The Do-able Molten Salt Reactor
a time for courageous impatience

Preliminary Draft for Discussion Only

Jack Devanney
Center for Tankship Excellence, USA, djw1@c4tx.org

1 History

After World War II, there was a big debate between the Argonne Lab led by Enrico Fermi and the Oak Ridge Lab led by Alvin Weinberg on how best to use nuclear power in peace. Both men were thoughtful geniuses. At the time, both thought that the world's supply of uranium was very limited, and both knew that only 0.7% of this uranium, the isotope U235 was fissile, that is, could be made to fission. This meant that for every ton of U235 produced about 140 tons of uranium were required; and, in order to be useful in a reactor, that uranium had to be put through an expensive enrichment process in which the U235 was separated from the much more common, but not fissile isotope U238.

In the early 1950's, the only non-experimental power reactor was the Navy's pressurized water reactor, which had been invented by Weinberg, and developed in a crash program for submarine propulsion. This reactor used highly enriched U235 in solid form. The working fluid was water at very high pressure (160 bar) but at a rather low temperature (330C).[1] Both Fermi and Weinberg believed that, if we tried to use this system for civilian power, we would very quickly run out of uranium.

Fermi argued for sticking with solid fuel based on U235, and the enrichment technology developed during the war. His solution to the fuel problem was to bombard non-fissile U238, which made up more than 99% of naturally occurring uranium with high energy neutrons in the reactors. This converts some of the U238 to plutonium which then can be fissioned. This became known as the fast breeder reactor. Most of the designs based on this concept use a liquid metal — often sodium — as the coolant.

Weinberg, following his mentor, the uber-genius Eugene Wigner, argued for a completely different approach. His idea was a liquid fuel reactor based on converting thorium to the fissile uranium isotope, U233. Thorium is 500 times more abundant than U235, much more easily mined, and requires no enrichment. The reactor is made up of a core of molten salt in which the U233 is dissolved, surrounded by a blanket, also a molten salt in which the thorium is dissolved. The blanket gets bombarded with some of the core neutrons converting the thorium to U233. Both fluids are continuously circulated. The core salt is run thru a heat exchanger, some processing to remove fission products and add some new U233 from the blanket. The blanket fluid is processed to remove the U233 which is sent to the core, and replaced with new thorium.

It turned out that there was far more uranium on the planet than Fermi or Weinberg thought. The industry fastened on the pressurized water reactor (PWR) that the Navy had developed. It was the quickest way to deploy civilian reactors. The PWR took advantage of the very expensive and difficult enrichment process developed for the bomb. The same companies who built the Navy's reactors could use almost exactly the same skills and knowledge to build the civilian reactors.[2] And the PWR had an attractive business model. Once you sold a reactor, the customer had to come to you for the very specialized fuel rods for the life of the reactor. In some cases, companies were willing to take a loss on the construction in order to obtain the fuel element cash flow.

Weinberg kept the liquid fuel concept alive at ORNL including building a 8 MW test reactor that ran successfully for four years, 1965 to 1969. But in 1972, Weinberg was fired at least in part because of his concerns about PWR safety.[3]

The decision was made to focus all the nation's reactor research effort on the fast breeder. In 1976, the Nixon administration shut down the molten salt reactor program. A few years later the fast breeder program, which was experiencing skyrocketing costs was effectively shut down as well.

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[1] The other form of light water reactor, the boiling water reactor uses a lower but still high pressure (75 bar). For our purposes, the differences between the pressurized water and the boiling water reactor are not important.

[2] In fact, the first civilian power reactor, Shippingport, was a navy reactor. It was originally intended for a nuclear powered carrier.

[3] The specific issue that appears to have gotten Weinberg fired was cladding swelling. Industry models indicated that in the event of loss of coolant in a PWR the zirconium fuel rod cladding would swell no more than 30%. Tests at Oak Ridge showed this number was way low. This was a critical issue. If ORNL was right, it is unlikely that the Emergency Core Cooling System could prevent a melt down. Worse the tests indicated that at loss of coolant temperatures, the zirconium would react with the oxygen in the steam destroying the cladding and releasing hydrogen. (This happened at both TMI and Fukushima.) When ORNL researchers were called to testify publicly Weinberg told them "act responsibly and tell the truth", which they did.

2 Comparison of Molten Salt with Pressurized Water

Forgetting about thorium for the moment, why did Weinberg, the man who invented the Pressurized Water Reactor, think that the Molten Salt Reactor (MSR) was a far better technology? The reasons are astonishingly obvious:

Excellent control characteristics

A molten salt reactor has a strongly negative feedback. As the core heats up, the salt expands pushing fuel out of the core, decreasing reactivity, and vice versa. The feedback is so strong the reactor is auto load following. Extract more heat, salt temp goes down, power output goes up and vice versa.

Fuel flexibility

A molten salt reactor can operate on a large range of fuels including plutonium and other nuclear waste. More importantly, the fuel can easily be changed on the fly. This means there is no need for excess reactivity to account for the fact that in a solid fuel reactor the quality of the fuel deteriorates over time. Nor need you worry much about variations in the fuel makeup. Solid fuel reactors, especially fast breeders, require a very even isotopic fuel composition to avoid hot spots. Finally, ***fuel can be moved around with a pump.*** There is no need for complex robotic fuel shuffling devices that must operate for decades in a highly radioactive environment without maintenance. This is the Achille's heel of many fast breeder designs.

Simplicity and Fixability

A solid fuel reactor requires thousands of highly engineered, highly stressed fuel pins. Some fast breeder designs require more than 50,000. Failure of a single fuel pin will shut the reactor down and force a difficult decontamination process. In the molten salt reactor's primary containment there are a few dozen components and only one moving part, a pump. And if something does break, you can remove the principle source of radioactivity, the fuel, and fix things.

Higher thermal efficiency

A molten salt reactor operates at around 700C. This translates into thermal efficiencies in the mid to high 40's. A PWR reactor operates at about 330C. This implies an efficiency of about 33%.

The MSR's operating temperature is limited only by material considerations. As materials improve, the temperature can be raised, and the thermal efficiency still further improved. At 850C, we can disassociate hydrogen from water efficiently and produce hydrogen based fuels.

Low pressure operation

A PWR operates at about 160 bar. High operating pressure means 9 inch thick reactor vessels and massive piping. Some of these forgings can only be done by a few specialized foundries, none of which are in the USA.

Worse, if we have a big piping failure, the pressurized water explodes into steam spraying radioactivity all over the place. We need a very large and strong containment structure. In the event of a loss of coolant, this enormous structure must somehow be kept cool despite all the decay heat in the core.

Now the reactor, heat exchangers and all sorts of plumbing are entombed in this massive mausoleum where they are nearly impossible to repair or replace. Therefore, we pretend that they will need essentially no maintenance for the life of the plant.

A molten salt reactor operates at near ambient pressure. There is no need to pressurize the system since the salts have very high (1400C) boiling points at ambient pressure. Depending on the design, portions of the primary loop are required to be at about 15 bar for pumping purposes, but the reactor itself will be at less than 5 bar. There is no phase change in the event of a rupture. In fact, due to the very low vapor pressure of the salt, nil gas is released by a primary loop rupture.

Low pressure means much thinner, cheaper, easier to fabricate, and easier to inspect piping. The primary loop is kept at the lowest pressure in the coolant system, so any leaks are inwards, the opposite of a PWR.

The containment structure just needs to be an air-tight radiation barrier, and just big enough to house the reactor core and the primary loop.[4] A 1000 MWe MSR can easily be put underground.

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[4] Due to the high level of radioactivity in the fuel containing primary loop, molten salt reactors use a secondary loop, also a molten salt, to transfer the heat from the primary loop to the working fluid of the turbine.

Far more complete fuel burn up

Perhaps the biggest drawback of solid fuel reactors is that the fuel cannot be completely consumed. As U235 fissions, it converts some U238 to plutonium and a whole bunch of fission products. The problem is that these fission products are trapped in the solid fuel. Some of these products are strong neutron absorbers, known in the trade as *poisons*. The build up of these poisons will eventually shut the reactor down or burst the cladding. So the fuel must be removed and replaced long before all the fissile material is consumed.

One of the most troublesome of the poisons is Xenon-135. ^{135}Xe, a gas, is an extremely strong neutron absorber with a half-life of about 9 hours. Xenon is the the reason solid fuel reactors cannot be safely restarted for several hours after a shut down. If a PWR is shut down, ^{135}Xe builds up. If the control rods are removed before the xenon decays, the reactor burns off the excess ^{135}Xe, and reactivity increases generating an unstable situation. Failure to manage this xenon transient properly was a necessary link in the Chernobyl cause chain.

In a liquid fuel reactor, xenon is almost a non-factor. It simply bubbles out of the molten salt as it is formed, extracted into the off-gas system, and allowed to decay. The other fission products can be continuously removed allowing the fissile portion of the fuel to be almost completely consumed.

The combination of the increased thermal efficiency and the much more complete fuel burn results in a fuel requirement that is one-third that of a PWR. And there is no need to shut the reactor down to refuel.

Orders of magnitude less very long-lived radioactive waste

More complete fuel burn up not only means we need less fuel; but much more importantly, it means less radioactive waste to dispose of, and that waste has a far lower half-life. When it comes to very long-lived waste, the key is the very heavy elements, the transuranics, most importantly plutonium.All the lighter fission products decay to background levels within 300 years, most within 30 years. But unlike a PWR, in a molten salt reactor, most of the transuranics stay in the fuel until they are “burned” (i.e. fissioned). A PWR produces about 300 kg of transuranic waste per GW-year. In the simplest and most straightforward version of the molten salt reactor, outlined below which involves start-up on U-235 and no fuel processing, the equivalent number is 25 kg per year, and all of this plutonium stays in the reactor for 30 years. Moreover, there is a very good chance that 30 years from now we will have an economically feasible means of returning this plutonium to the reactor. There are several promising methods that have been demonstrated at lab scale. If that happens, the system will produce nil long-lived waste.

Inherently far safer

With a liquid fuel, molten salt reactor, the phrase “core meltdown” is irrelevant. The core is already melted down. One by-product of this is totally passive shutdown in the event of power failure. The core vessel is fitted with a drain plug of frozen salt cooled by a fan. If the reactor loses power, the fan stops, the plug heats up, melts and the core salt and fuel drain to underground tanks. If the core somehow overheats, ditto. If there is a big leak in the primary loop, the core is drained to the same tanks.[5] See Figure 2.

The decay heat is transferred to the drain tanks which are fitted with sufficient passive cooling to keep the salt from over-heating with no operator intervention. There is no emergency cooling system to fail or screw up a la TMI.

Fission products either quickly form stable fluorides that will stay within the salt during a leak or are volatile, such as xenon, and continuously removed. There will be nil release of radioactive gases to the environment, even if all containment levels fail and the core salt somehow fails to drain to the drain tanks. The core salt is highly radioactive and would emit radiation in the event of failure to flow to the drain tanks, but that radiation would be confined to the immediate vicinity of the salt pool.

There is no water anywhere in the primary or secondary system, that could lead to steam explosions or hydrogen production. The hydrogen explosion danger, a key player at TMI and Fukushima, is non-existent. Of course, if Three Mile Island and Fukushima had been molten salt reactors, these names would have no meaning to us. In both cases, the freeze plug would have melted, and the core salt dumped into the drain tanks.[6]

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[5] Fluoride salts are extremely stable. This is in sharp contrast to liquid metal reactors where the metal, such as sodium, will explosively react with almost anything if there is a leak. However, it is very important to keep moisture and oxygen out of the MSR primary loop from a corrosion point of view.

[6] In the case of Three Mile Island, it is more likely that nothing would have happened. If a pump in the secondary loop fails, as happened at TMI, it’s quite likely the load following characteristics of the MSR would have allowed it to respond to the change in load without raising the core salt temperature to the level that would melted the freeze plug.

3 The Molten Salt Reactor Experiment

The keystone of the ORNL work on liquid fuel reactors was the Molten Salt Reactor Experiment (MSRE). The MSRE was an 8 MW thermal reactor designed to test the whole liquid fuel concept. The core, Figure 1, was a 1.4 m diam by 1.6 m high cylinder made out of a high nickel alloy called Hastelloy. Like a standard PWR, the MSRE was a thermal reactor, that is, the neutrons had to be slowed down in order for fission to occur. The material that accomplishes this is called the moderator. In the MSRE, the moderator was graphite. The core was filled with vertical graphite bars 50 mm square. Channels were machined into the faces of these bars. The core salt flowed upward thru these channels.

The core vessel was housed in a air tight, inerted concrete enclosure, Figure 2. Drain tanks were housed in a lower enclosure. The core drain line was fitted with a freeze plug, a fan cooled plug of solid salt. If the fan was turned off, or the system lost power, the core salt flowed to the drain tanks. The drain tanks were fitted with cooling systems capable of handling the decay heat of the radioactive salt. In the event of a primary loop rupture, the salt would also drain to the drain tanks. With no moderator, there was no chance of the core salt going critical in the drain tanks.

The primary loop was entirely within the air-tight containment. It exchanged heat with a secondary loop which was led outside the containment, and for the purposes of the tests cooled by radiators fitted with big fans. The secondary loop was maintained at a higher pressure than the primary, so any leak between the loops would be into the primary.

The MSRE operated for four years, and performed closely to ORNL's calculations. The xenon and other noble gases bubbled out a bit better than expected. The uranium and plutonium and most of the fission products stayed dissolved in the salt. The reactor was self-regulating, responding well to all sorts of upsets including a catastrophic radiator fan failure. Shut-down was as simple as turning off the power to the freeze plug fan. The reactor was simple to operate and reliable. In the last 15 months of its operation, it was available 87% of the time, an unprecedented number for a first of a kind, research reactor and better than many production reactors. The MSRE also demonstrated on-line refueling, removal of uranium from the salt, and removal of fission products.

A key concern was how the piping materials would stand up to the temperature, the salt, and the radiation. The MSRE plumbing, after 13,172 full power hours, 21,788 circulating hours in the primary loop, and 26,076 circulating hours in the secondary loop showed no signs of salt corrosion. The Hastelloy was in excellent condition visually. There was a minor amount of chromium transfer. Chromium leaches out (is oxidized) from the Hastelloy in the high temp core, and is deposited (reduced) in the low temp portion of the loop. They found that this could be controlled by modifying the UF3/UF4 ratio, If this ratio is high enough, there's nil free fluorine around and the salt is never oxidizing. UF3 was generated by periodically sticking a beryllium rod into the circuit, which sucked up any excess fluorine. Lab tests showed some superficial microscopic cracking. This was traced to the fission product tellurium. ORNL found that the tellurium attack could also be prevented by keeping the salt on the reducing side.

Finally, the lab tests showed loss of ductility due to helium forming on the grain boundaries. The helium was produced by neutrons interacting with ^{10}B. The boron was an impurity introduced from the refractories used in melting the alloy. ORNL found that by adding small amounts of boride producing material such as titanium or niobium to the alloy, they could keep the helium away from the grain boundaries. This resulted in a factor of 20 improvement in irradiated ductility. The new alloy became know as modified Hastelloy-N. These results have been confirmed by Russian tests in the 1990's. In fact, the Russians have developed variants which test even better than modified Hastelloy-N, producing corrosion rates in 650C molten salt of less than $5\mu m/y$.

As far as ORNL was concerned, at the end of the experiment, the key remaining issue was tritium. Tritium, a radioactive gas, is produced by neutron reactions with the lithium in the core salt. Tritium can worm its way through heat exchanger metal and eventually get into the turbine working fluid loop, and escape the system. There are a number of possible fixes, but the simplest and surest is to add a third loop to the system employing a nitrite-nitrate salt. Tritium permeating to the third loop will be oxidized to steam by the oxygen in the salt and drawn off in the loop's expansion space. This adds about 5% to the cost of the plant. On the plus side, the extra loop allows us to use a standard super-critical steam cycle with no modifications. This option requires no R and D.

Overall, the MSRE was an extremely successful experiment answering many questions, and raising almost no new ones. Indeed the MSRE was a remarkable technical triumph. What is even more remarkable, this triumph received no publicity.

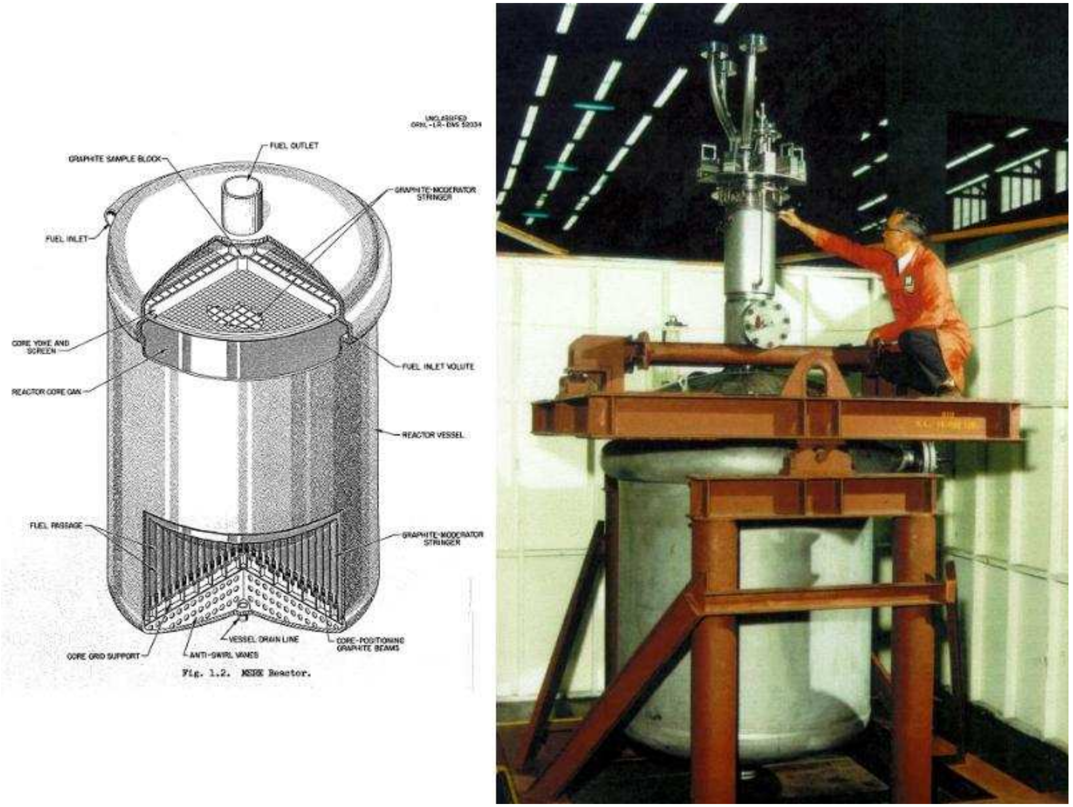
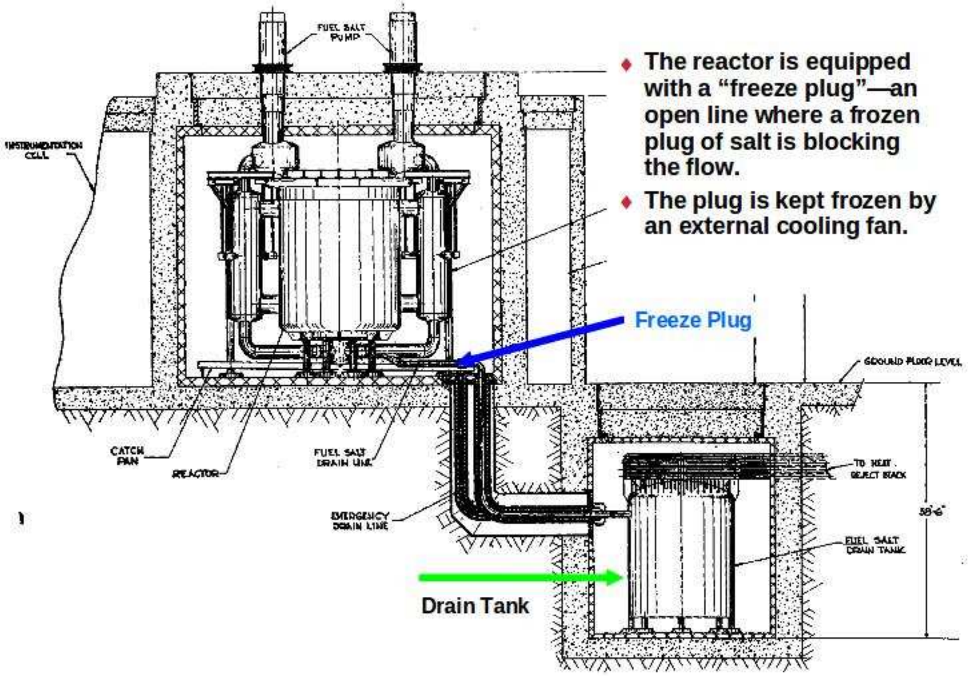


Figure 1: MSRE Core, figure courtesy of Kirk Sorensen, www.energyfromthorium.com



- **The reactor is equipped with a “freeze plug”—an open line where a frozen plug of salt is blocking the flow.**
- **The plug is kept frozen by an external cooling fan.**

Figure 2: MSRE Containment and Drain Tanks, courtesy of Kirk Sorensen, www.energyfromthorium.com

4 The Molten Salt Thorium Breeder Reactor

One reason for the lack of publicity is that ORNL wasn't that interested in the MSRE. They saw the MSRE as simply a step toward their real goal a thorium fueled reactor based on converting thorium to U233. This was their Holy Grail. Buoyed by the success of the MSRE, ORNL immediately moved on the thorium breeder. This was a terrible mistake, but an understandable one.

Thorium is 10 ppm of the earth's crust. Uranium is 2.5 ppm of which only 0.7% is U235. There is 500 times as much thorium around as U235. Thorium is easily mined and requires no enrichment. High quality thorium ore can be scooped off Indian beaches. If they could pull off a thorium based reactor, they would have solved the fuel issue for a millennium, and reduced fuel costs to a few mils per kWh.

Everything looked good with one crucial exception: how to keep the core salt and the blanket salt separated while at the same time properly bombarding the thorium in the blanket with neutrons. Their first thought was to alternate core salt and blanket salt channels in the graphite moderator. Very neat, the moderator and the barrier are one and the same. The neutron calculations showed it would work fine. The problem is that when graphite is bombarded with neutrons it first shrinks and then swells as the carbon atoms get shoved around in the lattice. Eventually, we will have a leak. This is not much of an issue if there is only one fluid in the core, but a big problem for a two fluid system. And we have a large number of problematic graphite to Hastelloy joints. The ORNL guys who were very smart and very motivated worked on this problem for ten years ***and never solved it.***

Eventually they went to a single salt concept in which the thorium was dissolved in the core salt, along with the fissile U233. The problem with this system is that you now have to remove the fission products without removing the thorium, and thorium chemically is very similar to some of the more important fission products. Also since the neutronics are much more marginal than for the two salt concept, it is necessary to remove the protactinium from the salt and allow it to decay to U233 before injecting it back into the reactor. This poses a proliferation risk. Finally, the process uses bismuth and bismuth dissolves nickel, the preferred material for handling fluoride salts. ORNL semi-convinced themselves that they had a solution to this processing issue, but admittedly it was far more complex than the simple MSRE processing system associated with the two salt concept. It has never been tested outside the lab. At a minimum, it was going to take a lot of R&D. To an outsider, it looks very unattractive. About that time the molten salt reactor program was shut down. The bismuth/nickel issue had not been solved when the program was terminated.

5 The Denatured (and Do-able) Molten Salt Reactor

The ORNL people had no money, but they weren't quite ready to give up. By the 1980's it was clear we were not going to run out of uranium for a while and issues such as proliferation resistance were becoming much more important than they had been. ORNL finally realized the country didn't need a thorium breeder. ***The country only needed vastly improved safety and vastly decreased long-lived waste.*** The country needed a full scale MSRE.

The remains of the ORNL group went back to the drawing board and designed a reactor that required nil on-line salt processing. They called it the Denatured Molten Salt Reactor (DMSR) to emphasize its proliferation resistance. Denatured refers to uranium whose fissile content is too low to be useful in a bomb. The DMSR was the first reactor purposely designed to be proliferation resistant, and it remains among the most proliferation resistant to this day.

The concept was a 1000 MWe liquid fuel, molten salt reactor that would be fueled once in 30 years.

1. The initial fuel load would be low enriched uranium and thorium. Over time the thorium would be converted to U233 and burned.
2. Other than bubbling off the xenon, there would be no salt processing, no removal of the fission products, just adding small amounts of U235 annually with enough U238 to keep the uranium denatured.
3. A low power density yielded 30 year lifetime for the graphite moderator, but resulted in a fairly large core (8 m in diameter, and 8 m high).

Building on the MSRE experience, the group, some of the best reactor designers in the world, crunched the numbers and produced a 162 page report, which lays out the reactor design in some detail.[7] They showed us that the concept worked. In other words, they gave us the design of a reactor which would be smaller, cheaper, far safer, and produce 12 times less long lived waste than a PWR. ***A reactor that could be built with no new technological advances.*** It's the Do-able Molten Salt Reactor.

The report has been ignored.[8]

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[7] Engle et al, Conceptual Design Characteristics of a Denatured Molten Salt Reactor with Once-through Fueling, ORNL/TM-7207, July 1980.

[8] This is not completely true. Several efforts have been made to resurrect the DMSR, most importantly, the Fuji project in Japan which essentially replicated and confirmed the ORNL DMSR calculations.

6 It's all Alvin's fault

How did we make such a bad choice? The three syllable answer: Rickover. Admiral Rickover was the acerbic, dictatorial head of the Navy's nuclear sub program. Once Weinberg pointed Rickover toward the PWR, the ascendancy of the PWR was almost inevitable. Rickover had originally intended to build a high temperature, sodium cooled, graphite moderated reactor. He was turned off by the PWR's poor thermal efficiency and high pressure. But the reactor had to fit within a 28 foot wide submarine hull. Weinberg pointed out that an PWR could be shoe-horned into a smaller space even after allowing for the extra thermal output required. Besides high pressure steam piping was something the Navy had lots of experience with. They knew next to nothing about handling sodium, except that, if sodium comes into contact with water, you have an explosion. This was in the late 40's, shortly before the molten salt reactor was invented.

Rickover with essentially unlimited funds and a maniacal drive fueled by the Cold War and the threat of extinction made the PWR, with all its problems, work.[9] In 1948, he started with little more than a sketch and some back of the envelope calculations. ***At the time there was no such thing as a pressurized water reactor at any scale.*** Nobody knew how to make control rods or fuel element cladding or bearings that could handle the PWR conditions. Rickover did not build a lab scale reactor. He went straight to a full scale on-land prototype inside a mock-up of a submarine immersed in a giant swimming pool. He ordered the ship before this prototype, the first PWR ever built, even went critical. In 1954, the first nuclear powered submarine, the Nautilus, was launched. The Nautilus immediately undertook a string of high publicized exploits. Rickover had created the PWR from scratch and he did it in six years.

When Eisenhower started the Atoms for Peace Program in 1953 he wanted results now. Atoms for Peace was a non-profileration program. Countries that signed on agreed not to build a bomb in exchange for access to the USA's civilian nuclear technology. To make this an attractive deal, Eisenhower needed a civilian capability and he needed it immediately. Rickover, who was a master at manipulating congress, grabbed control of the Atoms for Peace program, over the objections of nuclear scientists, and others who knew that Rickover would not consider anything but a PWR. Rickover wrote a mocking parody praising the wonders of the other concepts but among the wonders was "not available". In fact, at this time, some of the other concepts were much further along than the PWR was when Rickover committed to his full scale prototype.

In any event, Rickover made sure that the first US civilian reactors were PWR's. The first couple were essentially given to the utilities. Rickover's naval contractors were only too happy to sell their skills to the civilian side. Once they committed to the civilian PWR that became just about the sole focus of their work.

Meanwhile, Fermi and Weinberg were doing experiments at a far more leisurely pace. But Fermi's definition of leisurely was a lot more expensive than Weinberg's. He was spending hundreds of million dollars per year on the fast breeder and that spending was spread over many congressional districts.[10] And the fast breeder program was getting plenty of publicity.

Weinberg was spending 2 to 4 million dollars per year on molten salt and almost all that money was concentrated in one small town in Tennessee. The ORNL culture made matters worse. As you read the meticulous ORNL reports, you are struck by the complete lack of salesmanship. The reports focus almost entirely on problems and screw ups, potential problems, errors and possible errors in the calculations, and jobs undone. Successes and accomplishments are mentioned briefly if at all. Good engineering and very slow reading. No where in the voluminous ORNL library could I find the vision articulated in a manner understandable to outsiders.

But the thorium vision was there, and it messed them up. They spent way too much effort and time failing to solve the core/blanket barrier problem, when they should have been moving ahead with a scaled up MSRE.

In any event, almost no one outside of Oak Ridge understood the potential of the molten salt reactor. Few had even heard of it. There was zero political push behind the project. When Weinberg fell out with the AEC and the AEC's congressional backers on reactor safety, the molten salt reactor project was doomed.

There have been sporadic, weak attempts to revive the MSR; but they have gone nowhere. Part of the reason is antipathy to nuclear power, any kind of nuclear. Part of the reason is economics. During the 80's and 90's, fossil fuel was cheaper than nuclear and few were worried about CO2. Part of the reason is simple ignorance. When asked about the MSR at his 2009 confirmation hearings, Secretary Chu, a Nobel Laureate physicist, replied "One significant drawback of the MSR technology is the corrosive effects of the molten salts on the structural material used in the reactor vessel and heat exchangers." Dr. Chu may be the one scientist that President Obama really trusts; yet he is unaware that ORNL had solved the corrosion problem.

Very recently, there has been a flurry of interest in molten salt in the guise of the thorium breeder. But the proponents of the thorium breeder are selling something that does not exist and requires a major

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[9] Rickover was born in Poland, but his family emigrated when he was five fleeing the pogroms. Later his birth village was wiped out in the Holocaust. Rickover knew about extinction.

[10] The total expenditure on the fast breeder program was over 15 billion 2011 dollars.

technological breakthrough which may never occur. They are making the same mistake that ORNL made 40 years ago.

7 A Time for "courageous impatience"

"Good ideas are not adopted automatically. They must be driven into practice with courageous impatience.", Admiral Hyman Rickover. We need to start building a full scale, Denatured Molten Salt Reactor tomorrow. Thanks to ORNL, we are ready to go to design and engineering. We are far further along than Rickover was in 1948. The prototype plant would put the DMSR on the map, and make manifest the multi-order of magnitude improvements in long-lived waste and safety. And it will pin down the economics.

The whole design concept should be based on what we already know, basically a scaled up MSRE. The operating temperature should be a conservative 700C. The plant should employ a third nitrate-nitrite salt loop to virtually eliminate tritium releases. The design should be based on a super-critical steam turbine which uses standard modern coal plant technology.[11] It should be installed underground, Figure 3. The design should be modular, made up of large, fully outfitted, barge transportable blocks manufactured on an assembly line. On site work should be limited to excavation, footings, and dropping the blocks into place, the shipyard model. This will produce order of magnitude improvements in labor productivity, and similar improvements in quality control and inspectability. Each module will be about 550 MW thermal or 250 MW electric.

The prototype plant will be one of these modules. No further scale up will be required. Once the prototype has proved itself, we go immediately to full scale deployment. This is the way Rickover would have done it.

The project must have the enthusiastic support of the President, who can sell it as essentially a new form of energy, as different from current nuclear as a modern computer is from a mechanical calculating machine. See Table 1 for the talking points.

The project must be run outside the NRC licensing process, or it will be doomed from the start. Even Rickover could not have built the PWR under current regulatory procedures. The prototype plant experience could provide the basis for a completely new set of regulations tailored to the DMSR.

The schedule should be tight, allowing for no research. The prototype plant up and running in five years.

We should be working hard on the materials side to attempt to push future molten salt operating temps up to 850C at which point hydrogen generation becomes a realistic alternative. But there is no need to wait for this advance in materials. 700C is plenty, and far better than the PWR.

We should be working hard on the core salt/blanket salt barrier problem. If we solve this problem, the second or third generation MSR's can be based entirely on cleaner, more abundant thorium, and fuel costs pretty much disappear. But we don't need this break through and we can't wait for it.

All we need is the order of magnitude reduction in long-lived waste and the vastly improved safety of the DMSR. And we can have that in a very few years if we want.

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[11] The first DMSR's can be installed at existing coal fired plants replacing the boiler and its pollution.

Table 1: Points for the President to Consider

- In the 1950's, the civilian nuclear industry seized on the pressurized water reactor (PWR), which had been developed by the navy for submarine propulsion. Currently, just about all nuclear power plants are PWR's or its close sibling, the boiling water reactor
- While understandable and in fact almost inevitable, this was a tragically wrong choice. For there exists a technology that is more fuel efficient, inherently far safer, more proliferation resistant ***and produces 12 to potentially 5000 times less long lived, radioactive waste.***
- This technology is the liquid fuel, molten salt reactor developed by Oak Ridge in the late 1950 and 1960's.
- The liquid fuel, molten salt technology was demonstrated at Oak Ridge by the MSRE reactor which ran very successfully for four years between 1965 and 1969. ***The reactor was walk away safe.*** If the reactor lost power or the core somehow overheated, the molten salt and its fuel automatically drain to underground tanks fitted with passive cooling. If Three Mile Island and Fukushima-Daichi were molten salt plants, these names would have no meaning to us.
- Molten salt reactors are so compact that a 1000 MW reactor can easily be put underground.
- The highly proliferation resistant variant known as the Denatured Molten Salt Reactor (DMSR) ***requires no new technology.***
- For reasons that had nothing to do with the merits of the technology, the molten salt program was shut down by the Nixon administration.
- Thanks to the ORNL work and the MSRE, we can design and build a prototype 250 MW DMSR which will demonstrate the technology at full scale ***in five years.***
- This will create an essentially new source of non-intermittent energy, far safer than today's nuclear power plant, a form of energy that produces no CO2 emissions and much less long-lived radioactive waste.
- Creating this new source of energy can be the nation's new Sputnik moment. All you have to do is tell the nation: in response to Fukushima, we are going to go to the DMSR and we will do it in less than five years.

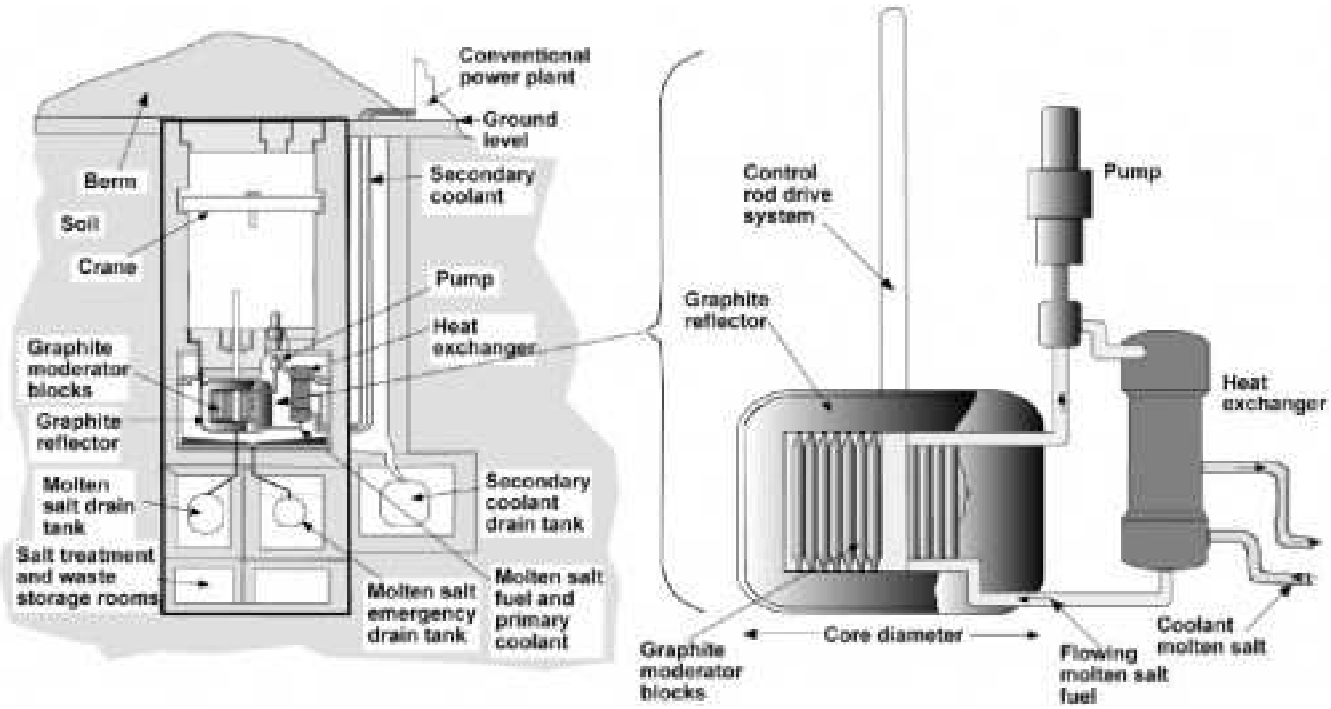

Figure 3: DMSR underground. From Moir and Teller, Nuclear Technology, Sep. 2005