Nukes, Part 6

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1. Introduction

I will start this Nukes Part by disagreeing with myself. In Nukes Part 4 I said:

A Small Modular Reactor (SMR) is basically a scaled-down and simplified Gen1 through Gen 3 light water reactor (LWR). In spite of some pre-Gen 2 issues with safety, this is a well-understood technology. SMRs seek to remedy the safety and economic issues while building on previous LWR technology.

Then there are a class of reactors generally called advanced reactors. They do not use water for cooling, heat transfer, and reactivity control, but instead use some other fluid. In my opinion, this amounts to opening up a new can of worms.

I reviewed one of these companies in Nukes 3… There are other Advanced Reactors being considered: Oklo Power, LLC, TerraPower, Terrestrial Energy and Moltex Energy.

In spite of claims by the above companies that the above designs are intrinsically safe, I don't buy it. I'm not going to review any advanced reactor designs in future Nukes, unless they are able to define a true breakthrough design that I can believe. I worked the first five years of my career in the nuclear industry – first on an "Advanced Reactor" (Clinch River Breeder Reactor)... I know of what I write.

There are many challenges in building a Liquid Metal Fast Breeder Reactor (LMFBR). That's what Clinch River was, and that is what TerraPower's design is. These challenges were not what sunk Clinch River, it was poor management by our federal government, specifically the U.S. Energy Research and Development Administration (ERDA).

I just spent several hours researching TerraPower, and feel like they have the resources to pull off a successful design, certification and first project. They specifically have:

- Very deep pockets (Chairman of the Board is Bill Gates, they have other Board Members with strong capital connections, and they have received some federal funding).
- Strong regulatory contacts (one board member is a former NRC Chairman)
- Many people with strong backgrounds in the nuclear industry: TerraPower participants include scientists and engineers from Lawrence Livermore National Laboratory, the Fast Flux Test Facility, Microsoft, and various universities, as well as managers from Siemens, Areva, the ITER project, and the U.S. DOE.
- Their design, the Natrium reactor, was jointly developed with GE Hitachi Nuclear Energy (GEH, GE Nuclear was my old employer and evolved into GEH), GEH has a deep history with LMFBR's and has a current design called PRISM.[1]

This post will review the innovative TerraPower design.

[1] GE Hitachi Nuclear Energy, PRISM, https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/prism1

2. Natrium Reactor

Natrium nuclear power plants represent a significant advance over the light water reactor plants in use today. The Natrium plant uses a sodium-cooled fast reactor as a heat source. This heat from the reactor is carried by molten salt from inside the nuclear island to heat storage tanks outside the reactor building, where it is utilized as needed for generating electricity or industrial processes. The net effect is that the overall plant can load follow, thus increasing the revenue and value of the plant while maintaining the optimum constant reactor power. At the same time the cost of the overall plant is reduced since many of the systems outside of the nuclear island need not be nuclear safety grade. The Natrium reactor enables these abilities because it operates in much higher temperature regimes than the light water reactor, thus pairing well to the temperature requirements of the molten salt heat transfer medium.[2]

Natrium reactors are uranium fueled. No Natrium reactor—from the demonstration plant, to the first set of commercial plants, or the subsequent larger plants—will use plutonium as a fuel. Both the demonstration plant and the first set of commercial plants will run on high-assay low-enriched uranium (HALEU). Natrium plants will not require reprocessing and will run on a once-through fuel cycle that limits the risk of weapons proliferation. Natrium technology will, nonetheless, reduce the volume of waste per megawatt hour of energy produced at the back end of the fuel cycle, by five times, without any reprocessing because of the efficiency with which it uses the fuel.

Author's comment: The above statement: *"...No Natrium reactor… will use plutonium as a fuel*" is only partially true. Although no plutonium fuel is loaded into the reactor, Plutonium-239 is bred and reacted in the reactor during operation. See the description on the next page.

TerraPower plans to build the 345 MWe Advanced Reactor Demonstration Program (ARDP) demonstration reactor with an integrated energy storage system and to market subsequent commercial reactors with a similar design and size.

Depending upon market conditions, future generations of Natrium reactors could be larger designs, up to the GW scale. Doing so could allow the reactors to take advantage of the benefits of "breed-and-burn" designs that would allow the plants to be refueled with natural unenriched uranium or even depleted uranium. By enabling refueling to occur with these enrichment plant wastes or unenriched materials, the risk of proliferation from exported reactors is further reduced. Inside the reactor core, the reactor does convert some U-238 into a fissile isotope (Pu-239), which it then uses as fuel with uniquely high efficiency before removal. This is the same basic process that occurs in the current generation of light water pressurized reactors, which have been successfully exported around the world…

The Natrium Demonstration Plant will prove out the systems and operations for the first generation of 345 MWe plants as well as qualifying many components for the larger breed-and-burn plants that follow. The plant will be started and initially checked out with the type of "sodium wetted" fuel that has been used before, including at INL. A transition to new higher performance fuel will then be made to achieve full commercial operations. The Natrium Demo is based on decades of sodium reactor operations and on a decade of focused development sponsored at national labs, universities, and companies.

[2] TerraPower, "The Natrium™ Program," May 18, 2021, https://www.terrapower.com/natrium-program-summary/

3. Fuel Cycle

The fuel cycle is one of the most innovative things about the Natrium reactor. The primary innovation by the Natrium reactor is that it is a Traveling Wave Reactor (TWR), described below.

Papers and presentations on TerraPower's TWR describe a pool-type reactor cooled by liquid sodium. The reactor is fueled primarily by depleted uranium-238 "fertile fuel", but requires a small amount of fuel enriched with uranium-235 or other "fissile fuel" to initiate fission. Some of the fast-neutrons produced by fission are absorbed by neutron capture in adjacent fertile fuel (i.e. the non-fissile depleted uranium), which is "bred" into plutonium by the nuclear reaction:[3]

Initially, the core is loaded with fertile material, with a few fissile fuel assemblies concentrated in the central region. After the reactor is started, four zones form within the core: the depleted zone, which contains mostly fission products and leftover fuel; the fission zone, where fission of bred fuel takes place; the breeding zone, where fissile material is created by neutron capture; and the fresh zone, which contains unreacted fertile material. The energy-generating fission zone steadily advances through the core, effectively consuming fertile material in front of it and leaving spent fuel behind. Meanwhile, the heat released by fission is absorbed by the molten sodium and subsequently transferred into a closed-cycle aqueous loop, where electric power is generated by steam turbines.

Authors Note: The above description omits the intermediate molten-salt loop and reservoir between the liquid sodium loop and aqueous loop. This is described in the first paragraph of section 2 and in section 4.

TWRs use only a small amount (~10%) of fuel enriched with uranium-235 or other fissile fuel to initiate the nuclear reaction. The remainder of the fuel consists of natural or depleted uranium-238, which can generate power continuously for 40 years or more and remains sealed in the reactor vessel during that time. TWRs require substantially less fuel per kilowatt-hour of electricity than do light-water reactors (LWRs), owing to TWRs' higher fuel burnup, energy density and thermal efficiency. A TWR also accomplishes most of its reprocessing within the reactor core…

Depleted uranium is widely available as a feedstock. Stockpiles in the United States currently contain approximately 700,000 metric tons, which is a byproduct of the enrichment process. TerraPower has estimated that the Paducah enrichment facility stockpile alone represents an energy resource equivalent to $100 trillion worth of electricity. TerraPower has also estimated that wide deployment of TWRs could enable projected global stockpiles of depleted uranium to sustain 80% of the world's population at U.S. per capita energy usages for over a millennium.

In principle, TWRs are capable of burning spent fuel from LWRs, which is currently discarded as radioactive waste. Spent LWR fuel is mostly low enriched uranium (LEU) and, in a TWR fast-neutron spectrum, the neutron absorption cross-section of fission products is several orders of magnitude smaller than in a LWR thermal-neutron spectrum. While such an approach could actually bring about an overall reduction in nuclear waste stockpiles, additional technical development is required to realize this capability…

[3] Wikipedia Article on Traveling wave reactor, https://en.wikipedia.org/wiki/Traveling_wave_reactor

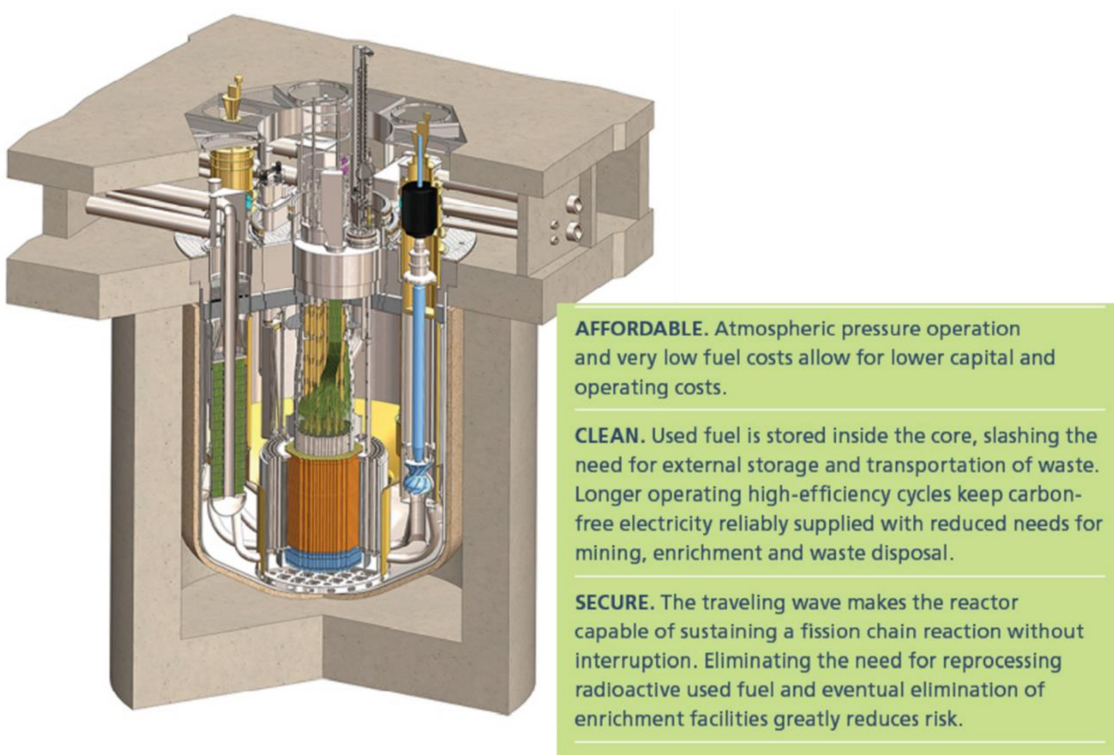
At one point that a TerraPower description seems to disagree with the above: *The reactor core is the true innovation of the TWR design... Periodically, to sustain the fission reaction, the in-vessel fuel handling machine shuffles the fuel, swapping expired fuel rods from the center of the core for fresh fuel rods from the outer edge.*[4]

I see no mention of a need to periodically shuffle fuel elements in the Wikipedia Description, but this is a minor difference. I did note from the Wikipedia description that the TWR technology rarely (every…*40 years or more*…), if ever needs to have depleted/expired fuel elements removed from the reactor.

It could be that the TerraPower SWR is designed to operate for its lifetime without adding or removing fuel from the reactor. And reshuffling is necessary for a lifetime longer than 40 years. If this is the case, it would be a game-changer. Many of the technical issues with previous LMFBR designs were related to removing, decontaminating (including sodium removal) and replacing core-components.

It would also be a major security feature. Within a few weeks of initial startup the core would be very radioactive, precluding any theft of bred plutonium. In one TerraPower document (a Fact Sheet linked to the reference 4 site) I saw the statement: "*Used fuel is stored in the core…*"

Although I could not find any specifics on whether the core was, in fact, underground, I did find the image and text below.



The core (orange) sets very low in the nuclear island and I would guess that it is well below-ground. Assuming a 60 to 100 year lifetime, during decommissioning it would seem reasonable to remove most of the components above the core, cap it with

[4] TerraPower, "Traveling Wave Reactor Technology," "An Innovative Nuclear Technology," https://www.terrapower.com/our-work/traveling-wave-reactor-technology/

concrete and effectively bury it. This would make it more secure than current Gen2 and Gen 3 reactor fuel, which is mostly above ground in dry casts. The encapsulated core would still be very radioactive, and once entombed, much too large and heavy to excavate. The site would still need to be reasonably secure, but it could be used for other nuclear functions, including new Natrium Reactors that would use the existing balance of plant.

Note that the above, is just my best guess as to how TerraPower intends to deal with the above issues, and I could be completely off base.

4. Other Innovative Features

The initial Natrium reactor is planned to be a 345 MWe, plus a GWh-scale molten salt energy storage reservoir. Together these can respond to peak power demand of 500 MWe for up to 5-1/2 hours.

Apparently the heat exchanger between the liquid sodium coming from the reactor core and the molten salt secondary heat exchange medium is on the nuclear island. This minimizes the amount of liquid sodium piping, and assures no radiation leaves the reactor island (the liquid sodium from the core is radioactive).

5. First Planned Deployment

TerraPower today announced Kemmerer, Wyoming as the preferred site for the Natrium™ reactor demonstration project, which is a TerraPower and GE-Hitachi technology, and is one of two competitively-selected advanced reactor demonstration projects (ARDP) supported by the U.S. Department of Energy (DOE). The company selected the Kemmerer location, near the Naughton Power Plant, following an extensive evaluation process and meetings with community members and leaders.[5]

"People across Wyoming welcomed us into their communities over the past several months, and we are excited to work with PacifiCorp to build the first Natrium plant in Kemmerer," said Chris Levesque, president and CEO of TerraPower. "Our innovative technology will help ensure the continued production of reliable electricity while also transitioning our energy system and creating new, good-paying jobs in Wyoming."

"This project is an exciting opportunity to explore what could be the next generation of clean, reliable, affordable energy production while providing a path to transition for Wyoming's energy economy, communities and employees," said Gary Hoogeveen, president and CEO of Rocky Mountain Power, a division of PacifiCorp.

"Just yesterday, President Biden signed the Bipartisan Infrastructure Deal and today DOE is already putting it to work with more than $1.5 billion heading to Wyoming," said Secretary of Energy Jennifer M. Granholm. "The energy communities that have powered us for generations have real opportunities to power our clean energy future through projects just like this one that provide good-paying jobs and usher in the next wave of nuclear technologies."

The Natrium reactor demonstration project's preferred siting is subject to the finalization of definitive agreements on the site and applicable permitting, licensing and support. TerraPower anticipates submitting the demonstration plant's construction permit

[5] TerraPower Press Release, "TerraPower selects Kemmerer, Wyoming as the preferred site for advanced reactor demonstration plant," Nov 16, 2021, https://www.terrapower.com/natrium-demo-kemmerer-wyoming/

application to the NRC in mid-2023. The plant is expected to be operational in the next seven years, aligning with the ARDP schedule mandated by Congress.

Members of the project team for the Natrium™ reactor demonstration project include:

- Bechtel Power Corporation
- GE Hitachi Nuclear Energy Americas, LLC
- PacifiCorp, a subsidiary of Berkshire Hathaway Energy
- Energy Northwest
- Duke Energy Carolinas, LLC
- American Centrifuge Operating, LLC (Centrus Energy Corporation)
- Global Nuclear Fuels Americas, LLC
- Orano Federal Services
- Argonne National Laboratory
- Battelle Energy Alliance, LLC (Idaho National Laboratory)
- Los Alamos National Laboratory
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory
- North Carolina State University
- Oregon State University
- University of Wisconsin