Briefing Paper on Thorium for Energy and Water Production

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Summary

The United States is at a crossroads. Our old energy technologies are no longer viable, and we need to find replacements that are reliable, safe, economical, and carbon free. We are also reaching the limit of high quality potable water that can be delivered in a way that does not add to the carbon footprint. In one of the great ironies of history, a big part of the answer to this dilemma could be a return to nuclear power, using the element Thorium in advanced nuclear power plants called Thorium breeder reactors.

Thorium is the most energy dense material on Earth. It is over 400 times more energy dense than Uranium[i] and millions of times more dense than coal, gas or oil. The best use of Thorium appears to be in a reactor called a Liquid Fluoride Thorium Reactor (LFTRs), which are Thorium breeders. These reactors can generate electricity and purify water using waste heat[1], and provide heat for a wide range of industrial processes. Because they are breeder reactors they generate new fuel as they consume old fuel, so their life spans are indefinite.

LFTRs do not use pressurized water for transferring heat from the core. This allows them to operate at atmospheric pressure thus eliminating the biggest source of danger in conventional reactors…high pressure water that can flash to steam. In addition, LFTRs do not use solid fuel, so they can be operated on a continuous basis. They do not generate significant amounts of high level radioactive wastes, which makes them safe from a nuclear weapons proliferation standpoint. Their low waste production occurs because they consume over 99% of their fuel, compared to less than 1% consumption in a conventional reactor.

From a water resources perspective LFTRs can be combined with power turbines and the waste heat from the power plants can be directed to thermal desalination systems to generate fresh water. A single plant therefore, located in an a semi-arid area, such as Denver, could generate both electricity and water from local resources (South Platte return flows) in a sustainable and environmentally friendly manner.

Here are some items that United States and States should do to foster this revolution.

1. U.S. must take a lead role in development of advanced nuclear power reactors.
2. Congress needs to fund development of a demonstration LFTR[ii] breeder, and then leave it to industry to commercialize these reactors. This was attempted by the U.S. Senate in the Thorium Energy Independence and Security Act of 2009.[iii]
3. Decision makers and the public need to be educated about this technology so that misplaced fears do not block its development.
4. An honest assessment of the risks nuclear power versus water and energy shortages needs to be made and put before the public. Each year hundreds of thousands of people die from hunger, sickness, water shortages, pollution and other conditions tied to shortages of water and power.
5. Demonstration thermal desalination systems need to be built in conjunction with existing gas turbine plants so that U.S. experience in their construction and operation can be obtained.

For more details go to https://aquacraft.com/category/aquablog/

[1] A typical power plant will only be able to convert around 40% of the thermal energy generated by the core into electrical energy. Most of the difference is waste heat that needs to be rejected. Using a thermal distillation system this heat can be converted into distilled water suitable for potable uses rather than simply heating up the atmosphere.

Introduction

As water engineers we know that civilization depends on having plentiful and economic supplies of fresh water for municipal, agricultural, commercial and industrial uses. These supplies must often be pumped to their point of use. Arguments have been made that a contributing factor to the fall of Rome was their failure to develop the steam engine for pumping water. This failure on their part required continued reliance on increasingly inadequate gravity supplies, animals, and slave labor. The Romans knew about steam power, but they never learned how to make a steam engine. If they had, the history of the world would have been different.

Good water management is able to avoid waste, and maximize the percent of available supplies that get applied to beneficial uses, but no matter how excellent the management practices, there will need for new freshwater supplies if we are to avoid breakdown of civil order, such as currently being seen in many parts of the world. If one looks, it can be seen that before many of these trouble spots burst onto the news they were also experiencing long term drought and economic dislocations brought about by water and power scarcity.

Collection, treatment, and distribution of water all require energy. Given a good supply of energy, however, even seawater or polluted brackish water can be converted to potable water and delivered to its point of use[iv]. The purpose of this paper is to explain that there is a nuclear technology available that can provide a virtually limitless supply of energy in a safe and economical fashion. This technology is the Liquid Fluoride Thorium Reactor, or LFTR. These reactors are vastly different from conventional pressurized light water reactors we are familiar with.[v]

Our purpose here is not to prove a point, but to lay out a set of facts as we understand them based on publicly available sources, with references that will allow the reader to perform due diligence and explore the subject. The key goal is to make decision makers and interested citizens aware that this technology exists, so that it can be incorporated into energy and water planning. It is surprising that in the country that developed atomic power including the first Liquid Fluoride Thorium Reactor, so few people are aware of its existence, or of its potential to provide a truly safe, reliable and environmentally benign source of power and water.

Why do We Need Advanced Nuclear Power?

Nuclear power is the only power supply that is carbon neutral and capable of supplying the large amounts of base energy and water that civilization in the 21st century will need. Wind and solar may provide energy during periods when these resources are available, but since there is no way to guarantee that wind and solar will be available at a given moment in time, back-up capacity is always needed. The preferred source for back-up is currently the natural gas turbine, but natural gas is not renewable, it emits CO_2 and radon gas to the atmosphere, and there is no guarantee that it will be available in the future as the natural gas fracking bubble deflates[vi]. In fact, burning natural gas to generate electricity is a terrible waste of this resource. Because Thorium reactors generate as much fuel as they consume they are for practical purposes renewable resources. Since they do not emit any CO_2, they are the only power source, with the possible exception of large scape hydropower, that can be used for base load that is also carbon free. Unfortunately, most of the large hydropower sites have already been developed.

What is Thorium?

Thorium is element number 90 on the periodic table. It is an actinide metal with some remarkable properties. It is also the most energy dense substance on the planet, more than 400 times as energy dense as Uranium. The average American's annual energy needs could be supplied by ~4 grams (0.15 oz.) of Thorium. Thorium is generally found as a bye-product of rare earth mining, so it can be obtained without developing new mines.

Thorium is only very slightly radioactive. Its half-life, the time required for half of it to decay is 2.4 billion years. The time it would take for a sample of Thorium to decay to the point where it was no longer radioactive would be ~14 billion years, or about the age of the universe. The long half-life is a measure of the low rate at which Thorium emits radiation. Really dangerous radioactive substances have very low half-lives, which mean that they emit very high levels of radioactivity over short periods of time.

Thorium is a fertile element, not a fissile one. This means that Thorium, by itself will never undergo nuclear fission, no matter how much of it is compressed into a volume. This makes is an inherently safe material that has no practical weapons uses. Thorium is not water soluble, and cannot be metabolized.

When Thorium is exposed to neutron radiation, however, it transforms into Uranium 233, which *is* a fissile material, but one which then decays into short lived fission by-products without yielding Plutonium 239, or any significant amounts of the other highly toxic transuranic by-products such as Neptunium, Americium, Curium etc. These are the long lived, toxic substances that require geologic isolation and are the bye-products of current highly inefficient light water reactors.

Thorium, as part of the Thorium-$Uranium_{233}$ fuel cycle, is the source of most of the geological energy that keeps the core and mantle of planet Earth hot and active.

The fact that Thorium generates $Uranium_{233}$ when exposed to neutrons means that it can serve as a breeder of new fuel. This new fuel can be fed back into the system to keep it running indefinitely. All Thorium has this ability, not just a small fraction as is the case with Uranium. This makes Thorium a renewable resource for all practical purposes, and allows electricity to be generated by "burning rocks".

Thorium is plentiful. It makes up approximately 10-20 ppm of the crust of the earth, and is found world-wide. The U.S. has estimates supplies of 595,000 tons of known reserves[vii]. Much of this is buried in containers in Nevada having been by-products of rare earth mining activities.

Thorium is often produced as a by-product of mining rare earth minerals, which are essential raw materials for modern economies. Currently, this is a problem for U.S. rare earth miners, since there is no current use for the Thorium, and regulations require that it be treated as a hazardous substance. Hence U.S. miners cannot economically produce rare earth minerals, which leaves the U.S. at the mercy of China for its supplies, but this is another story.

In 1942, when Glen Seaborg and his graduate students, while working at the Lawrence Cyclotron laboratory in Berkeley, CA, discovered that Thorium would generate fissile U_{233} when exposed to neutrons, and that when U_{233} fissioned it also generated more than 2.3 additional neutrons per fission reaction, he described this as a $50 quadrillion discovery, since he saw that the Thorium-Uranium cycle represented an essentially limitless energy source.

According to the published reports, with 5000 tons of Thorium/year as fuel the United States could generate its entire energy requirements, and replace:

- 65,000 tons of Uranium

- 5 billion tons of coal
- 31 billion barrels of oil and
- 5 trillion cubic feet of natural gas

This would be true carbon free energy independence, and the fossil fuels could then be used as feed materials for industry, agriculture and medicine.

How does the Molten Salt Thorium Reactor Work and What Makes it Better than Conventional Light Water Reactors?

There are several reactor designs that use the Thorium-Uranium cycle, but one with the most long term promise seems to be the Liquid Fluoride Thorium Reactor or LFTR, or "lifter", which is being actively pursued by several companies and governments around the world, but is still some years away from production. The LFTR is the reactor that is causing the greatest amount of interest, to us, in the so-called nuclear renaissance.

The LFTR was conceived of by Eugene Wigner and developed by Alvin Weinberg and H.G. MacPherson at the Oak Ridge National Laboratory (ORNL) at the time. This occurred during the period from 1955 and 1973.

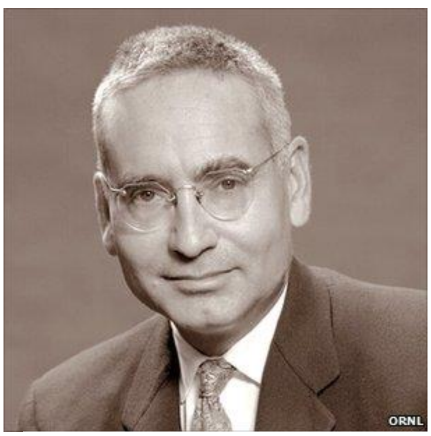

Figure 1: Alvin Weinberg

Weinberg was also the inventor of the conventional Uranium-Plutonium pressurize light water reactor, but he advocated switching from this technology to the LFTR for production of commercial power. This put him at odds with Admiral Hymen Rickover, who wanted pressurized water reactors for naval propulsion and also advocated the Uranium-Plutonium reactors because they provided a source of Plutonium for manufacturing nuclear weapons. While something of an over-simplification, the need to generate weapons during the cold war was a major factor in the decision to pursue the Uranium-Plutonium reactor and drop the Thorium-Uranium cycle.

A liquid fluoride thorium breeder reactor of the kind we are considering here can be thought of as a reactor in which the nuclear fuel is dissolved in a high temperature salt so that the fuel/salt mixture can be pumped between the reactor core and a heat exchanger. The melted salt is almost colorless and only slightly more viscous than water. The reactor core is designed so that this is the only portion of the system in which the fuel reaches a state of criticality sufficient to sustain a nuclear reaction. Once the fuel mixture leaves the reactor core it stops being critical and the nuclear reactions cease.

The preferred salt mixture for the Thorium breeder, according to the advocates for this design, consists of Lithium, and Fluorine, with a small amount of Beryllium. Figure 2 shows a simple schematic of how a breeding LFTR works. This version of the reactor consists of two streams of liquid salt: one, shown on the right side of the diagram, between the core of the reactor and the heat exchanger and the other, on the left side, between the Thorium blanket and the system that separates the U_{233} that is generated in the core, via a simple oxidation/reduction chemical process. This new U_{233} is fed back into the core providing fuel for the reaction. As long as new Thorium is fed into the blanket the reaction will sustain itself indefinitely. Another nice thing about these reactors is that they can also be fed Plutonium from decommissioned warheads or high level wastes from conventional reactors and "burn" it to a safe state.

The second part of the flow stream consists of the transfer of the core salts to a heat exchanger, which will generate hot gases, such as supercritical CO_2 for electric generation, industrial processes, or, of special interest to water engineers, water treatment, including thermal de-salination, and pumping. Because Thorium reactors operate at high temperatures they provide enough heat to both generate electricity and to supply waste heat to thermal desalination plants.

Conventional reactors run on solid fuel rods. These reactors must be shut down approximately every 18 months so that the old fuel can be removed and new fuel inserted into the core. The reason this is such a short period is that the solid fuels collect impurities (such as Xenon gas) which poison the nuclear reaction. In a LFTR the fuel is a liquid, so it can be processed continuously in a chemical separation facility and the impurities and other fission by-products can be extracted for sale. This allows the LFTR to operate as a continuous process rather than a batch reactor. It also means that the Thorium fuel can be much more fully consumed than in a conventional reactor. A LFTR uses over 99% of the energy in the supplied fuel, while a conventional reactor uses less than 1% of its fuel, leaving the other 99% behind as high level waste.

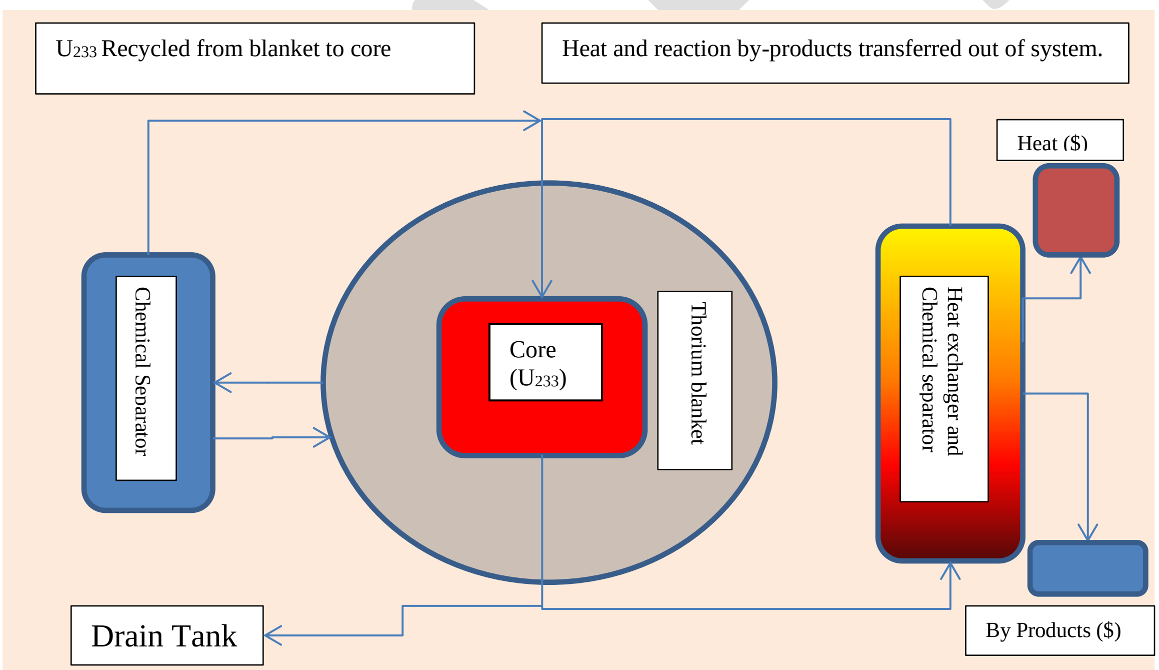

Figure 2: Simple schematic of a LFTR

Here are the advantages of a LFTR over a light water reactor (LWR).

1. A LFTR uses salt as its cooling agent, not water. The salt of choice (a mixture or Flouride, Lithium and Berylium) melts at 400 ^{o}C and boils at 1400 ^{o}C
2. LFTRs do not require water for cooling, but rather can be used to purify water through co-generation. This means they can be put in water scare areas such as

Southern California or Denver and used to generate power and fresh water from the ocean or polluted surface supplies.

3. Because the coolant is liquid at the operating temperature of the reactor it does not need to be pressurized. It operates a ~1 atmosphere of pressure. No pressure: no need for a major containment vessel.
4. The MSR will consume 99+% of its fuel, compared to less than 1% consumption in a LWR.
5. Thorium power plants can be built in a factory and shipped to existing power plant sites, so the existing sites can be used, and there is no need to lay out a new grid.
6. A LFTR can be “seeded” with U_{235} or PU_{239}, and once operating can consume spent uranium fuel from LWRs. The U.S. Currently has over 70,000 tons of spent fuel rods stored at reactors around the county. This is a way to eliminate this waste that also generates power and water.
7. A LFTR does not produce more than trace levels of high level transuranic wastes; it consumes them in the reaction yielding only low level or short half-life fission products, many of which are valuable. Most of the high level waste they generate is in the form of PU_{238}, which is a valuable isotope used for thermal power generation.
8. So, not only do LFTRs not create high level wastes, they can consume existing stockpiles of high level wastes, thus solving the “Yucca Mountain problem.”
9. LFTRs do not yield weapons materials. The products of a LFTR cannot be turned into nuclear weapons (at least not in a practical manner). This is at least part of the reason why they were rejected by the Department of Energy in the 1970’s in favor of the Fast Breeder Plutonium Reactors.
10. The LFTR is an inherently safe system: it is walk-away safe. If the reactor becomes disconnected from grid, for example in an earthquake, flood, or tsunami it will simply shut itself down and go dormant. It cannot melt, since it is already liquid; it cannot boil, since it can’t get hot enough to boil. The liquid in the system will simply drain to a special storage tank where is will cease being reactive and will slowly cool down. Once the emergency is over, the material can be re-melted and the reaction started again.
11. If the Fukushima reactors[2] had been LFTRs they simply would have gone dormant until the flood was over, and then could have been restarted once the cleanup was completed. There would have been no hydrogen explosions or venting of radioactive elements to the atmosphere, which would all have been safely contained in the salt solution, which bind strongly to elements such a iodine, cesium and strontium.
12. LFTRs can generate high temperature gas, which can be coupled to a gas turbine for generating electricity. The waste heat can then be used for a range of industrial processes, one being thermal desalination of brackish or sea water.
13. The fact that MSRs can operate without water for either cooling or energy generation makes them ideal for locations that are short of water. The fact that they can be used to treat and distribute potable water makes them essential for supplying the future water needs of humans on earth.
14. The United States had an operating LFTR at Oak Ridge for nearly 5 years, so the technology is not merely theoretical.

[2] These were GE BWR Mark 1 plants that were built in the 1970’s using designs from the 50’s and 60’s.

If LFTRs are so Good, Why Don't We Have Any?

The main reason why there are no working LFTRs in the United States, or elsewhere, is that this technology was abandoned by the Department of Energy during the Nixon administration in favor of the Fast Breeder Reactor, which used the Uranium-Plutonium fuel cycle that was familiar to the industry. The Thorium reactor did not generate passionate support in the Atomic Energy Commission, despite its advantages for civilian power production. One reason for this lack of interest was that it did not generate Plutonium, which was needed for weapons production. Also, at the time there was an abundant supply of cheap coal, and the impacts on the atmosphere and oceans of burning coal were not generally understood.

Once the decision was made to go forward with the Uranium-Plutonium cycle, the major industrial companies, such as General Electric and Westinghouse, came to understand the light water reactors, and made enormous investments in them. Given these investments there was a natural tendency to want to stay with what was known, rather than develop a radically different approach such as the LFTR, especially when coal was so cheap that there was little incentive for a new nuclear power reactor technology.

The driving force in nuclear reactor design after the Second World War was the desire of the U.S. Navy to have a reactor that would drive nuclear submarines, armed with atomic warheads. The pressurized light water reactor worked for this, and was quickly adopted by the Navy. Once it was developed and the manufacturers became familiar with its operation it was then used as the basis for the commercial power reactors. This was done despite the many drawbacks of pressurized light water reactors and their fundamental unsuitability for commercial power generation.

During the 1960's the liquid salt Thorium reactor continued to be developed as an experimental demonstration of the technology at Oak Ridge. The team headed by Alvin Weinberg and H.G. MacPherson built a test reactor that operated successfully for ~five years, and proved that the Thorium reactor was practical. For a number of reasons, including both getting jobs for Southern California, and generation of Plutonium for nuclear weapons, the Thorium reactor work at Oak Ridge was cancelled in 1973 in favor of the Fast Plutonium Breeder Reactor. This reactor design, which was cooled by liquid sodium, generated Plutonium from U_{238} much as the Thorium reactor generated U_{233} from $Thorium_{232}$ in its cycle. $Uranium_{233}$ is fissile, but has no practical weapons uses, while the $Plutonium_{239}$ is directly useful for construction of atomic weapons. (Although proponents of the Fast Breeder Reactors argue that getting Plutonium from a Fast Breeder Reactor is next to impossible.)[viii]

After the Thorium program was cancelled efforts to build a Fast Plutonium Breeder Reactor continued, but these were ill-fated, and while a successful demonstration reactor was built in Idaho, no commercial reactor was ever built. The entire program was finally cancelled under the Clinton administration. Since then there has been little innovation and no fundamentally new breakthroughs in nuclear reactor design in the United States.

Why Are Things Different Now?

Things are fundamentally different now for several reasons. First, it is generally understood that we cannot continue to burn fossil fuels for electrical generation. Between global warming and ocean acidification the continued burning of fossil fuels is threatening to destroy the planet's life support system.[ix] This means that not only do we need to not build any new coal or gas fired power plants, but we have to replace the existing inventory of both coal and gas plants with non-carbon based alternatives. This is a huge undertaking.

Second, there is simply not enough wind, solar or hydropower sources of energy available to meet the need for this new power. While natural gas supplies are currently large this is probably a short term effect of the fracking bubble, and cannot be counted on to continue.

Third, the existing fleet of first generation nuclear plants, which supply nearly 20% of the electricity generated in the U.S. are at the end of their economical lives, and they will start being retired over the coming years.

Fourth, the fundamental design flaws of the pressurized light water reactors are too clear to ignore. Three Mile Island, Chernobyl and Fukushima are all examples of these shortcomings. Relying on this technology is not an option. They are inherently unstable (operating at 70 atmospheres or more of pressure), highly inefficient (using less than 1% of the energy in their fuel), unsafe in emergencies (see Fukushima), and generate large volumes of highly toxic transuranic wastes.

Meanwhile, the need for energy continues and grows. We have a huge amount of investment to do just to stay in the same place with respect to energy. In order to supply the new population with energy, and the people in the world that have no access to energy will require that much more.

This combination of conditions puts humanity in a terrible dilemma. All of the old sources of energy are untenable, while the demand for energy grows. This is the kind of crisis that tends to focus the mind, and may allow us to take the bold steps needed to transform our entire energy economy from fossil fuels to a combination of the advanced nuclear plus whatever wind, solar, geothermal and hydropower can be generated. We simply have no alternative. Wind and solar are too intermittent and diffuse, and nuclear fusion is still decades from development, and there is no guarantee that the obstacles to its success can be overcome.

What Should Be Done?

The first thing that needs to be done is that we all have to educate ourselves better about this issue. We have to learn the history of the development of nuclear power to the extent we understand the basic differences between the Molten Salt Reactors, Fast Breeder Reactors and the conventional Light Water Reactors. Viewing the 10 videos on the Thorium remix web site is a good place to start, and then reading the books, such as Richard Martin's book, "Super Fuel", Alvin Weinberg's autobiography and the other books in the reference list could follow. Each of these sources contains other references, which the motivated readers could follow.

We have to disenthrall ourselves from the notion that renewables like wind and solar can replace the existing inventory of fossil fueled and old nuclear plants. They can help reduce fuel requirements, but they cannot replace the entire existing power system.

If we cannot rely on wind and solar, and must retire our existing power plants then we have to launch a major program to pick up where the Oak Ridge team left off in 1973 and build a new demonstration liquid fluoride Thorium breeder reactor.[x] Some speak of this as a new Manhattan Project, but this is nothing like a Manhattan project, since most of the fundamental work has already been done, and all we need to do now is the engineering. This is a large and challenging task, but not on the scale of either the Manhattan project, or the Apollo Program, for that matter.

Such a development process could easily be funded from carbon taxes, collecting royalties on oil and gas drilling, or by reallocating part of NASA's budget. (There is no way to ever colonize space without nuclear reactors, so NASA is a logical agency to take a lead in their development.) The Army could use these reactors for powering remote bases, and the U.S. Agency for International Development could use them to assist countries in need to water and power. (Since they have no weapons proliferation potential this technology can be safely exported.)

The U.S. government needs to set up a system for collecting Thorium from rare earth mines, refining and storing it, and making it available to the Thorium reactor industry. This will free up both the rare earth mining industry and provide the essential fuel stock for the Thorium energy economy.

Utilities must shed their complacency on the matter of new energy production. They cannot continue to rely on natural gas as an alternative to coal. Once natural gas prices start to rise, as they most certainly will, the cost of electricity may become prohibitive.

It is estimated that small Thorium reactors can be assembled in factories, much as Boeing or Airbus currently assembles jet airliners. They can be trucked or barged to the power plants and assembled. This theory needs to be tested. If it proves possible then the construction of these units can be standardized and the process can be scaled up. If Boeing can build 1 airliner per day then perhaps one LFTR per day could be built. At 250 MW per reactor this represents approximately 100 GW of electrical power generation per year that could be brought on-line. At this rate the entire 1000 GW generating capacity of the Country could be replaced in 10 years.

Consumers of electricity and environmentalists must demand that new generation nuclear power reactors, such as the LFTR, be developed and used to replace the existing fossil fuel and obsolete nuclear reactors. If we do not do this we have to consider the massive dislocations, social breakdown, wars and famines that are bound to occur as the energy and water systems gradually unravel, and as the continued use of carbon based energy sources destroys the atmosphere and the oceans.

Without energy, it will be impossible to do all of the things that are necessary to supply civilization with potable water. With shortages for both water and power many portions of the earth will become uninhabitable, but, with a good supply of energy any site with access to even polluted or saline water supplies can be made most comfortable[xi].

Compare the economies of the Gulf Emirates, which have abundant energy supplies and use these to manufacture drinking water by thermal desalination, and have a peaceful and thriving economy, to places like Syria and Yemen, with very poor energy supplies and chronic water shortages, and total breakdowns in civil society. The decision is ours to make.

The Energy/Water Connection: Thermal Desalination

Energy and water are inextricably bound together. It takes energy to produce and transport water, but the inverse is also true: given a large and reliable source of energy it is possible to turn even seawater or polluted water in high quality drinking water, and deliver it to where it is needed. The general opinion, however, is that desalination by any means is too costly to be practical, and hence desalination is often disregarded as a practical water source. This is a mistake, since even desalination using reverse osmosis, which requires high grade electrical energy has become highly efficient, and can be accomplished for approximately 10 kwh/kgal of produced water. For a typical single family home, that uses 100 kgal/year of potable water for indoor and outdoor uses, this amounts to an additional 1000 kwh of energy use per year, or approximately 6% of the average 18,000 kwh/year energy consumption of a typical single family household in the United States.

While RO is energy efficient it has its drawbacks. First it does require high grade electrical power that could either be used for other purposes, or not generated at all. Thermal desalination uses heat from the reactor or power plant that could not otherwise be used to generate electricity, and would have to be rejected using cooling towers. This energy is essentially free.

Secondly, the RO process can only produce water at 1% of the feed water TDS. So using RO to desalinate seawater, starting at 30,000 ppm salt will produce water that still has approximately 300 ppm salt, which is rather marginal for domestic use. Desalination, however, can produce water at around 25 ppm, which is very high quality with respect to dissolved solids by any standards.

Third, the RO process uses membranes at high pressure which tend to subject to both chemical fouling and mechanical damage. These can be difficult to diagnose in what amounts to microscopic level of the membranes. Distillers, however, are large devices that can be easily inspected. They tend to be more resilient to changes in water conditions.

Energy Requirements for Thermal Distillation

The theoretical energy required to distill water is based on the latent heat of evaporation, which is 1000 btu/lb of water or 102 MW/MGD of produced water. Reverse osmosis is capable of producing desalinated water for approximately 5 btu/lb or approximately 10 MW/MGD of produced water. Given this wide disparity in the theoretical energy requirements, why would any consideration be given to thermal desalination. As mentioned above: first the energy used for thermal desalination is waste energy, and secondly, in practice, distillers can be built that use substantially less energy than the theoretical requirement. The most efficiency distillers can produce water for between 4 and 15 MW/MGD. It is the combination of the more efficient distillers with use of heat that would otherwise be wasted that makes thermal desalination practical.

There are two main types of thermal distillers: multiple stage and multiple effect units. In both cases the heated source water is fed into a series of tanks, stages, or effects, in which the pressure is kept lower than atmospheric by evacuation. In the mutli-stage unit, see Figure 3, the feed water must be heated to above 100 ^{o}C prior to passing into the first stage. The vapor from this water is condensed using the feed seawater as a coolant. The distillate is collected in troughs above the seawater process water. Process water leaves the first stage and enters the second where additional water vapor is collected, and so-on. At each stage the process water is cooler, but the feedwater entering the system is cooler as well, and the vacuum on the system is greater, which induces evaporation and condensation.

A multiple effect distiller is shown in Figure 4. These are typically the most energy efficient types of distillers. Notice that the temperature of the vapor in the first chamber, or effect, is only 60 ^{o}C, which means that this type of unit can use the lowest grade heat from a power plant to generate distilled water. In addition, MED distillers do not require as much pumped seawater for cooling as do MSF units. This saves significant amount of energy.

A typical lay-out of a power/water cogeneration system is shown in Figure 5. This shows how the waste heat from a gas turbine plant, which could be using heated gases from a molten salt reactor, could be used after having passed through both a Brayton cycle turbine and a Rankine turbine, to generate distilled water in a multiple effect or multiple stage distiller.

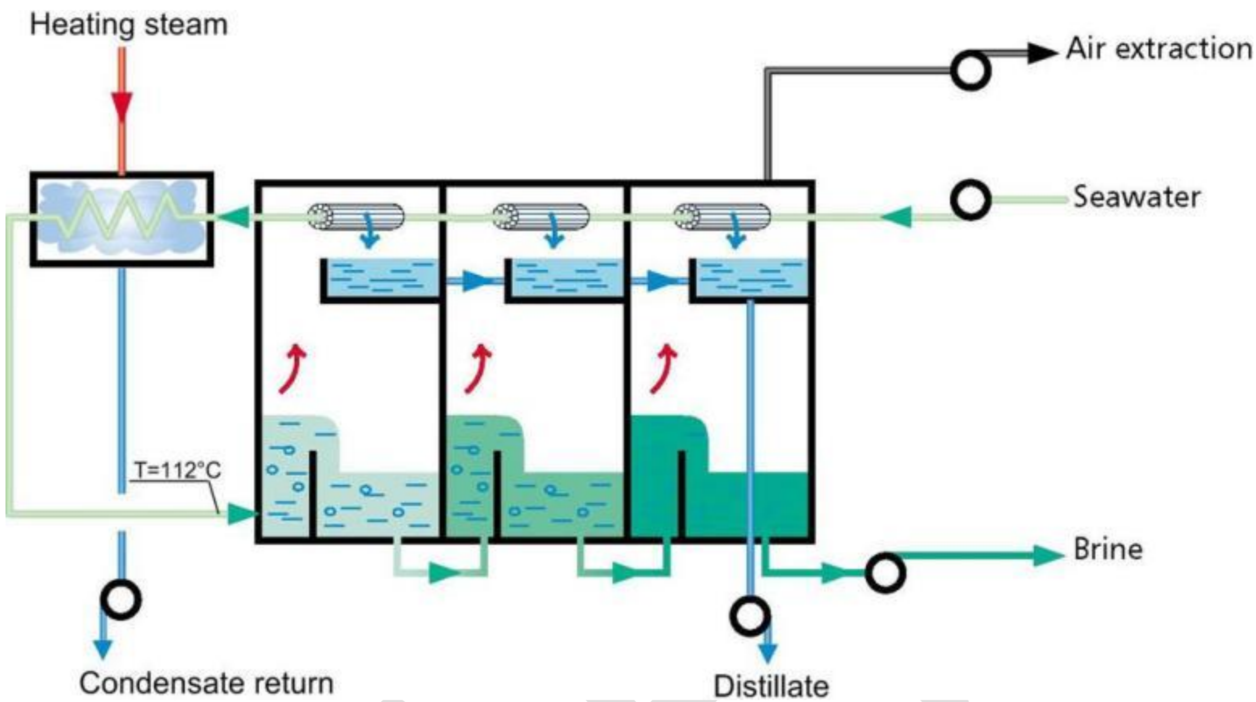

Figure 3: Schematic of Multiple Stage Distiller

Source: http://www.sidem-desalination.com/en/Process/MSF/

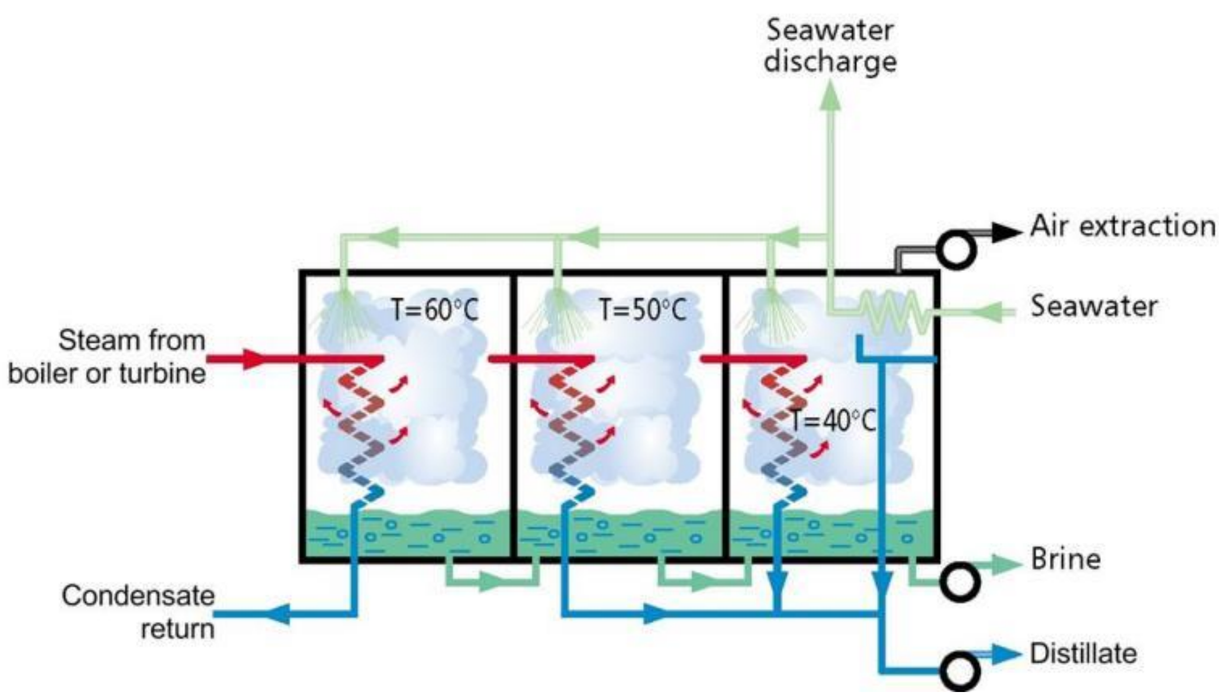

Figure 4: Schematic of Multiple Effect Distiller

http://www.sidem-desalination.com/en/Process/MED/

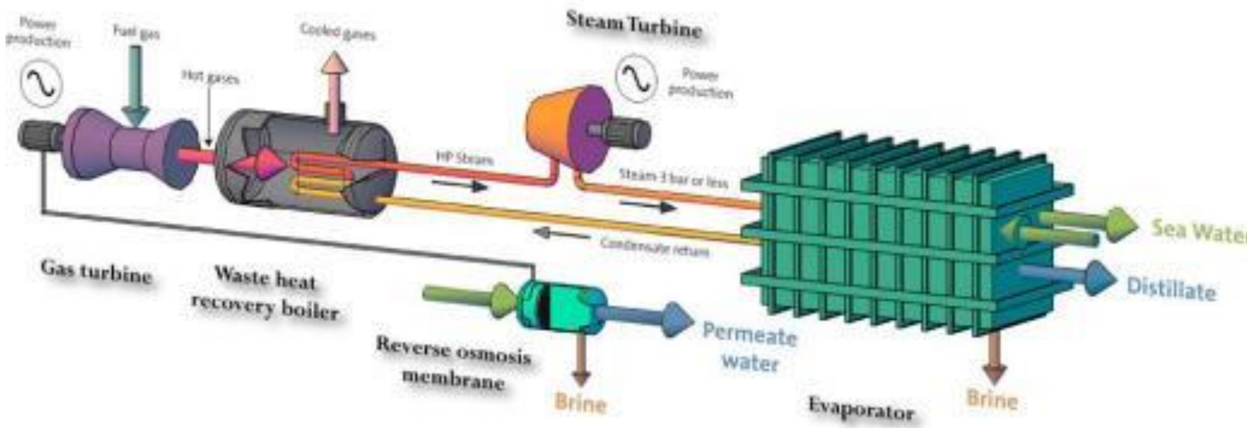

Figure 5: Schematic of gas turbine/distiller co-generation system

http://www.sidem-desalination.com/en/Process/Cogeneration/ST-and-DP/

Thermal distillation devices require both electrical energy to run pumps and thermal energy in the form of waste heat. Table 1 shows a summary of the electrical and thermal waste heat required per MGD of produced distillate. This table shows that if a MED distiller is used as much as 0.3 MGD of product water could be produced per MW of electrical and thermal energy. If connected to a 1000 MW_t power station this would yield 300 MGD or 109,500 MG/year. There are many power plants in areas that are short of water, such as Southern California where thermal distillation units might be employed to turn waste heat that is currently simply being rejected to the atmosphere into high quality drinking water. For example, Los Angeles Department of Water and Power has over 7000 MW of installed electrical generation capacity. While not all of this is likely to be available for co-generation, if it were, this could yield over 2000 MGD, which greatly exceeds the current average daily output of the City's water plants, which is 480 MGD. This would solve both LADWP's water problem and the problem of how to cool power plants without damaging the ocean or requiring high cost and high energy water from the State Water Project.

Table 1: Table of Energy Requirements for thermal desalination with water to power ratios

Type of Distiller	Electricity (MW/MGD)	Thermal Energy (MW/MGD)	Total Energy (MW/MGD)
Back pressure steam(MSF)	0.2	4.17	4.19
Gas Turbine Brayton Cycle(MSF)	0.2	6.67	6.87

Type of Distiller	Electricity (MW/MGD)	Thermal Energy (MW/MGD)	Total Energy (MW/MGD)
Back Pressure Steam (MED)	0.2	2.92	3.12
Gas Turbine Heat Recovery	0.2	5.0	5.2
AVG Power to Water ratio	0.2	4.7	4.9
Water to Power Ratio			0.1-.2MGD/MW

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2. Eugene Wigner, one of the pioneers of nuclear energy who conceived of and advocated the development of the MSR
3. Alvin Weinberg, student of Eugene Wigner, who created the first Thorium MSR test reactor at Oak Ridge in 1965
4. Kirk Sorenson, Former NASA engineer, turned nuclear engineer, who has dedicate himself development of a commercial Liquid Fluoride Thorium Reactor.

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End Notes

[i] This, I believe, is comparing Thorium as used in a breeder reactor to U235 in a conventional reactor. In the Fast Breeder Reactor (U238 to PL239) a much higher percentage of the Uranium fuel would be available, and the energy densities of the two materials would be more similar.

[ii] The wisest course of action might be to fund demonstration reactors using *both* the Thorium-Uranium and Uranium-Plutonium processes, and allow industry to determine whether one or the other is the best commercial choice. In the end, both options might be commercialized.

[iii] https://sites.google.com/site/rethinkingnuclearpower/aimhigh/thorium-energy-security-and-independence-act-of-2010

[iv] The way that this would be done with a LFTR would be to use the waste heat from the electric turbines for thermal distillation of the water thus turning the waste heat into potable water. The electricity from the power plant would then be used to pump the water to its point of use.

[v] The LFTR is one of several types of advanced, Generation IV, reactors that could be used. All share the common features of low pressure, high temperature, and good fuel efficiency. The LIFT has the advantage of using Thorium as its fuel supply and being a breeder reactor, which means it generates new fuel as part of its operation.

[vi] The view of the contrarian experts is that most of the gas wells developed using hydraulic fracturing in tight shale formations achieve 90% of their production in the first two years, hence it is necessary to drill large numbers of new wells simply to maintain current production levels. If all new well drilling stopped, gas production in most of the gas plays would drop by 50% in 1 year. For more on this go to see:

-http://mises.org/library/fracking-%E2%80%94-new-bubble-new-year

-http://davidstockmanscontracorner.com/this-time-its-the-same-like-the-housing-mania-the--subprime-shale-bubble-is-in-plain-sight/

-http://www.postcarbon.org/wp-content/uploads/2014/10/Drilling-Deeper_PART-1-Exec-Sum.pdf

-http://www.postcarbon.org/wp-content/uploads/2014/10/Drilling-Deeper_PART-3-Shale-Gas.pdf

Also, just google, "fracking bubble."

[vii] See: http://www.world-nuclear.org/info/Current-and-Future-Generation/Thorium/

[viii] The scientists and engineers at the Argonne National Labs have the most experience with Fast Breeder Reactors, and they contend that, what is now called the Integrated Fast Reactor does not pose a proliferation threat because it consumes all of the Plutonium it generates on site, and the fuel reprocessing is also done on site, which eliminates the dangers of interception during transport.

[ix] Even if the process of global warming cannot be stopped, development of non-carbon based energy supplies is an essential part of the adaptation process that must occur if human civilization is to continue.

[x] This could be broadened to include development of both breeder reactors: the Molten Salt Thorium Reactor, and the Fast Breeder Reactor. They use different sources of fuel and would not compete. The final decision on which to use would depend on which was most practical and economic to commercialize.

[xi] This is what could be called terraforming earth. Before we are ready to attempt to colonize Mars or any other planet we have to master nuclear energy technologies, which will be essential to support life. In fact, the first order of business for a space colony would be the construction of a reactor for energy production.