Book Review: The First Nuclear Era

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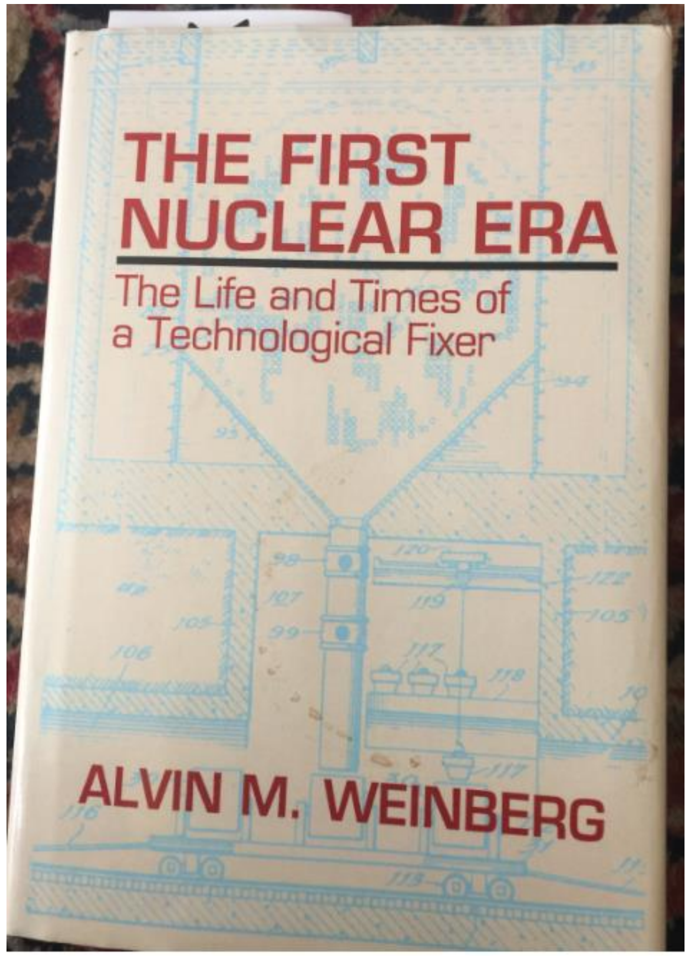
Background



According to the US Energy Information Agency, in 2017 the United States consumed 4.03 Billion Megawatt Hours of electrical energy. Windmills generated just 6.3% of this total, and other renewables, including solar, biomass and geothermal contributed another 3.2% bringing the total contribution of renewable energy to 9.5% of the national annual use (See Table 1). At the same time Nuclear power plants generated 19.9% of the total energy demand. It has been 42 years since President Jimmy Carter declared energy supplies to be the "moral equivalent of war" and launched the drive for renewable energy. In this period renewables have not been able to contribute over 10% of the national energy demand, while nuclear has consistently provided twice this and fossil fuels have been used to generate 62.8% of the national energy.

Right now there is a major movement by environmentalists and politicians who support them to eliminate both fossil fuels and nuclear energy from the electrical resource pool. The goal is to have a 100% renewable energy system. At the same time these groups also want to switch from oil and gas to electricity for transportation, home heating and industry. This would create massive new demands for electricity just as 90% of the existing generation capacity is being taken off-line in the name of the environment. Clearly, we are facing a situation where we could end up in a horrible situation if we continue down the "100% renewables" path. The same people who are advocating for the green energy path typically dismiss the possibility of nuclear power, but as explained in Weinberg's auto-biography their concerns over the safety, cleanliness and economy of nuclear reactors are based on inherent shortcomings of the pressurized water reactor, which was the unfortunate choice of American industry for commercial power.

As Alvin Weinberg explains in this book, there are probably 2000 different possible designs for nuclear reactors based on their fuel, the moderator used and the coolant. To date we have explored perhaps a half dozen of these in detail, a few more at the laboratory level. Yet, many people believe that nuclear energy is a failed system that can not be relied upon for safe and economic power based on our limited experience with a very specialized type of reactor, the pressurized water reactor. There is little awareness of a class of reactor designed by the Oak Ridge team in the 1960's that uses liquid fuel dissolved in molten salt specifically as a civilian power reactor. This reactor design by-passes the dangers that are inherent in large pressurized water reactors, since it eliminates the most dangerous part of the reactor, which is the water; not the fuel! This is true because in a pressurized water reactor any loss of coolant caused by either a break in the piping or a failure of the coolant pumps, can lead to exposure of the fuel elements, melt-down of the rods and explosions due to hydrogen gas releases. This inherent lack of safety in large water cooled reactors is why Weinberg argued against the use of pressurized water technology for large scale civilian power reactors (even though he was the person who invented them), and instead argued that civilian power should be generated by these inherently safe molten salt reactors. Furthermore, he explains that the element Thorium, could be used in molten salt reactors to breed new fuel as part of the reaction. He called the Thorium Breeder Reactor the Holy Grail of Nuclear power, since it would provide a virtually limitless energy supply. This is the topic of much of this book.

Bibliography

Weinberg, Alvin M., "The First Nuclear Era---The Life and Times of a Technological Fixer" American Institute of Physics (1994). 283 pages, $14.64 hardback.

Introduction

This is a personal history of the development of nuclear technology from creation of the first sustained nuclear chain reaction in December 1942 to sometime in 1974 when work on breeder reactors was ended, advanced reactor design was curtailed and reprocessing of spent fuel from conventional reactors was ended by President Carter in 1977. This history was written by Alvin Weinberg, one of the key players in the first nuclear era.

Reading Weinberg's history of the nuclear age is like reading Winston *Churchill's* history of the Second World War. Both men were eye witnesses to the events, and both were major players who actively shaped those events. While most people know about Churchill's role, few people today know about the role that Alvin Weinberg played in developing nuclear energy. This book tells his story and gives us a glimpse of the many other scientists, engineers, military men and politicians who participated in the First Nuclear Era.

The Book's Thesis

The book's main thesis can be captured in this quote from Ed Schmidt, who was one of Weinberg's advisors in Washington. Schmidt said:

"The first nuclear age is over.

Let us plan for a second nuclear era based on a more rational technology."

This quote raises two questions: If the first nuclear age is truly over why should we plan for a second nuclear age rather than simply abandoning nuclear power as a failure and rely on other sources of energy? Secondly, what were the irrational aspects of the first nuclear age that brought about its demise, and are there really more rational technologies that could replace them?

After reading Weinberg's personal memoirs I believe the answer to both questions can be seen. First, in my opinion, there is a critical need for advanced nuclear power. If we are serious about reducing our use of fossil fuels there is no practical alternative to nuclear energy. Humans already have a vastly oversized impact on the environment, and if we intend to rely on wind and solar we will have to cover enormous areas of land with these low density low grade power sources. What will be left for wildlife or agriculture? Secondly, it is clear from reading this history that the factor that made the first nuclear are "irrational" was that is was so heavily focused on what seemed to be overriding military necessities for weapons production. The early nuclear research efforts were devoted to production of enriched Uranium and Plutonium for bomb making, and development of reactors for power production was relegated to a distant second place. The second Nuclear Age, if we have one, will focus on civilian power production for electricity, industrial heat and water distillation.

Table 1: Electrical Generation by source (2017)

Net Generation (Thousand Megawatthours)		
Coal	Utility Scale Facilities	1,205,835
Petroleum Liquids	Utility Scale Facilities	12,414
Petroleum Coke	Utility Scale Facilities	8,976
Natural Gas	Utility Scale Facilities	1,296,415
Other Gas	Utility Scale Facilities	12,469
Nuclear	Utility Scale Facilities	804,950
Hydroelectric Conventional	Utility Scale Facilities	300,333
Renewable Sources Excluding Hydroelectric	Utility Scale Facilities	386,277
... Wind	Utility Scale Facilities	254,303
... Solar Thermal and Photovoltaic	Utility Scale Facilities	53,286
... Wood and Wood-Derived Fuels	Utility Scale Facilities	41,152
... Other Biomass	Utility Scale Facilities	21,610
... Geothermal	Utility Scale Facilities	15,927
Hydroelectric Pumped Storage	Utility Scale Facilities	-6,495
Other Energy Sources	Utility Scale Facilities	13,094
All Energy Sources	Utility Scale Facilities	4,034,268

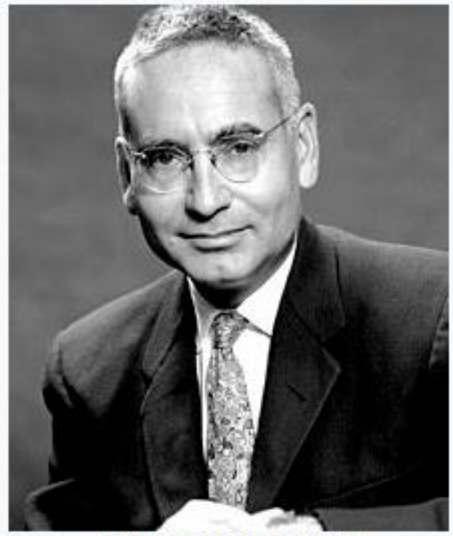
Source: https://www.eia.gov/electricity/annual/html/epa_01_01.html

Biography

Alvin Weinberg was born in 1915 to Russian immigrants. The family lived in Chicago, where Alvin's father was a tailor and managed a dress making factory. Alvin had a keen interest in mathematics and science. This interest led him into contact with some of the most brilliant physicists, scientists and engineers of the 20th century.

After receiving a PhD from the University of Chicago in 1939 he worked on the Manhattan Project. His main work was in Oak Ridge Tennessee where he worked under Eugene Wigner on reactor design. In 1948 he became director of research at Oak Ridge National Laboratory, and in 1955 he went on to become the Laboratory director. He left the directorship of ORNL at the age of 58, in 1973, after a disagreement about how the United States should move forward with reactor design and reactor safety. After he left ORNL he went on to lead a think tank on energy called the Institute of Energy Analysis (IEA). In his later years he studied the possibility of use of solar energy for electrical production and founded the Solar Energy Research Institute (SERI). So, the same person who designed the nuclear reactors that were most commonly used during the first nuclear age also founded the institute devoted to determining ways that nuclear power might be replaced with solar energy.

Alvin Martin Weinberg



Alvin Weinberg, c. 1960

Born	April 20, 1915 Chicago, Illinois
Died	October 18, 2006 (aged 91) Oak Ridge, Tennessee

Early Work

Surprisingly, Alvin began his scientific career as a biologist, not a nuclear physicist. He began his studies at the University of Chicago in 1931, at the age of 16 when most boys are sophomores in high school. Weinberg studied under Nicholas Rashevsky, who was the founder of a branch of biology that he called Mathematical Biophysics, the aim of which was to develop mathematical models of every biological process from cell division (aka fission) to population dynamics. Weinberg received his PhD in Biophysics in 1939 at the age of 24. As he tells it, his work in diffusion of materials in cells had direct application to the diffusion of neutrons in nuclear reactors.

Manhattan Project

After receiving his PhD Weinberg was hired by Carl Eckart to assist with analysis of the diffusion of neutrons in masses of Uranium in a possible nuclear reactor. This possibility was made clear by the discovery of the fission of Uranium by Lise Meitner and Otto Hahn in 1939. If the fission released more neutrons than were required for the initial fission, then it might be possible to create a self-sustaining chain reaction in Uranium. Hence, the understanding of neutrons was of great interest, and Weinberg's expertise in diffusion led him into the Theoretical Aspects subsection of the Uranium Section of the National Defense Research Council. Some other members of this council included Enrico Fermi, Gregory Breit, Henry Smyth, Leo Szilard and John H. Wheeler. During the period at the University of Chicago when Fermi was designing the first reactor in the famous squash court under the football stadium, Weinberg's job was to calculate what was called the multiplication factor (k) that showed how many neutrons were released by a fission reaction. Unless this factor was greater than 1 no chain reaction was possible, and unless it was greater than 2 no breeding would be possible.

Oak Ridge

Alvin Weinberg began working at Oak Ridge, then called the Clinton Labs, in 1943. At that time the main purpose of the lab was to construct a reactor, called the X-10, based on the design of the original graphite moderated reactor (aka pile) built by Fermi in Chicago. The X-10 reactor's purpose was to create Plutonium 239 from Uranium 238 through neutron bombardment in the reactor core. The irradiated Uranium slugs were removed from the reactor and the Plutonium was separated by chemical means. The work at Oak Ridge served as a guide to the full scale Plutonium production reactor in Hanford, WA. So, the original goal of the Oak Ridge Labs was to develop methods of creating Plutonium for weapons purposes. It was a weapons plant.

After the war the X-10 reactor was converted into a research facility for studying the effects of neutrons on various materials and to develop the best methods of shielding the reactors to prevent radiation injury to the reactor staff. This led to the construction of a higher energy reactor named the Materials Testing Reactor, which was a solid fuel reactor that was cooled and moderated by ordinary water. This was a great simplification that was suggested by Eugene Wigner, who was then the research director of the labs and supervised the project. The materials testing reactor (MTR) became the predecessor of the pressurized water reactor used by the Navy, under Admiral Hyman Rickover, to drive both submarines and aircraft carriers. This design has since been used and modified as the core of the civilian nuclear power program.

At this point it is important to recognize a vital fact in the history of reactor design at ORNL. Both Eugene Wigner and Alvin Weinberg were devoted to the idea that solid fuel was not the way to build a reactor, at least for civilian purposes. Solid fuel is difficult to work with and to manufacture; it requires frequent shut downs of the reactor to remove the "spent" fuel rods and replace them with new rods, and most importantly, solid fuel rods still contain ~95% of their original load of fissionable material when they are removed, so this requires that the rods be dissolved in acid and the fissionable material be separated and reprocessed. This is difficult work and offers an excellent opportunity to divert high level material for illicit weapons processing. The dangers of reprocessing solid fuels were a key reason why the process was halted by President Jimmy Carter. Without reprocessing, the spent fuel needs to be stored on site until it can be housed in a permanent storage facility, such as the Yucca Mountain site in Nevada. To date no such permanent storage facility has been constructed, so the spent fuel problem continues to mount.

Wigner and Weinberg wanted to dissolve the fuel in a molten salt liquid and operate the reactors on a continuous basis. A liquid fuel system does not require any fuel fabrication, so it is vastly simpler than a solid fuel system, which has been compared to a swiss watch versus a kettle. The wastes that require solid fuels to be removed from service can removed on a continuous basis, which eliminates the need for shut downs for refueling. Because the fuel does not need to be removed from the reactor it can be left in the reactor until it is completely "burned" up. This reduces the amount of high level waste to a minimum, and also allows the low level fission products to be continuously removed for either disposal or sale for medical and research purposes.

There were two liquid fuel designs investigated at ORNL: one based on water and one on molten salt. The water based system, or the Aqueous Homogenous Reactor (AHR), had Uranium fuel dissolved in water and it operated at 250 ^{o}C and importantly at 67 atmospheres (1000 psi) of pressure. While the AHR operated for over 1000 hours it had two major problems. First the water was corrosive to the stainless steel containment vessel and secondly, the uranium fuel tended to plate out on the inside of the vessel, which caused it to overheat and fail. Because of these reasons, the aqueous reactor experiments were terminated.

The second liquid fuel approach worked much better. It was based on fuel dissolved in molten salt. The salt of choice was one based on fluoride, lithium and beryllium. In its pure form this salt is non-corrosive to stainless steel. It melts at around 450 ^{o}C and stays liquid to 1500 ^{o}C. This makes it a low pressure coolant in place of the 1000 psi water in the solid fuel system. The fuels, U233, U235 or PU239 can be dissolved in the salt and circulated in the reactor providing a low pressure/high temperature system that is ideal for civilian power and industrial purposes.

Under Weinberg, and H.G. MacPherson, a very successful molten salt experimental reactor was operated at ORNL from early 1966 through 1969. At the end of this period the experiment was shut down so that the team could move on to the ultimate goal of the system, which was not weapons, but a breeder reactor that would generate as much fuel as it consumed using Thorium as the fertile element. Having a Thorium breeder reactor was what Weinberg described as the "holy grail" of nuclear power.[1]

In 1969 the research team at ORNL was fully anticipating that they would be authorized to move on to the design of the molten salt Thorium breeder reactor, but this did not happen. Instead the decision was made by the AEC reactor design team, headed by Milton Shaw, to abandon the Thorium breeder in favor of the fast Plutonium breeder being designed in Chicago's Argonne National Labs. This reactor was cooled with liquid sodium and bred Plutonium from Uranium 238. Its two main disadvantages were it had to be cooled with liquid sodium, which burns in air and explodes in water, and the Plutonium had to be constantly removed and reprocessed into new fuel elements. This re-opened the weapons diversion problem. In the end, the fast breeder never became commercially viable, and was cancelled during the Clinton administration, leaving the country with no advanced nuclear reactor program at all.

The Faustian Bargain

In 1970, after work on the molten salt reactor had been halted resistance to nuclear power was growing in the United States, led by David Lilienthal, former chairman of the Atomic Energy Commission, and head of the Tennessee Valley Authority. The opposition focused on four contentions: that nuclear

[1] As pointed out by Kirk Sorenson, Flibe Energy, the Thorium fuel cycle also has the advantages of producing virtually no PU 239 while producing several isotopes that are alpha emitters with great potential for medical purposes. It also produces PU 238, which is used for thermal power generators used in space probes.

reactors are unsafe, that they produce too much waste, that they are uneconomical, and given the U.S. abundance of fossil fuels, they are unnecessary.

Alvin Weinberg argued that over the long run nuclear energy was the best hope of ensuring human civilization an unlimited source of cheap and clean energy, and was the best way to avoid what he called a “Malthusian catastrophe”. He also recognized, however, that the main source of the problems with nuclear power was the water cooled reactors, which, ironically, he had invented. In his 1970 speech to the ORNL staff he said the following:

> “We at ORNL have a particular responsibility in this matter (of opposition to nuclear power)…The pressurized water reactor had its origin at ORNL, some 25 years ago. Thus, insofar as the debate over reactor safety centers around specific characteristics of water moderated reactors, we who helped set this course cannot properly avoid being involved.”

Weinberg is saying here that the pressurized water reactor that they designed, and specifically the adoption of the pressurized water for civilian power, had caused power reactors be become dirty, unsafe and uneconomical. He further went on to say that because of the adoption of pressurized water reactors we had made a Faustian bargain, where we could have abundant energy, but would have to rely on an inherently unstable system, run by a nuclear priesthood in exchange for the power.

The reason for Weinberg’s concern with pressurized water reactors for civilian power was that they had originally been designed for small systems to operate on ships. At a small scale it is easy to build reactors that are safe because the forces in the reactor are low. The main force he was worried about was not the nuclear fuel, it was the water. Water boils at 100 ^{o}C and power reactors need to operate at much higher temperatures. This means for the steam to have enough energy to generate power it had to be at a very high pressure (even at relatively low temperatures). Since the force of the stream on the pipes is directly proportional to the area, and the area goes up as a square of the diameter, the steam forces on the entire reactor system increase as a square of the size. If there is any break in the pipe the entire system will lose cooling and the reactor core will melt down releasing all the accumulated radioactive cesium and iodine as gasses into the surroundings. Trying to adopt small marine reactors to large commercial power plants was a fundamentally unsound and unsafe policy. He warned that serious accidents from loss of cooling were inevitable. This was the Faustian bargain.[2]

Rather than use low temperature, high pressure water cooled reactors, Weinberg and the ORNL team recommended the use of molten salt reactors which do not use water for cooling but molten salt. These reactors were high temperature devices but they operated at low pressures. This made them inherently safe from loss of coolant accident since the coolant was a stable liquid at the reactor temperature which would not boil. In addition, the salt coolant contained the dangerous cesium and iodine ions in solution as salts, so they could not escape the reactor vessel. In the event of a shut down the system would remain stable and cool itself passively.

Rather than accept Weinberg’s advice and develop molten salt reactors for civilian power the AEC fired him from his position at ORNL and affirmed the use of large water cooled reactors as the mainstay of the civilian power system. As spent fuel from these inefficient devices accumulated the concern over

[2] It should be kept in mind that the Three Mile Island accident was not caused by a broken pipe, it was caused by a stuck pressure relief valve.

waste disposal grew. This "waste" was really due to the inherent shortcomings of the solid fuel, and would have been consumed in a molten salt reactor. When the inevitable happened, and there were loss of coolant accidents first at Three Mile Island and then at Fukushima the public became convinced that nuclear power was a failed technology, when in fact what had failed was one, poorly chosen type of reactor.[3]

Conclusion

Alvin Weinberg said that he felt that the molten salt reactor, and eventually the Thorium breeder reactor based on molten salt cooling, was the best hope for human survival. The decision to abandon this technology was made by politicians and bureaucrats who were unfamiliar with the implications of their decisions. Richard Nixon, who was President at the time, admitted that science was not his strong suit in school, and he dropped it as soon as he could. He was more concerned with bringing jobs to Southern California. After he left Oak Ridge in 1973, Weinberg continued to work in energy policy and was instrumental in creation of the Solar Energy Research Institute, but he always felt that the most important work he had done was on the molten salt reactor. At the end of his life he said that he hoped that people in the future, when conditions changed, would realize that the molten salt design was a "pretty good idea" and would return to it.

Clearly, conditions have changed and now may be the time to return to the ORNL work to see if it can be brought to commercial use. Much of the basic work on the science of the system was done by the ORNL team, including operating a molten salt reactor for nearly 5 years. What we need to do now is more engineering and chemistry.

It is difficult to see an alternative to this type of advanced nuclear power reactor. Wind and solar take up huge areas, consume massive amounts of raw materials and produce only low grade and intermittent power. They always require back-ups for base load either with natural gas generators or prohibitively expensive batteries. Molten salt reactor can use any fissionable material for fuel, including the "waste" fuel from solid fuel reactors. Breeder reactor can create new fuel as they go, making them essentially a limitless supply of power. If we wish to have a carbon free electrical system, especially one that includes massive new demands for electric vehicle charging and heating we need to have this technology.

Weinberg ended his auto-biography with the following words of encouragement:

> "To deny a rebirth of nuclear energy is to deny human ingenuity and aspiration. This I cannot do. During my life I have witnessed extraordinary feats of human ingenuity. I believe that this struggling ingenuity will be equal to the task of creating the Second Nuclear Era. My only regret is that I won't be here to witness the success."

If we wait for private enterprise to develop the second nuclear era we will be waiting for a long time since private capital is too risk adverse to take on the initial development costs. A far better approach would be use form the type of public/private partnerships from the Manhattan project or the Space Program and fund the first costs publicly and then allow civilian industries to commercialize the results. The original molten salt reactor experiment was built by a few dozen people working with a few million dollars. There is no reason why can't do the same thing now.

[3] We do not include Chernobyl here since it was not a loss of coolant accident, but the result of an ill-advised test of emergency shut down procedures, which went very wrong.