Nuclear Reactors: The Frontier of Energy Innovation

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ABSTRACT

Climate change and humankind's increasing need for energy challenge today's scientists and engineers to constantly innovate to find more efficient and cleaner ways to produce energy. The obvious solution to meet these needs is nuclear energy. Nuclear energy is the cleanest, as a function of output, energy procedure capable of helping to power the world for centuries. Over the past decades, nuclear energy has fallen out of public favor due to the potential to weaponize the nuclear materials and the environmental risks that come with malfunctioning nuclear reactors and storage of waste products. Current designs of nuclear power plants will likely remain subject to the risk of malfunction due to environmental disasters, system malfunctions, or human error. I propose that the solution to negate these risks and provide a practical plan for increasing the world's dependence on nuclear energy lies with the construction of alternative designs of nuclear power reactors such as the Traveling Wave Reactor, which is being designed by the TerraPower company.

BACKGROUND

At the beginning of the nuclear industry, nuclear reactors were designed and built using a fast reactor. These closed systems relied on high-breeding rates to produce new fissile Plutonium fuel from uranium-238. The main reason fast reactors were popular was that they did not rely on a constant input of Uranium (which scientist at the time believed was in limited supply). It was later discovered that Uranium deposits are quite common and the need for high-breeding rate, closed systems lessened. As the years progressed fast reactor designs became less popular; and began to be replaced by advancing technology in Light Water Reactors (LWR). LWRs are the more common reactors built and operated in the second half of the 21st century. They are also the most common reactor to have significant malfunctions due to varying circumstances, which mostly have to do with the failure of cooling systems. This was most notably evidenced in the Chernobyl accident and the Fukushima Daiichi accident, where a failure in the cooling systems resulted in melting cores in the reactors and distributing egregious amounts of radioactive material into the environment. These risks will always persist in LWR designs no matter what precautions are taken. There is an alternative fast reactor design that would negate these risk factors and be economically competitive to LWRs. This design is the Traveling Wave Reactor (TWR).

The earliest known design of the TWR was put forth by Russian physicist, Saveli Feinberg, in 1958. He suggested a design referred to as a breed-and-burn fast reactor. The breed-and-burn phenomena is meant to mirror how a cigar slowly burns. In the reactor a wave of nuclear fission advances slowly through a fuel source which creates and consumes its fuel as it travels to the core. During Feinberg's times, his design was deemed too expensive and hard to build compared to other reactor designs. The TWR concept did not get a resurgence until Edward Teller and Lowell Wood started building concept nuclear designs in the 1990s eventually creating the TWR, that is worked on by TerraPower.

THEORETICAL BIAS

The Traveling Wave Reactor design is an ingenuitive piece of engineering that compartmentalizes many of the reactors functions to make the reactor more efficient and safer. The design is based on the elements of sodium cooled, fast reactor technology. This technology has been well researched and tested as a viable example of a working nuclear reactor. The basic layout of the TWR is very similar to most sodium cooled, fast reactors. There is a *"cylindrical reactor core submerged in a large sodium pool in the reactor vessel, which is surrounded by a containment vessel that prevents loss of sodium coolant in case of an unlikely leak from the reactor vessel. The pumps circulate primary sodium coolant through the reactor core exiting at the top and passing through intermediate heat exchangers located in the pool. These heat exchangers have non-radioactive intermediate sodium coolant on the other side of the heat exchanger. Heated intermediate sodium coolant is circulated to the steam generators that generate steam to drive turbine and electrical generators" (1).*

This design includes safety precautions where, in the event of a shutdown, decay heat is removed by motors and, if those become inoperable during a power failure, natural circulation cools the system through a Reactor Vessel Air Cooling System (RVACS) and the Auxiliary Cooling System (ACS). TWR uses the same basic layout as the system described, but there are a few modifications and advanced concepts. TerraPower has designed the TWR to have improved applications of RVACS and ACS as well as modify the function and inner workings of the core.

In most of today's reactors, criticality is only reached when there is an abundance of Uranium-235. A neutron hits a Uranium-235 atom causing it to split into Barium and Krypton isotopes. When enough neutrons strike fissile Uranium atoms, there is a surplus of neutrons made in the collisions which allow a self-sustaining reaction. The TWR can use depleted Uranium which has a greater abundance of Uranium-238 than Uranium-235. TerraPower figured to use Uranium fuel pins as the fuel for the reaction. The reaction is started by having Uranium-238 atoms absorb the excess neutrons to become the isotope Uranium-239. This quickly decays to Neptunium-239 which decays to Plutonium-239. The neutrons collide with the Plutonium which creates an excess of neutrons, enabling the reaction to be self-sustaining.

A key difference in the TWR's core is that it is not fixed. The Uranium fuel pins are arranged in a hexagonal orientation and the system allows where the individual pins are to change, congruent with the reaction taking place so that the reactor runs more efficiently and prolongs the life of the core. Having the fuel pins periodically moving in and out of the breed-burn region creates a standing wave of breeding and burning. This "fuel shuffling" allows three things to happen. One, it allows operators to control the power distribution and burn-up to be in safe conditions. Two, it controls how much excess reactivity exists in the core. Three, it extends the life of the reactor which is determined by the number of fuel pins still available for fission. The shuffling is done on the inside of the reactor by equipment which monitors various environmental factors existing in the core to then establish the best use of the shuffling. The equipment lasts for the entirety of the reactors lifetime and allows the core to be isolated and not in need of human tampering or outside fuel.

Economic Argument

As of 2009, the Nuclear Regulatory Commission projected that advanced light water reactor designs, LWR, cost an average of “$1,500 per kilowatt electric of generating capacity”(2). The goal for the Nuclear Regulatory Commission is to advance reactor production to be at an average of $1,000 per kilowatt electric of generating capacity. This would make nuclear reactors competitive to the combined cycle Natural Gas plant. TerraPower’s cost and revenue projection plans argue that it will be more cost effective than LWR and the projected goal of the Nuclear Regulatory Commission.

TWR will also be more economically efficient than LWR due to the type and amount of fuel needed in each. LWR needs a higher refined Uranium which costs more than TWR’s depleted Uranium fuel source and LWR require additional refined fuel every 18 months to sustain reactions, whereas the TWR fuel shuffling allows the core and fuel to last its entire lifetime. Once the fuel pins and the lifetime of the TWR is finished those fuel pins are able to be reused and made into new fuel pins again for future Traveling Wave Reactors.

TWR, also operates at a higher thermal temperature than LWR. This means that the TWR runs at a “higher efficiency and produce[s] about 20% more electrical power. In the 1-GWe power range, this additional 200 MWe represents an increased revenue of over $100 million annually” (1).

Lastly, TWR reduces cost due to reduced amount of waste produced by the reactions. This saves money by not requiring on-site or permanent storage for waste. Most of the fuel is used in the reaction and would reduce the waste amount when compared to LWR.

SAFETY AND ENVIRONMENTALLY CONSCIOUS

TWR fuel eventually decays into Plutonium-239, which is the main element used for the atomic bomb. When hearing, this the public is likely to have a negative view on the production of these plants. They would be relieved, however, to hear that although Plutonium is present in the reaction it is quickly used as fuel and will not accumulate in the reactor. Stray neutrons split the Plutonium almost instantaneously into fission products. This means that there is no way to use the TWR for nuclear proliferation or weaponry. There is also a concern that the liquid sodium, used in cooling the reactor and driving the generator turbans, is problematic. Liquid sodium is a toxic metal that is highly flammable when exposed to oxygen. This fact caused nuclear reactor failures in Superphenix, France and in Monju, Japan. At these plants the sodium leaked into the fuel cores and caused massive fires when it encountered oxygen. The TWR solves these problems in its innate physical design to cool the core and stop fission reaction even in a power loss or system failure. The design of the fuel rods themselves “moves heat out of the core much more effectively than the fuel rods in today’s typical reactors” (3). In worst case scenarios, the TWR will still prevent a meltdown because the fuel pins will expand when they get too hot. This expansion will allow neutrons to pass through the fuel pins without interacting with the Plutonium-239. This halts the reaction and cools the core naturally.

TWR will also burn fuel more efficiently which will reduce waste and be more environmentally friendly. TerraPower claims that “a 1200-MW reactor will generate only 5 metric tons of waste per gigawatt-year, whereas a typical reactor today produces 21 metric tons per gigawatt-year” (3). This means that there is a significant reduction in radioactive waste and is an important factor, when considering the safety of the environment and the reduction of climate change as the need for nuclear energy increases.

CONCLUSION

After reviewing the data and applications of alternative advanced nuclear power plants, I propose that a potential future threat to nuclear power plant safety is the continuation of building modern Nuclear power plant designs and trying to mitigate the dangers associated with them. The only surefire way to increase the safety and efficiency of nuclear energy is to innovate new designs that rely on advance concepts of physics and engineering that eliminate the safety and environmental concerns of nuclear power plant designs of today. Innovations such as the TWR, which is currently undergoing plans to build reactors in China, is the future of nuclear energy and will far exceed our growing need for energy and produce clean renewable energy for the world.

CITATIONS

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