Eduardo D. Greaves

Thorium as Nuclear Fuel In the Molten Salt Reactor

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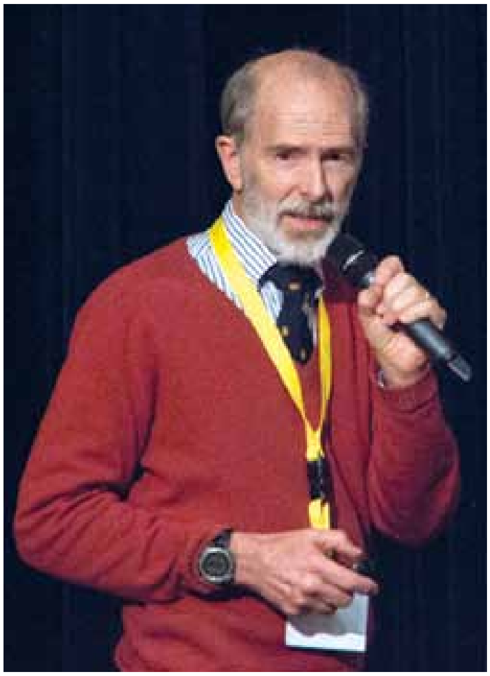


Daniel-Enrico Grasenack-Tente

Dr. Greaves told the conference: "The thorium molten salt reactor is capable of providing the clean, safe, and cheap energy necessary for the future of society."

First I would like to acknowledge some of my collaborators, in particular Sylvia Delpech, during my sabbatical leave this year in France.[1] I would like to dedicate this talk to the memory of Kazua Furukawa, who was a champion for the thorium molten salt reactor, and who died just over a year ago.

What am I going to talk about? The problems with nuclear energy technology; the current technology; the thorium molten salt reactor; and some of the various proposals and advantages of the molten salt reactor. And then, something of the perspectives worldwide for thorium molten salt reactors.

The first problem is the non-acceptance by society, after 60 years of development.

The first reason is the danger of nuclear weapons proliferation. We currently use uranium-235 or plutonium-239 to produce energy. The rest of the fuel—uranium-238—is a fertile material. With the neutrons, it produces plutonium. And of course, plutonium is very good because it produces energy; but it is also used for weapons. A 1,000 MW power plant produces 230 kg of plutonium per year. So can you imagine, worldwide, 1,000 nuclear reactors producing each 230 kg of plutonium? It becomes a proliferation nightmare. It's a problem, and it worries people.

Another problem is that the present reactors have the nuclear fuel elements inside the reactor core, which is like a compressed container, under very high pressure. And any problem with it is really a big problem. We saw what happened in Fukushima. Fortunately, none of them exploded or melted completely; it was just a little melting, and it produced enough hydrogen to have the explosions we all saw. So this is a serious accident risk.

With our current technology, we only use about 1% of the energy contained in the fuel. The fuel is used; it is damaged by the use, by the radiation; the damaged fuel elements have to be exchanged; and it produces nuclear waste. These elements have to be constructed with extreme care, which is expensive. And they turn into nuclear waste in 2-3 years, and this nuclear waste, if it is not reprocessed, is a problem: highly radioactive material, with thousands of years of half-life.

Why Use Thorium?

Now we go to the thorium molten salt reactor, which I call the true green energy system.

What do we want for the world? I think diversity,

1. Others named on the slide are Ritsuo Yoshioka, Alfred Lecocq, Laszlo Sajo-Bohus, and Haydn Barros.

and nuclear definitely can help to balance, as we saw from the previous talk. A clean technology, free of CO_2; a solution to nuclear waste. We want a safe technology, so that we can see the future with optimism, not with worry. We want to use our own resources: We in the Third World countries want to control our future, and not be subject to policies like the U.S. global nuclear energy partnership, which puts us in the category of users, with no control over our systems. And we want to use our own resources, so that we ourselves develop, not relying on the development of other countries. And we want to use non-proliferative-weapons technology.

The molten salt reactor is an idea that occurred to Eugene Wigner, and was developed by Alvin Weinberg. (Weinberg, by the way, also developed our current technology.) The fuel is not solid, but liquid. There are no fuel rods. The fuel contains mostly thorium—very little uranium. It circulates inside the reactor, and it goes out of the reactor to transport the heat to another cycle, which then transports the heat to the power-producing part.

Why use thorium? Thorium can be used either with plutonium-239, uranium-235, or the uranium-233 which is produced by the thorium which is inside the reactor. This thorium is now substituting for the uranium we had before. And it is fertile; it produces uranium-233, with which you can produce more energy; but it produces almost no plutonium—very little plutonium is produced in these reactors. Thorium is four times more abundant in the Earth's crust than uranium, so our resources are enough for 1,000 years of use. It produces much less nuclear waste—a fraction of the long-lived actinides. Fission produces nuclear waste, but also actinides, which are long-lived. Thorium produces very little; it is a very concentrated kind of fuel.

Why liquid fuel? The molten fluoride has a triple function. It is the fuel element, to consume and to produce energy; it is the heat-transfer medium; and it is also the fuel-processing medium. So in the same cycle, you produce the fuel, you transport the heat, and you reprocess the fuel.

What is this molten salt? It is a mixture of fluorides: lithium fluorides and beryllium fluorides. These are salts, like table salt. They are solid at room temperature, but at a high temperature they become a liquid, and it is clear, like water. It has very high specific heat and very low viscosity, which is ideal for heat-exchange media. It does not suffer any radioactive damage during use. With gamma radiation or with alpha radiation or the neutrons produced, it is not damaged at all; so it remains inside the reactor without being damaged, contrary to what happens with solid fuel elements. It is a good solvent for materials for fission, for elements of fertile material, and it has a nuclear property, which is that it has a very low neutron cross-section.

So, what does this liquid contain? It contains the fuel, which can be uranium tetrafluoride (either as what is used now, uranium-235, or what will be used in the future in these reactors, uranium-233, which is made in the reactor from the thorium). Or it can use plutonium. So the scheme which has been proposed is to burn all the plutonium which is in nuclear weapons now as fuel in these reactors, and to convert the thorium which is inside to uranium-233, and therefore produce more fuel.

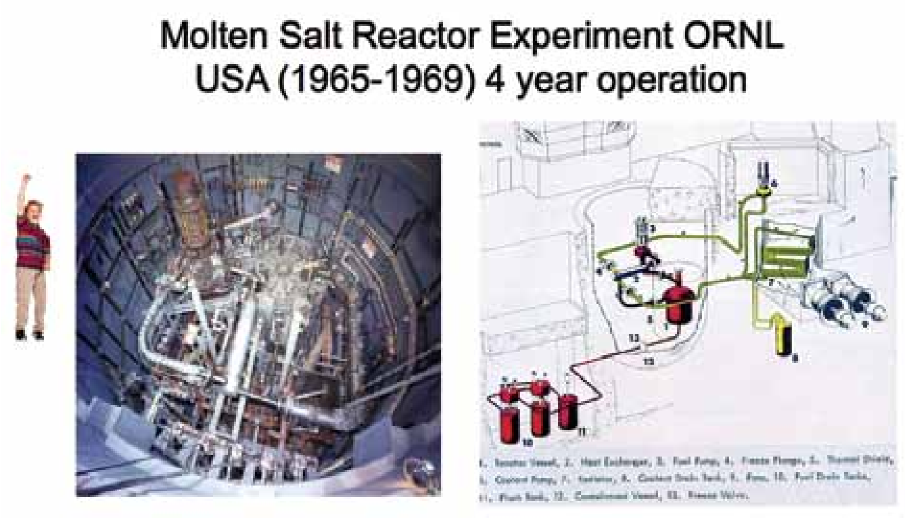
A Brief History

The idea first came about in 1954. The Americans had, due to the Cold War, the need to transport nuclear weapons from the U.S. to Russia, very far away. So they asked Oak Ridge National Laboratory (ORNL) if they could make a reactor that could fly. The aircraft reactor experiment was done; it was the first molten salt reactor. It worked perfectly for 200 hours, and it was light enough to be put into an aircraft. This gave them the idea to make a molten salt reactor for power production. That was the 1965-69 molten salt reactor experiment, which had a four-year operation. After that they created a proposal for a molten salt breeder reactor (1971). This was taken up by Japanese groups and developed into the FUJI reactor. Further proposals are the Mosart in Russia (2007), the molten salt fast reactor in France (2008), and several proposals which I will mention very briefly at the end.

Figure 1 is a photo of the molten salt reactor experiment at ORNL. It was a small thing (you can see this little boy on the side), and it did not produce electricity. All the power was just blown into the air. The diagram on the right side shows the reactor in the middle. The reactor was stopped every weekend, they drained the liquid to those tanks at the bottom, and on Monday they put it back up and continued the experiment. Very, very different from current reactors, which can't be stopped.

There are several kinds of proposals for molten salt reactors. The first classification is either two-fluid reactors or single-fluid reactors (**Figure 2**). The two-fluid

FIGURE 1



reactors have a core where the fission reaction takes place, and the neutrons go out into a blanket which is wrapped around it, which is there to produce more fuel. It is a complicated core design, but it has a very excellent breeding capacity. It can produce more fuel than it burns.

The single-fluid reactor is very much simpler, and has a low breeding factor, which means it burns more or less the same, or more, than what it is producing.

And there is another classification, the fast reactors and the thermal reactors. **Figure 3** shows two of the proposals for fast reactors—the Mosart, as described by Victor Ignatiev in Russia in 2007, at the Kurchatov Institute; and the EVOL European molten salt fast reactor. The latter is a proposal that is being studied currently, and very recently, at the end of last year, a meeting of EVOL showed this advanced core design [lower right] temperature distribution, which is much better from the flow point of view.

FIGURE 2
Classification of Proposed MSR

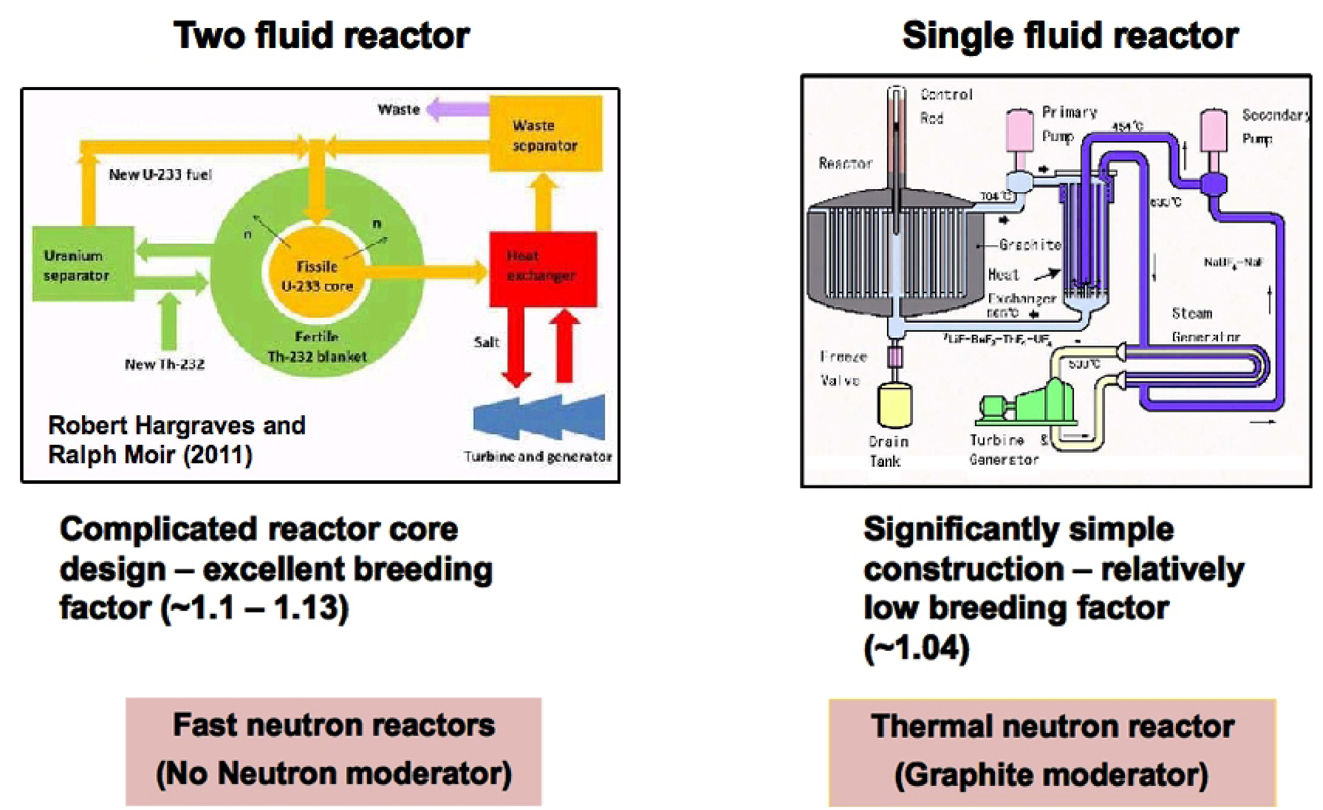
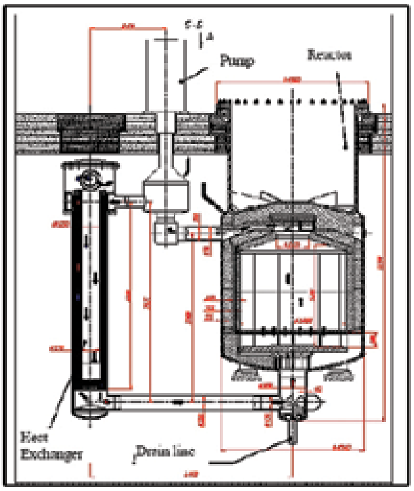
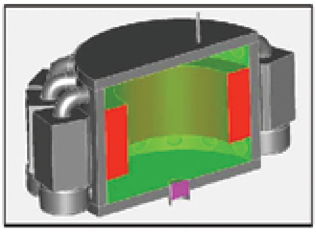


FIGURE 3
Fast MS Reactors

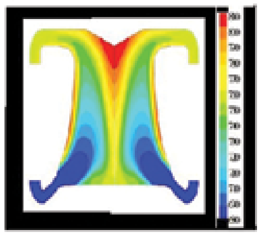
MOSART Fuel Circuit, RUSSIA
[Victor Ignatiev, et.al. 2007]



EVOL European MSFR



Reactor CORE



Advanced core design
Temperature distribution

The FUJI Reactor

Now I am going to talk about the thermal reactor, mostly the design of Kazuo Furukawa, who designed the MiniFUJI, then the concept of the FUJI reactor, and then the concept of the accelerator molten salt breeder.

What is the MiniFUJI reactor? It's a very small reactor (**Figure 4**). Why? The objective is to recover the know-how that was obtained at Oak Ridge, 40 years ago. It is one thing to have information: Libraries are full of information. But knowledge requires that you *do things* with this knowledge. And this is why it was necessary to make this little reactor, so that we actually *know* what we're doing, and find out all the difficulties.

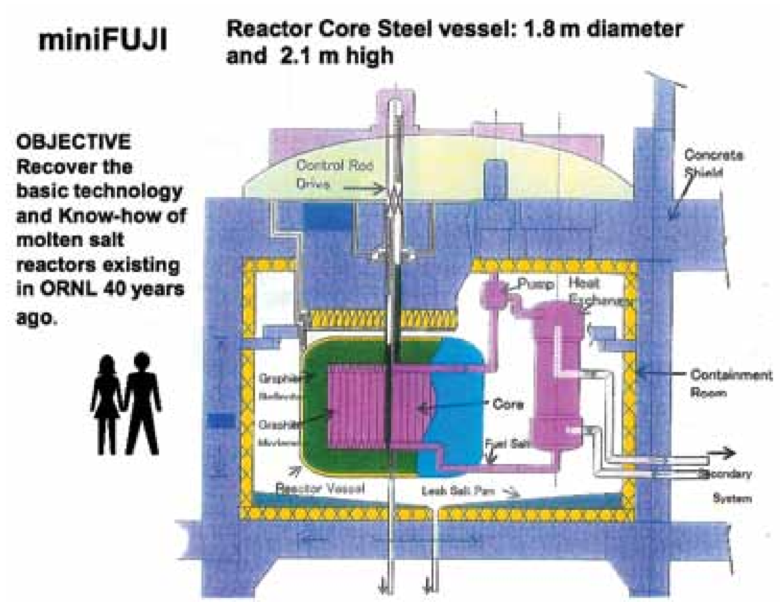
In this reactor, the contents of the reactor core are mostly pure graphite, with holes through it. Six percent of the volume is the liquid that is flowing through it. And there is a control by graphite rods. They work the other way around [from current reactors]: You increase the reactivity by introducing more graphite inside the core. **Figure 5** is a full view of the FUJI molten salt reactor. On the left side, you have the reactor's core, with three containment systems. There are

Some of the advantages of the fast reactors are that the core is extremely simple. It's just an empty tank! There's nothing that can go wrong there. It is extremely stable, because the fluid, if it becomes hotter, it expands; and when it expands, it reduces the reactivity, and therefore starts to cool. So it is naturally stable. Some of the experiments—mathematical, of course—that have been run, show that the reactor starts to heat up and then cools, oscillates, and comes to a steady state. This is what would happen if you suddenly stopped all the devices inside the reactor (like the case in Fukushima: suddenly, no electricity). It is very stable. It is a breeder reactor, which produces more fuel in operation.

But, the disadvantage is that it has a very long doubling time. This is the amount of time that a reactor needs to produce as much fuel as it has consumed. For the EVOL project, as described in 2008, the doubling time is about 40 years, which is very much longer than the doubling time of the demand for energy. So something else has to be done in order to produce more fuel.

Another disadvantage is that it requires a very complicated chemical-processing system. I shall not go into details of this.

FIGURE 4



two places at the bottom where, if you drain the fuel, it goes down there and becomes completely harmless, because the fuel only produces fission when it is inside with graphite. If the fuel flows out, it is harmless. When it cools, it becomes like a stone. On the right side, are the parts of the reactor that are to transport energy and heat, and thus to produce electricity.

Figure 6 shows the nucleus of the FUJI reactor. It is a small reactor, only 160 MWe. The idea is that it is so safe that it can be built right next to cities, and have very little expenditure for the transport of electricity. The diagram shows the first and second containment areas. If anything would happen, you would drain into one of the containers below.

FIGURE 5
Full View of FUJI Molten-Salt Reactor

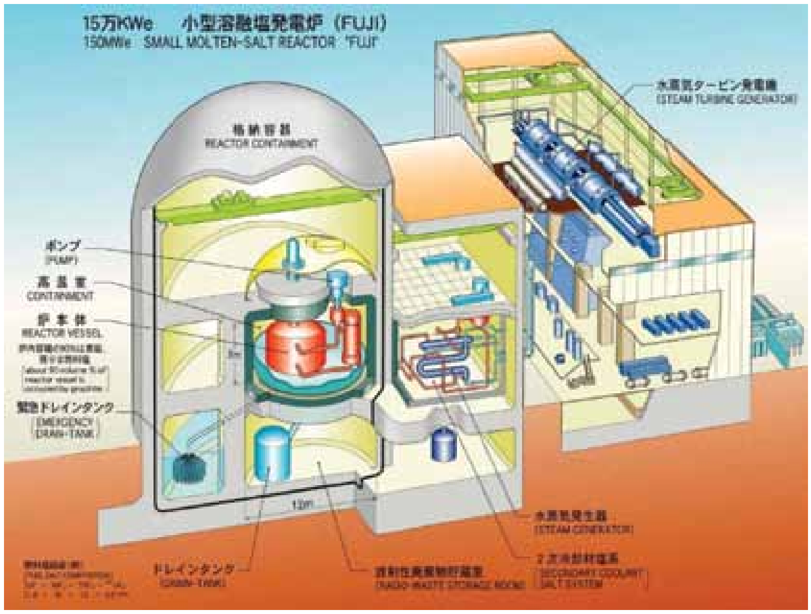
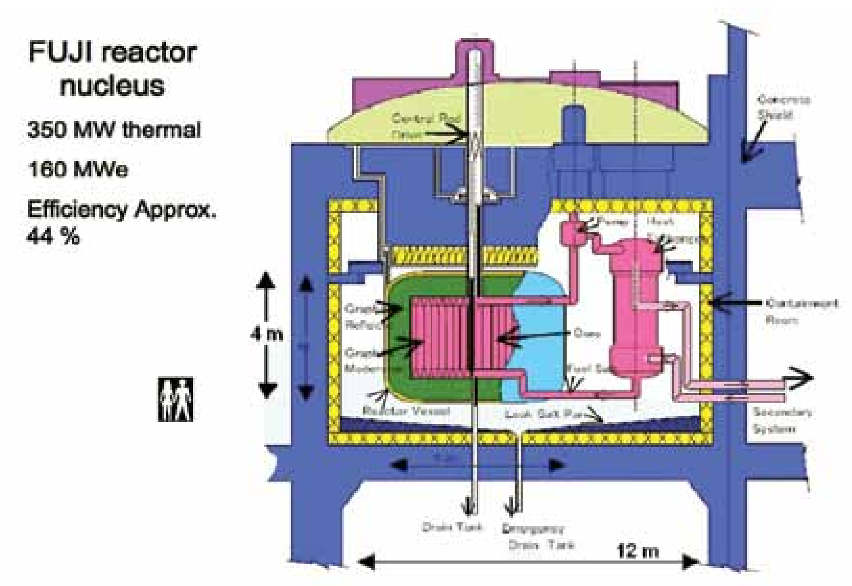


FIGURE 6



Advantages

What are the advantages of the molten salt reactor? It is practically impossible to have a severe accident, because it is under *very low pressure*, only about twice the pressure of a car tire, inside a steel container. And the molten salt is chemically inert; it does not react with water or air or anything. The boiling point is about twice the operating temperature [1,400°C compared to 7°C]. Any excursion to a higher temperature is safely below the boiling point.

There are many other advantages, but I don't have the time to discuss them all. I will just point out two of them.

One is that there is radioactive gas removal. You inject helium and it removes the radioactive gasses that are produced by fission. This was found, in the experiment by Oak Ridge, to remove some other radioactive materials as well. So if there were any problem, there would not be any gasses escaping from the reactor, because they are not there!

And there is another advantage, that there is no xenon poisoning. This is a phenomenon that was instrumental in what happened at Chernobyl. Xenon poisoning, in a normal reactor, means you have to have excess reactivity in order to overcome the poisoning by xenon. In this reactor, you are removing the xenon, so you don't have to have excess reactivity. This means the reactor can go up and down in power, which is something that is not done in normal reactors; they operate better always at the same power.

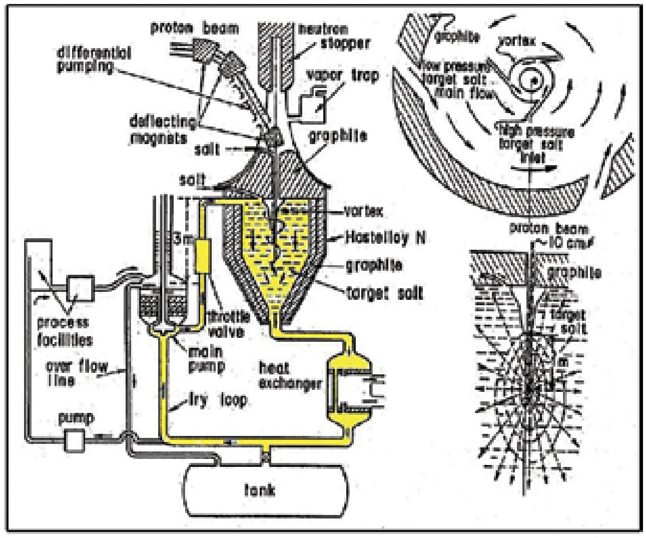
So this is a reactor that could provide energy for peak need; whereas during the night, when there is less need, you reduce the power.

Another point is the freeze valve. The freeze valve is below the reactor, and it is actively cooled by blowing air into an area where the salt is frozen. So if the electricity cuts off, the blowing stops; then the freeze valve would melt and allow all the fuel to fall down into the drain tank. The drain tank is designed for passive cooling, so that the fuel becomes solid in there. This would mean that if this reactor had been at Fukushima, nothing would have happened. After everything is repaired, you re-melt the fuel and pump it back into the reactor.

So there is the safety factor. The fuel is only critical when it is in the graphite, and the fuel becomes a solid, trapping the radioactive material. There is less nuclear waste. The fuel in the reactor can stay in the reactor permanently for 30 years, and thorium is a fertile material that produces very little in the way of actinides. The molten salt is an ideal medium for reprocessing and recovering uranium and plutonium from nuclear waste.

FIGURE 7
Fluid for Breeding U233 and Chemical Processing of Waste

Accelerator molten-salt breeder (AMSB) To "burn" actinides and produce more uranium 233 fuel

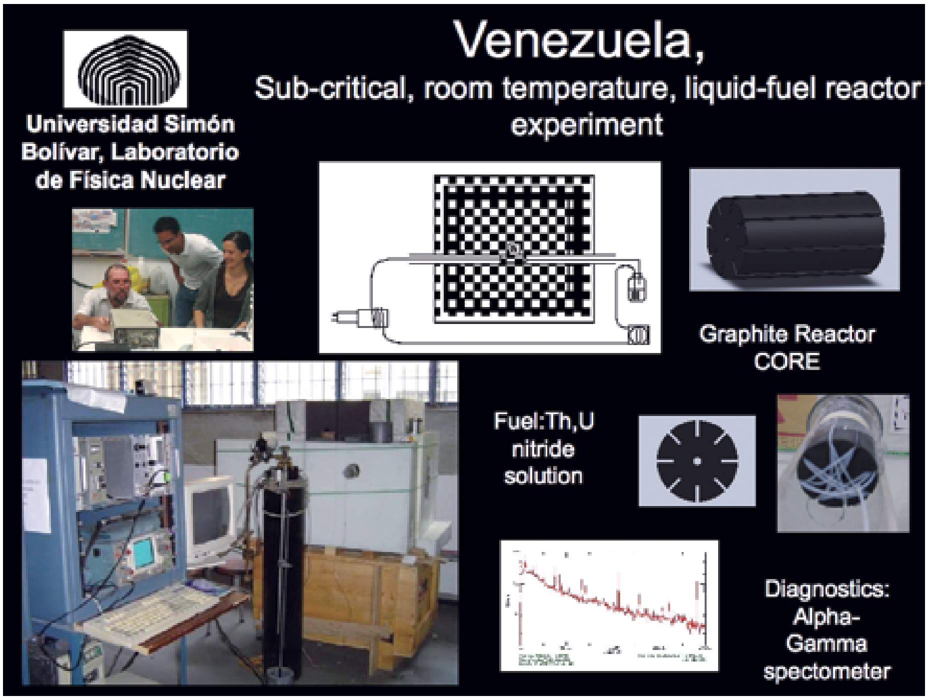


K. Furukawa, et al. Proposal & (Carlo Rubbia Patent)

Figure 7 is a proposal by Furukawa, which is to reprocess the fuel from current reactors by turning these fuels into fluorides, dissolving these fluorides into the molten salt, and pushing them into this device. At the top, there is an accelerator (not shown), a very high-energy accelerator that throws some protons into the fuel. It uses a nuclear process called spalation, which means that when a particle falls against a heavy ion, a heavy element, it loses a lot of neutrons: 40 neutrons per reaction. It is a very neutron-rich reaction. The reactor itself is not a neutron-rich device, but an energy-rich device. In this concept, you don't need a fast reactor to produce more fuel. The fuel would be produced in a device like this, where a neutron-rich reaction can produce a lot of fuel, by irradiating thorium and producing uranium-233, and also by burning the actinides from the reactors that are currently operating.

Now, on non-proliferation and terrorism: There is no production of plutonium. Weapons-grade uranium is burned up in the thorium reaction, and uranium-233 is produced. Uranium-233 was used for one atomic bomb, in 1955, and after that it was never used again, because it is very hard to produce a bomb with it. The reason is that it is very radioactive—not the U_{233}, but another uranium which is used with it. It is very difficult to produce

FIGURE 8



U_{233} without U_{232}, which has high radioactivity. Therefore, it is very difficult to work with; you couldn't stand next to the bomb, because it would kill you. Or you would have to shield it with so much lead that it would be very difficult for the airplane to take off.

Thus the molten salt reactor uses a very safe kind of fuel. There is no need for fuel-fabrication plants; no fuel elements that have to be exchanged or re-arranged regularly; low construction costs and low operating costs; economy in both the short and long run.

Zero nuclear weapons! Energy independence for us, and the use of our own thorium devices! (We have thorium in Venezuela and in Brazil.)

2013 Developments

A few brief comments:

In Europe, there are a quite a few countries working on it [France, Germany, Italy, United Kingdom, Czech Republic, Russia, Hungary], quite a few groups [EVOL, SNEPTP, ThEO, the Weinberg Foundation]. And there are 16 institutions participating in the EVOL development, with about 60 persons.

In Japan, there is a new proposal by Takashi Kamei; and there is the Thorium Molten Salt Forum, which includes 13 countries and several universities; and there is the FUJI reactor, which was designed there.

India is another emerging country coming into the molten salt camp. They have, for a long time, had a three-stage project, which, in the third stage, uses thorium. It was created by [Homi J.] Bhabha, the creator of the Bhabha nuclear center. Now they are thinking that the third stage might perhaps be a molten salt breeder reactor (MSBR).

The U.S. has two companies working on it. One is Flibe Energy: Kirk Sorensen is the man pushing it. And there is Transatomic Power, which is a spinoff from MIT, where some students work. And there is a Thorium Energy Alliance organization, which is very active in the U.S.

In Venezuela, we have a small facility where we are actually doing experiments, not with molten salt, not with high temperatures (**Figure 8**), but a room temperature experiment with liquid fuel. The spectra shown here were obtained about a week ago from the device that is operating there.

And the most advanced project is in China. China is definitely moving toward the molten salt reactor, in addition to other projects—pebble-bed reactors, fast reactors. They announced plans for spending $300 million in 2011 for molten salt reactor development, and now, very recently, in Shanghai, the Institute for Applied Physics is working with the support of the Chinese Academy of Sciences, and there is a budget this year of $100 million.

In conclusion, nuclear power is the only technology capable of supplying the world's huge demand for energy. Present day solid-fuel-reactor technology has problems, which have made in unacceptable to society, although they are producing very good service. There is a worldwide movement in support of the thorium molten salt reactor. The development of different forms of molten salt reactors is recommended, as competition will lead to the best technology.

The thorium molten salt reactor is a new technology capable of providing the clean, safe, and cheap energy which is necessary for future development of society.