THE *NUCLEAR NEWS* INTERVIEW

John Gilleland: On the traveling-wave reactor

The traveling-wave reactor, in concept, would use depleted uranium to produce vast amounts of energy without the need for enrichment plants and reprocessing facilities, which is why billionaire Bill Gates is interested in developing it.

TerraPower LLC has been launched by the company Intellectual Ventures to design a traveling-wave nuclear reactor that could run for 100 years without refueling or removing spent fuel. So convincing is the science behind the concept that billionaire Bill Gates has gotten involved to help finance the project.

Led by John Gilleland, TerraPower's chief executive officer, a team of researchers has run computer simulations and is doing engineering studies that have produced evidence that a wave of fission moving slowly through a fuel core could generate a billion watts of electricity continuously without refueling. Gilleland noted that these new reactors could reduce the amount of nuclear waste by using existing stockpiles of depleted uranium as fuel. "By extracting centuries' worth of energy from waste at enrichment plants, these reactors would turn a social and financial liability into an asset," he said.

Gilleland: "There is enough depleted and natural uranium to last for millennia without any reprocessing."

Gilleland, who has a long history in applied physics, founded and served for several years as CEO of Archimedes Technology Group, which develops solutions to nuclear weapons–waste problems. The company created a new technology, called the Archimedes filter, to separate radioactive materials from nonradioactive materials. He also did advanced energy systems work at Bechtel after serving as the U.S. managing director of ITER (originally the International Thermonuclear Experimental Reactor).

Gilleland, a member of the American Nuclear Society, talked about the traveling-wave reactor with *NN* editors Rick Michal and E. Michael Blake.

How does the traveling-wave reactor work?

The basic concept is to use depleted uranium as a fuel and to need no more than a small amount of enriched uranium to start a reactor. The reactor would be able to operate for decades without refueling and without chemical separations. In a certain sense, the way the reactor works is well known. It's the typical breeding concept and standard physics—U-238 going to 239, to neptunium, and finally to plutonium-239—but with a twist, which is the traveling wave. In a sense, the wave can be visualized as two waves—a breeding wave moving just ahead of a burning wave that consumes the bred material.

Visualize a cylinder a few meters long that contains U-238 or depleted uranium. A nugget of uranium enriched to 10 percent is put at one end of the cylinder and a wave 40 centimeters wide is built up that breeds and burns plutonium and produces a gigawatt of electricity as it propagates from one end to the other. It would take 50 to 60 years for the wave to go from one end to the other for a reasonable-sized core.

How did you get involved in the project?

Lowell Wood, an internationally recognized scientist-technologist, played a major role in drawing my interest. Other major players in the project are Nathan Myhrvold, founder of Intellectual Ventures, and Bill Gates, the chairman and cofounder of Microsoft. They looked around at the various energy systems and came up with this desire to improve nuclear and expedite its responsible deployment around the world. When I was called on in December 2006, I thought I would come in and tell them what was wrong with their thinking. But, basically, after researching the project, I never left. TerraPower is the first spin-off of Intellectual Ventures, and Bill Gates is the principal owner of TerraPower, although there are others who have a level of ownership.

What convinced you that the traveling wave could work?

We looked back at some of the work done by Edward Teller and Lowell Wood on the breed/burn concept. It seemed to us that the concept had promise, but, quite honestly, it looked like something that could not be readily achieved. But we decided that if we ran into certain problems, we could see if there was a way to walk around them. That is more or less what the effort has been about since then. Our mission is to try to bring the concept far enough along by using a serious physics and engineering effort such that a major nuclear player would consider the concept and then embark on developing the traveling-wave reactor for commercial deployment.

Why build a better mousetrap?

To provide some background, our group looked at renewable sources of energy to see if they could be counted on to provide for the needs of the United States and the planet. We advocate the pursuit of renewable sources of energy, but the fact is that they just can't provide the electric power that the world will need. That is why we will unfortunately end up burning even more coal, which has its well-known environmental problems, unless we use nuclear. We felt that the full deployment of nuclear could be achieved if we improved some things, namely the risk of proliferation, the economics of new reactors, the fuel supply, and the waste issue. We decided to form a group and start with a blank slate to see if we could address those things.

Have you come up with a design for the reactor?

Preliminarily, yes. We went through the physics reconfirmation of the traveling-wave concept. We looked at what the technology constraints would be and investigated the available technologies that could take the required energy densities and survive the material damage problems and so forth. After a lot of work, we came up with something that looks very much like the standard pool-type sodium-cooled reactor. That's what the engineering firm Burns and Roe is working on for us right now.

Do you foresee government involvement in your project?

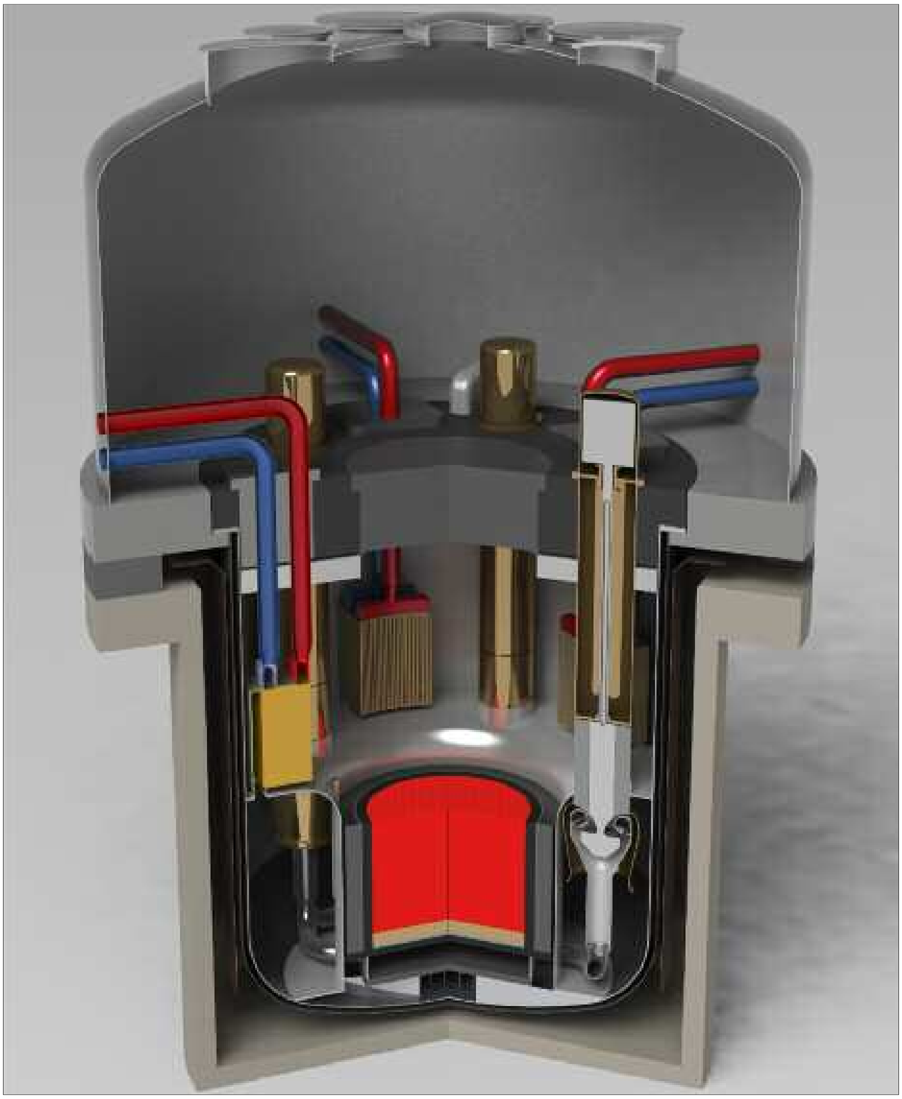
Yes, but not initially. Eventually, we might pursue an industrial partnership to develop the reactor core and the infrastructure needed to convert spent fuel from a light-water reactor to metal fuel for the traveling-wave reactor, for example. But we think that by sticking to a private initiative at this time, we can move along rapidly and be somewhat more immune to the ups and downs of government funding.

Could you talk about some of the research that has been done?

We took the existing Monte Carlo–based neutronics modeling tools and rebuilt them. That project was led by Charles Whitmer, an astrophysicist who is also a computer genius. We now have our own tools that are able to perform three-dimensional analyses. We've checked our codes against Rebus and other codes. Lawrence Berkeley National Laboratory ran tests to compare results with us, and Argonne National Laboratory also provided us with calibrations to check that we're on the right track. This all involved a couple of years of very intense development.

How have you used the code?

It allows us to watch the wave establish itself in 3-D and breed and burn. We have tracked about 2500 daughter products. The code is developed to the point that we can track very carefully what happens when we move fuel rods around and see what would go on for many decades in the reactor.



TerraPower has been developing conceptual designs for small as well as large-capacity traveling-wave reactors. The company said that a combination of advances available in existing component technologies, such as compact intermediate heat exchangers (the light tan vertical rectangle and the brown vertical rectangle) and electromagnetic pumps (not shown), has enabled it to focus its principal innovations on the design of a core (red) that can sustain a traveling wave of fission in multiple kinds of fuel. (Graphic: W. Wayt Gibbs, Intellectual Ventures, and Ash Odedra, TerraPower, LLC)

How does the reactor actually produce fast neutrons to the great extent that it is supposed to?

This is a fast-neutron system, and so it's the standard reaction, and the plutonium is putting out the spectrum. At the very high end, the neutrons are quite fast, and the reaction is quite insensitive to the presence of the fission products. We cannot do it with a thermal system because that would be much too sensitive to the fission products. The multiplication that we get in the fast-neutron system is high enough to allow both the breeding and burning of plutonium. We have to be able to sustain this breeding long enough to convert from a breeding phase to a burning phase. That involves a very severe environment for the materials. It's the reason that this idea hasn't been done before.

How much of the depleted uranium is actually converted to plutonium?

Initially, we are trying to hold the burnup down to 20 percent, but with development we may get to 30 percent and eventually to the order of 50 percent with improved materials or recladding.

This leaves you with a lot of U-238. Is the idea that eventually further input of enriched uranium would convert back to plutonium?

Even if we leave 50 percent of the U-238 as waste, we will have made a huge amount more energy than is possible with an LWR using a once-through fuel cycle. There is enough depleted and natural uranium to last for millennia without any reprocessing. The reactor would have, at one end, a sort of igniter of enriched U-235 that would start the wave. After that, the breeding and burning would sustain itself theoretically forever. If we have a long enough cylinder of depleted uranium or natural uranium, the wave will breed and burn for an infinite length of time. In other words, we don't need to load any enriched uranium ever again to keep this thing going. In the real world, we would have the wave propagate through the core for as long as we wanted—five years, 20 years, or 50 years or longer. Then we would stop it and add more depleted uranium rods and then just start it again. We can start and stop this wave with control rods just as we would a regular reactor. For each traveling-wave reactor, we need this igniter only once in the life of the reactor. After that, the enriched material is never needed again.

If no enriched material is needed, there is no need for enrichment facilities, is there?

That's correct. Once we have this type of reactor going, we don't need enrichment plants. All we need to get one reactor going is some enriched uranium, because after that we could borrow a few rods from it to start up and form the wave in the next reactor, and so on. Further, there is enough natural uranium and depleted uranium available that we can supply the world for thousands of years with energy without the need for reprocessing as it's known today. The base case for us is to take natural or depleted uranium, make metal fuel out of it, and use it as a basic fuel for the operation of this plant for some decades. You can choose your lifetime for the plant and the refueling schedule, but it's your choice whether you run the plant for some tens of years without refueling or a slightly shorter or longer time. During that whole period of time, the fuel is in the reactor vessel. You fuel it, and perhaps 50 years later you decide to take the fuel out. But you're not continually taking fuel out and putting it in wet or dry storage, so the reactor can be deployed widely without having to build new enrichment facilities—a big boost for nonproliferation.

Is there a moderator approach that helps ensure that you get the fast-neutron proportion that you want?

We're always fighting to keep it as hard a spectrum as possible and the losses as low as possible. But, in fact, the art form here is to minimize the amount of what I'll call the moderating and loss materials.

Has anyone ever tried to create this wave in the real world?

No. People have, of course, done breeding of plutonium from U-238 and studied it in the real world. That is sort of our physics calibration. But we take the same physics and say, "OK, if we could find a way to allow the cladding and the structure to take a much bigger beating from those high-energy neutrons, or learn to live with them, what could we do?" One thing we could do is sustain this breeding and burning wave.

Why are you using liquid sodium as the heat transfer medium?

We think liquid sodium is the best for this case, but we are looking without prejudice at others. We took our engineering test design to great depths with the sodium because the machines have operated already with energy densities in the range of 200–300 megawatts per cubic meter. It turns out that we need that sort of high-energy density in order to have the right conditions for the wave propagation. We looked at bismuth and bismuth lead for heat transfer. For those, we thought we would hold back for a while because there are well-known corrosion problems associated with them. We conducted an exercise to find a path that would involve the minimum technology development and to develop only those things that are essential to the achievement of this wave propagation and the benefits that accrue from it. As we looked around, we found that the sodium-cooled system pretty much fit. Looking at the Phénix fast spectrum test reactor in France or Monju in Japan as examples, we decided that slightly larger versions of them could accommodate one of the traveling-wave cores. The only development we would need, at least to start on this path to fission, would be the work on the core itself.

What is the timeline for your project?

If things go well, we could have our first power-producing system in the 2020 time frame, but that is making a lot of assumptions. We are starting out with a different core configuration, but everything else—fuel rods, materials, and so forth—is the same as something that has been tested before in reactors, so we think the time frame is achievable. We're also trying, as much as possible, to stick to the normal practices that one uses in making nuclear fuel.

Who are the other players in TerraPower?

I have mentioned Bill Gates, the financial founder and owner of TerraPower, and Nathan Myhrvold, the founder and CEO of Intellectual Ventures and the former chief technical officer of Microsoft. Bill and Nathan are both highly involved in the project in a technical way and not just in funding it, and so we have had some rather interesting marathon sessions with both of them. Other team members are David McAlees, a nuclear expert who has extensive experience as an executive in the nuclear business world and who was cochair of Siemens' Nuclear Division, and one of his former colleagues, Roger Reynolds, who was the chief technical officer of Areva in the United States.

On the physics side, we have a number of people who are known in the field: Charles Whitmer, who is working with Tom Weaver and George Zimmerman, both Lawrence Prize winners from Lawrence Livermore National Laboratory; Ehud Greenspan, who is a renowned nuclear engineering professor at the University of California at Berkeley; Pavel Hejzlar, our lead reactor designer, who ran a number of nuclear-related projects at the Massachusetts Institute of Technology; Jacopo Buongiorno, of MIT, who is working with Pavel on fuel performance modeling; John Nuckolls, who was the director at Lawrence Livermore National Laboratory; Charles Ahlfeld, an accomplished nuclear engineer who has led much of our engineering effort; and Kevan Weaver, from Idaho National Laboratory, who is now directing our technology research and development effort. There are others, too, who are prominent and well respected in the nuclear field. We have about a dozen people who have been involved in fast-reactor design, construction, and operation.

What about organizational cooperation?

Argonne is using its extensive experience to benchmark our efforts and conduct safety analyses. Ken Czerwinski is leading an effort at the University of Nevada at Las Vegas to test irradiated materials for us. We're also talking with Idaho National Laboratory and other institutions about supporting UNLV to do further testing of those materials. Finally, Columbia Basin Consulting Group is coordinating a virtual "who's who" of engineers who were involved in the design, construction, and operation of the Fast Flux Test Facility and other fast reactors.

When all is said and done with the reactor's fuel cycle, are all the minor actinides burned up?

No. We are looking at that issue, both with and without recladding the fuel. It appears that the reactor will leave behind less plutonium than would an LWR per unit of energy produced.

So, there are still fission products at the end?

Yes, the products are still in the reactor. They are not out where people can get to them. But by using this once-through system, we are achieving effectively about 100 times more energy production from a given mass of uranium than we can using an LWR. That's the motivation. Higher burnup, burning what right now is waste—namely depleted uranium—yields this incredible production. We figured out that we could supply every person on earth with the U.S. level of per capita energy consumption for 1000 years if we can make the traveling-wave reactor go. It's not just our opinion. It's the reason lots of people from many places are involved. I like what Charles Forsberg of MIT said: If this works, we will need only "one enrichment plant per planet." I would add, "Only for a while." It's a stunning thing to think about. NN