflict between 400 and 500 such displacements per atom on the materials inside the core by the end of the reactor's lifetime. No one really knows what happens to materials that have undergone such extreme punishment. A liquid sodium-cooled fast reactor that the United States operated for 30 years was irradiated to 200 displacements per atom, and the results were fairly encouraging. Today, there are no U.S. facilities available to obtain more data, however. Terrapower researchers are seeking to use Japanese or Russian facilities for this purpose, but it will take at least four years of full-time testing to accumulate the necessary information. For this reason alone, no one should expect to see a Traveling Wave Reactor operating for at least a decade.

> The difficult problems that need to be solved in order to make an ultimate reactor should not be taken to mean that the task is impossible. It is rather to be understood that many years of moderate up-front investment in problem solving will have to be undertaken.

Final Thoughts. All these next generation reactor designs get us at least partially to my ultimate reactor system. Such a reactor would share many aspects of the older designs but solve many of their faults as well. The difficult problems that need to be solved in order to make an ultimate reactor should not be taken to mean that the task is impossible. It is rather to be understood that many years of moderate up-front investment in problem solving will have to be undertaken. New large demonstration facilities, that tend to create entrenched vested interests and to be politically polarizing, should be avoided. If the final reactor system is to be economically competitive with conventional reactors, it will probably look much different from any we envision now. Although there are no magic bullets to solve nuclear energy's problems or the challenge of climate change, there may be a solution out there, waiting to be discovered and developed.

Article Notes

- William C. Sailor has been a staff member at Los Alamos National Laboratory since 1987. He received his PhD in nuclear engineering at the University of California, Berkeley, and has published more than 50 articles on nuclear instruments, nuclear energy and nonproliferation policy analysis. The author is indebted to Harold McFarlane of Idaho National Laboratory and Kevan Weaver and Laura Hermann of Terrapower, LLC for their help with this article.
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