

TRAVELING WAVE REACTOR

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INTRODUCTION

In the 2012 USA budget, \$853 million is allocated for nuclear research, including small reactors. A 30-person Company, TerraPower LLC, at Bellevue, Washington, with Bill Gates, Microsoft's founder, as a chairperson, proposes a conceptual design of a reactor that would use spent fuel from Light Water Reactors, LWRs and depleted uranium to run for about 60 years, breeding its own fuel as Pu²³⁹ from depleted uranium as U²³⁸. Venture capital firms Charles River Ventures and Khosia Ventures invested \$35 million into the project in 2010.

Contrary to the media-perceived physical movement of the breeding and burn waves in a slab or horizontal cylinder geometry, in the TerraPower latest concept, the fuel is shuffled into the burning region as it breeds enough fissile fuel to keep the reactor critical for long times.

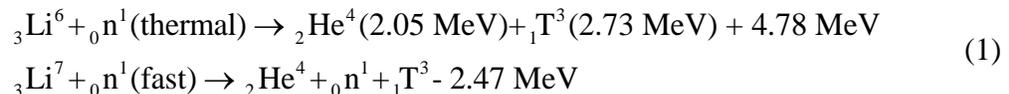
The Traveling Wave Reactor, TWR constitutes a reformulation of the Liquid Metal Fast Reactor, LMFBR and the "coupled cores" concepts and a reformulation of "Battery Reactors" based on Naval Propulsion reactors designs. As a function of time, the latest design represents a standing wave or a soliton, rather than a traveling wave.

The use of a Th cycle with a solid fuel or a molten salt coolant would present a larger more sustainable resource base alternative, since Th is four times more abundant than U in the Earth's crust.

HISTORY

The traveling wave reactor concept has been around for years. The concept dates back to 1958 and was first formulated by Saveli M. Feinberg who envisioned a nuclear reactor that uses depleted U in the form of the fertile isotope U²³⁸ as target material and a source of the fissile highly enriched U²³⁵ on an end of a long cylinder or parallelepiped, enough to generate a critical mass. A Be reflector would need to be used at the enriched fuel end.

Michael J. Driscoll in 1979 studied the breeding and burn concepts and Edward Teller and Lowell Wood in 1996 discussed the concept of "breed and burn deflagration waves" based on ideas from thermonuclear fusion in a cylindrical geometry where a tritium breeding wave and a DT burn wave are initiated at an ignited end of a cylinder of a compressed lithium deuteride LiD fusion fuel. With a source of neutrons, tritium can be bred in a "breeding wave" from the reaction:



Alternatively, for a higher energy release avoiding the Li⁷ endothermic reaction, Li⁶D can be used.

A fast neutron from the fusion reaction can in principle produce two tritons in these two reactions, sine it is re-emitted from the fast reaction, and is available, if not absorbed by other nuclei, to induce the second reaction at low energy.

The produced T can fuse with the D through the neutron producing “burn wave” DT reaction:



The neutrons produced from this “burn wave” are available to propagate the previous “breeding wave” of Eqn. 1.

Hugo van Dam in 2000 mathematically analyzed the fission waves, and Hiroshi Sekimoto analyzed a design concept designated as “Candle” in the 2000s.

It has been lately reintroduced by Lowell Wood from the Lawrence Livermore National Laboratory, LLNL. Nathan Myrhvold, a former Microsoft executive became receptive to the idea and brought the support of Bill Gates from Microsoft who is also investing in the Intellectual Ventures firm [2]. What interests them is that the concept is capable of turning “what is waste product into fuel.” John Gilleland and a network of researchers provide input to the project.

The fissioning of the fissile U^{235} isotope would generate neutrons as a traveling wave through the uranium core, breeding fissile plutonium, which would then fission, resulting in heat and neutrons to sustain the chain reaction, a process that could take decades before it depletes itself.

Scientists investigated the theory of the concept for many years, but never got beyond the conceptual design stage. One difficulty is that the concept envisions a one dimensional plate design, whereas neutrons travel isotropically in a three dimensional way. One would have to move the suggested Be reflector zone following the fissile zone. Alternative geometries are an enriched sphere surrounded by a breeding shell, or an enriched cylinder surrounded by a breeding cylindrical shell, which returns back to the basic LMFBR concept of a fissile central zone surrounded by a breeding zone.

DESCRIPTION

In this conceptual reactor design, highly enriched U^{235} or Pu^{239} fuel propagates a fission wave preceded by a breeding wave into fresh depleted uranium fuel in hexagonal pillars sitting in a liquid metal Na coolant, turning it into spent fuel. The fission gases accumulate in the space above the assembly. The heat generated is extracted by the sodium coolant using Na cooling pumps.

The traveling wave concept dates back to the early 1990s, but a working design has only emerged around 2009 by Intellectual Ventures which patented the design [1]. Commercial units are expected to be operational by 2020.

Considering the one dimensional wave equation:

$$\frac{\partial^2 \phi(x,t)}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 \phi(x,t)}{\partial t^2} \quad (3)$$

Which has a solution:

$$\phi(x,t) = Ae^{(i\omega t - kx)} \quad (4)$$

where:

- A : wave amplitude,
- ω : rotational frequency,
- k : wave constant,
- x : space coordinate,
- t : time coordinate,
- v : propagation speed.

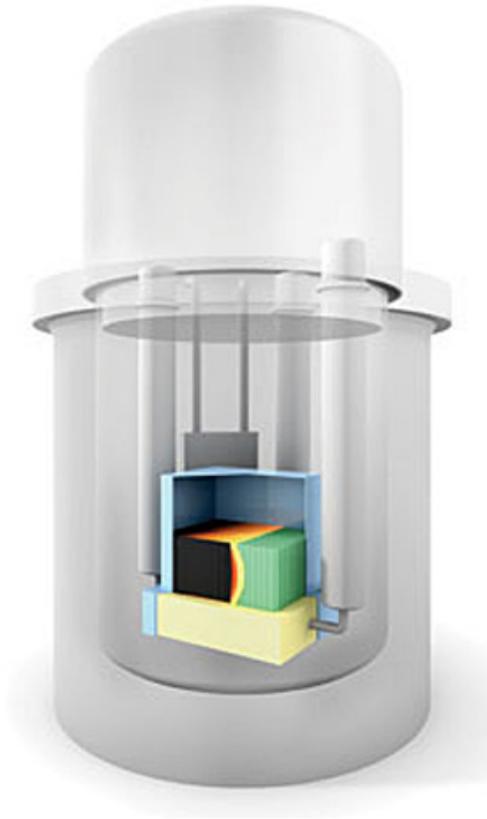


Figure 1. Schematic of Traveling Wave Reactor, TWR in slab geometry. Highly enriched U^{235} or Pu^{239} fuel propagates a fission wave (red) preceded by a breeding wave (yellow) into unused depleted uranium (green) in hexagonal pillars sitting in a liquid metal sodium coolant, turning it into spent fuel (black). The fission gases accumulate in the space above the assembly. The heat generated is extracted by the sodium coolant using the cooling pumps [1]. Source: Technology Review.

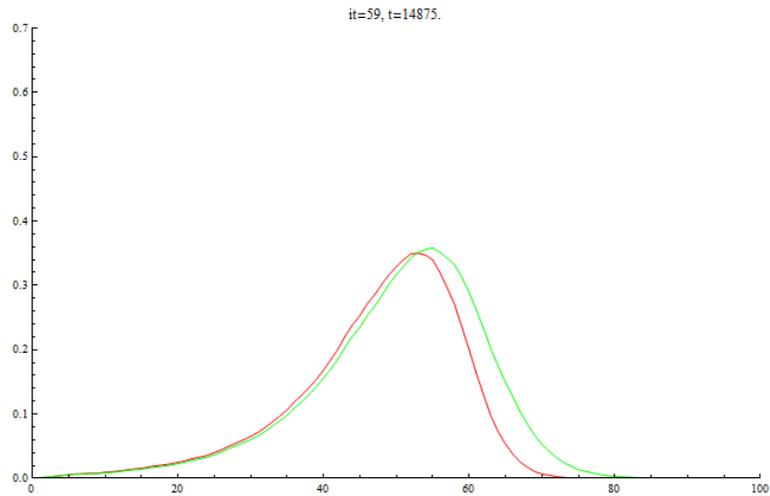


Figure 2. Traveling breeding and burn waves in depleted U. Source: UC Berkeley.

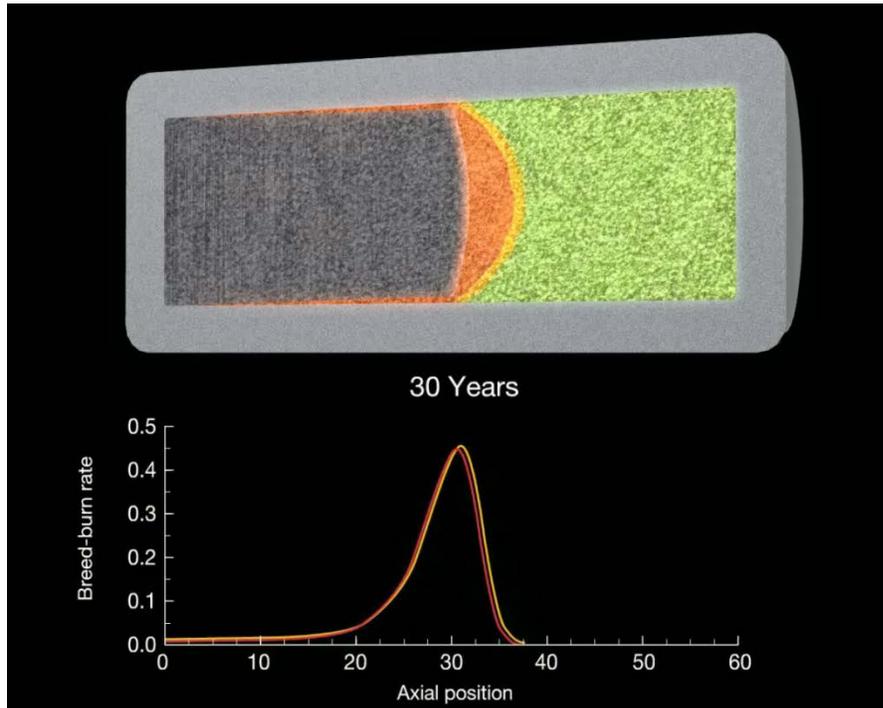


Figure 3. Traveling breeding and burn conflagration rates in horizontal cylindrical geometry at 30 years of lifetime. Source: UC Berkeley.

FUEL AND BREEDING

The fuel is an initial loading of highly enriched U^{235} or Pu^{239} that creates a fission wave that breeds further Pu^{239} in a propagating wave into the depleted uranium containing about 0.25 percent U^{235} compared with the 0.72 percent content in natural uranium. As an alternative, depleted fuel from naval reactors or from light water reactors can be used as an initial loading.

The active region, of less than one meter in thickness, moves along the reactor core breeding new Pu²³⁹ from the depleted uranium in front of it.

The end products are residual unburnt depleted U²³⁸, fission products and the actinide elements Np, Pu, Am, and Cm.

The produced actinides can be later recycled and burnt in the same configuration. If these are burnt, the remaining fission products take 300-500 years to decay to the same level of activity as the natural uranium that was mined from its ore deposit in the first place.

The fuel would be stored under water for about 5-10 years to allow its activity to decay. It would be then recycled to extract any Pu²³⁹ to reuse as fuel, and the fission products for disposal.

PERCEIVED ADVANTAGES

TerraPower's John Gilleland describes the potential advantages of the concept as:

1. The uranium isotope that is fed into the new nuclear reactors does not have to be enriched, which means it is less likely to be used in atomic weapons.
2. The fission reaction in the new process burns through the nuclear waste slowly, which makes the process safer. One supply of spent uranium could burn for 60 years.
3. The process creates a large amount of energy from relatively small amounts of uranium, which is important as global supplies of U²³⁵ run short.
4. The process generates uranium that can be burned again to create "effectively an infinite fuel supply."

Since the concept breeds its own fuel, it theoretically can operate for 20-200 years without refueling. The main limitation to about 60 years would be the material properties that can withstand the operating environment.

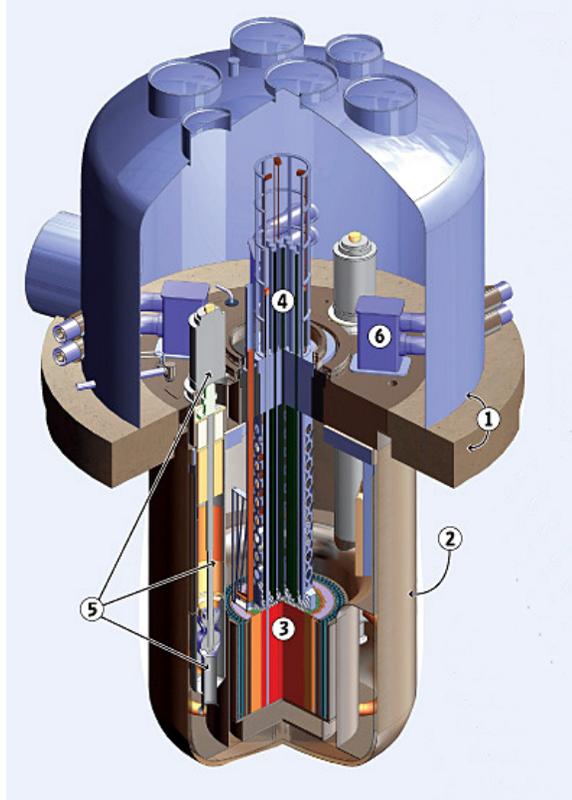


Figure 4. Pool type sodium TWR in vertical cylindrical geometry 500 MWe reactor using spent fuel elements. 1: Reactor head, 2; Below-ground reactor vessel, 3: Vertical cylindrical core with spent fuel and depleted uranium, 4: Control rods, 5: Four Na pumps, 6: Four heat exchangers with Na temperature inlet of 550 °C [2]. Source: WSJ, TerraPower LLC.

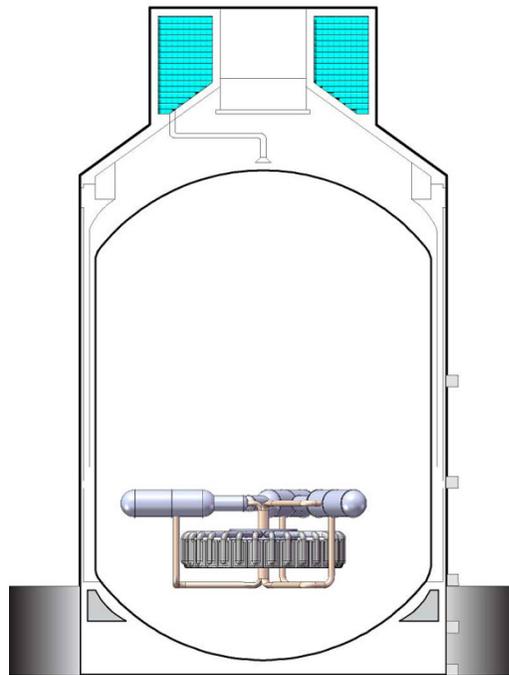


Figure 3. Conceptual design of a toroidal configuration of modular traveling wave wedge-shaped units inside an AP1000 containment system. Source: UC Berkeley.

DISCUSSION

The concept falls under the category of battery reactors which do not separate the bred fuel and hence eliminate proliferation concerns since the fuel can only be recycled in a fully safeguarded site. Once “ignited,” a steady state deflagration wave would propagate through a depleted U^{238} core breeding Pu^{239} then fissioning it as well as some U^{238} through fast neutron reactions.

Critics suggest that the technology is misguided, naïve and expensive. Supporters identify it as part of the new enthusiasm that is a part of the “nuclear renaissance.”

A privately funded research company, TerraPower in Bellevue, Washington with investment support from Microsoft’s founder Bill Gates, is developing the concept. At a TED (Technology, Entertainment, Design) conference in Long Beach, California he identified energy innovation as: “To prevent famine, poverty and the hardship that will come with global climate change we need ‘energy miracles’.” He encouraged optimism, along with heavier investment in solar, wind, battery and nuclear technologies. “We have to drive full speed and get a miracle in a pretty tight timeline.” TED is a nonprofit group dedicated to “ideas worth spreading.”

A TWR is smaller than the conventional LWR with modular 100-300 MWe units, compared with 1,000 MWe for the standard PWR or BWR. This provides the possibility to add units as demand develops.

The TWR theoretically can burn depleted uranium, a largely benign nuclear waste byproduct of uranium enrichment and use spent light-water reactor fuel. It would require less enriched uranium than conventional nuclear reactors.

A design problem involves the build-up of fission products such as Xe, Kr, Cs, I, and Sm which would act as neutron poisons. However, unlike thermal neutron reactors, as fast neutrons are used, the fission reaction is insensitive to the presence of the fission products.

Another problem is the reduction of the U^{238} concentration which is needed for passive safety by providing an overall negative temperature coefficient of reactivity through the Doppler Effect. After some burnup, reprocessing of the fuel may be inevitable.

A molten salt coolant may be preferable to a Na coolant, allowing the purging of the fission products and a higher level of operational safety than a liquid metal coolant.

The neutron multiplication obtained in a fast neutron spectrum allows both Pu breeding and burning. The breeding process must be maintained long enough to convert from a breeding phase to a burning one. The goal is to preclude any moderating and neutron absorbing materials, necessitating the use of a uranium metal alloy. For the wave to propagate a high power density is needed and Na allows the attainment of a power density of 200-300 MWth / m³.

Table 1. Power densities for different reactor concepts.

Reactor concept	Coolant	Power density [MWth / m ³]
Pressurized Water Reactor, PWR	H ₂ O	98
Boiling Water Reactor, BWR	H ₂ O	56
Canadian Deuterium Uranium, CANDU	D ₂ O	12
Gas Cooled Fast Reactor, GCFR	He	100
Lead Fast Reactor, LFR	Pb-Bi	69
Molten Salt Reactor, MSR	Molten Salt	22
Liquid Metal Fast Breeder Reactor, LMFBR	Na	350
Super Critical Water Reactor, SCWR	Super critical H ₂ O	100
Very High Temperature Reactor, VHTR	He	10

A fast neutron spectrum presents severe materials damage problems including atomic displacements as well as swelling caused by hydrogen and helium gases generation in a metallic lattice from (n, p) and (n, α) reactions.

The traveling wave reactor will require years of research and technology development. The liquid Na coolant is reactive with air and water, even though it operates at atmospheric pressure. As an example, the 280 MWe Monju plant in Japan began construction in 1985, went critical in 1995, and had a Na fire in 1995 as a result of a leakage of the liquid Na coolant, and has not operated since.

A traveling wave reactor based on the Th²³²-U²³³ fuel cycle with a solid fuel or a molten salt coolant would offer a larger more sustainable resource base alternative, since Th is four times more abundant than U in the Earth's crust. It would also provide more desirable proliferation aspects and safer operational conditions using a thermal or a fast neutron spectrum than the suggested U²³⁸-Pu²³⁹ present concept, and is worthy of detailed investigation. A particle beam and a spallation neutron source is other alternatives.

REFERENCES

1. Matt Wald, "TR10: Traveling-Wave Reactor," Technology Review, March/April, 2009.

2. Robert A. Guth, "A Window into the Nuclear Future," Wall Street Journal, February 28, 2011.