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A Forgotten Resource: Thorium

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The year is 1945, the morning of August 6th, 8:16am to be exact. The United States just dropped the world's first militarized atomic weapon on Hiroshima, Japan. With this singular act the world virtually witnessed the end of its second world war, the birth of warfare like never before, and the foreseeable death of nuclear power. With this act an aura of negativity and destruction accompanied the word nuclear that it would likely never be rid of despite untapped high grade energy potential that can outweigh its military application. The bomb dropped on Hiroshima was composed of 64 kilograms of 80 percent enriched Uranium 235 (^{235}U) with similar capabilities of highly enriched Plutonium 239 (^{239}P). In the act of research and development for militarized nuclear materials these two elements were determined viable. This was due to their unique physical properties that would allow them under the right conditions to produce a runaway fission, or atomic splitting chain reaction. Approximately 20 years later in 1965 amidst Cold War military efforts, Oak Ridge National Laboratory (USA) discovered another interesting nuclear material that did not share all the characteristics of ^{235}U and ^{239}P. This substance is known as, Thorium (^{90}Th) or specifically the more stable isotope, Thorium 232 (^{232}Th). When placed in a molten salt reactor (MSR) to produce power, ^{232}Th has the ability to accept a neutron, transmute, beta decay, and produce artificial Uranium 233 (^{233}U) for fission. This process is theoretically unable to melt down due to the high heat capacity of the MSR. This allows for thermal expansion slowing the reaction and decreasing temperatures creating a relatively stable periodic heat exchange that self-governs. Additionally, this process generates less high grade nuclear waste as a by-product of the reaction making this element ideal for high density power generation over destruction. Despite this seemingly great candidate, ^{232}Th was abandoned at Oak Ridge in 1969 due to its original funding source, nuclear engines for airplanes being cancelled. Subsequently, casting ^{232}Th and MSRs into the background noise of history.

Today, nuclear power derived from ^{235}U and ^{239}P based fission reactors account for ~11 percent of the world's electricity demand stationed in ~55 countries worldwide. This equates to a total installed base load capacity of over 390,000 megawatts (MW) of power. The United States accounts for ~30 percent of worldwide nuclear generation making it the largest single producer, which supplies nearly ~20 percent of the countries annual electricity demand. With a power density (W/m^2) several orders of magnitude greater than renewables and the next closest sources (Natural Gas, Coal, and Oil) requiring 17,000 ft^3, 1,780 lbs, and 149 gal respectively to equate one ^{235}U pellet. Another important aspect of nuclear power is that it's a source of non-carbon emitting power. With our civilizations activities driving observations of a rapidly changing global climate, there is a need to find viable forms of non-carbon emitting power. Another important reason to pursue safe, energy dense, non-carbon emitting power is due to our civilizations advancement requiring more high grade energy. It is estimated there will be at least a 28% increase in world energy demand by 2040. In order to turn the tide on climate change, and meet this growing demand current and future forms of energy production need to be at least carbon neutral.

Delving even deeper, as of 2016 the state of Nebraska got ~25 percent of its electricity generation from two nuclear reactors, Fort Calhoun, a part of Omaha Public Power District (OPPD) producing ~475 MW, and the larger Cooper, a part of Nebraska Public Power District (NPPD) producing ~775 MW. As of late 2016 Fort Calhoun was permanently decommissioned due to a loss of economic viability. Nuclear power at large in the world appears to be trending toward an era of decommissioning due to their life span expiring, and over regulation leading to economic constraints. Even more troubling, the ever-growing mix of warranted and unwarranted fear pushing society away from the source all together, which has fueled a lack of public and political will to rejuvenate and revitalize the sector.

When it comes down to the pure economics of the topic, nuclear power is hard to become or maintain viability when in competition with the other regularly available sources of power generation, such as fossil fuels and the increasingly competitive renewables. Due in part by societies fear of nuclear, the Atomic Energy Commission (AEC) 1946, and later Nuclear Regulatory Commission (NRC) 1975 was initiated to encourage but strictly regulate all nuclear processes in the United States. They have enforced numerous regulations some of which requiring certain personnel to be on site such as armed guards, designated and specified handlers of various materials, and inefficient bureaucratic plant operations, etc. This helps contribute to an unnecessarily high cost to produce power from nuclear. It must be noted that this industry needs regulation but warranted, efficient regulation that won't choke the economic viability out of it. When exploring current nuclear levelized cost of electricity (LCOE) including tax credit we find (on the order of $96/MWh) making it hard to compete against renewables and fossil fuels (averaging across the various forms $67/MWh). When analyzing economic estimates for ^{232}Th MSRs against other conventional forms of nuclear power generation, the following favor ^{232}Th based generation:

Capital Cost: (1 Giga Watt facility - $780 Million compared to $1.1 Billion)

Staff: (Staffing cost expected to decrease from ~$50 Million to ~$5 Million)

Waste: (Since $1/10^{th}$ by volume, ~$1 Million or less /year)

¢/kWh: (6.7, 4.2, 4.1, 1.4) [Conventional Nuclear, Coal, Natural Gas, Thorium]

Despite how much sense it might make to transition to ^{232}Th at large, there still is one major obstacle; public fear. Why so much fear and doubt of conventional nuclear power? One does not need to look far to find the answer. There have been three major instances in the history of nuclear power that demonstrate various levels of failure. These are, Three Mile Island, Pennsylvania 1979, Chernobyl, Ukraine 1986, and Fukushima, Japan 2011. Chernobyl was caused by poor USSR design and human error, Three Mile Island arguably didn't generate a substantial post melt down problem, and Fukushima was due to a natural disaster and inadequate cooling system fail safe design. What people need to remember is that engineers and scientists alike analyze and learn from each unforeseen issue and develop solutions to mitigate the reoccurrence. In addition to the warranted fear that surrounds the possibility of conventional nuclear core meltdowns, is the handling and storage of radioactive waste that is a byproduct of the process. Currently, long term storage is prioritized in the USA instead of recycling like many other countries that have nuclear power. This originates from fear due to the possibility for ease of access to enriched spent material for malicious intent. In order to address these concerns as previously mentioned, a primary benefit of ^{232}Th based nuclear power is the inability of meltdown in a MSR and the lack of high grade nuclear waste on the order of $1/10^{th}$ by volume that of conventional ^{235}U based nuclear power.

In order to make nuclear energy economically viable, remove public fear, meet ever growing global power demands, and decrease our civilizations carbon emissions for environmental reasons, ^{232}Th MSRs need to be re-explored and expanded. ^{232}Th is more relatively abundant than ^{235}U, theoretically cannot melt down (self-governing), produces $1/10^{th}$

the amount of high grade nuclear waste by volume, and when fully realized is predicted to be more economically competitive than conventional forms today.

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