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A PHYSICIST'S JOURNEY IN THE NUCLEAR POWER WORLD

Chauncey Starr

Abstract:

As a participant in the development of civilian nuclear power plants for the past half-century, the author presents some of his insights to its history that may be of interest to today's applied physicists. Nuclear power development has involved a mixture of creative vision, science, engineering, and unusual technical, economic, and social obstacles. Nuclear power programs were initiated during the euphoric era of public support for new science immediately following World War II -- a support that lasted almost two decades. Subsequently nuclear power has had to face a complex mix of public concerns and criticism. The author's involvement in some of these circumstances will be anecdotally described.

Although the physics of fission and its byproducts remains at the heart of all nuclear reactor designs, its embodiment in practical energy sources has been shaped by the limitations of engineering primarily and economics secondarily. Very influential has been the continuing interplay with the military's weapons and propulsion programs, and the government's political policies. In this respect, nuclear power's history provides a learning experience that may be applicable to some of the large scale demonstration projects that physicists pursue today.

Text:

As the year 2000 recipient of the Pake Prize, I am much honored by the APS Board to be placed in the company of the previous prize recipients. Although I have been involved in several areas of applied physics, the Board chose to recognize my contributions to nuclear power. In response to the invitation to present a short talk on that topic, I thought that this audience might find most interesting my personal experiences in nuclear power development as seen from an applied physics viewpoint.

My first contact with this subject occurred at an APS theoretical physics meeting on low temperature topics in Washington, D.C. on January 26, 1939, when Niels Bohr presented the fresh findings on the fission process. I had given a paper on paramagnetic dispersion measurements at cryogenic temperatures performed in the magnet laboratory at MIT. The Bohr/Fermi announcement changed the focus of the meeting, but I must sheepishly admit that the full perception of what this might lead to escaped me at the time. I have a photograph of the meeting attendees, many already famous, with a mix of non-entities including myself.

I had no further contact with nuclear work until 1942, when I was asked to join the staff of E.O.Lawrence at the UC Radiation Lab in Berkeley. At this time I was at the Bureau of Ships heading a group engaged in developing electronic devices to measure underwater transient forces. Lawrence and his project apparently had greater status, so I was permitted to move to Berkeley. That was my introduction to the Manhatten District.

(Condense or omit?)

My experience with Lawrence on the calutron project was an epiphany for me. My previous work had been either solo or with few associates, and on a very small scale with little funds. At UCRL, I was thrown into large scale, 24 hour/7day multiple-ideas research , with performance, not cost, the target. The calutron physics was clear, but this early equipment was replete with failure modes and unpredictability. Lawrence presided over this creative bedlam with a master's touch, discarding failures, pushing what worked, making decisions intuitively, and inspiring with his confidence. Fortunately my engineering/physics background fitted this situation very well, sufficiently so that I could make basic contributions. When the production facilities for U235 separation at Oak Ridge were approaching completion, Lawrence and the Manhatten District representative asked me to direct the pilot scale development facilities being installed there, and to act as a technical filter between the Radiation Lab and the production plants. I had available a large staff of engineers to support developments that continuously entered the production operations. I won't spend more time on the saga of uranium separation. The point is I learned how to manage big scale R&D under the pressure of a time target.

When the role of the calutron was over, I transferred to the Clinton Lab, also at Oak Ridge, to learn about "atomic reactors" (the term nuclear reactor is recent) from the work of pioneers like Eugene Wigner and Alvin Weinberg. The vision of producing useful power from fission existed from it original discovery, but had been diverted to creating Plutonium during the war years. The transfer of the Manhatten District to the newly formed Atomic Energy Commission established civilian power as a national goal. Now some of us were free to pursue this concept. In the break-up of Oak Ridge staffs after the war, I was offered an opportunity to explore new concepts by the North American Aviation Corp in Los Angeles (this later became Rockwell Internatonal). They were fighter aircraft producers and were interested in diversification. My wife and I had become enamored with California during our Berkeley days, so I accepted this offer, anticipating that it might be temporary. It lasted twenty years. I became a Vice-President of the Corporation and President of its Atomics International division.

My first nuclear task came from the Air Force, which requested a study of the possibility of nuclear propulsion of intercontinental missiles. The group I assembled did both conceptual and material research, and devised both rocket and ramjet designs. At the end of two years of study, we reported that although nuclear propulsion was feasible, chemical rockets would be substantially better. This report was declassified many decades later. Much to the consternation of the Air Force, I suggested that the project be halted. The company agreed to fund our return to civilian power, but this proved to be unneeded as the Atomic Energy Commission staff had become aware of our work and offered contract support. So in a few years Atomics International (AI) became one of the major AEC contractors in civilian power.

Now we entered the era of conceptual power reactor designs. As a reminder, it is relatively easy to initiate energy release with the spontaneous neutron emission from enough uranium isotope U235 (in natural U or U235 enriched) and a container that reflects the new neutrons produced back into the assembly. For each neutron used per fission, several neutrons are emitted, and some (0.73%) are delayed (~ 10 sec). This delay fortunately permits the reaction to be controlled by mechanical devices. As the bulk of the fission energy is in the kinetic energy of the fission fragments, which are easily stopped by solid matter, the result is concentrated heat production.

This simple process becomes more complex when applied to a practical energy source. The fission cross-section of U235 is very much higher for thermalized (room temperature) neutrons than for the fast fission neutrons. So efficient use of the fission neutrons requires slowing down by non-absorbing collisions in a moderating substance. So the choice of a moderator and a heat removing coolant opened the door to very imaginative combinations of materials and geometries. At Atomics International we worked with organic and liquid Na coolants. Wally Zinn at Argonne was working with Boiling Water and liquid Na/K. Others used water or helium gas. (Now Pb is being considered). Engineering feasibility became a dominant criterion in the early AEC demonstration program. I frequently appeared before its General Advisory Committee, which included the notables of that time such as Oppenheimer, Seaborg, etc., to defend AI's proposed concepts.

With the AEC actively supporting the "Atoms for Peace" promise, this was the heyday for the imaginative applied physicist/engineer. We all had fun. I remember Admiral Straus' face when he switched AI's Sodium Reactor Experiment (SRE) to join the Southern California Edison system – the first time nuclear power supplied a grid. I remember Glen Seaborg's delight at the launching of AI's Space Nuclear Auxiliary Power (SNAP-10), the first reactor to supply power to a satellite. We had our failures also, but the excitement of the next program was always there. I won't take time here to recount all the varieties of reactor concepts that were tried nationally. Each one was plausible, but many showed performance stoppers in the demonstration phase.

The Naval Reactor program under Admiral Hyman Rickover played a key role in the civilian program. Having gotten AEC and Navy support to create a nuclear navy, he drove everyone involved to develop a practical unit for submarine use, and followed this with large carrier units. Performance and quality were paramount. The carrier demonstration unit became the Shippingport civilian power unit. Shippingport was the forerunner for the Pressurized Water Reactor (PWR) so widely used in the industrial countries. The basic technologies developed for this naval program were made available to the civilian programs. Rickover was a difficult and demanding person, but as professional friends we got along well, probably because I didn't work for him.

The dominating national policy decisions came from the congressional Joint Committee on Atomic Energy (combined House and Senate into a single unit). They controlled the huge budget of the AEC. Over the almost two decades of its existence, the JCAE became educated and sophisticated about all the AEC programs, and cynical about scientists. Like others responsible for program performance, I appeared before this committee several times a year to explain, teach, promote, apologize, and try to keep out of trouble with the AEC. Congressman Chet Holifield, the dedicated spiritual leader of the JCAE, was a socialist in spirit when it came to atomic energy. He believed that the development was the result of a federal investment and belonged to the people, and the JCAE was its custodian. He accepted the private sector as a vehicle for delivering the benefits. The JCAE was a true pillar of strength for me. If they believed you would deliver on your promises, and tell them the truth when you got into trouble, their support would be there.

What is different today? The 1970s anti-establishment movements growing out of the opposition to the Vietnam War resulted in the disintegration of the powerful combination of the AEC and the Joint Committee. The AEC was subsumed by ERDA, the Energy Research & Development Agency, with a broadened responsibility, and of course a dilution of budget for nuclear. ERDA later became the DOE, the Dept. of Energy, with further dilution of nuclear's role. The JCAE was split and absorbed by the traditional committees of the House and Senate. Nuclear had no dedicated champion in Congress. So the shifting political winds left the future of nuclear to industry. A combination of the nuclear manufacturers and the Electric Power Research Institute (EPRI), which I formed in 1973 at the request of the US utilities, have since carried the bulk of R&D in nuclear power. I'll not explore here the continuing historical influence of the political scene.

The technical shifts since the early days have been equally significant. Two of the very early reactor design constraints were the high cost of enriched uranium and its relative scarcity world-wide. These focused strategic planning into reactors fueled by natural or low enriched uranium, and for the long-range the efficient use of uranium resources through the breeder. It subsequently developed that development of the gas diffusion plants substantially reduced the cost of enrichment. So the economic balance became determined by how much the performance life of the fuel elements could be extended by increasing enrichment to extend burnup-life. Further, the market for uranium ore stimulated the finding of very large mineral resources, so the need for the breeder was deferred some decades.

The choice of reactor coolant among water, gas (CO2, He), organics, liquid metals (Na, K, Pb) is an option for all reactor designers. That choice affects everything. The early initiative of the Naval program gave the bias of success to high pressure water systems for thermal spectrum reactors. Water is actually a complex and tricky coolant, but most existing power reactors use it, at about 2000 psi in BWRs (Boiling Water Reactor) or 2500 psi in PWRs (Pressurized Water Reactor). Because of the very high power density in breeders, liquid metal is the common choice. High pressure gas needs more demonstration. This is an area where engineering technologies determine choices.

The details of reactor designs have been dependent on basic and applied physics R&D. I'll mention just a few that exist today. 1. A continuous problem is the **radiation hardening** of construction materials (steel vessels, etc.) due to neutron bombardment. The issue is brittle vessel cracking due to thermal cycling during startup and shutdown. We are seeking a 60 year vessel lifetime. 2.The **lifetime of fuel elements** has a significant economic potential, and depends on many factors; such as *the loss of reactivity* when uranium is depleted; the *shift in heat transfer* from the center to the cooling surface as the consistency of the fuel is altered by the cumulative internal fission products; and of course, *corrosion* of the fuel cladding by the coolant. 3. **The safety package** including the *control system* *physics* during power transients; and the potential for hypothetical steam explosions and ejected control rods; the *control rod dynamics* in the combination of sensors, mechanical drives, and changing neutron distribution as burnup proceeds; c*ontrol rod lifetimes* as their absorbent gets depleted; the continuing *radiation decay heat* after shut-down, which becomes a pressing issue after a loss of coolant flow (e.g.Three-Mile Island). This last continues to be a challenging design issue. Added to the known problems is the cautious *regulatory overestimating* of visionary events, which require adding the burden of hypothetical failure modes to the package of realistic ones.

Such applied physics areas have played a continuing role in the drive to make nuclear power more economic and reliable, with old plants as well as new designs. Although it moves at a slow pace, research on the behavior in the reactor environment of materials, uranium fuels, and coolants, leads to changes in reactor operations and maintenance. The accumulated thousands of reactor-years of operating experience provide empirical data on all such questions, which gets fed back to the research. The R&D challenges for applied physics solutions remain one-step ahead of the past half-century of improvements in reactor operations, which have been substantial enough to make nuclear competitive with other electricity sources in many circumstances.

Where do we stand today? During the 21st century, global economic and population growth will create an annual energy demand conservatively estimated to be 5x today's (population 2x and per capita use 2.5x). This demand will strain all energy sources, and make nuclear power a necessity. Further, minimizing the environmental footprint of energy sources provides nuclear power a unique role. Public acceptance of radiation emitting technologies will also grow as their increasing use in medicine and pasteurization of food and water demonstrates the safety of the low radiation levels involved. With regard to the safe disposal of nuclear wastes, the technology exists today, and today's political barriers will eventually disappear. Nuclear technologies have opened a new domain awaiting fuller exploration for mankind's benefit.

Let me comment on the non-technical aspects of nuclear affairs. All of us who have invested many professional years in nurturing civilian nuclear power are deeply concerned about its present status and immediate future. We have learned that the implementation of our engineering concepts depends on the vagaries of non-technical economic, political, and doctrinaire environmental issues. Although these vary over the world, the US has been illustrative of almost all of them.

Economic issues are the most quantitative. Nuclear, coal, and hydro all need high capacity plants (500-1000 MW) for economic competitiveness. The large lump of capital required is justified where many decades of profitable operation is assured (30-60 yrs). Governments traditionally take such risks (e.g.,US Northwest hydro, TVA), as do private investments in a stable economic, growth, and regulatory environment. The post-1970 era in the US destroyed this stability, so most power plants committed for long-range growth were canceled. US nuclear stopped growing. The special environmental values of nuclear has recently encouraged maintenance of our existing plants for their operational lifetimes -- a few more decades.

And all power plants now face a new barrier resulting from the political deregulation of generation and dismemberment of our utility networks. This has created such uncertainty about utilities' futures that most private investment in new capacity needs are being met in very small increments, mostly by natural gas fueled high efficiency turbines. So an old concept of small modular high temperature helium cooled reactors, is being revived, notably by So.Africa and by a US-French-Russian-Japanese consortium. Obviously, if successful, these would find a market in developing countries without indigenous fossil fuels.

The albatross on the back of nuclear power's future is the resolution of spent fuel management. The earliest concept of the scientific community was the closed cycle with chemical separation of spent fuel and Pu recycling in fast breeders. The residual fission products are very small in volume and permit burial with miniscule risk to the environment. The pioneers understood this, and it is technically feasible today. The French, Russians, and Japanese remain philosophic adherents to this approach. The antinuclear movement has effectively politicized the availability of weapons Pu from any separation process, and persuaded the US government in the 1970s to mandate the "once through" sequence of direct burying of spent fuel. The economic realities support direct burial because present state-of –art of chemical separation, and of the fast breeder, make these very costly. Recognizing all this, several versions of an Internationally Monitored Retrievable Storage System (IMRSS) for the already large accumulation of spent fuel have been proposed, but no political action has yet been taken; probably because of the new sovereignty issues raised, and the obvious pressure from the antinuclear movement to keep the albatross of spent fuel. This topic is not on the "radar screen" of our nation's statesmen.

So what has this lifetime participation in the birth-pangs of a radically new energy resource taught me? First, it has reaffirmed my faith in the key role that applied physics has had and will have in bringing nuclear's benefits to mankind. I consider our present practices as "first generation". I have learned respect for the value of large scale funding of R&D. Ideas originate with individuals, but demonstration requires lumps of money. A trial of a small improvement in nuclear power operation is likely to be a gamble of 100 million dollars or more. Unlike the early history of the Internet, the garage-scale experiment doesn't exist in nuclear power. Only governments, or consortia of large companies, have such resources.

I've learned that annoyed as we may be with bureaucracies, government and corporate, we must make them function. I've learned that public support does not come from "facts", but rather from perceptions based on individual self-interest. I've learned that communication media are the most important channel to the public, and require much tutoring to do a credible job with integrity, otherwise the media creates mischief. The media merchandises attention-getting stories, and it is up to us to take the initiative to provide the background material, and to quickly correct significant published errors. The public seeks "black or white" answers, whereas most science provides shades of gray. We must learn to handle this. Unfortunately, in my day scientists were not given training in public communication.

Looking back a half century, I am pleased to have had the opportunity to contribute in a small way to mankind's future. I hope you all enjoy such an opportunity.