# Interview: The Dual Fluid Reactor

## *The Public is Ready for Nuclear Power*

*Dr. Ahmed Hussein is Professor Emeritus of physics at University of Northern British Columbia currently stationed at TRIUMF, Canada's National Laboratory for particle and nuclear physics in Vancouver, British Columbia. He is also an Associate Member of the Institute for Solid State Nuclear Physics (IFK) in Berlin, Germany. He was interviewed on September 16, 2014 by Robert Hux for* 21st Century Science & Technology.

**Robert Hux – Dr. Hussein, we met you recently at the Pacific Basin Nuclear Conference here in Vancouver, where you presented a very interesting new design for a nuclear fission reactor.[1] How does your design differ from the nuclear fission reactors which have been developed since the 1950s?**

Dr. Ahmed Hussein – Our reactor, called the Dual Fluid Reactor (DFR)[2], was designed to solve many of the problems which exist now with the current reactors that people are afraid of. Current reactors have some designs that actually originated in the military use of nuclear power in the old days of the Manhattan Project, and they were adapted to civilian use. The issues of safety have been addressed, and improved, in various generations of civilian reactors, but at a high cost. So the result is that building the reactor with all these safety measures to make it safe for operation actually added significantly to the cost of the reactor. However, one should know that even though the construction cost is high, the operational cost is much lower than fossil fuel power stations.

The other problems with these reactors are the amount of waste that these reactors produce, which has to be stored for a large number of years, and the concern for proliferation due to the need for enriched fuel. However, current reactors are much better and cleaner sources of energy than fossil fuels, the safety has improved, and I must add that a current 1000-MW nuclear power station produces about one cubic meter of waste per year which can be safely stored, and that should be compared to the millions of tons of green house gases and the 320,000 tonnes of ash containing toxic heavy metals and tens of thousands of tonnes of sulfur and nitrogen oxides that are produced by fossil fuel power stations. Furthermore, nuclear power reactors do not emit any radioactive materials into the atmosphere during operation, while coal-fired stations emit radioactive materials that are mixed naturally with coal.

Our reactor concept has a simpler design that avoids most of the problems that we have right now. And it will actually make nuclear power a lot cheaper, safer, mostly carbon-free, and better to use than any other energy source.

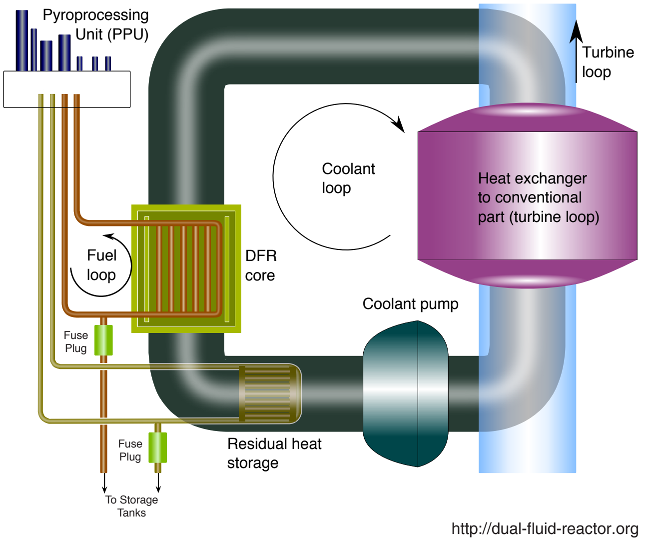



*Figure 1. Close-up of the DFR core region with part of the coolant cycle and the short-lived fission products storage inside the coolant conduit ahead of the core.*

1. A. Huke, G. Ruprecht, D. Weisbach, S. Gottlieb, A. Hussein and K. Czerski, The Dual Fluid Reactor- A New Concept for a Highly Effective Fast Reactor, paper presented at 19th Pacific Basin Nuclear Conference. Vancouver, British Columbia, Aug. 24-28, 2014.

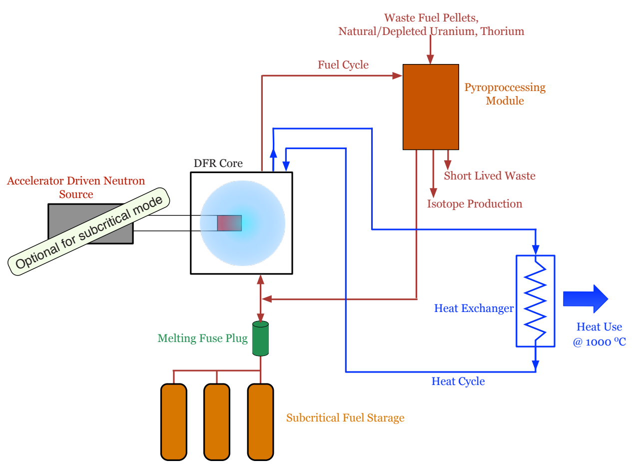
2. http://dual-fluid-reactor.org

**Can you describe how your reactor works?**

The reactor is really very simple. It is a fast, molten salt, metal-cooled reactor. Although, it bears resemblance to other reactor designs, it is actually different from all of them. The important feature of our design, that makes it unique, is that it uses two fluids: one as a fuel, and the other as a coolant. (Figure 1) This allows us to optimize each fluid for its specific function, in contrast to all existing molten salt reactor designs that use one fluid as fuel and coolant. This simple feature opens up the way to a host of improvements that makes our reactor unique among all generation-IV reactor designs.

The fuel fluid is molten natural uranium (U) or natural thorium (Th) salts (for example tri-chloride) while the coolant fluid is molten lead. The fuel is prepared from natural U or Th in an online "pyro-processing unit" (Figure 2). The liquid fuel is then pumped into the reactor core where a "critical mass" of fuel within a confined space creates the conditions for a self-sustaining fission chain reaction, producing energy that is carried by the circulating molten lead outside of the reactor to a heat exchanger.

The molten salt fuel allows continuous extraction of fission products, which are stored as liquid outside the reactor core and cooled with the same molten lead which cools the reactor core, until ready for shipment to medical or industrial uses, or stored in a passively-cooled location within the reactor facility.




http://dual-fluid-reactor.org

*Figure 2. DFR fuel and cooling loops. The pyro-processing module prepares the molten salt fuel which is pumped into the DFR core, and continuously extracts and separates useful isotopes from short term waste. Molten lead carries the heat from the DFR core and fission products out of the reactor to the heat exchanger. In case of loss of cooling, melting fuse plugs allow the molten salt fuel and the fission products to be drained out of the reactor core, safely shutting the reactor down.*

Moreover, the liquid fuel can be easily replenished by addition of small amounts of new fuel.

**You said that the DFR reactor is a "fast" reactor. Why is that important?**

There are two kinds of reactors: fast reactors and "slow" or "thermal" reactors. Most of the existing reactors in the world, such as the Pressurized Water Reactor (PWR) or the CANDU-Pressurized Heavy Water Reactor, are thermal reactors. Thermal reactors are designed to take advantage of the fact that there is a very large probability for a "fissile" or "fissionable" atom, such as uranium 235, to absorb a neutron into its nucleus and break up ("fission") into two smaller atoms plus a few more neutrons to sustain a fission chain reaction, if the neutron has a low energy and is moving slowly.[3] But when the atom fissions, it releases a large amount of energy and the new neutrons are travelling very fast, too fast to be easily captured by another fissile atom.

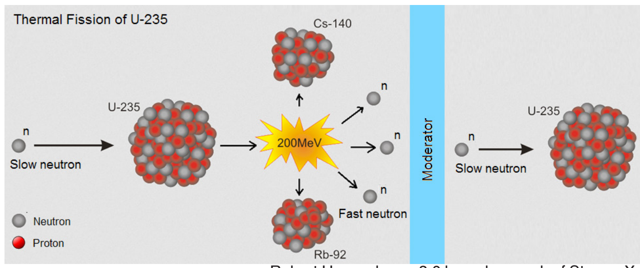



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*Figure 3. Thermal nuclear fission of U-235 initiated by the capture of a slow neutron produces two smaller atoms (Rb-92 and Cs-140 shown here only one possibility among many) and an average of 2-3 fast neutrons, which can be slowed down by interaction with a moderator (water, heavy water or graphite) to increase probability of capture by another U-235 nucleus and initiate a chain reaction.*

So, in a thermal reactor the fast neutrons are slowed down (and they become thermal neutrons) by adding to the reactor core a light-weight material called a moderator (e.g., water, heavy water or graphite) which is capable of efficiently absorbing the excess neutron energy. Although water is the best moderator because its molecules contain hydrogen whose nucleus (a proton) has a mass nearly equal to that of the neutron, water has the disadvantage of also absorbing some of the neutrons.

Most existing thermal reactors in the world and especially the ones that use water as a moderator or coolant cannot sustain a fission chain reaction, or

3. Uranium has two components which are distinguished by the mass and natural abundance of their atoms: uranium 238 (99.3%) and uranium 235 (0.7%).

criticality, using the 0.7% U-235 present in natural uranium. These reactors must increase the amount of U-235 to 3-5% through a complex and very expensive process called enrichment. The next best moderator is heavy water (deuterium oxide), whose molecules contain a heavy isotope of hydrogen, called deuterium, which has one neutron and a proton, and has the advantage that it not only does not absorb many neutrons but also releases some of its neutrons into the reactor core while moderating the fission-produced neutrons. Those extra neutrons make it possible to use natural uranium in heavy water–moderated reactors. Consequently, although the CANDU-PHWR reactors do not need enrichment of U-235, they do require a moderator, heavy water, which is produced through a complex and expensive process.

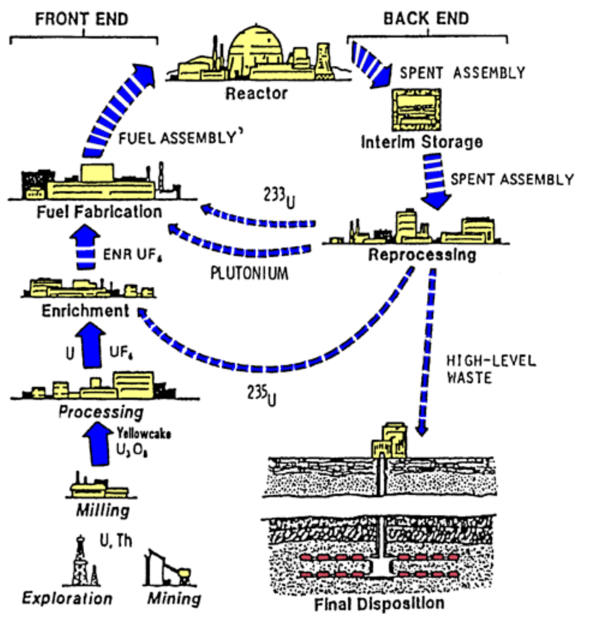


*Figure 4. The closed nuclear fuel cycle of existing nuclear reactors.*

*On the front end, uranium is mined, milled, converted into uranium hexafluoride, enriched to 3-5% U-235, and fabricated into fuel rods for use in light water reactors. Heavy water reactors (e.g., CANDU) do not require enrichment.*

*On the back end, six countries (China, France, India, Japan, Russian Federation and the UK) have a closed fuel cycle policy which reprocesses spent fuel to create new reactor fuel. All other countries have a "once through" fuel cycle in which spent fuel is stored in cooling pools at the reactor site, and is then stored in dry casks awaiting burial.*

*With the DFR reactor, mining and fuel fabrication are dramatically reduced, since nearly 100% of the uranium is consumed and the fuel is molten salt. In addition, uranium enrichment, reprocessing, and geological disposal of the used fuel are not required.*

Thermal reactors have further drawbacks. First, they cannot burn any more than 0.7% of the uranium (U-235) present in natural uranium ore. Second, current reactors use solid fuel rods and the only way to control the power output is by using control rods. These rods are made of a material like cadmium that absorbs neutrons in large quantities. Control rods move, mechanically, in and out of the reactor core. Partial insertion reduces the power output of the reactor and complete insertion shuts the reactor down. This system is susceptible to mechanical failure and consequent loss of reactor control. Third, while a thermal reactor cannot fission either the remaining 99.3% of the uranium (U-238), or thorium (Th-232), it can convert these fertile materials into fissionable isotopes of plutonium (Pu-239) and uranium (U-233), and it produces many other heavy elements, called actinides and medium weight elements called fission fragments. Most of these elements are heavily radioactive. The actinides, most of which cannot be burned in a thermal reactor, along with the fission fragments, accumulate in the fuel rods and continuously produce large amount of heat due to their radioactive decay. As a result the fuel rods need continuous active cooling even when the reactor is shut down. Failure of this active cooling could lead to core meltdown. Fourth, after the fuel in the rods is depleted, the rods, containing the actinides and fission fragments, are removed from the core and must be stored for a very long time (thousands to hundreds of thousands of years) in safe and secure sites that are geologically stable.

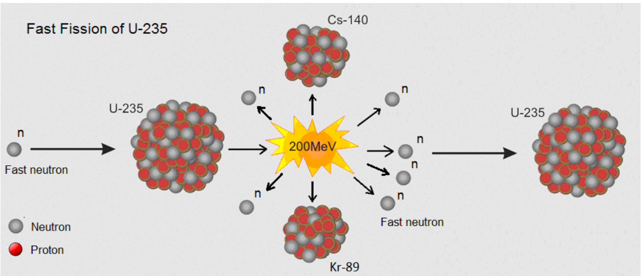


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*Figure 5. Fast nuclear fission of U-235 producing two typical fission products.*

Fast Reactors with liquid fuel like DFR, on the other hand, operate with fast neutrons. So, they do not need a moderator. Although the probability of fast fission is lower than thermal fission, this is compensated to some extent by the fact that fast fission produces more neutrons (about 4-6 neutrons per fission vs. 2-3 for thermal fission).

Those extra neutrons can also be used to change U-238 into the fissionable Pu-239; thus, while consuming its initial fuel, fast reactors produce new fuel right inside the reactor core.

Consequently, fast reactors consume almost 100% of natural uranium. Similar to thermal reactors, fast reactors cannot "initially" reach criticality with natural uranium. However, once the fast reactor is started up with the initial load of enriched fuel, it can be refuelled with natural uranium or thorium. Fast reactors can also use as fuel the waste (or better said, slightly used fuel) from existing reactors or the plutonium and uranium that are extracted from dismantled nuclear weapons. As a result, the life of nuclear fuels will extend to thousands of years.

In both types of reactors, fertile U-238 (or Th-232) is converted into fissile Pu-239 (or U-233) as well as other actinides, but fast reactors are more efficient in this process than thermal ones. As I mentioned before, many of the actinides have very long half lives.[4] Thermal reactors cannot burn the produced actinides, while fast reactors are actually very efficient in burning them. As a result, fast reactors produce much less radioactive waste with much shorter half-lives than thermal reactors.

**So rather than using water as the coolant like most of the reactors we've discussed, your reactor uses molten lead.**

Yes. Using molten lead allows the reactor to operate at a very high temperature, making it a very efficient reactor. Using molten salt fuel and molten lead coolant provide many passive safety features that make DFR an extremely safe reactor.

**The operating temperature of the reactor is …**

The operating temperature of the DFR is 1000 degrees Celsius. At this temperature the efficiency of heat transfer is quite high. We can achieve this because we are using molten lead as a coolant, which melts at 327 degrees Celsius and boils at 1750 degrees. In addition, we can operate at this high temperature at atmospheric pressure; another simplifying factor of our design. You can contrast the DFR with the PWR and the CANDU which use water for cooling the reactor. Water, as you know, boils at 100 degrees so the reactor would have to operate at lower than 100 degrees which would mean an extremely poor efficiency of heat transfer. So, the PWR and the CANDU operate at very high pressure in order to raise the boiling point of water, so they can operate at temperatures up to 350 degrees. The pressure needs to be as high as 70 to 150 times atmospheric pressure. This very high pressure is required to achieve a modest heat transfer efficiency. Reactor designs to accommodate such high pressure are quite complex and expensive.

**Does the lead coolant of the DFR have any advantages over other coolants used in fast reactors?**

Fast reactors generally require liquid metal to cool the high-power-density reactor cores. Since the pioneering work on fast reactors at Idaho's Argonne National Laboratory beginning in the early 1950s, which resulted in the Experimental Breeder Reactor-1 (EBR-1) and its successor EBR-2, the focus both in the United States and around the world has been on the use of sodium or sodium-potassium coolants.

However these materials aggressively react with air, water and various structural materials; they absorb neutrons to form short-lived, but highly radioactive species (like Na-24) which can release enough heat to form vapor bubbles in the liquid sodium coolant. These bubbles reduce neutron absorption, causing the fission rate to increase (positive void coefficient) and the reactor to run out of control. Consequently elaborate measures are required to ensure safe operation of these reactors, such as a sealed reactor vessel with a pressure greater than atmospheric pressure, double-walled piping and an intermediary cooling cycle, measures which have increased the costs of sodium-cooled fast reactors significantly above that of PWR reactors.

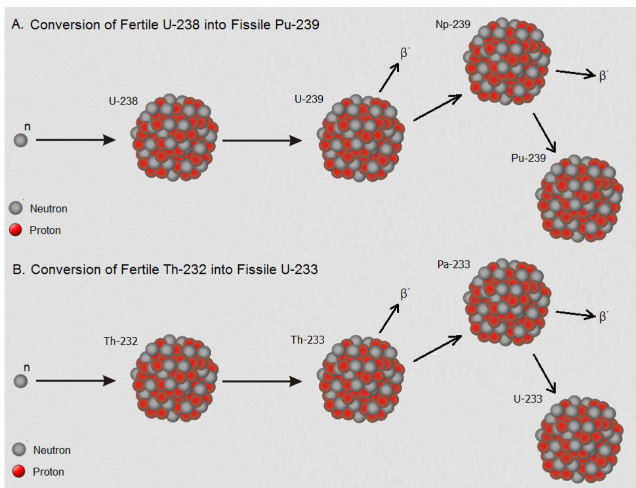


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*Figure 6. The real potential of nuclear fission depends on the use of fast reactors to efficiently create new fissile materials, through two paths: A. Conversion of the non-fissile uranium (U-238) into fissile Pu-239. B. Conversion of the more abundant thorium (Th-232) into fissile U-233.*

*Molten salt fast reactors with online separation of fission products, like DFR, do not need to shut down the reactor to reprocess the used fuel rods. The Pu-239 and U-233 (as well as the other actinides) can be consumed inside the reactor.*

4. The half life, $t_{1/2}$, is the time required for half of the atoms of a given isotope to undergo radioactive decay into a different isotope. The major radioactive emissions from irradiated nuclear fuel, after the fission products, come from actinides: plutonium (Pu-239, $t_{1/2}$ = 24,100 years and Pu-240, $t_{1/2}$ =6,561 years) and isotopes of neptunium, americium and curium with half lives ranging from 2.4 days (Np-239) to 2.1 million years (Np-237).

Lead, on the other hand, is a very stable element and does not interact much with other elements. It absorbs fewer neutrons than sodium. Some radioactive isotopes could form in lead after long exposure in the reactor, but they decay back to stable lead. Moreover, lead does not moderate (slow down) the fast neutrons as much as sodium does. So a lead-cooled fast reactor like the DFR which continuously removes the fission products (which can absorb neutrons) will have a greater number of neutrons available to perform useful work.

For example, if the DFR was operated to breed plutonium from the U-238 in natural uranium, it would take about 4 years to produce enough fuel for another reactor, similar to the present construction time for a nuclear plant. On the other hand, sodium-cooled fast reactors (such as the French Superphénix or the Russian BN reactors) with PUREX-reprocessing plants have a doubling time of 30-40 years. Breeding U-233 from thorium would have a longer doubling time than this because U-233 produces fewer fission neutrons than Pu-239.

**What are the passive safety features you mentioned before?**

Liquid fuel allows the use of fuse plugs that are actively cooled to stay solid during normal operation, but if, for any reason, the cooling of the reactor is lost and the core temperature rises, the fuse plugs melt, draining the fuel from the reactor core into subcritical storage tanks, as seen in Figure 2. This way the reactor never experiences core melt down. In addition, since it is a fast reactor with liquid fuel, the reactor does not need control rods or a moderator and has no mechanically moving parts in the core. These features simplify the core and reduce to a large degree the need for active safety.

As already mentioned, liquid fuel also allows the continuous extraction of fission products, and their safe storage and active cooling by the molten lead outside the reactor core. The radioactive decay of those fission products continues to produce heat even after the reactor shuts down. Their storage also has fuse plugs (Figure 1) so they can be drained into self-cooling tanks in case of coolant loss. With the burn up of the very long-lived actinides, the major source of radioactivity in the reactor comes from the fission products. However, the fission products which are not presently useful need to be stored for much shorter times (up to 300 years), which can be safely done within the reactor facility. Further, all isotopes that are useful for medicine or industry (like for example molybdenum-99/technetium-99m) can easily be extracted continuously to be processed and shipped out.

Moreover, in the case of loss of coolant (the most serious accident in a nuclear power reactor) even before the temperature increase can melt the fuse plugs, as the temperature rises above normal operating temperature the reactor becomes "subcritical" and begins to shut itself down, due to the negative temperature coefficient of the DFR.

One more thing, the reactor itself does not need water to operate, so it can be built in a subterranean location, while electricity generation that may need water to operate can be placed above ground. That makes the reactor a lot more secure and much safer compared to current designs.

**How long would it take to build a demonstration reactor and then move to commercialization?**

Our estimate, currently, is between ten and fifteen years. So far we have been studying the mathematics and the behaviour of the reactor as well as selecting proper materials for the reactor core. We haven't yet done any actual building. We just submitted a proposal to the European Union Commission for a research grant to study many aspects of the reactor, and after that we can move on to build a prototype. We think we can build a prototype to show that the reactor works, in between 7 and 8 years, maybe ten, and then another five years to actually produce a full-sized reactor.

**Do you expect any major hurdles while building a prototype?**

There will be hurdles of course, but I am not expecting any show-stoppers. The important issue here is that we are not inventing any new technologies: we are putting together several existing and proven technologies in an out-of-the-box way of thinking. Molten salt fuel and fuse plugs were proven to work successfully in the molten salt experimental reactor built and operated at Oak Ridge National Laboratory back in 1960s. The pyro-processing methods have been developed and used in the few waste reprocessing facilities built in France and elsewhere, and finally the Russian alpha class nuclear submarines successfully used a molten mixture of lead and bismuth as coolant. There will be problems in putting all these technologies together, but they will be the kind of problems which are solvable in my opinion.

**What kind of response are you getting from, for example the Canadian government or other governments around the world, in terms of being willing to invest in something like this?**

The situation with nuclear power is unfortunately similar to the car industry. If you look at the car industry now you find that most of the engines in cars nowadays are more or less the same engine that Henry Ford invented a hundred years ago. It's the same situation with nuclear power. The companies that produce nuclear reactors have their designs, they keep changing safety issues to the extent that new reactors are safer than the old ones, but the basic design is still the same design that came out

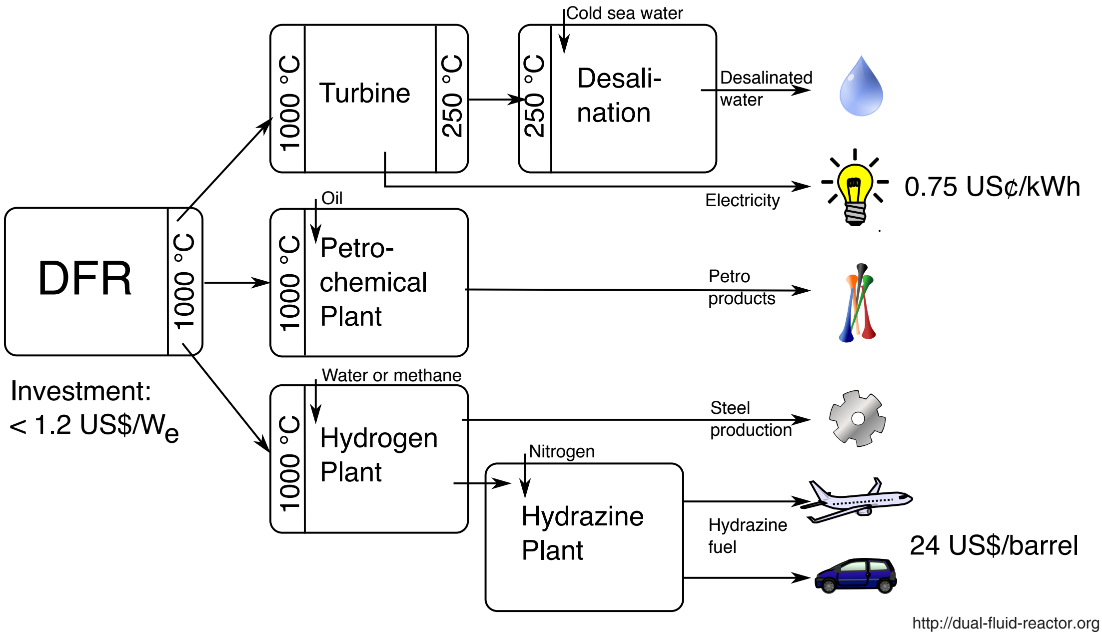


*Figure 7. DFR applications.*

from the Manhattan Project. Many of the reactor producers are reluctant to get into new designs. So we are struggling with that, but we are still trying and we are hoping to have a breakthrough soon.

We haven't contacted the Canadian government yet, but I just found out recently that the Canadian government has a section in the National Science and Engineering Research Council (NSERC) for funding projects related to generation-IV nuclear reactors. Actually the DFR can be considered as generation IV+. So, I am in the process of putting together a group of interested Canadian scientists and engineers to submit an application to NSERC for a research grant to complement the European proposal.

**Do you think that this new kind of technology could help us reverse the opposition to nuclear power that has developed in the last several decades?**

I really think so. We are meeting some opposition; however, I have been giving talks in many different places, and found the public is actually ready for nuclear power. They realize how terrible fossil fuels are. They are ready for nuclear power, particularly with something like the DFR which actually solves most of the problems with the current reactors. The public I think, is ready. A couple of years ago we had an experience in Germany that showed the public was very much interested in nuclear power, even though the government is shutting down nuclear reactors. So it looks like the public is really ready for it. Except that they haven't yet moved toward putting pressure on governments to replace fossil fuel based power stations with nuclear ones. We are trying very hard to educate the public about our reactor which is extremely safe, carbon-free during operation, and a lot cheaper to build and operate than any existing power source including wind, solar and coal. We are predicting that the cost of electricity produced by a DFR will be one-third of that produced by coal. The cheap electricity will make the production of synthetic carbon-free automotive fuels like hydrazine, and water desalination economically viable while keeping the environment clean

**At a certain point you have to bring in a higher energy flux density than even nuclear fission, namely thermonuclear fusion. What is your perspective on fusion?**

Nuclear fusion, in my opinion, is the ultimate energy source, particularly the deuterium-deuterium fusion; the fuel is abundantly available everywhere. So this is really the ultimate source of energy. Unfortunately, it is still not available yet, but there are currently concerted efforts taking place around the world like the ITER (International Tokamak Experimental Reactor) facility in France and General Fusion here in Vancouver, and laser fusion in the United States. But it doesn't look like we are going to have a working fusion reactor in the near future.

So in the meantime, to stop the problem with fossil fuels, I think we should switch to nuclear power and keep the current reactors going, and build new ones. And hopefully in 20 or 30 years nuclear fusion will be available, and then I think that everything else should shut down and rely on fusion alone.

Finally, I would like to mention that the concept of the dual fluid reactor was developed by a group of nuclear physicists, including myself, in the Institute for Solid-State Nuclear Physics (IFK) in Berlin, Germany.[5]

5. http://festkoerper-kernphysik.de