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Traveling Wave Reactors:

Sodium-cooled Gold at the End of a Nuclear Rainbow?

By Arjun Makhijani, Ph.D.

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The "Traveling Wave Reactor" (TWR) is a proposed reactor design that belongs to a set known as Generation IV designs that are different in a number of respects than the current commercial designs which use water to cool the reactor and slow down ("moderate") the neutrons that sustain the chain reaction. It was first conceived in 1958 but has been intensively investigated only since about 2006, most notably by TerraPower, a company formed in 2008 by venture capitalists, including Bill Gates of Microsoft fame (TerraPower 2013a and Intellectual Ventures 2013).

The TWR is a sodium-cooled "fast" reactor design, which means that energetic ("fast") neutrons sustain the chain reaction. The heat created by fission is carried away by liquid sodium, which is used to boil water (in a two-step process); in turn, the steam is used to drive a turbine-generator set to generate electricity. A TWR has never been built. However, the TWR has much in common with other sodium-cooled fast reactors though there are some important differences. Since many sodium-cooled fast reactors have been built over more than six decades in several countries, it is worth examining that experience to help evaluate the prospects for the TWR.

Sodium-cooled reactor experience

Sodium-cooled fast reactors have a checkered history. Some have operated well, while others have done poorly. The most recent commercial demonstration reactors belong in the latter category. The French demonstration reactor, Superphénix, operated at an average capacity factor of less than 7 percent over 11 years before being shut in 1996; the formal decision not to reopen it was made in 1998 (IPFM 2010, p. 10 and Chapter 2). The Japanese Monju reactor, commissioned in 1994, and connected to the grid in 1995, had a sodium leak and fire in 1995. It was closed until May 2010, when it was restarted for testing, but suffered another accident in August 2010. (NYT 2011). It has not been restarted since. A schematic of pool-type and loop-type sodium-cooled reactors is shown in Figure 1 (see next page).

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FIGURE 1

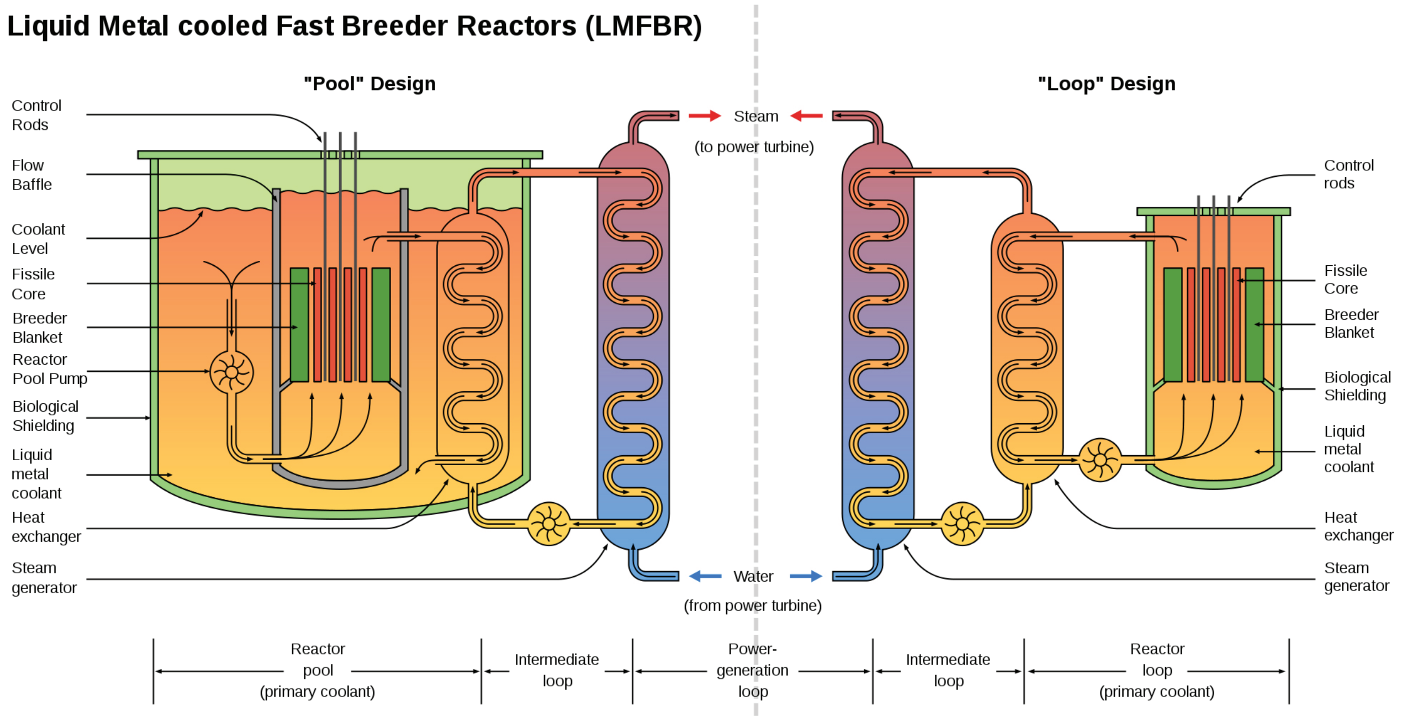

Figure 1: Schematic of Pool-Type and Loop-Type Sodium-Cooled Reactors. Turbine and electric generator not shown. (Source: Wikimedia Commons, author: Graevemoore, at http://commons.wikimedia.org/wiki/File:LMFBR_schematics2.svg)

One of the most difficult engineering problems with sodium-cooled reactors has to do with the fact that sodium burns on contact with air and explodes on contact with water. Further, some of the non-radioactive sodium nuclei of the coolant absorb a neutron and are thereby converted to intensely radioactive sodium-24. Leaks create difficult clean-up and maintenance and repair problems. This is especially so for primary leaks, but also true for secondary loop sodium leaks where no radioactivity releases are involved – as was the case with the 1995 Monju fire. Leaks are often followed by weeks, months, or even years of repair, cleanup, testing and inspection before the reactor can be restarted. Further, leaks have been a common problem in sodium-cooled breeder programs, including in France, the UK, India, Russia, and Japan (IPFM 2010, various chapters). Core meltdown accidents can also occur: two of the U.S. sodium-cooled breeders have had partial core meltdowns (IPFM 2010, pp. 92, 95). Sodium-cooled reactors have some safety advantages relative to present-day light water reactors, such as operation at low pressure, in contrast to light water reactors. But they also have safety disadvantages, including the potential for the reactor to continue to sustain a chain reaction in the event of coolant loss (IPFM 2010, pp. 8-9).

Even apart from the poor reliability in many cases, sodium-cooled breeder reactor capital costs have been very variable and have not decreased over time. Fermi I, built in the 1960s, cost about $4,000 per kilowatt, while the Fast Flux Test Facility, operational in 1980, cost over $10,000 per kilowatt. Superphénix cost, commissioned in 1986, about $4,800 per kilowatt, but Monju, commissioned nearly a decade later, cost over $20,000 per kilowatt (all in 1996 dollars – Makhijani 2010, Table 3). Overall, it is expected that costs of sodium-cooled breeders will be significantly higher than current reactors (IPFM 2010, p. 7), despite the fact that about $100 billion have been spent worldwide (2007 dollars) on the attempt to commercialize sodium-cooled breeder reactors, so far without success (Makhijani 2010, p. 36, where additional references can be found).

The ups and downs of the successes and failures of sodium-cooled reactors, including the commercial failure of the most recent ones, indicate that there has been no demonstrable learning curve. Proponents of sodium-cooled reactors, including traveling wave reactors, tend not to focus on how they plan to overcome the problematic parts of the sodium-cooled design history, centered in large part on sodium-related problems, but rather tend to focus on the vast available raw material to produce a large amount of power for the indefinite future.

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This misplaced emphasis on the theoretical ability of breeder reactors to stretch the uranium resource greatly has historically led to messianic pronouncements and promises. Compare, for instance, the statement in Ellis et al. 2010 about TWRs: "Such high fuel efficiency, combined with an ability to use uranium recovered from river water or sea-water (which has been recently demonstrated to be technically and economically feasible) suggests that enough fuel is readily available for TWRs to generate electricity for 10 billion people at United States per capita levels for million-year time-scales" with Alvin Weinberg, perhaps the best known Oak Ridge National Laboratory scientist, recalling, in 1981, his attitude in the 1950s: "…you had in the uranium in the rocks, in principle, an inexhaustible energy source–enough to keep you going for hundreds of millions of years. I got very, very excited about that, because here was an embodiment of a way to save mankind. I guess I acquired a little bit of the same spirit as the Ayatollah [Khomeini] has at the moment" (as quoted in Ford 1982, p. 25). Other examples can be found in Ford 1982 and in Makhijani and Saleska 1999, Chapter 3.

The TWR would use metal fuel, with a liquid sodium thermal bond (Ellis et al. 2010). This liquid sodium inside the fuel rod is meant to provide a good thermal connection with the sodium coolant and is similar to the fuel used in past sodium-cooled reactors. Such spent fuel would be unsuitable for disposal in a repository. The sodium has to be removed before disposal, a costly task, given that spent fuel is highly radioactive and sodium is pyrophoric.

Traveling Wave Reactor Specifics

The TWR is different in some specific respects from other sodium-cooled breeders. The most important difference is that in the TWR the breeding would be done in the core; by design the newly created plutonium would be burned without having to be separated first. In a conventional breeder, the plutonium breeding is done in a "blanket" outside the core; the plutonium would then be separated and fabricated into fuel in a reprocessing plant (onsite or offsite).

The initial TWR design proposed was that of a reactor in which the chain reaction front would proceed like a slow wave across the core much like a cigarette burning from tip to butt, with the ashes remaining (inside, in the case of the reactor) as waste. TerraPower has a video illustration of this concept; it can be seen on a YouTube video simulation (TerraPower 2013c). There would be little or no unused fissile or fertile material. An essentially 100 percent use of the uranium resource was implied. More detailed design work has apparently led to a change in this conceptual design in favor of a core that is more like a traditional sodium-cooled breeder, except that the fuel would be "shuffled" periodically, enable better breed of fuel in the core and long periods between refueling (Ellis et al. 2010, and Garwin 2010). Contrary to early implications, illustrated in the TerraPower video mentioned above, the first generation of the TWR would achieve a burnup of just 15 percent (Ellis et al. 2010).[1]

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[1] Design details of the present (2013) configuration are not publicly available.

Further, the design cannot burn the plutonium and uranium in present-day spent fuel inventory from today's light water reactors without reprocessing – a costly enterprise that would increase proliferation risks. Figure 2 (see next page) shows a diagram of the latest TWR public design.

Reprocessing (called "repurposing" by proponents – Ellis et al. 2010) spent fuel could substantially increase the fraction of the uranium resource that is used upward from 15 percent to over 50 percent, but at the cost of increased proliferation risk. Proponents claim that "repurposing" the fuel can be done "without the proliferation risk of fissile material separations" (Ellis et al. 2010). This claim does not stand scrutiny. Ellis et al. propose the same process as the one being developed for Experimental Fast Breeder II fuel. Figure 3 (see page 7) shows a pilot electrorefiner, at the Idaho National Laboratory, where the first sodium-cooled reactor, called Experimental Breeder Reactor I, was built in 1951. This technology, also known as "pyroprocessing" and "electrometallurgical processing," was developed for dealing with sodium-bonded metal fuel used in sodium-cooled breeder reactors (Benedict et al. 2007). A 2009 study by U.S. national laboratory experts concluded that the various reprocessing technologies, including the electrorefining process discussed in Ellis et al. 2010, would provide little additional proliferation resistance, so far as proliferant states were concerned, compared to the present-day PUREX process that has been a source of great concern (Bari et al. 2009). It is not a matter of what present-day nuclear weapon states *would* do with the technology, but what potential proliferant states *could* do with it.

Even with very high use of the uranium resource and repeated reprocessing, a deep geologic repository would be needed in any case. This is a central reason that the Blue Ribbon Commission on America's Nuclear Future recommended that a repository program should proceed independent of the nuclear power and reprocessing path chosen by the United States (BRC 2012, p. 27).

A once-through open cycle TWR would have an advantage over conventional breeders in that no reprocessing would be needed to achieve much greater use of the uranium resource relative to today's light water reactors. Direct disposal of spent fuel would reduce proliferation risk relative to conventional breeders, but this it would pose considerable difficulties. Specifically, the sodium used as a thermal bond in the fuel would have to be removed first. Present-day reactor spent fuel requires no comparable step and can be put into disposal containers without such intermediate steps, risks, and costs.

By the same token, the disposal of TWR spent fuel would create its own problems. The spent fuel would contain residual uranium and unburned transuranic radionuclides including plutonium-239. It would also contain the usual variety of short- and long-lived fission products, except that a much larger amount would be contained per unit volume due to the much higher burnup.

FIGURE 2

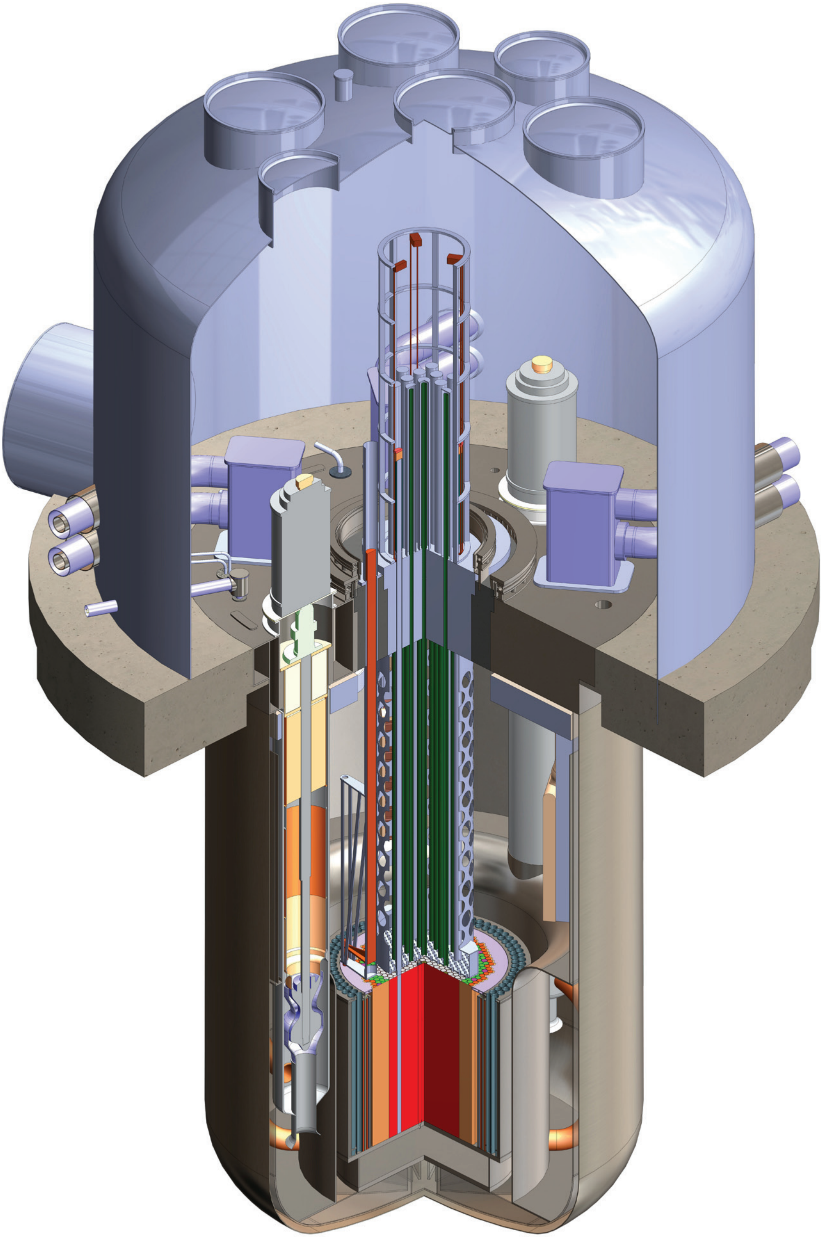

Figure 2: Traveling wave reactor. The core is at the bottom center. (Source: TerraPower. TWR-P Reactor, at http://terrapower.com/uploads/multimedia/TWR-P.jpg)

FIGURE 3

Figure 3: Pilot "Electrorefiner" for Experimental Breeder Reactor II at Idaho National Laboratory. Reprocessing for the TWR would presumably use a similar reprocessing technology. (Source: Wikimedia Commons, author: Argonne National Laboratory, at http://commons.wikimedia.org/wiki/File:EBRElectrorefiner.jpg)

As a consequence, the local thermal loads created by TWR spent fuel in a repository would be much higher than with today's spent fuel. This may make the site selection and repository design more difficult than it already is. For instance, it may increase the risk of local fissures in the vicinity of the disposal locations; such fissures could open up more pathways for radioactive materials to reach the human environment relative to present-day spent fuel. We have not come across any serious analysis of waste disposal and repository issues from proponents of TWRs that would be created by direct disposal of very high burnup TWR spent fuel.

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One extravagant claim is that the TWR would only need "one uranium enrichment plant per planet" (Wald 2009), the reality would likely be quite different. Without reprocessing, each first generation TWR would require about 1 metric ton of 15 percent enriched uranium per year (Garwin 2010).[2] While this reduces the separative work required by about a factor of five relative to light water reactors, widespread adoption of TWRs could require large numbers of enrichment plants configured to produce uranium enriched to a degree that is much closer to weapons grade than present-day reactors. If reconfigured, an enrichment plant that produces 1 ton of 15 percent enriched uranium would produce about 146 kg of 90 percent HEU, or nearly 6 bombs worth.

At a typical size of 3 million kilograms of separative work per year, a single enrichment plant would fuel about 90 TWRs. In bomb-enrichment configuration, each such plant could produce well over 500 bombs worth of enriched uranium. Proponents have suggested that the world could adopt this as its main power source to provide electricity at the current U.S. level worldwide for a global population of 10 billion (Ellis et al. 2010).

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[2] Garwin calculates that 60 metric tons of 15% enriched fuel would be needed for reactor operation at a level of 3 gigawatts thermal for 60 years (in addition to 320 metric tons of depleted uranium).

Safeguarding this global enrichment capacity sufficiently to ensure that not a single bomb's worth was diverted would be a very tough, possibly insuperable job.

Assuming TWRs would supply 70 percent of this total, a highly unrealistic 10,000 reactors of 1,000 megawatts (one gigawatt) each would have to be built. Even if burnup is doubled without reprocessing through fuel element repositioning in advanced TWRs, about 50 typical enrichment plants would be needed to fuel them. The replacement of old units (at a life of 50 years) would require one new enrichment plant to come on line each year. Recall that just one similar plant enriching uranium to 20 percent in Iran has created a major and prolonged security crisis that is so far unresolved. Fifty plants would be capable of producing well over 25,000 bombs worth of highly enriched uranium each year. Safeguarding this global enrichment capacity sufficiently to ensure that not a single bomb's worth was diverted would be a very tough, possibly insuperable, job. Less unrealistically, one might consider the International Atomic Energy Agency's high nuclear estimate of 1,137 gigawatts for the year 2050 (IAEA 2012, p. 17) and imagine that TWRs would supply 1,000 gigawatts of this total. Assuming these to be first generation TWRs since they would be built before 2050, even this smaller number would require ten typical operating enrichment plants, with one new plant being required about every five years as a replacement.

It is highly unlikely that enrichment plants can be internationalized or centralized in the West, a necessary precondition for a few very large plants to supply the enriched uranium for TWRs, should they become the mainstays of world electricity supply. Several decades of such proposals have not yielded a single enrichment or reprocessing facility under international control. Article IV of the Nuclear Non-Proliferation Treaty (NPT) has guaranteed to members an "inalienable right" to commercial nuclear technology that signatory governments are loath to give up. It should be noted that reprocessing has not been ruled out for TWRs and indeed is explicitly mentioned as one option for stretching the uranium resource further (Ellis et al. 2010). Reprocessing could reduce enrichment requirements significantly on the front end, but it would increase proliferation risks at the back end, where the separated material can be refined into weapons-usable plutonium (Bari et al. 2009).

In sum, contrary to claims, these heuristic calculations show that TWRs, like other sodium-cooled breeders, would create significant proliferation risks, with or without reprocessing, were they to be used as a mainstay of global power generation.

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Resource and Cost Considerations

The main argument that has been made for TWRs is that they can greatly expand the use of the uranium resource without reprocessing. But a paucity of uranium resources is not holding back nuclear power – it is the capital cost of the reactors. Reducing the cost of uranium resources significantly will do almost nothing to alleviate this problem, since the cost of mined uranium in existing power plants is roughly two percent of the overall cost of nuclear power. The much lower cost of mined uranium for TWRs will at most eliminate a few percent of the cost of power (including all capital and operating costs).[3]

The high capital cost and financial risk of nuclear reactors led the CEO of General Electric to say that he would "never do nuclear" were he a utility CEO because he would have to "bet my company" on the project (Financial Times 2007). TWRs do nothing to solve this problem; on the contrary, being sodium-cooled breeders, they are likely to be more expensive than existing reactors. Even if TWR capital costs are just $1,000 per kilowatt more than light water reactors, the added capital cost per kWh will be about one cent per kWh, which is roughly five times the cost of mined uranium for LWRs.[4]

So far as the ability of TWRs to contribute to a low-carbon source of electricity, it should be noted that the target date for elimination of most fossil fuel use (80 to 95 percent) for climate protection is 2050, about the same year that Japan hopes to commercialize the conventional sodium-cooled breeder (IPFM 2010, p. 53). On the more optimistic side, French breeder reactor advocates aim to replace half of France's nuclear capacity with sodium-cooled breeders by 2050, with the other half being light water reactors (World Nuclear Association 2013).

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[3] At $100 per kilogram of natural uranium. Nuclear electricity cost is taken as about 9 cents/ kWh, based on the AP1000 reactors under construction in Georgia and 8 percent average cost of capital. Ellis et al. 2010 estimate the uranium cost at 5 percent by assuming a very low cost of nuclear power at 5 cents/kWh.

[4] TerraPower's CEO, John Gilleland, expects the TWR to cost about the same as today's reactors but has been quoted as saying that "the jury is still not in on that" (Bullis 2011a). As noted above, the history of sodium-cooled reactor costs, discussed briefly above, provides little reason to believe that this expectation will be realized.

Even more optimistically, TWR proponents aim to have a demonstration reactor operating by 2022 and the first commercial reactor by the late 2020s (TerraPower 2013b). This is an impossible schedule, at least for the United States. The TWR design, like other sodium-cooled reactors, is so different from presently licensed reactors that the Nuclear Regulatory Commission will have to write regulations specifically tailored for them. For instance, accident mechanisms in sodium-cooled breeders are different than in light water reactors. It will take years for the Nuclear Regulatory Commission to staff up and acquire the necessary data and expertise to write the rules and do the safety and risk evaluations. As a result, certification and licensing of a demonstration reactor design is likely to take much longer than proponents have allowed for so far. Perhaps that is why TerraPower is reportedly exploring agreements with China and India (Bullis 2011b) even though China has little experience with sodium-cooled breeder reactors[5] and India's record so far hardly inspires confidence, having been plagued by leaks and accidents. Further, like other countries, such as France and Japan, that have pursued dreams of breeder reactors becoming a mainstay of electricity supply, India's breeder ambitions have suffered repeated setbacks and delays (Ramana 2012).

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But even if the most optimistic schedules are met, TWRs are at significant risk of being economically and technologically obsolete around the time of commercialization. First, they will be unlikely to compete with existing nuclear reactor designs because uranium is not a scarce resource and will not be for many decades. Second, distributed technologies, such as solar photovoltaics, microturbines, demand response, and storage are developing so fast that they present a "disruptive challenge" to the utility industry, as cell phones did to landlines. This is increasingly realized by the electric utility industry itself, as can be seen in a report by the industry's Edison Electric Institute published in January 2013 (EEI 2013).

A critical resource consideration has not entered the TWR discussion yet. The TWR is a thermal generation technology that, like today's reactors and coal-fired power plants, uses a lot of water. Each present-day 1,000 megawatt reactor evaporates between ten and twenty million gallons of water a day, with water intake requirements in the hundreds of millions of gallons a day. Water is far more likely to be a critical

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[5] China has just one pilot-scale sodium-cooled reactor (65-megawatts thermal) which went critical in 2010 (World Nuclear Association 2013).

resource in the coming decades – much more so than uranium. Higher efficiency can reduce this water requirement modestly, but solar PV and wind energy use essentially no water by comparison.

By focusing on the uranium resource issue, which is an economic non-problem for the foreseeable future (which one can reasonably define as less than 100 years given the scale and character of technological, economic, and security changes since 1913, the eve of World War I), TWR proponents have lost sight of the practical problems that have prevented commercialization of sodium-cooled breeders despite immense effort and expense over more than six decades. They have also not taken adequate account of the twenty-first century low-carbon distributed, renewable smart grid that is already emerging and that will likely become the center of the electricity system over the next two to three decades.

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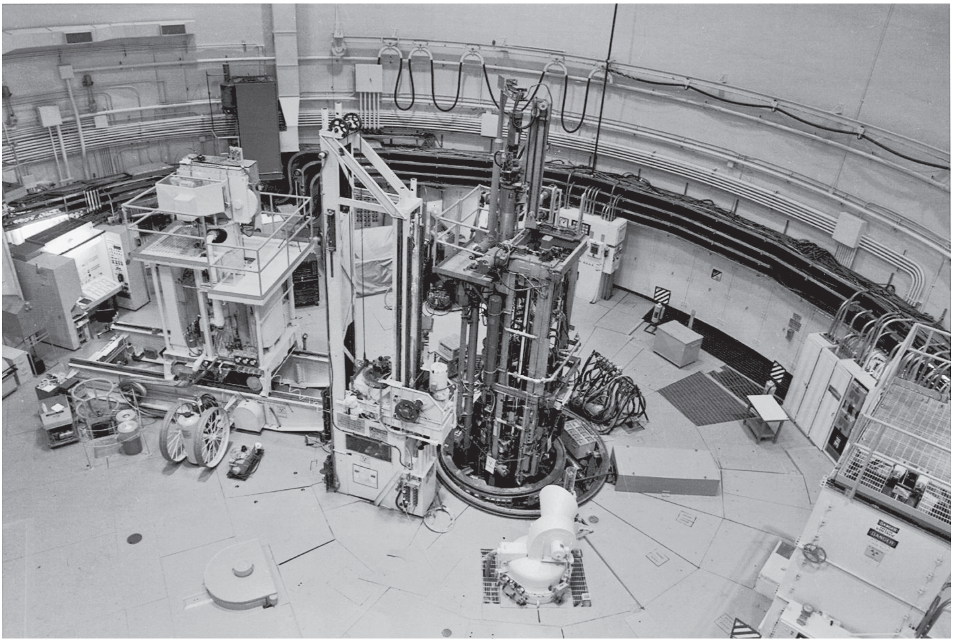
Experimental Breeder Reactor II Operating Floor



Source: Argonne National Laboratory, at http://commons.wikimedia.org/wiki/File:EBR-II_-_Reactor_operating_floor.jpg

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