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Bill Gates's Natrium Nuclear Reactor Is Not The Answer To Climate Change

In 2006, Bill Gates founded and is currently the chairman of TerraPower, a company to develop "advanced" forms of nuclear energy to combat climate change. TerraPower developed the "Traveling Wave Reactor" design.[2] This design is that of a sodium-cooled fast reactor which uses in situ breeding so that the reactor would be mainly fueled by only natural or depleted uranium. The spent fuel would not be reprocessed, so that the reactor would produce no separated plutonium. In 2015, TerraPower signed an agreement with China to develop this reactor. However, in 2019, U.S. technology transfer restrictions forced an end to this deal.

Instead, in 2019, TerraPower formed a partnership with GE Hitachi, which has developed its own sodium-cooled fast reactor design known as Prism.[3] The Prism design is that of a small plutonium fueled breeder reactor which would use fuel reprocessing to recover plutonium to produce additional fuel. GE Hitachi has had no luck selling its Prism reactor. One potential buyer, the UK Nuclear Decommissioning Authority, rejected the reactor design as being immature.[4]

The result of the TerraPower/GE Hitachi partnership was the development of the Natrium reactor design which apparently combines features of both the Traveling Wave Reactor and Prism. It is a sodium-cooled fast reactor. However, it is not a breeder but rather uses uranium fuel which will not be reprocessed. The reactor also will use a molten salt energy storage system so that it can provide increased amounts of electricity at times when various renewable electricity sources cannot.

In October 2020, as part of the Department of Energy's Advanced Reactor Demonstration Program, the Natrium design was one of two designs selected for construction as demonstration reactors. The U.S. government will foot half of the up to four billion dollar cost of Natrium. The reactor was to be built in seven years but the reactor is not planned to be completed until 2028, as TerraPower claims that the clock did not start running until April 2021.

TerraPower has promoted the Natrium reactor as "cost-competitive, flexible technology for the clean energy future."[5] It has particularly touted Natrium as a major part of the solution to climate change saying; "The Natrium technology is a carbon-free, reliable energy solution built

[1] This paper is the product of the author's personal research and the analysis and views contained in it are solely his responsibility. Though the author is also a part-time adjunct staff member at the RAND Corporation, this paper is not related to any RAND project and therefore RAND should not be mentioned in relation to this paper. I can be reached at GregJones@proliferationmatters.com

[2] John Gilleland, Robert Petroski and Kevan Weaver, "The Traveling Wave Reactor: Design and Development," *Engineering*, Vol. 2, No. 1, March 2016. https://www.sciencedirect.com/science/article/pii/S2095809916301527

[3] Brian S Triplett, Eric P. Loewen and Brett J Dooies, "Prism: A Competitive Small Modular Sodium-Cooled Reactor," *Nuclear Technology*, Vol. 178, May 2012. https://www.tandfonline.com/doi/abs/10.13182/NT178-186

[4] "Progress on Plutonium Consolidation, Storage and Disposition," UK NDA, March 2019, p. 11. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/791046/Progress_on_Plutonium.pdf

[5] Natrium Factsheet https://www.terrapower.com/wp-content/uploads/2022/03/TP_2022_Natrium_Technology.pdf

to address climate concerns before it's too late."[6] TerraPower envisions building a large fleet of these reactors to provide a significant fraction of the electricity generated in the U.S.

However, at best, Natrium reactors will only be a very minor source of electricity by the time the U.S. plans to be carbon-neutral in 2050. The rapid construction of these reactors is unrealistic and the Natrium demonstration reactor will probably not come online until the 2030s, if at all. Given the need to operate the demonstration reactor for some years before an attempt is made to scale-up the size of these reactors, utilities are unlikely to order more than a handful of Natrium reactors before 2050. Moreover, the fuel required for these reactors presents special problems. The higher degree of enriched uranium required by this type of reactor is not currently being produced and a source to produce it must therefore be created. In addition, current nuclear power reactors use fuel in oxide form but Natrium will use metallic fuel. New facilities will need to be created to manufacture such fuel. Further, since there is no national high-level nuclear waste repository, any new nuclear reactor site becomes a de facto semi-permanent high-level nuclear waste repository. This fact may limit the number of communities willing to accept these reactors. Finally, the novel design of this reactor raises new safety concerns which must be addressed before the reactor is licensed. Natrium appears to be on track to be yet another failed attempt to commercialize fast nuclear reactors in the U.S.

The Natrium Reactor Design

Many of the details of the Natrium reactor design are not publicly known for two reasons. First, the design of the reactor has not been finalized, as the blending of the Traveling Wave Reactor and Prism reactor designs is still ongoing. This fact may explain why, on different websites, TerraPower either claims that Natrium will be "four times more fuel efficient" than current nuclear power reactors or "will use uranium with about the same utilization" as current nuclear power reactors.[7] Second, TerraPower contends that most of the reactor design details that it is submitting to the Nuclear Regulatory Commission are proprietary.

It is known that Natrium is going to be a fast reactor. This means that it will operate using fast neutrons, which are neutrons that travel at high energy. They are released when uranium fissions. All current commercial nuclear power reactors contain a light material (a moderator--water, heavy water or graphite) to slow down the neutrons which allows the reactors to operate using uranium enriched to 5% or less. However, Natrium, using fast neutrons, will need to use uranium enriched to somewhere near 20%. Uranium enriched between 5% and 20% is known as High-Assay Low-Enriched Uranium (HALEU).

The reactor will produce a thermal output of about 840 MW. The fuel will be a metallic uranium zirconium alloy. So as to not to slow down the neutrons, the reactor will be cooled with metallic liquid sodium. (Natrium is Latin for sodium.) The sodium coolant will go through a heat exchanger and transfer the heat to a second sodium circuit. In other sodium-cooled fast reactor designs, this second sodium circuit transfers the heat to water, which is converted into steam to then drive a turbine and produce electricity.

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[6] "The Natrium Reactor: From Research to Reality," December 13, 2021. https://www.terrapower.com/natrium-reactor-reality-2021/
[7] https://natriumpower.com/ and https://www.terrapower.com/natrium-program-summary/

The Natrium reactor design is unique in that the second sodium circuit transfers the heat to a molten salt heat storage system. The specific heat storage system design is one that has been used in concentrating solar power systems.[8] The salt is "solar salt," an inexpensive mixture of 60% sodium nitrate and 40% potassium nitrate. The maximum possible operating temperature range is between the freezing point of the salt mixture (250^o C) and the start of the breakdown of the salts (560^oC.) For a safety margin to prevent salt freezing, the actual planned lower temperature is 290^o C. The reactor is reported to have a 41% efficiency which would make the high salt temperature around 490^o C. The reactor will have an electrical output of 345 MWe.

The heat storage system consists of two equally sized salt storage tanks, one hot (490^o C) and the other cold (290^o C).[9] The amount of salt in the system is approximately sized to completely fill one of the two storage tanks. In operation the heat is transferred from the second sodium heat exchanger to produce hot salt. This salt is sent to the hot storage tank. The hot salt then goes to a salt/water heat exchanger where steam is produced to generate electricity. The resulting cold salt is sent to the cold storage tank and then to the secondary sodium heat exchanger where it is converted back into hot salt.

When the reactor is producing 345 MWe, there is no net change in the amount of salt stored in the two storage tanks. However, if during the day there were a lot of solar power available, the reactor would produce less than 345 MWe, and increasing amounts of hot salt would be stored. Then, in the evening when there would be less solar power available but still high electricity demand, the hot salt could be drawn down, allowing the reactor to produce more than 345 MWe for up to five hours. The peak production could be 500 MWe. It is envisioned that when in operation, the reactor would always operate at full power with the changes in electricity demand handled by the salt storage system.

The 345 MWe output of the Natrium demonstration reactor is rather small. TerraPower envisions scaling up the reactor to at least 600 Mwe and most likely up to 1,000 Mwe.[10] Unlike the current Natrium reactors which would use HALEU fuel throughout their operating lifetime, TerraPower is considering changing the fuel and core setup in these scaled up reactors by using HALEU only for the startup core and then using lower enriched uranium (or even natural or depleted uranium) reloads in a manner similar to the "breed and burn" method proposed in the Traveling Wave Reactor design.

The Department of Energy as well as TerraPower have characterized the Natrium design as "advanced." However, there is nothing advanced about the Natrium design and the use of this term is just a marketing tool. The designs that the Department of Energy has termed as advanced are simply reactors that use non-aqueous coolants (in Natrium's case, metallic sodium). Such designs have been around for roughly 60 years and the various prior attempts to commercialize these technologies have all failed. Indeed, TerraPower has used these earlier attempts as sources

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[8] Thomas Bauer, Christian Odenthal and Alexander Bonk, "Molten Salt Storage for Power Generation," *Chemie, Ingenieur Technik*, Vol. 93, No. 4, 2021. https://onlinelibrary.wiley.com/doi/10.1002/cite.202000137
[9] In practice a number of smaller storage tanks could be used instead.
[10] https://www.terrapower.com/natrium-program-summary/

of data in licensing submissions to the Nuclear Regulatory Commission. It is not clear why TerraPower thinks its efforts will be more successful this time.

Unrealistic Construction Timeline

The Natrium reactor is scheduled to come online in 2028 but this timeline seems unrealistic. Building even a light water nuclear power reactor of the current design in such a short time has not been possible, let alone a first-of-its-kind demonstration reactor using new technology. An industry observer has said that the ability of TerraPower to meet the 2028 timeline remains "a concern" and that "the project needs to meet a long list of pioneering milestones as they relate to research, plant design, equipment testing and qualification, and procurement and construction."[11] TerraPower's website now states that the reactor will be completed in "the late 2020s" rather than 2028.[12]

As will be discussed in the next section, providing the fuel for this reactor will be a major problem, very likely leading to major delays. The bottom line is that assuming that the Natrium reactor is completed at all, it will likely not be until sometime before the first half of the 2030s. Given the need to gain operating experience with this new reactor, it will not be until the late 2030s before any additional orders for this reactor type will be made by U.S. utilities. This second wave will likely consist of only a few additional reactors, which will not be in operation much before 2050 when the U.S. plans to be carbon-neutral. Utilities will be especially careful about buying many of the scaled-up Natrium designs if they are unproven prototypes using a different fuel and core configuration. At best, the Natrium reactor design will only play a very minor role in combating climate change.

The Natrium Reactor's Fuel Problem

Unlike current commercial nuclear power reactors which use a moderator and therefore can use uranium fuel enriched to 5% or less, the unmoderated Natrium reactor must use uranium enriched to near 20%, which is termed HALEU. A major problem is that there is no source of HALEU to provide fuel for the Natrium reactor. When Natrium was first proposed it was suggested that the HALEU could be obtained either by blending down surplus highly enriched uranium (HEU) from the U.S. nuclear weapons program, or the HALEU could be purchased from Russia. But the surplus HEU is all spoken for as it is needed to fuel U.S. nuclear powered submarines and to be blended down to fuel the two Watts Bar power reactors which are being used to produce tritium for U.S. nuclear weapons. The current political situation rules out any HALEU purchases from Russia.

The U.S. Department of Energy is funding Centrus Energy to build a pilot centrifuge enrichment plant to produce HALEU but this plant's output will be nowhere near enough to meet the projected demand for HALEU from Natrium and other reactor projects.[13] The European

[11] Sonal Patel, "Coal Plant Site Unveiled for 500 MW Natrium Advanced Nuclear Pilot," *Power*, November 17, 2021. https://www.powermag.com/coal-plant-site-unveiled-for-500-mw-natrium-advanced-nuclear-pilot/
[12] Natrium Factsheet https://www.terrapower.com/wp-content/uploads/2022/03/TP_2022_Natrium_Technology.pdf
[13] Matthew Bandyk, "Nuclear reactors of the future have a fuel problem," *Utility Dive*," August 30, 2021. https://www.utilitydive.com/news/nuclear-reactors-of-the-future-have-a-fuel-problem/604707/

uranium enrichment consortium (URENCO) is another potential source for HALEU, as it has a large facility operating in New Mexico. URENCO has stated on several occasions that it would be willing to produce HALEU. But the facility would need to be relicensed, which is not a simple matter as licenses for the production and use of HALEU would have to consider fast neutron criticality accidents. Uranium enriched to 5% or below can never go fast critical, which automatically rules out various accident scenarios and explains the current 5% enrichment limit on the uranium used in and transported to commercial nuclear power reactors. URENCO has estimated that it could take seven years to relicense its New Mexico facility to produce HALEU. Indeed, in 2019, Melissa Mann, the then president of URENCO USA, said that it could take seven years just to develop and license containers to transport HALEU.[14]

The manufacture of the actual Natrium reactor fuel also poses problems. There are no facilities to manufacture the metallic uranium zirconium alloy fuel that the Natrium reactor would use, as current commercial nuclear power reactors use fuel containing uranium dioxide. A new facility will need to be built and licensed to produce the fuel. Since a single reactor will not use that much fuel, such a fuel manufacturing facility will be small and lacking in economies of scale.

The provision of fuel for a fleet of Natrium reactors raises a serious "chicken and egg" problem. No investor will want to build large facilities to produce HALEU and metallic fuel unless there is assurance of demand but utilities are not going to want to purchase large numbers of Natrium reactors without the assurance that they can buy the necessary fuel. Getting investors to produce HALEU and metallic fuel may be especially difficult, since TerraPower has suggested that follow-on scaled-up Natrium reactors may not even use much HALEU fuel but will shift to using low enriched or even natural or depleted uranium reloads. Both the utilities and fuel providers will likely move slowly to make sure that there is a rough match between fuel supply and demand. This factor alone rules out any rapid deployment of Natrium reactors and creates further doubt that Natrium reactors will play any notable role in addressing the climate change problem.

Nuclear Waste

At some places on its websites, TerraPower correctly terms nuclear power "carbon-free." However, at many other places (such as in a statement quoted above) TerraPower falsely claims that Natrium will produce "clean" energy. The former residents of the areas around Chernobyl and Fukushima could testify differently. Nuclear power produces its own kind of "dirt," which is simply different from that produced by fossil fuels.

TerraPower has stated that Natrium will produce a much lower volume of high-level nuclear waste than other nuclear power reactors. However, for the operation of a long-term nuclear waste repository, the important characteristics of the waste are its total heat and radioactive inventory and not its volume. To a first approximation, the characteristics of Natrium's high-level waste and that of current nuclear power reactors are about the same. A more detailed comparison will need to wait until TerraPower provides information about Natrium's spent fuel.

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[14] David Kramer, "DOE uranium contract raises fairness concerns," *Physics Today*, March 2019, p. 30. https://physicstoday.scitation.org/doi/abs/10.1063/PT.3.4161?journalCode=pto

Another difficulty in assessing the relative safety of Natrium's spent fuel arises from Natrium's use of a more chemically reactive metallic fuel, whereas current nuclear power reactors use oxide fuels. Oxides are stable ceramics and are less likely to release radioactive waste than reactive metals such as uranium and zirconium should a long-term high-level waste repository be breached with water. At any rate the options under consideration are building Natrium or additional renewable energy sources, not new nuclear power reactors of the current type. One needs to make the proper comparison of the environmental impact of the competing energy options.

TerraPower notes that the spent fuel from the reactor will be stored onsite but says that this will only be until a permanent geologic repository is identified.[15] TerraPower fails to mention that there is no prospect of this occurring for many years, since there is no current effort by the U.S. government to locate a permanent nuclear waste repository. Further the site would not only need to be identified but also brought into operation. Then the much older spent fuel from the many other reactors in the U.S. would need to be moved to the repository first. At the very best, therefore, the spent fuel will be stored at the Natrium reactor site for many decades. Indeed, the spent fuel will likely be stored at the reactors a century or more, which would make every commercial nuclear power reactor site a semi-permanent high-level nuclear waste storage repository. This circumstance may make many communities reluctant to host new nuclear reactor sites and further limit the ability of nuclear power to help limit climate change.

Reactor Safety

TerraPower has touted some of the safety features of its Natrium design. In particular, the core will be submerged in a large pool of metallic sodium. It has a high heat storage capacity and combined with a passive heat removal system, the reactor would be able to survive the loss of emergency power which was the cause of the Fukushima accident.

But the Natrium design presents its own safety issues. One such issue arises from is its use of metallic fuel. This fuel has a much lower melting point (about 1,500° C) compared to the melting point of the oxide fuels (about 3,000° C) that are used in the current nuclear power reactors in the U.S. The interruption of the cooling of the Natrium reactor fuel could occur for reasons other than the loss of power and if that occurs, the metallic fuel will melt far more readily than oxide fuels. The dangers of metallic fuel in such a situation was illustrated by an accident that occurred more than 50 years ago at the Enrico Fermi Unit 1 near Detroit. This was a small prototype sodium-cooled fast breeder reactor which used a uranium molybdenum alloy fuel similar to the fuel proposed for Natrium. A piece of metal broke off from the interior of the reactor and blocked the coolant flow resulting in the partial melting of two of the reactor's fuel elements. There was no release of radiation off-site but the reactor was shut down for nearly four years as a result of the damage.

Further, a major meltdown in a fast reactor (such as Natrium) would have consequences more serious than those from a similar meltdown of power reactors as currently designed. As was discussed above, all current commercial nuclear power reactors use a moderator and sustaining the nuclear chain reaction requires that the fuel and the moderator be interwoven. If the fuel in

[15] https://natriumpower.com/frequently-asked-questions/

such a reactor melts, then the moderator is excluded and the nuclear chain reaction stops. In a fast reactor, the melting of the fuel would lead to the exclusion of the coolant, which would increase the rate of the chain reaction and complicate efforts to bring the accident under control.

Another safety problem unique to the Natrium design is the possibility of a leak in the heat exchanger between the secondary sodium circuit and the molten salt circuit leading to a violent chemical reaction between the two substances. Any sodium-cooled power reactor faces a similar problem, but in all prior cases the heat exchanger involved metallic sodium and water. It is well known that these latter two substances react violently. TerraPower has claimed that the reaction between the molten salt and metallic sodium would be less intense. However, it is not clear if this would be the case since the nitrate salts are strong oxidizing agents. As there are no current safety data, TerraPower has stated in its submissions to the NRC that it will conduct experiments to address this issue.[16] However, TerraPower has also stated that this important safety data is proprietary. As such it will not be disseminated to the public. Without the public release of this safety data, some communities may be reluctant to allow Natrium reactors to be sited in their areas.

Conclusions

At best, Natrium reactors will be only very minor source of electricity by the time the U.S. plans to be carbon-neutral in 2050. The rapid construction of these reactors is unrealistic and the Natrium demonstration reactor will probably not come online until the 2030s, if at all. Given the need to operate the demonstration reactor for some years before an attempt is made to scale-up the size of these reactors, utilities are unlikely to order more than a handful of Natrium reactors before 2050.

The fuel required for these reactors is a special problem and will likely further delay any startup of the Natrium reactor. The higher degree of enriched uranium (HALEU) required by this type of reactor is not currently used in power reactors and new facilities will need to be built to produce it. Nuclear industry sources have stated that just the need to design and license containers to move this HALEU fuel could take seven years. Similarly, current nuclear power reactors use fuel in oxide form but Natrium will use metallic fuel. New facilities will need to be built to manufacture such fuel. The initial fuel manufacturing facility will necessarily be small and lacking in economies of scale.

The Natrium spent fuel will be less suitable for disposal in a permanent high-level waste repository since it uses reactive metallic fuel rather than the stable ceramic oxide fuel that is used in current commercial nuclear power reactors. Further, since there is currently no such repository, any new nuclear reactor site (including Natrium) becomes a de facto semi-permanent high-level nuclear waste repository. This fact may limit the number of communities willing to accept these reactors.

Finally, the design of this reactor raises safety concerns which will need to be addressed before the reactor is licensed. In a situation where the cooling of the fuel is interrupted, Natrium's

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[16] TerraPower Testing Program and Methodology Presentation Material, May 11, 2022: Natrium Testing and Methodology, NATD-LIC-PRSNT-0021, Slides 26-31. https://adams.nrc.gov/wba/view

metallic fuel will melt more readily than the oxide fuel that is currently used in commercial nuclear power reactors. As with any fast reactor, a fuel melt will increase the nuclear reaction by excluding the coolant. This behavior is in contrast to the current commercial nuclear power reactors where a fuel melt will end the nuclear reaction by excluding the moderator. A safety concern unique to Natrium is that a leak in the salt/sodium heat exchanger could lead to a vigorous chemical reaction between the salt and liquid metallic sodium. There is currently no information on how violent this reaction could be. TerraPower plans to perform experiments to address this issue but as TerraPower contends the data from these experiments is proprietary, it will not be available to the public.

In light of these many problems, Natrium appears to be on track to be yet another failed attempt to commercialize fast nuclear reactors in the U.S.