Overview: How the Borax Reactor Came to Be

Borax is best remembered as the nuclear power plant that made history in the spring of 1955 when it provided the first nuclear electrical power to an American town. It was a demonstration to show the progress that was being made at that time to make practical use of nuclear power. Not as well remembered is the fact that the plan to provide atomically produced electric power to Arco as a demonstration was initiated for political reasons relating to the cold war with the Russians.

Following World War II, there had been annual international conferences on atomic energy each year in Geneva Switzerland. The United States and Russia both attended these conferences but declined to participate because of the secrecy involving atomic technology and because it was assumed that the United States was far ahead of all other nations and did not want to reveal our advanced knowledge. The cold war with the Russians was in full swing and accusations were in vogue. The Russians were accusing the United States of directing all of our atomic research toward weapons while they were directing their research toward peaceful uses.

Preparations for the 1955 conference got underway in the fall of 1954. It was assumed that Russia and the United States would, as usual, have representatives present who would listen but remain silent in their smug, more advanced knowledge. However, things were about to change. The Russians announced that they were not only going to be present at the conference, but that they were prepared to present a paper on a five megawatt research power reactor that was designed to produce electricity for civilian use. It was obviously going to be a propaganda event. The Americans reviewed the situation and decided that they would like to participate in the conference to compete with the Russians and to do so in such a way that we could defend our honor and demonstrate our superiority.

At that time, in the fall of 1954, the Borax experimental program had been in progress for a little more than two years. It was in the early stages of experimentation following a third reactor modification, identified as Borax III. While earlier versions of the Borax experiments were conducted outdoors in the open air, Borax III was contained within the shelter of a sheet metal building. Operations of the new reactor had progressed to the point that it was a stable source of about six megawatts of steam at 300 lbs of pressure. The obvious next step in developing the Borax concept was to connect an electrical power generating system to the Borax steam source.

It was at that time that the idea was conceived to meet the Russian challenge by connecting a power generator to the Borax Reactor and use it as a demonstration plant by lighting an American town. There were some problems with this idea. Time was short. The 1955 International Conference on Atomic Energy was only about 6 months away. There was a serious question if an acceptable turbo-generator could be found on such short notice and installed along with the required cooling towers, switchgear and transformers. While the Borax III reactor could generate sufficient power, it needed some additional refinements to provide better safety and reliability.

The larger Shipping Port Reactor was under construction at that time. It would also produce electrical power but it was similar to the nuclear power plants developed for our nuclear submarines and aircraft carriers. The Russians could point to the military heritage of this reactor as part of their propaganda. It would be much better if a presentation could be made with a strictly civilian plant that was in no way related to the military. The Borax story would probably have an additional advantage because it involved an entirely new reactor concept that was previously unknown to the rest of the world The Borax Reactor plan was given the go ahead and proceeded on a crash basis. Work on the Shipping Port reactor also continued but it did not become operational until sometime later.

The Borax Reactor Program owed its beginning to a nuclear criticality accident that had occurred earlier on June 2, 1952 at the Argonne National Laboratory near Chicago. Some tests were being conducted on a Critical Assembly at Argonne to measure the characteristics of various control rods used in the reactor power plants on nuclear submarines. The Critical Assembly was a mockup of the Nautilus nuclear submarine reactor. It had real fuel elements and could be operated something like the real reactor but only at extremely low power. During these tests there occurred an operator error which caused the Critical Assembly to go prompt critical and resulted in a steam explosion within the assembly. The Critical Assembly was damaged and four operators received substantial radiation exposure and a shower bath as the water in the Critical Assembly was expelled from the assembly tank.

The Argonne staff marveled that the incident was so comparatively mild. It had previously been assumed that a water moderated reactor would be very unstable if allowed to go into a boiling state. The criticality incident gave indication that, perhaps, a water moderated reactor could be made to operate in a stable boiling mode. Plans were made to conduct an experiment to determine if the boiling concept was a valid approach for power reactors. The experiment was given the classified name, Borax, which was a shortened form for Boiling Reactor Experiment. The experiment was thought of as moderately risky. As planned, it would be a short term experiment that could quickly determine the feasibility of this approach. Because of the risk, it would be conducted at the Reactor Testing Station in Idaho. The experiment was to be conducted in the open air without benefit of a building, at a location just outside the perimeter fence of the Experimental Breeder Reactor No. 1 (EBR-I). It was assumed that the experimental tests would last no longer than one summer and would be terminated before the coming fall season.

The tests were conducted and it was found that the reactor did operate in a stable boiling mode. A series of transient tests followed to test the limits of stable operation by subjecting the reactor to many power surges. Some of these tests were rather spectacular with jets of water shooting up out of the open reactor tank, rivaling the appearance of the Old Faithful Geyser.

The test experiments were temporarily terminated in the fall of 1953 by the approach of winter. During the winter, a new set of control rod drives and some other changes were made in preparation for ultimately testing the reactor to its limit. The modified plant was given the designation of Borax II. At the same time, plans were being made for Borax III, which included a new pressure vessel capable of operation at pressures up to 600 lbs/sq. inch. Ultimately, Borax II was tested to destruction in a spectacular explosion that scattered pieces of the reactor over several acres of the surrounding desert.

Plans and preparation for Borax III were well underway in the fall of 1954 when information was received about the Russian plans to make their presentation at the Geneva Conference on their five megawatt nuclear power generating station. There was evidently some high level discussion at the Atomic Energy Commission that led to the decision to initiate accelerated construction of Borax III and make a connection to a steam power generator to complete a first-ever complete Boiling Water Reactor Power Plant.

Furthermore, plans were made to complete the project and make a connection to the local power grid in such a way that power was to be supplied to the town of Arco totally from the Borax III Reactor. This would provide the finishing touches to an American presentation at the Geneva Conference that would at least match and probably outdo the presentation to be made by the Russians.

The project was successful in spite of the fact that there were only a few months available to complete the project. The American presentation was made at the Geneva Conference on schedule. The presentation included spectacular footage of the transient tests and the story of the lighting of Arco, the first city ever to be supplied with electric power totally from atomic energy. There was tremendous response to the presentation. The American presentation definitely stole the show from the Russians.

The typical news releases followed. Our accomplishment was reported very favorably in several news magazines including “Time Magazine”. However, there were interesting details that have never been told. One reason is that, at that time, our work was classified and the Russians were not to know the details. Another reason is that there are some embarrassments in the story.

The story, by its nature, must be told in some detail if the situations we encountered are to be fully understood. However, some of the highlights are these: The lighting of Arco would have been completed two days earlier had things gone according to plan. But the power line to Arco as initially connected could not carry sufficient power and actually burned to the ground. The loss of the power line put the reactor in serious jeopardy, requiring super effort to recover and to finally complete the task.

Most of what I write here is from memory with some limited reconfirmation from other sources. I believe that what I write is correct but there may be some imperfections in the order of the events. These events took place more than 50 years ago. It is a long time to retain perfect memory, but these were days not easily forgotten. I had joined the Idaho Argonne engineering staff in January of 1952 as the youngest and only locally hired engineer. All the other engineers, physicists and an office manager had transferred from Argonne, Illinois. With my arrival, the Idaho Argonne technical staff included a total of ten people. There were other locally hired support people including two secretaries, a janitor, a machinist, and other mechanically talented people who were given the title of technicians. The entire group traveled to and from work in one twenty four passenger bus. I was initially the only Electrical Engineer in the group. I was hired because they had encountered some electrical complications in the EBR-I electrical circuitry. I arrived two weeks too late to participate in the first power operation of the EBR-I reactor when the first ever electricity was produced from atomic energy. I had been interviewed and accepted for the job the previous October, but could not report for work until after I had received my official "Q" security clearance.

All of the Technical Staff were on-the-job trained reactor operators and participated in the operational tests and experiments conducted on the EBR-I reactor. Several of the EBR-I staff, including myself, later became the primary leaders in the operation of the Borax Reactor and were the primary participants in the lighting of Arco. We were also the primary participants in the operation and history of the EBR-I reactor and were present when that reactor melted down. There are also several interesting details in that event that have never been told and beg to be documented while it is still possible.

I was not the most prominent participant in these events. The highest authority for both the EBR-I and Borax activities was Dr. Walter Zinn, who was Director of the entire Argonne National

Laboratory at the time. Dr. Zinn operated from his office in Chicago, but was present in Idaho during all the major events involving the early Borax Reactor activities. He was, however, not present when the EBR-I reactor melted down. Harold Lichtenburger was in charge of the Idaho operations throughout this period. I worked directly under Harold. All of the other Idaho technical staff at that time were effectively on the same working level as myself. However, they all had more work experience than I did which gave them a kind of de facto seniority. There were also various temporary technical experts who were loaned, or arranged to come to our site, to give added support for various projects. There were several additional temporary technical people present for the Borax tests and the lighting of Arco. Most of them came from Argonne, Illinois but I also remember one on loan to us from the Air Force, one from the Pratt and Whitney Co. and one from the Common Wealth Edison utility.

I have been able to track all of the original permanent technical team members involved in these tests. At this time, only a few are still living. There are, however, others still living, who were part of the temporary and support personnel. All of us were exposed to high doses of radiation. Even so, I'm not aware of any of our original team members having died of cancer. Our team seems to be dying on schedule at the same age and ailments as other people.

The official reports issued, following these events, present the official information approved at that time for release. They provide the basic technical results but do not tell about the adventures we experienced. While I did not have the primary authority or responsibility to report what happened, I was perhaps in the best position to observe and report what happened.

The Borax project was initially classified secret. It would not have been acceptable at that time to report everything about the project.

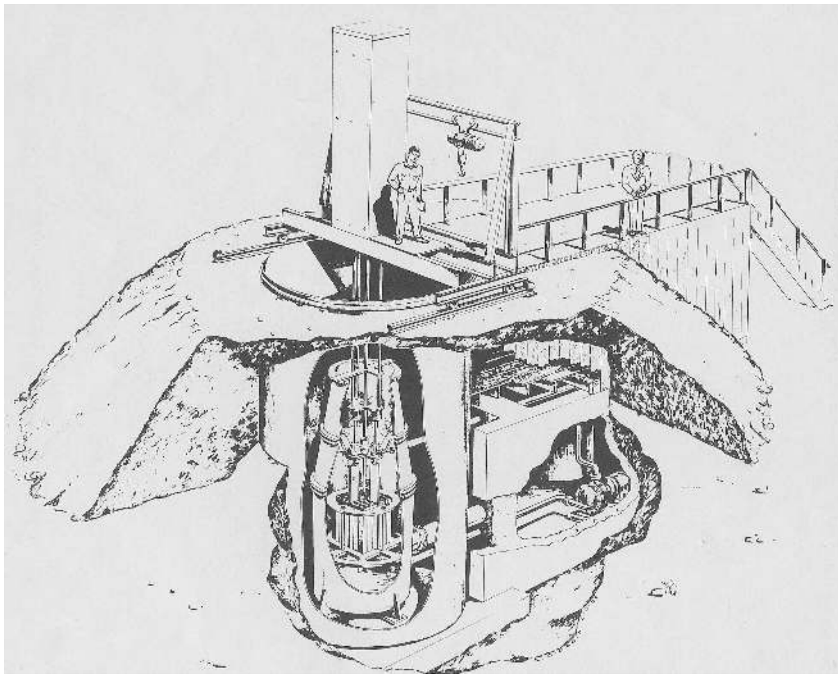
It is not surprising that, for several years, further description has been scarce. The pressure we felt and the shortcuts we took to meet our objectives may not be seen in a favorable light today. My co-workers and I have always marveled at the unreasonable fear of atomic energy registered by politicians and the news media. It appears to us that the public has been bombarded with exaggerated fear stories until they have become fearful of atomic energy in all forms. We have all felt that there must, eventually, be a return to a realistic view of atomic energy if the world is to maintain an adequate supply of electricity. We have all felt sure that the world will eventually discover that atomic energy can be a clean safe source for electrical energy.

Many people, like me, who have enjoyed great careers in atomic energy, have been slow to tell the details of the earlier experiments such as the Borax Project. If we tell of our free and easy handling of radioactive equipment and nuclear fuel and of our deliberately destroying an uncontained reactor, we may be severely criticized. However, if the minimal consequence that actually resulted is considered, then maybe the public will begin to realize that the risks associated with atomic energy are not so severe and can be made acceptable. New proven technology is now available to greatly reduce the risks we faced. We need not squander an opportunity to develop an abundant source of energy.

The Borax Reactor Arrives in Idaho

The first Borax Reactor arrived in Idaho in the spring of 1953. The decision to conduct the Borax experiment was made in Chicago, outside my area of vision. The hardware for the experiment was fabricated in Chicago and arrived in Idaho on a group of trucks and trailers. Two of the trailers became a semi-permanent part of the test facility. One trailer became the control room for the reactor. Another became the electrical control trailer with much of the electrical gear pre-mounted inside the trailer before shipment to Idaho. Pumps, the reactor tank, the shield tank and control rod drives arrived in other trucks and trailers. A small group of technical people also arrived, who had been recruited in Chicago. These people had designed and pre-built some of the mechanical assemblies before leaving Chicago. About half of the EBR-I staff was transferred to the project to join those who had arrived with the hardware from Chicago. I was one of those transferred from EBR-I. The control rod drives were the same ones that had been used on the critical assembly that had experienced the criticality event that led to the decision to initiate the Borax project.

The site selected for the control trailer was just outside the EBR-I perimeter fence. A site for the reactor was about one half mile further to the west. A pit was excavated in the ground to receive the reactor shield tank, pumps and supporting plumbing. A portion of the pit was walled off by concrete block and roofed over to become what we called the pump pit. The shield tank (from memory) was about nine feet in diameter, 12 feet high and open on top. It was placed vertically in the reactor pit, separated by a concrete block wall from the pump pit so that about half of the tank was below the surrounding ground level and half above. The dirt excavated from the pit was mounded around the shield tank and pump pit so that the profile of the project initially appeared to be nothing more than a mound of dirt. However, one end of the pump pit was left open. Some wood steps were constructed up the dirt mound to give easy access to the top of the shield tank. The reactor tank was placed inside the shield tank. There was no intent of placing a building over the test facility. The whole test was to be a one summer project to quickly learn if the boiling concept was a practical approach. The top of the shield tank and the reactor tank was open to the sky.

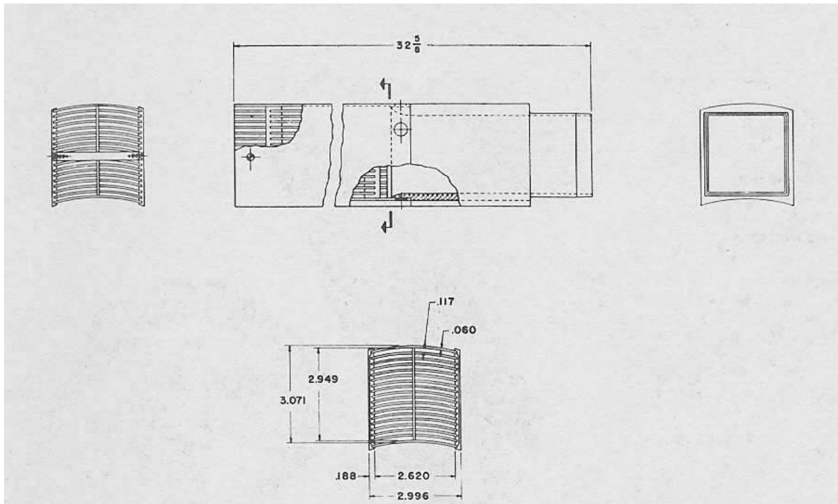


Cutaway Drawing of the First Borax Reactor

The reactor tank was fabricated in flanged sections and designed to withstand a pressure of 300 lbs/sq. inch. There was a top lid for the tank but it was not used for the initial tests, all conducted at atmospheric pressure. Parts of the reactor support structure were prefabricated in Chicago and later assembled in the reactor tank after the reactor tank was placed within the shield tank. However, some of the prefabricated parts did not fit and considerable modifications took place in the field while the reactor structure was being assembled. I remember, in particular, that there was a large "sparger plate" at the bottom of the reactor assembly. It was a thick metal plate with a network of holes drilled in it for the purpose of evenly distributing the coolant water flow up through the reactor. After it was installed, it was learned that it conflicted with other parts of the assembly. It was decided that it should be removed and abandoned. I remember a scene in which a technician, who had been lowered into the reactor tank with a pneumatic chisel, was chiseling the sparger plate into small pieces and throwing them up out of the tank, one by one. Meanwhile, the engineer who had designed the reactor structure, Douglas Layman, was looking on in frustration as his design was being modified before his eyes without his approval. It was only one of the many times that his design was to be modified on the spot by his superior, Dr. Walter Zinn.

Dr. Zinn, Director of Argonne National Laboratory, spent the entire summer with us. A small home had been rented for him in the modest Belair addition in Idaho Falls. Dr. Zinn was, to us, what Admiral Hyman Rickover was to the nuclear navy. He was decisive, brilliant and demanding, but on occasion, he could be unreasonable. Incidentally, Zinn and Rickover had limited respect for each other. They had first met when the nuclear navy was first formed with a staff of one man, Lieutenant Hyman Rickover. Rickover, at that time, was given a small office in a corner of the technical library at Argonne in Chicago.

Fuel for the first Borax reactor made use of slightly modified fuel subassemblies from the Material Testing Reactor (MTR). The MTR was already in operation nearby at the reactor testing station. These subassemblies contained a group of thin concave aluminum plates with the uranium fuel sandwiched inside the plates. The plates were spaced about 1/8th of an inch apart within the subassembly so that water coolant could flow up past each plate. The fully assembled subassembly was in the form of an aluminum rectangular box about 3 inches square and 3 feet long. The outer box was open on one side which exposed the first fuel plate to view. It was necessary to do some machining of the outer box of the assemblies to adapt them to the Borax support structure and application.



Borax Fuel Subassembly

Cooling of this first reactor depended on recirculation by free convection. The power, instrument and control cables were stretched out on the ground from the control trailer to the reactor, one half mile away. A water pipe line was likewise laid out on the ground from the EBR-I reactor facility well to the reactor.

There had not been sufficient time to do an adequate job of designing the project so there were many problems encountered during the construction of the reactor and the supporting equipment. I was deeply involved in the work on the electrical power and control circuits. More than once I found myself wandering through the Central Facilities Warehouse looking for anything that could be used to overcome some problem not previously anticipated. One problem that I remember is that there was no indicator in the control trailer to verify when the control rods were physically connected to the control rod drives. I was simply told to take care of the problem. There was not sufficient time to do anything more than a quick fix. The source of the information for the signal (the point of contact between the control rods and the control rod drives) was below the water level in the reactor tank. I chose a simple solution by running low voltage wires (12 volts) down into the reactor to the bottom of the control rod drives and mounting electrical contacts on each drive. When there was electrical contact, then the connection of the control rod was verified and indicated by a light on the control panel. This had the effect of putting a 12-volt charge on the water in the reactor tank. The electrical charge had no effect on the reactor and I felt sure that no one would be able to feel the charge while working on the reactor. I was wrong. We had one technician (Ed Denning) who insisted that he could not only feel the charge when working on the reactor, but that it was extremely uncomfortable. I couldn't feel it, but he complained loudly about it, and I took some condemnation from Dr. Zinn for my design.

The First Operation

It was mid-summer of 1953 before the reactor was ready to start operation. De-mineralized water was transported from the MTR facility to fill the reactor tank. The approach to "critical" (the onset of a chain reaction) was made in a well-established procedure in steps with the number of fuel subassemblies being increased one at a time between trial startups. Reactor criticality was achieved with no surprises. The usual tests for a new reactor were made. The reactivity worth of the control rods was measured and the overall temperature coefficient was verified to be negative. A series of short, increasing power runs were undertaken, slowly approaching a boiling condition in the reactor. The operation tests were kept short to minimize the radioactive activation of the fuel subassemblies. The immediate area around the reactor was vacated during each run.

Some technical explanation is needed here. New fuel subassemblies are essentially not radioactive. Most people do not realize that pure bomb grade uranium is essentially not radioactive. Natural Uranium ore, mined out of the ground, is slightly radioactive because it is a mixture of more than one isotope of uranium. The most common isotope, uranium 238, is slightly radioactive. As the reactor begins to operate, the chain reaction produces radioactive fission products that accumulate in the fuel. By keeping the power runs on the reactor low and short, the activation in the fuel was maintained low so that we were able to continue manually handling and manipulating the fuel subassemblies between test runs. The radioactivity of the fuel was rather high immediately following a run, but by waiting a few hours, the activity diminished to a level where we could approach the reactor and directly manipulate the fuel subassemblies. It should also be remembered that in 1953, the recommended limit on personal radiation was much higher than now.

In a water-cooled power reactor, there is a need to keep the coolant water pure because the minerals found in typical water become activated by the chain reaction. Pure de-mineralized water avoids this problem. However, the Borax reactor was open to the atmosphere and the water accumulated dust from the surroundings. Furthermore, in 1953, we had an infestation of flying ants. Each morning we found the water in the reactor had accumulated a large number of floating dead ants. As it turned out, water purity was not a problem because our power runs were low and short enough that the water showed no signs of significant activation. The reactor was supplied only once with de-mineralized water from the nearby MTR facility. From then on, the water was filled with water directly from the EBR-I well. I remember that during that first summer, Dr. Zinn made a presentation before the staff of the MTR reactor. A question originated from the audience about what was being done to purify the Borax reactor water. His answer was that he spit in the water each morning for good luck!

The behavior of the Borax reactor under boiling conditions is reasonably well documented. I assume that the documentation is still available in technical libraries today. These reports were initially classified. The reactor was found to be completely stable for low power boiling conditions. However, the instrumentation that monitored the reactor power displayed a rather noisy trace due to the steam bubbles in the reactor coolant passing in a random pattern in front of the power detectors mounted just outside the reactor tank. As the power level was increased, the reactor power behavior became more erratic and began to show signs of pulsating surges. At still higher power levels, the reactor began to surge dramatically in a pattern we called chugging. Each chug correlated with the bulk of the coolant water being periodically thrown upward out of the reactor tank. The water ejection had the effect of momentarily shutting down the nuclear reaction. As the water fell back into the reactor the nuclear reaction would begin again. These chugs would occur on a time cycle of about one second for each cycle.

I remember our site director, Harold Lichtenburger, bent over a power-indicating instrument on a table in front of the control console, intently watching each power chug indicated on the instrument, with his hand ready for action at the reactor shutdown button. This chugging phenomenon was fascinating, and we wanted to push the system near its limit but we did not wish to damage the plant until at least the last scheduled experiment. Harold said something like, "Shall I shut it down now or wait for still another chug"? Everyone was silent and he let it continue to surge until the surge pattern was well observed and recorded. We learned that, at the power threshold of chugging, the reactor would wander in and out of the chugging pattern. We were also able to identify the power threshold for when the chugging was likely to start, and that at higher power levels the reactor would enter into continuous but stable chugging.

It was previously known that displacement of coolant water in any water-moderated reactor would produce an effect to shut down the nuclear reaction. However, prior to the Borax tests, it had been thought that any boiling within a water-moderated reactor due to a power transient would not displace the water fast enough to shut down the reactor before major damage. It was also thought that boiling within a water-cooled reactor would probably cause the reactor power to be basically unstable. The Borax experiments conducted that summer demonstrated that the boiling process within the reactor was sufficiently fast to effectively restrain the nuclear reaction. It also demonstrated that boiling within the reactor did not cause the nuclear reaction to become unstable. It was yet to be determined if a boiling water reactor could be made to be a practical power plant.

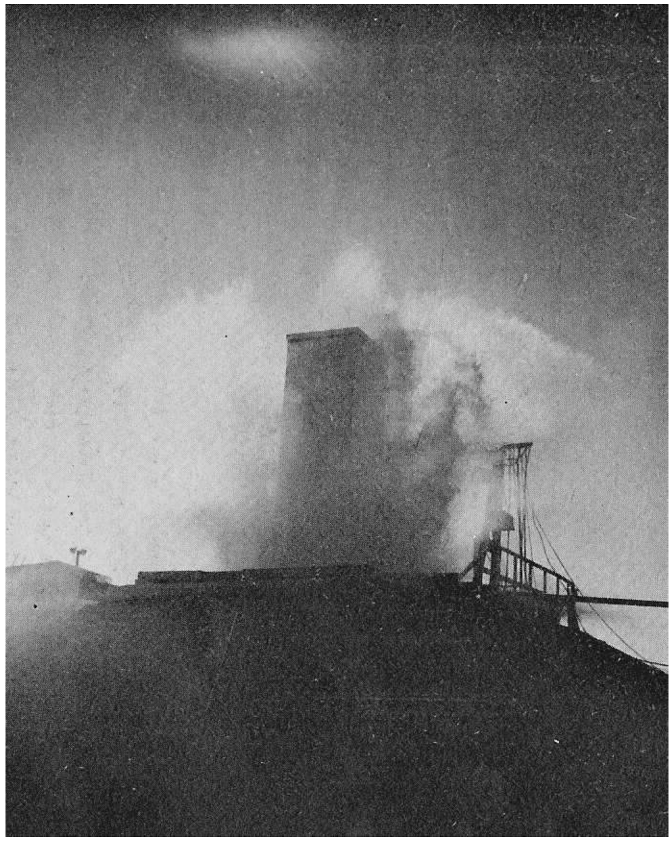
All the early Borax tests were conducted with the reactor tank open on top to the atmosphere. The reactor tank was technically designed to operate at a pressure of 300 lbs/sq. inch with the tank lid in place. The lid was installed so that testing could be done at pressure. During the last experiments that summer, the reactor was operated at successively higher pressure and for longer periods. I don't remember anything peculiar about these tests except that the reactor tank was poorly designed and, at pressure, it leaked badly from under the lid and from the flanged joints of the tank. Even so, we succeeded in operating the reactor in a stable condition with moderately increased pressure and at a substantial power. The steam produced from the power was released to the open atmosphere. These longer power runs had the effect of making the reactor more radioactive. It was getting more and more difficult to manually manipulate the fuel between runs without exceeding our personal limits on radiation exposure. There occurred an early snowstorm that year which convinced the administrators to shutdown the operation for the year.

The technical results of that interesting summer are reasonably well documented in publications written at the time. The Borax experiment had been intended to be completed within the summer. The results attracted so much interest that, without doubt, the tests would continue the following year, but winter experiments were out of the question. There was no building over the reactor and all the water lines were exposed to freezing weather. The winter was used to upgrade much of the reactor support equipment. The control rod drives were replaced with a completely new set of drives designed in Idaho. The control console in the control trailer was totally rebuilt. A new reactor tank rated for 600 lbs/sq. inch was placed on order but would not be available until Borax III.

The First Borax Modified and Became Borax II

By spring, the radioactivity of the reactor had decayed sufficiently that we could again manipulate fuel manually. By early summer of 1954, the upgraded reactor designated Borax II was ready for a new series of interesting experiments, culminating in a final test to the destruction of the reactor. These tests were conducted with the reactor tank lid removed. The new control rod drives provided much more convenient control, and were capable of introducing sudden changes in the power level to better test the limits of the boiling stability. A series of tests were undertaken in which larger amounts of reactivity was suddenly injected into the reactor. These resulted in power surges that expelled water from the reactor tank. As the tests became more and more severe, the water was expelled with such force that the tests began to look like the eruption of the Old Faithful geyser in Yellowstone Park. These eruptions could be seen from Highway 26, more than a mile away. Since there was no building over the reactor, the water eruption seen from the highway appeared to be coming up out of the ground. On at least one occasion there was a telephone call from an excited passing tourist, who described seeing a large jet of water erupting up out of the ground. The tourist was positive about what had been seen but wasn't at all sure that anyone would believe his story. Spontaneous water jets shooting up out of the desert floor are rare!

These eruptions were recorded on motion picture film and presented at several technical meetings, where they attracted great interest. They were destined to become part of the presentation at the International Conference in Geneva in 1955. They probably still exist, perhaps lost in some forgotten Department of Energy storage file.



Water Erupting from the Borax II Reactor

Some of the transient tests were sufficiently violent to cause the outside fuel plate of some of the fuel subassemblies to buckle outward. The MTR fuel subassemblies were designed with an array of the concave-shaped fuel plates mounted within the three walls of the subassembly. There was no outer fourth wall in the subassembly structure, which made the outer plate open to direct view. The power transients caused a pressure wave to pass through the reactor core. The pressure gradient across the outer fuel plate sometimes caused the normally-inward bow of the plate to reverse and to become permanently bent outward. This distortion of the outer fuel plate usually took place near the control rods and sometimes actually interfered with the control rod movement. During emergency shutdowns, it is important that the control rods can fall, or be driven into the reactor very rapidly, in less than a tenth of a second.

It was customary to check the free movement of the control rods just before the reactor was to be operated at power. There was a control rod timer to measure the drop time. Whenever the drop time was found to be slow, it was necessary to correct the problem before further operation. The most common cause of slow control rod insertion was the buckling of the fuel plates adjoining the control rods. When this happened, it was necessary to go down to the reactor and lift the offending fuel subassembly out of the reactor and bend the outer fuel plate back into shape.

Of course, the reactor was giving off radiation during these direct manipulations of fuel. The reactor was submerged under water, which provided some shielding from the direct rays from the reactor core. The space between the reactor tank and the shield tank was also filled with water to stop radiation from streaming out the sides of the reactor. It was still necessary to deal with the direct radiation coming from the fuel subassemblies when lifted up out of the reactor for repair. Our primary defense against the radiation was to work fast and keep our distance, as best we could, from the subassemblies while we were working on them.

There wasn't any real problem from radiation working over the top of the reactor because of the water shielding above the reactor core. We were free to grapple and move the fuel subassemblies under water. We used a long steel rod with a hook on the end for this purpose. When it was necessary to lift a subassembly clear out of the reactor up onto the deck, the radiation level would increase dramatically. We attempted to keep back at least a few feet from the subassembly during these manipulations, but the subassemblies weighed about 65 lbs. and it is difficult to hold an object that heavy very far away from you at the end of a long tool. We would quickly lay the subassembly out on the deck and then step back to view the needed repair. The normal repair usually was no more than to knock the first fuel plate back into its normal concave shape. In order to keep our distance for this operation we became skilled at using a wood two-by-four about ten feet long. We could stoop down and bring the two-by-four down with a bit of force to make contact with the entire length of the fuel plate at the same instant. The fuel plate usually snapped back into its proper concave shape. We could then replace the subassembly back into the reactor core and return to the control trailer.

These fuel manipulations usually took place after the reactor had been shutdown overnight, allowing the radiation to decay following operation. It was helpful that the fuel had been subjected to only limited periods of operation, otherwise the radiation would have been too high for these simple-minded methods. Even so, I do remember that when looking down into the reactor tank, that the fuel subassemblies sometimes gave off the well known, Cerenkov radiation glow, depending on how recent the last power operation had been completed. The glow was only observable while the subassemblies were under water.

The transient tests on Borax II were completed in early summer. They had provided insight on how a boiling reactor would behave in a runaway situation and established the upper limit of stable boiling operation. It had become evident that the upper stable power level could be increased if the fuel subassemblies were modified to include an extension on the top, to act like a chimney, to enhance the convective coolant flow. A modified version of the MTR fuel subassembly was developed, which included chimney extensions. All reasonable tests that could be conducted on that first reactor core were soon completed. The new reactor tank, rated for 600 lb. operation, had arrived on site before the transient tests were completed. The one transient experiment left to be conducted on that first Borax reactor was the test to destruction.

Plans for the Destructive Test of Borax II

Preparations to test Borax II to destruction required modification of the center control rod drive so that a large amount of reactivity (2.6% delta K over K) could be injected into the reactor as fast as possible. I designed the trigger mechanism to fire the control rod down out of the reactor. The trigger mechanism was a strong electrically-powered magnet with a 900 lb. spring pushing against it. When the magnet power was released, the control rod was fired out of the reactor with the accelerating force of gravity plus the 900 lbs. The reactivity of the control rod was technically much more than enough to drive the reactor into the operating area called "prompt critical." Nuclear reactors are designed to operate in the region well below prompt critical where the power level is controlled by the "delayed neutron fraction." In this range, the reactor power is easily controlled because changes in power occur slowly, but when the excess reactivity exceeds about .7%, the power level enters the area of prompt critical where the rate of power increase becomes extremely fast, as dictated by the "prompt neutrons."

Commercial reactors are carefully designed to avoid any possibility of operating in the prompt critical range. In the Borax reactor, it had been proven that sudden additions of reactivity were substantially neutralized by the displacement of water from the reactor core, due to the boiling action. It was known that the pressure generated in the reactor by the sudden addition of reactivity would quickly expel most of the water from the reactor. The outcome of the test would depend on the comparative speed at which the reactivity was added versus how fast the reactivity was neutralized by the expulsion of water and other effects. It was assumed that the reactor core would be damaged by the experiment. The extent of the damage simply was not known. The results of the test would indicate the extent to which a boiling water reactor would be inherently self-regulating. It was expected that, following the test, the reactor would be rebuilt, using the new 600 lb. reactor tank and the new fuel subassemblies with the chimney extensions.

No one actually knew exactly what to expect from the test. I believe that most of our people expected modest damage to the reactor core. Most of the preparations were based on that assumption. The attachments of the control rod drive assembly to the shield tank were reinforced to keep the control rod drives from being lifted from their mountings by the expelled water. The mechanisms were checked over carefully to verify that they were working properly. A high-speed multi-channel photographic oscilloscope was installed in the power trailer near the reactor to record the details of the event. A high-speed motion picture camera (at 1200 frames per second) and several still-cameras were placed around the reactor to visually record the event. The cameras and recorders were remotely controlled from the control trailer a half mile from the reactor. Local weather men were consulted to obtain weather forecasts to select the best time for the test. The most desirable weather would be a slight breeze from the north so that if a radioactive cloud developed, it would flow in the direction where there were no inhabitants for several miles. A north wind is counter to prevailing conditions, but it was learned that early in the summer mornings there is often a brief period when there is a breeze from the north.

It was expected that the power level instruments would be unable to accurately record the peak power level. This problem was to be overcome by placing an array of thin gold foils at various locations in the reactor core. These foils were about one centimeter square, attached to the outside of the fuel subassemblies. They were embossed with numbers to record their placement location in the reactor.

The Atomic Energy Commission was notified about the test, but no invitations were extended to any of the commission officials in the local Idaho Operations Office. At that time, the Idaho activities of Argonne National Laboratory were under the jurisdiction of the Chicago Operations Office of the Atomic Energy Commission and the Idaho Office had no say in what we did at Borax. Furthermore, I believe, at the time, the Argonne officials felt that their wisdom was superior to anything the commission could offer. There was some justification for this attitude. The Atomic Energy Commission was still a rather new agency, with a staff that had very little experience in the reactor field. Our director, Dr. Zinn, had been instrumental in establishing the commission. I believe that he felt that taking direction from the commission was the equivalent of taking orders from one's child. I remember one special "guest" that was present for the test. It was Rodger McCullough who, at that time, was the chairman of the National Advisory Committee on Reactor Safety (ACRS). I believe this committee still exists today. Rodger was an executive in the Monsanto Co. at that time.

The Final Destructive Test of Borax II

The day of the test was a day to be remembered for me. On that day, I received the highest radiation exposure of my career. A few of us got up early, before daylight, to go out to the site to prepare for the big event. At about 4:00 AM in the morning, I joined three or four other people, who rode out to the site in a car driven by Harold Lichtenburger. Dr. Zinn was one of the passengers. Other members of the Borax crew followed later. We planned to check things out and be ready for the big test by about 7:00 AM. A short, low power transient test run was made to verify that the equipment was all functional, followed by an inspection of the control rods to verify that all was ready. The test run was successful without complication. Unfortunately, when we went down to the reactor to check the control rods, we learned that a fuel plate, in at least one subassembly, had bowed out so that it was rubbing against the control rod.

This had become a rather common problem. There had been so many tests that subjected the outer fuel plates of the subassemblies near the control rods to pressure transients, that it took less and less pressure to cause them to pop outward toward the control rods. We had become rather proficient at removing the offending subassembly from the reactor and knocking the offending fuel plate back in place. This was usually done after some time delay following the last power operation of the reactor so that the radiation level had time to diminish. But this morning was not a good time to announce a delay. Guests had arrived to watch the test and the wind was coming from the preferred northerly direction. We knew that it would shortly change to the prevailing direction. I remember standing at the top of the reactor shield tank platform contemplating the problem. We were in communication with the control trailer by way of a sound powered phone. This was one of several times that Dr. Zinn showed his impatience. He was capable of making his wishes very well known. His message to us was made clear that we had better fix the problem and very soon.

Meanwhile, Dr. Zinn was embarrassed to keep his guests waiting for the big show. I had set up some smoke bombs on top of a tower near the reactor. These bombs were intended to be triggered electrically from the control trailer just before and after the test to indicate the direction and strength of the wind. While waiting for the test to begin, Dr. Zinn triggered one of the smoke bombs, perhaps to entertain his guests during the embarrassing wait. When the test continued to be delayed, he proceeded to trigger another smoke bomb. Unfortunately, the bomb failed to respond to the electrical control. The reason was partially my fault. Spare ½ mile long electrical conductors from the control trailer had become scarce, and I had used some compromise conductors that were too small to reliably trigger the smoke bombs. He let me know after the test that he didn't appreciate that the smoke bombs did not perform as expected.

Back at the reactor, I and two or three others, were considering our dilemma. Looking down into the reactor we could see that the fuel subassemblies were giving off an unmistakable Cerenkov glow. The pressure from Zinn to act was intense. It was clear that we would not have the luxury of waiting for the radiation level to die down. We felt that we had no choice. We lifted the offending fuel subassembly up out of the reactor, fixed it, and put it back in place. We vacated the reactor and joined a group of sundry other people that had assembled about the control trailer. Cameramen were there, standing by, ready to trigger the high-speed and still-cameras into action. Someone else was ready to start the high-speed oscillograph. If I remember correctly, the reactor was taken to a steady state low power level as the starting point for initiating the test. The test countdown started about an hour late.

The test was very dramatic, resulting in a genuine explosion that lifted the contents of the entire shield tank and scattered it in pieces over about an acre of the desert terrain. The control rod drive assembly went up into the sky as a unit until restrained by the numerous electrical cables connected to it. A mixture of water, smoke, steam and debris surged skyward. A loud impressive explosive report followed, delayed by the couple of seconds that it takes sound to travel the half mile to the control trailer. Pieces of semi-molten fuel rained down out of the sky. A small cloud did form that migrated slowly to the south. The event was much more violent than anticipated. There were a few of our people that suggested that the results were as they expected but I think that essentially, everyone was surprised at the violence of the event. I clearly remember Dr. Zinn looking pensively at the floor saying, "Well, we may never be famous but we sure as hell will be notorious."

The outcome of the event was made public, and it was by no means known in advance what spin the press releases would put on the event. We were pleased when the press releases described the event as being a very smart project. I remember that an article in "Time" magazine described the event in more than complementary terms. We were not offended when we were given more praise than we deserved. In later years we felt abused when the same publications described essentially the same team as being incompetent when referring to the partial meltdown of the EBR-I. I conclude from these observations that the reaction of the news media to such events is, at best, whimsical. I also conclude that the tone of the press releases is likely to follow whatever tone is established by the first one released.

Borax II Tested to Destruction

There was a construction crew working nearby on the new ZPR-III building, next to the EBR-I. When the test event was seen to be so severe the construction crew was evacuated just in case there could be an unseen health hazard. The Borax team remained around the control trailer discussing the event. I remember one visiting scientist checking his throat area with a Geiger counter to make sure that his thyroid had not somehow absorbed some radioactive iodine out of the air.

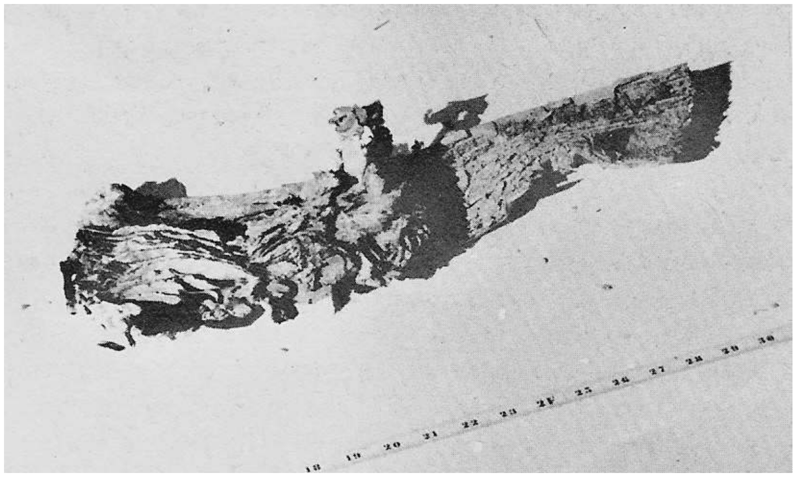
The camera crew had triggered their cameras as planned. However, the blast at the reactor had caused a failure of the electric power at the reactor site. It was known that the high-speed movie cameras had lost power before completely photographing the entire sequence. There was also a chance that the camera could have been damaged by losing power while the film was being fed through the camera at a terrific rate. There was a keen desire to go down to the reactor site and see things close up and retrieve the cameras before radiation caused the film to fog. Even more of a concern was the photographic film in the high-speed oscillograph. If the film was not retrieved soon, the best instrument record of the power transient would be lost. The radiation level would decrease exponentially during the early hours following the tests, but there was a real need to retrieve the film as soon as possible. The reactor was enclosed by a chain link fence. The gate into the reactor area was on the south side, which was in the path of the greatest amount of radioactive debris. If an early entry was to be attempted, it seemed best to enter from the north where the radiation would be least. Also, the power trailer, which housed the photographic oscillograph, was located on that side. An early survey was made from a four wheel drive pickup by making a wide circle through the sagebrush around the reactor site. It was concluded that an early entry could be undertaken by cutting through the fence on the north side to retrieve the film.

The volunteer for the task was Joe Harrer. He was dressed in protective clothing and driven down to the north fence armed with a bolt cutter to cut through the fence. It was assumed that he could quickly cut the fence to make a quick entry. As it turned out, a bolt cutter is not a very good tool for cutting chain link fencing. When he arrived at the fence, he started cutting through the fence from the bottom up. It took much more time than was expected and his allotted time was running out. He was exceeding the acceptable limit for personal exposure. In desperation he proceeded to enter as soon as he had cut enough strands to crawl through on his belly. He succeeded in his mission, but when he returned his clothes and chest were badly contaminated. I and one other person, Garth Stonehocker, were assigned to decontaminate him. We took him into the EBR-I facility where we proceeded to scrub him down. It wasn't until we had used some rather strong detergents that Joe tested clean.

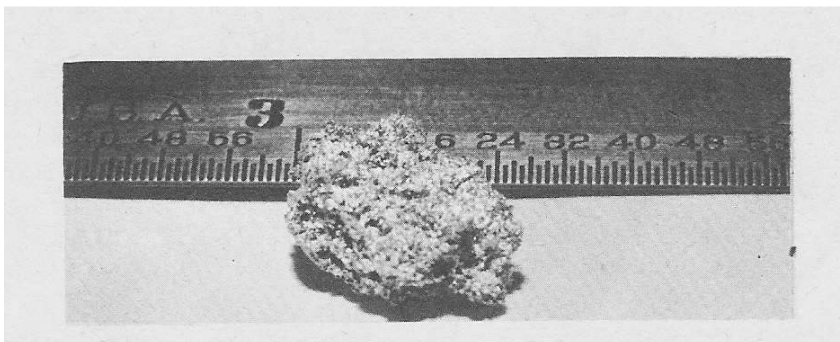
As the day progressed, several people were assigned the task of approaching the reactor site from different directions to survey the radiation levels and to provide first-hand damage reports. Before the day had passed, the radiation level decreased to a level where it became possible to briefly approach the mound of dirt surrounding the reactor shield tank. These assignments were passed around so that no one received an unacceptable amount of radiation exposure. An outdoor dressing station was established to dress everyone in protective clothing. I became involved in dressing and removing the protective clothing from those entering the radiation area and checking them for contamination. The standard clothing included a double pair of coveralls, gloves, head cover and double layers of shoe covers. The neck, sleeves and pant legs were secured with masking tape so that no clothing could flap open and no flesh could be exposed. Breathing masks with filters were used to avoid inhaling contaminated air.

Since I had received considerable radiation exposure in the morning prior to the test, I was not recruited, at first, to participate in the surveys being made about the reactor. But as the day went on, most of the Borax team had participated and had received considerable radiation exposure. Probably everyone had exceeded the normal 300 millirem weekly limit of radiation exposure and were knowingly exceeding it. The attitude at that moment was that this was a special occasion when the normal limit on radiation exposure could be, justifiably, exceeded. Toward the end of the day, when almost everyone else was "burned out", I was recruited to dress up and participate. I really wanted to go down to the reactor and see first-hand for myself what had really happened. Most of those who made these short visits to the reactor had been given a specific instruction to check on some particular item and report back. My assignment was different. I was to act as guide for Rodger McCullough, the visiting ACRS committee chairman. We were both dressed up carefully and I was given a hand held “Juno” radiation survey meter.

Upon arriving at the reactor mound, I noticed numerous pieces of reactor fuel scattered about the ground. It was relatively easy to identify scraps of fuel by color (aluminum color), evidence of the multilayered fuel plates, the slotted side plates of the subassembly and the response to our radiation meter. The fuel scraps showed signs of having been partially melted and solidifying in slag like chunks. The chunks had sharp, rough edges like volcanic clinkers. The smaller pieces tended to stick to the bottom of our shoe covers and follow with us. Rodger was slow to realize that we were indeed looking at reactor fuel but when he did, he became quite excited. He assumed that any reactor fuel would be extremely radioactive and shouted to me through his mask that my survey meter was surely not reading correctly. The meter did verify that it was fuel, but the radiation level was well within the range of the meter. What he did not understand was that the fuel from the reactor had not been subjected to long periods of high-power operation and therefore was not as radioactive as he had expected.



Fuel Subassembly Side Plate Fragment



Aluminum-Uranium clinker
Uranium fuel pieces expelled from the reactor

It was difficult to speak to him through my mask. It would take too much time to explain to him why the presence of fuel did not merit instant retreat. I think I tried to convince him that it wasn't really fuel. We walked a circle around the reactor mound. I saw numerous pieces of the reactor tank scattered randomly around the mound. The control rod drive assembly, which had taken flight up into the sky, was lying on its side on the north side of the reactor mound. Continuing around to the west side, we were able to look into the pump pit which I observed was flooded with several feet of water. There was a lot of pumice floating on top of the water which made the water look almost like it was a dry surface. The equipment above the water level was covered in a layer of pumice so that it was difficult to see the extent of damage. The pumice had come from the cinder block wall that separated the shield tank from the pump pit. The blast had pulverized a part of the wall. We had been instructed to not ascend the mound where we could have looked into the void where the reactor had been.

When I returned from this visit to the reactor, I checked my personal radiation meter and noted that through the day I had received 15 R. (roentgens) of radiation exposure. I recorded it on the personal radiation log along with many others who indicated similar exposures on that day. It should be noted that the "R" unit of radiation was used at that time to indicate radiation exposure. It was about that time that the standard procedure for radiation exposure was reduced to limit ourselves to no more than .3R (300 mr) per week. The unit of radiation exposure was later changed to the "Rem" which is roughly equivalent to the "R". Recommended limits on radiation exposure have been further reduced since our time.

Borax III Almost a Totally New Reactor

The Borax test to destruction created great interest in the atomic energy community. High level discussions took place outside my field of observation. The conclusions were that Borax had proven that the boiling water reactor concept was viable and could be developed into a workable power reactor. It was also concluded that the exact process of how the boiling process was coupled to the nuclear reaction was not precisely known. It also followed that there would be economic support for further tests and research to be directed in two different directions. One would pursue the development of the boiling reactor toward a viable power plant. The other would pursue basic research in the reactor kinetics relative to the interrelationships between the boiling and nuclear reactions. Argonne National Lab was given the choice to pursue either or perhaps both directions. Dr. Zinn was definitely interested in pursuing the power option. I believe that he declined pursuing the second direction. The second direction gave birth to the SPERT series of reactor experiments that was undertaken under contract to the Phillips Corp. It seemed sensible for Argonne to continue in the direction of developing a power plant. The 600 lb. rated pressure vessel had already arrived at the site and a new fuel subassembly design had been developed that would enhance the power production. On the other hand, the research on the reactor kinetics would require a whole new facility.

Our activities were soon directed toward building Borax III, the reactor that supplied the first atomic power, to light a town. At that time, we had no premonition of what we would be doing less than a year later. But first we had to clean up the mess left behind by the last experiment on Borax II. The first thing was to reduce the radioactivity in the area by gathering up all the small pieces of fuel laying about the area. We used almost everyone available for the task so that no one received excessive radiation exposure. We used tongs with hand operated fingers to gather the fuel pieces and other small debris. As each one approached their exposure limit for the week, they were assigned other tasks such as to help the workers into and out of their protective clothing and handle the vast contaminated laundry.

There was still one important piece of information to be obtained from the old reactor. As was mentioned earlier, there were a large number of gold foils placed in the reactor prior to the test. These foils become activated in the presence of neutron radiation. After being radiated, they give off gamma radiation that slowly decays back to background level. If these foils could be found soon enough, they would provide valuable information on the total energy released by the reactor test. To be effective, these foils had to be found before they decayed to a level too low to measure. There was no hope that all of the foils could be found. But the reactor event could be substantially documented, if a portion of the foils could be found. Every piece of fuel found was inspected in search of the foils. I do not remember if there were any foils found in the fuel pieces lying out on the ground. Later, the search was extended into the reactor shield tank where a sufficient number of foils were ultimately found. The foils, in conjunction with information from other instruments, revealed that the energy released from the event had been about 135 megawatt seconds and that the central control rod had not completely exited from the reactor before the event had effectively ended.

Our work continued into the hot summer-time weather. Working with face masks and protective clothing doubled the discomfort. I volunteered for the most radioactive work. This way I would arrive early at the limit on radiation exposure and soon be relieved from wearing the protective clothing. We recovered as much of the reactor machinery as possible. This included the control rod drives and some of the pump equipment. We disassembled each piece of equipment and soaked it in a strong detergent. The process was surprisingly effective. We found that some of the electrical equipment, like the selsyn motors, could be successfully soaked in vercene detergent without need of disassembly. After washing, heat drying and re-lubricating, almost all the control rod equipment was used again in the Borax III reactor.

The search for gold foils following the test was intensive. The obvious place to look for foils was in the shield tank. The reactor tank had been effectively blown to pieces and propelled out of the shield tank, leaving the shield tank essentially empty of the original reactor hardware. However, many small pieces of hardware and fuel remained in the shield tank below the surface of a few feet of dirty water. The water provided some shielding from the radiation streaming from residual debris in the shield tank, so that we could climb the reactor mound and look directly into the shield tank where the reactor had been previous to the test. The shield tank was mostly intact except that a large hole had been blasted through the side of the tank into the pump pit. There were other smaller holes through the side walls of the tank, made by flying projectiles. Some backfill dirt had dribbled back into the tank through these holes.

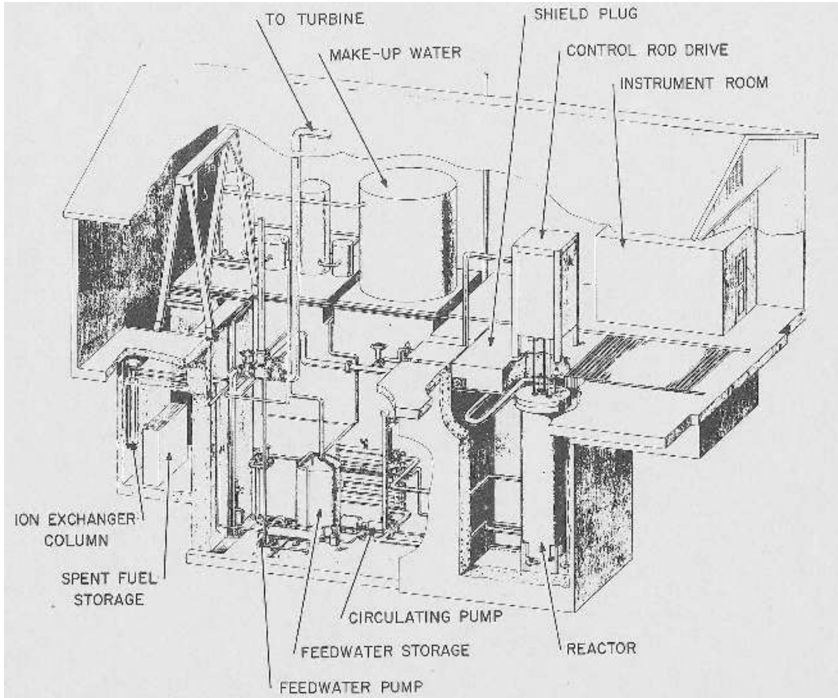
A ladder was lowered into the tank and the water level adjusted so that it was shallow enough to stand in with boots on, but deep enough to provide shielding from most of the radiation. Volunteers were recruited to descend into the tank to sift through and remove the debris and search for foils. I was one of the volunteers, but not the first. I was dressed with the usual protective clothing but with high rubber boots to wade about in the water. I took a short-handled shovel with me and a Juno radiation meter. I suspended the Juno meter on the end of a wire connected to the top of the tank. Earlier volunteers had removed all the larger pieces. Among these pieces was a dish shaped plate that had been the bottom of the reactor tank.

I was instructed to sift through the sludge in the bottom of the tank where I would be able to detect when my shovel made contact with any solid object. I was instructed to maneuver the objects one at a time to the surface where I could observe it carefully. I was to look carefully for foils adhering to the objects, and if the objects had no further interest to toss them through the hole blasted through the side of the tank into the pump pit. The pump pit also had several feet of water so that it provided effective shielding from the radioactive garbage that we threw into it. As I stepped off the ladder into the water, I detected that there were several inches of mud sludge on the bottom below the water surface. Upon locating an object, I could maneuver it without bringing it above the water surface to a location directly below the radiation meter. Then I could slowly lift it to break through the water surface. As it was brought to the surface, the radiation meter would indicate high if it was fuel. Even if fuel, the radiation level was never so excessive to prevent bringing the object to the surface, inspect it for foils and after inspection throw it through the hole into the pump pit. While the water provided shielding from the radiation, my feet were below the water level. I wondered how much radiation my feet were receiving. As this procedure continued, the general level of radiation inside the shield tank diminished so that the water level could be lowered and finally only mud remained. The mud was then very carefully sifted for gold foils. Eventually enough foils were found to establish what the total energy and power distribution was for the test.

Work on Borax III began almost immediately after the Borax II destructive test. Arrangements were made with the Morrison Knudsen Construction Company to start construction on the new reactor site about 100 yards to the north of the old site. The arrangement was a “cost plus” contract which meant that there was no delay in starting. The new reactor pressure vessel was placed below ground level in a concrete cell within a sheet metal building.

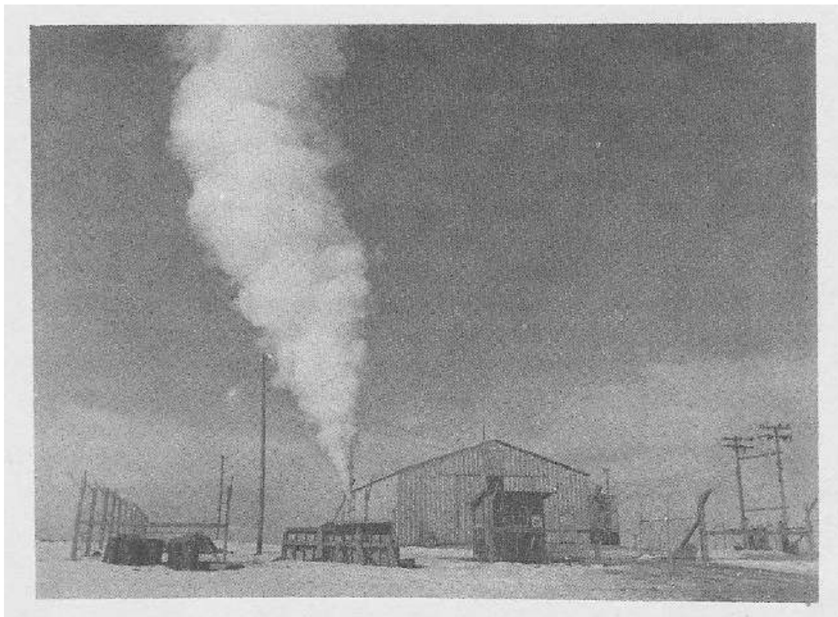
The location of the new site was selected by rotating the half-mile long control and power cables on an arc, with the control trailer as the center. A new water line was installed underground so that the facility could continue operation during winter months. The new facility also included water purification equipment.

The cleanup at the old site continued. As the fuel and other debris were removed, the level of radiation diminished. It finally became a matter of how thorough the cleanup should be. The cleanup activity continued until the remaining debris was too small to be identified and picked up. A layer of gravel was then spread over the area and a sprinkler system installed to keep the entire area wet. I can’t remember exactly what became of the pump pit. We used it for a garbage dump for both radioactive and non-radioactive junk. It may still be there, buried as we left it. The control rod drives and many other items were recovered, cleaned, refurbished and reinstalled in the Borax III facility.



The Borax III Reactor Building

The new facility was designed for power tests within the closed pressurized reactor. There was a pressure-regulating valve on the discharge pipe from the reactor vessel. The new fuel had chimneys to enhance the natural circulation through the reactor core. The installation was completed very rapidly. I don't remember just when Borax III was first made "critical" and placed in power operation. It was probably late in the summer of 1954. I don't remember any special problems during this period. I do remember that the reactor was successfully operated under about 300 lbs. of pressure at about 6 megawatts of power. The steam from the reactor was discharged to the atmosphere from a pipe that came out of the reactor building .The steam was slightly radioactive. The radioactivity was dominated by radioactive nitrogen having a half-life of a few seconds. We were able to verify the half life and velocity of the steam by holding a radiation meter close to the discharge steam line at various locations. The purity of the reactor water was more significant in the power experiments. Poor water purity would cause radioactive carryover in the steam. The PH of the water was also important to limit chemical erosion of the fuel cladding. I do not remember any transient power tests being conducted on the Borax III reactor.



Borax III in operation before the electrical system was added

Plans Made to Light Arco

Some political developments in the fall of 1954 led to our project to supply "atomic" power to the town of Arco from the Borax reactor. Following World War II, the Americans had the atomic bomb. Not many years passed until the Russians, French and British also had the bomb. It was generally accepted that the Americans were way ahead of the rest of the world in the total technology of atomic energy. The international community began a series of annual conferences on the peaceful uses of atomic energy. These conferences were held each summer in Geneva, Switzerland. The policy of the Americans, because of secrecy, was to attend but not participate in these conferences. These conferences did not command attention at my level until the fall of 1954 when the Russians announced that they would be making a presentation on their new 5-megawatt prototype power plant designed to provide electrical power for civilian consumption.

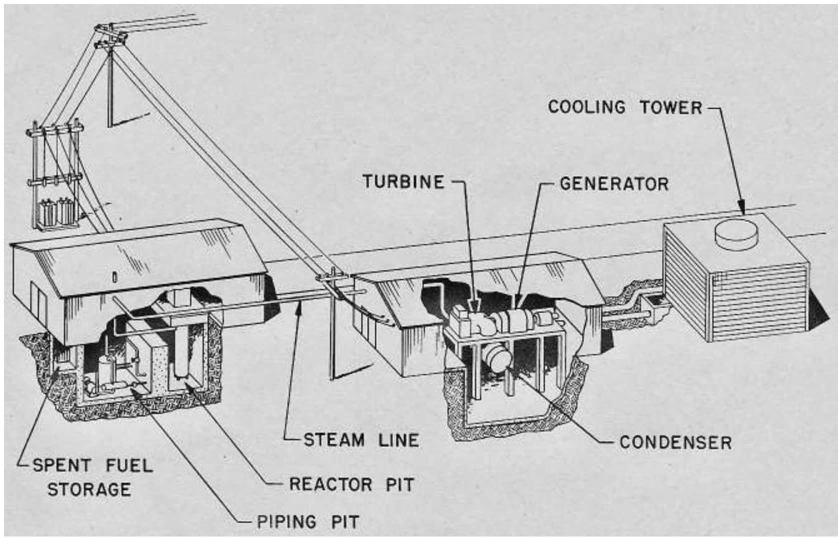
The whole world knew that the Americans were developing nuclear power plants for submarines, but there was little known about any activity to develop any civilian nuclear power plants. There was an electrical power plant being constructed at Shipping Port, Pennsylvania at that time, but it was a copy of a power plant designed for a nuclear submarine. The political implication was that the Russians would be able to point to their activity as proof that their efforts were directed to peaceful uses of atomic energy, while the Americans were directing their efforts totally to military applications.

Borax was producing steam that could be used to produce electricity. It was a new and very different type of reactor. It did not have a military application. Presentation of the pictures of the destructive tests of Borax would no doubt attract great interest. The only problem was that Borax did not have a connected electrical generator. There remained time before the conference to connect a turbo-generator if we worked really fast. However, it would require a special kind of turbine. Steam from Borax was saturated (wet) with no superheat. Modern turbines are designed to operate on superheated steam. New turbines must be ordered many months in advance, and ordering a wet steam turbine in this age would be very unusual. What was really needed was a steam turbine more like the type that was being manufactured 25 or 50 years before. The decision to go ahead with the project was made outside my field of vision, but we soon received word that the project was on with a very high priority.

Morrison Knudsen was again contracted, on a cost plus basis, to make the additions to the plant to convert it into a functioning power plant. I believe that it was someone in the Morrison Knudsen Co. that found the answer to the turbo-generator problem. They found an old retired Westinghouse 3.75 megawatt turbo-generator combination at a mill pond near Albuquerque, New Mexico. It had been manufactured in 1925. It was designed to operate on 300 lb steam (maybe it was 400 lb steam, I am not sure) and 75 degrees of superheat. The generator was designed to operate at 2300 volts. It was close enough to the Borax specifications to be useful. The unit was quickly purchased and shipped to Idaho along with its original turbine oil pump, exciter, switchgear and instrumentation. It arrived in Idaho without any manufacturer's information. The instrumentation was rudely handled in shipment. It ultimately became our job to make all this equipment work.

The power-generating plant, excluding the reactor was quickly designed and constructed by Morrison Knudsen. It included installation of the turbo-generator, the building housing the turbo-generator and switchgear, a cooling tower and an artificial load dissipater. Morrison Knudsen rebalanced the turbine and refurbished the exciter before installation. The turbine was a three bearing unit which was difficult to align. The Morrison Knudsen people seemed very capable and knowledgeable but when it came time to operate this equipment, we were on our own.

The instrumentation was very old and different than the equipment we were familiar with. The tachometer on the turbine was a vibrating-reed type. A series of tuned reeds were located within a small window with only the end of each reed visible. Each successive reed was tuned to a slightly higher frequency. The middle reed was tuned for the frequency matching the operating speed of the turbine. We expected to see this middle reed vibrating when the turbine was at rated speed. There was no other indicator to monitor turbine speed. The main power circuit breaker had a novel method for extinguishing the arc. There was a pressure tube connected to a high pressure bottle of nitrogen. When the breaker tripped to open, a jet of gas was fired up through the breaker contacts to extinguish the arc. It worked very well except the triggering of the gas jet made a noise similar to a shotgun blast. I was never able to avoid jumping when the breaker tripped, even if I knew when it was about to happen.



The Completed Borax III Power Plant

All of us had had experience operating the 250 KW generator connected to the EBR-I reactor. We were about to start up the Borax turbo-generator that was more than ten times larger than the EBR-I turbo-generator. Our prime concern was with the speed governor on the turbine. There was a three-stage governor on the front of the turbine, but there was no way to test it prior to real operation. We had no experience with a turbine of this type. We did not know what normal operation sounded like. We did know that a runaway turbine is a serious matter. When the time came to start the turbine, Mike Novick, our lead mechanical engineer, cracked open the inlet valve to the turbine and the turbine began to roll. We immediately noted that the background noise became very loud. We were scarcely able to converse above the noise. We had no idea if the noise was normal. We knew that proper startup should be done very slowly to permit temperatures to equalize. The turbine had so much momentum that it was difficult to correlate valve adjustments with the turbine response.

After adequate warm up time, more steam was admitted to the turbine. It was observed that the turbine failed to accelerate to full rpm. The problem was traced to an open valve on the bearing gland seal. When the valve was closed, the turbine began to accelerate. Then we began to worry about the possibility of over-speeding the turbine. We watched the vibrating reed tachometer intently. We observed the under-speed reeds start to vibrate and then the pattern of vibration move up through the range of reeds. We wondered if this was confirmation that the speed governor was not functional and that the turbine was beginning to over-speed. When Mike was about to push the trip button, we noted that the under speed reeds were beginning to vibrate again. What we didn't know was that the vibrating reeds were simply reacting to sub-frequency harmonics. Again the pattern of vibration moved up through the total range of the reeds, and then the under-speed reed also began to vibrate again. Mike again refrained from tripping the trip button. Finally, we observed the linkage on the speed regulators begin to move to restrict the flow of inlet steam. Gently, the speed regulator took over and regulated the speed to the exact correct speed with the proper vibrating reed indicating confirmation. It worked beautifully. We had worried for no reason.

The next step was to energize the generator. This was expected to occur as soon as we connected the exciter to the generator field. We made the connection but nothing happened. We checked the output terminals of the exciter and found that there was no voltage. The probable cause was that the output connections from the exciter were reversed. During the installation, there was no way to know which connection combination was correct. There was a fifty percent chance of getting it right. Normal output voltage from the exciter was 165 volts dc. The steam to the turbine was closed while we contemplated what to do. The turbine continued rolling and would continue to coast for at least an hour. There was some risk in working on the exciter connections while the turbine was still rotating because the exciter voltage could suddenly build up at any time. If we waited for the turbine to coast down, then a lot of time would be wasted. There was some pressure to correct the problem as soon as possible.

I volunteered to work the problem. I opened the terminal box on the exciter and removed the insulation tape from the two electrical cables. I was cautious to avoid being vulnerable if the voltage should suddenly build up. With tape and connector clamps removed, four bare cable stubs were exposed ready for reconnection. The first reconnection was made without problem. When I touched the remaining cables together, the voltage did build up. It was then necessary to clamp the last connection on a hot connection. The task was completed successfully. Steam was readmitted to the turbine and we were generating the first electricity ever from a boiling water reactor. We proceeded to check out the remaining switchgear and instrumentation. We soon connected the generator to the artificial load to observe the system performance under load. The artificial load was constructed with three parallel vertical steel plates mounted on insulators and submerged in a water bath with about three inches of separation. The load was adjusted by controlling the water level. As the water level was raised, more of each plate was submerged in water. The energy was dissipated by boiling the water between the plates. At night, it gave off a spectacular glow. It worked beautifully. We now had a working system and were ready to start working the problems to supply power to Arco.

Problems

There were several problems to be overcome before we could make the connection to Arco. The incoming power line to the Borax site had limited capacity. It operated at 12,000 volts while the Borax generator put out 2,300 volts. It was difficult to make these two systems compatible. Another very significant problem was in the reactor itself. It had become evident that a boiling water reactor requires considerably more reactivity control than does a typical non-boiling water moderated reactor. This is because some of the moderating effects of the water flowing through the reactor is displaced by the bubbles of the boiling water. This would be overcome in later reactors by designing a wider range of reactivity control into the control rods and loading more fuel into the reactor. It was too late to make such a major change in the Borax reactor design. It took some complicated trickery to overcome the problem in time for the Arco project.

It requires some technical explanation to understand the full implications of the reactivity control problem. A typical reactor is loaded with enough fuel so that reactor can achieve full power by withdrawing the control rods to some intermediate position. The control rods are made of materials that absorb neutrons. These materials are characteristically called neutron poisons. During the fuel loading process, the reactor is maintained in a shutdown condition by virtue of the control rods being maintained in position inside the reactor. The amount of fuel loaded into the reactor must always be restricted to less than the amount that would cause the reactor to start a chain reaction in spite of the presence of the control rods. On the other hand, the reactor must be loaded with enough fuel to overcome the negative reactivity effects of temperature and xenon while operating at power. As the reactor core heats up to produce power, it expands just enough to allow some neutrons to escape from the reactor. The xenon is a byproduct of the reactor itself which inhibits the chain reaction by absorbing neutrons. The control rods must have sufficient range of nuclear control to permit the reactor to go to full power, while retaining enough shutdown capacity to safely shut down the reactor under all conditions.

Xenon is a neutron poison that is generated by a rather complicated natural process within the reactor itself. When a reactor is operated at power, it generates a series of byproducts that over a period of time includes the radioactive product called xenon-135. It is a strong absorber of neutrons which tends to shut down a power reactor. The amount of xenon poisoning depends on the recent operating history of the reactor. This problem would normally be overcome by loading enough fuel into the reactor to override the xenon effect. But, the control rods must have enough range to overcome the increased fuel load when there is no xenon in the reactor. Xenon-135 is one of several decaying isotopes generated by the reactor, but while the reactor generates xenon as a byproduct of operation, the neutrons being generated by the reactor are also consuming some of the xenon. The reactor is therefore both producing and depleting the xenon whenever the reactor is operating at power.

The xenon slowly builds up as the reactor operates at power until it comes to equilibrium when the rate of generation becomes equal to the burnout rate by neutron absorption and decay. Then following reactor shutdown, the amount of xenon in the reactor continues to grow for several hours (about 10 hours), after which it reverses and decays with a half-life of about 9 hours, until it finally disappears completely. The xenon effect is a complex phenomena that all operators of water-cooled reactors are trained to thoroughly understand and deal with. It came into play in a dramatic way in the Arco project.

The Borax reactor had all the reactivity control requirements of a typical water-cooled reactor plus the negative reactivity effect of the bubbles in the reactor core caused by the boiling action. The net effect was that for sustained power operation, the Borax reactor needed to be loaded with extra fuel beyond the range of its control rods! Our project physicists came up with a solution for this problem that did not require rebuilding the reactor. Here is how it would be done: First, the water in the reactor would be salted with boric acid. Boric acid is a strong neutron poison. With the addition of the boric acid, we could deliberately add additional uranium fuel to the reactor above what would be safe if the boric acid had not been added. The quantity of boric acid would be adjusted along with the extra fuel loading so that the reactor could be started up and temporarily raised to full power. After a few hours of operation with the boric acid still in the circulating water, the effects of the xenon would begin to appear, and even with the control rods fully withdrawn, the power level would begin to diminish. At this point the water purification system would be turned on and the boric acid removed from the system while the reactor continued at full power. The reactor would then be at full power and available for an indefinite period for the production of electricity.

If there should come a need for reactor shutdown, the control rods would be adequate to shutdown the reactor so long as the xenon remained in the reactor. However, the xenon would remain in the reactor for only a certain number of hours. It would then be necessary to re-introduce the boric acid back into the circulation system before the xenon decayed out of the reactor core. Otherwise, the reactor would eventually start back up by itself! The plan was perfectly valid, but overlooked the fact that it required reliable pump power to re-inject the boric acid back into the system. It was almost unthinkable that we could lose pump power during the project to light Arco, but that is exactly what happened.

Meanwhile, the electrical system connections necessary to supply power to Arco also had severe problems. The transmission line that supplied power to the Borax site was a 12,000 volt line that brought power from the Central Facilities substation 2 ½ miles away. In addition to Borax, it supplied power to the EBR-I reactor complex, the new ZPPR-III building, and a local deep well pump that supplied water to all three facilities. The deep well pump was located about 100 meters from the Borax control trailer. The well pump electrical system had its own step-down transformer that converted the 12,000 high-line voltage to the 2300 volts actually used by the pump motor.

At the Borax reactor site there was a 37.5 KVA transformer that converted the 12,000 high-line voltage to 480 volts. Most of the support equipment at the reactor site operated at 480 volts. There was also a local supply transformer that converted the 480 volts to the standard 120/220 volts for instruments and miscellaneous items. The Borax turbo-generator output voltage was 230 volts. The obvious preferred arrangement to make an output connection to the incoming transmission line from the Borax generator would be to install a transformer that would convert the 2300 volts output of the Borax generator to the existing 12,000 high-line voltage. I don't know who attempted to locate such a transformer but it was reported back to us that no such transformer existed west of the Mississippi River.

There was an engineer on the Atomic Energy Commission staff at that time, whose office was in Idaho Falls. He gave directions as to how the connection was to be made. I don't remember his name. I never met him or talked to him. His very complicated plan called for making use of a local transformer at the Borax generator to step the 2300 volt output of the generator down to 480 volts. We were to start up the reactor system to full power, synchronize the Borax generator to the incoming line through the 480 volt transformer, then de-energize and isolate the 12,000 volt transmission line that normally served the Borax site, the EBR-I site, the ZPR-III site and the well. We were then to re-establish the entire transmission line from Borax to Central Facilities as a 2300 volt line, reconnect the Borax generator to the high line directly, then reconnect the well pump, bypassing its normal step-down transformer, directly to the high line, and leave the EBR-I complex and ZPR-III without power for the duration of the Arco connection.

This plan called for slugging (bypassing) all high line fuses from Borax to Central Facilities. It also called for a temporary substation to be set up at Central Facilities to convert the 2300 volt line from Borax to the voltage of the transmission line to Arco. This required the cooperation of the Utah Power and Light Company (UP&L) who owned the transmission line to Arco. UP&L was very cooperative and volunteered to bring in a trailer-mounted mobile substation and a man to operate it at Central Facilities. The plan required that we would have to synchronize and connect the Borax generator to the power grid through the rather weak 480 volt link, then disconnect the incoming line, leaving the Borax reactor standing alone supplying its own power while the transmission line to Central Facilities was being converted to 2300 volt operation. The 2300 volt transmission line then would be connected back to the Borax generator but would still be independent from the utility power grid. At that point, the UP&L operator, at the temporary substation at Central Facilities, would have to re-synchronize and reconnect the 2300 volt line back to the utility grid. He would have to do this without benefit of any control over turbine speed or generator voltage. His only method for making the needed adjustments would be by instructing me, 2 ½ miles away, stationed at the Borax generator control panel, by mobile radio. Finally, if all this was successful, he would disconnect the normal power source to Arco. At that point, the Borax nuclear reactor would be supplying all of the power to Arco. When it came time to disconnect the reactor from the Arco connection, all these actions would have to be performed in reverse.

The plan seemed <u>unworkable</u> to me and I voiced strong opinions to that effect. At that time, another electrical engineer, Bob Wallin, had joined our team. Bob agreed with me that the plan seemed unworkable. We pointed out that to provide power to Arco, we would have to also provide power to the Central Facilities. That by itself would not be a serious problem if it were not for the fact that the transmission line voltage was being reduced by more than a factor of 5. This would increase the line loss by the square of the factor (more than 25 times!). I estimated that the line loss would be in the order of 16 watts per foot of transmission line! I felt that the facts were so persuasive that our opinion would prevail without need of argumentation. I was wrong. I was informed that the AEC had the decision making authority in this matter and that they had instructed us to proceed with the plan. I was placed in the uncomfortable position of having to implement a plan that I had predicted would fail. As it turned out, I was decisively right.

The Argonne crew was not equipped or authorized to work on the transmission lines. At that time, the prime Idaho contractor for operations at the reactor site was the Phillips Co. They had a well trained high line crew who would be loaned to us to make all the required transmission line changes. They were brought into the picture and instructed on what changes and sequence would be required but were never informed about the details of reactor operation. As the day approached for the connection to Arco, several more technical people arrived on the scene from Argonne, Chicago. There were also some technical people loaned to the project from the military and from interested private companies. There was a movie filming team from the Air Force who made supporting movies. I remember seeing one sequence taken in Arco, prior to our connection, which would provide background footage, showing Arco as a rather prosperous little American town. To enhance their picture, they set up a camera at one end of a street in Arco and rounded up all the kids they could find with bicycles. At the appointed moment, all the kids were instructed to ride down the street in front of the camera to show Arco as a pleasant little American town with a lot of happy kids.

I remember one Air Force Colonel with very impressive technical knowledge that was loaned to our team, Colonel Nate Krisberg. There was also a top-notch technical executive from Common Wealth Edison, Cliff Zitek and a Physicist from Pratt and Whitney, Bob Cote. Our directions continued to come from Dr. Walter Zinn and his right-hand man, Harold Lichtenburger, my boss. These two men were decisive leaders and were quick to give directions. The Chairman of the Atomic Energy Commission, Lewis Strauss, was invited to be present for the lighting of Arco, but he declined. For us, it was a good thing. With all the problems that we were about to encounter, his presence would have been an additional complication.

Beginning the Arco Connection

I remember the three days leading up to the lighting of Arco almost better than any other three days of my life. Even so, I may make some errors in the exact sequence of events. During those three days, I never left the project day or night. I did catch a few cat naps on the lawn behind the EBR-I building. The Phillips Petroleum high line crew was present for most of the time, and I believe the Utah Power substation operator also remained in the area the entire time. I talked to him by radio many times, but I never actually met him.

The high line crew slugged (bypassed) all the high line fuses between Borax and Central Facilities. This was necessary because the electrical current to be transmitted toward Arco would definitely exceed the fuse ratings. The reactor coolant water was "poisoned" with boric acid and the reactor was overloaded with fuel elements according to plan. The reactor was started up and taken to full power. The operations continued while the xenon level in the reactor core increased. The water purification system was turned on and the boric acid removed from the coolant water. The turbo-generator was started up and after the usual warm up period, energized to produce power. Everything to this point proceeded without problem.

The next step was to parallel the Borax generator with the Utah Power grid. The method for doing this was less than ideal using locally available "make do" equipment. The 2300 volt output of the Borax generator was stepped down through a transformer to 480 volts. The actual paralleling operation was to take place between the 480 volt output from the Borax generator and the 480 volt output of the Borax substation that normally supplied power to the Borax facility. A large, portable, open framed circuit breaker was used for making the connection between the two systems. Closing this breaker would connect the Borax generator to the power grid. It was a compromise arrangement because the 480 volt system was a weak connection with far less capacity than the generator rating. The old style Borax turbo generator had massive momentum compared to the weak 480 volt interconnection. To guarantee stability, the two systems needed to be able to rapidly exchange significant power between them to lock the two systems firmly together. One of the Phillips high line crewmen connected a phase rotation meter to the 480 volt terminals of the breaker to verify that the phase rotations on both systems were in the same direction.

Closing the breaker had to be synchronized according to the rotor position and speed of the Borax generator relative to that of the power grid and at the exact same voltage. I was stationed at the voltage regulator to make adjustments of voltage. Mike Novick was stationed at the turbine speed control to make adjustments in speed. There was a portable voltmeter attached to the lines at the breaker to indicate the instant that the breaker could be successfully closed. Our guy at the breaker for this first try was Milton Wilkie. He was an ex-Navy Chief with considerable power plant experience. That first paralleling operation was successful on the first try. However, I could tell that it was a nervous interconnection because I could hear the turbine oscillating slightly. Any sudden load change could have caused it to go unstable.

The next step was to isolate the 12,000 volt transmission line and make preparations to convert it over to 2300 volt operations. This required many steps previously described. These actions were primarily done by the Phillips Co. high line crew, under direction from our people. I believe there were about a half dozen people on this crew. I can remember the names of the crew boss, John Yeates, and the crew leader, Harold Christensen. The 12,000 volt line was disconnected at Borax, at the Central Facilities substation, at the EBR-I substation and at the EBR-I well. Under this condition, Borax was isolated from all incoming power and supplying its own power needs. The facility was without a water supply until the line was reconnected. The EBR-I and the new ZPR-III facility were without incoming power for the duration of the connection to Arco. However, EBR-I facility did have a 100 hp emergency diesel generator. A cable was laid from the diesel generator out through the EBR-I perimeter fence to the Borax control trailer. This connection did not have capacity to supply all the needs for Borax, but could supply power to instruments so that the status of the reactor could be monitored even if other power sources failed.

Unfortunately, the diesel generator failed just prior to the time that it was really needed. The diesel had been put in operation early and was grinding away when the 12,000 volt high line was disconnected. A technician (Orin Marcum) was put in charge of it and instructed to stand by it throughout the project. In the early afternoon, he walked out to the perimeter fence and yelled for the attention of Harold Lichtenburger. He explained that the diesel had begun to knock and he was worried about continuing to operate it. At that point Dr. Zinn, overhearing the conversation, superseded all discussion with the emphatic order to "keep that S.O.B. running." Orin returned to his post and said no more. Soon, the diesel was making so much noise that we could hear it from outside the fence. Ultimately, Harold Lichtenburger went in to investigate. He found Orin seated in a cloud of smoke beside the diesel, wondering what to do. There was no choice. Harold shut the machine down and we proceeded without benefit of the emergency generator.

Once the high line was isolated, the process of reestablishing it as a 2300 volt line began. The 12,000 to 2300 volt step down transformer supplying the well pump was bypassed, and the pump motor reconnected directly to the high line. A direct connection was made from the Borax generator to the high line. The high line was, at this point, re-established at 2300 volts but still isolated from the

Utah power grid. We were now ready to make the tenuous connection to the power grid, followed by disconnecting the power grid from the line to Arco that would leave it powered solely from the Borax Reactor. These two actions were to be implemented by the Utah Power substation operator at Central Facilities. The substation operator had control of the switches to do these two actions. He also had a sync scope and voltmeter to determine when to do it. He had no controls to adjust the speed or voltage of the Borax generator. His control of speed and voltage was limited to instructions to me by mobile radio at the Borax generator control panel. I could hear him clearly but could only talk back when he released his talk button.

The Failure of the First Try

I was impressed with the confident, calm voice of the UP&L substation operator. He demonstrated the characteristics of an experienced operator as he described what he was seeing and what he anticipated doing. He succeeded in making the parallel connection to the power grid. Borax was then connected to the power grid, but supplying only a small amount of power. He called for more voltage. I increased the voltage by adjusting the voltage regulator on the generator control panel. It was still not enough voltage. I continued to increase the voltage until I finally was at maximum voltage. The voltage was 2700 volts at my location on the 2300 volt system, and the instruments indicated that the generator was only modestly loaded. We were clearly in trouble. The substation operator could not know what voltage we could maintain at his location until he disconnected us from the grid leaving us connected to Arco and the Central Facilities area. He disconnected us from the grid and he reported that the voltage immediately dropped to about 70% of normal. Even so, the Borax generator was still only indicating a modest load. The substation operator announced that he was aborting the connection but before he could make the disconnect, the power line failed. It was after dark and we were suddenly in the dark, surrounded by silence except for the coast down of the turbine generator. At that moment a new adventure began.

The high line crew was sent out to find and report the damage. It was soon reported that several pole lengths of the high line had crashed to the ground about half-way between Borax and Central Facilities. As the power line fell, it contacted telephone lines that were supported by the same poles. Almost every telephone serving the immediate area was knocked out of service.

The reactor had shut itself down as it was designed to do. It was in a stable shutdown condition, however, only as long as the xenon remained in the reactor. The scary thing was that we had no coolant pump power to re-inject boric acid into the reactor coolant. It would be difficult to calculate the behavior of the xenon accurate enough to predict exactly when the reactor would initiate a new startup on its own with the coolant system out of service! The time to self start was assumed to be in the order of 24 hours. If the power could be restored soon enough there would be no problem. Then we could pour more boric acid into the cooling water and pump it into the reactor. However, what would we do or what could we do if the reactor did startup before power was restored? Furthermore, we didn't even have power to activate the instrumentation to monitor what was happening in the reactor.

Another complication was related to the fact that the power of a reactor doesn't quite drop all the way to zero immediately after shutdown. It continues to produce about 1% of the operational power in the form of heat for a few hours after shutdown. This was not a problem if the reactor core was maintained submerged below water level. However, the residual heat is enough to cause boiling of the water and could boil off enough water to uncover the upper portion of the reactor. If this should happen early, then the reactor fuel could be damaged from overheating and possibly begin to melt. This would not happen if the reactor tank remained closed off and sufficient pressure maintained to avoid boiling. The Borax system was designed to maintain pressure after shutdown by isolation valves that closed off the steam exit from the reactor. These valves did close when the power failed and there remained sufficient pressure in the reactor tank to avoid boiling of the coolant water. However, the valves were pneumatically operated and if pneumatic pressure failed, the valves would go to an open position. The pneumatic pressure was maintained by a small compressor. It was known that the pneumatic pressure did tend to leak off over a period of time if the compressor was not operational.

I think back now, after all these years, about the situation we were in. It included a reactor that would definitely start up by itself, no instrumentation to monitor what was happening, a reactor that could uncover itself and perhaps be damaged if the pneumatic pressure was not maintained. Hopefully, the power would be restored before any of this would happen. Nevertheless, these were real threats, fully understood by Dr. Zinn and his nuclear staff. Dr. Zinn turned into something like a shouting Prussian General. It was not difficult to comprehend the pressure he was feeling. He was shouting at all of us, including the high line crew, as if they were his own employees. It was late, in the middle of the night, and everyone had been there for more than a day. There was no time to explain to the high line crew why he was so animated. He directed some of us to go anywhere we needed to round up one or more emergency generators and others to go look for a portable self powered compressor. He directed his staff physicists, Joseph Detrick, Nate Krisberg and Joe Thie, to do their best to calculate the residual xenon level in the reactor and to predict, as well as they could, at what time the reactor would begin to restart. I remember the physicists working slide rules, initially by flashlight, in the control trailer making these calculations. I also remember that he discussed a possible action that could be undertaken to save the reactor if all else failed.

If it appeared that the reactor would likely restart before power was restored, we could stack some containers of boric acid water at the top of the reactor ready to be poured into the reactor as fast as possible. When it appeared that the reactor was about to restart, we would release whatever pressure there was in the reactor tank and open one of the flanged holes in the top of the tank so that the boric acid water could be poured in by hand. In this plan we would take our chances on whatever damage may occur to the reactor from releasing the pressure. The amount of radiation exposure to the volunteers to pour in the boric acid was entirely unknown.

I was assigned to go look for a portable gas-powered compressor. Most places where something like this could likely be found were locked up for the night. I did find a small electric driven compressor and was directed to haul it to the reactor sight, hoping that a portable electric generator could be found to drive it. However, one of the technicians, Ed Denning, found a more immediate answer. He came driving into the site in a pickup. Trailing behind was a large diesel-driven compressor designed to supply air to several jack hammers at one time. Our needs could probably have been met by a ½ horsepower compressor, but this was no time to be concerned about over capacity. The only problem with the big compressor was that the outlet hose was about three inches in diameter and we needed to connect it to a small copper tube. Ed found the necessary hose reducers to make the connection. The diesel compressor was cranked up and the pressure in the pneumatic system brought up to full pressure in about two seconds. The diesel continued to idle for many hours, waiting for the occasional need for more air.

A connection to a small gas-driven emergency generator in the EBR-I building was put in operation and a line connected to the control trailer. This provided lights in the control trailer but the only instrument that could be totally powered from the control trailer was a temperature-measuring instrument. This provided an indication of the temperature inside the reactor. None of the nuclear instruments could be made to work with this power connection. The temperature instrument was better than nothing. It would indicate if the reactor was actually beginning to produce power. The high line crew was busy working through the night (with plenty of encouragement from Dr. Zinn). In addition to repairing the line, they had to undo all the actions that had been taken to convert the line to 2300 volt operation. The high line crew and the physicists were very busy through the night. I was able to get a little cat nap on the lawn behind the EBR-I building.

A New Transformer and a New Plan

The Utah Power temporary substation operator at Central Facilities was standing by but had nothing to do until the highline crew completed the transmission line repair. He was evidently bored through the night and decided to wander about the Central Facilities area. During his wanderings, he found the equipment that put the Arco project back on the road to success. It was some time in the middle of the night that his voice came on the radio. He said that he had been wandering through the fenced storage compound at Central Facilities and found a three-phase transformer that seemed to be just what we needed to operate the high line voltage at its normal 12,000 volts. It could be connected to convert 2300 volts power to 12,000 volts. Bob Wallin, the other electrical engineer on the project, and I heard him give this report. We shook our heads in unbelief. This is the type of transformer that we had originally proposed for the project but were told that there was no such transformer to be found west of the Mississippi. Early the next morning the transformer was loaded on a flat bed trailer and transported to Borax.

The high line crew worked through the night putting the line back into service. If I remember correctly it was late the next morning before the line was back in service, well before the reactor showed any signs of restarting. Before the day was over, there was a new feature added to the reactor tank. It was a vertical stub of pipe that was connected directly to a spare flange on the top of the reactor tank. It included a manual valve at both the bottom and the top of the pipe stub. The stub of pipe was filled with boric acid water. If there should ever be another occasion when the reactor could start up on its own, it could be stopped by opening the lower valve and letting the boric acid fall into the reactor. Never again would we be in that uncomfortable situation as we had been the night before.

Later commercial boiling reactors all have boric acid emergency dump systems as a standard backup shutdown feature.

The trailer with the three phase 2300 volt to 12,000 volt transformer onboard was parked near the turbine building. The high line crew immediately began to connect it into the system without unloading it from the trailer. The process for connecting Borax to Arco would be much simpler and very different than the night before. This time the Borax power system would have to be synchronized and paralleled with the Utah power grid only once to make the connection. It would be done by us at the Borax generator and it would be a connection made on a 2300 volt line rather than at 460 volts. The only time that the Utah power substation operator would be required to parallel the two systems would be after we had succeeded in lighting Arco and needed to reconnect back to the Utah Power system grid. However, we were yet to encounter some more surprises before success.

The circuit breaker used to synchronize and connect the Borax generator to the Utah power grid earlier on the 480 volts connection was rated at a high enough voltage that it could be used to do the same task on the 2300 volt connection. The breaker was moved outside the generator building to be near the new transformer, still loaded on the trailer. On a new connection, it is customary to always check the phase rotation of the two systems before the two systems are connected together. When this circuit breaker was used to connect the two systems at 480 volts, it was simply a matter of clipping the leads of a phase rotation meter onto the breaker terminals. This operation, of course, must be done carefully to avoid physical contact with the 480 volt terminals. On our first attempt to light Arco, this was done by one of the Phillips Petroleum high line crewmen. A similar check of the phase rotations was necessary for the 2300 volt connection, but working close to any live 2300 volt terminals is unthinkable. The same man proceeded to make the same check on the 2300 volt connection without realizing that this same breaker was now connected to 2300 volt lines, not 480 volts. The result was a near-fatal accident. Here is how it happened: We made the 2300 volt connections to the breaker before the lines were energized. I knew that the hand-held phase rotation meter could not be used on voltages higher than 480 volts. It is standard practice in such cases to isolate the high voltage by using voltage-reducing instrument transformers between the high voltage lines and the phase rotation meter. I installed three instrument transformers for this purpose, one for each phase, so that the test could be made at low voltage. I placed a color-coded ribbon around the 2300 volt equipment to indicate danger. Wires from the instrument transformers were brought out past the ribbon so that the phase rotation test could be completed without entering the area of high voltage.

When all the wiring and other normal arrangements were completed, the reactor was started up again with hopes that we would be more successful in lighting Arco than we had been the day before. The startup required salting the cooling water with boric acid, operating at power for a period to build in xenon, turning on the water purification system to remove the boric acid and turbine startup. The time had come to check the phase rotation. The Phillips Petroleum high line man, who had been on duty all night working to repair the high line, proceeded to do it. He had been scheduled to be on vacation and was not entirely happy to be at work. He lifted the warning ribbon and walked directly behind the circuit breaker which was now connected to a 2300 volt line. He proceeded to clip the leads from his phase rotation meter that he was holding in his hand onto the breaker terminals. His instrument exploded in a ball of fire and an arc developed across the breaker terminals. His arms were splattered with molten metal but he was otherwise only shook up. He went to the dispensary where they patched him up and he returned to work with bandages on his arms.

The arc caused a protective circuit breaker at Central Facilities to trip open, causing another power failure to the Borax site. The reactor shut down as it had the night before. The shutdown, like before, was again dependent on the temporary xenon built in the reactor. However, this time the power outage would only last as long as it took to get the central facilities substation operator to re-close the tripped breaker, and if all else failed, there was now a boric acid dump feature installed on top of the reactor. I remember explaining to Dr. Zinn who was nearby, what had happened. He told me in no uncertain terms that I was to get the substation operator at Central Facilities to immediately re-close the tripped breaker. The tripped breaker was located in the permanent Central Facilities substation, not the temporary substation established by Utah Power. This substation operator was an employee of Phillips Petroleum.

We didn't have a telephone at the reactor, but we did have a sound powered phone that I could communicate with the control trailer. I found myself talking to Nate Krisberg, the Air Force Colonel on loan to Argonne. I instructed him to call the Central Facilities substation and ask them to re-close the breaker. He proceeded to do as requested, but reported back that there were rules for when a breaker could be re-closed after being tripped. It would require the OK of the high line supervisor, John Yeates, before he could close the breaker. When I reported this back to Zinn, he became furious. He told me that I had to get that breaker closed. With the sound-powered phone still in my hand I tried to pass on to Nate Krisberg some of the pressure I was feeling, but I wasn't used to shouting at Air Force Colonels. Nate calmly told me that I was out of order trying to get the substation operator to violate his orders. That didn't relieve the fury that I was receiving from Zinn. In frustration, I tried to hand the phone to Zinn and told him to tell Nate whatever he wanted. He refused to take the phone. I laid the phone down and walked away.

I tried to locate John to explain the situation, but had difficulty finding him. I finally located him in the Central Facilities cafeteria having some soup. It wasn't long before the breaker was re-closed and we began again to start the long sequence of tasks necessary to supply power to Arco. A few of us used this moment to get some lunch at the cafeteria. I was seated at the same table as Zinn. I used the moment to explain how close we had come to electrocuting a man. The 2300 volt system at Borax was a floating system without a defined ground. Such a system is unusual. The present standards require that all power systems have established ground connections. The lack of a ground line connecting to the Borax generator was probably the way generators were being manufactured back in 1925 when this generator was manufactured. The significance in this event was that there was essentially no voltage to ground from any of the three power cables coming from the Borax generator. As a result, when the phase rotation meter exploded, it initiated a short circuit from phase to phase rather than from phase to ground. If the short had developed from phase to ground the current would have passed through the high line man holding the meter. When I explained this to Zinn, he made a provocative statement. I choose not to repeat it.

This incident gives me motivation to give my impressions of Dr. Zinn. He was brilliant, eccentric and temperamental. We viewed him as technically superior to the Admiral (Rickover). He was a direct assistant to Enrico Fermi on the Manhattan project. I was highly impressed with his technical discussions. He was very gifted with technical understanding and the ability to explain complex things in easy-to-understand simple terms. On the other hand, he was sometimes unreasonable, could definitely display a temper and even throw a temper tantrum. I remember one occasion when he got angry at a ladder and smashed it into pieces. I also remember him in front of an audience being bombarded with hostile questions. His response displayed patience, compassion and complete confidence. It didn't seem that any question, no matter how hostile, could unnerve him.

I don't remember any complications in recovering from the short circuit caused by the incident at the circuit breaker. We went through the whole startup sequence again. This time I did the synchronizing, paralleling and closing the circuit breaker to connect the Borax generator to the Utah Power grid. The arrangement was better than before, but we still did not have a genuine synchroscope, and the interconnection to the grid was still be a rather weak connection, subject to easy instability. I had the advantage of our previous experience. I noticed that the Simpson meter that had been used in the first attempt had rather slow response. I looked for a meter that had quick response. I ended up using a little two inch diameter voltmeter that was part of a clamp-on ammeter.

The phase rotational check was conducted this time using the connections from the instrument transformers without problem. It then became my turn to act. I had thought out my actions well in advance. I reported my every action on the radio as I did it. I knew that everyone on our crew was listening intently to my words. I did indeed feel considerable stress. I described the behavior of the voltmeter in front of me as it slowly evolved through maximum and minimum values. I announced that the next time it came around through the null point that I was going to close the breaker. I purposely closed a little ahead of the null point, because that allows the two systems a little extra time to exchange enough energy to lock the two systems tightly together. They locked together without a ripple. I was very pleased and later received many compliments for the smooth connection.

Success

Even though we were now connected to the grid, I noticed from the instruments on the control panel that our generator had picked up very little load. We wanted the generator to be loaded to about the level needed to supply Arco before we called to the operator in the Utah power substation to disconnect the Utah power feed from the line to Arco. I increased the voltage, as I had on the previous try, until we were again generating with a maximum of 2700 volts. Our instruments still indicated that we had picked up very little load. It was then that I learned something I had not previously understood. The output voltage of the generator is not as significant in picking up electrical load as is the throttle setting on the turbine. We increased the throttle setting and the load immediately responded. We contacted the Utah Power substation operator and told him we were ready for him to disconnect the feed from the power grid to the Arco line. As he did so, I was unable to observe any significant effect on our turbine load. It was, by then, quite late in the evening and the load to Arco was small. The load we picked up at Central Facilities was probably as big as the Arco load. In any case, we had succeeded. We were supplying all the power used by Arco from the Borax Boiling Water Reactor. This was the first time in history that any town had been totally electrified from a nuclear power plant.

This was not the first time that electricity had been generated from atomic power. That had happened 2 ½ years earlier at the EBR-I reactor just over the fence from the Borax Reactor control trailer. With Arco on line, everything was running smoothly. There was no indication of any abnormalities. It now seemed as if there was nothing much to do but let the machinery crank away. Several of us proceeded to take a rest just outside the door of the turbine building. We sat on the ground in the cool of the evening. It was a nice evening, the rest was welcome and there did not seem to be anything to prevent operating this way indefinitely. We felt we had succeeded but knew that the connections should last more than just a few minutes to add credibility to the project. We wondered how long would be a reasonable time. The decision would come from the control trailer where Zinn and Lichtenburger were watching over things. There wasn't much to do where we were. It was nice sitting there in the cool of the evening, jovially discussing the events of the past few days. It was more than an hour before word came from the control trailer that there was no point in continuing the connection to Arco. Everyone was tired and looked forward to some bed rest. Little did we know that we were about to enter into another interesting adventure.

The disconnect from Arco required that the Utah power substation operator first reconnect our system to the Utah Power grid. He had a syncroscope but would have to rely on me for adjusting voltage and speed to make the reconnection. I was stationed at the Borax generator control panel listening to him give directions by radio. This time it didn't go well. He announced that even though the velocity wasn't well matched, that he would act on the next revolution of the syncroscope. I'm sure that, given a little more time, we could have adjusted more closely to the needed speed, but he closed the breaker at the instant that the two systems were synchronized, but with a slight mismatch between the velocities of the two systems. This would not have been so bad if the line linking the Borax generator with the grid was strong enough to exchange enough quick energy between the two systems to lock the two systems together. Instead the Borax generator began to oscillate. I could hear the turbine momentarily speed up and then slow down in repeating cycles. The lights began to turn brighter and then dimmer in step with the sound of the turbine. The mass of the old 1925 turbine and generator was large compared to modern turbines. This contributed to the oscillations. In a period of less than a minute, the oscillations became more severe. I called Lichtenburger on the sound-powered phone and told him we should cut loose from the system to save our equipment. He said, “Do it.” I was too late. The power line failed again, much as it had on the first try. Several pole lengths’ of high line had fallen to the ground again. The reactor shutdown automatically as it had before and we were again in the dark and listening only to the coast down of the turbine generator. The high line crew was called upon again to work through the night to repair the line.

There would not have been any great reason to get the reactor immediately back into operation except for another political event that was about to take place. Argonne National Lab in Chicago had for several years become the host of what was called the International School of Reactor Technology. It was a school with somewhere between 50 and 100 students appointed primarily from third world countries. They were arriving the next day at the EBR-I, Borax reactor site for their annual visit to the National Reactor Testing Station. It would not be good for them to arrive with the reactors all shutdown and the power line fallen to the ground. Another implication was that the Russians were challenging the validity of the United States having an operating boiling water reactor for which there was to be a presentation at the International Conference. The students in the International School would be excellent independent witnesses to verify that the US did indeed have an operating boiling water reactor producing electricity. This was the motivation for repairing the high line and putting the Borax reactor back in operation as soon as possible.

Triumph

The high line crew met the challenge and so did we. The next day, when the bus load of international students arrived, the Borax reactor and generator were in operation generating electricity, but of course, not connected to Arco. The high line crew was gone and we were standing leisurely about as if it was just another day with nothing much to do. The power transformer was still sitting aboard the trailer in front of the turbine building, wired to the high line. The Russians did challenge the existence of the reactor. The students from the International School came to our defense regarding the Russians implying that the U.S. was faking the existence of the Borax reactor. They stated they knew that the United States did have a boiling water reactor because they had seen it and it was in operation and generating electricity when they were there.

There was little time to complete the preparation for the presentation to be given at Geneva. Several of our top leaders, Zinn, Lichtenburger and Detrich, left for Geneva to make the presentation with only a few days to spare. It was nice for us because we were allowed to relax a bit and things got very quiet around Borax for a few days. We were told that the presentation at Geneva was a great success.

It is now more than 50 years since the Borax III events. The Borax program didn't end with Borax III. There were additional later modifications of the Borax Reactor that were used to test variations of fuel designs and enhanced coolant circulation methods. These experiments continued into the 1960's. The Borax reactor building, the power plant and the cooling towers have all since been removed. The site has been returned to its normal desert environment. There is essentially nothing remaining at the site to indicate what happened there.

About half of the people who worked on Borax through Borax III were Idaho employees who were also part of the operating crew of the Experimental Breeder Reactor 1 (EBR-1). These two reactors were located next to each other, separated only by a fence. During the intensive activities at Borax, EBR-1 was shutdown. Following the lighting of Arco, both reactors were operated with a shared work force. Exciting events at Argonne-Idaho didn't end with the lighting of Arco. In November 1955, the same year as the lighting of Arco, the reactor core of the EBR-I reactor was accidentally melted. This event generated another interesting chapter in my professional career.

The EBR-I Meltdown

The EBR-1 was the reactor that had made history in December of 1951 when it produced the very first electricity from atomic energy. It had also proven the principle of the breeder reactor by producing more nuclear fuel than is used to generate energy. At the time of the lighting of Arco, EBR-I was nearing the end of its scheduled life. The new EBR-II reactor was already under construction. It was expected that the EBR-I personnel would complete the final experiments on the EBR-I and become the operating crew for the new EBR-II reactor.

I became a member of the EBR-I staff shortly after graduating from college. It was here that I obtained a first-hand knowledge of nuclear reactions and the fission process. EBR-I was a complete power plant, including a 250 KW steam powered turbo generator. It was on this power plant that we all got the nuclear and power plant experience we needed to conduct the Borax experiments.

The technical history of the EBR-I is well documented. It entailed less human drama that the Borax story. Nevertheless, it did include some interesting aspects that have either been forgotten or never told. The common public has the impression that a nuclear reactor meltdown is always a very serious accident with long-term consequences. That was certainly not the case in the EBR-I meltdown. I will endeavor to tell some of the details.

A contributing factor in the meltdown of the EBR-I was that it had a complex temperature coefficient. One of the first things checked on a new reactor, as it is first placed into operation, is to verify that the temperature coefficient of the reactor is negative. This coefficient has safety implications. If the temperature coefficient is positive, the reactor becomes more difficult to control. The coefficient is a manifestation of the thermal expansion of the reactor core and mechanical components as temperature is increased. Increased temperature usually slows down the fission process and causes the reactor power to trend downward. However, the effect can be either positive or negative. Any microscopic expansion or movement of the fuel elements can have considerable effect on reactor power.

The temperature coefficient of the EBR-I was determined to be comfortably negative during the first power operation. However, it was soon observed that reducing coolant flow through the reactor, while at power, caused the reactor power to increase. With the benefit of a negative temperature coefficient, it should have logically gone down. This apparent contradiction remained unexplained until after the meltdown and after the primary mission of the EBR-I had been completed. By the way, the coolant in the EBR-I was not water. It was a eutectic mixture of sodium and potassium called NaK, which is liquid at room temperature.

This peculiarity of the reactor sensitivity to changes in coolant flow had no impact on the operation of the reactor because the coolant flow through the reactor was not dependent on coolant pumps. Coolant flow was by gravity from a large supply tank located high up in the reactor building above the reactor. While the level in the supply tank was dependent on pump power, normal flow through the reactor could be maintained for about eight minutes following pump failure. Coolant flow rate was controlled by a valve located at the bottom of the gravity supply tank. It became standard practice to make no adjustments in coolant flow during power operation.

The experimental program for the EBR-I had been completed by November of 1955. The first electrical power from a nuclear power plant had been generated. The positive breeding gain of more than a factor of one had been proven. There was also one period when the reactor was operated with a plutonium fuel loading. The nucleonics of this first fast breeder reactor had been well documented and the operation of the power plant had become routine. The more advanced EBR-II was under construction. The time had come to shutdown the EBR-I and direct our attention to the EBR-II, except that the response of the reactor to decreased coolant flow remained unexplained. If this mystery was to be resolved, this was the time to do it.

All of the available ideas for investigating the phenomena seemed to involve high risk. Since the reactor was essentially at the end of life, this seemed to be the time when higher than normal risk would be acceptable. A plan was developed and the AEC was notified of the intent to conduct this high risk experiment. Later, when the experiment resulted in the meltdown, the AEC denied that they knew anything about it.

The planned experiment called for taking the reactor critical to a very low power level of only a few watts without coolant flow. The reactor power would be adjusted to a level to bring about a slight amount of core heating. Some additional high speed temperature instruments were connected to the reactor to better observe the results. It was anticipated that there would be a series of passes in which the slow approaches to power would be repeated. The reactor power would then be reduced after each pass to near subcritical. The results would then be studied and subsequent passes would follow depending on the observations of the previous pass.

The experiment was under the direction of my boss, Harold Lichtenburger, who was intently watching the high speed temperature monitor located on a table just behind the reactor console operator. The technician at the reactor console was Leonard McKay. He told me later that he had been instructed to anticipate a request to quickly reduce power when told to do so by withdrawing all the control rods. The controls on a fast breeder reactor react opposite to that of a conventional water reactor.

The EBR-I had three methods to reduce power or shut down the reactor. The first was by withdrawing the control rods. This was the most mild and slowest method for reducing reactor power. The second was by ejecting the safety rods by pushing the “Reactor Off” button.. This normally induced total shutdown but left the reactor conveniently ready for restart. The third method was a complete reactor shutdown by pushing the “Reactor Scram” button. This dropped the entire outer blanket away from the reactor tank. Restart following a full scram required about an hour.

The core melting incident occurred on the very first approach to low power. Harold saw that the power was rapidly increasing and yelled to Leonard to implement reactor shutdown. Leonard was still under the impression that he was only to withdraw control rods. Harold, seeing that the power was still increasing, reached over Leonard’s shoulder and pushed the reactor “Off” button. The reactor power briefly hesitated and then continued to rapidly increase. It was then that the automatic reactor safety system implemented a full scram shutdown triggered by a power level instrument. The power level dropped to zero.

At that point, it was not known if the reactor had been damaged or not. It was noted that the trace on the power level recorder had briefly gone off scale. There was no abnormal sound or other indication of reactor damage until a few minutes later when an area radiation monitor indicated high radiation level near the cover gas system. At that point it was known that there was at least some damage to the reactor core.

I was not involved in the experiment. I was in my office a short distance from the control room in the annex to the reactor building.

I heard the radiation alarm but didn't know the implication until one of the technicians, Donald Loosli, who had been in the control room during the experiment, came by my office and explained the situation.

It is necessary to give some technical information here to understand what followed. In the nuclear reaction a small amount of uranium fuel is consumed and replaced by fission products. It is the equivalent of the ash that remains after combustion by fire. The radioactive fission products are a mixture of metal, nonmetal and gaseous elements. After accidental melting, most of the metallic and non-metallic fission products remain encapsulated within the fuel. The gaseous fission products are free to escape.

In the EBR-I reactor, argon gas was used to occupy the void space at the top of the reactor tank and other components of the reactor system. Following the meltdown, the gaseous fission products naturally migrated to the argon cover gas system. This system included some supply and pressure regulating machinery that was not absolutely leak tight. The radioactive gas soon began to leak to the reactor building. These radioactive gases have limited biological concern because they have relatively short half lives and, with the possible exception of iodine, are not retained in the human body. The radioactivity in the reactor building continued to increase and soon resulted in the order to vacate the building. The building annex where my office was located continued for a time to be occupied, but it wasn't very long until all of us in the annex were instructed to pack up our records and belongings and move to the nearby ZPR-III building.

It was still hoped that the damage to the reactor was not severe. One of our health physicists was clothed in a Scott Air Pack and sent back into the reactor building to make a survey. It was hoped that the survey could be extrapolated to indicate the level of damage, but the survey was limited and the results inconclusive.

There continued an intense desire to know the extent of reactor damage. It would not have been difficult to purge the radioactive gas from the reactor building and re-enter. The top of the reactor could be opened, which would release additional radioactive gas but, that also could easily be purged. A good indication of the damage could then be obtained by pulling on the fuel elements, one at a time, to determine if they were free to be moved. Damage to the reactor would most likely be most extreme at the center of the reactor. Testing the freedom of the fuel elements, starting from the outside edge and moving toward the center, would give a good indication of the extent of damage. At some point, fuel elements would be encountered that were not free to move. That would indicate which and how many of the 61 fuel elements were damaged.

We, at that time, were no longer as free as we had been to make all of our decisions on-site without oversight. First, Harold Lichtenburger, our site director, notified his boss, Dr. Walter Zinn, the laboratory director, in Argonne, Il. Dr. Zinn then notified the AEC. The AEC was, at that time, beginning to exercise its legal authority in making decisions in matter such as this. This resulted in a frustrating political decision, with implications related to the cold war with the Russians.

A Political Decision with a Russian Connection

We were directed to do nothing until further notice. The rationale behind the decision requires another technical explanation. At that time the cold war with the Russians was no minor thing. The Russians had the atomic bomb and were conducting secret bomb tests in Siberia. The U.S. wanted to know as much as possible about these tests. One method used was by surveillance of the fission product gases that are released from a bomb test. The most important fission product gas was xenon, with a half life of about two weeks. The fission product gases migrate with the prevailing winds and become detectable for thousands of miles down wind. Evidently, the U.S. had many detection devices in service at many locations for this purpose.

It was noted that the fission product gases from the EBR-I were the same as those emitted from an atomic bomb detonation. If we were to open up the reactor tank of EBR-I, it would release additional fission product gases that could confuse the system used to monitor the Russian bomb tests. Eventually, the radioactivity of the fission product gases would decay to a level where it would have no effect on the Russian bomb surveillance program.

This restriction was very frustrating to us because we were extremely anxious to know the extent of damage to the reactor. Also, there was a question of what public announcement should be made concerning the meltdown event. EBR-I had been a classified project, but it had been described in some detail in the 1955 International Conference on Atomic Energy. If a public announcement was to be made, it would be a limited announcement. We would not be able to describe the extent of the reactor damage nor the reason why. I don't know who made the decision, but we were instructed to keep the event secret until we had more complete information.

The meltdown occurred in November. It wasn't until March, four months later, that we were given permission to open the reactor. Meanwhile, the secrecy had been breached by none other than the chairman of the AEC, Lewis Strauss, in a speech he gave in London. Our phones began to ring as newsmen inquired about the details of the meltdown. Our director, Harold Lichtenburger, responded to the calls by explaining that we were under orders not to respond to any questions for reasons of national security. The result was that the news media became hostile and started making up their own stories of what had happened.

The news media had, in past times, painted our actions as brilliant. Suddenly we were accused of hiding our incompetence under the protection of national security. We changed from being heroes to villains in the media overnight. One report stated that we had bypassed all safety monitors. The truth was that all safety monitors were in service, and it was actually the power monitor that initiated the full shutdown of the reactor.

In March we were allowed to open up the top of the reactor and begin to investigate the extent of the damage. It is necessary to describe some of the physical features of the reactor to comprehend what we found. The inner, highly enriched, uranium core of the EBR-I was physically about the size of a football. It was made up of 61 fuel rods about 3/8 inches in diameter. The fuel was in the form of highly enriched uranium pellets contained within the stainless steel rods. The active portion of the reactor contained about 50 Kg of highly enriched uranium-235. The fuel rods had long inert handles that extended up about nine feet to the top of the reactor tank. These handles, along with other support structure, provided shielding such that direct manual manipulation of the rods was possible from the top of the reactor without significant radiation exposure. The central fuel rods were surrounded by four rows of inner blanket rods. These were similar to the fuel rods except that they contained natural uranium instead of enriched uranium and were about one inch in diameter.

The inner blanket natural uranium rods were found to be free and were lifted up and removed from the reactor. However, only a few of the enriched uranium fuel rods at the outer edge of the central core were free to be removed. The remainder of the 61 fuel rods had been damaged to the point that they could not be removed. It was then obvious that most of the enriched uranium core had been significantly damaged or melted. The only way that the remaining fuel could be removed was to remove the total reactor assembly from the reactor tank as a unit. The design of the reactor assembly was such that it could easily be lifted up out of the reactor tank with the aid of the building crane. But, if this were to be done without radiation shielding, the radiation level in the building would far exceed acceptable levels.

A concrete cave was assembled on the top of the reactor to provide the necessary shielding from the high radiation levels that was expected as the reactor assembly was lifted up out of the reactor tank. The cave was constructed with some very large, heavy, concrete blocks that were borrowed from the Borax facility. A three-foot-thick glass window was included in the structure, and high intensity lights were installed within the cave. An exhaust fan was connected to the cave which took air from inside the cave and exhausted it through some high efficiency filters to the atmosphere.

The building crane was hooked to the top of the reactor assembly and was manipulated to slowly lift it from the tank. The active portion of the assembly was still submerged in the sodium potassium coolant when the lifting began. As the assembly was being lifted, it was taken from the reactor tank environment to open room air. I was one of many people present watching this interesting event. I noticed that Nak coolant was still dripping from the assembly as it was being lifted from the reactor tank. Since Nak is pyrophoric, there was some concern about the possibility of fire. I noticed that there was some smoke as the assembly lifted. Some fire-suppressing equipment was nearby, but we were still nervous because conventional fire suppression measures do not stop Nak fires.

Fortunately, there was no fire, and with the inner blank rods already removed, we got our first view of the damaged reactor core. It was evident that most of the inner core assembly had been melted. A power metal saw was lowered into the cave and the upper portion of the reactor assembly was cut away, leaving only the active portion of the reactor core. Some of the outer fuel rods were more or less still in tact and were removed. What finally remained was some thing like a large clinker containing about 35 Kg of enriched uranium. This clinker was placed in a specially-made coffin and shipped to Argonne, Ill. I do not know what became of it after that.
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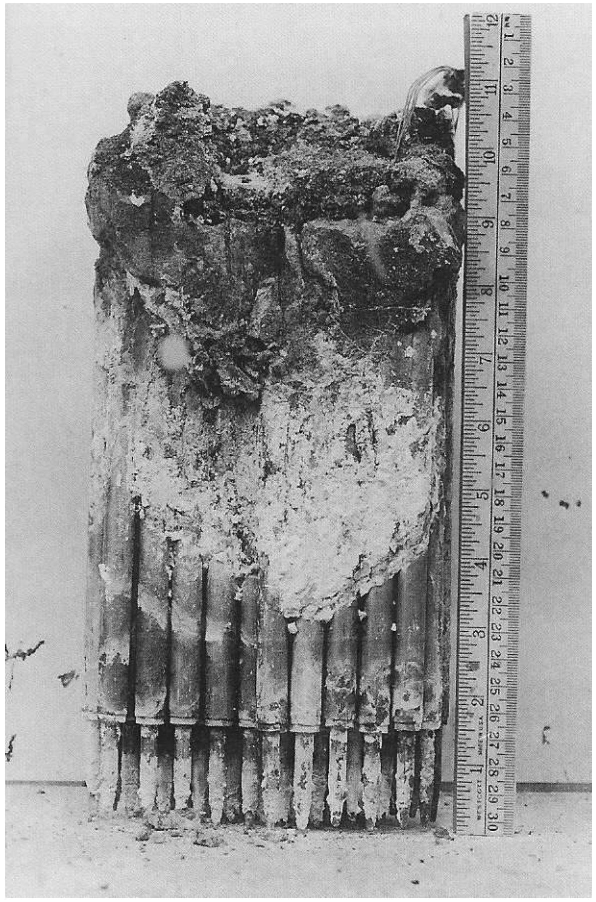
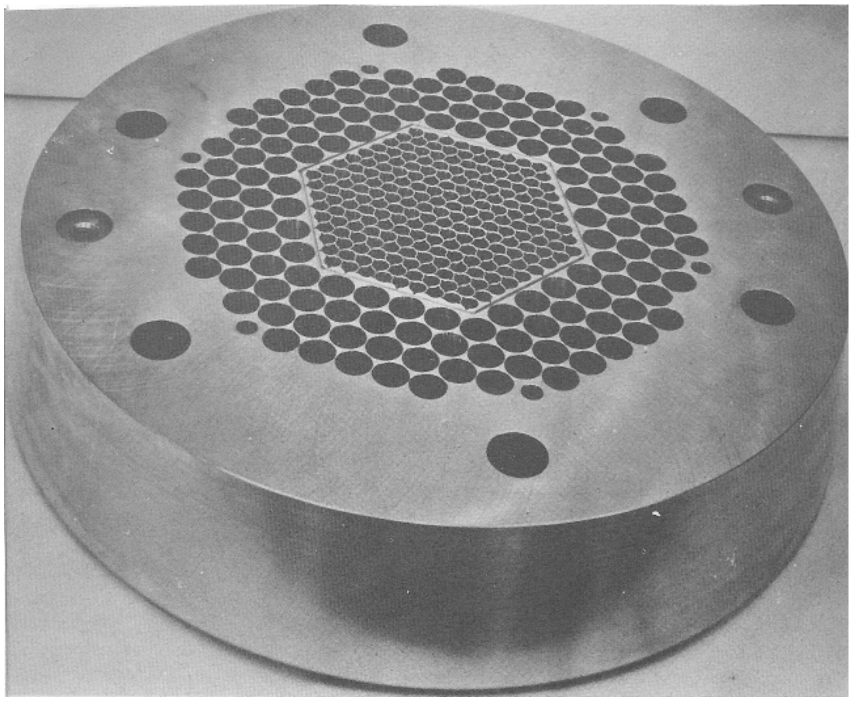


EBR-I Inner Core after the Meltdown

This would have been the end of the EBR-I program except that we still had not clarified the anomaly of the reactor response to coolant flow change, nor did we know what actually caused the reactor to meltdown. It was not acceptable to leave EBR-I with these unanswered questions. We were directed to rebuild the EBR-I reactor assembly and perform new tests to resolve these mysteries.

A few months later, the EBR-I was back in operation with a new core and reactor assembly. However, the reactor assembly was slightly different. The fuel elements were essentially unchanged, but instead of being supported by a large two inch thick support plate above and below the active part of the core, the new reactor had fuel rods contained in a group of hexagonal shaped tubes.



Two inch support plate
Thermo expansion of this plate found to be important

A more advanced method was used to investigate the coolant flow abnormalities of the reactor. The reactor was taken to power and the power mildly oscillated at different low frequencies. By recording the response of the oscillations, and using some complex mathematics, it is possible to identify resonances and time constants that are related to the reactor temperature coefficient. However, there was a problem. The rebuilt reactor did not have the coolant flow abnormalities seen in the earlier reactor.

The missing abnormality in the rebuilt reactor provided a clue to cause of the abnormality. In the earlier design, the fuel rods were supported above and below the active portion of the core, leaving them free to bow slightly in the middle due to temperature gradients within the reactor. In the new reactor, the fuel rods were restrained within the hex tubes and less free to bow. Therefore, the problem must have something to do with rod bowing. The next step in the experiment was to modify the fuel rods inside the hex tubes so that they were free to bow more like in the earlier reactor. The fuel rods were modified in only one of hexagonal tubes. This arrangement led to the sought after answer.

Cause of the Meltdown

Here is the final answer to the EBR-I mystery: The overall temperature coefficient was truly negative, but it was made up of two major components. One of the components was large and negative but slow-acting. The other was positive and fast-acting. The fast acting positive component was due to fuel rod bowing caused by uneven thermo expansion. The center of the reactor runs hotter than the outside. This tends to cause the fuel rods to bow inward toward the center of the reactor, and caused reactor power to increase. The large negative component was due to the large support plate at the top of the reactor core. It was subject to bowing downward when the temperature on the reactor side of the plate was hotter than the upper side. This caused the fuel rods to bow outward which caused the reactor power to decrease. The size and thickness of the support plate was relatively massive and slow to respond to temperature changes within the core. This explains why the temperature coefficient was always negative for slow temperature changes within the reactor. Fast changes in core temperature, like when coolant flow rate was changed, caused the positive component to become dominant. That is why the reactor melted in the last scheduled experiment of the reactor!

EBR-I was retired with honor and decommissioned in 1964. It is now a recognized national monument dedicated by President Lynden Johnson in 1966. It is open to visitors during the summer months.

Some References

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The Author

For me, Ray Haroldsen, it all began in 1928. I was born and reared in a devout Mormon family on a farm near Idaho Falls. During my early years, all of the farm equipment was powered by horses. Most of our neighbors had graduated to automobile travel, but there was still an occasional horse-drawn buggy to be seen. We had a Model A Ford car, but it was not used in the winter time when the roads were blocked by snow.

I attended a two-room rural grade school with two teachers, each teaching four grades. I decided very early that I was going to be an engineer. The same was true of my three brothers. We all attended engineering schools, and later all received advanced degrees. After graduating, I had a job for a short time as a blue print checker for the Bechtel Corp. I was hired by Argonne in October of 1951, but could not immediately start work because a "Q" clearance was required, which took several months. I actually arrived at work at the EBR-I in the second week of January 1952. The first power operation of the EBR-I, in which the first nuclear-generated electricity was produced, had already happened some three weeks earlier. I was sorry I missed that event.

I was soon integrated into the EBR-I reactor staff ,where I found that some of my co-workers had worked under the famous Enrico Fermi on the first reactor in Chicago. It was fun to hear them tell of those very early days when the first sustained nuclear reaction took place. Nuclear fission seemed like real magic to me. I had had a preview of the nuclear world through my older brother who was then working as a chemical engineer at Oak Ridge on fuel reprocessing.

On-the-job training continued through seminars and night school. We were instructed on the proper respect for radiation. We became familiar with the details of the death of Luis Slotin in Los Alamos from a lethal radiation dose from a criticality accident. To add emphasis, we were shown pictures of his horrible death as he lay on his bed. We all felt that we adequately understood the hazards of radiation. We had a health physicist on our staff from the very beginning, Newman Petit. He was very competent. It was his job to monitor all our activities to verify compliance with the standards of radiation control as they existed at that time. Even so, we did receive radiation doses that would be totally unacceptable today. It is interesting that none of my early co-workers, who are mostly deceased, died of cancer.

We were also taught to respect the harsh characteristics of the NaK coolant used in the EBR-I. If water is squirted into a bucket containing coolant, it explodes and scatters fire. The smoke from a NaK fire is very caustic. The last thing we wanted was for an untrained fire department crew to arrive at our premises to help us put out a NaK fire

Most of the reactors we worked on were small enough that we had the privilege of working on all phases including design, construction and operation. In addition to the EBR-I, EBR-II and the Borax reactors, I worked on the Argonne Fast Source Reactor (AFSR) and the Zero Power Reactor III (ZPR-III). I designed the electrical controls for those last two reactors.

The Argonne National Lab director, Dr. Walter Zinn, resigned his position in 1956 and formed his own company in Dunedin, Florida. This venture was funded by the Merrill Lynch Investment Co. Zinn invited some of his favored co-workers from Argonne to join him in his new company. That included my boss, Harold Lichtenburger, and me. I resigned my position at Argonne and joined the new company called The General Nuclear Engineering Co. While I was there, I worked on the designs of several reactors and concepts.

These included the Enrico Fermi Reactor in Monroe, Michigan, a CP-5 type reactor for Georgia Tech and a reactor in Venezuela called IVNIC.

It was only about two years until the new company was bought out by the Combustion Engineering Co. and moved to Hartford, Conn. I chose not to move to Hartford and returned to Idaho where I rejoined the Argonne EBR-II staff. I worked there briefly before I was transferred to Argonne, Illinois. There I worked on a design team on an advanced fast reactor that was cancelled just as construction was about to begin.

I left employment at Argonne in 1973 and transferred to the EG&G Company where most of my time was contracted to the Nuclear Regulatory Commission (NRC). This included one year that I was stationed in Washington, DC. The NRC used me as part of their review and inspection teams to scrutinized safety considerations on a variety of commercial nuclear power plants. These assignments required a lot of travel. Most of the time, I was able to operate from my home in Idaho. While working on these assignments, I became aware that there was considerable demand for licensed professional engineers who had reactor operating experience. During the last five years of my professional career, I worked as a freelance consulting engineer. There was plenty of work. I retired in 1993.

At the time I retired, the public reputation of atomic energy was extremely low. The work environment was not as pleasant, partly due to overly restrictive work rules. I was sure that, eventually, the public would re-discover nuclear energy and that our reputation would recover, but I couldn’t see recovery coming in my time. It seemed like a good time to retire.

In retirement I turned my attention to other things. I have enjoyed a variety of retirement activities. These have included teaching

English as a second language at a local college and for my church. I have worked in a church sponsored charity distribution store and I have enjoyed some interesting travel ventures. Meanwhile, I live in a home on the family farm where it all began. Life has been great!

Ray Haroldsen
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Some EBR-I Reactor Operators in 1954
Ray Haroldsen on the Left