B Reactor
Area 100-B
Hanford Site
Richland Vicinity
Benton County
Washington

HAER No. WA. 164
DOE/RL-2001-16

HISTORIC AMERICAN ENGINEERING RECORD

HANFORD CULTURAL AND HISTORICAL RESOURCES PROGRAM

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

MAKING PRESERVATION PART OF RESTORATION

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Historic American Engineering Record
B Reactor (105-B Building)
HAER No. WA-164

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Chris Willingham 5-3-01

Approved for public release; further dissemination unlimited

HISTORIC AMERICAN ENGINEERING RECORD

B REACTOR (105-B BUILDING) HAER No. WA-164

Location: Approximately 45 miles NW of Richland, Washington, on the Hanford Site in Benton County. Sec. 11, R 25 E, T 13 N.

Latitude/Longitude: 46 º 38 ' N, 119 º 39 ' E (Washington State)

UTM Reference: Zone 11 E 297440 N 5167287

Date of Construction: 1943-1944

Design: E.I. du Pont de Nemours & Co, Inc., Crawford H. Greenewalt, Technical Division
Metallurgical Laboratory, Enrico Fermi, Nuclear Physics Division

Builder: United States Army Corps of Engineers
General Leslie R. Groves, Chief of Manhattan Project
Colonel Franklin T. Matthias, Hanford Engineer Works Commander, Army Corps of Engineers

E.I. du Pont de Nemours & Co. Inc.
Frank Mackie, Manager Construction Division
G.P. Church, Construction Manager at Hanford

Present Owner: United States Department of Energy (DOE)

Present Use: Deactivated 1968; currently part-time museum

Significance: The B Reactor (the 105-B building at the Hanford Site) was the world's first production-scale nuclear reactor. It was rushed into construction during the height of WW II as part of the Manhattan Project, the urgent effort by the United States to create an atomic bomb before one could be built, it was feared, by Germany. The design for the reactor leaped from an extremely slender volume of research, most of which was barely a year old. In spite of the unproven technology and wartime constraints, the reactor was constructed and taken to criticality with complete success, all within a single year. In the first nine months of operation, it produced fissionable material (plutonium) for the world's first atomic bomb, the Trinity test in July 1945, and for the atomic bomb that was dropped on Nagasaki, Japan, in August 1945, which hastened the end of World War II. The reactor was listed in the National Register of Historic Places in 1992.

Report Prepared By: B Reactor Museum Association, PO Box 1531, Richland, WA, 99352
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Date: December 2000

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Introduction

The B Reactor is the world’s first industrial-scale nuclear reactor. Its sole mission was to transmute uranium into plutonium, which could then be fashioned into an atomic bomb. B Reactor’s role in history is unmistakable, as significant and world-changing as the discovery of fire, the first gasp of a steam-driven piston, or the first flight by the Wright brothers. Such events are recognized immediately for their import, and forever stand as milestones in the human timeline.

Being the first secures a spot in history, but many other factors play into B Reactor’s historical role. This stark concrete structure seems to focus a broad set of historical vectors and then send them on their way in completely new directions.

- The “pile,” as reactors were then called, was born of necessity in the urgent quest by the United States during World War II to build an atomic bomb before it might be done by Germany.
- This effort was encapsulated in the Manhattan Project, under the auspices of the Army Corps of Engineers, which may well be the largest scientific, engineering, and industrial project ever undertaken. Although the war was draining the country of materials and workers, the goal of building an atomic bomb was reached in less than three years.
- The fundamental research and experimentation with nuclear chain reactions preceded the reactor’s construction not by decades or even years, but by a matter of months.
- The industrial-scale B Reactor sprang from Enrico Fermi’s historic laboratory in Chicago, where he oversaw the construction of the world’s first chain-reacting pile in December 1942, just a few months before construction of B Reactor began.
- The million-fold leap from laboratory to industrial-scale power levels is remarkable. Whereas Fermi’s pile in Chicago produced power that never exceeded 200 watts (a measurement of heat, not electricity), the B Reactor operated at a power level of 250 million watts (megawatts, MW). In its later years, the reactor exceeded 2,000 MW.
- B Reactor was the first of three built and operated by DuPont at the sprawling Hanford Engineer Works in southeastern Washington state. The B Reactor was built in little over a year, and the entire Hanford complex in two. The reactors and other plutonium-production facilities that made up Hanford are recognized as modern marvels of engineering and heavy construction.
- The quantity of new technology that went into B Reactor is staggering. No one had ever dealt with even a fraction of the radiation that was generated in the Hanford piles. Reactor materials, cooling system, shielding, and instrumentation all had to be designed and built to withstand this entirely new environment, as were the work procedures needed to operate it.
- B Reactor was built for the short-term, but after helping to end the war it continued to produce plutonium for more than 20 years. The quality of its design and construction far exceeded the immediate wartime needs.
- Its role of making plutonium was the world’s first application of nuclear energy from a self-sustained nuclear chain reaction. The experience that was gained and the groundbreaking advances in technology that were made over its 24 year life span greatly influenced the design and operation of the nuclear reactors that were to come.
- B Reactor supplied plutonium for the world’s first atomic bomb, the Trinity test on July 16, 1945, and for the atomic bomb that was dropped on Nagasaki, Japan, on August 9, 1945.

- The reactor created tritium for the world’s first thermonuclear explosion, the hydrogen bomb test in November 1952, and established the processes and procedures for full-scale tritium production.
- Its role as a plutonium-production reactor, the world’s first, makes B Reactor a central player in the 45 years of atomic stalemate between the United States and the Soviet Union, the Cold War.

The reactor has already received broad recognition of its historical importance. In 1976, it was listed as a National Historic Mechanical Engineering Landmark by the American Society of Mechanical Engineers. In 1992, the reactor was entered into the National Register of Historic Places by the National Park Service. In 1993, the American Nuclear Society presented the Nuclear Historic Landmark Award to the reactor and in 1994, the American Society of Civil Engineers named it a National Civil Engineering Landmark. With its remarkable record of accomplishments and firsts, the role it played in world history, and its landmark status, the B Reactor is a worthy candidate for a document such as this Historic American Engineering Record.

Foreword by the B Reactor Museum Association

This history of Hanford's B Reactor is not just a work of historical investigation. It is also the outgrowth of the collected interests and lives of the members of the B Reactor Museum Association (BRMA). The BRMA was organized in Richland, Washington, in 1991 to promote the preservation of B Reactor and its conversion into a public museum.

To achieve those goals, BRMA has lobbied and worked with the U.S. Department of Energy (DOE), other governmental bodies, contractors working to clean up the Hanford Site, and the public. Although the reactor is still not open to the public, the goal of a B Reactor Museum is now officially shared by the Department of Energy.

Many members of the BRMA worked at Hanford and the B Reactor. Some arrived at Hanford during the top-secret war years and worked on construction of the plant. A few were there at B Reactor when it was first started in September 1944. All members of the BRMA, including even those who never worked at Hanford, have an appreciation for the intense historical focus that can be found at B Reactor.

A contract to write this Historic American Engineering Record was issued to the BRMA by Bechtel Hanford Inc, the DOE contractor whose responsibilities include overseeing historic and cultural resources at Hanford. Bechtel requested BRMA's authorship based on the group's long involvement with B Reactor. Tom Marceau, the technical representative and liaison at Bechtel, did much to facilitate the entire process, and his efforts are greatly appreciated.

At the DOE's Richland Operations Office, Dee Lloyd, the manager of Hanford's Cultural Resources Program, was a ready and helpful resource on many issues that arose.

The work on this document was organized and managed by project coordinator Gene Weisskopf, one of the few BRMA members who never worked at Hanford or in the nuclear industry. Gene was responsible for all aspects of the project and acted as the point of contact between the BRMA, Bechtel, and the DOE. He did the bulk of the research, writing, formatting, and associated tasks for this project. Many others assisted in many different ways.

Del Ballard and Lyle Wilhelmi helped to spearhead this project in the beginning, talking with Bechtel and BRMA members about how the job might be handled. Del spent many hours researching DOE plans and drawings, and provided much assistance and advice to the project coordinator as the work progressed. Lyle Wilhelmi did extensive searches for appropriate photographs, finding plenty from which the best were culled. Both reviewed much of this document and offered valuable comments.

Roger Rohrbacher wrote the first draft for the "Instrumentation" section, clearly explaining how the instruments both controlled the reactor and provided multiple and redundant safety systems. He answered countless technical questions throughout this project, always in clear, understandable language.

Miles Patrick wrote the draft that served as the basis for the material in the "Cooling System" section, and answered many questions about the all-important treatment of cooling water for B Reactor.

Jim Stoffels wrote the bulk of the "Tritium Production at B Reactor" section, and was frequently called upon for advice and counsel. He reviewed the final draft of this document, and offered valuable fixes and suggestions. Jim also secured the rights to include the three Yamahata photos of post-atomic bomb Nagasaki. The sobering images vividly illustrate the awesome power released by the plutonium that was produced at Hanford. We thank Shogo Yamahata, the photographer's son, for granting us permission to include the images in this document.

Ron Kathren reviewed the entire document in great detail, and thereupon revised and wrote more material for the section titled “Worker Health and Safety.” His longstanding expertise in the field of health physics added much to this document.

Kelly Woods provided the background, solid technical advice, and personal remembrances that were needed to bring to life a classic reactor problem laid out in the section named “Graphite Swelling and the Closure of B Reactor.” Kelly’s generous e-mail and telephone communications proved to be a boon to the success of this history.

Other reviewers donated substantial amounts of time to ensure the technical and grammatical accuracy of this document, including Tom Clement, Jim Frymier, Bill McCue, Richard Nelson, Pam Novak, and Jim Williams.

Many of the interviews excerpted in this document were made by Greg Greger, working with videographer Tom Putnam. Their efforts laid the groundwork for the continuing oral history of Hanford and B Reactor. We extend our thanks and appreciation to those who offered us their time and memories.

Many other BRMA members offered advice, suggestions, and encouragement, and their efforts are also reflected in this work, including Richard Dierks, Eugene Eschbach, Greg Greger, Joe Hedges, Annette Heriford, Roger Hultgren, Dee McCullough, Bill Michael, John Rector, Carol Roberts, Jerry Saucier, Bob Smith, and Harry Zweifel.

Others outside the BRMA also deserve recognition and our thanks. At the DOE Reading Room in Richland, librarian Teri Traub and Janice Parthree were immensely helpful during the research phase, and their kind demeanor is much appreciated. In Bechtel’s records-management group, our thanks go to Linda Montgomery and Ed Zugar who directed our searches for photos. We also thank Marjorie McNinch at DuPont’s Hagley Library in Wilmington, Delaware, for her courteous replies to our queries.

We are indebted to all the men and women who ushered in the Atomic Age at Hanford, a part of whose story we tell here. Under the pressures of a world at war, they worked in secret in a totally new, untried industry that might have failed catastrophically. Most of them had no knowledge of B Reactor’s and Hanford’s purpose, but they did have unlimited faith in their country and their cause. As for the other side of B Reactor’s world-changing story, we also recognize those who died in Nagasaki from the bombing on August 9, 1945; their place in history will forever be remembered.

The ultimate “thank you” goes to the members and supporters of the B Reactor Museum Association, without whose efforts the story of B Reactor and all it represents might never have been told.

1. The Manhattan Project

The B Reactor was born of necessity during the height of World War II. It did not mellow in the laboratories of great universities, spend years being fine-tuned in corporate research centers, nor slowly creep from the testing stage into mainstream life. What began as a tantalizing but doubtful scientific hypothesis was quickly pushed into a headlong dash to make the concept a reality.

The quest by the United States to develop an atomic bomb, in which the B Reactor played an important part, is an amazing story that takes on the breadth and tone of epic legend when told by Richard Rhodes in his *The Making of the Atomic Bomb*. The story about the roots of the Manhattan Project that led to the construction of the B Reactor as briefly told in this section is largely based on material in the Department of Energy's document, DOE/RL-97-02, which is a survey of historically significant properties at the Hanford Site.

1.1. World War and the Prospects of an Atomic Bomb

The Second World War burst onto the world with the German invasion of Poland in September 1939. The seemingly endless tensions, bickerings, and civil wars in Europe had exploded into outright war. Immediately after the invasion, Britain, France, Australia, and New Zealand declared war on Germany, while the United States proclaimed neutrality.

The Manhattan Project had its roots in the Advisory Committee on Uranium (ACU), which was formed in October 1939 by President Franklin Roosevelt to explore the feasibility of atomic weapons and atomic power. The critical importance of the investigation had been suggested to Roosevelt in a letter written by physicists Leo Szilard and Eugene Wigner, and signed by noted physicist Albert Einstein. The ACU embarked on an ambitious research program that was carried out through contracts with colleges, universities, and public and private research institutions.

In April 1940, Germany invaded Denmark and Norway, capturing a very specialized plant at Vemork. This factory could separate out from natural water those molecules with a heavy isotope of hydrogen. Scientists familiar with the theories of generating nuclear power knew that this *heavy water* could be a key ingredient in the mechanism. Germany's possession of the plant did not bode well. Nor did the progress of the war. In May, Germany invaded France, Belgium, Luxembourg, and the Netherlands. In June they marched into Paris, and in July Germany began to bomb England in what was to be called the Battle of Britain.

The ACU focused on examining the possibilities of the highly fissionable isotope uranium-235 (^{235}U). However, on March 6, 1941, a research group led by Dr. Glenn Seaborg at the University of California succeeded in creating and isolating the first, submicroscopic amounts of plutonium-239 (^{239}Pu), estimated to weigh only 0.25 millionths of a gram (micrograms, µg). Then, on March 28, the same group demonstrated that ^{239}Pu would fission when bombarded with slow (thermal) neutrons. For an introduction to the basics of nuclear physics, see Appendix A, which also discusses the first harnessing of nuclear energy by Enrico Fermi and his team in Chicago in 1942, which was the prelude to the B Reactor. (Kathren et al. 1994: 31-32, 34)

During 1941, the Second World War continued to escalate in Europe and Asia, while the United States remained out of the fray, separated by two great oceans. In June, Germany attacked the Soviet Union, bent on subjecting that country to the same fate that had fallen on most of Europe. In June, President Roosevelt signed an order that froze German and Italian assets in the U.S. The same action was taken against Japanese assets in July, when relations with Japan were also suspended. In August, the United States announced an oil embargo against the aggressor states. The war was pulling inexorably on the United States, but the country continued to withhold its citizens from the fight.

In the first week of December 1941, the ACU decided to sponsor an intensive research program on plutonium. The contract was placed with the Metallurgical Laboratory (Met Lab) of the University of Chicago, under the direction of Nobel Prize-winner Dr. Arthur Compton. The goal was to perform the research that would lead to the design, construction, and operation of a plant for the conversion of uranium into plutonium. Dr. Vannevar Bush, head of the Office of Scientific Research and Development (the OSRD was the umbrella organization over the ACU), recommended that the Army Corps of Engineers carry out the construction work for such a plant.

1.2. War Comes to the United States

On December 7, 1941, the Japanese raided the U.S. naval base at Pearl Harbor in Hawaii, and suddenly the war had come home. What had been a series of haunting newspaper articles and newsreels about events in far-off lands was now a bloody awakening to the realities of modern war.

With the Japanese invading an American military base, the U.S. military felt that a Japanese invasion of the mainland could be imminent, and they worried that Americans of Japanese ancestry would be inclined to aid the Japanese invaders and might take part in acts of sabotage. Therefore, in February 1942, in the midst of growing wartime alarm and patriotic fervor among the general population, President Roosevelt signed Executive Order 9066. This gave the military the power to exclude anyone from any militarily sensitive areas of the country. The actual result was that anyone of Japanese ancestry was moved out of the west coast into internment camps farther east. Although there was opposition expressed by the Quakers (Society of Friends) and the American Civil Liberties Union (ACLU), the exodus went quickly, and the specter of yet more barbed wire-enclosed camps became a haunting image of the war.

In June 1942, Dr. Bush presented a feasibility report on the plutonium project to President Roosevelt. Bush stated that five basic plutonium production methods were “nearly ready for pilot plant construction,” that an atomic weapon made from plutonium was feasible, and that it might be developed in time to influence the present war. The next day, the Army Corps of Engineers began to form a new “district” (division) that would be in charge of building the plutonium production plant. The name chosen for the new district was Manhattan Engineer District (MED), which would not arouse suspicion or give away its purpose. In fact, it was chosen simply because the office of a key Corps official was located in Manhattan. The formation of the MED was announced in August, and on September 17, newly appointed Corps of Engineers supply and procurement officer Brigadier General Leslie R. Groves was appointed to lead it

1.3. The Hanford Engineer Works

The planned site for the plutonium production plant was the Clinton Engineer Works, located at present-day Oak Ridge, Tennessee. In late 1942, however, discussions with key bomb development scientists such as J. Robert Oppenheimer and others pointed out to MED officials the hazardous nature of the plutonium processes under development. Further discussions with officers and scientists of the DuPont Corporation, the prime contractor for the plutonium project, underscored these hazards. As a result, a consensus was reached at a December 14, 1942 meeting to search for a more remote site in one of the western states. It was just a couple weeks earlier, on December 2, that Enrico Fermi and his team created the world’s first controlled, self-sustained nuclear chain reaction at the Met Lab in Chicago. If Fermi had not succeeded, the future of nuclear power and B Reactor would have been in grave doubt.

The future Hanford Site was scouted in late December and the selection was approved in January 1943. The factors that made it desirable included its remoteness from large population centers and an abundance of clean water, electric power, accessible rail service, and heavy aggregate for making concrete. Land acquisition proceedings were begun, and ground was broken in March 1943 for Project 9536, the Hanford Engineer Works (HEW, the earliest name for the Hanford Site).

In the course of the next 29 months, the MED built the world's first, full-scale, self-contained, plutonium production facilities at HEW. The three essential steps in the process were carried out in three geographically separate areas on the Site:

- Uranium fuel elements were fabricated and jacketed in the 300 Area.
- The fuel was irradiated in the 100 Areas.
- The irradiated fuel was chemically dissolved and separated into plutonium, unconverted uranium, and various fission byproducts in the 200 Areas.

All other areas of HEW functioned to provide support services to the crucial 100, 200 and 300 Areas. One of the support areas, the 1100 Area, included the HEW Village, constructed on the original Richland townsite to house the Hanford Site's operational personnel. Figure 1 shows the layout of the Hanford Site and its location within eastern Washington state. A stunning view of the 100-B complex and the B Reactor in operation is shown in Photograph 1, which was one of the first photographs released to the public after the atomic bombing of Hiroshima.

The HEW plutonium production project succeeded. This feat represented enormous and unprecedented achievements in engineering and physics, the largest scale-up in the history of chemical engineering, and pioneering accomplishments in uranium fuel fabrication and environmental monitoring.

An outstanding document from September 1943 (HAN-43508) summarizes the plans and technical basis for the entire process at Hanford. Of particular interest is its tone, which expresses the hopes, uncertainties, and dangers surrounding the construction and operation of the Hanford Site. It was prepared as an addendum to the formal contract that would soon be signed by DuPont and the U.S. government. (Evidently, for the preceding nine months, all the construction at Hanford had been performed under a simple letter of agreement.)

2. Reactor Construction

Just months after the very first controlled nuclear chain reaction in Chicago on December 2, 1942, work began on the full-scale plutonium production facilities at the Hanford Site. This short time span left little room for the traditional design and modeling gestation period between concept and construction, and was just the first of many challenges for the scientists, engineers, and construction personnel who built the Hanford Site.

Excavation for the B Reactor (the 105-B building), which housed the nuclear pile, began in October 1943. Less than a year later, on September 13, 1944, construction was essentially completed and the nuclear reactor and all its supporting structures and systems were turned over to the operating personnel. (DuPont 1945: 778)

2.1. Worker Recruiting

When Enrico Fermi needed a work crew to help carry and stack graphite blocks for some of his experimental piles, he managed to round up a dozen young men from the Columbia University football squad. Another time he recruited 30 high-school drop-outs waiting for their draft notices. Building the B Reactor and the rest of the Hanford Engineer Works was not quite as simple. (Rhodes 1986: 397, 430)

At the peak of Hanford construction in mid-1944, there were some 45,000 workers on the Hanford payroll, and an average workforce of 22,000 throughout the life of the project. To achieve these numbers and maintain the workforce, DuPont's recruiters interviewed some 262,040 applicants throughout the United States, and hired 94,307. (Thayer 1996, 93)

Finding this many workers was a monumental task. The Depression had ended and World War II was in full swing, and a major portion of the working population in the United States was already either working or in the armed services.

Furthermore, the Hanford Site's remote location, high-desert terrain, and somewhat inhospitable weather did little to attract recruits; in fact, those regional attributes frequently scared them off. The site was 20 to 40 miles from the closest towns, and larger cities were even more distant (Spokane at 150 miles; Seattle at 225 miles). The construction camp that housed most of the workers on the site was a vast conglomeration of barracks and small trailers in an arid, dusty expanse of desert. The camp was thrown together for the short-term with few amenities.

> Oh the stories we heard, there were gangsters and everything else, they threw a bunch of people in jail, and it was just rough. According to what we heard, it got to be 135 degrees in the summertime, you could fry an egg on the sand, and there was a dust storm everyday. Nonetheless, you know, there was no grass, no lawns, and when the sun reflected right back on you; it was hot. But not unbearable, like we kind of thought it was down there. *Glenn Stein, 1-Aug-1992*

> When I arrived in February 1944, I didn't see too much of the dust situation until the summer months came on. I lived in a dormitory for a year after arriving here and I do remember the dust storms that we had during the summer. I recall one night I left the

> window open and I woke up in the morning with a big coat of dust all over everything. Dust was a big problem. With all the construction work and lack of trees, the ground was torn up and the least bit of wind would bring up what we call the Termination Winds. People would come here, take on the job, and not realize the weather conditions in this area. They'd work here for a while and everything was rosy until the wind would start to blow, and you'd get one of those terrific dust storms. They'd say, "This is enough for me, I'm leaving," and they would terminate. *Monty Stratton, 8-Jun-1993*

The level of skill required for many jobs in the brand new field of pile construction was beyond the reach of many potential workers. The top-secret nature of the project meant that prospective employees were told very little about the purpose of the project or even the nature of their job. All work within the 105-B exclusion area (surrounding the 105 pile building) was classified, so that all workers there were required to have a security clearance, which undoubtedly eliminated some otherwise acceptable candidates. (Wahlen 1991: 10-11)

On the other hand, there were a number of reasons why the Hanford Project was a great place to work, even with its rather severe living conditions. The Depression was just ending, and a full-time job with high wages and plenty of overtime was a dream come true for many Americans.

> I remember that well, because I checked what the average [worker's salary] was and it was just about exactly what I was getting as a lieutenant colonel. *Frank Matthias, 26-Sep-1992*

The project was war-related and of critical importance, and anyone working there could feel proud to be helping in the war effort, even if they knew little about the project or what the final product would be.

> In reflecting back, I've always felt privileged to have been a part of it. You always felt in those days, well, you should have been in the service. I went up to Chicago and twice tried to get into the Navy, and each time they'd say "Well, what are you doing now?" And I'd say, "Well, I'm in explosives," and they'd say "There's the door, get out." But you always felt that you should have been, in your age group, you should have been in the Army and not out here. But you did feel some sense of gratification that you had some part in ending the war. *Harry Zweifel, 14-Dec-1991*

For those who had known the region before it was torn apart for Hanford Site construction, and for those who stayed on at Hanford afterwards, the lack of urban amenities and the endless horizons were one of the region's most valued features.

> It was a marvelous place to grow up. I still think that it was the greatest place that a child could ever grow up. We had such freedom—we swam, we rode horseback, and we hiked. We had such a close-knit community [in the original towns of Hanford and White Bluffs], if there were any activity going on, everybody in the community participated. *Annette Heriford, 15-Dec-1991*

> I was going to college at Pullman and I came home in 1943, the first summer between terms in school, to find out that my parents were going to have to move off their property. At that time they [the Corps of Engineers and DuPont] were anxious to have anybody work on the project that already had a home there, because they didn't have the construction started yet on the women's barracks or anything like that in Hanford. So

> they were anxious to have anyone work that had a home there. So my parents didn't move out of their home, even though the government had taken it over almost a year earlier. They had to rent it from the government. So I worked for the construction project when DuPont first came in here the summer of 1943. *Yvonne McGee, 2-Aug-1992*

Once the adjustment was made to the hardships of camp life, those same hardships forged a deep camaraderie among the workers. This was also true later, after permanent housing and the semblance of a town had been built for Hanford's thousands of operating personnel. They had all embarked on a new life in a new land, helping to build and operate the very first part of a brand new industry.

2.2. Job Priorities

The Hanford Site had been chosen for its remoteness and sparse human population, but these attributes became gross impediments when it was time to begin construction. There were essentially no support facilities or commercial infrastructure that could be converted to offices, warehouses, factories, and the like, to support the mammoth work force and project activities that were fast coming to the Hanford Engineer Works.

DuPont established its first construction office for the Hanford Project on February 25, 1943, in temporary quarters in the town of Pasco. This was the largest and most well-equipped town in the vicinity, and was a major rail center for the region, as well. But it was nonetheless a small, rural town, 30 air miles from the Hanford Site and across the Columbia River from it. Today, the cities of Pasco, Kennewick, and Richland are known as the Tri-Cities.

As DuPont's personnel began to arrive, the company rushed to secure buildings for offices, warehouses, shops, and so on, eventually leasing a patchwork of "store buildings, rooms, basements, warehouses, and other facilities to provide necessary space." For example, it established its Purchasing Office in the front basement room of the Midstate Amusement Corporation. (DuPont 1945: 16-17)

A critical part of this initial groundwork was communications, and DuPont immediately set up a teletype room with a direct transmission line to their offices in Wilmington, Delaware. However, this was not yet the age of computers and digital networks—the teletype connection was active only from 7:00 AM to 3:00 PM (local time), with extended hours and additional machines added as time went on. (DuPont 1945: 16-17)

DuPont officially began construction of its Hanford Project on March 22, 1943, when it opened an employment office in Pasco. Although this is DuPont's "official" date, surveying and site preparation were already in progress at the 100-B Area. A few months later during the summer, DuPont began the transition to more permanent buildings on the Hanford Site. Because most new workers arrived by train at the Pasco rail station, DuPont maintained the Pasco employment office throughout the major portion of construction. (DuPont 1945: 17)

To clarify and prioritize the next steps in the project, about this time DuPont sent employees to investigate several large-scale construction projects in similar geographic and climatic conditions, including two in Nevada: the Basic Magnesium plant and Boulder Dam. From their investigations, DuPont established a list of tasks that would be key to starting the project; the first ten items at the top of the list were (DuPont 1945: 18):

1. Immediate housing for employees
2. Housing and temporary offices, warehouses, etc.
3. Existing feeding facilities
4. Health and sanitation
5. Mileage and shoe rationing
6. Temporary employment office

7. Existing hotel accommodations
8. Project feeding and housing facilities
9. Milk supply
10. Food procurement

None of these tasks had anything to do with actually producing plutonium; the job of simply preparing to build the production facilities at Hanford was a monumental undertaking in itself.

The culmination of many of these tasks was the Hanford Camp, the temporary construction camp that was built on the Hanford Site at the town of Hanford. It began housing workers in April 1943. Although the original town of Hanford was quite small, it provided the best of all the possibilities. It was within the boundaries of the Hanford Site, but would not be in the way of ongoing construction. There were existing buildings that could be converted, water, electric power, a railroad line, and highway access. (DuPont 1945: 42)

Hanford Camp was a sprawling complex of barracks, trailers, hutments (later called Quonset huts) and other temporary buildings that housed the majority of the Hanford workers during the construction phase. The group-living conditions in each building meant that there had to be separate living quarters for men and women. It is interesting to note that DuPont’s job was made even more difficult by the sentiments of the times: separate quarters were required not just for men and women, but for white men and white women as well as “colored” men and “colored” women. (DuPont 1945: 86)

2.3. Security During Construction

The construction and later operation of the Hanford Site took place under tight security to protect the secret plutonium production methods, and to avert attempts at espionage and sabotage. As soon as DuPont established its offices in Pasco in February 1943, it established a Security Agent, whose job was to create a security department and draft plans and procedures that would ensure the security of the project. (DuPont 1945: 47)

Every aspect of design and construction was scrutinized and then structured to maintain security. The general rule was that employees or visitors to the site should know only as much as necessary to complete their jobs, and as few people as possible would know the entire scope of the project and its inner workings. (Thayer 1996: 48)

The security department’s primary duties included protecting the buildings and infrastructure of the project, classifying and protecting information, and designing emergency evacuation plans. In line with these responsibilities, the security department screened prospective employees and visitors to the project, and eliminated those with suspect backgrounds. Identification badges were assigned to employees and visitors, which established where they were allowed to go and what type information they were allowed to see. All Hanford was patrolled and well guarded; a typical perimeter fence guard tower is shown in Photograph 2. (DuPont 1945: 47-48)

In general, in the 100-B Area (and this was true for other two Hanford reactor Areas 100-D and 100-F), only the pile building and its adjacent structures were deemed “classified” with restricted access. In effect, this subset of the 100 Area included the 105 and 116 structures (the pile building and its tall ventilation stack; see Figure 2). Because of the security needs, and because of the highly specialized and complex construction involved in the pile building, a “105 Area” was defined around the pile. The structures in this area were built under the supervision of a separate DuPont organization known as the 105 Area. This group, headed by a division engineer, managed all activities related to the pile proper. (DuPont 1945: 661; Wahlen 1991: 3)

This meant that workers could access any of the other buildings in the 100 Area without having special permits or badges, which facilitated progress of the work. As the structures in the 105 Area took shape, a temporary fence went up around them, and workers and those delivering materials needed the proper identification to enter. This ongoing process inevitably slowed down construction to some extent, but it was necessary to the overall security of the project. (DuPont 1945: 661)

Most of the construction drawings (plans or "blueprints") for the 100 Area buildings (those outside of the 105 Area) were not classified. However, about a third of the plans for the 115 building (Gas Purification Facility) were classified, as were those for the 105 building. The limitations on access to the classified drawings were another impediment to the pace of construction, as personnel were not free to refer to these drawings as the need arose. (DuPont 1945: 662)

Although security measures may have hampered the efficiency of the operations, the Hanford Site was nonetheless taken from bare ground in March 1943, to the first shipment of finished product (plutonium) in a scant 23 months.

> I didn't know [the purpose of the construction] until after I'd been here a short while. I pretty much had it figured out. Now, after I was made foreman, then the foremen, engineers, and superintendents were the only ones who ever saw a drawing! We had to go into a vault inside the reactor building, look at the drawings, figure and get your dimensions, make notes, then you go out to your crew and tell them what to do and what your dimensions were! I had to make notes in my little notebooks, you know, it was hard to remember all those dimensions, but we did pass on the information and it worked out very well.
>
> You'd never see a drawing out on the floor; no one saw a drawing except the foremen and the superintendents. Which brings out a strange story. I was 1A in the draft when I came up here, and I got my notice to go to Spokane and take my physical with some others. I passed my physical, I came back, and it wasn't too many days before I got my notice to go into the Army. So I gave this notice to the superintendent, and he says "You cannot go, there's no way you can get in the Army; you know too much about what is going on. This is a highly secret project." So I did not have to go in the Army; my two brothers did, but I did not. *Rudy DeJong, 6-Apr-1995*

2.4. The Origins of the A Reactor

The 105-B building, the B Reactor, was situated within the 100-B Area on the Hanford Site. Figure 2 shows the area and its major structures; the diagram is from an early DuPont history of the Site (DuPont 1945: 690).

The other two reactors built during the Manhattan Project were 105-D and 105-F, which resided within the 100-D and 100-F Areas, respectively. All three areas were located in the northern portion of the Hanford Site, on the south shore of the Columbia River and its all-important water for cooling the piles. (Refer back to the map in Figure 1).

At the time the Hanford Site was first chosen in January 1943, the plan had been to build eight piles, each with a thermal power level of 100 megawatts (MW). Sites for each pile were chosen along the banks of the Columbia River. Soon after, DuPont and the University of Chicago settled on a 250 MW pile design. Consequently, only three piles would be required to meet the immediate military requirements for plutonium, and only three of the eight sites at Hanford would be used. The inherent dangers in operating these new and unproven nuclear reactors necessitated their being located as far as possible from population centers or other Hanford complexes. Instead of placing the piles in the first three sites on the river, they were instead laid out using every other one. The sites at either end were not used to provide a further margin of safe distance. By this approach, only sites B, D and F were used, and that's how the world's first production-scale pile came to be called the B Reactor. Although six more piles were built later in Hanford's history, there never was an A Reactor. (IN-6263 1945: 50, 66; Rhodes 1986: 498-499)

2.5. Site Preparation

The three 100 Areas formed a triangle at a sharp bend in the Columbia River, with the 100-D Area at the top of the triangle (northernmost). The 100-B Area was situated approximately 7 air miles southwest of 100-D, while 100-F was approximately 9.5 miles southeast of 100-D. Each area was rectangular; the 100-B Area was the largest at 724 acres, and averaged about 460 ft above sea level. (DuPont 1945: 636-637)

Geologic studies were performed in all three areas by the Portland office of the U.S. Geological Survey to determine soil conditions and the availability of ground water for sanitary usage. The landscape they found was generally covered with sagebrush and cheatgrass on a very sandy topsoil about one foot thick. Approximately one-fourth of the region was rocky soil with gravel and boulders (up to 2.5 ft in diameter) exposed and below grade. The geologic work included core borings that varied in depth from 95 ft to 540 ft. The typical profile consisted of very sandy and rocky ground, beneath which lay mixed sand, gravel, and some cobbles and boulders, down to at least 50 ft below the surface. (DuPont 1945: 637)

To facilitate accurate horizontal and vertical control for all surveying, layout, and construction activities in the 100 and 200 Areas, a "Plant" coordinate system was established. This created a grid within the Hanford Site, where all distances were measured from a central point. This zero point for the north-south and east-west axes lay within Section 17, Township 11N, Range 28E. As indicated in Figure 3, the center of the 100-B Area is located near W80000, N70000 on this Plant coordinate system. This map appears in the DuPont construction history, page 643. (DuPont 1945: 641-642)

General survey work for location and definition of the pile areas was started on March 19, 1943, and was completed in the 100-B Area on April 15, 1943. Construction in this Area was officially opened on August 27, 1943, when ground was broken for the 107-B Retention Basin, part of the substantial water treatment facilities for the pile. (DuPont 1945: 641, 645)

Layout of the 105-B building began October 9, 1943, when reference points on the center lines of the process unit (the pile itself) were established, and the building was staked out for excavation the next day. (DuPont 1945: 778)

2.6. The 105-B Building

The 105-B building would house the nuclear pile, its fuel loading and unloading facilities, control rod and safety rod facilities, the operators' control room, and various work areas. It would essentially serve the same purpose as the squash court used by Enrico Fermi for his experimental piles in Chicago, only on a very much larger scale. The building is shown during the latter stage of construction in Photograph 3.

The 105 building was somewhat pyramidal, made from reinforced concrete and cement block, with a portion of it being steel frame. The overall dimensions of the building were 120 ft x 150 ft x 120 ft high. Its area was approximately 24,000 ft^2, with a displacement volume of approximately 2,000,000 ft^3. The main portion of the building housed the process unit (pile), which was somewhat cubical. The pile's outer dimensions (including its thick shielding) were approximately 37 ft from its front to its rear (roughly west to east), 46 ft side to side (north-south), and 41 ft high. Figure 4 shows a cutaway diagram of the structure; Photograph 4 is a diagram of the floor plan of the reactor's main floor. (DuPont 1945: 788, 809)

Any impurities, such as dust, could ultimately reduce the pile's ability to sustain a nuclear chain reaction (the pile's *reactivity*). Therefore, to control the building's environment during construction of the pile itself, a large temporary structure was attached to the building to act as an air lock. It allowed the transfer of personnel and construction material in and out of 105-B without upsetting the positive air pressure inside. (DuPont 1945: 780)

The 105-B Reactor building was divided into the following essential rooms and service areas (DuPont 1945: 809):

- The charging area, or work area, was a large concrete room in front (west) of the charging (front) face of the pile. It was large enough so that any of the 40 ft long aluminum process tubes could be inserted or removed from the pile for maintenance purposes.
- Behind (east of) the discharge (rear) face, separated from the pile by a 5 ft thick concrete wall, was the 20 ft deep water-filled pool, the irradiated fuel storage and transfer basin.
- To the left (north) of and opposite the pile, separated from it by a 3 ft thick concrete wall, was the main control room. It housed virtually all of the instruments and mechanisms for controlling the pile and maintaining its safety. The control room was air conditioned and lined with acoustic material for the comfort of the operators. Adjacent to it and separated from it by a glass partition were two control room offices.
- Above the control room and offices were the rooms that housed the nine horizontal control rods (HCRs), with which the pile operator controlled the pile's reactivity. The rods were approximately 75 ft long, arranged in three banks of three rods each. The inner rod room, abutting the near (left) face of the pile, is where the irradiated portions of the rods were located when the rods had been withdrawn from the pile. A 3 ft thick shielding wall separated this room from the outer rod room, or apparatus or rack room. This room housed the portions of the rods that were never inside the pile and therefore not irradiated. It also contained the driving mechanisms for inserting and withdrawing the rods, and the water lines for cooling them.
- Adjacent to the work area (to the west) was the valve pit, which housed the main connections and control valves for the process water lines that came from the Process Pump House (the 190-B building) and ran to the pile. In the back of the valve pit was a laboratory where water-quality analyses were made.
- The building ventilation fan room was located to the south of the valve pit. Here were located the main blowers, heaters, and air filters for the entire building's heating and ventilation systems. There were two dual-drive (steam and electric) supply fans and four exhaust fans (two steam and two electric). The exhaust fans were located in separate concrete cubicles to isolate them from the supply system. A concrete enclosed exhaust duct ran from the fan room to the 200 ft high stack (identified as 116-B), and exhausted the air from the 105 building. The building was given a positive air pressure that was maintained at approximately 1 in. of water compared to the outside air pressure. (HAN-10970, 811; Wahlen 1991: 1-2)
- Above the pile suspended from cables were 29 vertical safety rods (VSRs), which could be dropped into the pile to *scram* the pile—kill its nuclear chain reaction very quickly and shut down the pile. About 40 ft above the pile were the winches that were used to pull the VSRs out of the pile. Also above and to the left side of the pile were five tanks of boron solution that made up the last ditch safety system.

2.6.1. Quantities of Materials Used in 105-B

The following quantities of materials went into the construction of the 105-B building, exclusive of the pile itself (DuPont 1945, 810):

Structural steel	390 tons
Reinforced concrete	17,400 yd^3
Concrete block	50,000 blocks
Concrete bricks	71,000 bricks
Roofing	25,000 ft^2

2.6.2. What's a "Scram"?

The word *scram* had been in use in the English language since the late 1920s, meaning "to go away at once," especially if you weren't wanted. The term was adopted early in the new field of nuclear piles to denote a fast shutdown of the pile, especially in potentially dangerous situations. But there's one other possible origin of the term that can spark a smile.

> *Scram* came from the days of Fermi's pile in Chicago. Nobody was sure just what sort of problems might come up, so they had several backup safety systems to shut down the pile. They had a safety control rod hung above the top of the pile, and it could be dropped into the pile very quickly to kill the reaction and shut it down. The way they'd drop that rod is, they had a man standing by with an ax who'd just cut the rope in an emergency. He was the *safety control rod ax man*: S-C-R-A-M. *Bill McCue, 27-Mar-1998*

2.7. The Pile

At the heart of the 105-B building was the process block, or pile—the nuclear reactor. It was modeled after Fermi's CP-1 and later experimental piles, and included graphite blocks, uranium fuel, and neutron-absorbing control and safety rods. But the scale of the B Reactor dwarfed all aspects of Fermi's piles. For example, simply compare the massive 105-B building and its accompanying facilities in the 100-B Area to Fermi's squash court, or the Hanford Site's hundreds of square miles of eastern Washington desert to downtown Chicago. Where Fermi's famous pile was designed to operate at power levels measured in single-digit watts, the B Reactor was designed to operate at up to 250 megawatts, and would eventually be operated at levels as high as 2,000 megawatts (see "What Was Missing in Fermi's CP-1" in Appendix A for a discussion of other deviations in design).

For a general arrangement of the pile assembly, see Figure 5. The pile consisted of the following main components (DuPont 1945, 788):

- Thick concrete foundation
- Steel baseplate 1.5 in. thick
- Cast iron bottom shield 10 in. thick
- The cubical stack of graphite blocks, 36 ft wide, 36 ft tall, and 28 ft front to rear
- Cast iron thermal shield walls and top approximately 10 in. thick surrounding the graphite
- Steel and Masonite biological shield walls and top about 4 ft thick
- Welded seams and seals that made the entire pile gas-tight
- 2,004 aluminum process tubes, running from the front face to the rear face of the pile, to hold the uranium fuel and carry the cooling water

Other pile-related components, which will be discussed in later sections, include the horizontal control rods, vertical safety rods, fuel loading and unloading facilities, instrumentation and control mechanisms, cooling system support buildings (which together dwarfed the 105-B building), and other support facilities.

The pile was constructed to the most rigid standards in dimensional tolerances, quality of materials and workmanship, and cleanliness. Once the pile had been operated, its radioactivity would make it extremely difficult, or most likely impossible, to correct any errors introduced during construction. Not only that, but the urgent schedule of this wartime project left little room for delays due to callbacks once work was completed.

Another factor that complicated the construction of the pile was the massive amount of materials that went into that small area (DuPont 1945, 795):

Masonite, 0.125 in. thick	2,500,000 ft^2
Steel plate	4,415 tons
Cast iron	1,093 tons
Graphite	2,200 tons
Copper tubing	221,000 ft
Saran tubing (a flexible plastic)	176,700 ft
Aluminum tubing	86,000 ft

2.7.1. Foundation, Base Plate, and Bottom Shield

When the foundation of 105-B was poured, the pile area was given a massive footing about 23 ft thick, which was completed in three pours. The first was a rough foundation pour. The second enclosed the instrument ducts and gas headers that led to the pile. At this point, a 0.25 in. steel plate lining was installed over the concrete that would later be covered by the third pour. The plate would eventually be welded to the pile’s walls to provide a gas-tight enclosing membrane for the pile (to keep air out and helium in). Also at this level, a 1.5 in. thick steel base plate was set into the concrete around the perimeter of the pile, which would create a solid, level platform for the laminated outer walls of the pile. (DuPont 1945: 788; INDC-311: 1-2)

Once the base plate was laid, structural steel T-section frames were erected for the two side walls, which provided rigidity and the framework for the laminated biological shields. The framework was laid 4 ft apart on each wall and welded to the base plate. Each T-section consisted of a 2.5 in. flange 4 ft wide, and a web of 0.5 in. steel 50.5 in. deep. The space between each T-section served as a bay, in which a 4 ft block of biological shielding would later be placed. The shielding is discussed in the next section, where Figure 6 shows the relationship between it and the steel framing. (INDC-311: 3)

At this point, the first row of prefabricated 4 ft laminated biological shield blocks, or *B blocks*, was laid for the front wall, and two rows were laid for the rear (the rear foundation was one B block lower than the front, due to the depth and layout of the fuel discharge chutes). Once the blocks were welded into place, the third concrete pour was made within these blocks for the pile’s base. The concrete reached to about the top of the B blocks. (DuPont 1945: 788; INDC-311: 5)

These front and rear first rows of B blocks were below the base of the graphite pile, and had no holes in them for process tubes or other pile access. They served to block any radiation that might leak through the edges of the pile’s foundation. (HTM 1945: 817)

A 1 in. layer of grout was laid on top of the final layer of concrete, which served as a base for the bottom 10.25 in. thick thermal shield of water-cooled cast iron blocks (the bottoms of which were at a level about 6 in. above the concrete floor of the 105-B building). The shield blocks had grooves in them to receive 0.75 in. stainless steel cooling pipes. The diagram in Photograph 5 shows a cross section of the pile foundation and base. (INDC-311: 2, 5)

The cast iron thermal shield blocks had been meticulously machined, so that the top face of each varied by no more than 0.003 in. They were laid precisely to form a smooth, level surface, with accuracy maintained to ±0.005 in. (DuPont 1945: 795)

Such exacting tolerances were to be maintained throughout the building of the pile. Care was also taken to eliminate any foreign material from this layer, which could diminish the pile's reactivity or cause mechanical or structural complications during pile operations. The cast iron bottom shield served as the base for the graphite blocks that made up the bulk of the pile.

Once the bottom shield had been laid, the next row of B blocks could be set in the front and rear faces. Near the base of these blocks ran a horizontal row of 3 in. holes for the 0.75 in. stainless steel cooling pipes that would run through the cast iron base blocks. Near the top of these B blocks were the first two rows of holes for the pile's process tubes (as shown in Figure 7). (INDC-311: 5)

As the B blocks were erected, cast iron shielding blocks were laid up for the interiors of the side walls of the pile. On completion of the side walls, work began on laying the graphite pile and placing the cast iron shield blocks for the front and rear walls. (DuPont 1945: 788)

2.7.2. Shielding

When the B Reactor was operating, the pile would produce extremely high intensities of ionizing radiation, far beyond any levels that had ever been dealt with before, and of sufficient magnitudes to be lethal, with exposure times of only a few seconds. The people who operated the pile would have been quite safe if they had simply remained at a safe distance from the pile. Unfortunately, remote operation at a distance of tens or even hundreds of *miles* from the pile was quite impractical.

Instead, two essential shields were built around the pile to block, or to be more accurate, to greatly reduce the radiation levels in the surrounding work areas:

- 10 in. thick cast iron thermal shield enclosed the graphite
- 50 in. thick biological shield of alternating layers of Masonite and steel made up the outer walls of the pile

Figure 6 shows a cutaway view of the pile and its shielding. Note the 24 in. layer of graphite at the outer edges of the pile. This zone of blocks, called the *reflector*, was not penetrated by process tubes. It was intended to increase the reactivity of the pile by reflecting neutrons back into the area of uranium fuel, where the neutrons were needed. In doing that job, the reflector also substantially reduced the amount of gamma and neutron radiation that emanated from the pile. Nonetheless, the small amount that passed through the reflector would have been deadly to anyone standing nearby, and the two outer shields were of critical importance. (HTM 1945: 416)

2.7.2.1. Thermal Shield

The thermal shield consisted of interlocking cast iron blocks that surrounded the graphite pile on all six sides. The interlocking joints ensured that no crack or space would allow radiation to pass straight through, and greatly increased the shield's effectiveness. As discussed earlier in section 2.7.1, the shield layer at the bottom of the pile also served as a precisely leveled platform on which to stack the graphite. (HTM 1945: 815)

Most of the heat produced by the pile was removed via the water-cooled process tubes that surrounded the uranium fuel cylinders, or *slugs*. Only about 0.2 percent of the total heat produced was absorbed by the shielding that surrounded the graphite. The thermal shield derived its name from the fact that it absorbed 99.6 percent of this heat, mostly through the absorption of slow neutrons and gamma rays, and to a lesser extent by slowing down fast neutrons. Removing even this small fraction of the pile's total heat from the shielding was a crucial heat transfer problem, due to the relatively small volume of cast iron shielding that had to do the job. (HTM 1945: 416, 503)

To remove this heat, the entire thermal shield was cooled with water. The shielding in the front and rear walls was cooled by the 2,004 process tubes that carried the uranium fuel and cooling, and which penetrated both of those walls. The two sides, bottom, and top were cooled via 0.75 in. stainless steel pipes that ran through grooves in the blocks, spaced 8.375 in. (8 3/8 in.) on center. There were a total of 208 shield-cooling tubes in the pile, each of which carried a water flow of 3.5 gallons per minute from a separate supply header. This outer row of cooling tubes can be seen in Figure 5, Figure 6, and Figure 7. (HTM 1945: 416, 513)

The thermal shield absorbed only a fraction of the intense ionizing radiation that emanated from the pile. That which passed through it (quite a bit of which was fast neutrons) would still be of sufficient intensity to be dangerous or even deadly to persons outside the pile. However, the heat-producing energy level of the radiation that escaped through the thermal shield was of a low enough order (about 1.5 kilowatts) that removing heat was no longer an issue. Dealing with this remaining threat to health was the task of the outer biological shield. (HTM 1945: 416)

2.7.2.2. Biological Shield

Fast neutrons are most easily slowed down by elements of low atomic number. Hydrogen, for example, takes on about half of a neutron’s energy at each collision. A pressed wood-fiber product called Masonite was a popular, nonstructural building material in the war years and for years afterward. While not at all exotic, it was readily available and happened to have a hydrogen content of about 6 percent. On the other hand, a high-density metal such as iron does a good job of absorbing thermal (slow) neutrons and gamma radiation. Therefore, the outer biological shield was devised as a sandwich barrier of steel and Masonite, which would slow down fast neutrons and absorb the resulting slow neutrons, and also absorb gamma radiation. (HTM 1945: 807)

The shield consisted of six 4.5 in. layers of Masonite (each consisting of 36 sheets of 0.125 in. Masonite), for a total thickness of about 27 in., and six 3.75 in. layers of steel (about 22.5 in.), for a total shield thickness of about 50 in. The layers were laminated, beginning with an inside layer of steel and finished with an outside air-tight welded metal enclosure for the pile. Tests showed that each 4.5 in. of biological shielding reduced the neutron intensity by a factor of 10, so that the entire 50 in. of shield produced a reduction of 10^{10}. By comparison, about 15 ft of concrete would be needed to have the same shielding effect, so the savings in materials, building space, and time were substantial. (HTM 1945: 815-816)

The arrangement of the biological shield blocks are shown in Figure 6, Figure 7, and Photograph 5. The thick biological shield enclosed the entire pile, except for the bottom where it was not needed, and was built in two different ways.

2.7.2.2.1. B Blocks

The front and rear walls of the pile were penetrated by the 2,004 process tubes, which required precise alignment all the way through the pile. There would also be personnel working outside each of those walls, so that the shielding would have to be as tightly constructed as possible.

For these reasons, the front and rear biological shields were factory-built as 4 ft cube-shaped blocks, called B blocks. Each weighed about 10 tons; 121 were used for the front wall, and 132 for the rear (because the rear wall of blocks started one row lower than the front). The blocks came to the site ready to be installed, requiring only a cleaning with carbon tetrachloride (a highly toxic solvent that is no longer used for cleaning purposes). But care had been taken to measure each block precisely as it left the factory, so that the craftspeople on site could lay the blocks with as little dimensional variation as possible. (DuPont 1945, 791).

Most blocks had holes for 36 process tube assemblies. The edges of the blocks fit together with tongue-and-groove joints, which added strength while also eliminating any cracks through which radiation might escape. (HTM 1945: 817)

Any deviations in their lay-up could have affected the smooth insertion of the process tubes or allowed radiation to leak out. Tolerances were therefore very tight for these massive blocks, ranging from ±0.005 in. for the blocks near the bottom to 0.015 in. for the blocks near the top. (DuPont 1945, 796).

> I came to Hanford in late 1943, as B Reactor was coming up out of the ground. I was a Senior Engineer, in charge of the flow of workers and materials, and the installation of the blocks in the front and rear faces of the process block [the pile]. We used an overhead trolley crane that ran over the process block to move the blocks into place. Each block had a tremendous screw eye in its top. We'd pass a cable sling through it and use the crane to pick it up, move it horizontally, and lower it into place. There were steel plates added across the outside face of them, which were welded and then peened [hammered] to intensify the strength of the weld. The peener worked right behind the welder. Those blocks fit with very close tolerances, and I've always felt that not nearly enough credit has been given to the craftspeople who constructed the pile. *F.W. "Bill" Michael, 2-May-1998*

2.7.2.2.2. Site-Fabricated Laminations

The biological shielding for the right and left sides, and the top of the pile, was built on-site from sheets of 0.125 in. Masonite and 1.875 in. steel. They were fitted between the steel T-beams that supported the walls and formed the top of the pile. At the edges and corners of the pile, the laminations overlapped one another in a stair-step fashion to prevent the direct escape of radiation. (HTM 1945: 817)

Again, tolerances were extremely tight: the sandwich panels had to fit against the T-beams with a gap of less than 0.005 in. at any one point. (DuPont 1945: 795)

2.7.3. Graphite

As in Fermi's CP-1 pile (refer to Appendix A), the graphite in B Reactor served to moderate (slow down or reduce in energy) the fast (high energy) neutrons that would be freed by the fissioning of a uranium-235 nucleus. The slow neutrons were then available to fission more ^{235}U, or to be absorbed by ^{238}U atoms that might then undergo the transmutation process to plutonium-239 (^{239}Pu).

The lattice of uranium and graphite within the pile would also closely match the CP-1, as dictated by the physics of nuclear chain reactions: the graphite blocks were 4.1875 in. square, and the uranium fuel was spaced 8.375 in. on center. However, the graphite used in the B Reactor was of much higher quality and purity than was attained for the CP-1, as was the precision with which it was milled to size and then stacked in the pile.

2.7.3.1. Manufacturing the Graphite

The specifications for the pile's graphite were unprecedented, requiring a purity never before demanded of the world's few graphite manufacturers. The excess reactivity of the nuclear chain reaction could be so tenuous that the slightest impurities would have imperiled its success.

Although larger graphite blocks could have been used to lay up the pile, there was a manufacturing advantage to producing the smaller sizes (about 4 in. square and 48 in. long). In the graphitizing process, impurities within the graphite migrate to the surface where they are carried away, so it takes less time for a smaller block to achieve a given level of purity. (HTM 1945: 404)

So much graphite was required for the pile (about 2,200 tons) in such a short time that several manufacturers were involved. There were small but critical variations in graphite quality among them, and among the many batches they produced. Just as Fermi had done with his Chicago piles, the quality of each graphite block determined its position in the pile.

During manufacturing, each block was stamped with a number that signified its quality. Other identifying numbers were added during the milling process on site at Hanford, so that each block's overall quality was well known by the time it was ready to be laid in the pile. (DuPont 1945: 789)

Of the essential materials used in the production of graphite, the highest quality was found in three grades of petroleum coke (Kendall, Cleves, and Toledo) and two grades of pitch (Chicago and Standard). In combination, these two produced batches of graphite that were ranked in the following descending order of quality: Kendall-Chicago, Kendall-Standard, Cleves-Standard, and Toledo-Standard. These grades were arranged in the pile as shown in Figure 8. The center of the pile was the most critical area where the greatest neutron activity took place, while the activity decreased farther from the pile's center. Therefore, the highest quality graphite (the best of the "nuclear" grade) was reserved for the central portion of the pile, while the graphite of lesser quality was used in the outer areas. The lowest quality blocks were used in the 24 in. reflector at the edges of the pile. (HTM 1945: 404)

2.7.3.2. Milling the Graphite Blocks

When the graphite blocks arrived at Hanford, they had not yet been milled to their finished dimensions. This was to be done on-site, with the consequent strict supervision of quality assurance. The milling was done in the 101-TC building, which was situated near the old Hanford townsite. It was originally built as a temporary structure, but served as the graphite shop for Hanford piles until 1953. (DuPont 1945: 789; Gerber 1993: 18)

The 101-TC building was the first to be given restricted access (January 18, 1943). Unlike the 105-B building, that restriction was lifted when the pile fabrication work was finished and all pile-related materials had been removed from it (January 10, 1945). (DuPont 1945: 799)

The first 315 tons of graphite to arrive at the Hanford Site were milled and installed in the 305 test pile, located in Hanford's 300 Area just north of the town of Richland. The experience gained while preparing this batch resulted in a much higher degree of efficiency and accuracy by the time the graphite for B Reactor was milled, beginning December 10, 1943. (DuPont 1945: 789-790)

Milling the graphite blocks to their finished sizes was mostly performed on converted woodworking machines in an assembly-line fashion. Jigs and pre-set guides were employed, so that the operator had little to adjust before beginning to mill a block.

> The nuclear grade graphite used in the Hanford piles was not your pencil lead variety. This was very high density graphite (the denser the carbon, the better it served as a neutron moderator), more akin to cast iron than soft pencils. It wasn't as strong as cast iron; you could still chip off pieces if you weren't careful; but milling the graphite was about as tough as milling iron. Each 4 x 4 x 48 in. block weighed about 50 to 60 pounds, and "No," you couldn't drive a nail into it! The milling tools that were originally used at Hanford gave way to true machine tools. *Coy Love, 1-Jul-98*

To accommodate the 2,004 aluminum process tubes that would run from the front to the rear face of the pile, about a fifth of all the blocks were bored through their length with a hole approximately 1.75 inches in diameter (a cross section can be seen in Figure 9). The corners of all the blocks in each process tube layer were given a 0.39 in. bevel cut along their length to form a small triangular passage for the helium atmosphere in the pile. To help remove any water from the pile, either from moisture condensate or from leaks in the process tubes, 0.25 in. weep holes were drilled on 12 in. centers, extending from each of the four beveled corners of the block into the longitudinal hole. Figure 10 shows a cross-sectional view of several layers of blocks. (HTM 1945: 404, 519, 522)

In terms of woodworking, the tolerances that were required for the graphite were unheard of; any deviations in the blocks could quickly mount up as the pile's 100-plus rows of blocks were stacked. The holes that had been bored in the graphite had to align precisely with the 2,004 holes in the front and rear face B blocks, otherwise the process tubes could not be inserted all the way through the pile. The same was true for the openings for the horizontal and vertical controls rods; there was little room for error. For example, the cross-sectional measurements for each graphite block had a tolerance of ±0.005 in., the squareness tolerance was ±0.004 in., the length tolerance was ±0.006 in., and the tolerance for the diameter of the hole that was drilled through the length of some of the blocks was kept within +0.003 in. and –0.000 in. (could be no smaller than the specified diameter). (DuPont 1945: 789-790)

> I was in the tool room of the Remington Arms Plant, with an extensive machining background. That plant had over 20,000 workers, and there were 1,200 of us in the tool room building making the tooling just to make the thirty and fifty caliber ammunition.
>
> I arrived at Hanford on February 29, 1944. I was brought out here to machine the graphite for the reactor core, and to work on the tooling for the machinery. My experience with graphite prior to this time was as a lubricant, a graphite dust like we used in locks. I knew that graphite was used in the chemical industry in high temperature vacuum furnaces, but it was a new experience for me. At that time, I didn't know anything about what we were really doing; it was just a job that had to be done. I didn't know what the product was, and really didn't want to know, because security was very, very tight.
>
> The graphite came in to us in the 101 building in square blocks a little over 4 ft long and a little over 4 in. square. Now, these were not smooth or uniform, they were just rough castings, rough blanks. Now these blanks had been inspected for purity prior to getting to us in the 101 building. They had to make sure that each block we machined was a block that would meet their reactor standards.
>
> They did not want any foreign material contaminating the blocks. We had to be very careful when we were using any oils to lubricate the machines that we lubricated only the machines and not any blocks, or left any blocks around that could become contaminated.
>
> First, the holes were drilled and then the blocks were machined on the outside, square, with the hole concentric to all four surfaces. So that way when they were put together they would all align. Some of them had keyways in them and some of them were just like blocks. The tolerances on the squareness of the graphite was less than the thickness of a sheet of paper. They had to be square, they had to be the exact size, and the hole concentric. We had micrometers that were four inches long that were made just for doing that.
>
> I was amazed when we started making tooling for use out on the line, it just didn't last—the graphite was extremely abrasive to cutting tools. Most of the equipment we used was not metalworking equipment, it was woodworking equipment, and we were

> running the cutting tools at woodworking speeds. Maybe if we could have slowed it down…But basically we machined an awful lot of blocks.
>
> We would take that 4 ft piece and drill the hole through its length in less than a minute, with vacuums pulling all the chips and dust out. Then when we started using the planers to go over the outside of the block, it was also at woodworking speeds. Obviously it worked, as long as the cutters were sharp. And our job was to keep those cutters available so they could do what they needed to.
>
> But probably the thing that impressed me more than anything else was the procurement that they had. Every once in a while, we would get orders for a new size block that we didn't have any cutters for. Invariably, if I needed a cutter one day, the next morning when I come to work, we had it. It might not be a new one, but it was one that would get the job done. I might have to sharpen it, or even take it down a little thinner for a specific dimension. But very seldom did they ever delay acquiring anything that you needed. *John Rector, 7-Sep-91*

A random sampling of the blocks (approximately 17 percent of the total) were tested for purity and quality in the 305 test pile. This involved placing a block in the pile, measuring the effect it had on a beam of neutrons, and comparing that to a standard. By the time a block was ready to go into the B Reactor pile, it had a variety of markings on it, all of which were included in the extensive records that were kept, and this was well before the time that computers were the norm. (DuPont 1945: 790)

> It was a very low level power that we were getting out of that reactor [the 305 test pile]. The purpose of it was to test the fuel and graphite against known standards before they were put into the B Reactor. We had channels that would go through the test reactor. We'd load a channel up with graphite (or fuel) and as we'd push one in it expelled one out the other side. *Dee McCullough, 15-Dec-1991*

> Another factor that affected the laying of the graphite within the pile was simply compression—the blocks at the bottom of the pile were under a heavier load than those at the top, and would therefore compress somewhat more. This needed to be taken into account when calculating the thickness of each layer, but compression testing wasn't formalized until the later years. *Coy Love, 1-Jul-98*

2.7.3.3. Laying the Graphite Blocks

The finished size of the B Reactor graphite pile (within the thermal and biological shields) was 36 ft wide x 36 ft tall by 28 ft deep (front to back), or 36,288 ft^3. The typical graphite block was 4.1875 in. (4-3/16 in.) square by 48 in. long, or about 0.5 ft^3 per block. Therefore, something on the order of 75,000 graphite blocks were used to build the pile, although the number is actually higher because so many smaller and different sized pieces were used. Photographs 6 and 7 show workers laying the graphite within the pile.

Before any blocks were laid in the pile, they were first installed in a small mock-up pile in the 101-TC building to ensure that any variations were discovered before the blocks were committed to the pile. Each mock-up included about 25 layers of blocks, erected on the standard cast-iron thermal shield base that was used in the pile. When finished, all 25 layers were carefully checked for all required measurements. Each block was then marked to denote its exact position in the mock-up. This marking, together with the various quality designations, became the unique “fingerprints” for each block, shared by no other. Charts were created that showed exactly where each block would be laid in the 105-B pile. (DuPont 1945: 790)

> I remember we would get enough blocks made up for one level, a four and three-sixteenths in. layer. They would lay this up in the 101 building in the mock-up (its surface was exactly the same as the surface at the base of the reactor) to make sure that everything fit, was in line, and that there were no mismatches of all the pieces going together.
>
> After we got the first layer done, they would start the second layer, same thing. Every piece was laid as it would be in the reactor—exactly. The layers were inspected to meet all the criteria of the drawings. Then they would start disassembling, one layer at a time. They would take each block, wrap it, and identify it as to its number and location. They’d keep working all the way down till they got every block identified as to where it went in the final assembly.
>
> Sometimes the fabricators out in the area were moving faster than we were. By the time we got a layer of blocks machined, they would want to take those out. It was just a fantastic scheduling job to be able to get all those components together, with all of the variations and sizes. *John Rector, 7-Sep-91*

> The mock-up pile would be taken down in reverse order, palletized, and taken to the pile building. There the palettes would be lowered into the pile, and the blocks would be assembled according to their markings. By having the blocks already arranged in the order they would be used, the work went much more quickly and handling was kept to a minimum. Remember, even though the pile consisted of 48 in. long blocks, there were many thousands of unique blocks to deal with that had been cut or milled for specific locations in the pile. For example, there were openings through the pile for the 9 control rods and 29 safety rods, and many blocks were cut for the keys that helped stabilize the pile. For the piles built in later years, the time it took to lay the graphite was drastically reduced, to about two weeks. While the pile was being laid, the interior of the pile building was under “clean room” conditions, so all other work was halted. The faster the job was done, the sooner work could continue in the rest of the building. *Coy Love, 1-Jul-98*

As mentioned earlier in 2.7.1, the pile rested on the cast iron thermal shield, which itself was laid on the concrete foundation. The graphite blocks were stacked in alternating layers (as shown in Figure 10), so that the long dimensions of the blocks were all parallel within one layer, and at right angles to the long dimension of the blocks in adjacent layers. This added structural stability to the pile, as did the graphite keys that were added, especially on either side of openings in the pile, such as for control rods. (HTM 1945: 404)

The blocks that had been bored for the process tubes were aligned in alternate rows in alternate layers, which spaced the process tubes on 8.375 in. (8 3/8 in.) centers both vertically and horizontally, the same spacing used in Fermi’s Chicago piles.

The diagram in Photograph 8 shows the graphite pile from the outside. Note the openings for the horizontal control rods and the vertical safety rods. Photograph 9 shows a cutaway view of the pile's interior.

> The outer walls were all in at the time you were laying the carbon blocks; they were all to height. We had to use mercury levels to level all those [graphite] blocks. I was also involved setting the outer blocks [the B blocks], which were quite large, and they had to be set very accurately. It all had to be accurate; if you were off just a little bit, if the height would get out of line or the width, then the [process tubes] would not be able to go clear through the reactor [and gun barrels at either end]. Sometimes you'd have to move a whole layer [of graphite blocks] if you got off too far, but the important thing was to be very accurate from the time you laid your first carbon block. And it was checked very carefully, and they had an inspector watching things pretty carefully. Then you laid your carbon blocks, then you laid your gun barrels in. It was pretty clean. They had carloads of Kotex coming in, I mean a lot of Kotex, which made a lot of people wonder why. But those were used as swabs going through the gun barrels and [process tubes]; that's the way we swabbed all those pipes. *Rudy DeJong 6-Apr-1995*

The laying up of the graphite blocks required the same precision that was used for the cast iron block base of the pile: ±0.005 in., far beyond that normally expected for a "brick-laying" job. To center each layer of blocks, workers used traditional wires and plumb bobs. Later, in the lay-up of the pile for the D Reactor, this method was discarded and miner's transits were used above the pile. This method was further refined so that in the F Reactor, four surveyor's transits were used, one at the center line on the top of each side wall. (DuPont 1945: 789, 795)

> The magnitude of the graphite problem was terrific. Graphite was not very strong; pieces were easily chipped off and it had to be very carefully handled. Any sweat from the workers had to be kept out of the graphite. The graphite itself had to be extremely pure, and it was purer than had ever been made before. The development in this short period of time was astronomical. I know the graphite in the B Reactor was not as high quality as the graphite in the D Reactor, which was not as high quality as the graphite that was eventually used in the F Reactor, and they came on line within six months of each other. The techniques were evolving that rapidly. The cleanliness and precision in which the graphite was laid was absolutely outstanding, in my book. When they ended up with that stack almost 40 ft high, there was less than a quarter of an inch from perfection, from being absolutely perfect. *Don Lewis, 14-Dec-1991*

The elimination of dust and foreign particles from the pile was of great importance, as any contamination might reduce the pile's reactivity or cause mechanical problems. That's why all work in the pile building that could produce dust or dirt was suspended during the laying of the graphite. After each layer of blocks was laid, it was thoroughly vacuumed. To avoid any dirt and particles shed from workers' clothing while laying the graphite, they wore special outer clothing that they donned in a changing room before entering the air lock to the 105-B building. (DuPont 1945: 788, 805)

The job of laying the graphite blocks in the 105-B pile was finished June 1, 1944. (DuPont 1945: 790)

2.7.4. Process Tubes for Fuel and Coolant

The uranium fuel system for the B Reactor was far more sophisticated than that used by Fermi in his experimental piles. Fermi had inserted small lumps of uranium into holes in the graphite blocks to form the nuclear matrix. There was no need for a mechanism for replacing the fuel, or a means for cooling the pile's meager power output.

The B Reactor, on the other hand, was designed to work at power levels a million times higher than Fermi's piles, in order to produce plutonium as quickly as possible. This required a method of removing the irradiated fuel so its plutonium could be extracted, and replacing the fuel with fresh fuel to continue the process. Also of critical importance was a cooling system that would take away the immense heat generated by the nuclear reaction. Eugene Wigner at the Met Lab had suggested, and DuPont engineers had concurred, that water was the best candidate for the cooling job, given all the parameters of heat transfer, availability, construction schedule, and engineering complexities. (Rhodes 1986: 411, 498)

But using water brought new complications to the entire process. In a graphite-moderated pile such as B Reactor, water is a rather strong poison for the nuclear chain reaction. Therefore, the cooling system needed to introduce as little water as possible into the pile at any given moment (the flow rate, however, could be increased to provide adequate cooling). The uranium fuel also needed to be protected from the cooling water to prevent oxidation of the metal and to prevent the release of radioactive material into the water. The immense power levels the pile would reach meant that any problems with the cooling system might quickly lead to disastrous consequences. (The extensive water pumping and treatment facilities, as well as the path of coolant through the pile, are discussed later in section 2.9)

2.7.4.1. Process Tube Configuration

To carry the nuclear fuel and the cooling water, the B Reactor employed 2,004 process tubes, which ran from the front face of the pile to the rear face. As the graphite blocks were being laid within the pile, work also progressed on the front and rear outside faces of the pile, which were readied for the insertion of the process tubes when the interior of the pile had been finished. (DuPont 1945: 789)

The tubes were spaced 8.375 in. on center across the face of the pile. They were laid in alternate layers of the graphite blocks, so the vertical spacing of the tubes was also 8.375 in. (see Figure 10, Photograph 8, and Photograph 9). (HTM 1945: 404)

Looking at the front or rear face, the tubes were arranged in a somewhat circular fashion, because that was the most efficient shape for the chain reaction. Eugene Wigner's conceptual design had required about 1,500 tubes arranged in a circle about 28 ft in diameter, which would produce a somewhat spherical arrangement in the 28 ft deep graphite pile. However, the DuPont engineers had taken advantage of the dimensions of the square pile and added another 500 tubes around the purely circular design specification, producing a somewhat square cross section. Figure 7 illustrates how the tubes were arranged on the faces of the pile. The small dots around the edges of the pile (15 per biological shield block) represent 1.625 in. tie rods into the biological shield. The rectangle of the smallest dots that surround the rectangle of process tubes represents the cooling tubes that went into the thermal shield. (Rhodes 1986: 559-560)

The square cross section was 42 tubes on a side (6 tubes per B block), adding up to 1,764 tubes. Two rows of 30 tubes each were centered on each of the four sides of this square, which produced another 240 tubes, for the total of 2,004. Because the extra tubes beyond the 1,500 were on the perimeter, they did not add much reactivity to the pile—about one-tenth of that contributed by the central tubes. (HTM 1945: 1106-1107)

Nonetheless, adding the outer tubes did not require any changes in the general design of the pile, and still provided a somewhat rounded cross section. The 2,004 tubes were more than would be needed to achieve a nuclear chain reaction, but as it turned out, all would be needed in order to achieve the full

250 MW power rating for the pile. In fact, when the pile was first started up and achieved criticality, those extra tubes around the conceptual circle would prove invaluable to the pile's success (this is discussed in the next chapter in the pile startup section). (HTM 1945: 414)

A convenient numbering system was created by assigning each tube a four-digit number based on the two-digit numbers of its horizontal and vertical rows. The horizontal rows were numbered from 01, at the bottom, to 46, at the top. The vertical rows were numbered from 51, on the left, to 96, on the right. Therefore, the very first tube on the left side of the bottom row was 0159 (there were no tubes 0151–0158, as the corners of the square pile did not have tubes). The tube in the ninth horizontal row and the fifteenth vertical row from the left would be 0965. The numbering system allowed operators to identify a tube for recharging, for example, so that the workers at both the front and rear faces of the pile would open the nozzles on the same tube. The tube numbers were also important for tracking the history of the fuel slugs within each tube, because a slug's position in the pile would predict the amount of plutonium it would contain after a given amount of time. (HTM 1945: 905)

2.7.4.2. Process Tube Components

The process tubes were made of a very pure and soft "2S" aluminum, and their interiors had a "72S" zinc-alloy coating. That wasn't the perfect material, but it was the best considering its availability, resistance to corrosion, low neutron-absorption rate, and its well-understood behavior in manufacturing. Each process tube was about 44 ft long. (HTM 1945: 403, 508)

The tubes were 1.73 in. outside diameter (OD) by 1.61 in. inside diameter (ID). During normal operations, each contained 32 uranium fuel slugs, canned in aluminum jackets, that measured 1.44 in. OD by 8.7 in. long. This left a narrow annular gap of 0.086 in. around the fuel slug, through which the cooling water could pass. Two *ribs*, or *rails*, ran along the inside bottom half of the tube, and for its entire length. They supported the slugs and allowed the water to flow on all sides of them. Figure 9 shows a cross section of a typical tube and fuel slug within the graphite of the pile. (HTM 1945: 409, 508, 813)

It is interesting to note that this seemingly very narrow annulus through which the water flowed was an extremely important aspect of the cooling system. The poisoning effect of water on the chain reaction meant that the thickness of the water blanket around the fuel slugs had to be kept to a minimum. The resulting design allowed water to flow evenly around the slugs. The water pressure was maintained at about 200 pounds per square inch (psi), which meant that it passed through the tube at a high velocity, about 19.5 ft/sec, with a flow rate of about 20 gallons per minute (gpm). This provided a sufficiently large heat transfer to keep up with the pile's tremendous heat output. (HTM 1945: 409, 508, 514)

In the design of more traditional industrial cooling systems, the tube diameters could have been made larger to allow for a larger volume of cooling water. But in the case of a nuclear chain reaction, more uranium fuel would have been required in order to counteract the additional absorption of neutrons by the extra water (the poisoning effect). As with many other components of the pile, building an efficient machine had to be balanced with the necessities of sustaining a chain reaction. (HTM 1945: 409)

The 0.086 in. gap for water between the fuel slugs and the process tube was evidently about as tight a space as could be allowed. In a report in May 1944, concern was expressed about the thermal expansion of the fuel slugs during pile operations. The report suggested that it may have been prudent to shrink the outside diameter of the fuel slugs from 1.440 in. to 1.438 in., with a tolerance of +0.000 in. and –0.006 in. Given the report's May publication, when completion of the pile was only four months away, the report warned that

> …it is unwise to relax the oversize tolerance on the diameter of the slug, or the undersize diameter of the tube, or oversize height of the rib. Indeed, consideration might

> well be given to reducing the oversize tolerance on the slugs if it is still feasible so to do. (DUH-1001)

Each process tube penetrated the biological shield through a surrounding steel sleeve 7.5 ft long called the *gun barrel* tube, which was supported in the shield by cast iron shielding sleeves called *doughnuts*. The process tube terminated with a flared end, called a Van Stone flange, that served as the transition point between the end of the tube, the end of the gun barrel, and the stainless steel nozzle that connected to the tube's end. Making those flanges was a delicate operation due to the thin aluminum walls of the process tubes and the exacting tolerances that were required—the thickness of the tube wall could not vary by more than +0.001 in. or –0.000 in. The diagram in Photograph 10 shows both the inlet and outlet ends of a process tube. (Thayer 1996: 7; HTM 1945: 508; DuPont 1945: 796)

Fabricating the Van Stone flanges for the process tubes was a difficult and delicate operation. The job was performed on each end of the tube after the tube had been inserted through the pile. The process also required that the twin ribs that ran the length of the tube be removed at the flanges. The thinness of the aluminum tubing and the required tolerances added up to several hundred spoiled tubes that had to be replaced. More work was undertaken to perfect the technique of forming the Van Stone flange, and the result provided a very workable method that allowed the tubes to be installed at the D and F Reactors with few problems. (DuPont 1945: 800)

A tube nozzle assembly was fitted to each end of the process tube. At the front face, the nozzle contained an orifice of adjustable size that controlled the flow of cooling water into the tube. Water flow could be increased for the hotter, central tubes in the pile by using a larger orifice for each of those tubes. Smaller orifices could be used for the cooler, outer tubes that generated less heat. The nozzle also allowed the insertion of new fuel slugs. The nozzle at the rear face controlled the passage of cooling water out of the tube, and allowed irradiated fuel slugs to be pushed from the tube. The joint between the gun barrel and the outside of the biological shield was made gas-tight by an expansion bellows welded to the outside shield plate. Water was fed into the nozzle assembly through a coiled aluminum tube called, somewhat whimsically, a *pigtail*. (Thayer 1996: 7; HTM 1945: 508)

> We had a lot of people who came from acid plants at the smokeless powder plants. When you'd walk one of them into the front face area of the pile, the guy would say "Now I see why we couldn't get any stainless steel!" Because here was the front face with 2,004 stainless steel nozzles, 4 in. stainless steel headers to carry the water, big risers on each side to feed the thing, and with stainless steel 4 in check-valves—everything was stainless steel. And of course, because they had been working with nitric acid, they had to have stainless steel. But they had been running into wartime priorities, and so basically that was one of the first impressions that the acid people had was "Wow, look at all that stainless steel." *Bill McCue 28-Oct-1994*

2.7.4.3. The Fuel Column

When B Reactor was first started, each process tube held 32 of the 1.5 in. x 8.7 in. uranium fuel elements, or slugs, each of which contained about 8 lb of unenriched (natural) uranium. The 2,004 tubes in a fully loaded pile, therefore, contained over 64,000 uranium slugs weighing half a million pounds. Keeping track of all these slugs was an ideal job for the early computers from IBM, which are discussed in Chapter 3. As mentioned earlier, the uranium in each slug was encased in an aluminum "can," both to prevent oxidation of the uranium by the cooling water, and to prevent any fission fragments from escaping into the water. One reason the slugs were manufactured to this short length was to reduce their tendency to warp—the ribs that supported them in the tube also impeded the flow of water somewhat, so the bottoms of the slugs ran relatively warm. (HTM 1945: 409)

A new fuel slug could be handled without danger, such as when it was loaded into a process tube. After a few weeks irradiation in the pile, however, the "hot" slug was extremely dangerous—in close proximity, a fatal dose of radiation would be accumulated within seconds. (HTM 1945: 811)

During fuel loading, or *charging*, operations, inert or *dummy* slugs that contained no fissionable materials were placed at either end of this *fuel column*. Dummies were generally the same diameters as the fuel slugs, but otherwise came in a variety of styles and could play numerous roles. Dummies would be arranged in various patterns within a tube, depending on the physics or safety requirements deemed necessary by the pile operators. The order of fuel and dummy slugs within a typical process tube is shown in Figure 11, which also shows a sampling of dummy slugs.

Dummy slugs would be used in numerous ways (HTM 1945, 414, 416, 814, 905):

- All types of dummies served as spacers to keep the fuel slugs centered within the length of the process tube, and within the inner boundaries defined by the 2 ft thick neutron reflector zone of the graphite pile, and well within the boundaries of the thermal shielding that surrounded the graphite.
- Tubular aluminum dummies that were perforated with 48 holes, 0.3125 inches in diameter (see slug G in Figure 11) were used to reduce the radiation that would otherwise flow from the ends of the tubes or into the biological shielding, without excessive poisoning of the chain reaction. These *perfs* also improved the cooling effect of the water in the tube through mixing.
- Aluminum-jacketed slugs filled with a neutron-absorbing material, such as 90/10 lead-cadmium alloy, would be placed in specific tubes in the central portion of the pile to "flatten" the pile's neutron flux (make it more uniform; see "Going Critical" in Chapter 3) by poisoning the chain reaction in that otherwise hottest of regions (see slug F in Figure 11). These slugs were about 6 in. long, which helped to differentiate them from fuel slugs during charging operations.
- Lead slugs sheathed in aluminum (see slug H in Figure 11) served as strong shielding by scattering and absorbing gamma radiation, and might also be used to flatten the pile's neutron flux.
- When *fringe tubes* (those in the outer areas of the pile) were not needed and could be left empty, they would overheat if left dry, but would absorb too many neutrons if filled with water. In this case, the tube would be loaded with solid aluminum dummies, which had a much smaller poisoning effect on the neutron flux, to take the place of fuel (see slug D in Figure 11).
- When tubes in the outer corners of the pile were left empty (cooling was less important in the far reaches), stainless steel shield plugs would fill each end of the tube. These slugs were 1.625 inches in diameter, and were slotted so that they fit over the ribs in the tube. This effectively blocked the escape of radiation and of air that would contain a radioactive isotope of argon (see slug C in Figure 11).
- Two stainless steel dummy slugs with a total length of 13.125 in. would complete the loading pattern at the far downstream end of a tube, where the outlet nozzle and tube joined (see slugs A and B in Figure 11).
- An aluminum *papoose* slug could hold a sample for irradiation when the papoose was loaded into a process tube.

As shown in Figure 11, there were almost as many dummy slugs in a process tube as there were fuel slugs. During a fuel charging operation, hundreds of dummy slugs might be pushed out the rear of the pile along with the fuel slugs. The dummies were now somewhat radioactive, although not nearly as much so as the fuel slugs. The amount of radiation depended on the material from which a slug was made, and the slug's location in the pile. About half the aluminum perf slugs could be removed from the water of the spent fuel storage basin immediately, and put back into inventory to be reused. Others could be left underwater in the storage basin until their radiation had decayed to a safe level, and then they, too, could be reused. (HAN-73214: 6)

Stainless steel dummies could also be reused immediately; their positions at the ends of the process tubes exposed them to little radiation. Any aluminum-clad lead slugs, however, were normally disposed of by burial. They were too hot to handle, were frequently damaged during the discharge, and had a very long-lived radioactivity. (HAN-73214: 6)

2.7.5. Atmosphere

Enrico Fermi had understood that his experimental piles would be slightly more conducive to a chain reaction (would be a bit more reactive) if he could eliminate the air from the pile (see Appendix A). The largest component of air is nitrogen gas (78 percent), which is a relatively good absorber of neutrons. Any air within the pile, therefore, would serve to poison the chain reaction. (HTM 1945: 418)

Another problem associated with air in the pile is argon gas. Although it makes up only a tiny portion of a given volume of air (about 0.9 percent), argon readily becomes radioactive when exposed to the intense neutron *flux* (flow rate or density) of a pile (more so than the all the other gases in air combined). It was almost impossible to make the pile absolutely gas-tight, so any air within the pile could leak into the surrounding work areas, where the radioactive argon gas could present a hazard to the workers. (HTM 1945: 418, 1017)

To eliminate both these problems, the pile's atmosphere was replaced with circulating helium gas (later, carbon dioxide would be included, as well). Helium absorbs no neutrons within the pile and is the one element in which radioactivity cannot be induced by neutron bombardment. There were still more advantages to a helium atmosphere. Helium has a fairly high thermal conductivity (five or six times that of air), meaning that it would aid in the transfer of heat from the pile's graphite, shields, and control-rod passages to the 2,004 cooling tubes. Helium is inert, which made it easier to detect water leaks within the pile by sampling the gas as it circulated out of the pile, at which point the helium gas could then be dried and purified. Finally, if the pile were not sealed to the outside atmosphere, the normal variations in atmospheric pressure would actually affect the pile's multiplication factor, *k*, producing slight changes that would make it more difficult to maintain the stability of the chain reaction. (HTM 1945: 418, 504, 519, 1017)

The helium atmosphere was most needed when the pile was operating at higher power levels, which would not be reached until several months after the pile was first started. This afforded an unusual luxury within the intense construction schedule at Hanford—the helium-related facilities were not completely finished until *after* the pile had already been started. (HAN-73214: 52)

2.7.5.1. Helium Circulation

Helium circulated through the pile at approximately 2,600 ft^3/min via five high-speed turbo-blowers. The circulation system, shown in Figure 12, was shielded to block any radioactivity that might have been picked up in the pile. Adjacent to the 105-B Reactor building was the Gas Purification Building, 115-B, which contained all the circulation and purification equipment, such as blowers, coolers, filters, dryers, and purifiers. Helium gas was stored nearby in the Process Gas Storage station, 110-B, which was on a railroad spur for incoming helium shipments. (HTM 1945: 519, 1021; HAN-73214: 49, 55)

The route the gas took through the pile is illustrated in Figure 13. The helium entered the pile through a 24 in. duct, about 15 ft beneath the thermal shield base of the pile. The duct made a bend toward the charging face of the pile, where it connected to the center of a 24 in. header that ran parallel to the charging face. From this header, the helium flowed up through slots and into the 4 in. space between the thermal and biological shields. It then flowed through the joints in the thermal shield blocks and through the pile toward the discharge face via the beveled channels in the graphite blocks (see inset in Figure 13) or around the sides and top of the pile. The flow rate within the pile was approximately 5 ft/sec. At the rear of the pile, the gas made its way through the thermal shield blocks and into the 4 in. space between the rear thermal and biological shields. From there, the helium flowed through a discharge header and into a 24 in. duct that returned to the 115-B building. (HTM 1945: 520-522, 1020)

For reasons of worker safety and simple economics, it was important to keep gas leakage to a minimum. This was no small matter in the case of the pile. Not only was it a huge fabricated box with thousands of feet of welded joints, but it also had thousands of openings, including the 4,008 process tube ends that protruded through the front and rear faces. Perhaps because it was the first of the three piles at Hanford, the B Reactor leaked two to three times as much helium as the other two piles. (HAN-73214: 61-62)

Pressure tests of the pile were begun on July 20, 1944, and repairs were made to the leaks that were discovered over the next three weeks. When construction of the helium system outside the pile was finished, pressure tests were performed on it beginning August 12, 1944. After the pile was started, the circulating gas was not run through the purification system until October 14, and reached the desired 99 percent or better purity on November 29. (HAN-73214: 4, 60)

The first shipment of 194,000 ft^3 of helium arrived at 110-B by railroad tank car on August 14, where it was transferred to high-pressure storage tanks. As it arrived from the manufacturer, the helium was 96.0 to 98.5 percent pure. It would have to be further purified to better than 99 percent before it would be used in the operating pile. (HTM 1945: 1017; HAN-73214: 50)

2.7.5.2. Helium Drying and Purification

It was important to dry and purify the helium as much as possible, because any impurities, such as water, air or other gases, or dust, might poison the chain reaction in the pile, become radioactive, or interfere with the heat transference from the pile to the helium. (HTM 1945: 812, 1020)

The helium that arrived by rail tank car went through a purification process before being stored in high-pressure tanks. The circulating gas in the pile could be purified, as well, although that was generally needed only after the initial startup to purge the pile of air and other contaminants, and after maintenance work that allowed air to enter the pile. (HTM 1945: 1018)

The circulating helium was tested for moisture content in order to reveal any leaks within the pile. Samples could be drawn from the main gas duct, or from 10 sampling tubes that penetrated the rear shielding into the 4 in. gas plenum. There were also 90 other sample lines at the rear face that were normally sealed off, but could be connected in order to determine the location of a leak more precisely. (HTM 1945: 1022)

It was important that the gas be thoroughly dried, which was done by sending it through a silica gel drier. When the 3 ft thick drier became saturated, circulation was shifted to a second drier, and the saturated gel was dried by passing heated helium through it. (HTM 1945: 1020)

To remove other impurities, the gas was compressed to high pressures (approximately 700 psi) and refrigerated to low temperatures (0 to –30 °C) , and then circulated through a series of activated charcoal (carbon) filters. The carbon would be regenerated by applying a high vacuum to it. (HTM 1945, 1020-1021).

2.8. Fuel Charging and Discharging Facilities

The B Reactor was a production pile, and needed an efficient means for adding new fuel to the pile and removing the irradiated, plutonium-bearing fuel, while also maintaining safety for the workers. The combination of the pile's process tubes and aluminum-clad fuel slugs made this a relatively straightforward process: operators would push new fuel and dummy slugs into a tube from the front face, while any slugs already in the tube would be pushed out the rear face. This process, known as *pushing*, was therefore one of charging and discharging at the same time. In spite of this simplicity, the process was greatly impeded by several factors:

- This job had never been done before, so the early stages of pile refueling served as a testing period for the equipment and procedures.
- The 2,004 process tubes averaged 59 fuel and dummy slugs per tube, which added up to a tremendous amount of work, even though only small sections of the pile would be pushed at any one time.
- Pushing was an extremely dangerous process; a single discharged fuel slug at the feet of a worker could give a lethal dose of radiation in a matter of seconds.
- When the pile was shut down for more than about 20 hours, it could be difficult to get it restarted. (HAN-73214: 26-27)
- The ever-present sense of urgency made efficiency of critical importance in any operation, let alone one that was actually getting the plutonium out of the pile and on its way to being processed.

In light of these issues, there were many changes and improvements made to the refueling process in the early days of pile operations. We will discuss the pile's charging and discharging components here, as they were during the period before and soon after startup. The steps and equipment involved with the charging operation will be discussed in "Fuel Charging and Discharging Procedures" in Chapter 3, Reactor Operations.

2.8.1. Front Face

Both the front and rear faces of the pile were equipped with an elevator platform that spanned the width of the pile, and allowed workers to access any of the 46 rows of process tubes. The elevators traveled at 20 ft/min. The *charging elevator*, or *C-elevator*, at the front of the pile could hold a 6,000 lb load. During charging operations, the slug-pushing and related equipment would be fastened to the inner railing of the elevator, boxes of fuel and dummy slugs would be loaded on, and the elevator would raise this load and the operators to the appropriate row of tubes that were to be refueled. (HTM 1945: 906)

At the base of the front face of the pile was the *elevator pit*, which allowed the elevator to drop below the floor level of the work area so that operators could access the pile's lower process tubes. Refer to the diagrams in Photograph 5 and Figure 14 to see a side view of the pile and the location of the charging and discharging elevators.

2.8.2. Rear Face

The *discharge elevator*, or *D-elevator*, at the rear face was similar to that at the front, except that its load capacity was rated at 50,000 lb in order to accommodate the shielded cab it carried. This cab would protect an operator during emergency maintenance at the rear face when there were high levels of radiation, such as from the operating pile or from a hot fuel slug. The cab was basically a rotatable turret, shielded with 7 in. of lead, with a periscope and power-driven tools for the operator to use in completing the task at hand. The operator entered the cab through a shielded passageway on the fourth balcony of the rear face area. (HTM 1945: 826, 906)

After the pile had been shut down for a charging operation, workers would ascend the rear face on the elevator to open the outlet caps of the tubes that were being refueled, and to attach the necessary equipment to them. Before the slugs were pushed from the process tubes, the workers would leave the area and raise the discharge elevator *above* those tubes, so that no irradiated slugs would fall on it. (HTM 1945: 906)

The procurement of the shielded elevator cab during construction illustrates some of the difficulties encountered during the Hanford project, and the no-nonsense ways in which they were handled. The site remoteness required close attention to logistics to avoid serious delays. Numerous means of transportation, including air and rail express, and truck shipments were used wherever necessary. Many items, particularly for the 105-B building, were given special handling and were flown directly to the project by the Air Transport Command of the U.S. Army Air Force.

The large amount of experimentation and test work required on the elevator cab greatly delayed its shipment to the project. Consequently, a request was made and approved for shipping the cab to the project by railway express. Because of this decision, it was necessary to convert the wheels, couplings, and hose connections of a freight car so that the car could be handled by a passenger train. Conversion was made at the Reading Railroad Company’s yard at Reading, Pennsylvania, and the car was sent to Wilmington for loading. It was then hauled by various passenger trains across the country to the project. To ensure that the car would not be side-tracked and would be given preferential handling, a DuPont expeditor rode the passenger train. (DuPont 1945: 804)

The rear face area was surrounded by 5 ft thick concrete walls to protect workers from the high levels of radiation that were present when the pile was operating at its normal higher power levels. This was an especially hazardous area when hot slugs were being pushed out the rear of the pile. Once the workers had prepared the tube nozzles, they had to vacate the rear of the pile before slugs were pushed out. Several balconies along the rear wall allowed easier access to the elevator and the rows of tube ends on the rear face of the pile. Periscopes were provided that allowed workers to monitor the process while working safely behind thick concrete walls. One periscope was located in the ceiling of the rear face area, and another in the wall facing the rear face of the pile. Also on this wall was a *fly-eye* viewer that contained four wide-angle lenses. Another periscope was at the door that led to the entrance of the operator cab on the elevator, and yet one more periscope was by the labyrinth that led to the discharge area balconies. (HTM 1945: 913)

A *labyrinth* was a convenient way to provide a doorway through a thick shielding wall without having a thick, heavy door, and without having to open that door and thereby allow the radiation to pass through. The concept is a simple one. Radiation on one side of the labyrinth can pass through the maze only by scattering off its walls, which diminishes the radiation’s energy, as illustrated in Figure 15. Thin, lead-shielded doors would also be provided to further shield the scattered radiation. Two of the rear-face area labyrinths are shown in the 105-B floor plan in Photograph 4. Labyrinths were also used elsewhere in the building, such as between the inner and outer control rod rooms. (HTM 1945: 824a)

2.8.3. Discharge Equipment

The original design for handling the irradiated slugs as they were pushed from the rear of the process tubes revolved around the notion that it would be quite inadvisable to let the uranium slugs fall freely into the basin at the rear face of the pile. The force of the heavy slug hitting the water, the concrete below it, or other discharged slugs might lead to splits or ruptures in their thin aluminum jacketing. Once again, the solution was simple in concept but stubbornly complex and inefficient in actual use. (HAN 73214: 26-36)

As a slug was pushed from a tube, it would enter an L-shaped aiming tube that was positioned over a discharge funnel in the water below. The slug would drop through the aiming tube and into the funnel, at which point it would travel through a rubber hose down one of three water-filled concrete *discharge chutes* at the rear base of the pile, which were also padded with neoprene *mattress plates* that cushioned the fall of any slug that missed the funnels. At the lower end of this sloping chute, under some 18 ft of water, was a gate-like *escapement*. Here an operator who was standing on the floor above could work the gate to sort the fuel and dummy slugs into separate buckets beneath the water.

The water in the discharge chutes was 4 ft deep at the face of the pile, and the chutes sloped downward at a 36 degree angle, ran under the 5 ft thick concrete wall, and ended at a point 4 ft 6 in. above the floor of the discharge basin. It was here, with the fuel safely shielded under the deep water, that a worker would load the fuel into buckets and move it to temporary storage. Figure 14 shows a side view of the rear face, discharge area, discharge chute, and the collection and weighing area. (HTM 1945: 909)

Note that the extension of the chute into the collection area was one of the components that was planned but not built, perhaps because the procedures for fuel charging and discharging would change quite a bit as experience was gained. (HTM 1945: 913)

This discharge system was first tested on September 10, 1944, some two weeks before the pile was started and before the storage basin at the rear of the pile had been filled with water. The results of this and later testing, and of actual charging operations soon after the pile was started, were far from satisfactory. (HAN-73214: 28)

Countless problems were encountered, mostly due to slugs jamming the aiming tube, funnel, rubber hose, or escapement (these problems are well-documented in HAN-73214). The original system was abandoned for an ultimately simple technique—slugs were allowed to fall from their tubes into the discharge chutes below, without the funnels to catch them or the rubber hoses to carry them from the pile. This free-fall method went into full-time use on February 22, 1945. A key factor that made possible this seemingly dangerous procedure was the improvement in the manufacture of the aluminum-jacketed uranium fuel slugs. These were structurally much stronger than the earlier unbonded slugs that had been tried, and seemed able to withstand the fall into the discharge chutes. (HAN-73214: 27)

A *tip-off* discharge fixture would be attached to the end of a tube, which extended the drop-off point out from the face of the pile and allowed slugs to free-fall from the tube without hitting the nozzles below. The mattress plates in the chutes, having been reinforced, helped to cushion the fall. The diagram shown in Figure 14 shows the path of a falling slug.

To further streamline the fuel unloading process, the escapement gates were removed during a pile shutdown (December 20 to 28, 1944) after the basin had been pumped dry. (HTM 1945: 70)

2.8.4. Fuel Storage Basin

At the lower end of each discharge chute, on the safe side of the thick concrete wall, workers would sort the fuel slugs into stainless steel buckets (about a half-ton of slugs in each) and the dummy slugs into galvanized steel buckets. Each bucket was to hold a specified number of slugs, and a scale was used to weigh each bucket as a means of verifying the number of slugs it contained. Each bucket's above-water rack was tagged with a label that identified its contents (remember, keeping track of fuel slug history was an ongoing and highly important job). (HTM 1945: 811, 913; HAN-73214: 69-70)

The slugs at this point were hot, but not nearly as hot as they had been in the operating pile. Their radiation would drop by a factor of 10 after being out of the pile for an hour or two, and by another factor of 10 during the next 60 days. That's one reason why hot fuel slugs were stored for about that long before processing; the radioactive decay made the subsequent chemical separations in the 200 Area safer and easier to manage. Another benefit of the waiting period was that it allowed sufficient time for virtually all of the neptunium-239 in the fuel slugs to decay into plutonium. (HTM 1945: 811, 1118)

Water for the basin came directly from the underground storage tanks at the 183-B Filter Plant. The deep water kept the slugs sufficiently cool, and a constant water flow through the basin helped to further cool the slugs and reduce any clouding in the water from the lubricating oil that was used during the charging operation (again, these fuel charging procedures will be discussed in more detail in the Chapter 3 on operations). (HTM 1945: 811, 913; HAN-73214: 69-70)

The hot fuel from the pile remained safely underwater in the fuel storage basin. This area behind the pile, and separated from it by a concrete wall, is shown in the diagram in Figure 16. The basin was approximately 81 ft wide and 68 ft long, and divided into two sections (the larger for dummies, the smaller for fuel slugs). A wooden floor for workers covered the 20 ft deep basin, which is shown for a typical reactor in Photograph 11. The slug-laden buckets at the bottom of the basin were suspended from rods that passed through slots in the floor (see the photograph) and attached to a monorail system on the ceiling of the basin area. The monorail tracks were 4 ft on center, with a corresponding slot in the wooden floor beneath each rail. This arrangement allowed the workers to move the buckets throughout the area, and leave the dummy slugs and the fuel slugs in holding areas until the fuel slugs were ready to be shipped to the processing area, or the dummy slugs were cool enough to reuse. The buckets, rods, and monorail system can be seen in Figure 14 and Figure 16. (HTM 1945: 912-913)

The original procedure was to store the irradiated fuel in the basin for a day or less, and then transport the fuel to one of the three 212 Lag Storage Buildings in the 200-North Area. The *lags* (fuel slugs) would be stored there in another deep water-filled basin until they had cooled sufficiently to be processed. They would then be transported to the 200 Area's T Plant (221-T) or B Plant (221-B) for the chemical separations process. As time went on and production rates rose, this dual transport system became a burden in the flow of fuel from the pile to the processing plants. The extra handling also increased the risk of accidents or radiation exposure. Therefore, in the early 1950s, the 212 buildings were phased out of the process, and the irradiated fuel was simply kept in the pile storage basin for its full decay period, at which point the slugs would be shipped to the chemical processing facilities in the 200 Area. (Gerber 1993: 10, 35)

2.8.5. Fuel Transfer Area

When a bucket of fuel was to be shipped to the 200 Area for further storage or processing, it would remain underwater while a worker moved it via the monorail system to the adjoining fuel transfer area, which measured approximately 74 ft wide by 25 ft long (look back at Figure 16). Here the bucket would be placed within a lead cask (both still underwater) that had 12 in. thick walls and a heavy lid. The cask would then be lifted out of the water by a crane and placed in a special water-filled tank on a rail car (the water at this point was for cooling, not shielding), and then taken to the 200 Area. (HTM 1945: 824a,)

2.9. Cooling System

The cooling system for B Reactor was perhaps the most important component of the pile, for reasons of both production and safety. The pile was cooled by a single-pass water system; in other words, the cooling water passed through the pile only one time. The system consisted of the Columbia River as the source and ultimate destination for the water, pumps, treatment facilities, distribution piping, effluent handling, and many safety systems and procedures to ensure that the pile would never be without adequate cooling.

> The many components of the water treatment process and its backup and protective provisions all illustrate the beauty of the design and the thoroughness of those 1943 engineers and scientists. They anticipated potential problems and built in effective features that assured the safety and continuity of operations in the face of such unusual complexities, uncertainties, and needs. The system was extremely well thought out, yet it was designed and constructed very quickly and with great care. *Miles Patrick, 22-Jun-1998*

The pumping and processing of the cooling water accounted for almost three-fourths of the 100 Area's electrical demands. Electricity was provided by 230,000 volt transmission lines that connected the electrical systems of the Grand Coulee Dam and the Bonneville Dam, which were on the Columbia River above and below the Hanford Site, respectively. These transmission lines fed the Midway Station in the northwest corner of the site, about six air miles to the west of the 100-B Area. It, in turn, fed a substation in each 100 Area, where the voltage was reduced to 13,800. (DuPont 1945: 637; HTM 1945: 306)

2.9.1. Cooling Capacity

It's important to remember that the rate of heat generation in an atomic pile is directly proportional to the neutron flux and, therefore, the rate at which plutonium is produced—more heat equals more plutonium. But a pile that isn't cooled effectively and constantly will soon turn itself into a molten mess and die a quick death. It might also inflict the same consequence on workers and people in the surrounding countryside. (For a vivid description of the possible consequences of a loss of water in the pile, refer to the 1943 contract addendum, HAN-43508.)

Therefore, the amount of plutonium that could be produced at B Reactor was limited by the rate at which the generated heat could be removed from the pile. In later years, the primary modification to the pile that allowed much higher power levels to be attained was enhancing the water pumping, treatment, and piping facilities to increase the flow of water through the pile. (HTM 1945: 501; HAN-73214: 73)

Water was chosen as the coolant for the Hanford piles for various reasons, but primarily because it was available in large quantities, had a high heat-transfer coefficient, and was well understood among engineers. The decision to use water was not an easy one, because although water is an effective coolant, it is also an oxidizer of uranium and, in a graphite-moderated pile, an effective poison for the chain reaction (refer back to section 2.7.4, "Process Tubes for Fuel and Coolant"). These problems explain the need for the very thin (0.086 in.) annular space for water flow in each process tube, and the aluminum jackets for the fuel slugs. Although 30,000 gallons of water would be pumped through the pile each minute, the very thin water passages allowed only about 400 gallons of water to be in the pile at any one moment. (HTM 1945: 503-504; HAN-43508: 7)

The pile could be severely damaged if the cooling water were allowed to boil, so the system was designed to maintain effluent temperatures at or below 65 °C. The temperature also served to limit corrosion of the aluminum process tubes and fuel slug jackets. (HTM 1945: 514; OUT-1462: 16)

The pile generated enormous quantities of heat; the creation of one gram of plutonium liberated approximately 80,000,000 BTU, or 1,000 kW days of energy. Most of the heat (about 94 percent) was produced within the aluminum-jacketed fuel slugs. About 6 percent was produced within the graphite due to the slowing down of fast neutrons and the absorption of gamma rays. A small amount was also generated within the thermal and biological shields. (HTM 1945: 501, 503)

The first three Hanford piles were designed to operate at 250 MW. To remove that amount of heat while keeping temperatures for the fuel slugs, process tubes, graphite, and effluent water all within desired ranges, each pile required a water flow of about 30,000 gpm. As a means of comparison, the year-round average water consumption in 1942 for the city of Wilmington, Delaware (DuPont's home city), with a population of 125,000, was 11,000 gpm. (HTM 1945: 505)

2.9.2. Columbia River

A major factor in choosing the location for the Manhattan Project's plutonium production piles was the need for a reliable supply of clean, cool water in very large quantities. The Columbia River in eastern Washington state was nearly ideal for this purpose. It was the second largest river in the United States, with an average annual flow of 121,000 ft^3 per second past the Hanford Site. (HTM 1945: 306)

Its waters were quite pure compared to other major rivers, and also relatively cool, with lows of about 3 °C in the winter and highs of 20 °C in the summer, with a typical seasonal average of about 12 °C. (HTM 1945: 514)

The pile needed clean cooling water to prevent corrosion of the aluminum fuel jackets and process tubes, and to prevent the buildup of scaling deposits on the aluminum. The slightest impediment to water flow in the cooling tubes could make a substantial difference in the pile's plutonium output and its safety.

The water cooling system for the B Reactor and the other piles at Hanford were of a single-pass design, in that water was taken from the Columbia River, run through the pile, and then returned to the river. For this reason, it was important to minimize the presence of minerals in the cooling water that went into the pile, as they could result in the production of undesirable radionuclides, which would then end up back in the Columbia River when the water was discharged.

Another need that was met by the Columbia River was the large amount of electrical power it provided from the Grand Coulee dam, which was just coming on line as the third hydroelectric generating plant on the river. Much of this energy was needed to pump the large volume of pile cooling water. In fact, one of the four main switching and control stations fed by Grand Coulee was located adjacent to the Hanford Site, about five miles from the 100-B Area.

2.9.3. Primary Pumping and Treatment Facilities

With the great Columbia River flowing right past the site, the engineers had a wonderful opportunity to design an outstanding water system for cooling B Reactor. Much of this design was quite similar to that of a conventional municipal water supply system, but there were some very significant differences to meet the pile cooling requirements, primarily the very large flow rate of clean water and the exceptional reliability that was required.

> The original design provided multiple and backup systems to assure uninterrupted water supply to the reactor at all times. The system included electric pumps that carried most of the load, assisted by steam-driven pumps idling on the same lines. The electric pumps were fitted with large flywheels; in case of electric failure they would keep the pumps running for the short time it took the steam pumps to come to full power. In case of failure of the pumps at the river, the export water lines from the pump houses at Reactors D and F could provide water to B Reactor. If everything else failed, there was always the elevated water storage tanks, sufficient to cool the reactor through shutdown (and gravity never fails). *Miles Patrick, 9-Sep-1998*

The water pumping and treatment facilities were many times larger than would have been used for more conventional industrial plants. It was essential that the supply of cooling water to the pile be maintained at all times and under all circumstances, in order to keep the pile in a safe condition. The water system therefore included several features to provide redundant capabilities, including independent energy sources to maintain continuous water supply to the pile. Several other requirements influenced the engineering design of the water system:

- Prevent corrosion in the various parts of the system, especially in the aluminum process tubes and fuel jackets in the pile.
- Prevent the formation of scale and other deposits on the fuel and the process tubes, which could slow the flow rate and hinder heat transference.
- Minimize the introduction of extraneous material into the pile that might have a negative impact on the nuclear process or cause the formation of undesirable radioactive byproducts that could be released into the air or the river.
- Incorporate the flexibility to adjust to the uncertainties inherent in a large, complex machine that would be performing a process that had never been done before.
- Allow for the construction of the water plant in an incredibly short period of time.

The resulting water treatment plant provided three systems. The primary system was electrically driven, and handled the normal pumping and treatment duties for all phases of pile operation. A second, steam-powered pumping system served as a backup in case of an electric power failure. The third system was the so-called “last ditch” system, and utilized two elevated water storage tanks and a pipeline that connected all the piles on the Hanford Site. These last two systems were designed to supply enough water to the pile to maintain adequate cooling while the pile was shut down. The structures of the water system were by far the dominant ones in the 100-B Area. A diagram of the cooling system is shown in Figure 17. (Wahlen 1989: 5)

Note that both the D and F Reactors were built with refrigeration units in their cooling systems, which would lower the temperature of the cooling water that was sent to the hottest process tubes in the central portion of the pile. Realizing that the upper limit to the pile’s power level was determined by how well the pile could be cooled, refrigeration was a logical addition to the water system. Early experience showed that refrigerating the water could lower the inlet water temperature by 3 to 5 °C. (HAN-73214: 79)

In order to speed up the construction of B Reactor, and because refrigeration might be desirable but was not at all required, the refrigeration facilities were not included in B Reactor (in fact, they were never utilized at the other reactors). For the same reasons, while demineralization facilities were built into the water system at D Reactor, they were left out of B Reactor. (HTM 1945: 1005-1006)

2.9.3.1. 181-B River Pump House

Water was pumped from the Columbia River at the 181 building, the River Pump House. It is shown in Photograph 12 while under construction; its pumps are shown in Photograph 13 The water came in from the river through an intake channel that was dredged below the level of the riverbed to ensure a supply of water even when the river was low, and lined with rock and concrete. There were seven electric pumps, each with a capacity of 10,000 gpm. As part of the second water system, three stand-by condensing steam turbine pumps were available, each with a capacity of 7,500 gpm. (HTM 1945: 1006)

The capacity of the pumps, which was much greater than the 30,000 gpm that would be needed for the pile, served as a backup in case the D or F Reactors had problems with their own pumping systems. The water would be sent to the troubled pile via the export water system, which also served the 200 Areas; it’s discussed a little later. (DuPont 1945: 1200)

2.9.3.2. 182-B Reservoir and Pump House

The water was pumped from the river to an open 25 million gallon reservoir at the 182 building, the Reservoir and Pump House, as shown in Photograph 14. The stored water served as reserve water for pile cooling, condenser water for the steam condensers, and raw water for the separations plants in the 200 Area. The concrete reservoir was 513 ft long and separated into two unequal sections by a wall 1 ft below the water level. The incoming water flowed into the larger, 15,000,000 gallon section, called the emergency reservoir, which was kept full at all times. It overflowed the separating wall into the smaller section, called the raw water reservoir. (Wahlen 1989, 5; HTM 1945, 1006; OUT-1462, 17).

As part of the water system's design safety, a line ran directly from the raw water reservoir to the headers in the valve pit at the reactor building. In the event of problems with the water treatment system, this line could be used to bypass the treatment and ship raw water directly to the pile. (HTM 1945: 1014)

The 182 building had seven electric pumps that could each pump 6,000 gpm. In the event of an electric power failure, the second cooling system had three condensing steam pumps, each with a 4,000 gpm capacity. (Wahlen 1989: 5; HTM 1945: 1006)

2.9.3.3. 183-B Filter Plant

From the raw water reservoir, the water was pumped through two 36 in. lines to the 183 building, the Filter Plant, which is shown in Photograph 15. A wider view of this part of the 100-B area is shown in Photograph 16. Although the Columbia River water was unusually pure river water, it nonetheless needed extensive filtering, purification, and chemical treatment before it could safely be run through the pile. The formation of even the thinnest film within the pile's process tubes would have a dramatic and undesirable effect on the flow of water through the narrow passage around the fuel slugs.

The Filter Plant could handle about 38,000 gpm. The incoming water was treated with chemicals before filtering, which could include lime, ferric sulfate, activated carbon, and chlorine to discourage the growth of algae. The treated water flowed from mixing chambers to flocculators, where the water remained for about 20 minutes to allow coagulation. The water was then sent to settling basins for approximately three hours, where the suspended matter could settle out. The water then passed through a filter bed of anthrafilt (granular anthracite coal), sand, and gravel. The filtered water was then discharged into two underground *clearwells* (reservoirs) each of 5,000,000 gallon capacity. The separated solids were removed from the system and returned to the river by washing out the settling basins and by periodic backwashing of the filter beds. (HTM 1945: 1007)

2.9.3.4. 185-B Deaeration Facility

From the clearwells, the water was pumped through underground piping to the 185 building, the Deaeration Facility, where dissolved gases and entrained air introduced in the filtration process were removed. For example, the deaeration process could reduce the carbon dioxide content of the water from about 70 parts per million (ppm) to 2 ppm, and the oxygen from 14 to about 0.05. At the time of construction, it was believed such gases in the cooling water could affect the heat transfer capacity of the water, but this turned out to be of only minor significance, and the deaeration facility was discontinued. (HTM 1945: 1010-1011; Gerber 1993: 1; OUT-1462: 19)

There were two groups of five deaerators, each being 11 ft in diameter and 56 ft high. See Photograph 17, which shows the towers standing above the rear of the 190-B building. They were elevated so that the tops of the tanks were 160 ft above the ground, which allowed for gravity flow to storage tanks beneath them. Sulfuric acid and sodium dichromate could be added to both the inlet and outlet water of the deaerators to inhibit corrosion of the aluminum process tubes and fuel jackets in the pile. (HTM 1945: 1011)

2.9.3.5. 190-B Process Pump House

The water flowed from the deaeration towers to four above-ground steel storage tanks in the 190 building, the Process Pump House, which is shown in Photograph 17. Each tank was 90 ft in diameter, 43.5 ft high, and held 1,750,000 gallons. The tanks had floating pontoon roofs to seal off the water while also discouraging the reabsorption of air. Photograph 18 shows an aerial view of the 100-B area during construction, in which the tanks of the 190-B building are clearly visible. (HTM 1945: 1014)

From these storage tanks, the water was pumped directly to the pile by twelve sets of pumps in the 190 building (ten sets of pumps were normally in use, while two were spares). Twelve steam turbine pumps moved the water from the tanks to twelve electrically-driven pumps, some of which can be seen in Photograph 19. Each set of pumps could deliver 3,000 gpm to the pile, at a pressure of 350 lb/in^2. The system of dual pumps would maintain a reduced flow to the pile in case of a failure of either steam or electric power. The steam pumps could supply about 35 percent of the normal flow, while the electric pumps could supply 80 percent. (HTM 1945: 506)

Coupled to each electric motor shaft was a 4,600 lb flywheel, with a diameter of 48 in. and a thickness of 9.5 in. In the event of an electrical power failure, the spinning flywheels would continue pumping water to the pile for 20 or 30 seconds, long enough for the pile to be shut down and for the steam pumps to be brought up to speed to continue the flow of water while the pile was cooling. (Wahlen 1989: 9; HTM 1945: 1014; OUT-1462: 18)

2.9.3.6. 105-B Process Unit

Each set of pumps in the190 building was connected to a 12 in. pipe that ran through an underground tunnel to the valve pit in the 105-B building, on the other side of the concrete wall from the pile’s work area (opposite the front face of the pile). An interior view of the valve pit is shown in Photograph 20. As originally built, six lines would have carried refrigerated water intended for the central, hotter process tubes in the pile, had cooling facilities been available at B Reactor. The other six lines would have carried unchilled water to the tubes outside the central zone. Refrigeration was never added to B Reactor, so all process tubes received the same water. The six “chilled” 12 in. water lines joined into one 20 in. header in the valve pit, which fed two 20 in. headers that ran to the base of the pile. The six “normal” 12 in. water lines ran to their own 20 in. header, which also split into two 20 in. headers that ran to the pile. At the base of the pile’s front face, the water was routed upward through 20 in. risers on each side of the pile, with a “chilled” and a “normal” line on each side. Figure 18 shows a diagram of the water flow from the risers across the front face of the pile. (Note that Wahlen and Gerber refer to 36 in. headers and risers, but those were added in the 1950s during the CG-558 upgrade.) (HTM 1945: 506, 1014)

The water from these risers was distributed across the front face through 39 four-inch crossheaders for the 46 rows of process tubes. Photograph 21 shows the front face of the pile and much of its related plumbing. The top and bottom crossheaders supplied a single row of tubes. The next three crossheaders at the top and bottom supplied two rows of tubes each. Alternate crossheaders in the rest of the pattern supplied two rows of tubes in the central zone, or two rows of tubes in the fringe zone, respectively. The piping was arranged for “submerged cooling.” If water flow to a process tube were stopped, the tube would remain full of water. Cooling water was supplied from a crossheader to a process tube via a coiled length of 0.5 in. aluminum tubing, the pigtail, which allowed for thermal expansion. (Wahlen 1989: 18)

A side view of the rear face of the pile is shown in Photograph 22. Except to a trained eye, it looks very much the same as the front face.

2.9.3.7. Effluent Water

As the water passed through the process tubes, it would be heated by the fuel slugs and become quite hot (65 °C was the preferred maximum). The effluent piping system at the rear of the pile was essentially the same as the inlet piping system in reverse. Pigtails on the rear of the process tubes fed the effluent into crossheaders, which in turn connected to two vertical 36 in. risers (one on each side of the rear face). These risers routed the water into a common 36 in. crossover line that discharged into a 42 in. downcomer that contained a vertical baffle to slow the water's flow. The fact that the crossover line was higher than the top of the pile ensured that water would not empty from the pile if the supply water were cut off. From the downcomer, the water flowed into the cushion chamber, a cement enclosure lined with cypress planks at the bottom of the downcomer. From there, gravity moved the effluent through a 48 in. concrete underground sewer line to the 107-B Retention Basin. Figure 19 illustrates the effluent water piping at the rear of the pile. (HTM 1945: 513, 1016; Gerber 1993: 6)

Because the cooling water had been acidified, provisions were included to add a neutralizing agent to the hot effluent water in order to prevent corrosion of the concrete sewer line and retention basin, and to protect aquatic life in the river. (HTM 1945: 1016)

2.9.3.8. 107-B Retention Basin

During the time the water was inside the pile, some of its oxygen would be converted to a very high energy gamma-emitting nitrogen isotope, and other radionuclides could be created from any minerals or other impurities in the water. Most of these nuclides have a half-life of only a few seconds. Therefore, it was important that the effluent water be retained for a short period of time to allow the radioactivity to decay before the water was returned to the Columbia River.

The water from the pile flowed through the 48 in. sewer to the 107 facility, the Retention Basin, where the water would be held for three or four hours while its short-lived nuclides decayed. A typical retention basin is shown in Photograph 23. It consisted of two adjoining reservoirs, each 114 ft wide and 465 ft long, with a total capacity of about 7,200,000 gallons. Wooden fences, sometimes called s*tilling walls*, were built across each basin to slow down the flow of the effluent water as it passed from the inlet to the outlet. (HTM 1945: 1016)

The water exited the basin and flowed through a concrete pipe to the bottom of the Columbia River, far from shore, where the hot effluent water mixed with the waters of the river. When the pile was operating, about 30,000 gpm of relatively hot water was being dumped into the river. However, the average flow of the Columbia River was on the order of 54,000,000 gpm, so the dilution of the hot water took place quickly and effectively. A short distance downstream, the temperature rise was almost imperceptible.

2.9.4. Backup Cooling Systems

To ensure that the pile always had an adequate supply of cooling water, backup provisions were built into the cooling water system. In the event of an electrical power failure, the pile would be shut down immediately and the second cooling system would take over. While not designed to cool the pile at operating temperatures, this system could handle the pile's cooling needs while it was shut down and cooling off.

The second cooling system included the steam-powered pumps at the various pumping stations in the system, which could be brought up to speed soon after they were called into service. In that short interval, the flywheels on the electric pumps in the 190-B building would maintain the flow to the pile.

The third cooling system (the last ditch system) included two key components. The first was the two elevated water tanks, 187-B-1 and 187-B-2, that stood 160 ft tall on opposite sides of the 105-B building.

Each steel-plate tank was 41 ft in diameter, 39 ft tall, and held 300,000 gallons of filtered water. They were connected to the headers in the valve pit at the reactor building. If water pressure to the pile dropped below the static pressure of the tanks, a check valve would open and let the water flow from the tanks by gravity into the pile. (DuPont 1945: 743)

> Our big problem was we didn't want to lose the cooling water to the reactor for fear of a meltdown, or something of that sort. And we used to talk about the backup we had for the cooling system. We had four big storage tanks in the 190 building that would last us for so many hours. Then there were two high tanks of water that would last us for a little bit longer. And my supervisor and I one day were talking about how far away we could be before the water ran out…We didn't know what would happen if we lost our water, because at that time the water was considered as one of the moderators. So when the D Reactor came along we loaded D Reactor to dry critical…instead of putting water in. Then they continued to load the reactor and then test and make sure that we had plenty of rods [control rods] to take care of it. So we were able to load D Reactor completely full of fuel without any water. Then we knew that if we lost water at B Reactor that we would be safe [the control rods would hold the reaction even without the poisoning effect of water]. *Dee McCullough, 15-Dec-1991*

The tanks were designed for the short-term cooling of the pile, until the primary or secondary cooling system was operating again, or until the other tertiary system began to operate, which was the export water system. This water line supplied raw water from the 182-B reservoir to the 200-East and 200-West Areas. It also ran to the reservoir at D Reactor, which in turn had a line connecting its reservoir to the one at F Reactor. This 42 in. concrete main allowed water to be transferred from one pile's reservoir to that of another in case of an emergency in that pile's water system. It was an important component of the cooling system for the B Reactor. (HTM 1945: 1007, DuPont 1945: 1200)

2.9.5. 184-B Power House

If all electrical power were lost, the system of stored energy in the pump flywheels and the stored water in the various reservoirs and elevated tanks provided the time needed to bring backup steam-turbine driven pumps into full operation to maintain adequate cooling of the pile while it was shut down.

Steam for this purpose was provided by the 184-B Power House, with its two 300 ft stacks and coal storage pit. It is shown while under construction in Photograph 24. The building held four 100,000 lb per hour boilers. The Power House also included a small turbine-generator set that could supply electrical power to the most critical electrical systems. Coal was kept in storage to permit steam production for up to six months. (HTM 1945: 1030-1031)

2.10. Control Mechanisms (Rods)

The B Reactor's nuclear chain reaction was controlled in the same way that Fermi's CP-1 was controlled—long control rods coated with neutron-absorbing material were inserted or withdrawn from the side of the pile to decrease or increase the pile reactivity, respectively.

The safety control mechanisms built into B Reactor also mimicked those in the CP-1. Neutron-absorbing rods were hung above the pile and could be dropped into the pile to effect a rapid shutdown, or lowered into the pile to ensure a total shutdown. A third safety system consisted of a neutron-absorbing liquid, not rods, that could be poured into the pile to reduce its reactivity.

2.10.1. Horizontal Control Rods

The B Reactor employed nine *horizontal control rods* (HCRs) that entered the pile from its left side (as viewed from the front of the pile). The operator in the control room moved these rods in or out via remote controls to increase, decrease, or maintain the pile's chain reaction.

The nine rods were laid out in three rows of three rods, about 5 ft apart both vertically and horizontally. Each rod was about 75 ft long and 3 in. across, and entered the pile through a hole in the shielding. The entire length of the rod's rectangular hole into the pile was lined with an aluminum *thimble* that prevented the pile's helium from escaping.

The HCRs were divided into two groups. The operator at the pile's controls used seven *shim rods* to control the bulk of the pile's reactivity and to adjust the neutron flux distribution within the pile. The other two *regulating rods* (the two top outside rods) handled the minute-to-minute adjustments. The shim rods were driven by hydraulic motors, while the regulating rods were electrically driven. All nine rods were otherwise the same. (HTM 1945: 612)

It is interesting to note that the original design of the pile had included only three control rods, but nine were eventually included to give an added factor of safety and control. As it turned out, operating experience showed that the extra rods were not at all a luxury. Under some circumstances during startups, the pile's energy level could accelerate much more rapidly than had been anticipated, and the extra control rods were needed to restrain the growth of the neutron flux. (OUT-1462: 78)

Each HCR was divided into two sections; a diagram is shown in Photograph 25. Only the inner section (the part nearest the pile) entered the pile. This 36 ft portion included three aluminum tubes that had been coated with boron-containing compound (for the first 29 ft of their lengths), which would absorb neutrons within the pile. The three tubes carried circulating cooling water (about 10 gpm), and were enclosed within an aluminum casing for rigidity. (HTM 1945: 607; Wahlen 1989: 19)

The outer 39 ft section of the control rod, which never entered the pile, was mounted to a rack that engaged a pinion on the drive mechanism, and carried the cooling tubes to flexible hose connections at the end of the rod.

In normal operation, the section of the HCR that went into the pile became intensely radioactive, and workers would need protection when the rods were withdrawn from the pile. Instead of enclosing each control rod in a protective shield, the room that housed the rods was divided into two rooms. When the rods were withdrawn from the pile, the entire length of the inner sections of the rods were contained within the *inner rod room*. Workers would not enter this room if any of the rods were even partially withdrawn from the pile. The arrangement of these two rooms above the control room is shown in Figure 4, the cutaway view of the 105-B building. (HTM 1945: 612; DUH-10771: 7)

The outer portions of the rods, which were never actually in the pile, passed through openings in a thick shielding wall to the *outer rod room*, or *rack room*, which housed the rod-driving mechanisms and supporting racks. A typical rack room is shown in Photograph 26. Connecting the inner and outer rooms were labyrinths that blocked radiation while allowing access to the inner room. Safe entry could only be made either when the rods were either fully inserted into the pile or after the pile had been shut down and the rods had cooled off for about a week. (HTM 1945: 612)

The two electrically-driven regulating rods were used for fine-tuning the reactivity of the pile and could therefore be inserted or removed in small increments. The operator could move just one rod at a time at two different speeds, such as 1 in. per second or 0.01 in. per second. The gearing could also be changed to provide different high and low ranges. These slow rates of travel show just how delicately the pile could be controlled. (HTM 1945: 612)

The seven shim rods were operated by a hydraulic drive mechanism, powered by an electrically driven oil pump. An additional safety feature would insert all seven shim rods completely into the pile to shut down the pile when the safety circuit was triggered. This was a weighted hydraulic *accumulator* that stored oil under high pressure, similar to the hydraulic lift used to elevate a car in an auto repair shop. To scram the pile in the event of a power outage or other pile-threatening event, the weight of the accumulator would pump the oil to insert the shim rods into the pile at the relatively fast rate of 30 in. per second. The various events that could trigger the No. 1 or No. 2 safety circuit scrams are discussed later in section 2.11.2. (HTM 1945: 614)

The shim rods alone could absorb a sufficient number of neutrons to shut down the pile, except when there was a complete loss of water from the pile. In that case, the pile's neutron multiplication factor, *k*, would increase dramatically, say from 1.000 to 1.025. In the micro-world of fissioning nuclei, this would increase the rate of the pile's chain reaction so quickly that it would soon become catastrophically explosive. To handle this possibility and to provide a backup mechanism for shutting down the pile, another set of rods hung above the pile, ready to be dropped at a moment's notice. (HTM 1945: 614)

2.10.2. Vertical Safety Rods

Above the pile hung 29 *vertical safety rods* (VSRs), or *drop safety rods*. When their release mechanisms were triggered, they could drop into their respective aluminum thimbles in the top of the pile within 2.0 to 2.5 seconds. Their design and spacing meant they could reduce the pile's value of *k* by about 0.038, normally more than enough to drop the value of *k* well below 1.000 and shut down the pile. Their layout is shown in Figure 6 and Photograph 8. The top of a typical pile with its VSRs is shown in Photograph 27. (HTM 1945: 614)

Each VSR was a 35 ft long, 2.25 in. diameter tube of steel with a 1.5 percent boron content to absorb neutrons. Unlike the HCRs, these rods normally remained withdrawn from the pile, and therefore needed no cooling. Each rod was suspended above the pile by steel cables to an electric winch some 40 ft above the top of the pile. The winch was locked by an electromagnetic clutch. In the event of a power failure or other safety-circuit fault, the clutch would be deenergized, freeing the cable and allowing the VSR to plunge into the pile. (HTM 1945: 614, 616)

Each VSR had a steel plug around its bottom and top, which effectively sealed the thimble and greatly reduced the radiation that would otherwise stream from those openings in the pile. The VSRs were normally inserted into their thimbles so that their lower ends aligned with the bottom of the biological shield blocks at the top of the pile, so that there was little radiation entering the thimble above the plug. Nonetheless, the 29 holes in the top of the pile meant that this area would always be a radiation hazard zone. (HTM 1945: 616)

2.10.3. Last Ditch Safety System

The horizontal control rods and vertical safety rods were amply able to shut down the pile, as long as it was possible to insert them into their thimbles in the pile. However, this might not be possible in the event of a major disruption to the pile, such as an earthquake, enemy bombing, or internal explosion. If the pile shifted several inches, the rod thimbles might be shattered and the rods would then be useless. (HTM 1945: 616)

The pile designers anticipated this sort of devastating event, just as Enrico Fermi had with his pile in Chicago, and the solution was the same for both. A third pile-control mechanism known as the *last ditch safety system* consisted of a group of five 105-gallon tanks sitting on top of the pile. Each was filled with a 1.0 to 1.5 percent boron solution, kept under 75 psi of air pressure. Six pipes ran from each tank to six of the VSR thimble openings. In the event of a safety circuit trigger or a manual command from the control room, a fast-acting Belfield valve on each tank would open, and the boron solution would run into all the VSR thimbles, whether the rods were inserted or withdrawn from the pile. Later, the solution would have to be removed from the thimbles with a thin flexible tube, by applying air pressure to the thimble supplemented by applying suction to the tube. (HTM 1945: 619)

> The Belfield valves permitted us to quickly drop the poison solution into the thimbles for the vertical safety rods, in case of an event where the reactor was going to run away and you couldn't get the VSRs in. Before startup, I spent about three months up there [atop the B Reactor] working on the Belfield valves, dropping the solutions (just water for testing), timing it, testing the circuits, and so on. *Harry Zweifel, 1-Jun-1998*

This liquid poison, although never needed for an emergency, posed a potential problem several years later when the VSR thimbles began to leak helium from the pile. If the solution had been dumped into a leaking thimble and spread to the graphite in the interior of the pile, the boron could have severely degraded the pile's ability to maintain a chain reaction. So in 1953, it was decided to replace this liquid system with one of boron-steel ball bearings, the Ball-3X system. (Wahlen 1989: 20)

In early August, 1944, a certain *Mr. Eugene Farmer* toured the B Reactor in anticipation of the pending initial startup. One of his concerns was that the last ditch safety device should *not* be tested or used with the actual boron solution. Any leakage of the solution into the pile might seriously lower the pile's ultimate power level. It was agreed that any testing of the device would only be done with water, and that the device really wasn't needed in the weeks ahead because the pile would be operating at very low power levels after initial startup, so an emergency requiring the last ditch system was very unlikely. The man who expressed so much concern over spoiling the pile's reactivity had lots of experience trying to raise a pile's reactivity. His code name was *Eugene Farmer*, but his real name was *Enrico Fermi*. (HW-3-526: 2)

2.11. Instrumentation

The operators at B Reactor would have more than 5,000 instruments to monitor. Some instruments would display their readings, others record them, sound an alarm, or actually control the pile. Just about all of them were in the control room, located at the left of the pile and below the horizontal control rod rooms. It was here that personnel controlled the power level of the pile and monitored the reactivity of the pile, the temperature of the graphite and shields, the temperature, pressure, and flow rate of the cooling water, and much more.

This would be the world's first production-scale nuclear reactor, and the designers paid close attention to the instruments, controls, and procedures.

> Due to numerous unknowns during reactor plant design, safety and the reliability were particularly important considerations. Moreover, the design was completed before more sophisticated and complex analysis methods were available. This required some rather novel approaches to design problems, especially in the area of instrumentation. Three concepts were followed to produce the required level of safety and reliability:
>
> 1) Fail-safe: An arrangement such that any failure in an instrument system would allow the safest condition to occur. For example, a pressure gauge is associated with each reactor process tube. In addition to abnormally high and low flow conditions, any instrument component failure, loss of electric power, loose connection, broken wire, etc. in the system would scram the reactor—the safest condition.
>
> 2) Redundancy: The use of multiple instrument components or systems to accomplish a given task. For example, four ionization chambers and their related

> electronics were used to monitor neutron flux in the reactor. If any one of these four exceeded pre-selected limits, the reactor would scram. In this case, all four would have to fail before reactor operations were in jeopardy.
>
> 3) Diversity: The use of different methods to achieve similar results. For example, instruments measured both the outlet temperature and water flow in each process tube to determine whether adequate cooling was being maintained. *Roger Rohrbacher, 22-Jun-1998*

Because this was the first production-scale pile, many enhancements and modifications were made to its instrumentation and safety systems, especially in the early days of operation, just as there were changes made to many of the pile's mechanisms and procedures. The discussion in this section describes the pile at the time when it was first started in September 1944.

> The amount, complexity, and unique character of instrumentation needed for the 100-B Area (and the rest of Hanford) required so many instrument mechanics (called technicians after the late 1950s) and engineers that finding so many was just not possible. It turned out that almost all the personnel were trained right at Hanford. The original training course covered about four weeks, and included lectures and demonstrations. Further training courses included methods of calibration, review of probable trouble areas, study of important parts, and more. *Roger Rohrbacher, 22-Jun-1998*

2.11.1. Control Room

Operators would monitor and control the pile from the control room, which can be seen in the cutaway view of 105-B and its floor plan, shown in Figure 4 and Photograph 4. Other processes outside the 105-B building, such as the water pumping and treatment facilities, generally had their own, state-of-the-art conventional measurement and control systems.

One operator sat in front of the main control panel in the control room, where he could watch the instruments that displayed the pile's power level and control rod positions. An *annunciator* displayed 28 conditions, any one of which would automatically scram the pile or sound an alarm for operator intervention. The operator could adjust the control rods to maintain the pile's reactivity at the specified level, and could also push a button to scram the pile when it was deemed necessary. A typical main control panel is shown in Photograph 28. A schematic of the main control panel instruments is shown in Figure 20. (OUT-1462: 15)

Four other instrument panels in the control room monitored thousands of different conditions in the pile, including:

- Water pressure at the inlet of each of the 2,004 process tubes
- Water temperature at the outlet of each process tube
- Water flow through the pile
- Water supply pressure
- The state of the helium gas system
- Radiation in various parts of the 105-B building

Several other operators would monitor these instruments. They would rotate their jobs among the different gauges during their shift to maintain their alertness and accuracy. Perhaps the most important component of the pile's instrumentation were the safety circuits.

2.11.2. Safety Circuits

The pile *safety circuits*, or automatic shutdown systems, consisted of a variety of instruments that were linked electronically with pile controls. When specified limits were exceeded in an instrument, the pile would be shut down automatically—a scram.

There were two safety circuits for the pile, called the No. 1 and No. 2 safety circuits. The first was intended for potentially severe problems, and would shut down the pile as fast as possible by dropping all 29 vertical safety rods into the pile, and by quickly inserting the seven hydraulically-driven shim rods. The No. 2 safety circuit was for the minor or less critical problems, and would insert only the shim rods. Additionally, the pile operator could trigger either circuit by manually pressing a push-button on either side of the main control panel. (HTM 1945: 728)

The problems that would automatically trigger the No. 1 safety circuit included:

- Low water pressure in any of the four risers at the front face of the pile
- High radioactivity in the discharge water, indicating that a fuel slug may have ruptured
- High neutron density within the pile
- Electric power failure to the pile or to the pumps in the 190-B building

The No. 2 safety circuit could be triggered by the following events:

- Low oil level in any of the three accumulators for the shim rods
- High or low water pressure at the inlet end of any of the 2,004 process tubes
- High effluent water temperature
- Moderately high neutron density in the pile
- Low cooling water supply to the HCRs
- The lowering of any VSR unless the trigger was by-passed by the operator

Safety was an overriding concern in pile operations, and the instrumentation was the most important means for maintaining it.

2.11.3. Pile Reactivity

The primary measure of the pile's chain reaction was the neutron density, or flux, within the pile. One problem with the design of the instrumentation that measured this reactivity was the incredible range of neutron density involved. Imagine having a thermometer that was scaled from 1 to 100 billion. That was the case with the pile. When it was running at full power, the neutron flux was 100 billion times greater than when it was shut down or running at very low power. To handle this range, two different sets of neutron monitors were needed.

The high-level flux was measured by four ionization chambers installed in different tunnels under the pile (they can be seen in the diagram in Photograph 5). The very small current developed by these chambers was measured by picoammeters located in the control room. At the time, these Beckman meters (named after the company that made them) were called micro-microammeters, and were state of the art. The amplified signal was sent over a cable to indicating meters on the main control panel, which would indicate the pile's reactivity to the operator, who could then adjust the regulating rods as necessary. The signal could also be recorded in the control room, and would trigger the safety circuit when the flux exceeded a preset level. (HTM 1945: 707)

> The problems associated with the major components of this system (the ionization chambers, cable, and the small current amplifier) were unusual and difficult to solve. Various types and styles of ionization chambers were tested and modified for possible use. The chamber-to-cable seals were unsatisfactory, but that was solved by further development. A boron-coated chamber was eventually selected for this use.

> Because of the high-voltage amplification used in the micro-microammeter, it was found that flexing the cable caused wide excursions in the meter. The cable instability was due to fractional changes developed between the cable shield and the cable insulation. When the cable shield was removed and the insulation given a coating of colloidal graphite, the problem was greatly reduced.
>
> Measuring current flows of one trillionth of an ampere was not thought possible during the days of vacuum tubes (until about 1945). However, the Beckman Instrument Co. had recently developed a practical pH meter that included just such an amplifier. Beckman modified this amplifier to specifications developed by DuPont. The requirements included a range of 10^{-12} to 10^{-7} ampere. The results were successful but not trouble-free; special knowledge and skill were required to maintain these amplifiers. *Roger Rohrbacher, 22-Jun-1998*

When the pile was shut down or running at very low power levels, the low-level neutron flux monitor system, or subcritical monitor, would measure its reactivity. Its primary use was to determine when the pile achieved criticality and the rate of rise of power level.

The galvanometer system consisted of one ionization chamber under the pile connected to two galvanometers in series. One galvanometer provided a signal (deflection) proportional to the neutron flux, while the other registered the deviation from a preset level. In this way, the system could show small changes in the neutron flux. This system also included shunts and potentiometers at the control room console to compensate for range changes. (HTM 1945: 707-708)

2.11.4. Cooling Water Pressure and Temperature

The importance of the cooling water to the successful operation and safety of the pile cannot be overstressed. An active process tube running dry would not be a minor problem. Even if it didn't destroy the pile, it could do serious damage to the tube and its surrounding graphite, while compromising safety. Of course, while the pile was being repaired, the production of plutonium would come to a halt. That's why the vast majority of all the instruments were dedicated to monitoring the pile's cooling water. These instruments could scram the pile or alert the operators, but actual control of the water system was handled in the various water-supply buildings in the 100-B Area. (HTM 1945: 711-712)

The water pressure in each process tube was monitored continuously, for a total of 2,004 gauges and associated hardware. If the pressure in any gauge exceed the specified range, a scram would be triggered via the No. 2 safety circuit. The sheer number of gauges was a significant factor in itself, because normal-sized gauges might have filled the entire control room. The *Panellit* gauges that were ultimately used (they were named after the company that manufactured them) were notable at the time for their petite size. Even so, the Panellit board measured some 24 ft long by 9 ft high. A typical example is shown in Photograph 29. (HTM 1945: 718)

> One of the duties in the control room would be to record the pressure from each of the 2,004 Panellit gauges. In an eight-hour shift, the crew would read one-third of the gauges, and enter the data on paper, the old-fashioned way. Not only that, but there were two numbers to write down for each gauge; it would have been a great place to have a computer. *Richard Nelson, 11-Sep-1998*

A sensing line ran from the inlet end of each process tube, just downstream of the orifice that controlled the flow of water, to the Panellit pressure gauges and switches in the control room. A *bourdon* *tube* in each gauge rotated a disk to reflect pressure changes. Two magnets on the dial were positioned for high and low trips.

During initial use, small variations in pressure caused a number of accidental scrams via the No. 2 safety circuit, most often because the gauges were not properly *dampened*. In fact, a worker just bumping against the Panellit board might cause any one of the gauges to trigger a scram. Additional operating experience showed sufficient protection was obtained by bypassing the safety circuit, and having only an alarm sound when any of the 2,004 switches opened. After gaining yet more experience with the system of Panellit gauges, they were once again added as an input to the safety circuit. (HAN-73214: 17, 39)

A thermocouple was installed at the outlet end of each process tube to measure the water temperature after it had flowed through the tube. Each thermocouple was connected to a plug board in the control room. These temperatures could be recorded in various forms, such as by individual tube for trend recording or for a pre-selected number of tubes. Two temperature recorders were installed for this use. The temperature difference between the hot effluent water and the cool influent water, when combined with the rate of water flow, could be used to compute plutonium production within each process tube (more power equals more heat equals more plutonium). (HTM 1945: 716)

2.11.5. Pile Power Level Calculator

The pile’s power output was a simple calculation based on the amount of heat it generated. The initial instrument for this purpose was called a pile MW (megawatt) meter. The temperature rise in the water passing through the pile was multiplied by total water flow, and totaled to determine the heat generated. The output was adjusted to read directly in megawatts on a recorder in the control room. (HTM 1945: 717)

2.11.6. Miscellaneous Indicators and Recorders

Various other gauges and recorders were monitored in the control room. They occupied about 30 ft of panel space; a typical section of gauges is shown in Photograph 30. One important instrument was the fuel slug rupture monitor. This system monitored for slug jacket failures by detecting abnormal radiation (beta activity) in the pile outlet water. Eight beta-sensitive ionization chambers were installed in sample rooms near the rear face of the pile. Outlet water sample lines were run from the rear crossheaders and discharge risers through an annulus in a chamber via a solenoid valve that operated on a time cycle. The time cycle allowed short half-life activity to decay, so that they would not be confused with the longer-lived activity. (HTM 1945: 720)

Other control room instruments included:

- Graphite moderator temperature
- Thermal shield temperature
- Reactor helium system analysis, especially for water content that might indicate a coolant leak
- Control rod position
- Vertical safety rod positions (in or out)
- High tank temperatures and pressures
- Control rod cooling water temperature
- Total water flow to pile
- Top of inlet riser pressure
- Retention basin activity level
- Export water system pressure

2.12. Supporting Facilities

The 100-B Area consisted of many more structures than just the 105-B pile building. As originally built, there were 32 buildings and 22 other facilities. Of particular importance to the men and women who worked in the 100-B Area was the Main Gate House, 1701-B, at the perimeter fence of the 100-B Area, about a half mile from the 105-B building. It's shown in Photograph 31. Each floor of this two-story wooden structure was about 940 ft^2. (DuPont 1945: 652; Wahlen 1989: 30)

All workers entering the 100-B Area came by the building's *clock alley*. They would show their HEW identification badges and pick up another identification badge that contained radiation-detecting film—a dosimeter, which they would wear while inside the 100-B Area. On the second floor of 1701-B were facilities for the Badge Processing workers, who would read these dosimeters on a regular basis and record any doses received in each employee's permanent record.

A second access point was inside the 100-B Area. The Badge House, 1702-B, restricted access to the 105-B Exclusion area around the 105-B Reactor building. This was a 400 ft^2 wooden structure, where workers would again show their identification in order to gain entrance to the reactor area. (Wahlen 1989: 30)

In later years after the end of WW II, the 1701-B Gate House was felt to be no longer needed and so was torn down. The 1702-B building was then replaced with a more substantial, concrete-block building that was identified as the 1701-BA.

The 1704-B Supervisor's Office and Laboratory housed the offices for area-wide administrative and technical personnel. This T-shaped wooden building had about 8,000 ft^2 of floor area; it's shown in Photograph 32.

The following list shows the principal numbered structures in the 100-B Area at the time of completion in 1944. Most have been demolished; the notable exceptions are 105-B (the pile building), 116-B (the stack), and 181-B (River Pump House). (Gerber 1993: A1-A3)

103-B	Fresh Metal Storage Building
105-B	Reactor Building
107-B	Retention Basin
108-B	Chemical Pump House
110-B	Helium Storage
115-B	Helium Purification Building
116-B	Reactor Exhaust Stack
151-B	Primary Substation
152-B	Secondary Substations (10)
153-B	Distribution Substations (8)
181-B	River Pump House
182-B	Reservoir and Pump House
183-B	Filter Plant
184-B	Power House
185-B	Deaerating Plant
187-B	Process Water Elevated Storage Tanks (2)
188-B	Ash Disposal Basin
190-B	Process Pump House
1608-B	Process Sewage Lift Station
1701-B	Main Gate House (for 100-B Area)
1702-B	Badge House (for 105-B exclusion area)
1704-B	Supervisor's Office and Laboratory

1707-B	Change House
1709-B	Fire Headquarters
1713-B	Storerooms
1715-B	Oil and Paint Storage Building
1716-B	Automotive Repair Shop
1717-B	Combined Shop
1719-B	First Aid Station
1720-B	Patrol Headquarters
1722-B	Area Shop
1734-B	Gas Cylinder Storage Building

2.13. Construction Progress and Problems

The work that was performed at the Hanford Engineer Works was of monumental proportions, rising from bare desert to fully functional industrial complex in a scant two years, while creating a nuclear technology that had only just been discovered. Even under peacetime conditions, the project would have garnered notoriety for its cutting-edge developments and, especially, its complete success. During the incredible push of wartime production and urgency, however, the story takes on legendary proportions.

> I learned to admire enormously what I consider to be one of the world's greatest engineering jobs ever—the design and excecution of those three reactors, of which B was the first. The mere fact that they were able to do it in such a short time bewilders people today, of course. And if those people realized the sheer engineering technical excellence, they would be even more bewildered. *Eugene Eschbach, 8-Dec-1992*

The construction efforts at Hanford were under continual assault from a variety of impediments, many of which have already been mentioned: the do-or-die schedule, shortages of workers and materials, the tight security that was required, and the brand new technology being implemented in the key components at the Site—the three reactors. Many of the problems are directly associated with the 105 reactor buildings, where little previous experience could be applied, security was the tightest, and a mountain of materials for the pile had to be assembled into a very small space. Other hurdles and solutions deserve mention, as well.

2.13.1. Highly Skilled Labor

The primary labor difficulty in building the B Reactor (the 105-B building) was one of quality rather than quantity. Because of the very limited working space in the 105-B building, it was not possible to speed up the work simply by adding more people. The only way to increase the labor supply was by extending the work day with multiple shifts. The pile was given top priority in the construction schedule in the early part of 1944, and retained that status until completion.

On December 3, 1943, the work on the pile was put on two nine-hour shifts, and on January 1, 1944, a third shift was added. This continued through March 1, 1944. Most other crafts in the 105-B building were placed on a three-shift schedule from February 15, 1944 until completion. In addition to the shift work and extended hours, Sunday work was utilized whenever necessary. (DuPont 1945: 803)

Among the more illustrative examples of the new methods developed in the construction of the B Reactor were the welding techniques that were needed to handle the pile assembly (DuPont 1945: 797):

- Each of the three reactors at Hanford would require more than 50,000 linear feet of welded joints and about 100 tons of welding rods.

- The reactors were constructed to a maximum tolerance of 0.015 in., and welded joints had to correspond.
- Warping and shrinking, always a problem with welding, would have to be kept to an absolute minimum.
- The thickness of the plates involved made precise welding difficult.
- The importance of the job meant that no welding flaws could be allowed.

The welds provided gas tightness to the reactor as well as structural support. The basic method by which warping and shrinking problems were avoided was by peening (hammering) the welds. The weld was deposited in small amounts and then peened before cooling. This greatly reduced the contraction that normally takes place during cooling. (DuPont 1945: 797)

In February 1944, a conference was held in Wilmington, Delaware, that was attended by members of the design and construction divisions of DuPont and several welding specialists from engineering, shipbuilding, and steel companies. The issues were the various welding problems that would be encountered in the construction of the reactors at Hanford, and the result was a set of welding standards. (DuPont 1945: 797)

The standards developed at this meeting were modified slightly in the field as a result of experimentation, but in general were followed throughout construction. In addition, several welding experts were on the job to supervise the welding and to give the qualifying tests to the welders.

Recruiting a sufficient number of welders for work on the pile was particularly difficult because the necessary welding techniques were extremely complicated for that time. Not only that, but in many cases the welder was ultimately responsible for seeing that his own work was done according to specifications. In other words, it was not possible to inspect the welds other than by visual examination. In many cases, any weld failures would have been extremely difficult or even impossible to rectify. (DuPont 1945: 792)

Therefore, only welders of the highest skill level were selected. Before a welder was chosen for work on the pile, his background was thoroughly checked from a security angle. His work record was investigated, in many cases over the previouos 10 to 15 years, to determine his mental attitude and reliability. If he proved satisfactory, he was given a rigid welding test in the field to determine his qualifications as a craftsman. This test was so difficult that out of all the highly skilled applicants, only about 18 percent qualified. (DuPont 1945: 792-793)

> I do remember one thing. The welders all had a helper working with them, to help them move things and clean the weld if it had to be chipped. One welder was saying to this one young fellow that was working with him, “Now watch it.” He meant for him to close his eyes [and not look at the blinding light]. After a while this fellow says “I can’t watch it anymore; I can’t see it any more.” *Rudy DeJong 6-Apr-1995*

2.13.2. Exacting Work

The precision demanded in the building of the B Reactor has been described in the discussion of the laying of the pile’s cast iron thermal blocks, the milling and laying of its graphite blocks, the forming of the aluminum process tubes, the making of the sandwiched biological shielding, and more. The need for such accuracy arose from several factors:

- Nuclear piles were an entirely new technology.
- Any defects in construction would most likely detract from the pile’s ability to sustain a chain reaction.
- Once the pile had been activated, it would be next to impossible to correct any internal problems.
- The pile’s success or failure might very well determine the outcome of the war.

- A failure might turn deadly for workers and local inhabitants.

The need for precision tolerances, the massive size of the pile, and the unusual materials used made construction a difficult and slow process. Compounding these problems were the need to develop new construction techniques and new methods of handling both common and unusual materials, such as graphite, aluminum, and Masonite.

Before and during construction of the pile, numerous tests were needed to ensure that progress was occurring as specified. For example, as already mentioned, the graphite used in the pile was tested for purity and placed accordingly in the pile. There were a number of other tests on materials and on the pile itself during construction, including (DuPont 1945, 795-796):

- All aluminum process tubes were given a 350 lb hydrostatic test and a thorough visual examination of the exterior of the tubes before they were installed.
- All bellows between the gun barrels and the face of the pile were first pressure tested under water.
- All gun barrels were checked for size to ensure proper clearance for the aluminum process tubes.
- All cast iron doughnuts were checked for eccentricity, size, and high spots.
- All welds in the steel membrane beneath the cast iron base were vacuum tested for gas tightness before the final pour of concrete.
- Numerous pressure tests were made on the welded seams to determine their gas tightness.
- An air pressure test of 63 in. of water, with an allowable leakage of 1 ft^3 per minute, was made on the entire pile before installing the aluminum process tubes.
- After tube installation, a second pressure test was run with an allowable leakage of 1 ft^3 per minute.
- When the nozzles were installed on the process tubes, each tube was given an air test of 50 lb and then a 350 lb hydrostatic test, each with a permissible loss of 2 lb in a 15 minute period.
- When the pile was completed, the process tubes were subjected to a final 350 lb hydrostatic test, with an allowable drop through all valves, flanges, and so on of 10 lb pressure in 2 hours.

2.13.3. Materials Procurement

Gathering the huge quantities of materials that were needed was in itself a monumental task. Separate “programs” were set up at DuPont in Wilmington for each of the different types of material going into the three 105 buildings. There was a graphite block program, a nozzle program, a gun barrel program, a B block program (the biological shield blocks), an aluminum tube program, and numerous others. (DuPont 1945: 794)

These programs consisted not only of locating vendors to perform the fabrication work, but locating sources of raw materials, as well. Each program was planned and developed so as to provide sufficient quantities of materials at the right times. If more than one fabricator or source of supply was necessary for a particular type of item or material, additional vendors were located. Each program was scheduled to fit in with the other programs, as well as with the fabrication work required on the project site. (DuPont 1945: 794)

The 105-B building was the only building in the 100-B Area actually delayed from early completion because of difficulties. This delay was for only two or three weeks, and resulted from the late delivery of material handling equipment. For a time during construction, the procurement of B blocks, aluminum tubes, gun barrels, and nozzles appeared critical, but the difficulties were surmounted in sufficient time to prevent delay in the completion of any of the three 105 buildings. (DuPont 1945: 795)

For example, as already described, the discharge elevator cab for the B Reactor (and for the D Reactor, as well) was late being shipped from the factory. However, by arranging special handling for the cab, it arrived at the project in sufficient time to prevent delays in the scheduled completion dates.

2.13.4. Duplication of Plans, Materials, and Tasks

One factor that helped speed up construction at Hanford was the use of three piles that were all essentially the same. Many of the original engineering drawings were used for all three piles, materials could be ordered in triple rations, and many workers would be able to take the experience they gained on B Reactor to one or both of the other two piles.

There were some additions made to the 105-B building during construction that were then incorporated into the 105-D and 105-F buildings. For example, the valve pit and valve pit laboratory were doubled in size, and a small office added. In addition, for the 105-D and 105-F buildings, a concrete block-enclosed storeroom was added beneath the structural steel framework of the horizontal control rod rooms. None of these changes affected the actual progress of the building inasmuch as the construction of the pile was the limiting factor in all three pile buildings. The only major difference in the 105 buildings was that the valve pit piping and water piping to and from the 105-D building was entirely stainless steel, while stainless steel was used only in locations where replacement was either difficult or impossible in 105-B and 105-F. (DuPont 1945: 798-799)

> After the B Reactor, I was transferred to D Reactor and completed that, and then we went to F. And when F was completed, I left there to go back to Operations; that was on January 1, 1945. *Rudy DeJong, 6-Apr-1995*

2.14. Cutting Through the Red Tape

The speed at which the B Reactor and the entire Hanford Site were built continues to amaze anyone who has ever worked in the field of heavy construction. For that matter, it’s even more amazing to anyone who has tried to replace a kitchen faucet on a Saturday morning, and finished the job in the afternoon—the following Saturday!

Not only was it all built quickly, but given the goals of the project, the Hanford operation was a complete and resounding success, as was the entire Manhattan Project. Countless explanations for this timely success have been catalogued in the years following WW II. Each of them seems to make perfect sense, but even taken together they still don’t seem to explain the superlatives of the job that was accomplished at the Hanford Site.

Thayer lists a number of these reasons, and some new ones, too, in his *Management of the Hanford Engineer Works in World War II*, and almost succeeds in leaving the reader with an understanding of how all that work was completed in so short a time. Perhaps the Manhattan Project is the 20th century version of Egypt’s pyramids or Britain’s Stonehenge. Several critical factors seemed to have played a major role in the success of the Manhattan Project and the construction of the B Reactor.

2.14.1. Urgency

The ongoing emergency of World War II drove every aspect of the economy in the United States and in countries throughout the world. The prospect of actually developing an atomic bomb of devastating power would certainly have been a wartime incentive, but the thought of Germany or Japan coming up with the bomb first was unthinkable.

This overriding sense of urgency translated into a potent stimulus for taking on projects that would otherwise seem impossible, spending more money than would ever be acceptable in calmer times, and basically doing whatever might be necessary to get the job done.

2.14.2. Authority

The responsibility for the entire Manhattan Project rested in the hands of General Leslie Groves, whose position of authority was just a step or two removed from the White House. Nor were there multiple agencies involved with the ultimate direction of the project, leaving no room for discussion, debate, compromise, and so on.

As Thayer points out, to succeed under a crisis schedule, individuals must be given the responsibility for a job, along with the freedom to perform it. Groves was told to get the job done, and then left alone to do it. Similar granting of authority along with responsibility was passed down the line, so that managers were able to spend more time directing rather than overseeing, questioning, and double-checking.

> That's right, we didn't have anybody that held us back; it was great. And all of that was simply because Groves had been put in full charge of this project and he could sneer at almost any other government agency, because he had the President's backing. He was a very intelligent man, really very competent. He was really a genius, but he didn't spend much time trying to make people like him. *Frank Matthias, 26-September-1992*

> I think people had confidence in the management of the plant; it was all being run by DuPont. It was not at all like the atmosphere is today, with so many government agencies in the picture that you don't know what the final decision is going to be. This way you would ask the problem up the line and you would get an answer back down the line. And you would go with it, and you would believe in it. Because you had faith, you had confidence in the people who were running the show. *Tom Clement 15-Mar-1992*

2.14.3. First-Rate Players

It seems that just about everyone agrees that DuPont was the right company for the job of building and operating the Hanford Site. They had long experience in designing, building, and operating large manufacturing plants, and had an organization already in place for building the multitude of diverse buildings and systems at Hanford. Thayer sums it up by saying that when you're on a crisis schedule, you'll need a *turnkey* organization, such as DuPont, to get the job done.

> It was a tremendous achievement, and imagine building three reactors in one year. Look how long it takes to build one now. It went fast, amazingly fast. *Rudy DeJong, 6-Apr-1995*

Another point of unanimity is that craft workers who built Hanford were top quality. The precision required in much of the work was far beyond that of usual construction projects. The skills that were brought to the jobs played a key role in Hanford's success. Besides the quality of the work, there was also the vast quantity of it. For much of the life of the project, craft workers labored six days a week, nine hours a day, with many hours of overtime and work on Sunday. Managers often simply never left work.

2.14.4. Unlimited Resources

If Germany had pursued the atomic bomb with as much vigor as did the United States, would they have had the natural resources to succeed? It's hard to say in light of the astronomical quantities of personnel and materials that went into the Manhattan Project. The size, diversity, and industrial capability of the United States seem to be an integral factor in the success of the project.

In terms of a construction budget for Hanford and the Manhattan Project, by all normal standards it was nonexistent. Although cost estimates were made (that turned out to be quite accurate), the job was not going to be limited by a ceiling on costs. Thayer rightly emphasizes that the managing agency for a crisis construction project must be given top priority for all material and personnel resources. Whether it was procuring mountains of pure graphite or shipping B blocks by passenger train, those in charge of the Manhattan Project did not fuss about costs.

In fact, another point in Thayer's history is the importance of being able to eliminate the usual practice of competitive bidding if that helps get the job completed more quickly, as well as getting a no-strike agreement from the unions involved.

2.14.5. New Scheduling Techniques

There is one specific matter of interest that also helped DuPont complete their work at Hanford. Well before DuPont's involvement with the Manhattan Project, the company had garnered extensive experience in designing and building complex production facilities. To help schedule these major construction projects, around 1940 DuPont invented and then refined a very effective scheduling technique, which at some point in its evolution came to be called the Critical Path Method (CPM). With this scheme, all necessary project activities are defined, put in sequence, and assigned relevant durations. The activities are then plotted on a schedule drawing where sequential activities are connected "tail-to-head" to the prerequisite activity. As the plot develops, the longest sequence of activities is identified, and the *critical path* is thus determined. At that time, all CPM drawings were hand drafted, but DuPont's CPM was the forerunner of modern, highly advanced computerized construction scheduling techniques. (Thayer 1996: 66)

DuPont had used this method for several years before its application on the Manhattan Project. By 1943, CPM had been refined to a very effective stage that included nodes, branching activity lines, parallel activities, float or slack time in parallel non-critical activities, and so on. This proved to be a very effective way to identify where the emphasis was required in the project in order to ensure the earliest completion. Colonel Matthias once said "I've always thought that that CPM system of DuPont's was what led us to do a very efficient job at Hanford." (Thayer 1996: 66-68)

2.14.6. Secrecy

Perhaps the one factor that allowed all the others to blossom was the absolute secrecy that enshrouded the entire Manhattan Project. Even Vice President Truman was out of the loop, and learned of the ongoing project to make the atomic bomb only when he became President after President Roosevelt died. No one in the Senate or House of Representatives knew the full extent of the project, and they certainly had no involvement with its financing, location, schedule, and so on.

The secrecy bestowed to the project the freedom to do whatever was necessary to get the job done—no political arguments about where it should be built or how the money should be spent, no land-use permits, no long debates about budget overruns, no outrage because a contractor is related to a politician, and on and on. In short, by suspending all the usual practices of a democracy, the project was allowed to proceed at top speed, and was completed on time with great success.

Between March 1943 and September 1944, the 100-B Area (and most of the Hanford Site) went from bare desert ground to a sprawling, technologically advanced industrial complex, meeting the original construction schedule. Within that two years, a new industry was established in the world where none had existed before. Its mission was to manufacture a previously unknown element, plutonium, that had been discovered only a short time before.

The resounding success of the project is even more remarkable considering that manpower and materials were in short supply during that time of war, and that not just one, but three reactors were built, along with the three separation plants in the 200 West and East Areas, the 300 Area Fuel Fabrication and Research Laboratory, and the town of Richland. These efforts at the Hanford Site rank among the most outstanding construction achievements in history.

3. Reactor Operations

The construction of the B Reactor, its supporting facilities in the 100-B Area, and all the other facilities at the Hanford Site was a tremendous achievement, worthy of the highest praise. Had the B Reactor been a gunpowder factory or an assembly plant for mechanized vehicles, the story after construction would have receded to a more mundane tale of typical factory operations. Such is not the case, however, because the pile and the entire Hanford Site were involved in a brand new technology that had only just been yanked from the laboratory.

The story of the beginning of operations at B Reactor is also the story of the first days of the Atomic Age, when a heretofore untapped source of energy was first harnessed by mankind. The initial startup of the pile has all the tension, excitement, and mystery of the best novels, while the ongoing hurdles of daily operations, first-time procedures, and unexpected complications could humble the most experienced engineers.

3.1. Initial Startup of the B Reactor

The DuPont company had agreed not just to build the Hanford Engineer Works, but to operate it, as well. As construction came to an end, DuPont’s role continued at Hanford, and it took up the duties of actually producing plutonium.

As construction was coming to an end in the 100-B Area during the summer of 1944, the operations personnel, the *P Department*, were quickly getting up to speed with the procedures and equipment that would be needed to run the pile. The activity included training sessions for pile operations, acceptance tests on equipment, weekly meetings among the top supervisory personnel in the various 100-B Area departments, and discussions among scientists and engineers to ferret out as many potential problems as possible. All the main components of the water cooling system outside the pile were brought on line during July, and pipe lines were flushed and tested. All equipment for the pile was tested, as well, except for that which could only be tested after the pile was charged with uranium and a chain reaction initiated. (OUT-1462: 82-84)

Testing of the pile was formally begun on July 12, 1944, while construction crews were still present. Some procedures, however, required the same secrecy and security that surrounded much of the pile’s construction and were therefore off-limits to all but authorized personnel. For example, when construction forces left the 105-B building during the week of August 20, P Department personnel loaded dummy slugs into the process tubes that would not be needed in the initial startup of the pile. (HAN-73214: 3-4, 9)

3.1.1. Pile Configuration for Startup

The pile had 2,004 process tubes for uranium fuel, but only a few hundred tubes in the central portion of the pile would be needed to start a chain reaction and take the pile critical, although at very low power levels. Once the pile and procedures had been tested during low-power operations, fuel could be added to the pile until its full power rating of 250 MW was reached, which was expected to require about 1,500 fully loaded process tubes. Therefore, only the central 1,595 tubes were actually connected to the water cooling system. The outer 409 tubes were empty, except for six 8 in. grooved stainless steel dummy slugs that were inserted at each end to provide shielding for the people outside the pile. Of the 1,595 tubes, 895 were filled with solid aluminum dummy slugs instead of uranium slugs, which could later be replaced with fuel as needed. That left 700 tubes in the central area of the pile, which would be charged with uranium slugs when the time for startup arrived. (HAN-73214: 8-9, 66)

The water supply to each process tube was ultimately controlled by a narrow, removable orifice plate in the tube's inlet nozzle. For the pile's initial startup, the nozzles in all the uranium-bearing tubes had a 0.24 in. diameter orifice. This meant that all tubes would receive the same water flow, and that the water system could pump the design rate of 30,000 gpm through the pile. Soon after startup, however, as the true operating parameters of the pile were revealed, orifice sizes would be reduced for the outer regions of the pile, where the chain reaction would be less intense than in the central regions. Ultimately, as many as four different orifice sizes, from 0.24 in. to 0.14 in., would be employed in roughly circular bands around the pile's center. (HAN-73214: 9-11, 74-76)

3.1.2. Charging to Criticality

The plan for loading uranium fuel for the startup of the world's first production-scale nuclear reactor was to proceed in four stages:

- Dry critical: Only enough fuel would be loaded into process tubes in the central portion of the pile to bring the pile to criticality, but without any cooling water in the tubes. The absence of the poisoning effect of the water meant that the dry critical state was the smallest possible critical size for the pile.
- Wet critical: Once a dry critical state was achieved, the cooling water to the process tubes would be turned on, which would effectively poison the chain reaction and drop the pile to subcritical levels. More tubes around the central tubes would be loaded with fuel, until criticality was again achieved.
- Charged for operations: More tubes would be charged with fuel to allow the pile to reach a power level at which a variety of tests could be performed on a fully functional system.
- Charged for production: The pile would eventually be loaded with enough fuel to raise its power to the maximum rated level of 250 MW.

The first fuel was loaded into the pile at 5:44 PM on September 13, 1944, less than a year after construction of the pile had begun. Enrico Fermi, slide rule at the ready, was on hand to oversee the operation, as were other scientists from the Met Lab. Tubes were loaded with a prearranged set of dummy slugs and 32 fuel slugs, similar to the arrangement shown in Figure 11. The slugs were first lubricated with an equal mixture of water and water-soluble oil, and then loaded by hand into the tubes. (HAN-73214: 8; HW-3-1560: 3; OUT-1462: 84)

> Fermi basically knew the configuration that had to be used in charging, and he was in direct control of saying how many, and when, and so forth. He was aiming for something on the order of 600 tubes, and they needed to be in a spherical [or cylindrical] configuration so you would have the highest density of neutrons in the center. You would start with all the rods in, and load about half of the tubes you had estimated would be needed. Then you'd call the control room and tell them to pull out the rods. You'd withdraw the 29 vertical rods, and start withdrawing the nine horizontal control rods. You would pull the four corner rods first, because they would be the farthest out in the configuration [in the least reactive part of the pile]. Then you might pull out all the top row and leave the middle three in there. But you'd still get no reaction. So then you'd pull out another half a rod, or another rod until all the rods were out, and at that point you

> were watching the galvanometer screen in the center of the control panel. If you got nothing, you would report that you got no reaction and you would put the rods back in. *Bill McCue, 28-Oct-1994*

The dry critical loading started in a central rectangle of tubes, 22 tubes on a side. As fuel was added, frequent measurements and tests were made to determine the neutron flux within the pile, and the results were compared to calculations to ensure that the expected results were, indeed, the actual. The dry critical condition was achieved when 400 tubes had been loaded, at 2:30 AM on September 15. (HAN-73214: 9, 85)

> So finally, as you took the rods out you began to get a white light moving across the screen that indicated that neutrons were flowing in the reactor. The neutrons were reaching the ion chamber underneath the reactor, generating an electrical current that was driving the galvanometer, causing the galvanometer to turn and the light to shine on the mirror and reflect back on the screen. And as that began to move across the screen, you could pull another rod out to make it go a little faster or you could push it in another inch or so to slow it down. At that point that indicated you had a reaction. So that was dry critical. *Bill McCue, 28-Oct-1994*

This stage was important, but real success would not be achieved until the pile had finally been charged for operations—you wouldn't produce much plutonium when the pile was running at kilowatt (kW) power levels instead of megawatt (MW). Nonetheless, at this dry critical phase, a variety of tests were carried out under the chain-reacting conditions of the pile, including the effectiveness of the horizontal control rods and vertical safety rods, calibration of power-level indicating instruments, and the effect of additional tube loading on reactivity. This careful study took time, but it allowed for a smoother and faster startup of D and F Reactors in the coming months. (HAN-73214: 9-10; OUT-1462: 85)

> The next thing would be to load to wet critical. So you have [loaded process tubes] here in the middle; you'd start loading around that so that you'd make a bigger cylinder, and maybe just one ring of pieces around, and again you'd have the rods withdrawn and test again. If you get nothing, you put them back in, and you'd load some more around that. Again Fermi would be telling them which ones to load, and the supervisor would have to run the elevator up and down to find the tube, take the nozzle cap off, put the pieces in…well, first you turn the water off in this column, in this row here, so that you don't wash the uranium pieces out of the tube. You'd turn the water back on and then go to the next one and so many more. And again you'd go back and tell the control room to pull the control rods, and they'd pull them. If you got nothing, you'd try it again, until finally you get to the situation where you're getting your reaction and you have the water on, and that's wet critical. *Bill McCue, 28-Oct-1994*

Dry fuel loading continued until 748 tubes had been charged, at which point the cooling water was allowed to enter the pile. The water proved too much of a poison for this number of tubes, so additional tubes were loaded. It was calculated that the wet critical state was reached on September 18 when 834 had been loaded. Loading continued into the early morning of September 19, until 903 tubes were charged for operations, which (it was hoped) would allow the pile to reach the planned low-level power levels for preliminary tests of the fully functional pile. Soon after, two tubes were discharged of their fuel due to loss of water pressure, leaving 901 active tubes. (HAN-73214: 10; OUT-1462: 85)

3.1.3. Starting for Production

A battery of tests, measurements, adjustments, and repairs were performed with the pile running at low power levels during the week following charging for operations. These included measurements of the ratio of fast to slow neutrons, water flow and pressure, and the pile's reactivity and how it was affected by the control rods, graphite reflector, and other pile components. There was also testing of the instruments, safety circuits, and backup equipment. (HAN-73214: 10-12, OUT-1462: 85)

With preparations completed, on September 26, 1944, the vertical safety rods were withdrawn, and the horizontal shim and regulating rods were withdrawn as needed, until the pile achieved criticality at 10:48 PM, with the 901 fully loaded process tubes. This is generally regarded as the official startup of the B Reactor, and is the point at which production, not testing, was the main objective. Power was allowed to increase until just after midnight on September 27, when it was leveled off at 200 kW. After taking more measurements, power was gradually increased to 9 MW, far more than any previous experimental pile had achieved, and the first planned step on the way to 250 MW. (HAN-73214: 13-14, OUT-1462: 85)

The initial startup at B Reactor was a complete success. All the hurdles had been surmountable ones, and it looked like it was "full speed ahead" to the full production schedule. The jubilation lasted but a few hours.

3.2. The Case of the Poisoned Pile

In the planning of the Hanford reactors, countless scenarios had been defined, resulting in appropriate solutions being built into the pile and the procedures for operating it. Due to the lack of experience with nuclear piles, however, many scenarios could only be imagined, with their solutions being only general and inexact.

3.2.1. Pile's Death Blamed on Missing Neutrons

When a pile is brought up to a certain power level, a few small adjustments in the positions of the control rods should stabilize the power and keep it steady at the desired level. Soon after the B Reactor was brought up to 9 MW, the operators noticed that they were having to withdraw the control rods bit by bit in order to maintain power at that level. Somehow the excess reactivity in the pile was diminishing—more neutrons were being lost than were being created in the chain reaction. With all the rods withdrawn, the pile's neutron multiplication factor, *k*, nonetheless eventually dropped below 1, and at 6:30 PM on September 27, the pile was considered "dead." The control rods were inserted and the pile was shut down. So much for nuclear chain reacting piles. (HAN-73214: 14; OUT-1462: 76)

> At that point you sit there, and as long as the rods are out you have to have this man at the control panel. In the office behind the control room, there were quite a few people, including Crawford Greenewalt, Enrico Fermi, Dr. Szilard, John Marshall, and probably a number of our supervisors and superintendents. They seemed to be in conference, so I waited until my supervisor, Francis Dineen, came through and I said, "Dinny, what did they decide?", meaning what did they decide had caused it to shut down. And because I had asked the wrong question, he didn't respond immediately, and finally he grinned and said "Oh, you know what they were doing? They were making up a pool as to when the reactor would come back to life!" *Bill McCue, 28-Oct-1994*

There were a number of experts on hand to consider this puzzling and serious problem, including physicists Enrico Fermi and John Wheeler, as well as DuPont's technical liaison at Hanford, Crawford Greenewalt. They quickly checked the obvious, such as water leaks into the pile or a loss of the helium atmosphere. Everything checked out; no one knew the answer. After the pile had been shut down for about six hours, they were measuring the level of neutron production by inserting test foils into the pile. When the control rods were pulled out, the pile again went critical, and by 7:00 AM it had regained all the reactivity it had lost and was once again running at 9 MW, which only added to the confusion. When the pile again fizzled out twelve hours later, the situation looked grim. (OUT-1462: 76-77; Rhodes 1986: 558-559)

> It turned out that my shift was off for two days, and during that time the reactor turned around and started coming back. And my neighbor, who was an instrument supervisor, he came over to my house and said "Well, that baby was born." So I wasn't actually out there at the time that the thing turned around, but I do remember and appreciate the opportunity I had of working with *Dr. Farmer* [Enrico Fermi's code name]. One of the other things that I remember is that the physicist that he had with him was a woman, a Dr. Marshall [Leona Marshall], and she had a two-foot slide rule that she was manipulating very fast and all. Of course, in those days, that was about the best calculator that we had, those long slide rules. *Dee McCullough, 15-Dec-1991*

3.2.2. A Not So Inert By-Product

Before the pile was built, there had been suspicions by some of the physicists, especially John Wheeler, that the fissioning of uranium might produce by-products that, by absorbing large quantities of neutrons, could drastically interfere with the chain reaction. In other words, no matter how well one designed and built the pile, a successful chain reaction in the pile might also be the making of its own demise.

Fermi, Wheeler, and the other physicists present at the B Reactor startup broke out their slide rules and soon came up with a plausible answer, based on the timing of the successive shutdowns and restarts. The culprit seemed to be xenon-135 (^{135}Xe), an isotope of the inert gas xenon. Further study later showed that a small amount of xenon was formed directly as a product of fission, but most was formed indirectly from the decay of iodine-135 (^{135}I). This previously unexplored isotope of xenon was a tremendous absorber of neutrons—its capacity to capture neutrons was about 150 times that of cadmium, the most absorptive nucleus previously known. Its half-life of a little over nine hours meant that, once the pile was shut down, its poisoning effect would quickly diminish over the period of a day. It was xenon that caused the reactor to shut down, only to restart after a period of time. John Wheeler has been given credit for explaining the xenon problem. (HTM 1945: 1305-1311; OUT-1462: 77-78; Rhodes 1986: 558-560)

The iodine to xenon transmutation is part of a larger chain of fission by-product decays, the primary components of which look like this (each element's half-life is shown in parentheses): tellurium (0.25 hours) to iodine (6.6 hours) to xenon (9.4 hours) to cesium (25 years) which finally decays to barium, a stable isotope. Of these elements, only xenon severely poisoned the pile. (OUT-1462: 77)

All of this was unknown when the B Reactor was first started, but it all came to light very quickly over the next several days. Suspicions were confirmed at one of the experimental reactors at the Argonne Lab near Chicago, and calculations were then formalized to explain the process. The question at that point was simple, even if the answer might not be: What engineering or procedural solution could be put to work with this huge machine that was otherwise unable to perform its intended job?

3.2.3. Conservative Design Pays Off

As it turned out, the only available solution to the xenon problem was to increase the amount of fuel in the pile to overcome the poisoning effect, because what was needed were a few more neutrons to compensate for those that were absorbed by the xenon. The physicists in Chicago who had designed the water-cooled Hanford piles, led by Eugene Wigner, had based their work on the available nuclear physics, and came up with a pile consisting of about 1,500 fuel-bearing process tubes, arranged as a cylinder with a circular cross section. This was the necessary design, given the known parameters of the science, to build a pile capable of producing 250 MW of heat.

But circumstances and concerns had led to a pile with 2,004 tubes, not 1,500. When concepts were turned into drawings, the DuPont engineers opted for a pile with a square cross section, not circular, most likely because it would certainly be easier to build and maintain, while wasting only a little space at the four corners around the circular array of tubes. Refer to Figure 7 for a general arrangement of the tubes at the front face of the pile.

According to Rhodes, it was physicist John Wheeler who related to DuPont his worries of unknown pile-poisoning by-products, and recommended the additional 500 tubes around the central 1,500. Arrangements were finally made to add the extra tubes, but only after the B block shielding for the front and rear faces had already been manufactured, so that the extra holes had to be added to the blocks. (Rhodes 1986: 559-560)

In an interview with DuPont engineer George Graves, Sanger makes it clear that Graves was the one who, under the urgings of Wheeler, pushed for the extra factor of safety in the most critical aspect of the pile's design—the amount of fuel it could hold. Thayer goes a little farther, and reports that it was Graves who insisted on the extra process tubes for the piles. (Sanger 1995: 57; Thayer 1996: 53)

However the decision was made, it was a wise and prudent one—the original design of 1,500 process tubes with 32 fuel slugs each would simply not have allowed the pile to reach its 250 MW power rating. Calculations that included the effect of xenon would later show that such an arrangement would not even reach 100 MW. (OUT-1462: 77)

So it was that the faces of the pile were constructed with a somewhat square array of process tubes, instead of a circular one. After Wheeler's theory was confirmed, work immediately commenced to begin adding additional fuel to the pile. In the end, the additional process tubes helped to solve the xenon problem by giving the pile a larger critical mass.

> So it was necessary to add more tubes of metal to the reactor in order to overcome this. You see, the reactor is not only making xenon from the decaying iodine, but the reaction is also "burning off" some of the xenon that is there. So if you have enough excess tubes you can reach an equilibrium, where you're burning off as much as you're forming, and you balance out at that level. *Bill McCue, 28-Oct-1994*

There was yet another conservative design factor that played an important part in the pile's success. The original design had called for three horizontal control rods, but the ultimate result of nine rods gave much more control over the pile's neutron flux, and allowed the operators to fine-tune that flux in ways that a three-rod unit could not have done. The extra rods also gave a much greater factor of safety to the pile, as their extra neutron-absorbing capacity could keep the pile in check when starting up under some otherwise hazardous conditions. (OUT-1462: 78)

3.2.4. Ramifications for Future Startups

Before construction even began on the B Reactor, procedures were being written for its operation that were based on the best available knowledge. Once the pile was started, a vast new store of knowledge became available, and procedures had to be written and revised on a daily basis.

The discovery that xenon developed in the fuel during operations created a particularly complicated issue when it came to the procedures for restarting the pile after a short shutdown. The problem was linked to the rather short half lives of ^{135}I, at 6.6 hours, and its daughter by-product ^{135}Xe, at 9.4 hours, and to the fact that during operation xenon is constantly being “burned out” of the pile through the capture of neutrons (its poisoning effect), which transform ^{135}Xe into the non-poisonous ^{136}Xe.

The sequence goes like this. Immediately after the pile is quickly shut down, such as during a scram, it retains a positive reactivity coefficient, in that all the factors that affect its neutron multiplication factor, *k*, are as they were during operations. Restarting the pile involves little more than withdrawing the control rods. But within 15 minutes of a shutdown, the reactivity coefficient begins to turn negative as the pile’s graphite moderator cools (a detriment to the chain reaction) and the xenon builds up in the fuel. The xenon builds up because it is still being created from the decay of iodine in the pile, but it is no longer being burned out once the flow of neutrons has all but stopped. These negative factors increase until the rate of xenon decay finally exceeds the rate of its formation from the iodine, at which point the reactivity increases until it again becomes positive. Normally, this took about nine to ten hours after a scram. Therefore, it would be difficult or next to impossible to restart the pile during the period between about a half hour and 10 to as much as 20 hours after shutdown (the time span varied depending on the power level at which the pile had been operating). (HAN-73214: 17; HTM 1945: 1306)

It is from this anomaly that the *quickie* evolved—a shutdown that lasted less than about a half hour. If the shutdown lasted any longer, the pile would enter the period of doldrums, and might not be operable for another 10 hours or more. When the future of the country might depend on the continuous operation of the pile, there was immense pressure on the operators to restart the pile within that 30 minute window after a scram or necessary shutdown.

> You would be vexed by anything that shut you down, and you would get going again as soon as you could, because basically that was what we were supposed to be doing. And of course, the other is self-driven urgency. If you had a scram, if the reactor was shut down for any reason, you had something on the order of 38 minutes, a fairly short period of time to correct that condition and get going again, or the [xenon] poison would overtake you and you’d be face with a 14 hour shutdown. And of course, 14 hours gave you an opportunity to discharge metal, make repairs, or all sorts of things, so you always had a maintenance program set up for whatever you needed to do if you had a longtime shutdown. *Bill McCue, 28-Oct-1994*

The presence of xenon also complicated the process of restarting the pile after a long shutdown.

> Xenon-135 has a half-life of nine hours. So 18 hours after shutdown three-quarters of the xenon present just before shutdown has disappeared. Of course, there is additional xenon formed from decay of iodine-135, but after about 20 hours of shutdown the pile is fairly xenon-free. The Hanford piles were designed to operate at 250 MW with 1,500 tubes in the absence of xenon. When xenon was encountered, loading another 500 tubes gained enough reactivity to overcome the amount of xenon poison at that power level. The nine control rods gave enough variable poison so that the rods could keep the pile subcritical with no xenon [such as after a long shutdown) and be critical with full xenon at 250 MW.
>
> But now when you raise the power level to 2,000 MW, you make a large increase in the amount of xenon at equilibrium, somewhere between doubling and tripling. So you need a lot of variable control to keep the reactor subcritical with no xenon and still be critical with full xenon. The nine control rods did not have enough neutron-absorbing ability to do this at the higher power levels. Therefore, in a xenon-free pile extra control strength could be added by loading poison into some fuel tubes temporarily. After the

> pile had been started and the xenon had built up part way, you would shut down long enough to discharge that poison. By the way, the drop safety rods [VSRs] could not be used for reactor control because they were not cooled. *W. Kelly Woods, 13-Sep-1998*

3.3. Onward to Full Power

On September 30, work began on charging an additional 102 process tubes with uranium fuel, and that was finished on October 3. With the 1,003 loaded tubes, the pile was brought to criticality and taken to 10 MW, and later that day to 15 MW. It was kept at this level until October 5, when the pile was shut down so that more fuel could be loaded, bringing the total to 1,050 tubes. The pile was started the next day, and eventually taken to 38 MW. Nonetheless, measurements showed that still more fuel would be needed to get more power out of the pile. (HAN-73214: 14)

Between October 12 and 15, the number of charged tubes was brought to 1,128, and the pile was taken to 50 MW, and then raised to 60 MW on October 17. Two days later, the pile was shut down again and more tubes were charged, for a total of 1,300. Power was brought to 75 MW and then later increased to 90 MW. Finally, on October 26, the pile was shut down for fuel charging, ending up with 1,500 active tubes. This allowed power to be increased to 110 MW on November 3, but even that couldn't be maintained with 1,500 tubes, and power was cut back to 90 MW on the 5th. Further tests were made and data collected, and on November 20, the pile was shut down so that 1,595 tubes could be made active. Other work was performed while the pile was down, and on November 30, the rods were pulled and the pile achieved 125 MW. Power levels were maintained between 115 and 130 MW, but it became evident that *all* 2,004 tubes would have to be charged in order to get to the 250 MW design rating. So the pile was again shut down on December 20 to complete the fuel loading. (HAN-73214: 14-15)

Another way that the critical mass of the pile was increased was by loading extra uranium slugs into the tubes. When the loading went from 1,500 to 1,595 tubes, the additional 95 tubes each received 35 uranium slugs, not 32. This was also done with the remainder of the tubes in the pile when they were charged, as well as for the central 1,500 tubes when their slugs were later discharged and new slugs were added. A few months later, however, the 32-slug pattern was once again put to use, as the pile's reactivity had shown a slight increase. (HAN-73214: 66)

> It didn't take them too long and they said, "Well, okay, you just have to put in several more slugs per column and we think we'll be all right." As I remember, that's what they said, "We think we'll be all right." So we went up very fast and as I recall, we put in about 50 more inches of slugs and we were doing that as fast as we could. As a matter of fact, it's kind of interesting. Doc [John] Marshall was a nice young guy, and you could talk to him a lot, and we had these old charging machines. You'd take your slug out of a box, put it on a little ramp and it rolled down, and then you had a lever and you pushed that. And I got him on one of the machines charging, and then wouldn't give him any relief! And he kept talking "Come on, I gotta go somewhere," and I said "Well, you just stay and do a few more tubes and you'll be all right." And he laughed and he was a good sport about it, but that was a real critical period. And you wondered, you know, you had to have faith that [Arthur] Compton and those guys knew what they were doing…and they did. *Harry Zweifel 14-Dec-1991*

One factor in the pile's increasing reactivity was the boron in the graphite moderator. Even though the graphite was of the highest purity, it nonetheless contained some boron, about 0.4 ppm of graphite. This tiny amount degraded the reactivity of the pile, as boron is a big absorber of neutrons. Over time, however, the boron would slowly be “burned out” as it absorbed neutrons, resulting in an increase in the pile’s reactivity. (HTM 1945: 1311)

In order to charge beyond the originally planned 1,595 tubes, the remaining 409 tubes had to be connected to the water system. That and the charging took place through December 28, when all 2,004 tubes were made ready (although only 2,002 were actually in use, as two were disconnected due to difficulties). The pile was placed in operation again, and the power level was increased to 150 MW on December 29, and to 180 MW the next day. Finally, after several more incremental increases, the design rating of 250 MW was reached on February 4, 1945. (HAN-73214: 16)

When it was determined that all the process tubes would be needed, changes had to be made to the inlet water orifices. Of the 2,002 active tubes, the central 1,004 tubes were left with their 0.240 in. orifices; the 448 tubes around this central area were fitted with 0.175 in. orifices; and the outer 550 tubes received 0.140 in. orifices. (Later, a fourth zone would be added with 0.200 in. orifices.) With this zoning of the cooling water flow rate, the central tubes, which would run the hottest, received the largest flow, while the outer, less reactive tubes received the least. This also made it possible to get by with the 30,000 gpm maximum flow rate from the process water pumps, which had been planned for less than 1,600 tubes. (HAN-73214, 74, 80-81; Note that the number of tubes mentioned on page 74 of HAN-73214 is probably incorrect; refer to the table on page 80 and the chart on page 81.)

The cautious, step-by-step procedures that were taken during the startup of B Reactor greatly facilitated the startups of D and F Reactors. On December 17, 1944, the D Reactor was made ready for service. No time was wasted now—a full 2,000 tubes were charged with fuel, 35 slugs each. The rods were withdrawn and the pile went critical that evening. The experience gained at B and D Reactors made the startup of F reactor even smoother. Here the operators charged 1,994 tubes with 35 slugs each, and began operations the afternoon of February 25, 1945. (HAN-73214: 18-19)

In spite of the many stoppages when fuel was added to the B pile to increase the power level, production was proceeding and plutonium was being created in the pile’s uranium, albeit at a slower rate than planned. The tide of the war was already turning by the end of 1944, but the need for plutonium to finish the bomb effort was as urgent as ever. With the B Reactor and the other two Hanford piles up and running, the next step was to discharge irradiated fuel from the piles and send it to the separations plants in the 200 Areas.

3.4. Fuel Charging and Discharging Procedures

Although designing, building, and actually starting the B Reactor would have been quite enough of a story in itself, the real purpose of the pile was to create plutonium by irradiating its uranium fuel slugs. Once fuel in a given process tube had been irradiated for a sufficient amount of time, new fuel would be pushed into the front of the tube, which would push the irradiated fuel out the rear of the tube.

The components of the pile that were used during fuel charging and discharging (also called pushing) were discussed in the previous chapter in section 2.8. The discussion now considers the equipment that was used and the typical procedures that were followed once the process had been fine-tuned after startup.

3.4.1. Factors Affecting Plutonium Production

Several key factors affected the rate at which plutonium was created within the pile:

- The pile had to be in a chain-reacting state (critical) in order to provide neutrons that could be absorbed by ^{238}U, the first step in the transmutation of uranium into plutonium.
- The rate of plutonium production was directly proportional to the pile’s power level—more power meant more plutonium.

- The rate of production was also related to the length of time that a fuel slug was inside the operating pile.
- The closer a slug was to the center of the pile, the more neutrons it would be exposed to. Slugs near the fringes of the pile were exposed to about a tenth as many neutrons as those in the center, and therefore had to be left in the pile much longer to produce the same amount of plutonium.

It's easy to see why it was so important to keep the pile operating as close to its maximum power rating as possible in order to ensure maximum plutonium production. A reduction in power meant a concomitant reduction in the rate of plutonium production.

3.4.2. Keeping Track of the Slugs

A fully loaded pile with 2,004 process tubes would contain about 65,000 fuel slugs. Because the reactivity in the pile dropped off with distance from the center of the pile, process tubes were exposed to varying levels of the neutron flux and, therefore, the slugs in them would be producing varying amounts of plutonium. Keeping track of plutonium production would have been a bookkeeping nightmare had it not been for the recent invention of electronic data processing machines—computers.

To this end, the production life of each process tube was recorded via a punch card using equipment supplied by International Business Machines (IBM), and originally installed in the 1704-B Area Office building. This equipment included a key punch machine, reproducer, sorter, multiplier, and accounting machine. When it was time to discharge some fuel from the pile, the pile operators could ask the computer operators for a report listing all tubes in which the average amount of plutonium had reached a specified level. The mechanization of this endless task played a major role in the successful operation of B Reactor. (HAN-73214: 71; HTM 1945: 905)

> We had a man by the name of Bill Rankin who was in charge of the IBM machine. He would punch a card for, I guess, for each shift on each tube from these temperature maps. When I was transferred over to the 100-F Area, they told me that the bottom drawer of the file cabinet was top secret and I was not entitled to look at it. Because those were Bill Rankin's cards. By putting those things through a sorter and through a computer, he could integrate the number of hours that had been operated on any one tube, and he could determine at what point the plutonium in that tube would have reached a certain concentration, and that it was now time to discharge that tube and replace it with fresh slugs. *Bill McCue 28-Oct-1994*

> When you finished your shift at the reactor, you always inventoried the fresh fuel you had not yet charged. The supervisor just coming on shift would inventory the fuel, too, and the tallies had better agree. I remember on one occasion they were off by one slug. As it turned out, one of our tech grads [an interning worker] had taken one home as a paperweight souvenir. The FBI caught up with him, and I'm sure he had grave regrets at that point. It wasn't that the fuel was expensive, but you can imagine how valuable it would be for a foreign country to be able to dissect a slug to see how we figured out the fuel-canning problems. *Richard Nelson, 11-Sep-1998*

3.4.3. Charging from the Front Face

When it was time for a scheduled fuel reloading, the pile was first shut down in an orderly fashion (as opposed to the sudden shutdown of a scram). Normally, the horizontal control rods were slowly inserted into the pile to lower its reactivity over the span of an hour, and then bring it to a halt. This avoided drastic temperature changes within the pile. (HTM 1945: 903)

Once the pile was shut down, an hour or more might be taken for routine maintenance before charging began. This time period allowed the neutron flux in the pile to fall to a negligible amount, and for the fuel slugs to lose some of their more intense radioactivity (although they were still deadly when discharged from the rear of the pile). (HTM 1945: 218, 903)

Fresh fuel slugs were brought from the 103-B Fresh Metal Storage building to the front face work area of the pile. Workers put the boxes of fuel slugs, dummy slugs, and charging equipment on the elevator and raised it to the appropriate level for the tubes that were to be refueled. Water flow to those tubes was cut to a minimum, allowing just enough cooling water to dissipate the residual heat, provide radiation shielding to protect the workers at each end of the tubes, and maintain the poisoning effect on the pile's reactivity. (HTM 1945: 903, 1203)

> We'd valve-down the front crossheader that fed the row of tubes we were going to charge, and put the corresponding rear crossheader to the drain, which prevented the effluent water from the other rows (that were still under pressure) from backflowing into the tubes we were charging. One minor annoyance was the chilled and unchilled risers. They both carried the same water, but a single crossheader might not feed all the tubes in the row you were working on. *Richard Nelson, 11-Sep-1998*

Each of the selected tubes was fitted with the charging equipment on the front face, which was basically an adapter between the tube's nozzle and the charging machine. At the same time, operators were making those tubes ready at the rear face. When a tube was already full of fuel and dummy slugs, it took some effort to push in the new slugs to discharge the irradiated ones. Lubricating each slug with a 50/50 mix of water and water-soluble oil reduced the friction and also the scratching that the slugs could produce in the tubes. The process soon evolved to lubricating the entire tube instead of each slug. The oil was stored on the elevator in a 70 gallon tank, which was enough to lubricate 12 tubes, just about the maximum number of slugs that the elevator could safely carry. (HTM 1945: 906-909)

A hand-cranked charging machine was used to push the dummy and fuel slugs into a tube. It took three workers to feed slugs into the magazine and operate the machine, and it soon proved to be less than adequate for the job. Within the first week after startup, a lever-action charging machine was built at Hanford, as shown in Figure 21. A worker could insert a slug with one or two pulls of the lever arm. This device provided a more uniform force on the column of slugs, which helped ensure that each irradiated slug exiting from the rear of the tube fell where it was supposed to. (HAN-73214: 29)

3.4.4. Discharging from the Rear Face

While workers pushed fresh slugs into the front of the process tubes, dummy slugs and irradiated fuel slugs were pushed out the rear. In theory, there was not much to do at the rear of the pile except get out of the way as the hot slugs exited the pile. In fact, however, the process proved to be rather complicated, which was compounded by the fact that there were so many process tubes with so many slugs.

After the pile was shut down for the charging operation, workers entered the rear face area of the pile, mounted the discharge elevator, and raised it to the appropriate row of tubes. They opened the nozzles on those tubes and attached the appropriate discharge equipment. Before any fuel was discharged, the workers had to leave the area or risk being exposed to deadly levels of radiation.

The original procedure and equipment for handling the slugs involved an L-shaped aiming tube beneath the process tube, into which each slug would drop as it was pushed from the process tube. The slug would fall from the aiming tube into a funnel at water level that fed into a long rubber hose that led the slug into one of three water-filled concrete discharge chutes at the rear base of the pile. The slug discharged from the hose at the lower end of this sloping chute, under about 18 ft of water. An operator standing on the floor above would sort the fuel and dummy slugs into separate buckets beneath the water.

The problems with this system were many. Slugs frequently jammed in the aiming tube, in the funnel, or in the hose. If the workers at the front pushed too hard on the column of slugs, one or more slugs might be pushed out the back and miss the aiming tube completely. With luck, such a slug would fall all the way into the basin water without striking any nozzles on the way down, and not land instead on a ledge or the discharge elevator (which was supposed to be raised *above* the highest row of tubes that were being discharged.). (HAN-73214: 31-32)

> The piece would hit on the side of this rubber-lined funnel, bounce and go down into the funnel, and then go through a rubber tube down to the sorting devices. That was the only flaw we found in our design—when you were faced with a 14 ton discharge [3,000 to 4,000 slugs), you didn't have time for all that individual drop. When they went out the aimer and dropped, the first piece might hit the funnel and bounce about the same time the second piece came down, and they both would choke the funnel. Then you'd have to push the funnel out of the way and let the pieces fall free. *Bill McCue, 28-Oct-1994*

The revised procedure that was thoroughly tested and put into service in early 1945 was based on the simplest of all possible techniques—simply let the slugs exit the rear of the tubes and fall freely into the basin water. The only trick was ensuring that the slugs exited the process tubes somewhat beyond the nozzles, so that they would not strike the other nozzles below. (HAN-73214: 34)

The primary piece of equipment was the *tip-off* discharge fixture that would be attached to each process tube that was being refueled, as shown in Figure 22. It ensured that the exiting slugs fell far enough out from the face of the pile to avoid the other nozzles. It also caught the lubricating oil and water that ran from the process tube, and drained it out a pipe into a trough that ran to a process sewer. The trough served multiple tubes, as shown in Figure 23. Preventing the oily mix from falling into the basin water was of great importance, as the oil would not only cloud the water and make it difficult for workers to view the slugs in the basin, it would also serve as a source of radiation contamination. (HTM 1945: 909)

When slugs were pushed out the rear of a process tube, they fell into the basin water, landed on the padded mattress plates, and then slid down the sloping discharge chutes to the fuel storage basin. A worker standing on the floor above sorted the fuel slugs from the dummy slugs.

3.4.5. Initial Fuel Discharge

The first discharge of irradiated fuel slugs was a test run performed on November 6, 1944. This was much earlier than would be normal for fuel processing, but even mildly hot fuel was badly needed to test the various fuel-handling and chemical separations facilities in the 100 and 200 Areas. Only one tube was discharged, but it nonetheless took six hours. This was due in part to the novelty of the procedure, but also because workers were using the original aiming tube, funnel, and rubber hose equipment, which were plagued with problems. The fact that the fuel was actually hot this time no doubt lengthened the procedure. (HAN-73214: 30-31)

The plan for normal refueling was to discharge about 80 tubes (about 10 tons of fuel) while the pile was shut down. Because of the effect of xenon on the pile, it was important to complete the fuel loading and ancillary maintenance and repair work within about 24 hours, or the pile would be more difficult to control at startup (refer back to section 3.2.4). This meant that a discharge rate of 10 to 12 tubes an hour was needed, which was far more than was being handled with the early equipment. (HAN-73214: 33)

The first scheduled discharge of irradiated fuel was done between November 24 and 28. Although the fuel had not been irradiated to full production levels, it had been "baked in the oven" long enough to create a sufficient amount of plutonium for processing. The original charging procedure was followed, more or less, and only 42 tubes were discharged during a three-day period. The highest rate of refueling was 10 tubes in an eight hour shift. The next scheduled discharge took place on December 26 and 27, during which the funnel-and-hose method was abandoned in favor of the free-fall method. This helped to process as many as 23 tubes in an eight hour shift. As equipment and procedures were improved, the discharge rate increased substantially. By the end of February, 1945, 50 tubes were being discharged in an eight hour shift. (HAN-73214: 31-34; OUT-1462: 87-88)

3.4.6. First Plutonium Shipment

The first "official" batch of irradiated fuel slugs from the B Reactor was processed at the 221-T building in the 200-West Area beginning on December 26, 1944. Prior to that, smaller, less irradiated batches had been put through the process for testing purposes. The processing had started earlier than was planned, because the bomb designers at Los Alamos had been clamoring for any small quantity of plutonium, as they had been working with only tiny laboratory-sized samples. On February 5, 1945, DuPont officially transferred the first small batch of plutonium nitrate to Lieutenant Colonel Franklin Matthias of the Corps of Engineers. This plutonium and the shipments that followed would eventually find their way into the first atomic bomb that was detonated in New Mexico the following July. (OUT-1462, 89-91; Rhodes 1986: 604)

This was Hanford's first product, and it was up to Col. Matthias to get it to Los Angeles, where he would transfer the material to a representative from Los Alamos. No armored cars were involved, nor any snaking convoys of military vehicles. Instead, Matthias hand-carried the plutonium in a specially rigged, two-foot square box, wrapped in paper and tied with rope. The plutonium was secured within the box in a small test-tube, surrounded by lead. He and an aide drove from Hanford to Portland, Oregon, where they caught a train to Los Angeles. There they met an officer from Los Alamos who would take the shipment by train the rest of the way. Matthias relates an interesting dialog between him and the Los Alamos representative at the train station. (Rhodes 1986: 604-605; Thayer 1996: 172-173)

> At the railroad station this officer came up and I said "Well, have you got a locked room to go back to New Mexico?" and he said "No, I had trouble getting it so I have a berth, an upper berth." So I said "Well, you know what you're gonna be carrying?" And he didn't know, so I said "Well, it cost $350,000,000." That was the cost of our project [Hanford] up to that point. So he kind of got a little bit shaky and went back to the station and came back with a locked room that he could use to get back. *Frank Matthias, 26-September-1992*

After that, shipments were eventually made by Army ambulance-type panel trucks in a caravan of three trucks, with a car leading and following. This was believed to be a sufficiently safe method, because so many army vehicles were on the road at that time. (Rhodes 1986: 604-605; Sanger 1995: 196-198)

3.5. Technical Problems and Solutions

The successful startup of the B Reactor was evidence of the outstanding work performed by scientists, engineers, construction managers, craft workers, and so on. The need for excellence, ingenuity, and know-how did not stop when operations began, however.

Throughout the life of the pile, the goal and top priority was the production of plutonium in the shortest time consistent with safe operation. Day-to-day production brought a variety of significant new problems that had to be handled quickly and surely to keep the pile running, while ensuring its safety and longevity. As time went on, many of the solutions also served to enhance production from the pile and to improve the new piles that followed. (HTM 1945: 1101)

Some of the more significant problems that were overcome included the canning of the uranium fuel slugs, the pile-threatening expansion of the graphite moderator, purging the water system to remove film from the process tubes, dealing with fuel slug failures, and simply finding workers to operate the piles.

3.5.1. Fuel Canning

The uranium fuel slugs for the pile were fabricated at the Hanford 300 Area. Finding a suitable means of preparing the uranium for life in the pile turned out to be a major effort in the B Reactor story. It was one of the first problems that looked as though it might prevent the operation of the B Reactor altogether, and the story took place before the pile was even completed. The importance of this problem is described in section 8.52 in Smyth.

The size and shape of the uranium fuel slugs (cylinders approximately 8 in. long by 1.5 inches in diameter) had been dictated by the physics of the pile and the limitations on handling the hot fuel when it was discharged from the pile. Uranium is quite chemically reactive, more so than iron, so the slugs had to be sealed off from air, water, and other agents. Also, the intense radioactivity that would be generated in the slugs had to be contained lest it get into the cooling water and, ultimately, into the Columbia River.

Sealing each slug within an aluminum jacket, or can, was concluded to be the most likely method for success. This apparently simple procedure in fact proved to be extremely complex. It was critical that the can interfere as little as possible with the passage of neutrons, so as not to poison the pile, and that it readily transfer heat from the uranium to the surrounding water in the process tube. The can also had to be strong enough to withstand the thermal and physical shocks it would receive during use. All aspects of the manufacturing process had to be kept to very strict tolerances, both in materials and craftsmanship. Finally, the process had to work for not just one or two, but for tens of thousands of slugs, all of which would be exposed to high temperatures and, more importantly, a tremendous amount of radiation.

> We were called in and told that the biggest problem confronting the whole Manhattan Project at this time was the ability to can the uranium slugs and make them ready for the pile. The piles were already being built; B Reactor was just about ready to go, and we were hearing this news (although at the time we didn’t know the actual schedules involved). This problem is discussed in the Smyth Report, and it just points out that if we had not been able to can the uranium slugs properly, the B Reactor might never have been started.
>
> The canning methods at that point had been mechanized for production, and although not unsuccessful, the success rate was only about 15 or 20 percent. That was far too low to supply the slugs for a Hanford pile, let alone for three piles. They wanted our group of six or seven to set up a test line, which was going to be a manual operation. The problem wasn’t so much the ingredients or machinery, but the methods, temperatures, and timing.
>
> We were actually able to go from the bronze dipping into the aluminum and to the canning, and I think it was almost like manna from heaven when we finally got the correct temperatures. After the uranium slug had been bronzed and cleaned, the critical

> thing was to get the correct aluminum eutectic (alloying) temperature so that bonding would occur between the uranium slug and the aluminum can. The temperatures of both the slug and the bonding agent were critical. *Roger Hultgren, 24-Aug-1998*

The canning process that was finally established just weeks before the fuel was needed for the initial startup at B Reactor is described quite well in the *Hanford Technical Manual*, Section A, Metal Preparation (HW-10475A), and includes these main steps:

- The uranium metal was extruded into long rods, from which 8 in. slugs were machined on a lathe.
- Each slug was cleaned with nitric acid to remove oxidation.
- The slug was dipped in a bath of molten copper-tin alloy (bronze) to prevent the uranium from alloying with the bonding material that would later be added.
- The slug was dipped in a bath of molten tin to remove excess bronze; excess tin was removed by centrifuging.
- The aluminum can for the slug was cleaned and filled with molten aluminum-silicon bonding material.
- The slug was dipped in a molten bath of the same bonding material and immediately pressed into the can, discharging excess material.
- An aluminum cap was inserted into the open end of the can.
- The cap was machined to precise dimensions and welded to the can.
- Finally, the finished slugs would be put through a rigorous inspection, including spending 40 hours in a steam autoclave that would drive moisture through the slightest flaw in the aluminum can. The uranium next to the flaw would oxidize and swell, visibly blistering or distorting the can, a tell-tale sign for the inspectors.

Although the steps in the process may seem straightforward, the end results were quite dependent on the precise way in which the steps were performed, the temperatures of the baths, and the amount of time between each step. It took considerable efforts to eliminate all the possible problems, because any one of them alone could affect the results. Much time was also spent devising a suitable means of testing the finished slugs, so that those of lower quality could be discarded—only first-rate slugs would be used in the pile. Eventually, it was learned that lowering the temperature of the various baths by 50 ºF (10 ºC) resulted in a huge gain in the number of the best cans produced—from 5 percent to 75 percent. But this improvement wasn't made until August 14, 1944, just a month before the B Reactor was first loaded with fuel. Not only that, but it was decided that *all* existing slugs would be rejected in favor of ones being produced with the new process. Other improvements were made to the canning process that soon led to an overall rejection rate of only about 2 percent. (OUT-1462: 74-75, 83)

3.5.2. Graphite Swelling and the Closure of B Reactor

Perhaps the greatest setback encountered in the early days of pile operations, second only to the pile-stopping effect of xenon poisoning, was the growth (expansion) of the pile's graphite moderator—after the pile was put into operation, the 36,000 cubic foot block of graphite literally began to swell.

3.5.2.1. Understanding the Problem

This type of problem had been predicted by physicist Eugene Wigner in late 1942, when he hypothesized that fast neutrons in the pile could induce changes in the graphite (the term *Wigner's effect* would later be applied to the graphite problem). (Wahlen 1989: 16)

As soon as the pile was taken critical for the first time, scientists began to study the graphite. Captain Frank Valente of the Corps of Engineers reports in his diary that on September 27, 1944, three papoose slugs were loaded into the pile, each of which contained a sample of graphite. Any changes to the samples over time would help predict changes in the pile’s graphite perhaps 30 percent ahead of time. (MED-1004: 27-Sep-44)

> The basic information on irradiation effect in graphite came from irradiating small samples of graphite, mostly in water-cooled test holes that entered the reactor on the side opposite the control rods. Samples were about 0.5 inches in diameter by 4 in. long; a few were irradiated in process tubes between fuel elements. Irradiation temperatures were about 30 ºC. The major effect of graphite irradiation from a reactor standpoint is expansion, caused by energetic neutrons knocking carbon atoms out of their normal position in the graphite. *W. Kelly Woods, 26-Aug-1998*

Indeed, changes were taking place to the graphite moderator, and they were by no means subtle. About a year after startup, expansion of the graphite in the center of the pile had already reached 1 in., and was increasing at the rate of 0.1 in. per month. The swelling was also being seen at the D and F Reactors. The changes were due to the intense radiation from the pile’s neutron flux, which caused the carbon atoms in the graphite’s crystal lattice to realign themselves. The swelling was causing the process tubes to bow, the steel gun barrels to be bound tightly in the graphite, and the neoprene seals to be stressed at the region where the top shield joined the side shields. Operators worried that further expansion could split these seals and the Van Stone flanges where the aluminum process tubes connected to the gun barrels. It was estimated that in the worst case, the entire pile could be re-tubed in about three months. Nonetheless, excessive graphite expansion could preclude even re-tubing. It was especially worrisome that such displacements might prevent the full insertion of one or more of the control rods or vertical safety rods, which could have catastrophic results in an emergency. Therefore, they regarded the graphite problem as the single most important factor affecting the ultimate “life” of the pile. (Gerber 1993: 18)

> We were assigned to find a method for measuring the amount of growth. So we got our heads together to investigate the bowing [bending] of the process tubes, which would indicate the amount of growth in the graphite. We came up with a very simple approach. We would set up a transit on the charging elevator and place a lighted target inside a process tube. We would pull the scale through the tube, one or two feet at a time, and take a reading with the transit at each position. With that data you could plot the bowing of the process tube. When we had enough data they could calculate the rate of growth of the graphite based on the amount of nuclear activity it had been exposed to. *Tom Clement, 15-Mar-1992*

> The growth was monitored with gauges between the top and side shield. In addition, one hole in the center part of the reactor and another in the top center were emptied and were used during pile shutdown to measure tube contour along its length relative to the front end of the tube. Besides the transit and light method, the elevation could be measured by pouring water into a hose connected to a hollow target with an opening on top, and measuring the water level when the water overflowed the target. *W. Kelly Woods, 26-August-1998*

The distortion was not at all uniform. It was directly proportional to the intensity of the neutron flux, so that a higher flux encouraged more expansion. This meant that the center of the pile, where the flux was the strongest, would be more likely to expand than the edges, where the flux was the weakest.

However, the rate of distortion was also very strongly dependent on the temperature of the graphite, such that cool graphite would expand substantially *more* than hot graphite under the same flow of fast neutrons. In other words, the effect of temperature on the graphite in the pile was exactly opposite of the effect of the neutron flux. Temperature was so crucial to the expansion that the cooler edges of the pile were actually expanding quite a bit *more* than the graphite in the highly irradiated but thermally hot central portion. (HW-18453: 3-4)

3.5.2.2. Facing the Inevitable

Once the problem was identified, it was all too easy to predict that, given a steady rate of expansion, the pile would at some point no longer be functional. Therefore, in early 1946, a Graphite Expansion Committee was formed, with representatives of engineering, manufacturing, and health physics. Their work included developing methods for measuring the amount of expansion and the many effects it was having on the pile. In the spring of 1946, experiments demonstrated that the graphite expansion could be reduced by *thermally annealing* the graphite (heating to improve a material), but this work was so preliminary that it was considered inconclusive and not ready for implementation. (Gerber 1993: 18)

The possibility of losing one of the three piles and then the other two soon after was of crisis proportions. Therefore, once the war was over and the wartime atmosphere of urgency no longer existed, the Army decided in early 1946 to shut down the B Reactor to eliminate further expansion stresses; this was done in March. They would hold the B Reactor in reserve for the future, as a backup for the other two piles. They could restart B Reactor either when a solution had been found to the graphite problem, or when its use was of national importance even if it meant an early demise of the pile. (Gerber 1993: 18-19)

The graphite expansion problem, with the consequent closure of B Reactor, was of such critical importance that it led to the decision in mid-1947 to construct new 105 pile buildings in each of the three 100 Areas. The new piles would be connected to the existing cooling systems and replace the original piles. The estimated cost for all three was 116 million dollars. Before all three were begun, however, it was decided that efforts should be concentrated instead on building a completely new 100 Area, 100-H, and just one new replacement pile in the 100-D Area, to be called the DR Reactor, for “D Replacement”. (HW-24800-34: 5-6)

3.5.2.3. Finding a Simple Solution

The 100-H Area and the DR Reactor were both completed, but fate and lots of hard work obviated the need for the planned BR and FR piles. A workable solution for graphite expansion was found that allowed the B Reactor to be started up once again in July 1948 (there was also great pressure for more plutonium production for national defense). The answer turned out to be similar to the annealing solution that had already been identified, only the annealing process had a new twist.

> C.W.J. Wende (head of the Pile Technology Division in the Engineering Department) proposed that adding oxygen to the helium atmosphere in the reactor might cause selective combustion of the displaced carbon atoms and thus reduce the expansion. This was tried in 1946 with encouraging results. Subsequently, the experimental program using small samples showed that the benefits came from *nuclear annealing*, a previously unrecognized phenomenon, and did not come from selective oxidation.
>
> When irradiated at low temperatures (less than 100 ºC), most of the effects, including expansion, could be overcome by *thermally annealing* the sample in an oven at 2000 ºC. But it was discovered that continuing to irradiate in the reactor at a temperature

> of 250 ºC produced much the same annealing. (This newly discovered phenomenon of *nuclear annealing* was declassified for the Atoms for Peace Conference in Geneva in 1955.)
>
> Replacing the high conductivity helium with low conductivity oxygen (or carbon dioxide) raised the temperature of the graphite. With the reactor operating at 250 MW, the normal graphite temperature with pure helium was about 100 ºC, and that was increased to about 250 ºC by using oxygen or carbon dioxide in place of [some of] the helium. Once nuclear annealing was recognized, carbon dioxide was used because it was cheaper than oxygen. *W. Kelly Woods, 26-Aug-1998*

The addition of CO_2 to the pile was so effective that by 1954, the B Reactor was operating with a gas atmosphere composed of 40 percent He and 60 percent CO_2. (Gerber 1993: 19-20, 24-25; HW-18453: 2-3)

It was the higher graphite temperatures resulting from the addition of the CO_2 and, later on, from increased power levels, that prevented all three of the original piles from becoming totally inoperable because of graphite expansion. (DUN-6888: 52)

3.5.3. Purging the Water System

Many of the B Reactor's components were critical to its nuclear reactivity. For example, any impurities in its graphite moderator might diminish the ability to sustain a nuclear chain reaction. The pile's water-cooling system also affected the reactivity within the pile but, more importantly, it played a critical role in the pile's safety. So it was of the utmost importance to keep the water flowing through the process tubes, both in terms of increasing plutonium production and decreasing the chances of a life-threatening disaster.

The narrow gap for water flow between the cylindrical fuel slugs and the aluminum process tubes that contained them measured just 0.086 in. This tiny annulus for such a critical aspect of the pile was necessary to reduce as much as possible the poisoning effect of the water on the pile's reactivity. The miniscule heat-transfer ability of the volume of water surrounding the fuel slugs was compensated for by pumping the water through the pile at fairly high pressure, about 200 pounds per square inch (psi), which equates to about 20 gallons per minute (gpm) through each tube. The tremendous amount of surface area (the tube walls and the fuel slugs) produced a substantial pressure drop as the water passed through a tube, so that the pressure at the outlet nozzle was about 18 psi. (HTM 1945: 514)

The narrow water passage through the process tubes meant that *any* reduction in size or any slight blockage could produce dramatic results in pile operations, all negative. This is why so many of the buildings and systems in the 100 Areas were dedicated to the filtering, treatment, and pumping of the cooling water. Even with all the care and attention given to the water, it had been anticipated that some filming would occur in the process tubes, and that even a thin film would diminish the water's flow rate and its ability to cool the fuel slugs, thereby causing heat build-up within the pile.

At the Hanford Corrosion and Materials Experiments facility (CMX), steam from a railroad locomotive was used to heat jackets surrounding full-length ribbed process tubes. Here it was discovered that a ferrous-gelatinous film could form and greatly increase flow resistance in the process tubes. It was here that materials were developed that could be used to purge the process tubes and scour them clean of film.

By early December 1944, barely two months after startup, operators had measured a 10 psi increase in pressure drop between the water inlets and outlets of some of the process tubes that were being monitored, indicating that impurities in the water had built up film on the tube surfaces, as anticipated.

Consequently, they performed the first purge (cleansing operation) of the cooling system on December 12, 1944. The purging material used was oxalic acid solution added to the cooling water before it was pumped through the pile. This made just a limited improvement in the pressure drop, but that gain was lost soon after. A second purge was performed with the same inadequate results. In fact, examination of special corrosion slugs showed that a calcium oxalate film had been formed. (Gerber 1993: 11-12; HAN-73214: 76-77)

As a direct result of testing at the CMX facility, on January, 26, 1945, another purge was made by injecting a suspension of Super Cel, a diatomaceous earth, at a rate of 100 ppm into the cooling water, and pumped through the pile over the period of an hour. This time the purge made a marked difference in decreasing the pressure drop. Thereafter, Super Cel was the purging material of choice, and was used about once a month in purges throughout the 1940s. (Gerber 1993: 11-12; HAN-73214: 77)

> During the first diatomaceous earth purge of B Reactor, I was assisting in the supervision of Power operators who were controlling the injection equipment. While stationed in the pump pit, I glanced up at the handrail surrounding the operating floor. There were so many “Big Brass” from DuPont, the Army, Technical, and Engineering, as well as various scientists, all leaning against the handrail that I wondered if the structure would collapse! *Jim Frymier, 20-Sep-1998*

> A second discovery at CMX involved shielding elements at the ends of the tubes. Argonne physicists said that to block radiation from streaming out the ends of the process tubes, there should be a 50:50 mixture of lead and water. The water would moderate the fast neutrons and the lead would absorb the gamma rays. Crawford Greenewalt, future president of DuPont, said that was easy to solve. He arranged for lead slabs with a cross section about 50 percent of the hollow tube to be jacketed with aluminum. The lead slabs were then twisted into a spiral. To keep the pieces from rotating in the tube they were clamped in the middle and the ends were twisted in opposing directions. Finally, there was concern that if many of these shielding pieces were at right angles to one another there would be serious restriction in the flow of water. This was solved by having projections on the ends of the elements so that the water could flow between the elements as necessary. Many thousand of these spiral shielding elements were fabricated for the reactors. Fortunately, some of them were delivered to the CMX Laboratory where it was discovered that the elements were useless. When one tried to push against a column of the spiral shielding elements in a process tube, the column was unstable and buckled, and it was impossible to push them out of the tube. *W. Kelly Woods, 10-Sep-1998*

3.5.4. Fuel Slug Failures

That a fuel slug might fail within the pile was an ever-present danger, one that was multiplied by the more than 60,000 slugs that could be in the pile at any one time. If the aluminum jacket were to develop even a pin-hole leak while in operation, cooling water could reach the uranium, which would oxidize and swell, just as iron does. This could produce blisters in the aluminum jacket, weakening it while beginning to block the flow of water in the process tube. Ultimately, a swollen slug might block the flow of water completely, or become lodged in the process tube and be impossible to remove using the normal charging tools and procedures. (HW-3-1121: 1)

A slug might also swell due to the presence of fission products between the uranium fuel and the aluminum jackets. This problem was alleviated through a combination of extruding the uranium metal before canning it, and putting the fuel slugs through a heat-treating process before putting them into service in the pile.

A slug failure could progress to the point where the blistering in the aluminum broke loose. This increased the dangers of blocking the cooling water and lodging the slug tightly in its tube, while also releasing radioactive material into the water, which would eventually reach the Columbia River.

In an August 1944 tour of the almost completed 105-B pile, Enrico Fermi (under his working name *Mr. Eugene Farmer*) was said to have urged the engineers and operators to give particular attention to developing tools and procedures for dealing with stuck fuel slugs. Ideas were being pursued for tools that could remove stuck slugs, and a machine was being developed for pulling out entire process tubes should that be necessary. (HW-3-526: 2)

The primary method for detecting a slug failure was by monitoring the radioactivity in the effluent water from each of the crossheaders on the rear face of the pile. When the radioactivity exceeded the calculated background level in the water, an investigation would be made to see if the higher levels were, indeed, due to a failing fuel slug. (HW-3-1121: 1-4)

Slug failures had occurred at the test piles at Oak Ridge, but there were none at the Hanford piles during World War II. There were, however, many cases of blistering or other unusual fuel jacket problems that did not release any radioactivity or hinder the water flow, but garnered much attention and concern as the slugs were studied after discharge within the water-filled fuel storage basin. There were also cases of badly warped slugs that stuck so soundly in their process tubes that the tubes had to be removed. (Gerber 1993: 13-14)

The first actual rupture of a fuel slug at Hanford occurred in May, 1948, at the F Reactor. This was followed by two slug ruptures in September and November at the B Reactor. Both failures required replacement of the affected process tubes, rear pigtails, nozzles, and thermocouple lines, which severely hindered pile operations for several days. As the power levels of the three original Hanford piles were increased during the years after the war, the number of slug failures increased, as well. For example, the three piles together experienced 115 failures in 1951, 140 in 1952, 93 in 1953, and 211 in 1954. These numbers did fall somewhat in the later years of operations. (DUN-6888: 44; Gerber 1993: 26-27)

> We were a frightened bunch of puppies when we realized that we had a slug with a hole in it. The first episode at getting one out, how to do it, all the learning—it just hadn't been done anywhere before, you know? We had to build all the equipment, figure out how to push it, what to do with it after we pushed it out the rear nozzle into the pool. How do you handle that? And what about the water, was it going to be contaminated so badly? I think with the first ruptured or stuck slug we were down for a week. *Harry Zweifel, 14-Dec-1991*

The following is taken from a technical report of a later fuel element failure that illustrates the difficulties involved with detecting and correcting the problem, as well as the dangers—the report also mentions that "During the removal of the downstream section of the tube, four people exceeded the permissible limit (radiation) as indicated by their badge and pencil readings [dosimeters], and have been temporarily restricted from dangerous work." (HW-22570: 1-8)

> SUMMARY: The B Reactor was shut down at 10:50 AM on October 22, 1951, to remove a ruptured slug from tube No. 3465-B. During attempts to remove the ruptured slug, the tube parted and the rear gun barrel was forced out approximately 13 in. The gun barrel was replaced, the rear section of the tube removed, and the ruptured piece was then

> removed using the pneumatic charger. The remainder of the tube was then removed, the new tube installed, and recharged with metal. The total downtime required to effect the removal of the rupture and the tube replacement was 79.8 hours.
>
> DETECTION: The initial indication of the rupture was observed on the effluent water monitoring system at approximately 9:40 AM on October 22, 1951. Header sample analysis substantiated the presence of a rupture and the reactor was shut down. A reading of 5 R/hr was obtained on the rear face pigtail of tube No. 3465-B.
>
> REMOVAL: The first attempt to discharge the contents of the tube with the pneumatic charger was unsuccessful. A push pole was inserted into the tube and the charge was moved approximately eight inches by tapping the charge with the pole. The pneumatic charger was tried again and the charge moved an additional five inches and stopped. At this time, it was evident that the tube could not be discharged in the normal recovery time, so it was decided to attach the "pluto-cap" and hose to the tube and allow the metal in the tube to cool.
>
> When entering the rear face to attach the "pluto-cap" it was noticed that the nozzle and gun barrel on tube No. 3465-B extended approximately thirteen inches beyond its normal position. Further investigation revealed that the tube had parted approximately fourteen feet from the downstream end, allowing the gun barrel to be pushed out. An estimated 160 gallons of water leaked into the reactor before tube 3465-B could be isolated from the process water system.
>
> After the tube had been isolated, the rear gun barrel was pushed back to its normal position. Six perforated dummies were then splined out of the downstream end of the tube and a piece of rope, used as a choker, was attached to the rear end of the tube. The tube was pulled out four feet and cut off. The remainder of the downstream section of the tube was secured to the gun barrel and its contents were pushed back in to the reactor with a push pole. The downstream section, free of metal, was then pulled out and dropped into the storage basin. A roller type tip-off was attached to the gun barrel flange and the tube was discharged with the pneumatic charger, using normal forces. The upstream section of the tube was removed by standard tube removal procedure and the new tube was installed and recharged using regular production loading.

3.5.5. Worker Recruiting

Finally, there was one not-so-technical problem that arose because the technology of nuclear reactors was brand new—there was no existing pool of workers to operate them and no established university programs in pile technology. There just weren't a lot of pile operators around in 1944, and those who might go by that title had not been one for more than a year or two, and they certainly had no experience with water-cooled, multi-megawatt piles such as those being finished at Hanford.

As recruitment efforts for construction personnel at Hanford wound down, efforts to hire reactor operators and technicians were just winding up. Many workers came directly from the ranks of DuPont, who plucked likely candidates from DuPont plants throughout the country. Moving to Hanford was an exciting time for most of the workers, as expressed in the following remembrances.

> In July, 1943, I was working with the DuPont Company at the Oklahoma Ordnance works in Pryor, Oklahoma, and they told me to just lock up everything in the place and go to Wilmington, and there I would be told what I was supposed to do. And so we did, we closed the house and we left. I took my wife back to West Virginia to visit, and I went on to Wilmington. We were taken up to the second floor of the DuPont Building, there

were several of us, and we went into a secured area and we sat down at a table and they gave us a technical manual about six inches thick, and told us that we should read that, but that basically they were designing all this on a 60 percent probability that it would work. And I was told that I would be going out there, but first that I should go to the University of Chicago for six months to work with the physicists there, and that basically we were to be as helpful as we could and learn all we could because when we got out to Hanford we would be doing it.

So we got a lot of reactor experience [at Chicago] before we were sent out about August of 1944 to the 100-B Area. It was nearing completion, and at that time you could roam around the building, explore, and learn what was in the building, crawling in instrument tunnels and places like that so that we would know the building intimately. Then as it began to get completed, we had thirteen supervisors on a shift and no operators! *Bill McCue, 28-Oct-1994*

I was an area supervisor for DuPont at a TNT plant at Joliet, Illinois, and they turned the plant over to another company and moved about 1,200 of us out here from Joliet. This was in the summer of ‘44, basically operating people. *Floyd Britson, 15-Mar-1992*

I came to Hanford from Morgantown, West Virginia, in August of 1944. I was working for DuPont and the opportunity came up to transfer to Hanford if you so desired. At that time it was a very hush hushed project. All I knew was that I was going to Pasco, Washington; I knew my job title and I knew my salary. They gave you your travel allowances, tickets and so forth, and I went on two weeks vacation and then I came to Hanford. [When I first started,] I recall I had to get up at 4:00 in the morning to get to work at 8:00. I had to walk and then catch an intercity bus, and by the time I got to the area I had changed buses five times. And that made a long day of it. I had to repeat it in the evening. But fortunately I only had to put up with that for about two months. *Jim Frymier, 14-Dec-1991*

I came to Hanford in July 1944. We went through orientation, of course, and the next day we started school. And I went to school approximately three months before I went to D Area, because [the field of] instruments was new to me, as it was to practically everyone else. We had boys from back east who were teaching us about control. But now I look back and see that we were pretty green out there! *Glenn Stein, 1-Aug-1992*

I was an employee of the DuPont Company; joined them at Carneys Point, New Jersey, in the smokeless powder plant they have there. I was in training for their military explosives program and went to Charleston, Indiana, where I was a control chemist in the laboratories there, and eventually worked into being a line supervisor in the acid and organics part of the plant. One day I was called into my superintendent’s office and he indicated to me that he had another assignment for me, and he didn’t know exactly what it was but he sent me to the office of the service superintendent of the plant. And I was told that I was going to the TNX Project [DuPont's new manufacturing unit in charge of Hanford]. This was supposedly a super secret project that we'd heard about but didn't know anything about. And even the superintendents didn't know anything about it. All he told me was that they had train tickets and reservations for me to go to Knoxville, Tennessee [near the Clinton Engineer Works at Oak Ridge], from Charleston, Indiana, where I was working.

[At Oak Ridge] we were moved into dormitories and began our training there, and we were told that we were in training for a production plant out in the state of Washington, and we heard several names: we heard Pasco, we heard Kennewick, we heard Hanford and we didn't know what they all meant at the time, but we stayed there in Oak Ridge at the Clinton Laboratories in training to operate an atomic pile. After our clearances went through, they revealed to us what we were doing, the kind of work we were in.

We stayed at Clinton Laboratories, learning how to operate the X-10 reactor, which was the second reactor made. The first one, of course, being the Chicago pile (reactors were called piles in those days). About three months later, we came out here [to Hanford]. I got here on May 11, 1944, and got set up in the dormitory room and was immediately assigned to the 300 Area as part of the operating crew for the Hanford test reactor, the Hanford "pile." *Don Lewis, 14-Dec-1991*

I started to work for DuPont in 1937 when I first got out of college. I started making viscose rayon and then I helped start up the first nylon plant in Delaware. Then they shipped me out to Ohio to make ammunition for the war effort, and then on out here. So I have an awful lot of respect for them. [On arrival at Hanford] everybody was working at least six days a week. It was a long day. The time you left the dormitory and caught your bus, at about 6:00 or 6:30 in the morning, and then got back about 6:00 or 6:30 in the night, it was a long day. And then you'd have to go over to the cafeteria. *Tom Clement, 15-Mar-1992*

We were very short on electronics people, because the services had grabbed all who were available, so we were very short-handed. In fact, my previous experience had been in theater sound work before the war, so I had some electronics experience. I was called one day by the employment people, who said they had a man they were going to send out to me. They thought he might be a big help. And his qualifications were that he lived next door to a ham radio operator. So that was about the type of electronics people we were getting at the plant [B Reactor]. Even then we were able to get the plant going and on schedule in good time. *Dee McCullough, 15-Dec-1991*

Construction was laying off carpenters, so we hired a bunch of carpenters for power operators. We had brand new equipment, nobody was used to it, and so it didn't make

> much difference what their past profession was—they had to learn all over again. *Floyd Britson, 15-Mar-1992*

3.6. Worker Health and Safety

From the outset, the scientists and engineers recognized that in addition to the neutron and gamma rays that would be produced during the operation of the pile, vast quantities of what had been termed "radium-like materials" would be produced on an unprecedented scale. Only a few grams of radium had been isolated, equivalent to a few *curies*, a measure of the quantity of radioactivity. A curie of radium required special and rigorous safety precautions when handled or used. The radioactivity that would be produced in the pile, however, would be equivalent to more than 1,000 *tons* of radium and hundreds of millions of curies.

Human experience with ionizing radiations and radioactive materials was very limited, although by 1940 had developed to the point where it was understood that a sufficiently high dose of radiation could cause untoward biological effects and even death. Similarly, it was understood from the unhappy experience of the watch-dial painters that ingestion of radium into the body could also lead to serious and even fatal results. The dial painters were largely young women who worked painting clock and watch dials using luminescent paint that contained radium. They ingested significant quantities of radium because of their habit of forming a pointed tip on their paint brushes by twirling it in the mouth; the brushes, of course, were loaded with the radium-bearing paint. By 1940, many hundreds of young women had acquired significant depositions of radium in their bodies; many died from bone cancer or other diseases related to the ingestion of radium.

Accordingly, radiation safety considerations dictated to a considerable degree the design of the pile. The shielding described in section 2.7.2, and the self-shielding provided by the graphite core of the pile, were necessary to reduce the ambient radiation fields to tolerable levels during normal reactor operations. But there was still the problem of external radiation fields associated with specific procedures such as fuel discharging, and great concern about the production of radioactivity, which not only produced radiation fields but which also could result in serious harm if taken into the body, even in small amounts.

Plutonium presented special problems. This element is virtually nonexistent in nature (the small amounts of plutonium that we detect in our environment are largely a result of weapons testing), so there was no record of human experience on which safety standards could be based. By analogy with radium, it was clear that plutonium would also be a highly radiotoxic material. This had been recognized by its discoverer, Glenn Seaborg. After thinking about the vast quantities of plutonium that would be produced, he wrote in a memo to Robert Stone, the chief medical officer of the Manhattan District, on Wednesday, January 5, 1944 (Kathren et al. 1994: 368):

> It has occurred to me that the physiological hazards of working with plutonium and its compounds may be very great. Due to its alpha radiation and long life, it may be that the permanent location in the body of even small amounts, say one milligram or less, may be very harmful. The ingestion of such extraordinarily small amounts as some few tens of micrograms may be unpleasant if it locates itself in a permanent position. . .
>
> In addition to helping to set up safety measures in handling so as to prevent the occurrence of such accidents, I would like to suggest that a program to trace the course of plutonium in the body be initiated as soon as possible. In my opinion, such a program should have the highest priority.

Seaborg goes on to record in his diaries that, before the month was out, arrangements were made to transfer health physicist Herbert M. Parker, “. . .the best man we now have available. . .” to oversee radiation measurements at Hanford, as well as to add a physician with specific knowledge in radiation effects. (Kathren et al. 1994: 396-397)

By the time the B Reactor went critical for the first time, an extensive operational occupational health and safety medicine program was in place, buttressed by numerous research studies designed to gain a better understanding of the hazards of plutonium (Stone 1951).

3.6.1. Monitoring the Area

The B Reactor had a number of built-in radiation monitoring instruments that were used to measure the pile’s activity for production purposes, and also to ensure the safety of workers and the environment. Areas and components that were monitored included the effluent water at the pile and in the retention basin, ventilating air, the discharge area, the inner control-rod room, the area above the pile, and the helium gas that circulated through the pile. Areas that would normally have no radiation but were constantly populated were also monitored to ensure the safety of workers, including the control room and the fuel transfer area. Before workers entered potentially hazardous areas, a Health Instrument inspector with a portable detector would first survey the area and determine a safe distance and time for anyone working there. (HTM 1945: 827-828)

3.6.2. Radiation Protection Standards

Although all aspects of industrial health were considered, including such toxics as heavy metals, organic solvents, and fluorine, special emphasis was placed on radiation safety. All workers were given a comprehensive preemployment physical examination to ensure their fitness for the job for which they were hired, and radiation workers were routine monitored with blood tests and urinalyses. To minimize exposure to radiation, new construction or extensive remodeling of buildings was to involve a health physicist or a physician at an early stage in the design and throughout construction.

The special radiation hazards involved were neutrons, electromagnetic radiation such as X- and gamma rays, beta rays, and alpha particles. Neutrons and gamma rays were produced in the pile and thus posed a hazard during pile operation; shielding around the pile was the primary mechanism by which neutron exposures were controlled. When the pile was shut down, this source of radiation was essentially halted. However, the fission products produced in the pile and in the uranium slugs as a result of irradiation emitted penetrating gamma rays as well as the more easily shielded beta particles. So long as the material remained in the pile, the pile shielding would provide adequate protection. Removal of the slugs during the refueling process, however, was a necessity, as was maintenance work on radioactive components of the pile. Therefore, a number of techniques were used to reduce radiation exposure to acceptable levels. These included shielding to the extent practicable, increasing the distance between the worker and the source of the radiation, and limiting the time of exposure.

In addition to these three physical means of control, an extensive system of administrative controls was introduced, including worker education and training, and oversight of operations by specially trained personnel known as monitors or Health Instrument Technicians. Worker radiation exposures were monitored by special instruments developed by the Health Instrument Division, and all workers carried with them at all times their own personal monitoring device which measured their accumulated dose of radiation.

Alpha radiation, and specifically the alpha emitting element plutonium, posed special problems. As an external hazard (i.e., a hazard from outside the body), alpha particles do not pose a serious problem. These relatively large particles can be shielded by virtually anything—a few inches of air, a sheet of paper, or even the dead outer layer of the human skin. But when taken into the body and deposited in living tissues, they possess enormous potential for biological damage.

Accordingly, efforts were taken to prevent the intake of radioactive materials into the body. The air in work areas was continuously monitored by drawing it through a filter and then measuring how much radioactivity was deposited on the filter. Workers were forbidden to eat, drink, or smoke in areas known to have the potential for loose radioactive contamination. Monitoring techniques, such as analysis of the urine for plutonium, were utilized to determine if and how much plutonium had been taken into the worker's body, and to act as a check on how well the preventative measures were working.

Although some limits for radiation exposure had been established, these by and large applied to protection of exposure from external sources of radiation—i.e., from penetrating radiations outside the body. Doses were measured in terms of *roentgens*, a unit of radiation derived from the amount of ionization (charged particles) that the radiation produced in air. While the roentgen unit was suitable to exposures such as those that might be received from medical X-rays and gamma rays from radium, it was not particularly suited to characterizing the doses from other radiations, specifically neutrons, beta particles, and alpha particles from radioactivity within the body.

Although the roentgen was used to characterize exposure, other more descriptive units were developed and used at Hanford, including the *rep* (roentgen equivalent physical) for beta radiation and the *rem* (roentgen equivalent man) for describing the biological dose from any kind of exposing radiation, external or internal. Special attention was given to assuring their adequacy when applied to B Reactor and to the plutonium project.

Specific standards did not exist for neutrons, fission products, or plutonium. Accordingly, much of the effort of the Health Instrument Division was focussed on the development of adequate standards and the means to measure radiation and radioactivity to ensure that the standards were not being exceeded. Of necessity, suitable standards had to be promulgated and put into operational use even before the pile went critical. Thus, in May 1943, a value for permissible atmospheric concentrations of iodine-131 (^{131}I), a radioactive form of iodine, was put forth. Somewhat later, a permissible concentration for ^{131}I in water was established. To confirm that these permissible concentration levels were adhered to and were, in fact, effective, the necks of workers were monitored to ensure that the amount of radioactive iodine in their thyroid glands (located in the neck) was within permitted limits.

Prior to pile operation, standards were also developed for radioactive fission products and plutonium. These included not only limits on airborne radioactivity, but also radioactivity in drinking water. Thus, two routes of entry of radioactivity into the body—inhalation and ingestion—were covered. There was also a third route through the skin, whether via a wound or by skin absorption. Control of loose contamination was one means by which percutaneous intake was limited, but standards were also established for how much plutonium could be safely carried or deposited in the body. Thus, a permissible amount of plutonium, set at only 5 millionths of a gram (0.000005 g), was established, and an extensive program of worker monitoring through urinalysis carried out to ensure that this level was not exceeded.

3.6.3. Measuring Personal Dosage

Workers might be exposed to varying types of radiation for varying amounts of time at varying distances—in other words, the amount they received could not be determined by measuring just one instance of exposure. To quantify the total radiation exposure received, each worker typically carried two personal dosimeters on his person. These were small ionization chambers that were read out in a suitable reader by a Health Instrument Technician at the close of the shift, or more frequently as indicated by exposure conditions. The dosage information was retained for each worker, and tallied and compared to the maximum allowable dose for a given period of time.

> We knew that radiation was dangerous, but we weren't too worried. We were in instrumentation; we knew that we were protected as long as those instruments worked, and we were sure to keep them working. And I thought they were very good about taking care of us in there; as far as we knew none of us was getting overexposed, and they were real careful about hauling us out [from hazardous areas]. We were always dressed in what were then called SWP clothes [Special Work Permit; later called RWP, for Radiation Work Procedure]. You took off your own personal clothing and put on the SWPs, which were coveralls, head covers, gloves, shoe covers, everything—you were covered completely. Even had a face mask if that was necessary. I guess there were probably times I might have worried a little bit, but most of the time I felt that they were pretty much taking care of us. *Glenn Stein, 1-Aug-1992*

The pocket ionization chamber dosimeter was about the size and shape of a fountain pen or pencil, and nicknamed "pencil." It would be electrostatically charged before it was issued to a worker. After a week (sooner if a higher than normal dose was suspected, and daily in later years), the pencil would be left at the 1701-B gate house, where it would be read by the "pencil girls" as they were often known (reading the pencils and recording the data was one of the first production jobs at Hanford that included women). The amount of discharge indicated the amount of gamma exposure the worker had received, and the dose would be recorded in that worker's permanent records. When a worker went into a hazardous area, two pencils were issued to ensure a more accurate reading and as insurance against failure or accidental discharge of one. By 1945, more than 1,000,000 pencils had been read. (Smyth [1945] 1989: 151; Stone 1951: 479)

The primary means of monitoring external radiation exposure was with the film badge, which was a simple strip of photosensitive film, much like camera film, that was housed in the worker's identification badge. The film would be developed after about a month (sooner if a higher dose was suspected), and the amount of "fogging" would indicate the amount of radiation the badge and the worker had received. Both beta and gamma radiation would cause the film to fog. To estimate how much of each had been received, part of the film was shielded in the badge so that only radiation of higher energies (normally gamma) would penetrate and expose that portion of the film. This degree of exposure could then be subtracted from the surrounding exposure to give the amount of gamma and beta received.

Internal radiation exposure was evaluated through measurement of plutonium in the urine of selected workers. Blood counts were regularly made, because it was known that abnormalities in the blood, such as a reduction of the white blood cell count, would be among the earliest signs of radiation effects.

> I was a Medical Technologist at Kadlec Hospital in Richland. One of our duties was to make regular trips to the Hanford Site to get blood and urine samples from workers. We'd draw the small amount of blood from the ear instead of the finger, so as to avoid contamination when the worker returned to his job. We'd later check the blood for unusual cells, abnormally low counts of white blood cells, and the like. The urine would be checked for kidney function. Because of the secrecy at the Site, we were told nothing about radiation. But my training in college, especially with medical X-rays, made it clear that radiation was involved at the Site and most likely the reason for our work. *Idelle Hultgren, 27-Aug-1998*

> There must have been a dozen of us Medical Technologists at Kadlec Hospital, where normally you'd expect to see three or four in a hospital of that size. I started at the

> end of 1944 and worked until the middle of 1945. We'd work out at the Site for two weeks at a time, taking blood samples and analyzing them. We did complete blood counts and differential analyses under a microscope. We were told nothing about the work at Hanford; we stayed in a small room taking samples and were barely allowed to leave the room! *Mary Rohrbacher, 9-Sep-1998*

3.6.4. Health Instrument Technicians

The Health Instrument Section (later "Division") was responsible for setting up radiation protection rules and standards, and for monitoring Hanford workers and the environment for radiation exposure and contamination. It was charged with the creation of suitable instruments to monitor radiation levels and radioactivity in the air. They developed a number of portable radiation monitoring instruments that were given colorful names: Cutie Pie, Samson, Juno, and Sandy (after the dog in the cartoon strip Little Orphan Annie). An attempt to name an instrument Pluto met with General Groves's ire—the name was too close to plutonium and could thus give a clue as to what was going on at Hanford.

A variety of methods were used to monitor radiation. Geiger-Mueller counters were quite sensitive and were typically used to estimate low level radiation fields. However, for technical reasons they could not be used to measure doses. This was reserved for the ion chambers, and especially the new lightweight Cutie Pie. It was developed in 1943 to supplement and ultimately replace the heavier and less responsive Beckman MX-2, the only commercial instrument of its type available at that time.

Portable neutron monitors were also developed using boron trifluoride (BF_3) gas-filled proportional counters. The health physicists also produced air samplers to measure airborne radioactivity, and devised laboratory techniques to measure radioactivity in air and water.

One essential Health Instrument job was that of the inspector, or monitor, who would be armed with a radiation-detecting instrument and be responsible for watching over Hanford workers as they went about their jobs. This was an entirely new field of work, just as nuclear piles were also new, and there was no ready pool of experienced personnel, even in the post-war years.

> My wife Margaret and I were interested in this area in eastern Washington, so I drove out to Hanford in late 1950 to visit a friend from college who was working here as a Radiation Monitor Supervisor. He said they were hiring monitors and I should look into it. I had been a commercial photographer for a couple of years, and I gave the personnel office my photography qualifications. But their only photography-related job was in identification, and they thought I was overqualified for that. They were hiring monitors, though, and I needed a job, so that's what I became. *Greg Greger, 26-May-1998*

An inspector might spend a quiet day surveying the reactor or one of the other sources of radioactivity at Hanford, and writing reports on the levels that were found. At the other extreme, when workers had to enter a hazardous area, it was the H.I. monitor who would first determine the nature of the radiation hazard, and then prescribe the parameters within which the workers could accomplish the job at hand. Those rules might include the length of time a particular worker could remain in the area, at what distance the worker should remain from the radiation source, whether breathing equipment would be needed, and so on. It was a complex equation based on multiple and changing variables.

> Health Instrument inspectors were not medical people; they were trained technicians who understood their instruments, radiation dosage allowances, and how and where radiation could emanate from the pile, its effluent water, fuel slugs, and so on. The daily routine went from practically nothing to very, very busy. There was lots of writing,

> surveys to be made, and data to record, although monitors weren't responsible for keeping track of each individual's dosage records. It was the monitor's job to set safe time limits for workers going into any area where radiation was detected. For example, if we were told a job would take about two hours, we might say "Someone who works here for two hours will receive a full day's dose." The supervisor would then find a worker who had not received any exposure that day, who still had a full day's dose "in the bank." *Greg Greger, 26-May-1998*

The job of H.I. inspector was a curious mix of danger and safety. The danger came because it was the monitor with the instrument who had to assess the radiation hazard, and was therefore the first person on the scene (which brings to mind the coal miner's canary). But the job was safe because the monitor's primary purpose was to find and quantify potential hazards. The monitor wasn't directly involved in the care and feeding of the pile, so there was little chance of accidentally spending too much time in a hazardous area while replacing a valve, painting a door, and so on. Nonetheless, the monitor was responsible for the safety of a lot of people, and there was little room for inattentiveness, mistakes, or carelessness.

> The health monitor was the first guy in and the last guy out. We were always rubbing up against the 300 mrem weekly exposure maximum. There was quite a long period when we'd routinely be burned out before the year was out [reached the maximum annual dosage]. We'd be at 300 mrem a week [the allowed weekly dose at the time] as long as we could hang on, and then they'd rotate us to a different job for the rest of the year. My total lifetime dose was about 85 rem [85,000 mrem], which is quite high compared to most people, but within acceptable limits. *Hank DeHaven, 29-May-1998*

Sometimes the pressures of plutonium production would conflict with the mission of the H.I. monitors: production vs. caution.

> You had to keep your sense of humor. They always thought we had the best job, you know, a racket. It wasn't physically demanding, and there were no mops or tools involved. But they were generally quite happy to have us around; they had their favorite ones. We'd go back and forth between their needs in operations and the H.I. safety requirements in order to get the job done while keeping them safe. Some H.I. guys would stop a job pretty quickly if the numbers didn't look right. But we would usually try to help out, and recommend how the job might be done with as little exposure for the workers as possible, and in as a little time as possible. *Hank De Haven, 29-May-1998*

Overlapping a part of H.I. duties was the Patrol Group. It consisted of operating personnel who would patrol the pile building and other areas with a detection instrument, looking for contamination or problems that could lead to contamination. The Patrol would record the findings of their surveys, and use that information to aid in the safe operation of the pile. The Patrol Group worked closely with the H.I. Section, but did not usurp their duties and responsibilities. For example, if the Patrol detected abnormal activity in one area of the pile, they would notify the H.I. Section. (HAN-73214: 42)

> We all had our chances in the early days of carrying Beckmans around, but you got one arm longer than the other—they must have weighed 35 pounds. We'd traipse around the building with these, always checking to make sure that there were no leaks and no stray radiation. That was one of the jobs that the patrol people did in combining with the

> radiation monitoring experts. We'd check the doors to the rear face to make sure that the air flow was in the right direction, with nothing leaking out from the door. We went across the top of the reactor and made sure that there was no gas leaking up there. Of course, we didn't go within the circle of the VSRs [a unsafe zone due to radiation]. *Harry Zweifel, 14-Dec-1991*

The H.I. inspectors relied on their instruments to perform their jobs; a careful survey of the hazardous area in question was critical to establishing safe parameters for the work to be performed. Much of the early development of these instruments took place at Hanford. Over the years they became more accurate, more sensitive, more adaptable, lighter in weight, and more reliable. The story of the H.I. Section and the role its personnel played goes far beyond the scope of this document. A thorough record of the instruments they used can be found in *A Historical Review of Portable Health Physics Instruments and Their Use in Radiation Protection Programs at Hanford, 1944-1988* (PNL-6980).

3.6.5. Security and Secrecy

The secrecy that surrounded the construction of Hanford continued on into the years of operations. During World War II, the entire population of the United States was, to a certain extent, living under the fear of attack, and that fear was heightened at any production site for war materials. The risk at Hanford of sabotage or direct attack was a constant concern. An attack on the Site would have seriously disrupted a major link in the U.S. atomic weapons program, and could have spread devastating amounts of radiation throughout the surrounding land. Such an attack never happened, and if there were any acts of sabotage, none has been publicly reported nor is known to any of the Hanford workers interviewed for this document.

> I know at one stage of the game, we expected to see bombers come across, and we were always out looking around in the sky to see if we could spot any planes coming in. We'd make a crack about seeing one up there, but of course, we never did see any, and we had defense units around from the army and so forth. *Tom Clement, 15-Mar-1992*

There was, however, one indirect attack on the Hanford Site that was quite successful in shutting down operations, albeit for just a couple minutes and without damage. In the latter part of the war, the Japanese launched thousands of hydrogen-filled balloons carrying small explosive or incendiary devices, knowing that the prevailing winds would take them eastward toward the North American continent and, hopefully, into the United States.

On March 10, 1945, one of those balloons drifted into eastern Washington and struck one of the electrical transmission lines that fed the Hanford Site. This caused a power surge and a subsequent two-minute power outage at Hanford that in turn caused the B Reactor and the other two piles to scram automatically. That such a small, random act of war could disrupt operations raises the thought of how easy it might have been to stop operations completely with an occasional, even small-scale air attack. (HAN-73214: 18, 23)

> We used to see some of these balloons from Japan coming over. In fact the riggers got some parts of one and brought it in. We were cautioned to beware of those things, because you never knew what explosives they might have. This had to be in 1945. *Rudy DeJong, 6-Apr-1995*

In any event, security measures at Hanford remained tightly enforced throughout the years of World War II. Workers in operations were told only as much as they needed to know to perform their jobs. Very few at Hanford knew the complete story of the B Reactor and the other piles, even fewer knew of the Hanford Site's mission, and very few indeed knew the goal of the Manhattan Project.

> Oh yes, there were rumors, such as the old one where two little kids are playing, and one asks the other, "What does your daddy do out there?" And the other kid says "Well, he works in the toilet paper factory." "Well how do you know that?" And the kid answers "That's all he ever brings home." That's one of them. To be frank, people were indoctrinated in the security aspects of the place, and just learned to keep their mouths shut. On the job or in town, you didn't say anything, period, not even to your wife, friends, or at a party. They knew that people who tipped their elbow pretty heavily were also under scrutiny. And aside from being patriotic people, they were just afraid to say anything because of their jobs and livelihood, and the prosecution that would be forthcoming. *Jim Frymier, 14-Dec-1991*.

> We were given documents to read in which the consequences were spelled out very specifically for what the punishment would be if you released certain information; it was spelled out in black and white what the punishment would be—death! Yes, you would be executed or subject to punishment which could result in execution if certain things happened, so you had to be very careful about not saying things that could lead to that type of punishment. *Monty Stratton, 8-Jun-1993*

The rush to produce plutonium at Hanford continued from the startup of B Reactor and the other two piles into the summer of 1945. In the midst of the chaos of war and all the uncertainties of the Manhattan Project, what was once thought impossible was soon to happen.

> In June or July of 1945, management talked to each of us and told us that there would be some news forthcoming, and to neither confirm nor deny the release. When I first heard about it, I was back east due to a death in the family when the news broke when the bomb was dropped. At that time, I was in West Virginia; you hardly saw anything about Hanford. It was all Oak Ridge. When I got back, why, the employees were just flabbergasted. *Jim Frymier, 14-Dec-1991*

> We were concerned about enemy bombing, and the fact that we had air corps and air bases all around here, we felt that we were being protected. So we knew that whatever we were doing probably was a big effort in how the outcome of the war would come. So we knew that it would be some sort of means of demolishing the enemy. And just how that would be I wasn't too sure, and I don't think a lot of us were. *Dee McCullough, 15-Dec-1991*

> I don't ever remember discussing it with my friends, because we knew it [Hanford] depended on security for success, and when I look back I am amazed that people really didn't discuss it. We wanted to contribute everything we could to this effort, because it was a serious war at that time. When they [Corps of Engineers] came in 1943, all they told us was that it [the land belonging to the locals] was needed for a war effort, and

believe me that’s all I knew until the day that they dropped the bomb. *Annette Heriford, 15-Dec-1991*

I had no idea what we were making, no idea whatever. In fact, I never knew what we were making until they dropped the bomb. It was the first I knew of it. *Glenn Stein, 1-Aug-1992*

4. The Time Between Before and After

There are certain events that win their way into the history books from the moment they occur: the first time a human takes to the air or the first stone thrown in revolution. But even events such as these might still require the trained eye of an expert to explain the subtle details of their significance, so that one might come to understand why the world was one place before and another after.

In the case of the B Reactor and the Manhattan Project, an expert analysis is not needed to understand the ultimate historical significance. The wartime crash program came to a resounding end in a single instant in time, an instant that forever separates the before from the after, the history that was from the history that was to come. That instant is indelibly etched into the consciousness of the world.

All the successes that were won during the experimentation in Chicago, the design and engineering of the first production pile, its construction, and finally its operations, were all prelude to the sole reason for the pile's existence—to produce a few pounds of plutonium that could be fashioned into an atomic bomb.

4.1. Trinity Test: July 16, 1945

Fuel slugs that had been irradiated in B Reactor begain arriving in the 200-West Area for processing in late December 1944. As noted in section 3.4.6, the first shipment of plutonium left Hanford for Los Alamos in early February 1945. In the few months that followed, B Reactor and the other two piles produced enough plutonium for two atomic bombs. (Much of the story that follows can be found in Richard Rhodes's *The Making of the Atomic Bomb*.)

On July 16, 1945, in what was code-named the Trinity test, the world's first nuclear explosive was detonated at the Alamogordo Bombing Range, a vast desert in New Mexico about 200 miles south of the Los Alamos Laboratory. Developed under the direction of J. Robert Oppenheimer, this was a massive spherical *implosion* device, the core of which was a mere 13.5 pounds of plutonium, about the size of an orange, the product of B Reactor and Hanford. This small mass of plutonium was slightly subcritical—it would not sustain a chain reaction on its own. At 5:30 that morning, an intricately timed detonation sequence set off a sphere of high explosives that surrounded the core. The immense pressure of the blast literally imploded the plutonium sphere, compressing it to about half its original size. In the smaller and much denser configuration, the plutonium sphere suddenly became supercritical. At the precise instant of compression, a neutron initiator released a shower of neutrons into the plutonium.

As in Fermi's first successful pile, a nuclear chain reaction began, but in this case it was taking place in pure fissile material, the equivalent of pure ^{235}U, and the reaction was completely uncontrolled. In a fraction of a second, the chain reaction tore through the lump of plutonium, releasing energy equivalent to 21,000 tons of TNT—21.0 kilotons. The overpowering success of the test was undeniable to the observers six miles away, as was the fact that the Atomic Age had definitely arrived.

4.2. Hiroshima: August 6, 1945

In all the history before 5:30 AM on July 16, an intense military effort was required to destroy a city. In the latter years of WW II, the job could be done through a concerted, well-organized air attack involving hundreds of planes, thousands of flyers, and several thousand tons of bombs. The devastation of Coventry and Dresden are two well-known examples.

Another example is Tokyo. On March 10, 1945, 334 American B-29 Superfortress bombers rained 2,000 tons (2 kilotons) of incendiary explosives onto the city in a precise pattern for maximum effectiveness. The city was built largely from wooden construction that readily cooperated with the ensuing fire. In a matter of hours the city was in flames, a conflagration that surpassed anything the military had seen before. In just one night, approximately 16 square miles of the city were destroyed, with the loss of life numbering over 100,000. The science and art of war had reached a new level.

While the Trinity test was being prepared in New Mexico, the components of a second atomic bomb were being transported to Tinian, an island held by the United States in the South Pacific. This bomb was not of Hanford plutonium, but of ^{235}U, painstakingly separated from natural uranium at the Manhattan Project's Oak Ridge Site in Tennessee. Uranium is slightly less fissile than plutonium, and could be brought to critical mass in a very much simpler way than implosion. A "bullet" of uranium would be fired from a gun into a target of uranium rings, thereby forming a critical mass that would chain react and explode. It was so certain to work that no test was needed.

The bomb was over 10 ft long, 2.5 ft in diameter, and weighed almost 10,000 lb. Nonetheless, it was dubbed *Little Boy* because it was long and slender compared to the globular Trinity device. It was loaded into the *Enola Gay*, a B-29 bomber named after the mother of its pilot, Capt. Paul Tibbets.

In the first hours of the morning of August 6, 1945, the Enola Gay took off from Tinian with a single bomb as its only payload. A single plane with a dozen crew members was about to perform the same job as the vast air armada that destroyed Tokyo. The target was the city of Hiroshima. At 8:15 that morning, the Enola Gay reached its target without incident, and the bomb was dropped. Some 43 seconds later, the bomb detonated 1,900 ft above the city, with an explosive power of 12.5 kilotons.

The extent of the damage from this instant in time was previously unimagined. Close to four square miles of the city were annihilated by the blast, the heat, and the fire that erupted. Almost two-thirds of all the buildings were completely demolished, and most of the rest were heavily damaged. In terms of human life, the effects were more difficult to measure, because there was another blast effect that did not destroy buildings but did destroy living tissue—radiation. The various sicknesses brought on by heavy doses of radiation took days, weeks, and months to play out. It is estimated that by the end of 1945, 140,000 people had been killed by Little Boy. That number increased to 200,000 five years after the blast, and because of the lingering effects of radiation, there is no distinct point in time when it can be said that all deaths are accounted for.

4.3. Nagasaki: August 9, 1945

The atomic bomb dropped on Hiroshima—the first put to actual use in war—was only the first part of a "one-two" punch designed to send an unmistakable message to Japan about the futility of their continuation of the war. An implosion bomb, with Hanford plutonium at its core, was being readied on Tinian.

On the evening of August 8, it was loaded aboard another B-29, *Bock's Car*, named after its usual commander, Frederick Bock, but which was flown that night by Major Charles Sweeney. The bulbous casing of the spherical bomb garnered it the name *Fat Man*. A few hours into the morning of August 9, the plane took off for its target in Japan. Once again, a crew of a dozen men was on its way to perform the work of thousands.

The forces of nature and destiny conspired to produce unacceptable weather for sighting the chosen primary target, the Kokura Arsenal, so the plane went on to the secondary target. At 11:02 AM, the plutonium bomb detonated 1,650 ft above the city of Nagasaki. The efficiency of the implosion-type bomb was evident in its larger yield of 22 kilotons.

A vivid photographic journal of the Nagasaki aftermath was captured by Yosuke Yamahata, a Japanese military photographer who walked through the devastated city with his camera the day after the bombing. On foot, Yamahata twice passed through the *hypocenter* of the atomic bomb explosion (*ground zero*, the point on the ground directly beneath the bomb).

Photographs 33 and 34 form a panorama that was made from three adjacent 35 mm frames. The view is looking south across residential neighborhoods toward the center of the city, with the smokestacks of the Mitsubishi armaments factory still standing at the far right in the distance. The twisted metal framework close in at the right is the remains of a baseball field grandstand.

The third image, Photograph 35, was taken from the pathway winding through the panorama, which was formerly the main street of Nagasaki. Few burned bodies were generally visible in the aftermath, because many of the dead had been completely reduced to dust and ash by the heat of the fireball. The overhead crosspieces mark the tracks of the Nagasaki trolley system. The Mitsubishi smokestacks can again be seen standing in the distance, somewhat closer than in the panorama.

The hilly topography of the city limited the area of damage and the number of deaths compared with Hiroshima. Nonetheless, 70,000 people died from the bomb by the end of 1945, and 140,000 altogether over the five years afterward.

4.4. IT'S ATOMIC BOMBS

With the dropping of the uranium bomb on Hiroshima, the primary atomic secret was a secret no more—the United States had managed to tap the power of the atom. The intense secrecy surrounding Hanford and the other sites of the Manhattan Project was relaxed to the degree that the story of their role in the war effort could now be told.

On August 6, residents of Richland awoke to the headlines in their local newspaper, *The Villager*, which blazed "IT'S ATOMIC BOMBS." Even though Hanford plutonium was not used in the Hiroshima bomb, the fact that Hanford and its workers played a direct role in the secret bomb project was made known. To most of the workers at Hanford, the news was very much a surprise, and a momentous one worthy of great pride.

Everyone had been working long hours under tough living conditions without knowing the true purpose of their work. There was a sense of elation upon finally learning that they had been directly involved with unlocking one of nature's best kept and most fantastic secrets, one that was now in the possession of their country and no other.

News of the Nagasaki bomb soon followed. For those at Hanford, it was perhaps the biggest news of the war, and it was due to their labors in a remote desert outpost.

> When the first bomb was dropped, the guy in Groves's office, his security colonel, called me about 7:00 in the morning and he said "Listen to the news at 7:00 on the radio," and that's when they announced that the bomb had been dropped in Japan, and all the doubt was gone and everything was successful. Now that was a relief 'cause that knocked off the real security pressure. We were smothered by news people and we didn't have time to think for about three days; Richland was swamped with people. I had made arrangements anticipating this, with the Army's Signal Corps—some extra telephone coverage into our place [the Hanford Site]. So I had telephones every place. It only took an hour or so [after the news came out] for people to come pouring in. That was quite an excitement. *Frank Matthias, 26-September-1992*

> We were sitting around the lunch table in the instrument shop–I think it was in D area at the time–when I received a phone call and was told that they had dropped the bomb on Japan. And it was a result of our work here, and I should make that announcement to the instrument technicians that were sitting around the table, too. That was quite a surprise. I can't remember just what the responses were of the people, but I can remember I didn't waste too much time to call my wife and tell her. We were all, of course, proud of the hand we had in that. And even though how disastrous it was over there, it did save a lot of our soldiers lives. And the fact of the prospects of the nuclear age and being in at the beginning of it, and what we could make of it in the future was quite interesting. *Dee McCullough, 15-December-1991*

> John A. Wheeler was an outstanding technical person at Hanford. He was a professor at Princeton University with an international reputation as a theoretical physicist. He had the remarkable ability to explain complex subjects in lay language, and DuPont arranged for him to be on loan from Princeton.
>
> Wheeler subscribed to the Albuquerque newspaper, and when he read in that paper about a big explosion and speculation that a munitions storage had blown up, he knew that the test of an atomic bomb at Alamogordo had been successful, and that its military use was imminent. So we were not too surprised to learn of the Hiroshima bomb. On the job we were advised not to call home about President Truman's announcement. When I did get home at the end of the day, I found that my family had not been listening to the radio and was unaware of the news. I was rather proud of my wife's mother who said "What do you mean, an 'atomic' bomb—a little teeny bomb?" *W. Kelly Woods, 13-Sep-1998*

> My wife and I had gone on a vacation trip up to Mt. Rainier. All of a sudden this information became available—we read in the newspaper that a bomb has been dropped and the President has announced so much information. So we wondered, how much can we talk about? Well, we decided we'd better be quiet about it; don't say anything. We got a frantic telephone call from my supervisor trying to reach us at Mt. Rainier. He finally got a hold of us and he says "Don't say anything!" He was so afraid that we would start talking after reading the newspaper that had been released that said Hanford was involved in this bomb. He was so afraid that we would start saying things that we shouldn't. In fact, I don't think we told people we even worked at Hanford, so we escaped any consequences. *Monty Stratton, 8-June-1993*

A few days later, on August 14, the Japanese formally surrendered and the Second World War was over. That the two atomic bombs hastened the end of the war would be hard to deny.

> When the war ended, I was living in Richland and that was a day of celebration to us, because we had lost a lot of fellas, per capita. So it was open house. All up and down the streets. And I remember people putting out washtubs full of beer, Coke, whatever. It was a very friendly community to begin with, but even people you didn't know that

> well…it was like one big family that day. It was an exciting time and we knew that the fellas would be coming home. And I think we felt a little different, too, because having lost our home [the family home at the town of Hanford] and gone through that sadness, I think we had a feeling of pride because we had contributed, we had truly given, by giving up everything we did. *Annette Heriford, 15-December-1991*

That the B Reactor, Hanford, and all the sites of the Manhattan Project played an extraordinary role in WW II is unmistakable. Many believe that without them the war would have dragged on, with an inevitable land invasion of Japan and the loss of countless additional lives. Looking back from the historical perspective, it is difficult to capture the sobering, life-or-death context of 1945.

> After surviving the end of the conflict in Europe, I was among those chosen to go to the Pacific theater for the invasion of Japan, which everyone agrees would have been a slaughter. The second bomb was dropped when we were en route at sea. Not until I came to work here did I know of the B Reactor's special role, and I have had a special regard for it ever since. *Greg Greger, 29-May-1998*

5. The B Reactor in the Atomic Age

When the hostilities of the Second World War finally ended on August 14, the military's urgent need for plutonium evaporated, along with the need for warships, airplanes, tanks, guns, and other war-related materiel. The feeling among many Hanford workers echoed the sentiments of just about everyone from any country involved in the war: "Our job is done, now let's go home." Nonetheless, the shipyards and airplane factories were not vacated after the war and Hanford carried on, as well, albeit at a very much reduced pace.

Servicemen came home from the war, but those who had lived in the towns of Hanford and White Bluffs had no homes to come to—the Hanford Site was not going away. The enormous construction camp was dismantled, and B Reactor went from round-the-clock shifts to daytime operations. With the looming graphite expansion problem (see Chapter 3) and the absence of wartime pressures for plutonium, the B Reactor was shut down in March 1946 and remained out of service until June 1948.

Once the war was over, attention could be turned to the new field of nuclear reactors and their potential for supplying virtually infinite amounts of energy. It took almost a year after the war before Congress passed the McMahon Atomic Energy Act of 1946, which established the civilian-run Atomic Energy Commission (AEC) beginning in 1947. Its duties were to oversee the development and use of nuclear power in the United States. After the transition to civilian status, the Hanford Engineer Works (HEW) was renamed the Hanford Works (HW).

The contract between the United States government and DuPont was terminated in September 1946; DuPont had constructed the plant and then operated it for two years. In the ensuing years, a number of different contractors managed the operations. DuPont was followed by General Electric, which operated the plant until 1964. In that year, the Hanford Site Operations was decentralized, and Douglas United Nuclear Corporation became the prime contractor for operation of facilities in the 100-B Area. Douglas United was reorganized and became United Nuclear Corporation in 1970, and later, UNC Nuclear Industries. Consolidation of many of the operations at the Hanford Site, including 100-B, was implemented in June 1987 by the U.S. Department of Energy-Richland Operations Office, and contracted to Westinghouse Hanford Company.

> After the war, DuPont wanted to get away from Hanford, though all the reasons they used went down the drain when DuPont took on the Savannah River job. (Real reason: then DuPont President Carpenter wanted to get out of the nuclear business and later new DuPont President Greenewalt wanted to get back in.) Anyway, DuPont considered their mission accomplished, and arrangements were made for General Electric to take over at Hanford. I was faced with a personal decision: which was more important, six years tenure with DuPont or three years experience with nuclear energy? I chose the latter and stayed on at Hanford. It was exciting to be in on the development of a brand new source of energy, even though the initial use was military. In 1955, after Congressional legislation made private investment in the nuclear field possible, I accepted the chance to transfer to San Jose [California] to work on the nation's first privately funded commercial nuclear power plant, the Dresden-1 plant for the Commonwealth Edison Company in Chicago. *W. Kelly Woods, 13-Sep-1998*

In the 20 years after WW II, the swing of the political pendulum and that of world events would send Hanford activities on an equally wide-ranging arc, from production rushes to job-cutting lulls. In that time, great strides were made in the peacetime uses for nuclear power, and much of the new technology was developed at Hanford.

5.1. Increasing Power Levels

Knowing that plutonium production is directly related to the pile's power level, it doesn't take an atomic scientist to realize that if you can increase the pile's power output, you'll make more plutonium. As the Cold War began its four-decade reign, the pressures to produce more plutonium increased. The short lag after the war was soon forgotten in the rush to build an arsenal. When it became apparent that it wouldn't be long before the United States was no longer the sole owner of the "Secret," the need for atomic bombs became urgent.

To increase production, more piles were built at Hanford, but the existing piles were also asked to increase their output by increasing their power levels. When B Reactor was reactivated in 1948 after its two-year operations hiatus, it was soon taken to 275 MW, about 10 percent higher than its nameplate power rating. This was just the beginning, however, because virtually each year in the next 20 brought yet higher power levels. (Gerber 1993: 20)

By 1956, the pile was operating at 800 MW, and it was time to reevaluate all its components and procedures in order to maintain that power level or, if all went well, exceed it. To that end, project CG-558 was initiated, named Reactor Plant Modifications for Increased Production. Time and money would be expended to retrofit all the existing piles so that they could run at yet higher power levels.

> We were able to raise the power level of the nuclear reactor, and therefore the production of plutonium, by a factor of 10, without having to change very much in the reactor at all. We just had to increase the amount of water we ran through it, and we increased the temperature that we allowed it [the effluent water] to rise to. The DuPont people had designed it so conservatively…that it allowed *us* to be heros, when we should really be taking our hats off not to each other, but to the DuPont people. *Eugene Eschbach, 8-Dec-1992*

The essential factor for increasing the pile's output was the cooling water—more water would be needed to take away the extra heat that would be produced. Increasing the size of the process tubes to create a larger jacket of water around the slugs would have cooled them more effectively, but the extra water would have reduced the pile's reactivity. Instead, new, larger pumps were added to increase the pressure and flow rate. The work included modifications to the piping systems, electrical systems, and other components and fittings within the pile. Before the CG-558 project, the water plant at B Reactor could pump as much as 46,300 gpm through the pile; after the work was done, the capacity had risen to 71,000 gpm. The B Reactor was the first Hanford pile to be so outfitted; it was shut down between September 22 and December 8, 1956, to complete the work. (DUN-6888: 51; Gerber 1993: 25-26)

With the improvements made to the pile itself, and with more operating experience and refined operating procedures, B Reactor's power output was increased substantially, reaching 1,440 MW in early 1958; 1,900 MW a year later; and 2,090 MW in early 1961. The power levels varied during that time, as production schedules, maintenance, and outages dictated. But the power remained near the 2,000 MW range into 1964, nearly 10 times the power for which the reactor had been designed. (DUN-6888: 49)

After 1964, the AEC changed the operating limitations on the piles so that they were based not on MW levels but on the temperature of the effluent water leaving the pile. For the last three and one-half years of B Reactor's operation, the temperature limitation was established at 95 °C, compared to the WW II limitation of 65 °C. (Gerber 1993: 21)

5.2. Tritium Production at B Reactor

One project that began a few years after the end of the war is in many ways representative of the dynamic mix of history-making efforts at Hanford, and how those efforts were driven by the history being made outside eastern Washington.

The "Super," a bomb of essentially unlimited explosive power based on thermonuclear fusion, had been proposed by Edward Teller in 1942, and its theory developed at Los Alamos that summer. The implosion type atomic bomb (A-bomb), such as the one used on Nagasaki, was fueled by plutonium, Hanford's *raison d'etre*. The Super (hydrogen or H-bomb) was based on an A-bomb, but additionally required tritium, a heavy and radioactive isotope of hydrogen (^{3}H or T). Tritium decays by emission of a soft (low energy) beta particle and has a half-life of 12.3 years. (Bethe 1982: 46)

Tritium was first produced in 1943 in the CP-2 experimental pile at the Argonne National Laboratory near Chicago. This pile had been built from Enrico Fermi's dismantled CP-1 pile, famous for producing the world's first self-sustained chain reaction in December 1942. Neutron irradiation of a lithium fluoride (LiF) target produced tritium by the reaction: $^6\text{Li} + \text{n} \rightarrow {}^3\text{H} + {}^4\text{He}$ (where "n" is a neutron). Work on tritium production continued for several years at both Argonne and the Clinton Laboratory (Oak Ridge, Tennessee), but the effort met with limited success. Continuing difficulties were experienced with fluorine liberated during irradiation of the target, and with erratic variations in tritium yield. Moreover, LiF posed a significant hazard to both personnel and equipment because of its strong chemical reactivity. (Reed 1952: 1, 3)

5.2.1. Production Facilities Established at Hanford

Development work on both the process and equipment for tritium production continued at Argonne until July 1948, when Hanford was asked to take over the project. The new project at Hanford was authorized by a September 20, 1948 letter from the Hanford Operations Office of the Atomic Energy Commission (AEC) to the Hanford Works contractor, at that time the General Electric Company (GE). Designated the P-10 Project, it covered the design, construction, and operation of facilities for the production and extraction of tritium from lithium-bearing target slugs. (Reed 1952: 3, 13)

Tritium separation facilities at Hanford were established in the 108-B building next to the 105-B building (the B Reactor). This was the Chemical Pump House, the four-story building that had been used for adding chemicals to the pile's cooling water. The first floor contained target slug fabrication facilities, a can-opening room for irradiated slugs, and building machinery. The second floor housed offices, an instrument repair shop, changing rooms, and a "cold line" room where unirradiated uranium was used in procedure development. The third floor contained the tritium extraction facilities, primarily a large "hood room" where the process lines were located inside exhaust hoods. The third floor also contained an instrument development room, a mass spectrometer room, an emission spectrometer room, and a Health Instrument (i.e., radiation protection) station. The fourth floor contained the exhaust air system with air filters and scrubbers as well as equipment for monitoring radioactivity in the exhaust air. (Gerber 1993: 44)

A special shielded cask and truck were provided to move irradiated slugs from the piles to 108-B. Initially, the target slugs were irradiated in the B Reactor and the other Hanford reactors as neutron-absorbing *fringe poison* that helped control reactivity during startup. (DUN-6888: 45)

The P-10 Project got off to a bad start. On September 22, 1948, in B Reactor and on October 20, 1948, in F Reactor, rupture of LiF slugs (LiF wafers separated by copper disks in an aluminum can) and subsequent rupture of reactor process tubes necessitated shutdown of both reactors for repairs. (Reed 1952: 4)

> We specified that the copper discs would have a considerable number of holes to provide for the accumulation of gases within the target, and also to facilitate heat conduction from the hot region near the axis of the target. These target assemblies were made at the Met Lab.
>
> The lithium targets were being irradiated in the F Reactor. We began to run into a problem where the process tubes were developing leaks and water was getting into the graphite. So we were very unhappy when we cut open some lithium assemblies and found that they were not being made to our specifications. Someone at the Met Lab decided that it was silly to have a lot of holes in the copper discs, and instead they just drilled one big hole, leaving a copper ring. This prevented the transfer of heat from the axial region and was responsible for the troubles at F Reactor. *W. Kelly Woods, 6-September-1998*

As an alternative to the problematic LiF, the Argonne Lab had already considered an aluminum alloy of lithium in 1947. Test samples of 3.5 percent lithium in aluminum were irradiated at Hanford beginning in the latter half of 1948. The lithium-aluminum (Li-Al) slugs gave higher tritium yields per exposure unit than did the lithium fluoride, and the yields were also relatively predictable. In addition, none of the Li-Al slugs was seen to be swelling in the pile, and the tritium could be extracted at a lower temperature from these slugs. (Reed 1952: 4)

By January 1, 1949, over 500 Li-Al target slugs fabricated at Argonne were under irradiation at Hanford, and five months later there were more than a thousand. Later that year, fabrication of the slugs was transferred to the 108-B building at Hanford. There, Li-Al alloy was made in a vacuum induction furnace by dropping lithium into molten aluminum in a graphite crucible. Cast billets were sent offsite to be extruded into rods. The extrusion press in the 300 Area fuel fabrication plant was not used because the Li-Al alloy could not be contaminated with uranium. (Reed 1952: 4-5)

Roscoe Teats, supervisor of target fabrication, was there when the first rods were extruded. The manufacturer was not told what the billets were made of, he said, because “It was all Top Secret!” The Li-Al rods were returned to 108-B, where they were machined to slug size and canned in aluminum. (Teats 1998)

5.2.2. The Need for Tritium Intensifies

Hanford’s initial facilities for tritium extraction were completed and placed in operation in March 1949. The facilities consisted of two glass process lines based on classical glass vacuum equipment with manually operated glass valves. Vacuum was produced by mercury-diffusion pumps while tritium-bearing gases were evacuated and compressed by mercury-piston Toepler pumps. Tritium was released into the “glass lines” by melting the target slugs in a stainless steel tube furnace under vacuum. The initial processing was of LiF slugs. The first Li-Al slug extraction was made in August 1949 in a third glass line.

Extracted tritium and accompanying “tramp” hydrogen were separated from other gases by diffusion through a hot palladium barrier and collected in a 0.5 liter glass flask. When the tritium pressure in the flask reached one-third atmosphere, an operator “tipped off” the flask by heating the connecting glass tubing with a torch until the tubing collapsed under atmospheric pressure and fused together. The glass flasks handled by the operators in this manner contained hundreds of curies of tritium. The flasks were packed in special shipping containers and shipped to Los Alamos; none was ever broken. (Eschbach 1998)

The Soviet Union's first test of an atomic bomb on August 29, 1949 (dubbed "Joe 1" in the U.S. after Joseph Stalin), increased pressure to raise the development of the Super to a high priority. In October 1949, Fermi and other scientists on the General Advisory Committee to the AEC wrote a report that opposed the Super on ethical grounds. By its very nature, they said, such a weapon "cannot be confined to a military objective but becomes a weapon which in practical effect is almost one of genocide." (Rhodes 1995: 401)

However, events conspired to override such qualms. On January 27, 1950, British physicist Klaus Fuchs confessed to spying for the Soviet Union. Since Fuchs had worked on the Super at Los Alamos, a race with Stalin was unavoidable. One week later, President Truman told his Special Committee on the Super, "What the hell are we waiting for? Let's get on with it." (Rhodes 1995: 407, 411-412)

The pressure to produce tritium was intense at Hanford. Eugene A. Eschbach, an engineer on the P-10 Project, related that President Truman's office was calling the head of Hanford's Technical Division every month "to find out where the stuff was." (Eschbach 1998)

By December 1949, five glass lines were in operation at Hanford and the facilities had achieved a tritium extraction rate for one-shift operation that was 85 percent of the pile discharge rate. The full pile production load achieved later consisted of approximately 7,500 Li-Al slugs. (Reed 1952: 5, 8)

Tritium production could only be accomplished at the cost of reduced plutonium production. For every kilogram of tritium produced, it was necessary to forego the production of 80 to 100 kilograms of plutonium. To make up for the loss of neutrons due to the target slugs, some fuel slugs with enriched ^{235}U were added to the F and H Reactors to enhance their power output for full production of plutonium. (Rhodes 1995: 380; Reed 1952: 5, 8)

It was also very important to forecast accurately the tritium production rate. Otherwise, more target slugs might be loaded than necessary, which would take away too much from the pile's plutonium production. For this purpose, one of the glass extraction lines was built as a super-precision line. Through special techniques of construction, operation, and measurement, the line achieved a precision and accuracy in gaseous mass balance of "five 9s" (99.999 percent), and enabled tritium production to be predicted with 98 percent accuracy. "We were very fastidious," Eschbach said. (Eschbach 1998)

Tritium production in the Hanford reactors was about 3.5 times the most optimistic estimate made when the P-10 Project was initiated. Tritium purity, in terms of freedom from other hydrogen isotopes, was also much higher than expected due in part to the high quality of the vacuum apparatus developed for extraction. Purity averaged 93 percent—high enough to avoid an expensive and wasteful isotopic separation step. (Reed 1952: 5)

5.2.3. Technical Hurdles

The successful construction and operation of the pioneering tritium production plant at Hanford required the solution of several major and many minor problems, the most important of which was the control or elimination of radiation hazards. During routine operations, the highest personnel exposure was due to gamma radiation from the activation products in the irradiated Li-Al slugs. The soft beta radiation from the extracted tritium could not penetrate the glass walls of the extraction apparatus. Nevertheless, there were radiation problems, not ever completely solved, associated with handling thousands of curies of tritium per day. Tritium leaked into the work environment, for example, by diffusion through the heated furnace tubes and through organic gaskets in the apparatus. As an isotope of hydrogen, tritium in the air readily forms tritiated water vapor, which is absorbed through the skin. (Eschbach 1998; Stannard 1988: 711-712)

Work area monitoring was limited at first because no survey instruments were available that were capable of detecting tritium's low-energy beta radiation. Later, a new instrument with a windowless probe, called a "Pete" (for P-10), was developed. Personnel monitoring for tritium contamination was done by urinalysis in a laboratory established in the 200 Area. In spite of the use of special protective clothing and half-face fresh air masks, urinalysis routinely showed operating personnel to be contaminated with tritium, occasionally in excess of the maximum permissible limit. (Reed 1952: 7, 82, 86)

Another serious hazard was exposure to mercury vapor from the considerable quantities of mercury used in the vacuum pumps and other parts of the apparatus. Instruments were available for mercury vapor detection. (Eschbach 1998)

The original production commitment established in 1949 required Hanford to deliver a certain quantity of tritium to Los Alamos by the end of 1950. That goal was achieved by July, 1950. The commitment was doubled and the higher goal was attained by the end of the year. By the end of 1950, the P-10 Project group had grown from an initial seven personnel to 50. (Reed 1952: 6, 65)

The beginning of the Korean War in June 1950 heightened tensions between the United States and the Soviet Union, and spurred expansion of the U.S. nuclear weapons program. That same month, President Truman approved construction of two heavy-water reactors for tritium production at the new Savannah River site near Aiken, South Carolina. Only four months later he approved plans for three more. (Rhodes 1995: 447)

The soon-to-be-increased tritium production capacity called for increased extraction capacity, as well. Because of the limited processing capacity and significant hazards of the glass lines, Eschbach and a co-worker, Herb Zuhr, designed a "metal line." This was built at GE's General Engineering Laboratory in Schenectady, New York, and installed in 108-B. The metal extraction system incorporated the latest all-metal high vacuum technology: stainless steel hardware with remotely operated electromagnetic valves. This system virtually eliminated operator exposure to tritium. (Eschbach 1998)

While the glass lines could each process only five slugs at a time, the metal line was equipped with a furnace pot that could process a batch of some 30 slugs. The extracted and separated tritium was collected in a 12 liter metal container for shipment to Los Alamos.

5.2.4. The Thermonuclear Bomb

A serious problem was discovered at Los Alamos in 1950. Mathematician Stanislaw Ulam, assisted by Cornelius Everett, checked Teller's calculations for the "classical Super" and found that the calculations were wrong. An extraordinarily large amount of tritium would be necessary to make Teller's original scheme work. (Bethe 1982: 47)

In 1951, Teller and Ulam invented a unique new concept for a *staged-thermonuclear* weapon, in which an atomic bomb primary (using nuclear fission) "ignites" a fission-fusion secondary. This immediately became the focus of the thermonuclear design program. Planning for a test of the new concept began in September 1951.

The first staged-thermonuclear test device, a giant "sausage" 6 ft in diameter and 20 ft long, was assembled on Bikini Atoll in the South Pacific in 1952. Code-named "Ivy Mike," the bomb was detonated on November 1, 1952 (October 31 in the U.S.), with a yield 1,000 times more powerful than the Hiroshima bomb—10.4 megatons (million tons of TNT). The fireball alone exceeded three miles in diameter. (Rhodes 1995: 501-510)

Although several more years of development were required for the H-bomb to be packaged as a deliverable weapon, the course was set for tritium to become a standard ingredient of weapons in the U.S. nuclear arsenal. In 1952, the main tritium production mission was transferred from Hanford to the new

Savannah River Plant, where the Hanford-designed metal lines were used. Hanford continued to irradiate lithium target slugs and ship them to Savannah River for extraction into the 1960s. (DUN-6888: 45]

5.3. Other Significant Projects

The changes made to B Reactor to enhance its power output, reliability, and safety were the vanguards of the advances made in the field of nuclear energy, as were the special projects that were conducted there. The table shown below lists a few of the upgrades that were made to the pile after the rush of WW II, which illustrate the range of improvements that were made. The prefixes in the project names are C (Construction Project), A (AEC Managed), G (General Electric Managed), and I (Irradiation Processing Department). (DUN-6888: 53-56)

Project	Date Project Was Closed	Project Title
C-76	---	Pneumatic Charging Machines
C-323	4-3-50	Vertical Rod Replacement
C-347	2-28-51	Replace Process Tube Nozzles
C-420	12-16-52	CO_2 Bulk Storage Facilities
C-438	4-1-54	Ball 3-X Safety System
C-475	10-31-52	Crossheader Pressure Monitoring
C-483	6-12-53	Downcomer Repairs
C-495	3-31-53	Earthquake Detectors, 100 Area
CG-558	12-13-57	Reactor Plant Modifications for Increased Production
CG-583	5-1-57	Moisture Monitoring System for Detection of Leaking Process Tubes
CG-666	2-16-60	Zone Temperature Monitoring
CG-705	9-16-58	Reactor Trip for Loss of Rod Cooling Water
CG-706	3-30-61	Installation of Improved Reactor Gas Instrumentation
CG-707	3-17-60	Improvements to Reactor Nuclear Instrumentation
CG-709	5-1-59	VSR Improvements
CG-786	1-9-59	Flux Monitoring Dual Trip System
CGI-802	2-20-61	Pressure Monitoring System, High Speed Scanning Type for Temperature Monitoring
CGI-806	6-12-61	Nuclear Instrumentation for Reactor Safety and Control
CGI-817	7-25-60	Crossheader Pressure Differential Indicators and Alarm System

5.4. Reactor Population Growth

The first two reactors built after the war, H and DR, were planned as emergency replacements for the original three Hanford piles when it looked as though they might be put out of service due to the graphite expansion problem. The other piles were built to expand plutonium production while modernizing the facilities. The following table lists all nine Hanford reactors, their startup and shutdown dates, and their design power ratings. (DOE/DP-0137: 25-26)

Reactor Name	Startup Date	Shutdown Date	Power Rating (MW)
B	September 1944	February 1968	250
D	December 1944	June 1967	250
F	February 1945	June 1965	250

H	October 1949	April 1965	400
DR	October 1950	December 1964	250
C	November 1952	April 1969	650
KW	January 1955	February 1970	1,800
KE	April 1955	January 1971	1,800
N	December 1963	January 1987	4,000

Note that the N Reactor was the only pile not of the single-pass design. It used a closed-loop, recirculating cooling system, and was also designed to generate electricity from the heat created in the pile.

The international and atomic tensions of the Cold War in the late 1940s and early 1950s pushed the United States to build the C Reactor. It was located close to the 100-B Area, creating a new Area called 100-B/C. This proximity to the existing 100-B facilities enabled the designers to take economic advantage of some of the existing utilities, services, and structures. The C Reactor was of a sturdier breed than the earlier reactors. For example, its design power level was 650 MW, and its process tubes had a water annulus 25 percent larger than those in the existing Hanford reactors. Its cooling water flow was planned to deliver 62,000 gpm, with the capability of expansion to reach 80,000 gpm. (Gerber 1993: 106)

The C Reactor was put through a "cocooning" process that was completed in 1998. Most of the 105-C building was demolished, and the inner structural shell that surrounded the pile was sealed for long-term storage. The plan is to move the pile, its shielding, and concrete base to an appropriate disposal area on the Hanford Site in approximately 75 years. When the B Reactor reopens as a museum, the relic of the C Reactor will stand as a silent companion, a reminder that there once was a heyday for graphite piles at the Hanford Site.

5.5. Deactivation: February 12, 1968

In the 43 years of operations at Hanford, more than 67,000 kilograms (about 147,000 pounds or 74 tons) of plutonium were produced, most of which was suitable for use in atomic weapons. That's enough plutonium to manufacture 13,000 atomic bombs such as the two that were used in the Trinity test and on Nagasaki. When combined with the output of the plutonium-production reactors at the Savannah River site in South Carolina, the United States produced more than 103,000 kg of plutonium between 1944 and 1994. (DOE/DP-0137: 25, 26)

Given plutonium's half-life of some 24,000 years, the need to produce more tonnage essentially disappeared. Of even greater importance was the dissolution in 1989 of the Soviet Union, the chief atomic rival to the United States during the Cold War. The need for more plutonium simply dissolved along with it. In the words of John Herrington, former Energy Secretary, the United States was "awash in plutonium." By 1998, as a result of the START I and START II treaties with Russia, thousands of nuclear warheads were being dismantled and 55 tons of U.S. plutonium had been declared excess. A program was under way to dispose of the excess plutonium by one of two methods: immobilization in vitrified high-level radioactive waste prior to storage in a permanent repository, or using it in a mixed oxide fuel (MOX) to power existing reactors.

Before that time, though, the B Reactor reached the end of its useful economic life. On January 29, 1968, the AEC issued a shutdown order for B Reactor that took effect on February 12. At that time, the reactor was reclassified from being in service to "Plant and Equipment for Future Use." It was decided to keep the water-filled irradiated fuel storage basin in service, along with all necessary electrical, water, monitoring, and support services. This would allow the storing of existing fuel slugs from the pile, as well as slugs in the future from the C, KE, and KW Reactors. Also to remain in service were the 107-B

Retention Basin and the water lines between it and the 105-B building, which would allow the disposal of the constant current of water that sustained the fuel storage basin in a safe condition. The water would also provide an emergency backup disposal facility for C Reactor, which was to remain in active service in the 100-B/C Area. Other facilities left in service for the C Reactor and the other Hanford reactors that relied on the export water system included portions of the 115-B Gas Purification Building, 181-B River Pump House, 182-B Reservoir and Pump House, and 184-B Power House. (Gerber 1993: 89-90)

The 105-B building and its cadre of support facilities in the 100-B/C Area were maintained for the next 12 years in a standby status, with a restart capability of 18 to 24 months. The reactor was finally declared excess property in the early 1980s.

Today, the Area stands virtually empty, devoid of the industrial hustle and bustle of its operating years. With virtually all the supporting structures gone, the 105-B building stands alone as a landmark to humanity’s first step on the path to controlling nuclear energy. Although the reactor will never again sustain a nuclear chain reaction, it may yet tap an even more powerful source of energy—the hearts, minds, and souls of those who visit it.

6. Appendix A: Prelude to the Atomic Age

The B Reactor sprang from the concerted wartime efforts of an entire nation, as a key part of the Manhattan Project. The reactor was also the logical culmination of many years of scientific inquiry that was carried out by men and women throughout the world.

Understanding the essential structure of the atom was a lofty scientific endeavor that was worthwhile in itself. Once it was understood that the nucleus, the core of the atom, contained unimaginable amounts of a completely new type of energy, people were struck by the more worldly dream of harnessing this virtually limitless "atomic energy."

To understand how the B Reactor performed its atom-splitting miracle, and the considerations that went into its design and construction, it will be helpful to take this short tour of the science that led to the opening of the atomic nucleus. The science culminated in the unleashing of atomic energy in a rather incongruous laboratory—under the stands of a sports stadium in Chicago, and how the newfound knowledge in this historic milestone was immediately put to work in the B Reactor.

6.1. The Development of Nuclear Science

There has always been some confusion about the use of the term "atomic energy." What we're talking about in this document is the energy within the nucleus of an atom, and that is rightly called "nuclear energy." To be strictly correct, the phrase "atomic energy" should be used to refer to the normal chemical reactions that involve atoms in their entirety, both the nucleus and its accompanying electrons.

Although the two terms may be technically distinct, it was nonetheless "atomic energy" that first made the headlines and captured the imagination of the world. Henry DeWolf Smyth named his 1945 report *Atomic Energy for Military Purposes*, and the first nuclear-related government organization was called the Atomic Energy Commission. Even *The Villager*, the weekly newspaper in the city of Richland (the government-run city for Hanford workers) proclaimed "IT'S ATOMIC BOMBS" on August 6, 1945, when news of the Hiroshima bomb was made public. In keeping with this ongoing subtle confusion, the phrases atomic energy and nuclear energy are used interchangeably in this document.

6.1.1. The Law Defied

For most of the 19th century, scientists lived by the law of the conservation of energy, which states that energy (or matter) can neither be created nor destroyed. It was the one small hurdle that stymied every inventor who dreamed of a perpetual motion machine, or the alchemists who searched for a method of turning lead into gold.

Although a chemical reaction such as that caused by setting fire to a lump of coal might appear to create energy and destroy matter (the coal), in fact the process utilizes oxygen in the air and the energy that was already chemically bound within the coal. The lump of coal is simply a *form* of energy; the *source* of that energy is nothing more than the sun, which grew the plants that decomposed and eventually became coal.

When coal burns it appears to shrink into a small amount of ash, but it has actually been transformed into other forms of matter, including gas and smoke. In fact, burning a quantity of coal in a completely closed vessel (one large enough to contain sufficient air for the flame) would leave that vessel weighing exactly the same after the coal had been burned to ashes. Nothing would be added to or taken away from that closed system.

By the beginning of the 20th century, however, it was becoming apparent that this rule of conservation was weakening under scientific scrutiny. The alchemists throughout history may not have been far from the truth after all (although the prospects of a perpetual motion machine are still assumed to be nil).

Near the end of the 19th century, scientists became aware of a new energy source—radiation. It was first identified by Henri Becquerel in France, when he found that a piece of uranium (U) would blacken (expose) a photographic plate without sunlight or any other visible energy source. Although undetectable to the eye, the uranium was emitting some form of energy.

Becquerel's work was influenced by the earlier discovery of X-rays by Wilhelm Röntgen, and was subsequently studied intensely by Pierre and Marie Curie, who coined the term *radiation*. In the 30 years that followed, scientists throughout the world eagerly pursued this tantalizing new energy source, which in turn opened up the exploration of the atom and its nucleus.

6.1.2. Matter and Energy Conversion

The vision of harnessing a seemingly infinite supply of power had already been expressed by the French writer Jules Verne. For example, in his 1869 book *Twenty Thousand Leagues Under the Sea*, Captain Nemo, of the submarine Nautilus, explains that his ship is run entirely by electrical power. Although it wasn't the power of the atom, it was nonetheless great science fiction in 1869. But the manner in which Nemo generated that electrical power points to the potentials of an infinite power source:

> So it is this sodium that I extract from sea-water, and of which I compose my ingredients. I owe all to the ocean; it produces electricity, and electricity gives heat, light, motion, and, in a word, life to the Nautilus. (Verne [1869] 1963: 56)

As scientists advanced their understanding of the atom, Albert Einstein leapt ahead in 1905 with his theory of relativity. In part, his thesis stated that matter and energy were the same, and that one could be transformed into the other according to the equation $E=mc^2$, where energy (E) equals mass (m) times the speed of light squared (c^2).

Applying this equation to a kilogram of matter, if it could be converted entirely into energy it would release $2.5\text{x}10^{10}$ (25 billion) kilowatt hours (kWh) of energy. As a comparison, burning an equivalent sized chunk of coal would produce about 8.5 kWh of energy. That means that three billion kilograms of coal would have to burned to release the same amount of energy. (Rhodes 1986: 172; Smyth [1945] 1989: 2)

6.1.3. The Atom Revealed

As discovery followed discovery in the early 20th century, the picture of the atom came into focus and was found to contain three basic particles:

- The *proton* is a primary particle within the atomic nucleus. It carries a positive electrical charge and, for our purposes, is assigned an atomic mass of one unit. The number of protons in a nucleus, the *atomic number*, determines the type of atom, such as helium, carbon, sulfur, tin, or gold.
- The *electron* resides outside the nucleus but is tightly bound to it. It carries a negative charge that equals the proton's positive charge. Under normal conditions there are an equal number of electrons and protons in an atom, so the atom is electrically neutral. The electron's atomic mass, however, is negligible compared to the proton (about 0.0005 of the proton's mass).
- The *neutron* is found in the nucleus of all atoms except the lightest form of hydrogen, and is electrically neutral (carries no charge), hence its name. Its atomic mass is just about the same as that of the proton.

Normally, the positively charged protons in the nucleus would be expected to repel one another, as like-charged objects will do. It is the immense binding energy forces within the nucleus that overcome this natural tendency, and that can provide the exception to the law that energy or matter cannot be created or destroyed.

6.1.3.1. Elements

All matter in the known universe is made from about 100 unique elements, each of which is built from only one kind of atom and can therefore not be broken down into other components in the course of everyday chemical actions.

For example, table salt is sodium chloride, a combination of the two elements sodium and chlorine. It is fairly easy to break salt into those two component elements, but that's as far as one can go with chemical means. Sodium will always be sodium, and chorine will be chlorine.

The hydrogen atom is the lightest and simplest element, containing a single proton and a single electron, with an atomic mass of a bit more than one mass unit. Helium comes next, with two protons, two electrons, and an atomic mass of a shade more than four mass units due to the presence of two neutrons in its nucleus.

Progressing through the periodic table of the elements (where the elements are arranged in order of their atomic numbers) reaches uranium, with 92 protons, 92 electrons, and an atomic mass of about 238. The extra mass is accounted for by 146 neutrons.

6.1.3.2. Isotopes

Although all the atoms of one element contain the same number of protons (the atomic number) and electrons, their mass can differ because they can contain a different number of neutrons. Atoms of the same element but of a different mass are called *isotopes* of the element, and are identified by including their mass number as a superscript before the element's atomic name abbreviation. For example, any given sample of the element carbon might be found to contain the isotopes carbon-12 (^{12}C, atomic mass of 12, the most abundant isotope of carbon), ^{13}C, and ^{14}C, these last two having one and two extra neutrons, respectively. (Note that in earlier chemical nomenclature, the atomic weight *followed* the element's abbreviation, such as C^{12}.)

Chemically, the isotopes of an element are virtually identical, and are indistinguishable during normal chemical processes. They can, however, be identified by their differences in mass, such as by using a mass spectrograph. As pointed out later in this document, the fact that it is extremely difficult to separate the various isotopes of an element is one of the primary reasons for the existence of the B Reactor.

6.1.3.3. Radiation

One distinguishing aspect of isotopes of any given element is that some are stable and some are not. An unstable isotope may spontaneously transform itself (break down or decay) into an isotope of a different mass or even into another element, until it eventually becomes stable (has a stable number of protons and neutrons). It makes this transformation by emitting energy, which we call radiation. There are four main types of radiation:

- *Alpha particles* are positively charged, with an atomic number of two and an atomic mass of four, essentially the nuclei of helium atoms.
- *Beta particles* are negatively charged high-energy particles, essentially electrons, that are created by the breakdown of a neutron into a proton in the nucleus.

- *Gamma rays* and *X-rays* are electromagnetic radiation and therefore have no atomic mass or electrical charge. Gamma rays are a by-product of decay in the nucleus, and their emission does not change the isotope; X-rays may also be emitted from excited atoms.
- *Neutrons* are electrically neutral, and may be emitted from a nucleus during radioactive decay or when the nucleus fissions. Neutrons account for much of the radiation in an operating nuclear reactor.

It's important to note that radiation is a direct manifestation of Einstein's mass and energy formula; when there's radiation, there's matter to energy transformation, or vice versa. (Hughes 1957: 21)

In the process of shedding an alpha particle, an atom's atomic number is reduced by two, meaning that the atom has become a different element. When an atom emits a beta particle, the atomic number is increased by one, again creating a different element.

Radioactivity decreases over time, or *decays*, until the isotope has completely decayed. This process occurs at a precise rate for any given isotope, and is expressed in terms of the *half-life*, which is the length of time it takes for its radioactivity to be reduced by half. For example, ^{14}C, mentioned earlier, has a half-life of 5,730 years. After that many years, its radioactivity is 50 percent of its initial value. At 11,460 years, it is down 50 percent of that 50 percent, or 25 percent of its original value. The half lives of isotopes can range from mere heart beats to geologic spans. For example, ^{15}C has a half-life of just 2.5 seconds, while the half-life for ^{238}U is 4.5 billion years.

6.1.4. Splitting the Atom to Release Its Energy

In 1919, Ernst Rutherford at Cambridge University used a beam of alpha particles to transmute a few atoms of the element nitrogen (N, atomic number 7, mass 14) into an isotope of the element oxygen (O, atomic number 8, weight 17), along with the expulsion of a single proton for each transmutation. His experiment had "split the atom" and essentially fulfilled the alchemist's dream. (Rhodes 1986: 137)

Over the next 20 years, tremendous strides were made in the study of nuclear transformations. The discovery of the neutron in 1932 completed the picture of the atom that would be needed to tap the energy of the nucleus. The lack of an electrical charge made the neutron a particularly potent nucleus splitter, because the neutron would not be repelled by the positive electrical charge of the atomic nucleus.

In late 1938, Otto Hahn and Fritz Strassman determined that splitting the nucleus of a uranium atom via a (relatively) slow-moving neutron produced several new atoms that were smaller than the uranium. These slow-moving neutrons are known as *thermal neutrons*, because their energy levels are no higher than that of the surrounding material. Significantly, Hahn and Strassman found that these fragments, although suspected of being the remnants of the breakup of a uranium nucleus, had a smaller mass, in total, than did the original uranium atom. (Smyth [1945] 1989: 24)

It remained for the exiled Jewish member of the team, Lise Meitner, and her physicist nephew, Otto Frisch, to explain the process and propose the name *fission* for it, as suggested by Frisch. This was just one of many new words and phrases that would come into being to describe the new particles and processes that were being discovered. In 1939, it was discovered that the energy released when a uranium nucleus fissioned was equivalent to that predicted by Einstein's equation. (Hughes 1957: 29; Rhodes 1986: 263)

Enrico Fermi, working at Columbia University in New York, determined that in the fissioning of a uranium nucleus, on average about 2.5 new neutrons were released. This discovery led to the possibility of inducing fission in one uranium atom, which would then release two or three neutrons that would induce one or more other uranium atoms to do the same, and so on. Conceivably, this could produce a self-sustaining "burn" in the uranium, much like lighting a fire in a pile of wood. This ongoing *chain reaction* could result in a continuous release of energy from the nuclei of uranium atoms, either uncontrolled in a blinding flash, or somehow controlled and harnessed like a carefully banked fire.

Soon after Fermi's results were published, another link in the chain reaction was made at the Radiation Laboratory at the University of California at Berkeley, where Glenn Seaborg discovered a new element with atomic number 94, which he later named plutonium (Pu). Given the structure of this new element, it appeared to be even more fissionable than uranium.

As the pieces of the nuclear puzzle fell into place, it was inevitable that attempts would be made to generate and harness the energy of nuclear fission. But world events took this ongoing scientific investigation and turned it into an urgent, seemingly life-or-death quest.

6.2. The Birth of Nuclear Power

This part of the story belongs to Enrico Fermi, who is credited with bringing the necessary pieces together to usher in the Atomic Age. Of course, there were many, many others who played key roles at this critical stage, but it was Fermi who guided the final efforts to tap the power of the nucleus.

He and his wife Laura, who was Jewish, had left Fascist Italy in 1938, under the pall of government-sponsored anti-Semitism and an increasingly restrictive regime. They left ostensibly to go to Sweden to accept the Nobel Prize, which he had been awarded for his work in exploring the nucleus and the effects of thermal neutrons. Once he had the prize and the accompanying cash award in hand, the couple hurried on to the United States, where a professorship at Columbia University was waiting.

As the developing tensions in Europe headed towards outright war, the research and experiments Fermi might have pursued were soon redirected and funneled into the largest government-sponsored effort ever undertaken in the United States.

6.2.1. What the Germans Might Be Building

In August, 1939, Albert Einstein, under the urging and guidance of scientists Leo Szilard, Eugene Wigner, and Edward Teller, sent a letter to President Roosevelt. In it he advised the President of the possibility of creating a uranium bomb of horrendous power, and that the Germans might very well be moving along that path. He urged the President to consider developing such a bomb for the United States as the only way to counterbalance the looming German threat.

The letter helped to spur on the events that followed, which inevitably led the United States and its allies to pursue the making of a nuclear bomb, under what came to be called the Manhattan Project. As it turned out, Germany had, indeed, been investigating the possibilities of a nuclear weapon and undoubtedly had the necessary intellectual base for the job. But their efforts were short-lived, due to the immense scope of the work that would be needed and the demands of many other wartime projects.

In the United States, however, government funding began to flow into nuclear research and experimentation. Fermi's role at Columbia University was to investigate the fissioning of uranium, and how a machine might be built to control a nuclear chain reaction, and thereby harness the resulting nuclear power. It took three more years of progress to achieve that goal.

6.2.2. Determining the Feasibility of a Chain Reaction

Fermi's investigation hinged on one critical determination: how many of the neutrons, on average, that are released after a uranium nucleus fissions are available to continue a chain reaction? This number, the neutron reproduction or multiplication factor *k*, would determine the success or failure of a chain-reacting machine.

As mentioned earlier, Fermi's experiments had already shown that a fissioning uranium atom releases about 2.5 neutrons on average. This extremely good news meant a self-sustaining nuclear chain reaction was a possibility, because more neutrons were produced (2.5) than were required (1) to fission another nucleus. However, there were many factors that would effectively reduce that number to a value much less than 1, including the quantity and quality of the materials and the efficiency of their arrangement. Now he had to calibrate this degradation in a real-world chain-reacting machine. (Rhodes 1986: 397)

After all the deleterious factors are accounted for, there are three possibilities for *k*:

- If less than one neutron is available from each fissioning nucleus (*k*<1), the chain reaction will continue for awhile, but eventually it will slow to a halt. Each generation of neutrons that are released during fission will be somewhat fewer than the preceding generation.
- If only one neutron is available (*k*=1), a chain reaction will have been created that will continue, theoretically, indefinitely. However, the slightest degradation in the real-world machine would lower the value of *k* below 1, and the chain reaction would eventually end.
- If more than one neutron is available (*k*>1), even just slightly more than one, the chain reaction will increase in scale dramatically, and not stop until the uranium is either expended or scattered to the four winds due to the force of the energy release.

The effect of neutron propagation is not unlike the study of generations in fruit flies or people. If 2.5 neutrons, on average, are "born" from each nuclear fission, and 2.0 survive to create a next generation (by fissioning two other nuclei), then there will be 4 neutrons in that second generation (2 X 2), 8 in the third (4 X 2), 16 in the fourth, and so on. The population will grow exponentially, not shrink, so that more than a billion neutrons would be released in the 30th generation. The trick with nuclear fission is that those 30 generations would not propagate in days or months, but in thousandths of a second, while releasing incredible amounts of energy.

So you can see that even if the value of *k* is just slightly greater than one (that amount greater than one being known as *excess reactivity*), the chain reaction would still reach tremendous values in the blink of an eye.

Fermi had to address all the *k*-reducing factors inherent in a chain reacting machine, in order to determine if a self-sustaining chain reaction were possible. Those same critical factors had to be addressed later during the design and construction of the B Reactor.

Rarity Perhaps the greatest hurdle to achieving a *k* greater than 1 is that not just any uranium atom is likely to fission when struck by a neutron. The most abundant isotope of uranium, ^{238}U, will generally not undergo fission in an encounter with a thermal neutron, although it may absorb the neutron and then transform into a different element altogether (neptuniam-239). However, the isotope ^{235}U is highly fissionable; it can undergo fission with either fast or thermal neutrons, but it is especially susceptible to the slow ones. It would make a very efficient fuel in itself for a chain reaction, but the problem is that this isotope occurs in natural uranium in tiny amounts, on the order of 0.7 percent. (Smyth [1945] 1989: 32)

Of course, if you could separate the ^{235}U from the ^{238}U, you'd have a chain reaction any time you wanted. But the separations process would be extremely complex, time-consuming, and tremendously expensive in materials and labor.

Speed The nucleus of ^{235}U will readily fission when struck by a slow-moving (thermal) neutron, and ^{238}U is somewhat less likely to absorb a thermal neutron than a fast neutron. Therefore, if it were possible to use only thermal neutrons in the chain-reacting machine, the value of *k* would increase substantially. (Smyth [1945] 1989: 34)

Unfortunately, the neutrons freed when a nucleus fissions are fast moving. Therefore, in order to maintain a chain reaction, something had to be introduced within the uranium that would slow down these neutrons, or moderate their speed, without absorbing them. The uranium would have to be used in conjunction with a suitable *moderator*. Of several possible choices for the moderator, only graphite (a form of pure carbon) proved to be workable, affordable, and available.

Size A neutron released from a fissioning atom may encounter another atom, or else it will eventually pass through the outside edge of the uranium and be lost, thereby lowering the factor of *k* (this loss is known as *leakage*). In a small lump of uranium, neutrons are much more likely to be lost to the outside than those in a larger chunk.

Fermi was faced with the need to determine an appropriate size for the chain-reacting machine, one that would provide a sufficient number of uranium atoms to create what came to be called a *critical mass*. Anything smaller than a critical mass (*subcritical*), and you'd have a cold or perhaps sputtering chunk of uranium. Anything larger, and your machine would be *critical*, with the energy of the universe at your fingertips.

So the trick was to assemble a sufficiently large matrix of uranium chunks within a moderator to achieve a critical mass. Calculations had shown that mixing the moderator and uranium into an evenly dispersed block would be ineffective. Instead, the best method would be to create a *lattice* (three-dimensional structure) of uranium chunks in a specific size and shape within a moderator.

The shape of that lattice was quite important; the most efficient shape would be one that had the least amount of surface area per given volume—a sphere.

However, too much success could be dangerous. If you built up a mass of uranium greater than a critical mass, the value of *k* would increase and the chain reaction might proceed so quickly throughout the uranium as to reach explosive levels in a fraction of a second. The right amount of uranium was therefore of critical importance.

Purity Scientists discovered early on that any defects in the design or implementation of a chain-reacting system would diminish the value of *k* and jeopardize the success of the chain reaction. Impurities in the uranium or moderator, for example, could absorb neutrons and reduce the chance of further fissioning; the presence of even 1 percent boron in the uranium would lower the pile's *k* by 1,980 percent. It was a very delicate equation. (HTM 1945: 213)

Control mechanism Assuming that the chain-reacting machine could be built to sustain a value of *k* greater than 1, once you started that machine you would need to control it, just as you must control the speed of an engine. In this matter, the delicate balance between a successful chain reaction and a fizzle meant that it would be relatively simple to put a brake on the reaction by introducing a material that would absorb neutrons, thereby lowering the value of *k* and "poisoning" the chain reaction.

With all these variables taken into account, a mechanism for creating and sustaining a nuclear chain reaction started to become clear. Fermi and his team built a succession of more than two dozen machines before they could finally claim victory.

6.3. Building a Self-Sustaining Chain-Reacting Machine

Fermi's work on a chain-reacting machine was driven by two motives. First, creating and sustaining a nuclear chain reaction would be an historic milestone, and a goal worthy of a scientist's lifetime of work. Of more immediate importance was his project's role in the efforts to explore the possibilities of making a nuclear weapon. Once science understood the subtleties of a chain reaction within a controlled machine, it could then work towards making an uncontrolled chain reaction—a nuclear bomb. There was another factor, however, that made the importance of a chain-reacting machine paramount.

Glenn Seaborg's discovery of element 94, plutonium, provided an entirely new motivation for a chain-reacting machine. If plutonium turned out to be as fissionable as was predicted, it would make an excellent material for a bomb. Plutonium could be produced by bombarding natural uranium (consisting mostly of ^{238}U) with thermal neutrons, precisely the setup within the heart of a chain-reacting machine, where the same thermal neutrons would also fission the ^{235}U atoms to sustain the chain reaction. The process goes something like this (Smyth [1945] 1989: 29, 38):

^{238}U + 1 neutron transforms into ^{239}U
^{239}U decays in 23.5 minutes (on average) to Neptunium-239 (^{239}Np)
^{239}Np decays to Plutonium-239 (^{239}Pu) in 2.3 days

The final bonus was that separating the plutonium from the uranium, although never done before, would be a relatively straightforward chemical process, quite the opposite of collecting the isotope ^{235}U, which at that time was next to impossible to separate from natural uranium in any usable quantities. Nonetheless, it is important to point out that one of the lines of attack in the Manhattan Project was to separate ^{235}U from natural uranium and fashion the ^{235}U into a bomb of immense power. Facilities to carry out that separations process were built at Oak Ridge, Tennessee. The other line of attack was to produce plutonium by irradiating natural uranium, and that was the job of Hanford and the B Reactor.

Through dozens of experiments, Fermi and his team fine-tuned the design of a chain-reacting machine. They were no longer tinkering with laboratory bench-top experiments. These were huge, room-sized devices that required not milligrams, but tens of thousands of kilograms of materials in order to reach the necessary critical mass.

Each of these machines that so elegantly manifested the underlying laws of the universe resembled nothing more than a large pile of graphite blocks. In fact, that is how Fermi referred to his new machine, simply as a *pile*. This endearing, homespun name would stick for years to come, even when the more mechanically descriptive term *nuclear reactor*, or just plain *reactor*, came into use soon after, and eventually supplanted “pile.” (Rhodes 1986: 395)

Through each iteration, they worked to refine the size of the machine, the arrangement of the uranium within it, the quality of the materials, and a method for controlling it, all in an effort to raise the value of k until it was greater than 1.

In early 1942, in the midst of these experiments, the Office of Scientific Research and Development decided that it would be best if the work on chain reactions were moved from Columbia University to the University of Chicago. Here, the new Metallurgical Laboratory would serve Fermi and others in their work. The “Met Lab” name was strictly a guise to conceal the true nature of the nucleus-busting work that was going on. (AEC 1955: 7)

That summer, the Manhattan Engineer District was established within the Army Corps of Engineers to manage the entire nuclear weapons work. In September, General Leslie Groves was assigned to manage the project. (AEC 1955: 9)

It was at the Met Lab on December 2, 1942, that Fermi and his team finally created the first self-sustaining chain-reacting pile, the Chicago Pile Number One (CP-1), as it was later called. Its design was of critical importance to that of the B Reactor. The E. I. du Pont de Nemours company (DuPont) was already rushing ahead on the design of the plutonium production piles at Hanford, and had actually started the design process of B Reactor several months earlier. Everything that Fermi incorporated into this pile was soon built into the B Reactor, only on a larger scale that could produce plutonium for the Manhattan Project. (Thayer 1996: 41)

6.3.1. Pile Building

Fermi’s “laboratories” in Chicago were ensconced in the rooms beneath the concrete stands at the University of Chicago’s Stagg Field, where his associates had already built several experimental piles while he was still working in New York. Stagg Field was not the first or most suitable choice, however. Work had already begun on a more appropriate building in the Argonne Forest, a site about 20 miles from Chicago, by the firm of Stone and Webster. Ongoing labor disputes delayed the job, so that Fermi continued his work at Stagg Field. It was about this time that General Groves was able to convince DuPont to take over the construction of the coming plutonium production piles and processing plants for the Manhattan Project. (Rhodes 1986: 431-432)

Therefore, Fermi’s “reactor building” was no more than a doubles’ squash court that measured 60 ft x 30 ft x 26 ft high; half of its height was below ground level. It was a substantial concrete structure, which added a small measure of safety to the surrounding community in case of an accident. Nonetheless, it was located on a university campus in the heart of Chicago, which was a less than desirable location for the grand premier of the unleashing of nuclear energy. But Fermi felt confident that keeping the pile under control would not be a problem, and that any hazards would not be of the city-leveling variety. (Rhodes 1986: 432-433)

6.3.2. Pile's Moderator and Fuel

Fermi began building CP-1 on November 16, 1942. Like the earlier experimental piles, it was to consist of layers of graphite blocks, the moderator, interspersed with lumps of uranium, the nuclear fuel. This was to be a huge structure, somewhat spherical in shape, about 25 ft in diameter. It ultimately required about 45,000 graphite blocks weighing about 771,000 lb, 80,590 lb of uranium oxide, plus, when it became available, another 12,400 lb of more suitable uranium metal. This was more or less the minimum size of the critical mass for a chain-reacting machine, given the quality of the materials and workmanship that were available. (Rhodes 1986: 436)

The graphite blocks were milled on site to a finished size of 4.1875 in. x 4.1875 in. (that's 4-3/16 in.) and were cut to 16.5 in. lengths. A fourth of them were drilled with two 3.25 in. holes about 8.25 in. apart, into which the lumps of uranium would be placed. This meant that most lumps of fuel would be an equal distance in all directions from any other fuel. Other blocks had to be slotted for the neutron-absorbing rods that would be inserted into the pile to control the pace of the chain reaction. (Rhodes 1986: 430)

The base of the pile was made up of graphite blocks laid on the floor of the squash court. This was followed by a layer of the graphite block that had been drilled; each of the two holes now contained a five pound spheroid of uranium. By alternating layers between drilled graphite blocks with fuel and solid graphite blocks, the fuel was thus dispersed evenly throughout the pile in a somewhat spherical shape, each fuel element about 8.375 in. (8-3/8 in.) from the others in all directions. (Rhodes 1986: 433)

There were no means for unloading the fuel from the pile, short of dismantling the entire pile, block by block. This was strictly an experiment, and one that would operate at minute power levels. It was designed to show the feasibility of a nuclear chain reaction, not to create plutonium. The design of the B Reactor, however, would have to provide for a safe, efficient, and speedy method for removing irradiated fuel and adding new fuel.

The purity of the graphite and uranium in CP-1 was of critical importance; any impurities could decrease the chances of creating and sustaining a chain reaction. Fermi had tested the various shipments beforehand, and he now arranged the materials in the pile to take best advantage of those with the highest purity. (Rhodes 1986: 433)

As it turned out, Fermi's team received a quantity of very high quality graphite that would help to increase the value of k. They also received the 12,400 lb of uranium metal, which was more fissionable than the uranium oxide they had been using. Together these efficiencies decreased the critical mass required, and allowed them to reduce the size of the pile from 76 layers to only 56. The finished pile would be about 25 ft wide, but only 20 ft tall. (Rhodes 1986: 435)

6.3.3. Outer Air-Tight Bag

Fermi knew that air within the pile would tend to dampen the chain reaction, so he ordered a 25 ft square balloon-cloth bag from the Goodyear Rubber Company (of tires, blimps, and rubber rafts fame). They would leave one side of the bag open, build the pile within the bag, seal the bag, and then evacuate the air from it, giving a small but helpful increase in k.

However, the same increases in purity and quality that allowed them to reduce the number of rows of graphite and fuel meant that they could also forego the bother of sealing the bag and pumping out the air.

6.3.4. Control Mechanisms

Fermi would control the rate of the pile's chain reaction with *control rods*, each of which was simply a long wooden stick to which was nailed a piece of cadmium sheet metal. Cadmium is a strong absorber of neutrons, so inserting a rod into the reactor would subdue (poison) the chain reaction. (Rhodes 1986: 433)

CP-1 incorporated three different sets of rods: control rods, safety rods, and a last-ditch safety rod. It was calculated that inserting any one of these rods into the pile would keep the pile subcritical. (Smyth [1945] 1989: 244)

Several control rods were operated by electric motors and could be controlled remotely. The primary control rod was manually operated. With all the other rods pulled from the pile, this one rod would hold the chain reaction in check. An operator (they weren't called that then) could slowly pull the rod from the pile, while scientists checked instruments and made calculations, watching for the pile to go critical. The rod's length was calibrated so that its withdrawal or insertion could be controlled precisely. (Rhodes 1986: 438)

A weighted safety rod was fastened outside the pile. If the pile's chain reaction were to exceed a preassigned safety level, instruments would trigger this rod and it would automatically plunge into the pile. Yet another safety rod was suspended above the pile by a rope. An operator stood by, ax in hand, ready to cut the rope holding the rod in case of emergency. The birth of nuclear power was thus, rather dramatically, attended by a man with an ax. (Rhodes 1986: 438)

One final last-ditch safety system was included in CP-1. Standing above the pile were three men, each holding a glass jug of cadmium-sulfate solution. In the event of a dire emergency, they could smash the jugs onto the pile, the solution would run through the pile, and the cadmium would help to kill the chain reaction. (Rhodes 1986: 438)

6.3.5. Instrumentation

Several types of instruments were employed in CP-1 to measure the neutron flow within the pile. The results would be used in calculations to track the rate of the pile's chain reaction, and to determine the pile's neutron reproduction factor, k. Safety was also a reason to monitor the pile. Once the pile reached a value of k greater than 1, if not kept controlled it could go on to reach excessive power levels very quickly and bombard the squash court with a deadly level of radiation. It would also soon overheat and destroy itself (and perhaps some small piece of Chicago) in the process.

Boron trifluoride counters measured the less intense levels of neutron activity. Indium strips were placed at strategic points in or around the pile to measure the flow of neutrons over time. Ionization chambers measured the higher levels of neutron radiation that would be achieved as the pile reached criticality. It was this type of instrument that would trigger the gravity-controlled safety rod if preset levels of neutron activity were exceeded. The instruments were wired to produce an audible click, much like a Geiger counter, and also to record their results continuously on paper. (Rhodes 1986: 434, 437-438)

When it came time to build the production piles at Hanford, the amount of instrumentation increased dramatically, as every process connected with the pile's operation had to be monitored and controlled to achieve the desired power levels while maintaining safety.

6.3.6. Achieving Criticality

Because a chain reaction can occur spontaneously within a critical mass of uranium, the process of building the pile layer by layer also built up the value of k within the pile. As the pile grew, Fermi would regularly have the control rods removed and would then take careful measurements of the pile's neutron activity, which he would compare to his own calculations. In this way, he was able to monitor the pile's progress while also verifying his own calculations of the physics involved. His slide rule and instruments allowed him to anticipate quite accurately the amount of neutron generation (reactivity) at any given level of the pile.

When they removed the control rods, the neutron flow within the pile (flux) would increase as the chain reaction took off. But as long as the pile was smaller than its necessary critical mass, the increase in reactivity would gradually taper off and increase no further. The chain reaction was not yet self-sustaining; *k* was still not greater than 1.

Finally, at the 56th layer of graphite blocks, as Fermi's calculations had predicted, the increase in neutron flux did *not* taper off, but continued to rise without stopping, doubling about every two minutes. They had reached their goal—a chain reaction that grew larger, second by second. It was only the insertion of a control rod that brought the chain reaction to a halt. Fermi later calculated that the pile had achieved a *k* of 1.0006, sufficiently greater than 1 for the chain reaction to be self-sustaining. (Rhodes 1986: 440)

Fermi's history-making success with CP-1 was the verification that was needed to proceed with the design and construction of the production piles at Hanford.

6.4. What Was Missing in Fermi's CP-1

Fermi's experimental Chicago pile was designed only to prove that it was possible to achieve a self-sustaining nuclear chain reaction, not to create the plutonium for the world's first nuclear weapon. For that reason, several critically important features that would be built into B Reactor were completely missing from Fermi's CP-1. In this laboratory version of a pile, these missing features were either unnecessary, unattainable, too costly, too complex, too time consuming, or simply not yet conceptualized.

Geographic location A nuclear pile was brand new and completely unproven technology. The uranium fuel in an operating pile of industrial size would be extremely radioactive, so the safest place to build one was many miles from any population center. Plus, the plutonium production piles would be top-secret, wartime efforts, which also favored a secluded location.

Power levels The production piles were being built to produce plutonium, as much and as quickly as possible. Because the rate at which uranium is transmutated into plutonium is directly proportional to the pile's power level, the higher the power the better. It was estimated that Fermi's CP-1 produced a mere one-half watt of power on December 2, 1942, although 10 days later it would be taken as high as 200 watts. The Hanford piles, on the other hand, were designed to operate at 250 million watts (megawatts, or MW), which would dramatically influence the design of virtually every component in the piles. (Smyth [1945] 1989: 98)

Unloading and loading fuel As mentioned earlier, there was no need to unload fuel from Fermi's pile. In a production pile, however, mechanisms and procedures would be needed to allow irradiated fuel to be discharged from the pile and new fuel added, all in a timely, efficient, and safe manner.

Plutonium/uranium separation For the same reason, Fermi had no need for a facility for chemically separating plutonium from irradiated uranium. But the necessary laboratory work was already progressing in that arena, and would lead to a major part of the construction and operations at the Hanford site.

Air-tight pile enclosure Another complex arrangement, the air-tight enclosure for the pile, was not included in CP-1 but would be an important component of the B Reactor. Its shell would be far more substantial than a Goodyear balloon-cloth bag.

Pile cooling Fermi's experimental pile produced only data, and was meant to operate only at extremely low power levels for short periods of time. For these reasons, no system for cooling the pile was needed. In a pile designed to create plutonium, however, the million-fold increase in power would produce vast quantities of heat. An efficient, highly reliable means for cooling the pile was an absolute necessity.

Electrical power The electrical requirements for CP-1 were nominal, consisting of a few motors for its control rods, lighting, instrumentation, and so on. When it came time to choose a site for the B Reactor and the other plutonium production piles, however, the availability of municipal amounts of cooling water and electrical power were two key factors in the decision. Cooling and power would be so important to the safe operation of the pile that several backup systems for each would be part of the B Reactor's extensive support facilities and systems.

Protective radiation shielding The CP-1 had no special radiation shielding, as it ran at very low power levels for only short periods of time. Fermi and his team would be exposed to relatively little radiation in the squash court. On the other hand, if Fermi had let the pile's chain reaction continue to increase, the room would soon have been drenched with dangerous levels of radioactivity, and the world might have had its first reactor *meltdown*. (Rhodes 1986: 440)

Health and safety monitoring In this same vein, there were no extensive systems for monitoring the squash court for radiation. This was an experimental device designed for the very short-term.

Quality of Materials and Workmanship Any defects in the material or workmanship in CP-1 would have threatened its ability to maintain a chain reaction. Fermi's team did the best they could in securing the purest graphite and the highest quality uranium, and carefully laying the pile together. For the B Reactor and the other production piles, the standards would be raised very much higher. The future of the United States and its allies might very well rest on the success of these piles, and they had to be built to the highest standards. They would produce tremendous amounts of radiation and heat, and must hold together under that stress (for at least the duration of the war).

All in all, Fermi's pile was truly a laboratory experiment, albeit one that had to be built room-sized in order to work (achieve a critical mass). Under less urgent conditions, another pile would then have been constructed that more closely matched the requirements of a true production pile, but was still just a model of the ultimate pile. This *semiworks* would have let the physicists and engineers work together to design, build, and debug the entire system before committing to a final production unit. (Thayer 1996: 42)

Such a pile, named the X-10, was begun at the Clinton Engineer Works in Tennessee (the site that was later called Oak Ridge). Lessons learned during its construction aided greatly in the construction of B Reactor, and ongoing tests after it was taken to criticality also added to the store of experience that allowed the B Reactor to achieve its operational goals. The plutonium the X-10 produced, even though in minute amounts, was extremely important for use in the design of the plutonium separations chemical process that would later be built at Hanford.

However, the X-10 never fulfilled its role as a semiworks, as it was not completed until November, 1943, *after* construction had already started on B Reactor. Even more important, the X-10 pile was cooled by air. While the X-10 was being constructed, the decision was made to cool the B Reactor not with helium gas, but with water. Therefore, the influence that the X-10 pile had on the design and construction of B Reactor was very much less than would have been preferred under normal conditions. (Rhodes 1986, 547; Thayer 1996, 42; Smyth [1945] 1989: 106, 142-143)

The exigencies of war turned this usual and customary requirement of building and testing a semiworks into an unaffordable luxury. Instead, construction started on B Reactor less than 10 months after Fermi's laboratory success with CP-1. This leap from concept to reality, from watts to megawatts, from micrograms to kilograms, is one of the truly amazing feats that were performed during the Manhattan Project, and is perhaps the first of the B Reactor's many historic "firsts."

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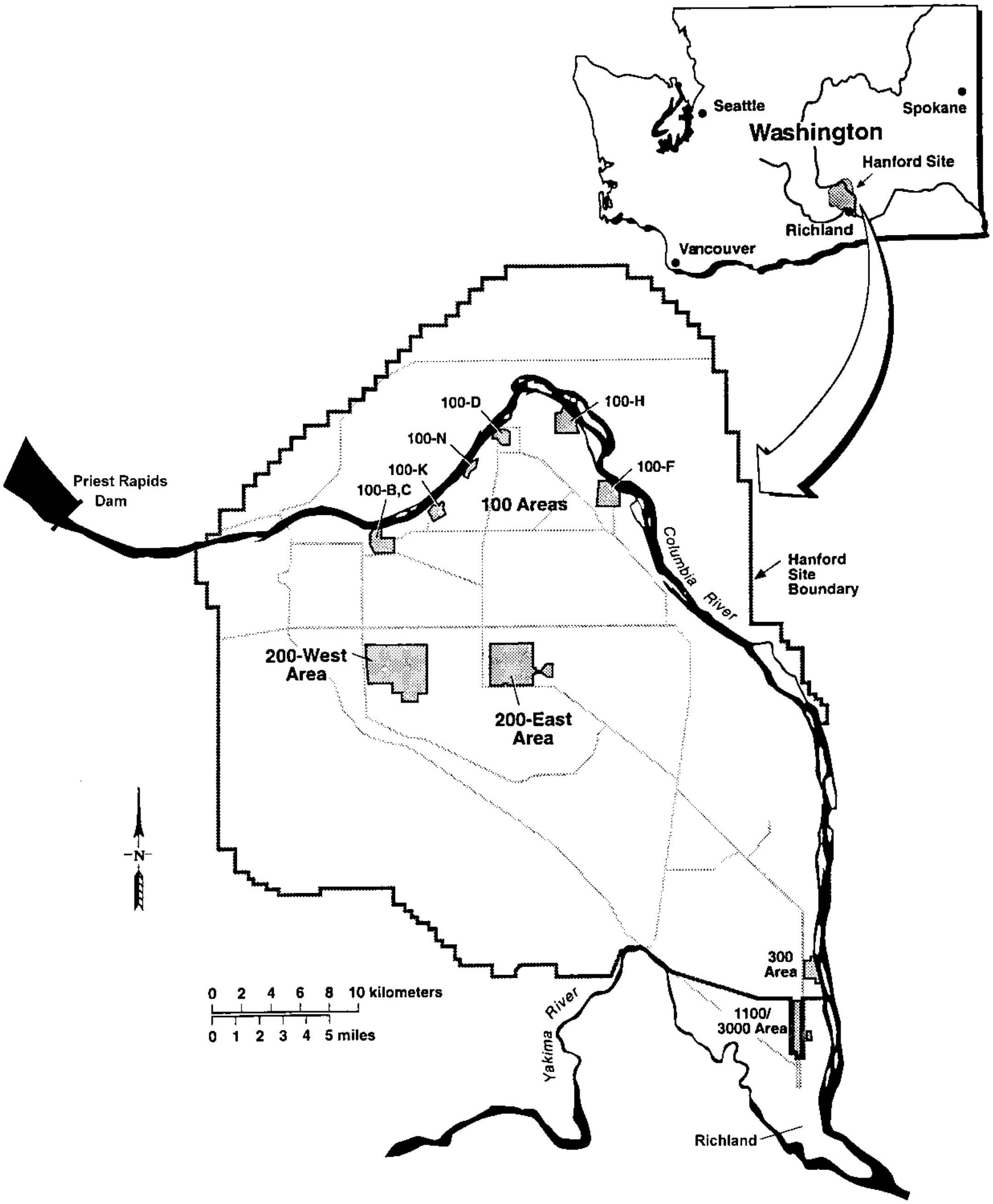

Figure 1: The Hanford Site resides in eastern Washington state on the banks of the Columbia River. Nine graphite-moderated nuclear reactors were built during its 50 year role as one of the nation's plutonium production plants.

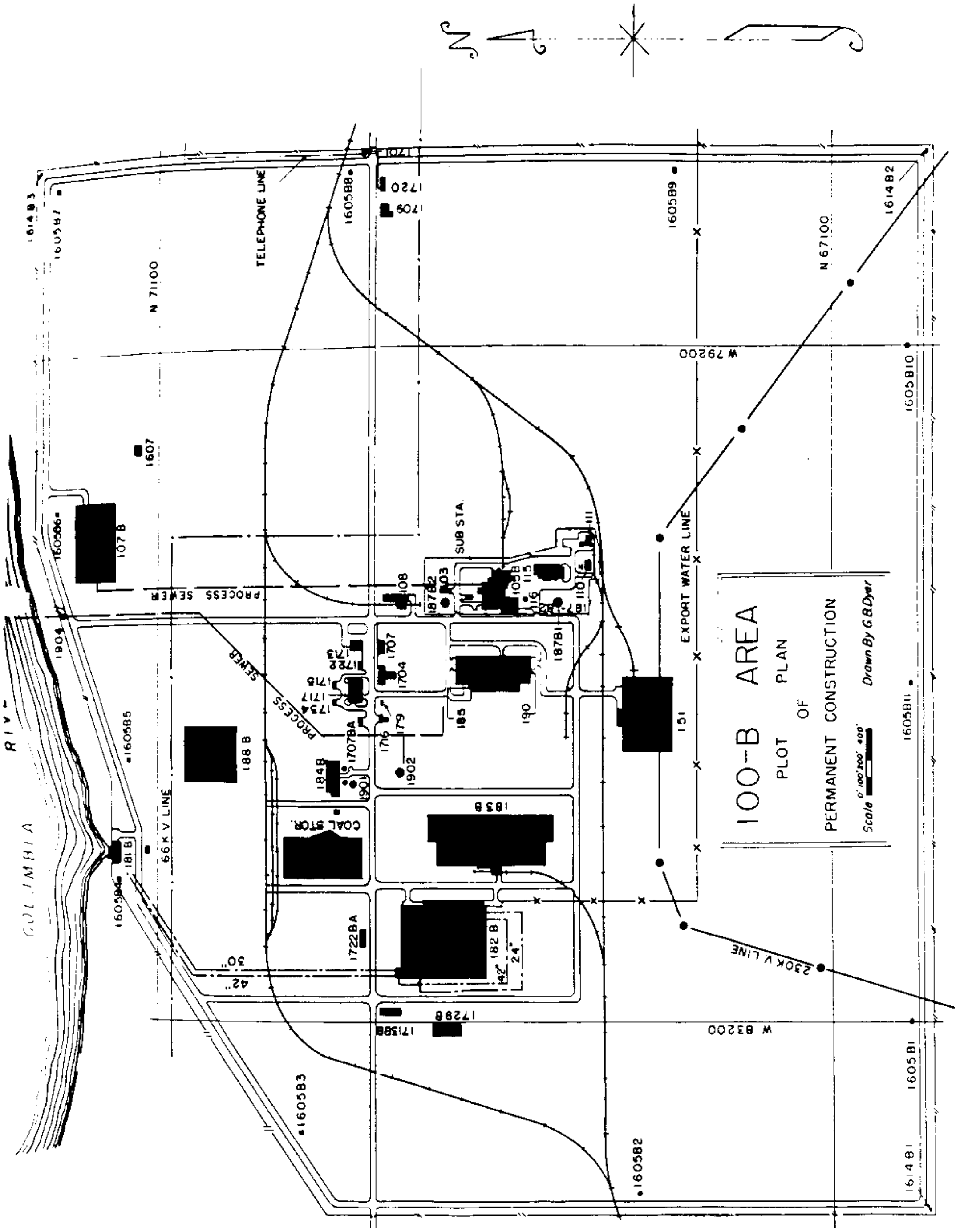

Figure 2: The 100-B Area and its primary facilities as it was soon after completion in 1944.

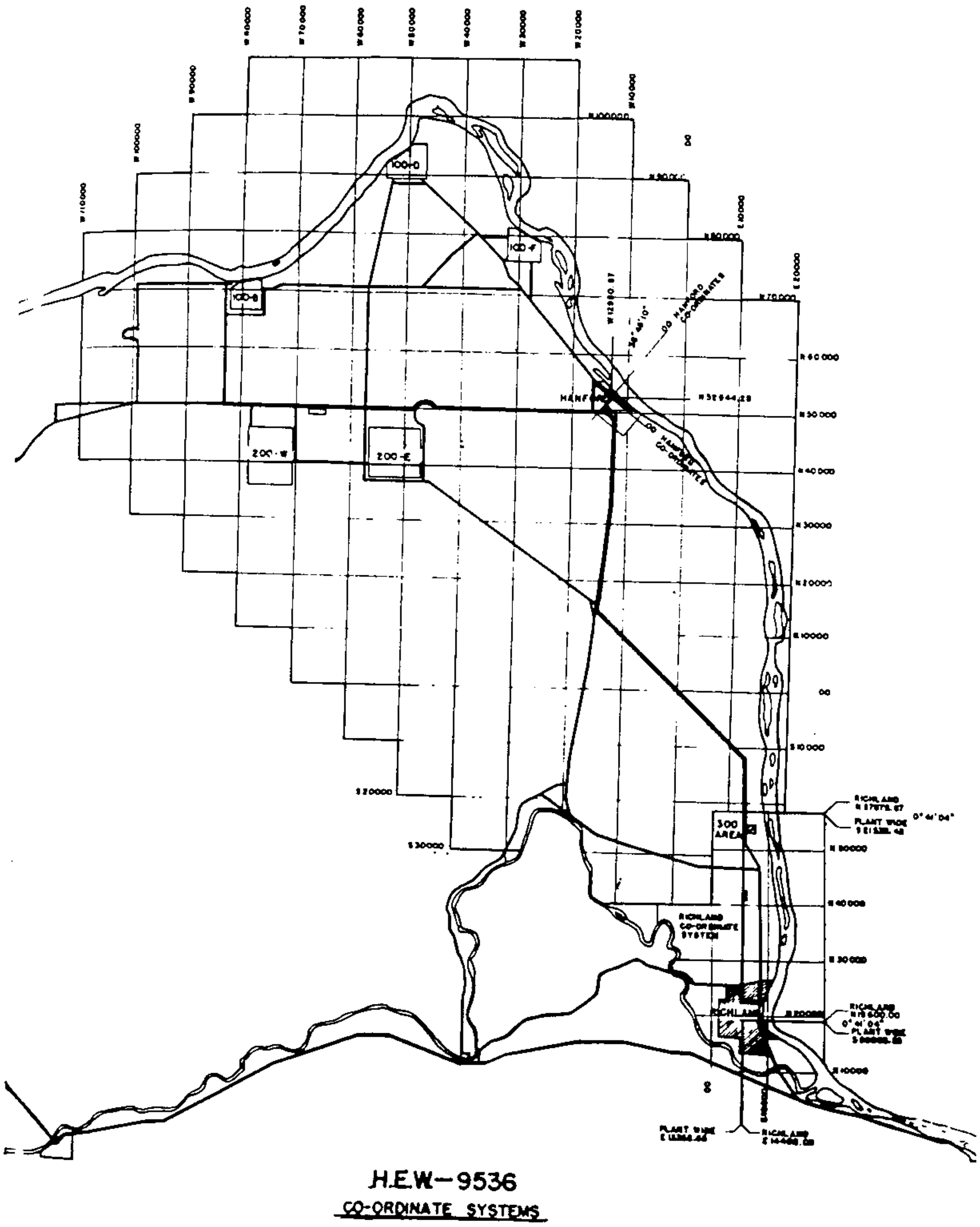

Figure 3: The Plant coordinate system divided the Hanford Engineer Works into a convenient grid.

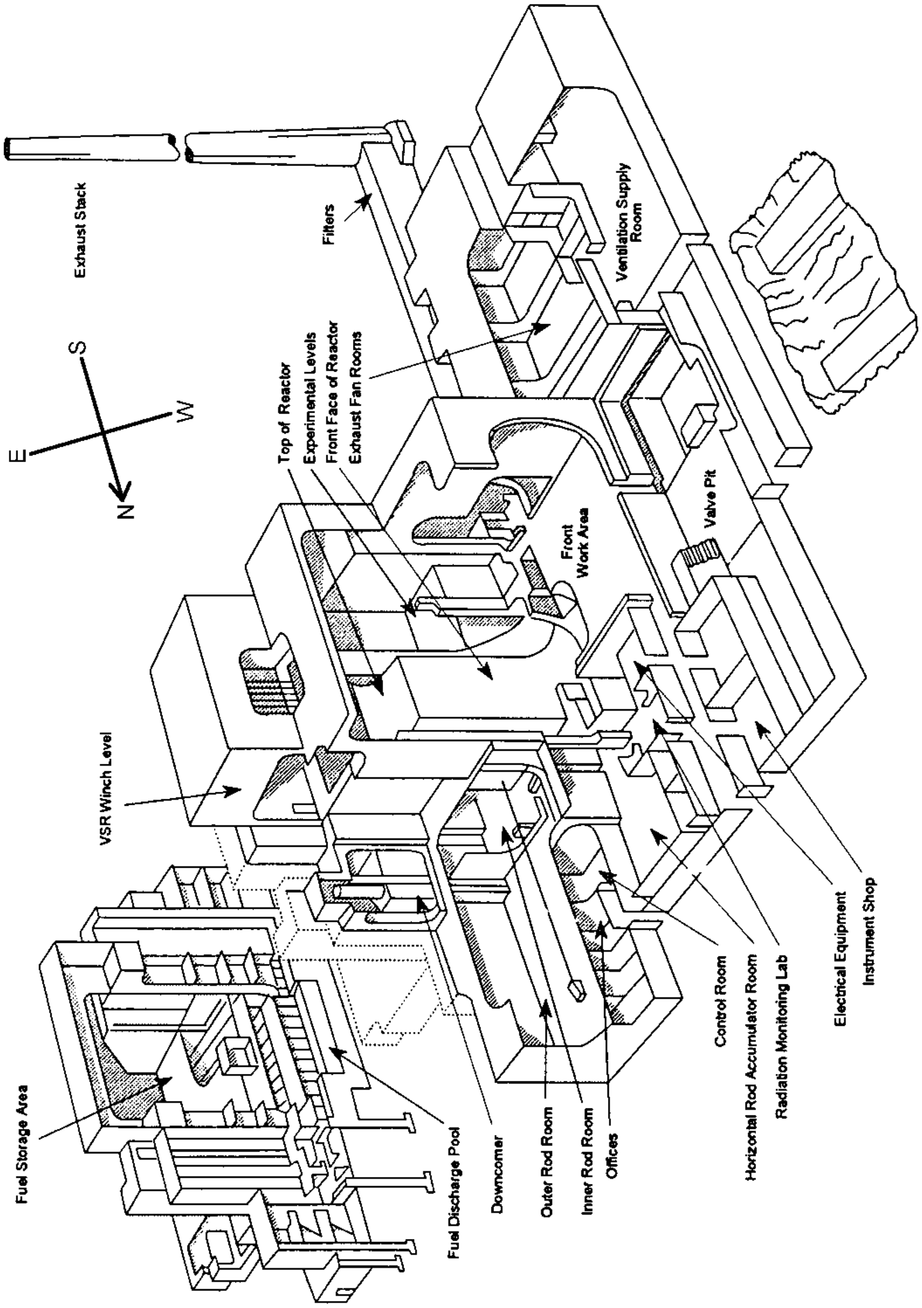

Figure 4: A cutaway view of the 105-B building.

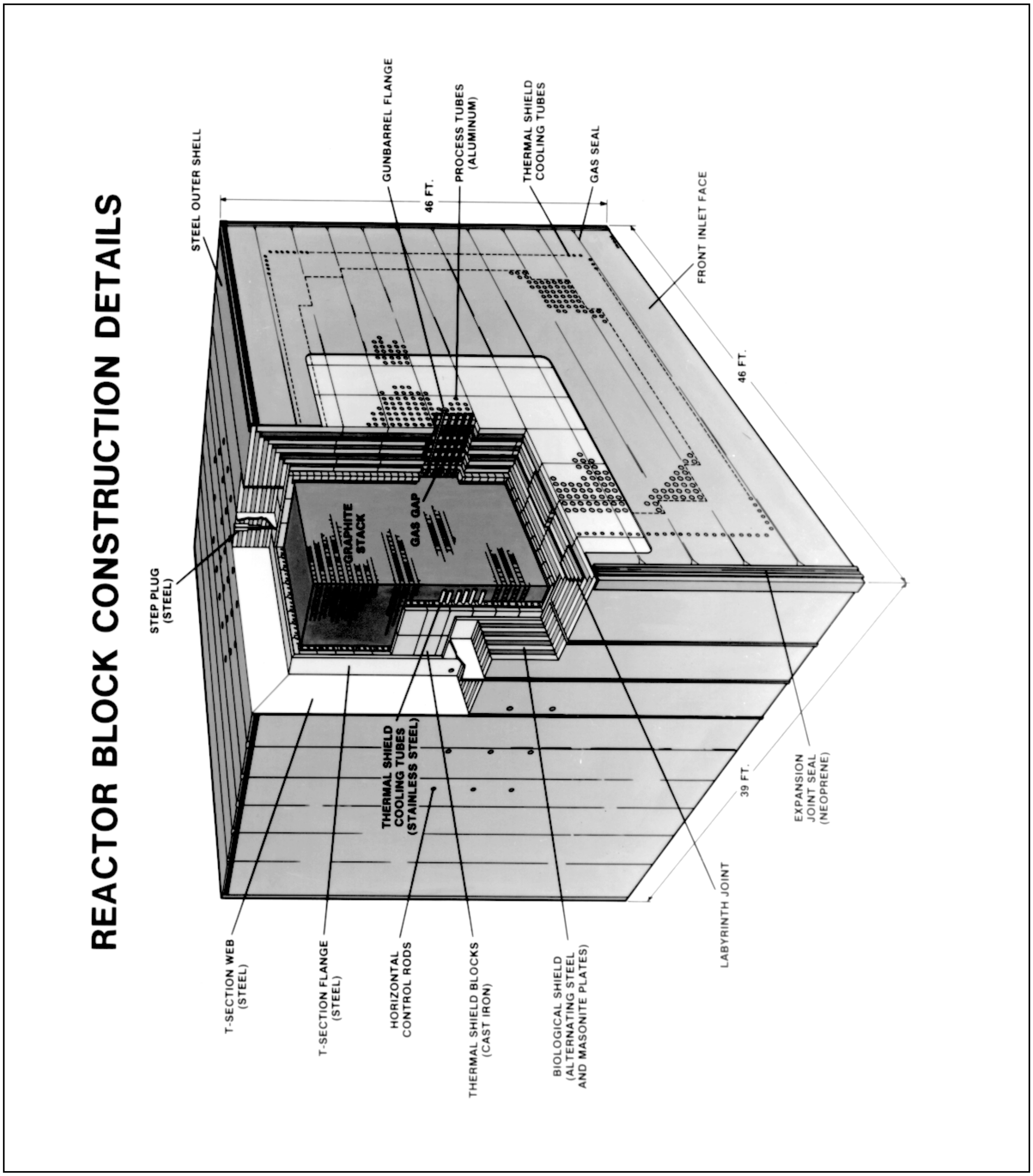

Figure 5: The general arrangement of the pile assembly.

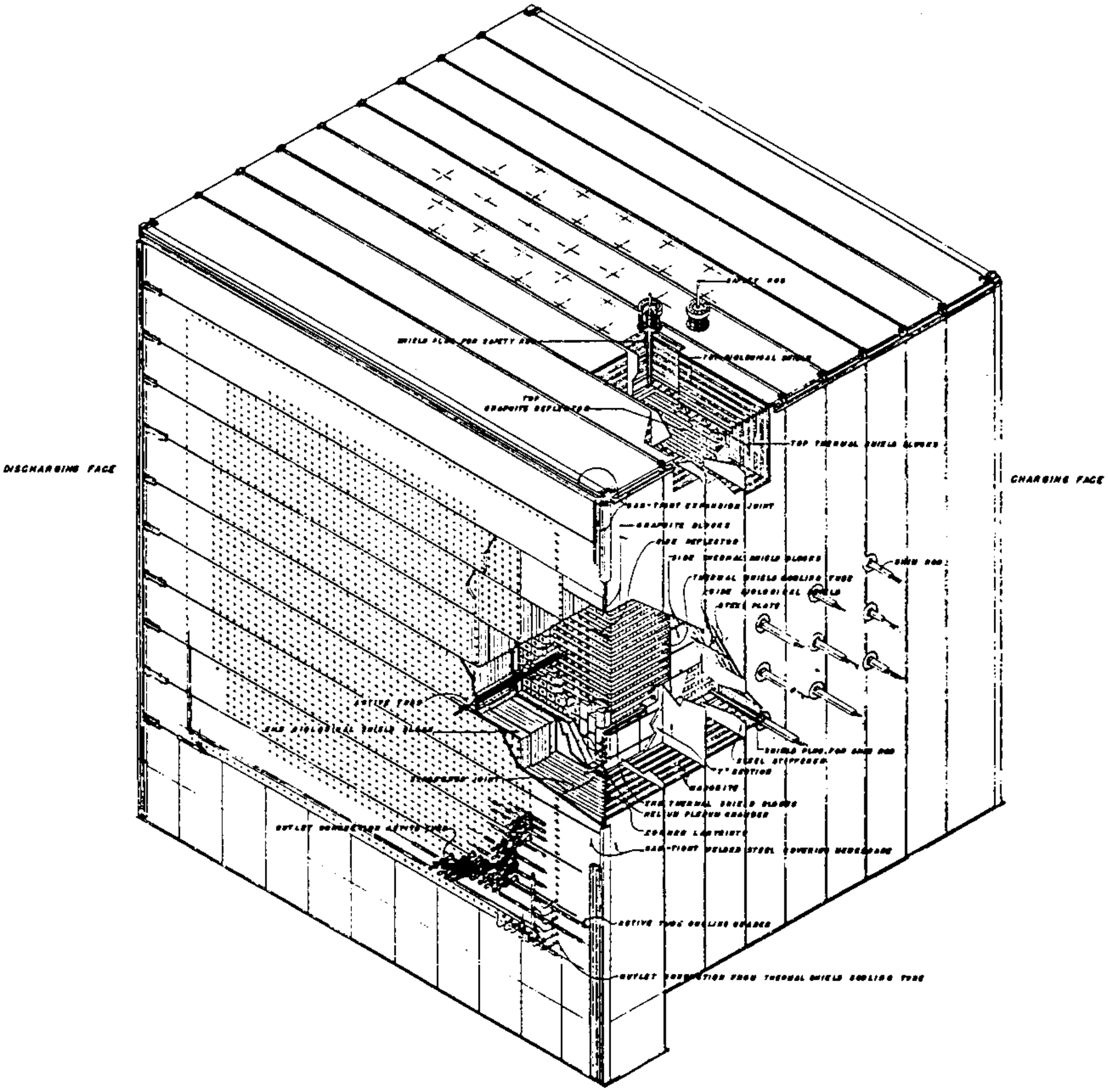

Figure 6: A cutaway view of the pile showing the graphite interior, cast iron thermal blocks, and biological shielding.

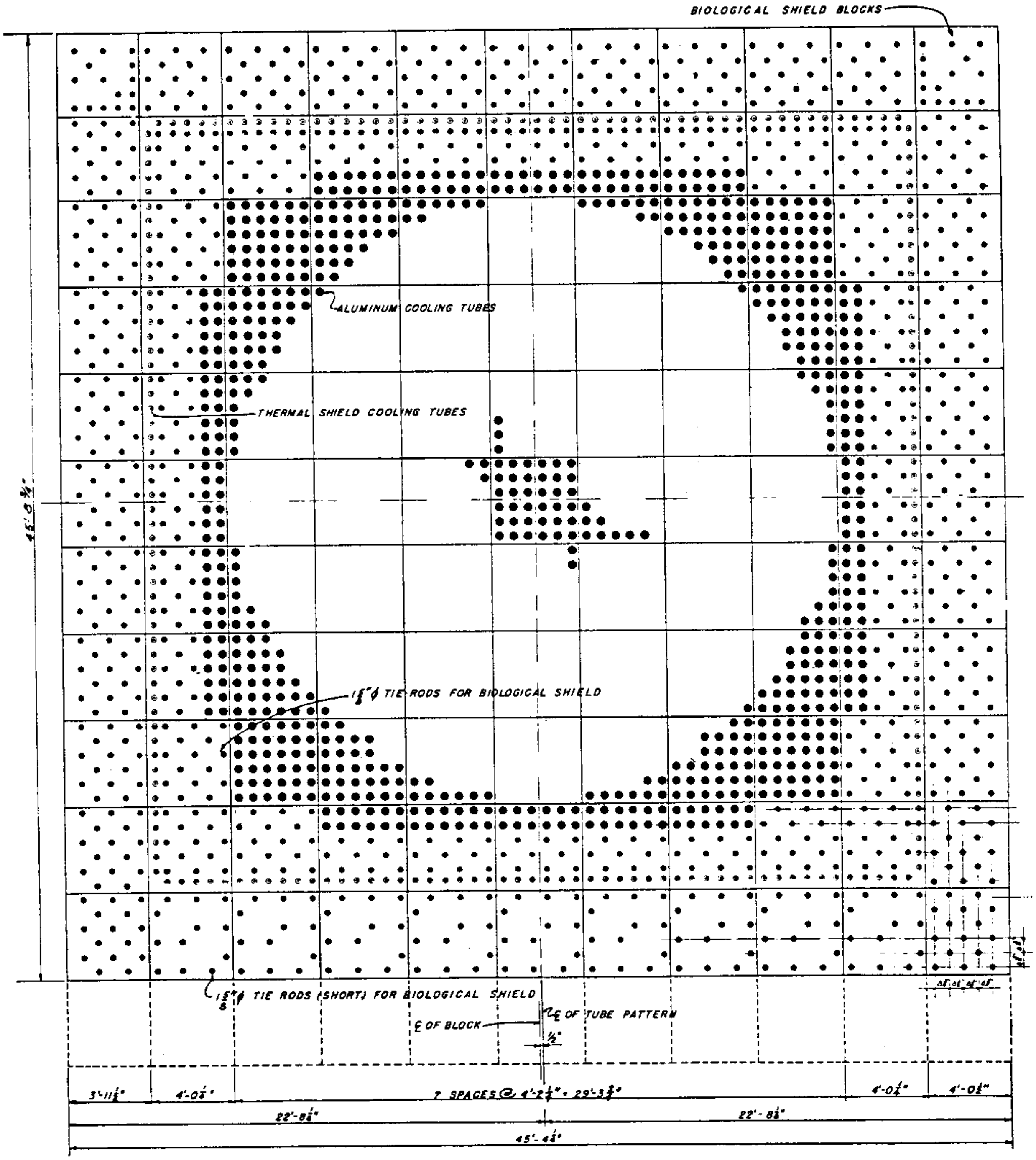

Figure 7: The 2,004 process tubes were spaced 8.375 in. on center and arranged in a somewhat circular fashion when viewed from the front or rear face.

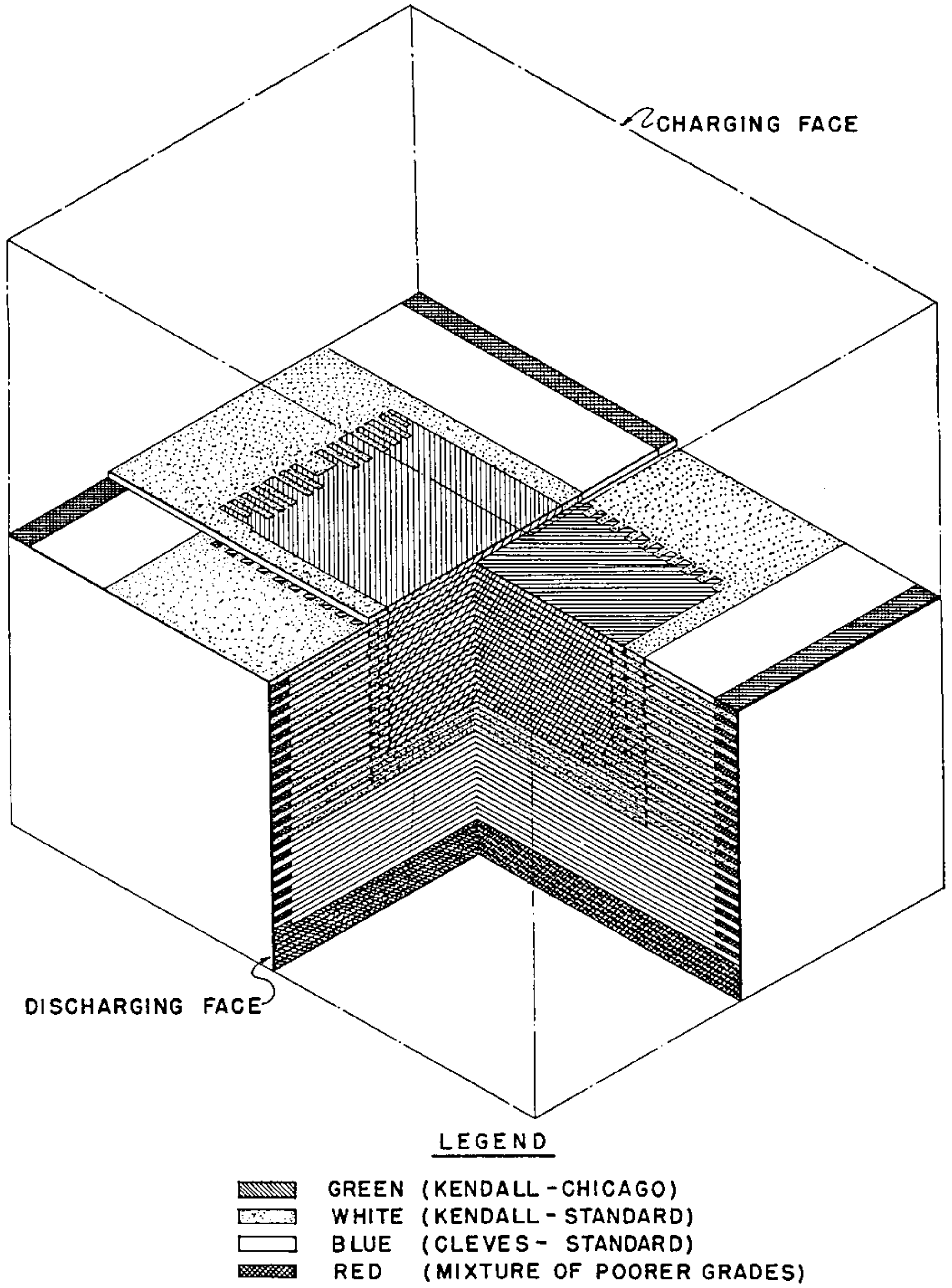

Figure 8: The highest quality graphite was used in the central portions of the pile.

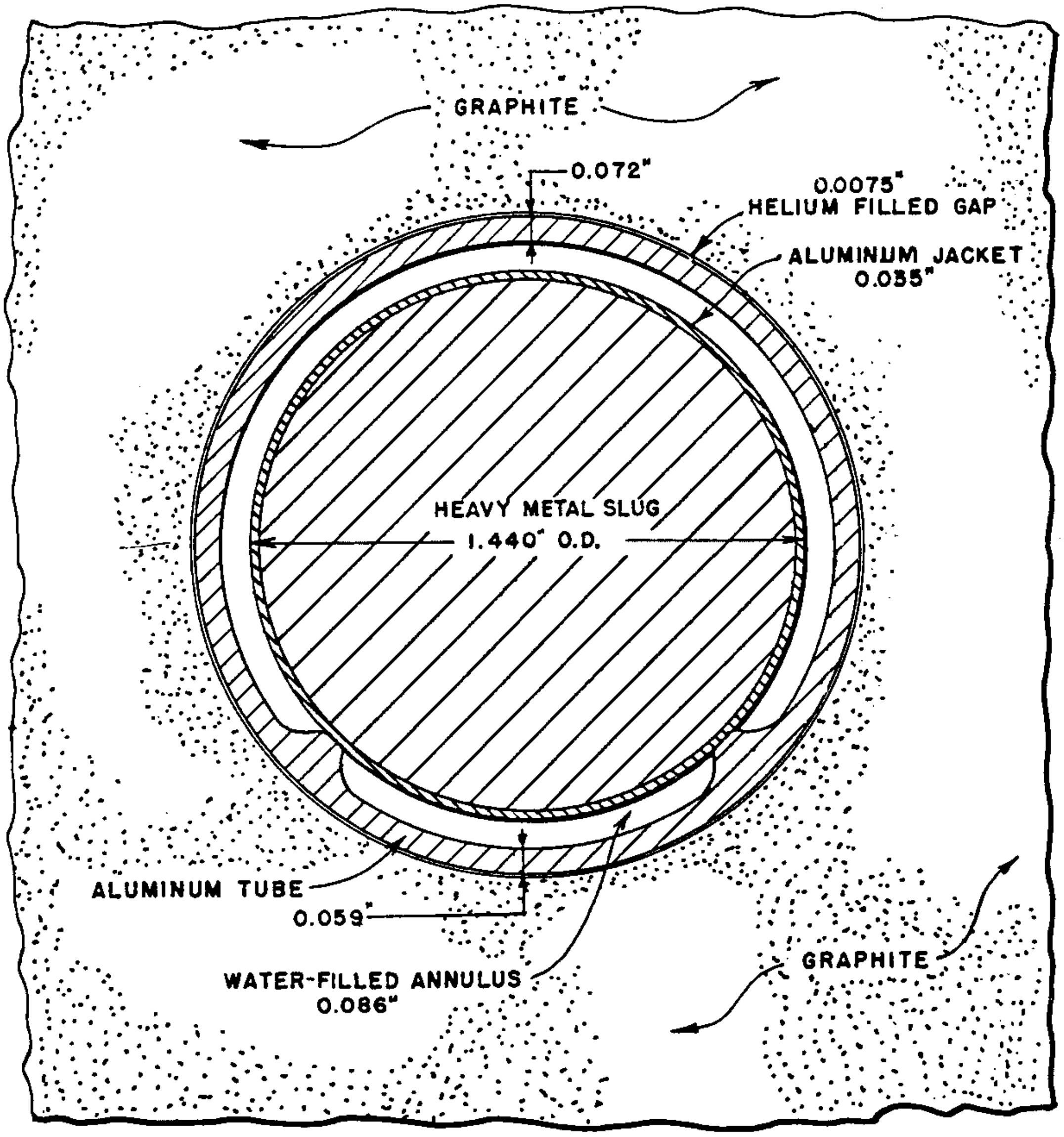

Figure 9: A cross section through a process tube showing the surrounding graphite, the tube, and a uranium slug.

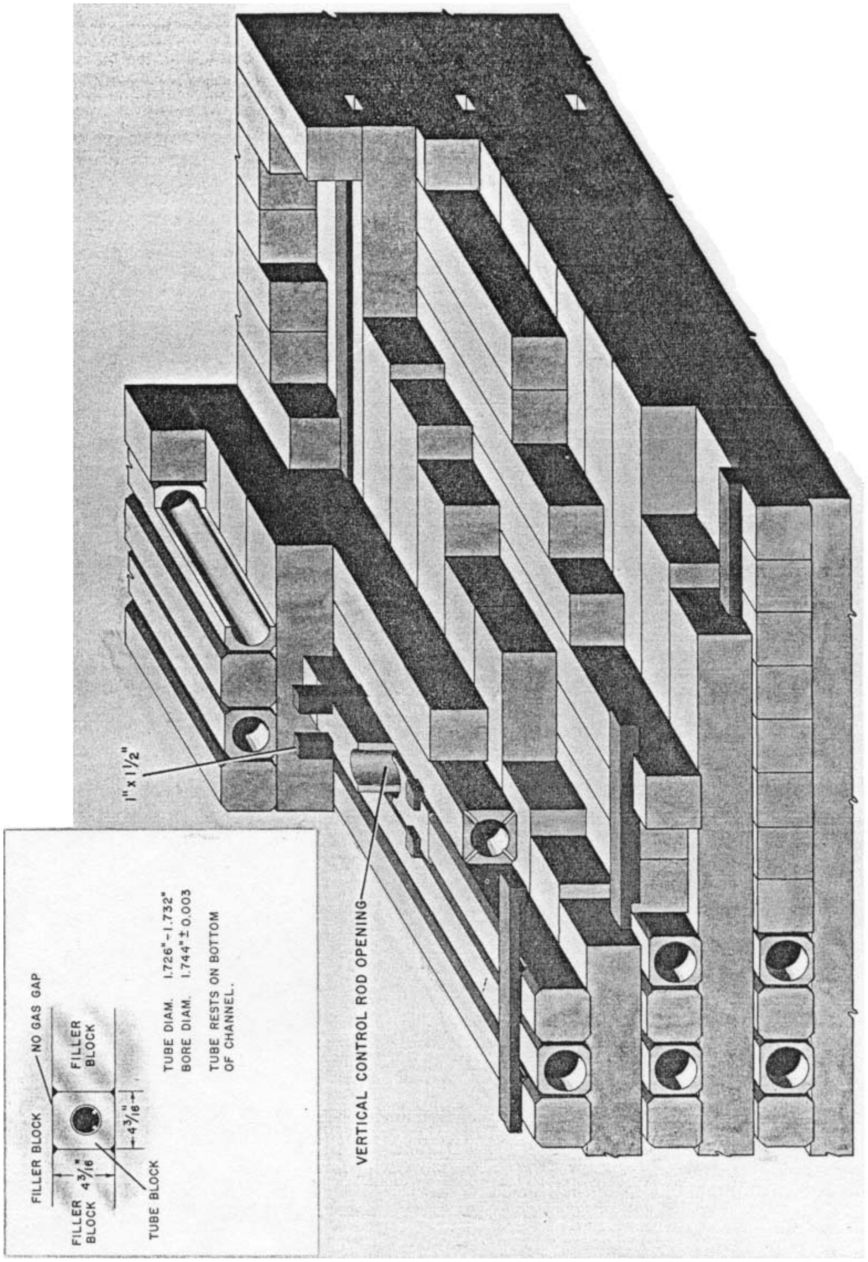

Figure 10: Graphite blocks were bored out for the process tubes and beveled to provide a passage for the pile's helium atmosphere. Graphite keys helped to bind the layers together.

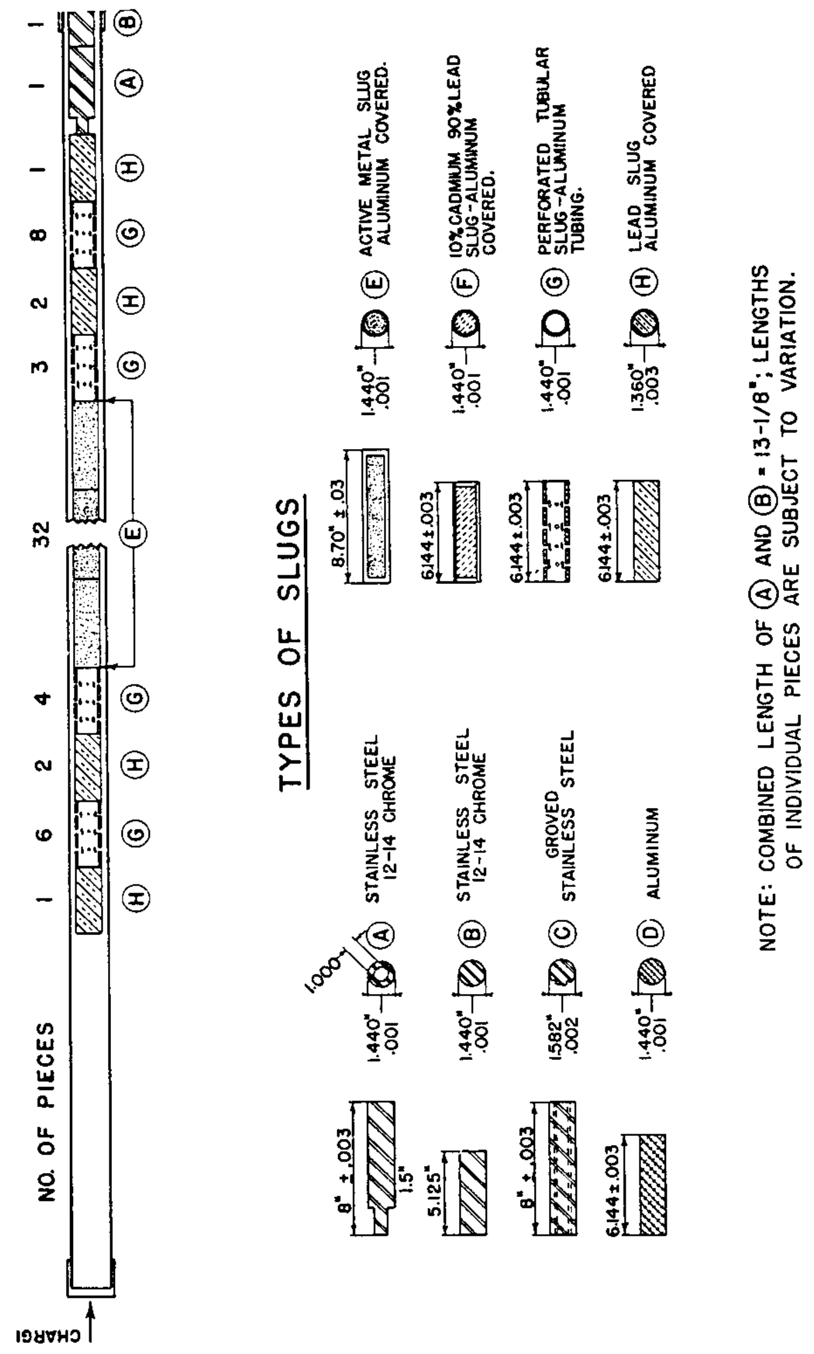

Figure 11: The arrangement of fuel and dummy slugs in a typical process tube.

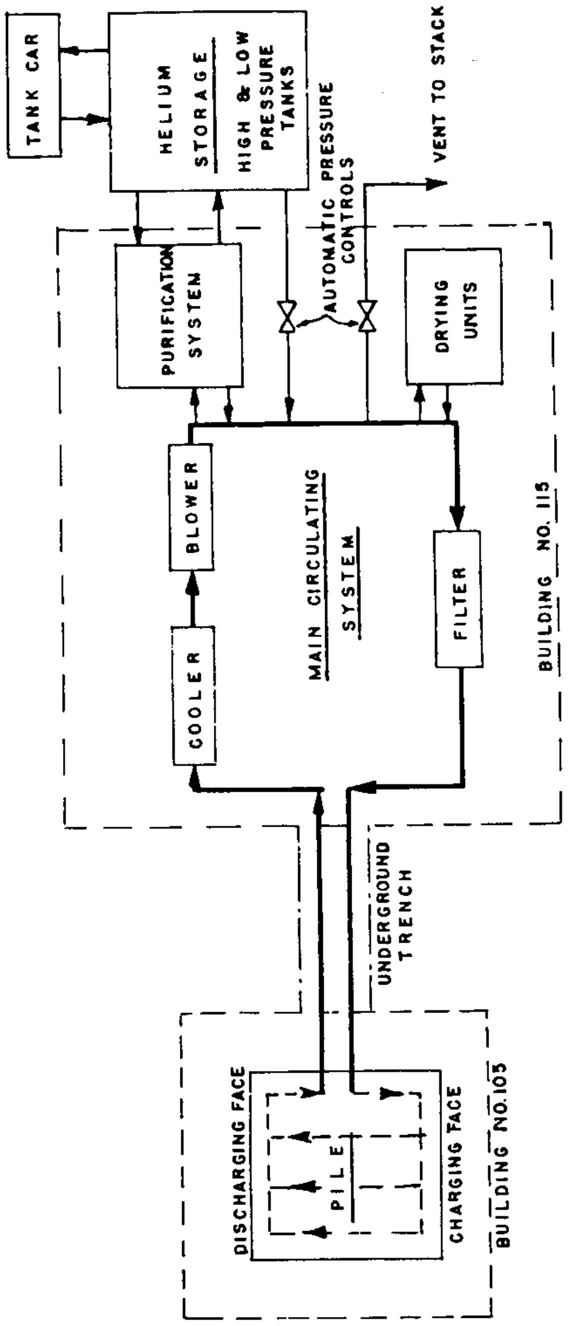

Figure 12: The helium atmosphere circulated from the 115-B building, through the pile, and back again, where it was purified and dried before returning to the pile.

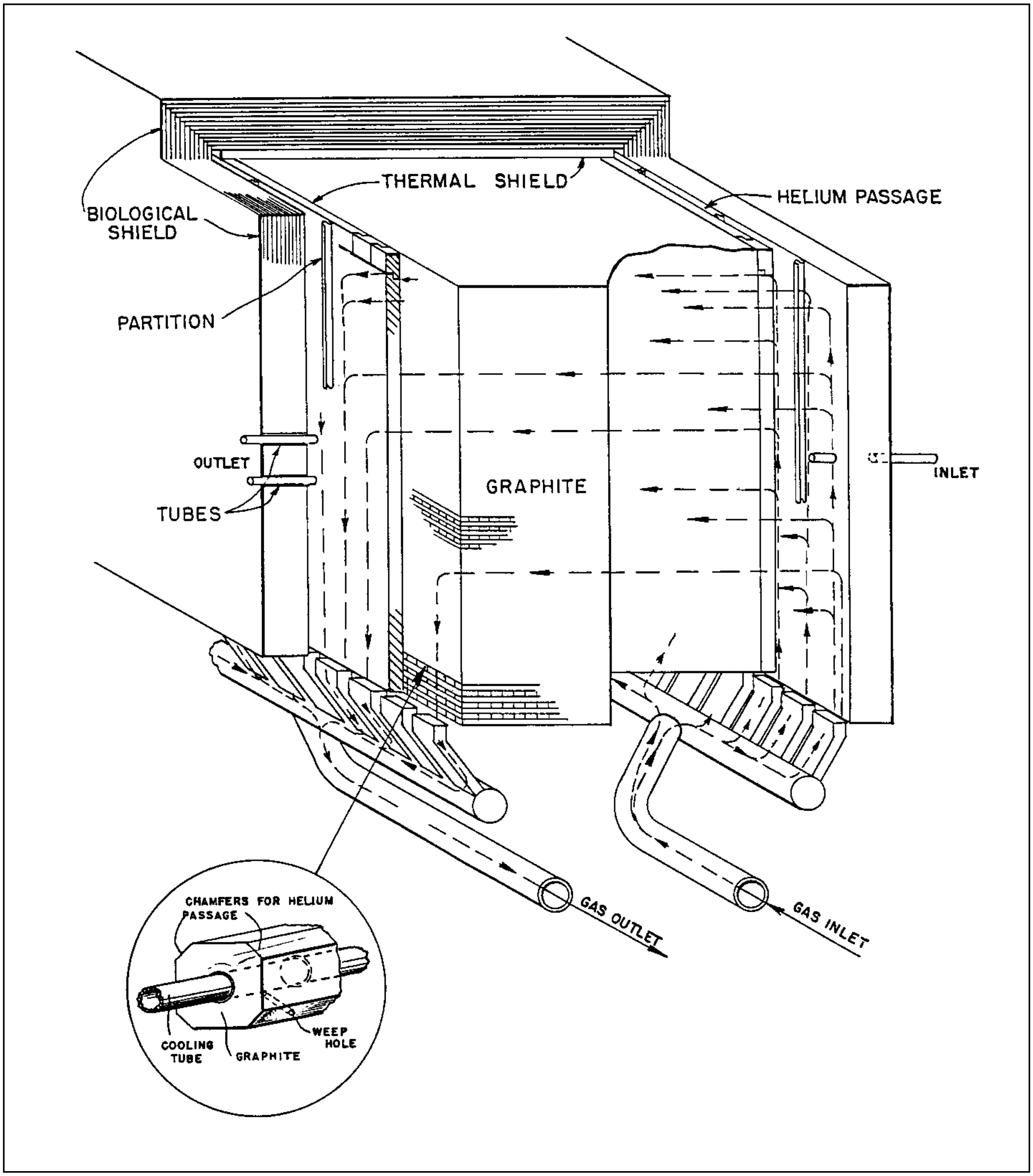

Figure 13: The helium circulation within the pile.

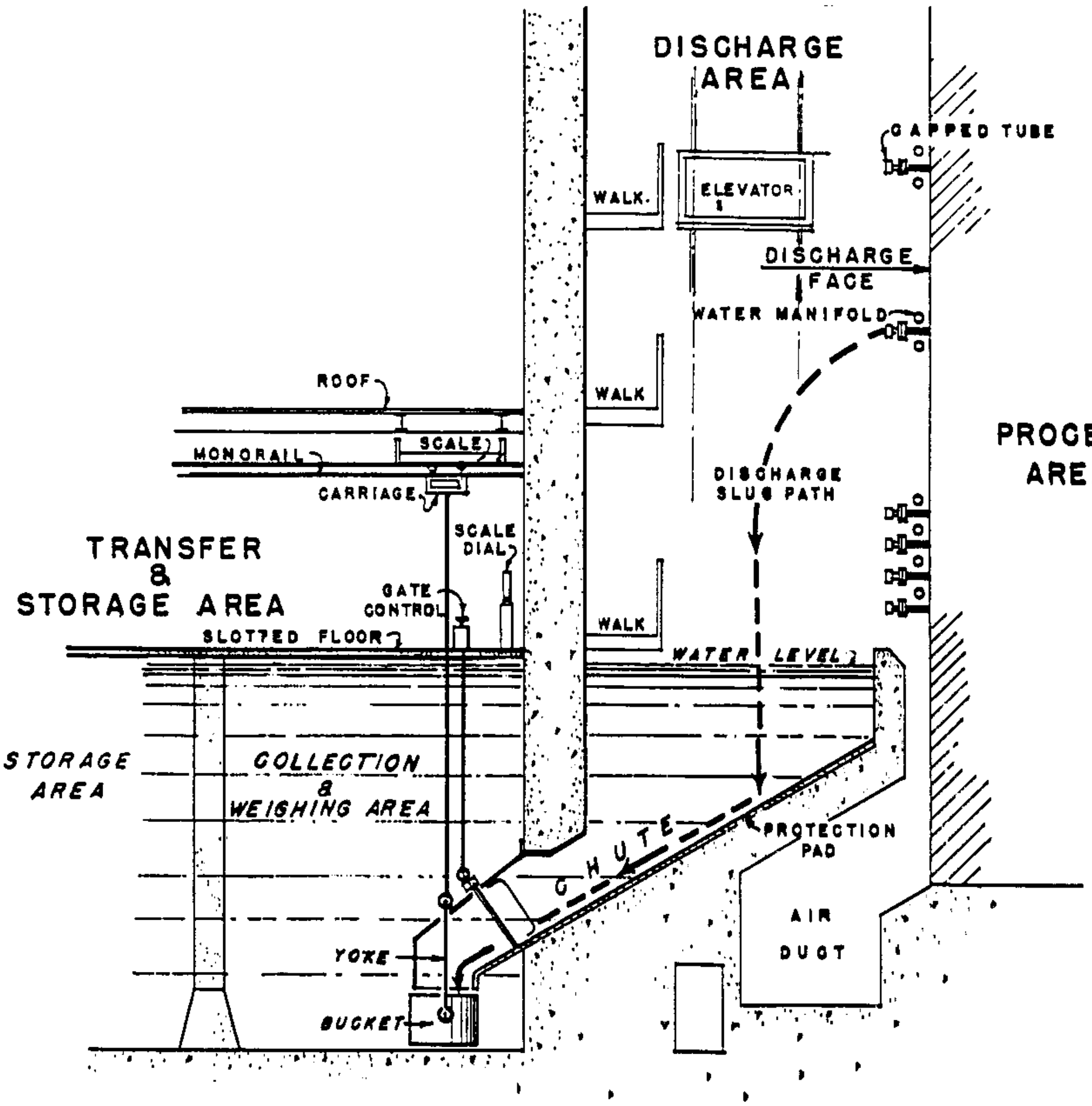

Figure 14: The discharged fuel slugs fell into the water-filled discharge chute, where they slid downward to the fuel storage area where they were loaded into buckets.

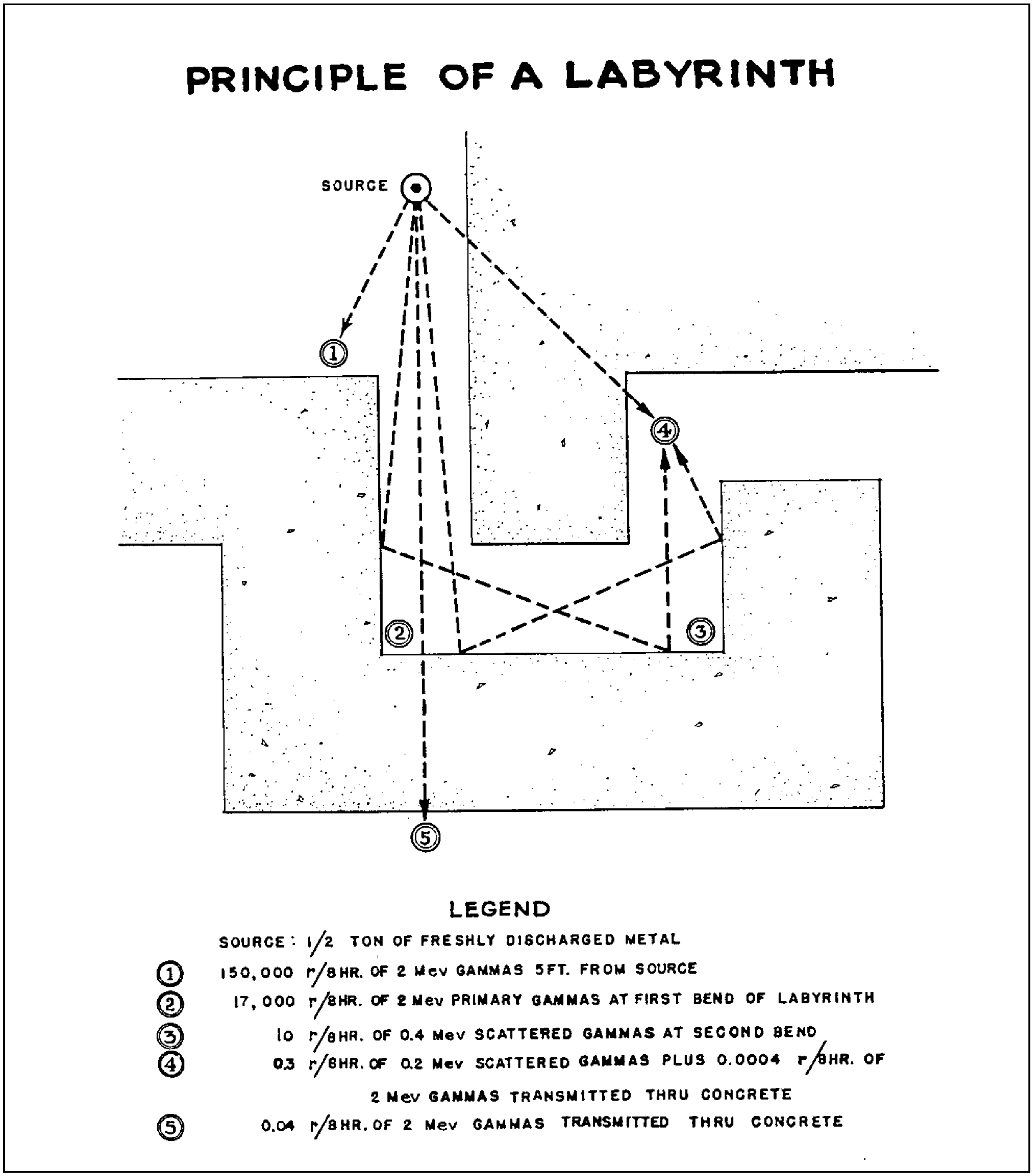

Figure 15: A labyrinth allowed access through a thick shielding wall without the need for an equally thick door.

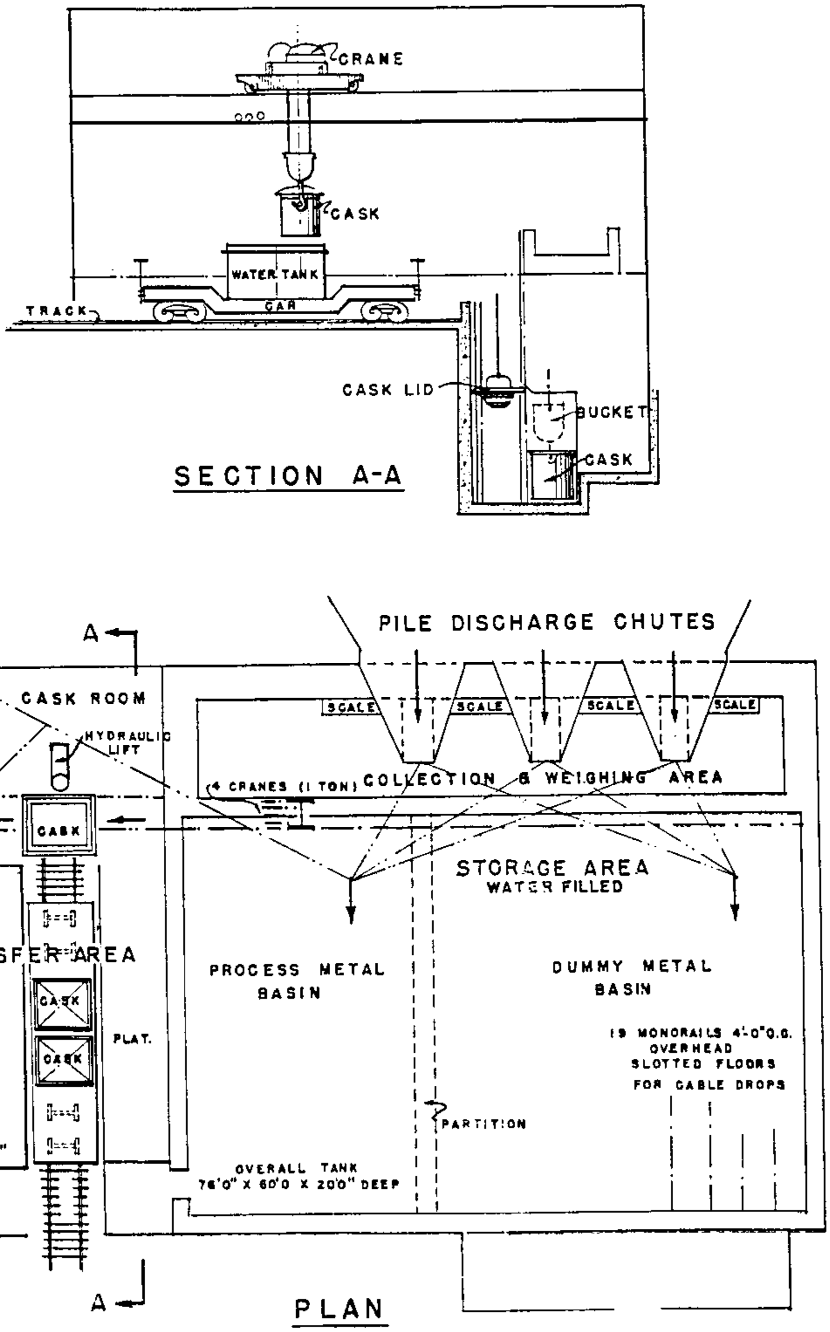

Figure 16: Irradiated fuel slugs arranged in numerous buckets were stored safely under 20 ft of water beneath the floor of the fuel storage area.

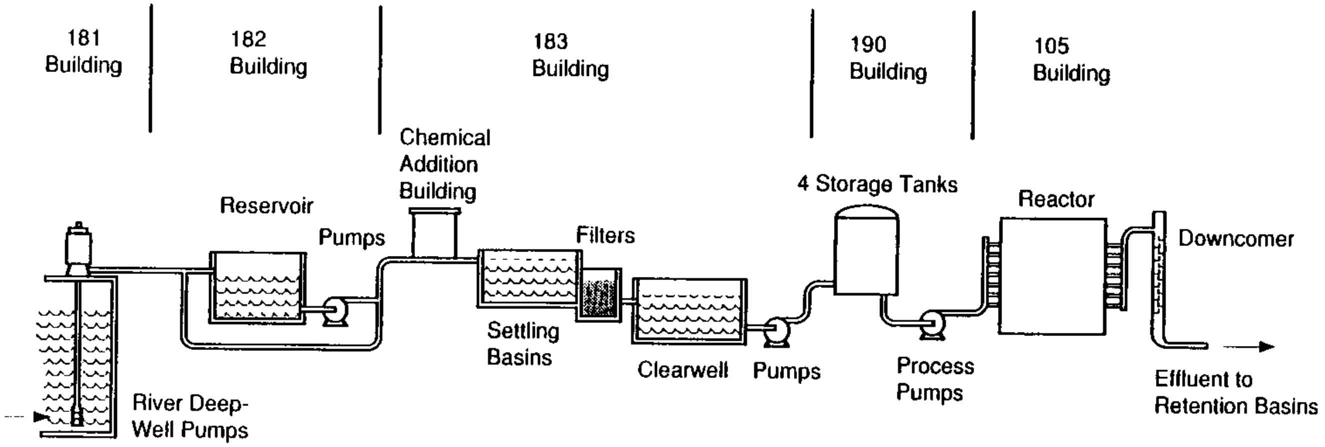

Figure 17: The water system in the 100-B Area.

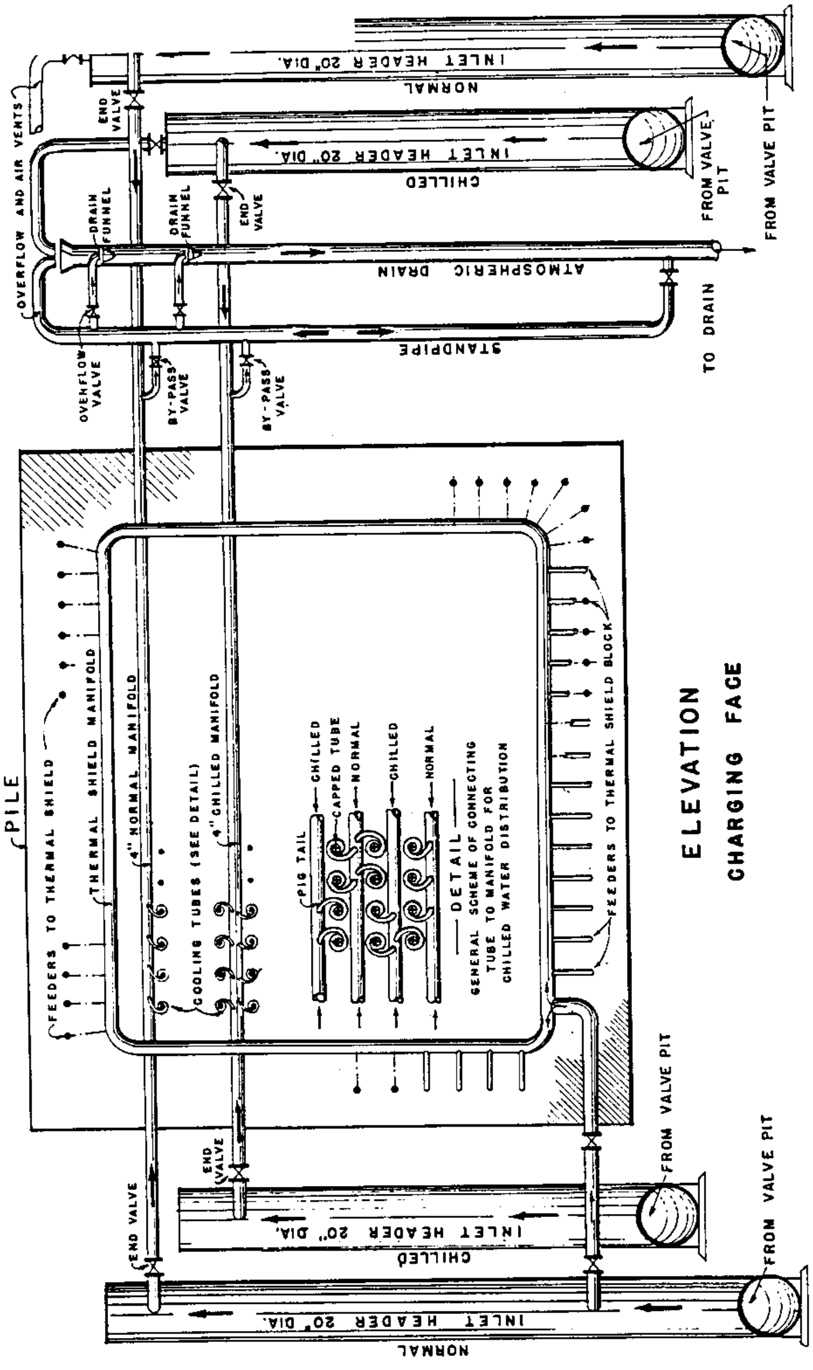

Figure 18: The influent water system at the front face of the pile.

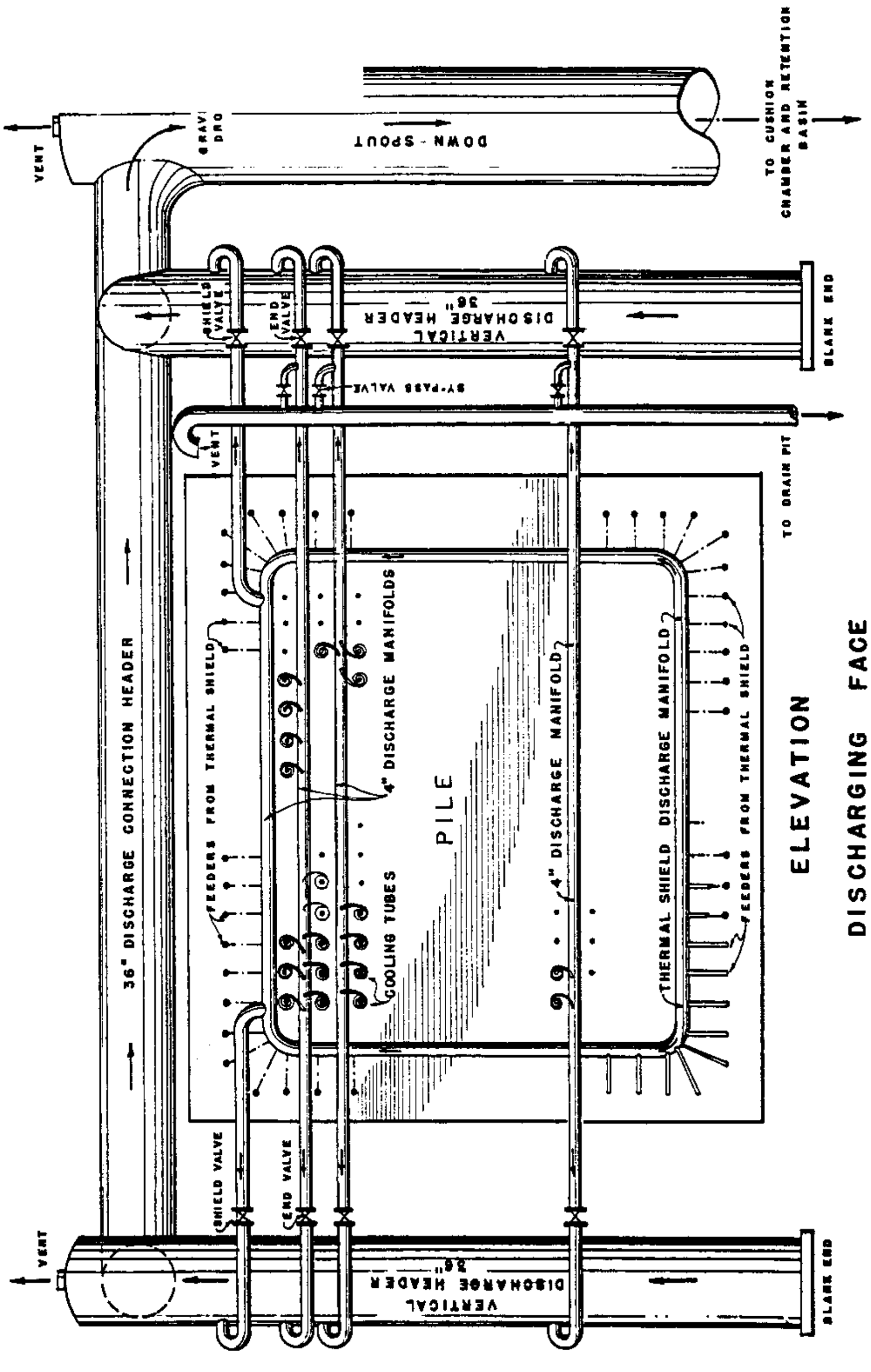

Figure 19: The effluent water system at the rear face of the pile.

7. Index to Figure 20, Main Control Panel

1) L&N recorder operated by Beckman micro-microammeter and neutron chamber under the pile, Beckman #2
2) L&N recorder operated by Beckman micro-microammeter and chamber monitoring water activity in the downcomer, Beckman #1
3) Multi-point L&N recorder operated by Beckman micro-microammeter and neutron chambers under the pile, Beckmans #3 and #4
4-5) Blank panels
6) Continuous single-point recorder recording position of regulating rod in use
6A) Toggle switch for selecting regulating rod to be recorded at item 6
7) Voltmeter and switch for measuring battery voltage in galvanometer system
8) Switches to by-pass first “out” limit switches on shim rods
9) Nine switches for cutting the nine Selsyns in and out of service
10) L&N circular chart recorder for differential power level indicator
11-19) Nine Selsyns indicating the position of 7 shim and 2 regulating rods. Regulating rods are 11 and 13; green light over each Selsyn shows when rod is all in; red light shows when rod is all out
20) Range switch for differential power level indicator
21) Shunt for level galvanometer
22) Duplicate Selsyn for #1 regulating rod
23) Ground glass scale for level galvanometer
24) Ground glass scale for deviation galvanometer
25) Twenty-eight drop annunciator
26) Duplicate Selsyn for #2 regulating rod
27) Shunt for deviation galvanometer
28) Indicating meter for Beckman #1
29) Indicating meter for Beckman #2
30) Indicating meter for differential power level indicator
31) Indicating meter for Beckman #3
32) Indicating meter for Beckman #4
33) Push button to drive in the 7 shim rods at high speed; can be locked down with key
34) Electric interval time
35) Electric clock with sweep second hand
36) Push button operating #1 safety circuit; can be locked down with key
37) Alarm lights for discharge water monitor
38) Indicating lights for doors into discharge area at 0, 10, 20, and 30 foot levels
39) Switch to select regulating rod to be operated
40) Duplicate of 39 for other control rod; interlocked so only one rod at a time can be operated
41) Switch for high speed, low speed selection of one regulating rod
42) Switch for direction selection of one regulating rod
43) Switch for high speed, low speed selection of other regulating rod
44) Switch for direction selection of other regulating rod
45) Switch to move a shim rod in either direction; green light above switch indicates if pump controlled by this switch is in operation
46) Ten-point selector switch for selecting which of the 7 shim rods is to be moved
47) Duplicate of item 45 for second hydraulic pump
48) Green lights show when accumulator levels are above normal operating height
49) Amber lights show when the accumulator levels are just below normal operating height
50) Red lights show when levels have dropped to a point where the “low” annunciator flags drop

51) Five indicator lights show green when safety rod power, shim rod power, #1 regulating rod power, #2 regulating rod power, and instrument power are on
52) Keys for locking power off on the above 5 systems
53-55) Fifteen key by-pass switches for by-passing various safety circuits as necessary during repairs and maintenance
56) Control for withdrawing or lowering safety rods individually or in groups, depending upon setting of individual rod controls
57) Controls for tripping 29 safety rods individually; green light above each control indicates when rod is in, and red light shows when rod is out
58-59) Switches to turn on shim rod oil pumps
60) Selector switch to put “A” hole neutron chamber on either #2 Beckman or the galvanometer
61) Switch to operate both shim rod pumps simultaneously to drive rods at twice normal speed
62) Reset button for alarm lights for item 37

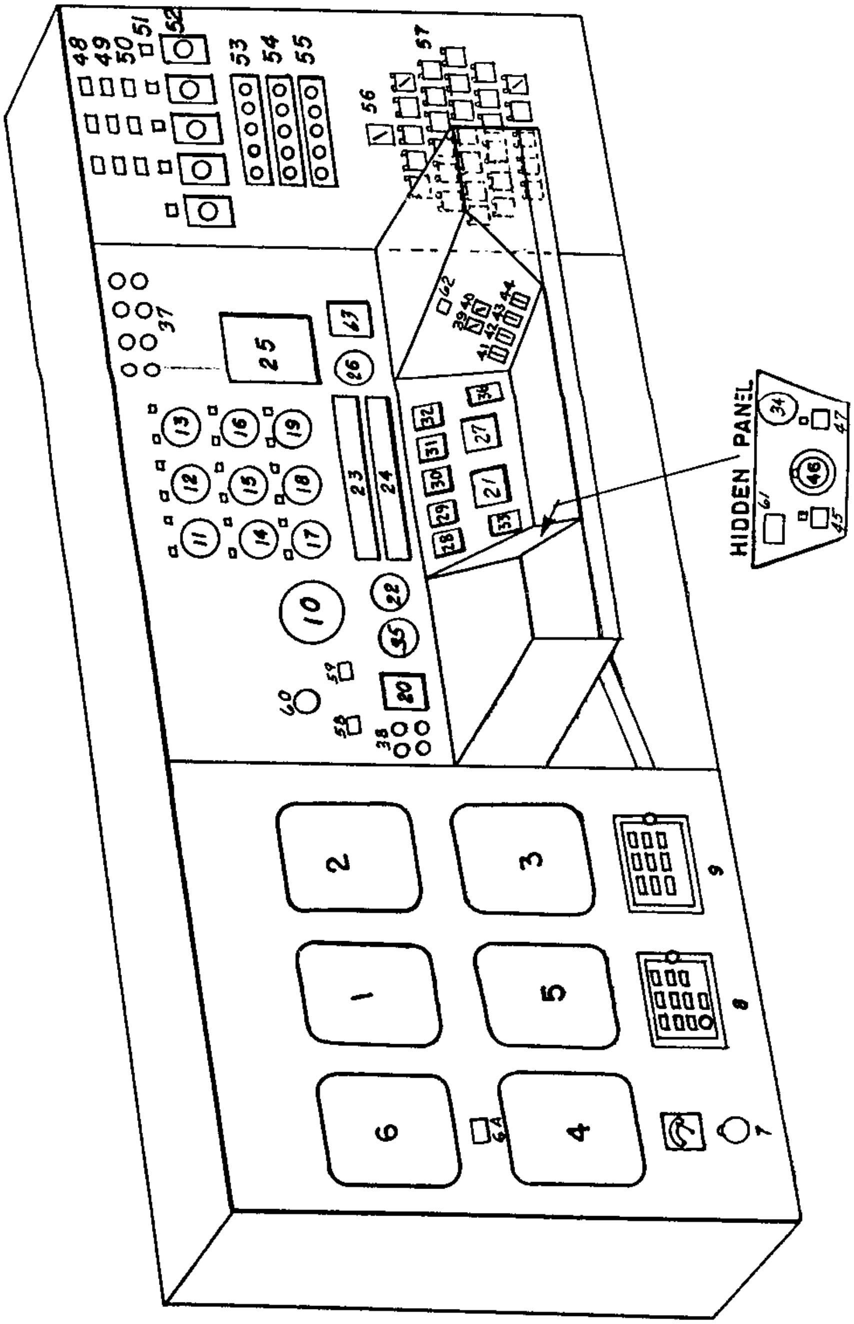

Figure 20: An operator regulated the pile and monitored for problems while seated at the main control panel. (See the Index on the previous two pages.)

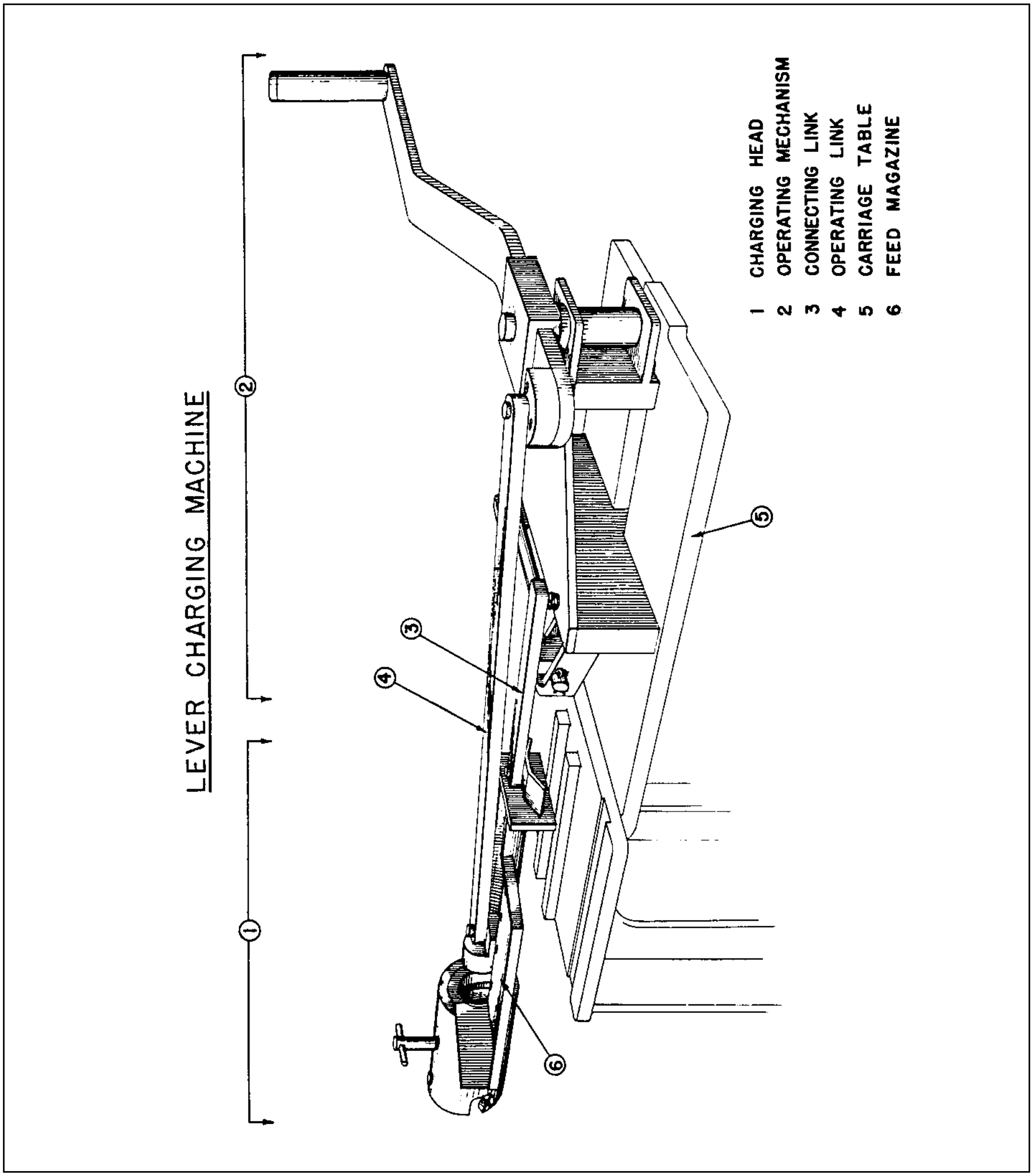

Figure 21: The lever-action charging machine proved to be more efficient than the original equipment, and provided a more uniform force on the slugs.

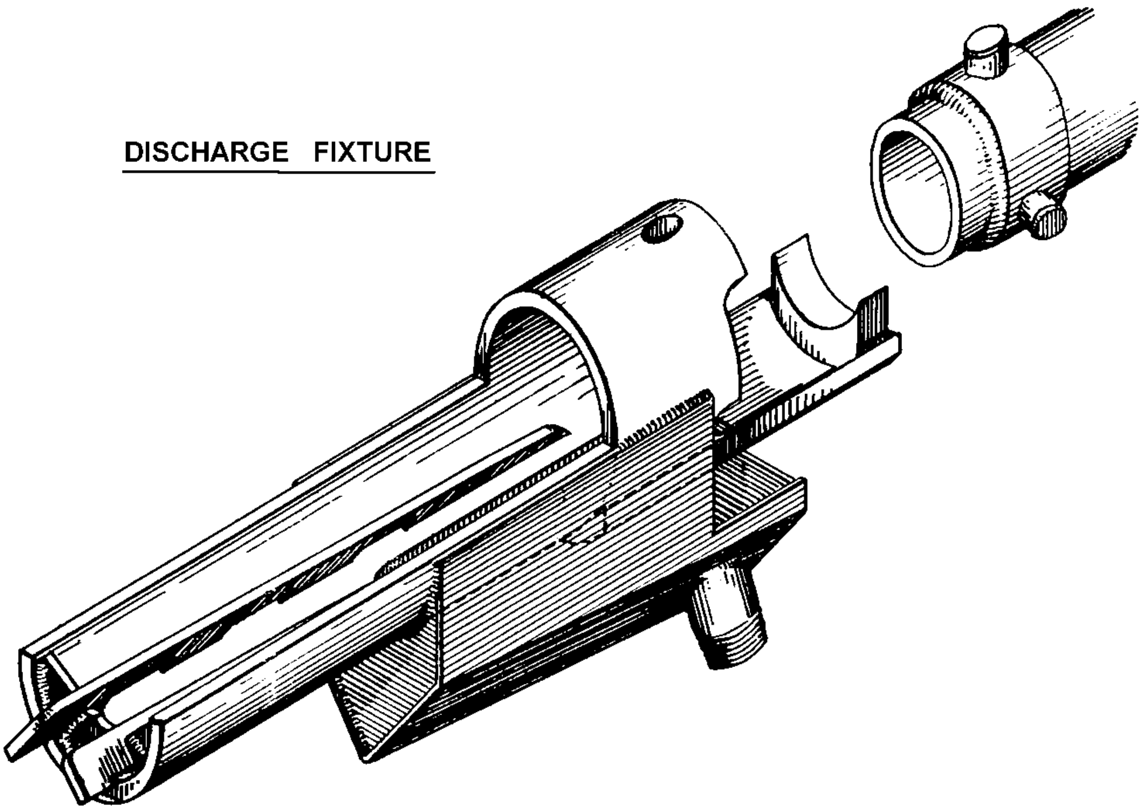

Figure 22: The discharge fixture for the free-fall method of fuel discharging.

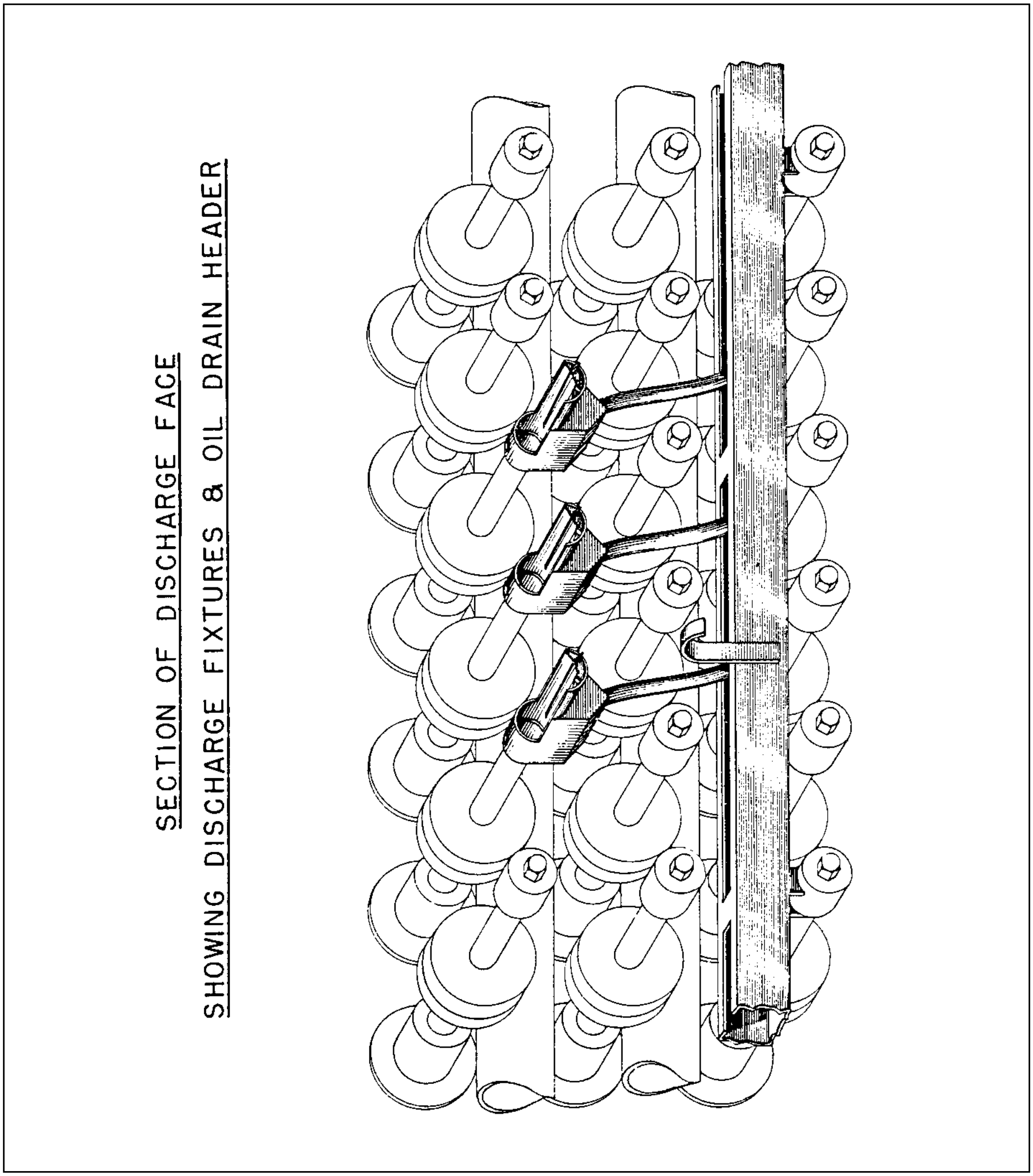

Figure 23: The oil drain trough carried away the oil and water lubricant, which would have clouded the basin water and become a source of radiation contamination.

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Wahlen, R.K., “History of 100-B Area,” WHC-EP-0273, 1989.

Additional Reading

For a truly remarkable telling of the story of the atomic bomb, read Richard Rhodes’s *The Making of the Atomic Bomb* (Simon & Schuster, New York, 1986). A wealth of first-hand information can be found in Leslie Groves’ *Now it can be told: the story of the Manhattan Project* (Harper, New York, 1962).

For an account of the after-effects of the Hiroshima bomb, read John Hershey’s *Hiroshima*, first printed in the August 31, 1946, issue of *The New Yorker* magazine and since published in book form (A.A. Knopf, New York, 1985). For a first-hand account of the Nagasaki bombing and aftermath, read Takashi Nagai’s *The Bells of Nagasaki* (Kodansha International, Tokyo: distributed through Harper & Row, New York, 1984) and *We of Nagasaki* (Duell, Sloan and Pearce, New York, 1951)

For more on Hanford during and since World War II, read *Working on the bomb: an oral history of WW II Hanford*, by S.L. Sanger (Continuing Education Press, Portland State University, Portland OR, 1995), and *On the home front: the Cold War legacy of the Hanford nuclear site*, by Michele Stenehjem Gerber (University of Nebraska Press, Lincoln, 1992).

HISTORIC AMERICAN ENGINEERING RECORD

INDEX TO PHOTOGRAPHS

B Reactor
Area 100-B
Hanford Site
Richland Vicinity
Benton County
Washington

HAER No. WA-164

Photographs by unknown photographers; unless otherwise specified, photographs date from early 1944 through 1945. They are listed in the order they are referenced in the text. Following each photograph's caption is a letter-number code that identifies the photograph in the Department of Energy's archives. The 4 in. x 5 in. photographs were printed from 4 in. x 5 in. negatives.

Several diagrams are included as 8 in. x 10 in. photographs. The originals were 11 in. x 17 in. pages in the Hanford Technical Manual that is referenced in this document (HTM 1945). The diagrams were photographed onto 4 in. x 5 in. negatives.

WA-164-1	Aerial view of the 100-B Area in January 1945, looking toward the northwest. This is one of the first photographs released to the public in 1945, and is perhaps the most often used photograph of 100-B. [P-8015]
WA-164-2	One of the guard towers (building 1605-B) in the 100-B Area in January 1944, typical of those permitting surveillance of perimeter fences. [P-1176]
WA-164-3	The 105-B Reactor Building under construction with the exterior nearly completed except for the tall ventilation stack. [P-1994]
WA-164-4	A diagram of the floor plan of B Reactor's main floor. [HTM 1945: 424]
WA-164-5	A cross section of the pile's foundation, base plate, B blocks, and thermal shield blocks. [HTM 1945: 422]
WA-164-6	Workers laying up the graphite core of the 105-B pile. In the lower-left can be seen a portion of the rear face of the pile, the top of its shielding wall, and the gun barrels protruding through it. The inside of the front face of the pile and its gun barrels can be seen toward the upper-right side. The angled top of the front shielding wall can be seen in the picture. All four walls were "stepped" in this manner where they joined with another wall or the ceiling to form a "labyrinth" joint, so that radiation would not have a straight route through any gaps in the joints. [D-3045]

WA-164-7	Another picture of workers laying up the graphite core of the 105-B pile. This view is towards the rear of the pile. The gun barrels can be seen protruding into the pile. [D-3047]
WA-164-8	An external view of the B Reactor's graphite pile. [HTM 1945: 405]
WA-164-9	A cutaway view of the graphite pile. [HTM 1945: 406]
WA-164-10	Each process tube ended with a water- and fuel-handling connection. [HTM 1945: 509]
WA-164-11	The work area of a typical fuel storage and transfer basin. The wooden floor was built over the 20-foot deep water-filled basin. Buckets filled with irradiated fuel or dummy slugs at the bottom of the basin were suspended from rods that passed through the slots in the floor and were hung on trolleys attached to the monorail tracks suspended from the ceiling. [85-H807]
WA-164-12	The 181-B River Pump House under construction in March 1944, with the 184-B Power Plant in the background. View is to the southeast. [P-1882]
WA-164-13	The River Pump House pump room, in this case in the 100-F Area in January 1945. In the 100 Area, the pumps supplied water to the 100 Area and to the export water system that ran to D and F reactors and the 200 areas. [D-8248]
WA-164-14	The 182-B Reservoir under construction in March 1944, showing the divider which was normally covered by water. View is to the northwest. [P-1877]
WA-164-15	The 183-B Filter Plant with settling basins in January 1945. The 182-B Reservoir and Pump House is on the left in the background, and the coal storage pond for the 184-B Power House is in the upper right. View is to the northwest. [P-8012]
WA-164-16	Contextual view of the 100-B Area, looking toward the northeast in December 1944. The River Pump House is in the distance on the river (left of center); the 184-B Power House stands with its two tall stacks, its Coal Storage Pond (to its left), and its 188-B Ash Disposal Basin (towards the river). Also seen are the 182-B Reservoir (foreground on the left), the 183-B Filter Plant (foreground right of center), and the 107-B Retention Basin (upper right near the river). [P-7835]
WA-164-17	The 190-B Process Pump House in January 1945, with the 185-B Deaerating Plant towers standing above the rear of the building. View is to the northwest. [P-8016]
WA-164-18	Aerial view of the 100-B Area under construction in Janaury 1944, viewed to the north. The 105-B Rector building can be seen to the right of center; the 190-B Process Pump House with its four large tanks is to the left of center; the 181-B River Pump House on the Columbia River is at the top-left side of the picture; and the 184-B Power House is just south of the River Pump House (note the shadows of its two tall stacks pointing northeast). [P-1186]

WA-164-19	Interior of the 190 Process Pump House, in this case in the 100-F Area in February 1945. Steam-driven pumps are on the left and electrically-driven pumps are on the right. [D-8440]
WA-164-20	The Valve Pit in the 105 Reactor building (F Reactor in this case), with chemical addition vats. [D-8307]
WA-164-21	View from the work area of the front face of the pile in the 105 building, in this case at the F Reactor in February 1945. The 2,004 pigtails and process tube nozzles are neatly aligned in rows and columns across the face of the pile. The cooling water risers stand at the left and right of the pile and the distribution crossheaders run across its face. The pipes running vertically at the bottom of the pile carry cooling water to the thermal shield. The low railing along the floor in front of the face prevented workers from accidentally falling into the charging elevator pit. [D-8320]
WA-164-22	A side-view of the rear face of a typical pile, in this case the F Reactor in February 1945. The low railing and walkway are part of the discharge elevator. Notice the vertical row of numbers on the right that identified the rows of process tubes. [D-8326]
WA-164-23	A typical 107 Retention Basin, in this case in the 100-F Area in February 1945. The Columbia River is in the background and the 184 Powerhouse is at the left. [P-8458]
WA-164-24	The 184-B Power House under construction, viewed to the northeast in March 1944. The sewer line exiting to the Columbia river was used mainly for effluents from back-washing the filter basins. A separate Process Sewer Line (out of the picture to the right) for cooling water leaving the pile went to the 107-B Retention Basin, and ultimately to the river. [P-1881]
WA-164-25	A typical control rod, showing the neutron-absorbing inner end and the rack-mounted outer end. [HTM 1945: 610]
WA-164-26	A typical outer rod room, or rack room, showing the racks for the nine horizontal control rods (HCRs) that would be inserted or withdrawn from the pile to control the rate of reaction. In this case, it is in the 105-F Reactor in February 1945. The view is looking away from the pile, which is out of the picture on the left. Several of the cooling water hose reels for the rods can be seen at the end of the racks near the wall. [D-8323]
WA-164-27	The top of a typical pile, F Reactor in February 1945 in this case, showing the vertical safety rods (VSRs) and the cables that support them. The rods could be dropped into the pile to effect a rapid shutdown. The four silver-colored drums on the left contained boron solution and are part of the last ditch safety system. Should the VSRs channels become blocked by an occurrence such as an earthquake, the solution could be dumped into the VSR channels to help shut down the reactor. [D-8334]

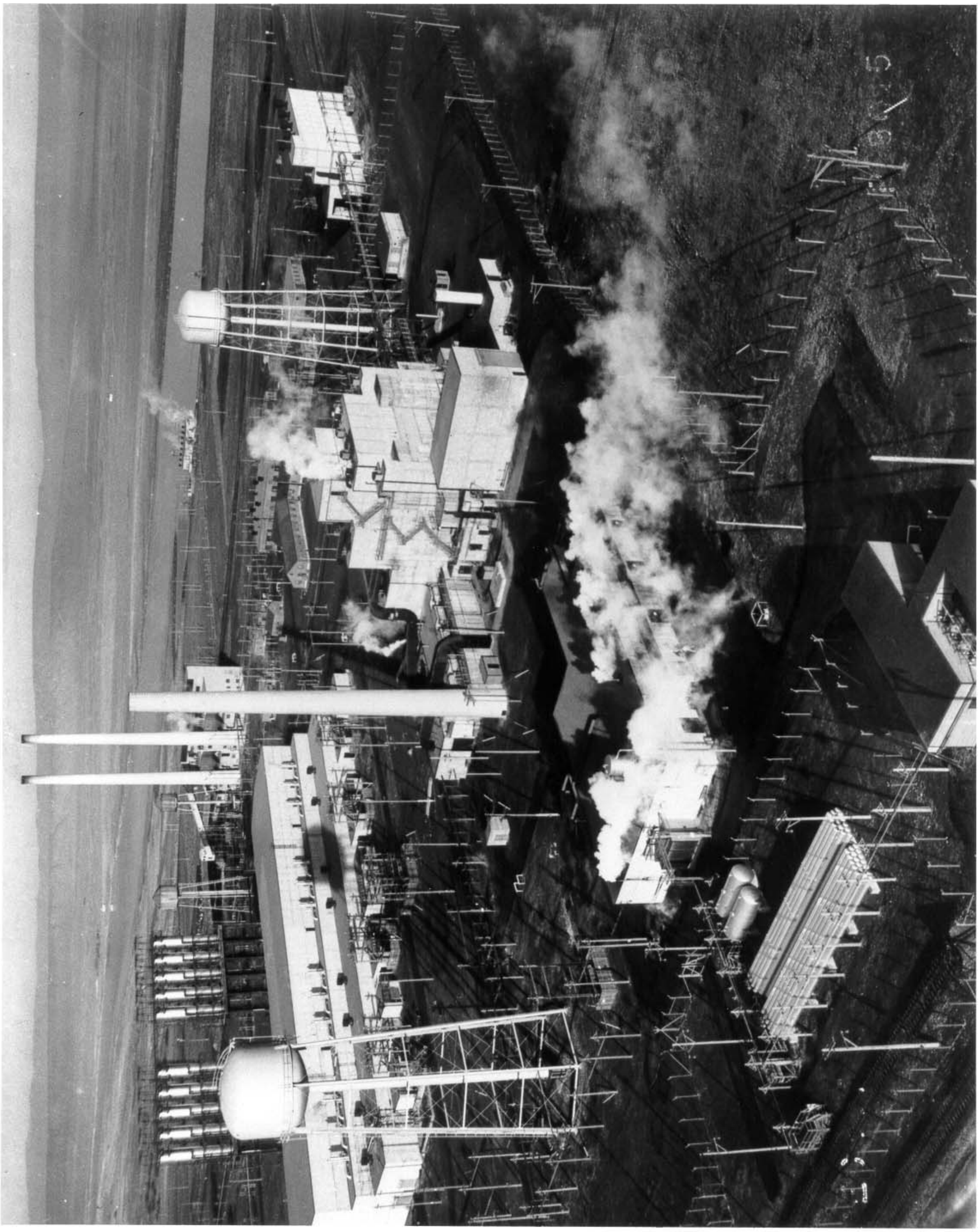
WA-164-28	A typical main control panel in a 105 reactor building, in this case 105-F in February 1945. A single operator sat at the controls to regulate the pile's rate of reaction and monitor it for safety. The galvanometer screens (the two horizontal bars just below the nine round gauges that showed the positions of the control rods) showed the pile's current power setting. With that information, the operator could set the control rod positions to increase, decrease, or maintain the power. [D-8310]
WA-164-29	An early picture of the Panellit gauges in the control room of a typical 105 reactor building, in this case 105-F in February 1945. There was one gauge for each of the pile's 2,004 process tubes. Each gauge monitored the tube's water pressure to ensure adequate cooling. Notice the wooden ladder, which operators could use when reading or adjusting the gauges. In later years, a large sign was installed across the top of the wall of gauges that read "Caution: Bumping This Panel Can Scram The Reactor." [D-8311]
WA-164-30	Miscellaneous gauges and recorders on the wall opposite the Panellit gauges in a typical control room, 105-F Reactor in this case in February 1945. The temperature recorder for the 2,004 process tubes is at the far right side. [D-8308]
WA-164-31	The 1701-B Main Gate House in March 1944, viewed to the northwest. Its clock alley provided controlled access to the 100-B Area. The second floor was used to read radiation-detecting pencil dosimeters and to replace radiation-detecting film badges worn by employees. [P-2006]
WA-164-32	The 1704-B Supervisor's Office and Laboratory building, which also contained the classified materials vault. This type of wooden construction was typical in the 100-B Area. Viewed from the northwest in September 1944. [P-4445]

All of the above photographs were reproduced from negatives stored at the Hanford Site Records Holding Area in the 712 Building, Federal Building complex, in Richland, WA.

The next three photographs, WA-164-33 through WA-164-35, were taken by Yosuke Yamahata, a Japanese military photographer who walked through the devastated city of Nagasaki with his camera the day after the bombing. On foot, Yamahata twice passed through the hypocenter of the atomic bomb explosion. Permission to include these photographs was generously granted by the photographer's son, Mr. Shogo Yamahata:

Nagasaki, August 10, 1945, by Yosuke Yamahata;
copyright Shogo Yamahata, courtesy IDG Films,
digital restoration by Unison.

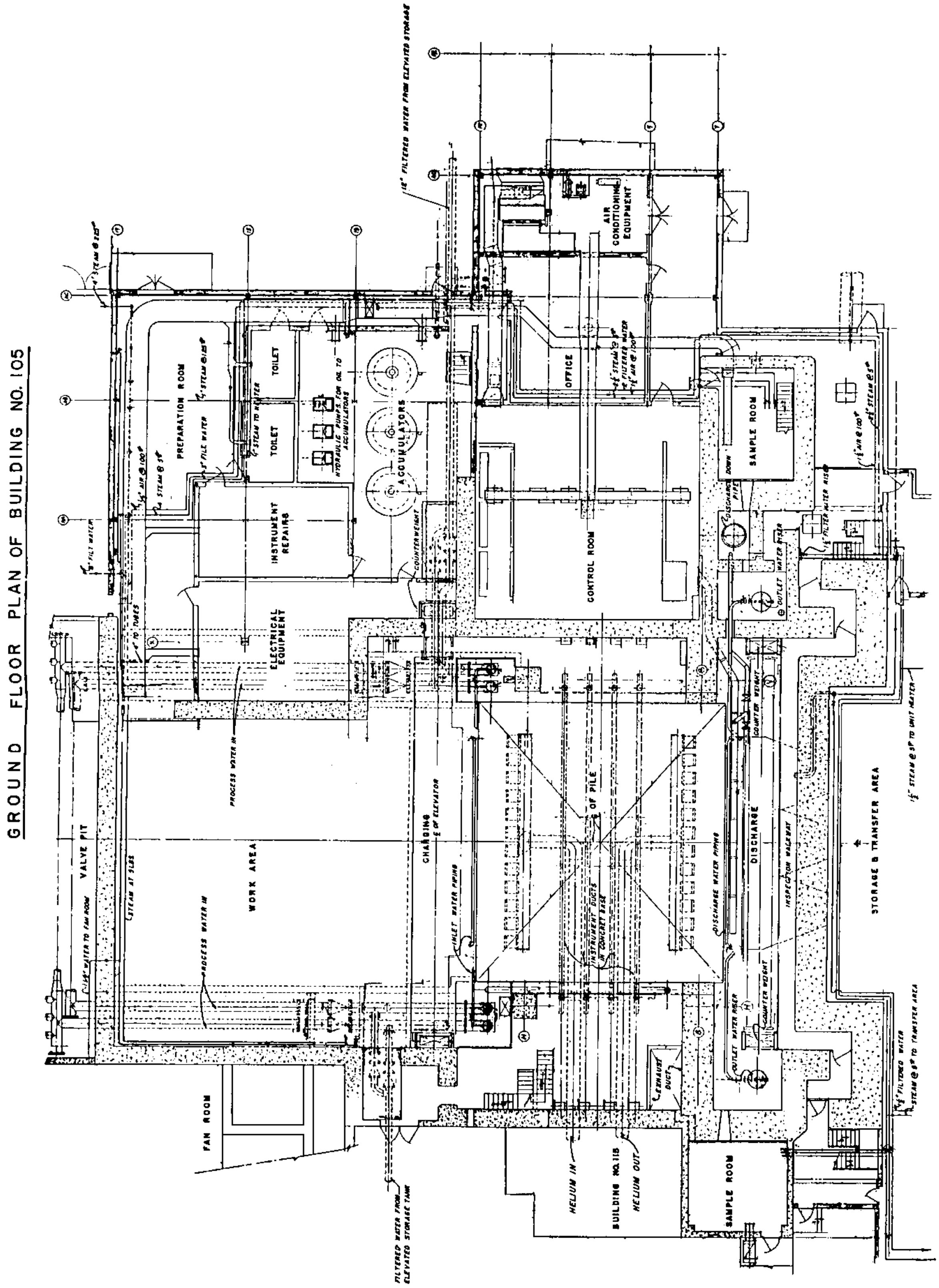
WA-164-33	This photograph and the next (WA-164-34) form a panorama that was made from three adjacent 35 mm frames. The view is looking south across residential neighborhoods toward the center of Nagasaki, with the smokestacks of the Mitsubishi armaments factory still standing at the far right in the distance. The twisted metal framework close in at the right is the remains of a baseball field grandstand.
WA-164-34	The right side of the panorama formed with photograph WA-164-33.
WA-164-35	This photograph was taken from the pathway winding through the panorama (WA-164-33 and WA-164-34), which was formerly the main street of Nagasaki. Few burned bodies were generally visible in the aftermath, because many of the dead had been completely reduced to dust and ash by the heat of the fireball. The overhead crosspieces mark the tracks of the Nagasaki trolley system. The smokestacks of the Mitsubishi armaments factory can again be seen standing in the distance, somewhat closer than in the panorama.



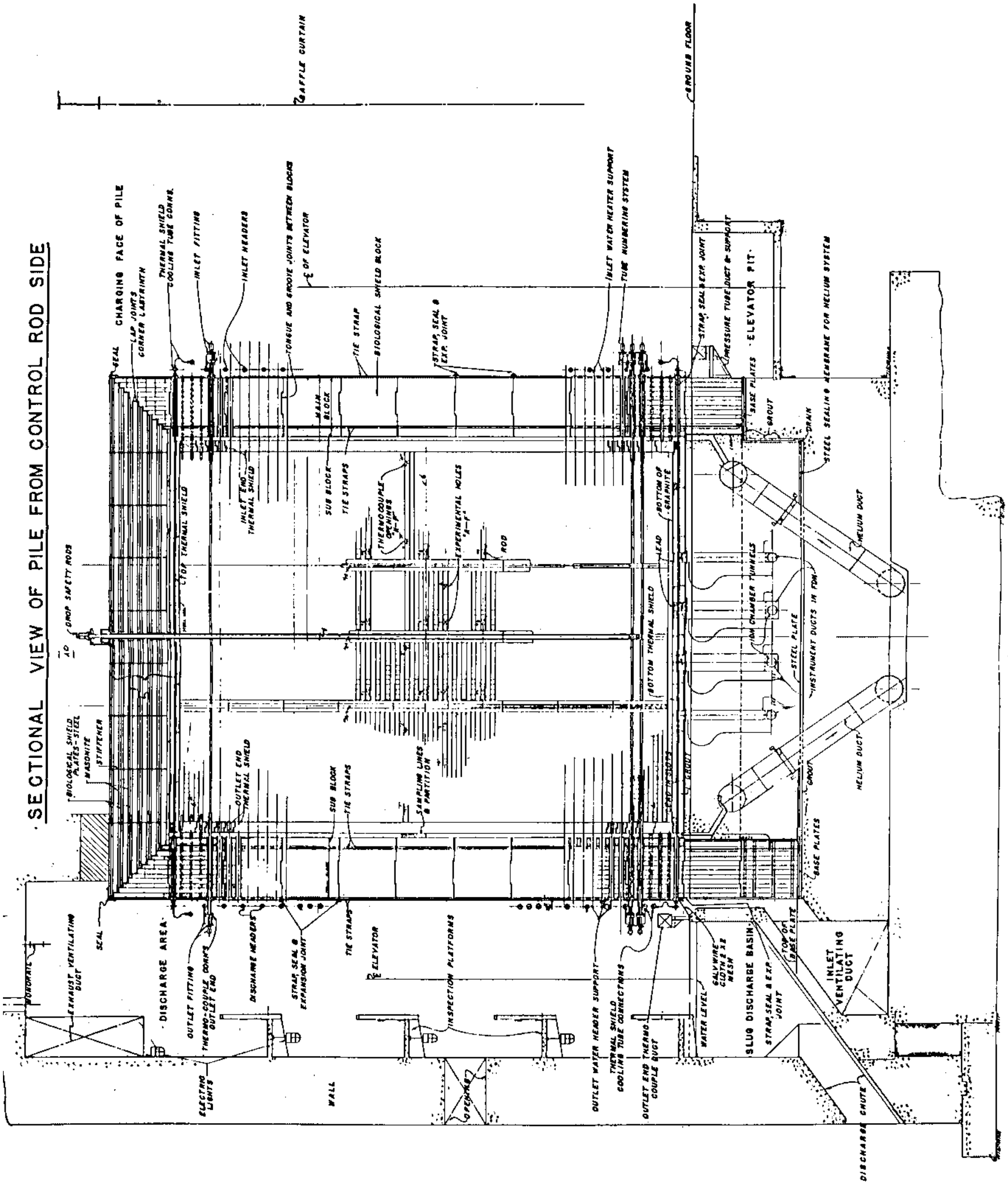
Photograph 1: Aerial view of the 100-B Area in January 1945, looking toward the northwest. This is one of the first photographs released to the public in 1945, and is perhaps the most often used photograph of 100-B. [P-8015]

Photograph 2: One of the guard towers (building 1605-B) in the 100-B Area in January 1944, typical of those permitting surveillance of perimeter fences. [P-1176]

Photograph 3: The 105-B Reactor building under construction, with the exterior nearly completed except for the tall ventilation stack. [P-1994]



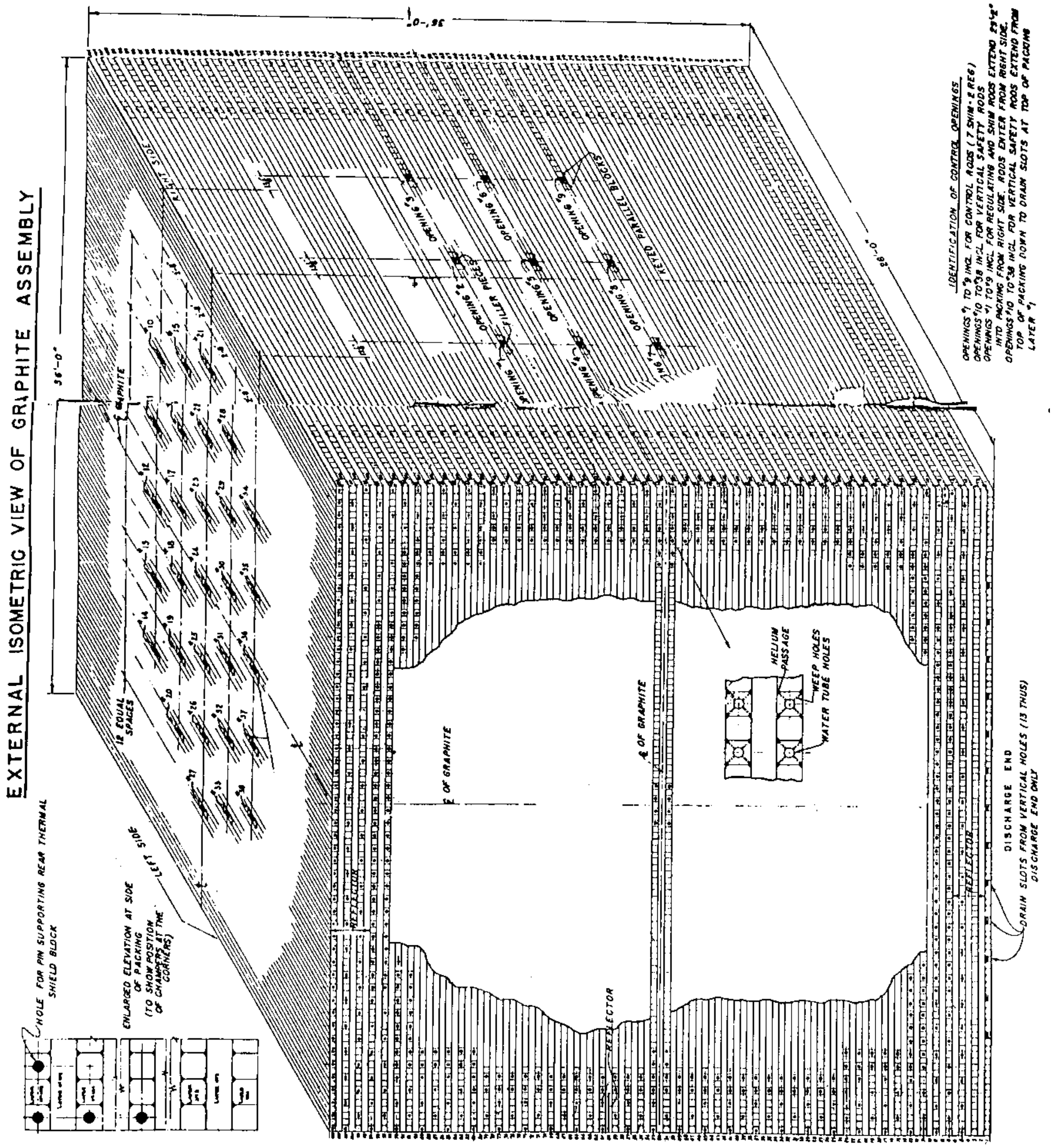
Photograph 4: A diagram of the floor plan of B Reactor's main floor. [HTM 1945: 424]



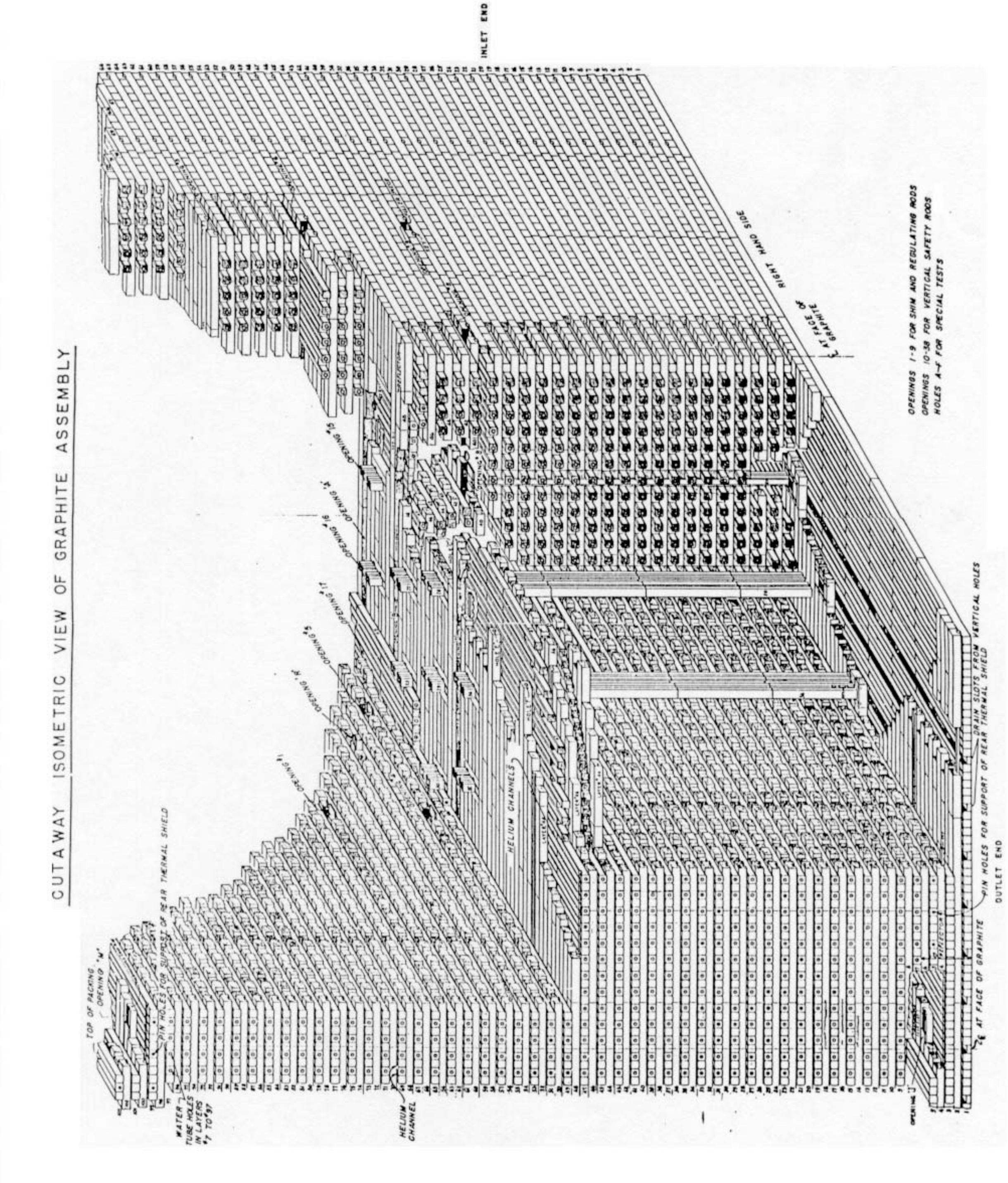
Photograph 5: A cross section of the pile's foundation, base plate, B blocks, and thermal shield blocks. [HTM 1945: 422]

Photograph 6: Workers laying up the graphite core of the 105-B pile. In the lower-left can be seen a portion of the rear face of the pile, the top of its shielding wall, and the gun barrels protruding through it. The inside of the front face of the pile and its gun barrels can be seen toward the upper-right side. The angled top of the front shielding wall can be seen in the picture. All four walls were “stepped” in this manner where they joined with another wall or the ceiling to form a “labyrinth” joint, so that radiation would not have a straight route through any gaps in the joints. [D-3045]

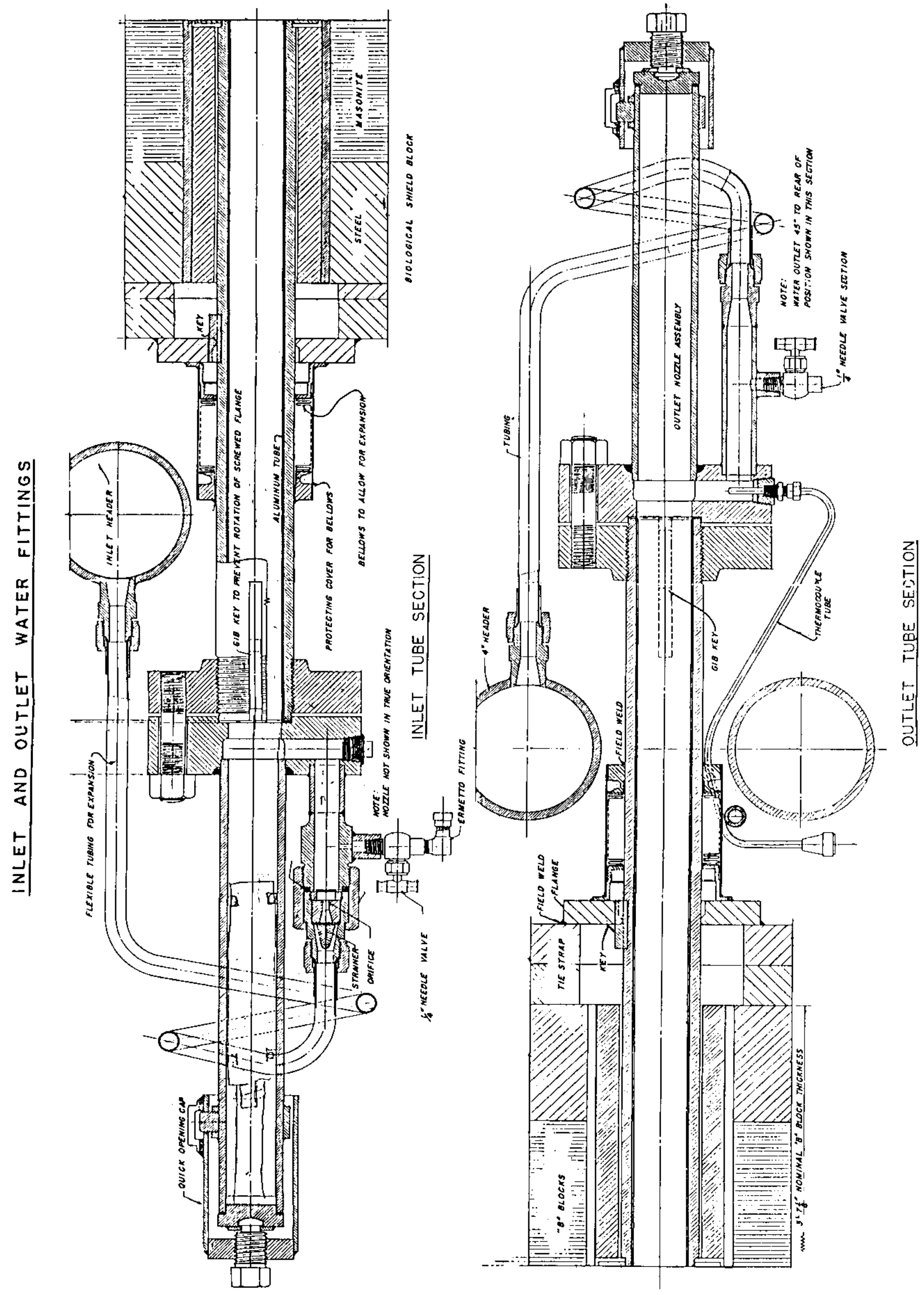
Photograph 7: Another picture of workers laying up the graphite core of the 105-B pile. This view is towards the rear of the pile. The gun barrels can be seen protruding into the pile. [D-3047]



Photograph 8: An external view of the B Reactor’s graphite pile. [HTM 1945: 405]



Photograph 9: A cutaway view of the graphite pile. [HTM 1945: 406]



Photograph 10: Each process tube ended with a water- and fuel-handling connection. [HTM 1945: 509]

Photograph 11: The work area of a typical fuel storage and transfer basin. The wooden floor was built over the 20-foot deep water-filled basin. Buckets filled with irradiated fuel or dummy slugs at the bottom of the basin were suspended from rods that passed through the slots in the floor and were hung on trolleys attached to the monorail tracks suspended from the ceiling. [85-H807]

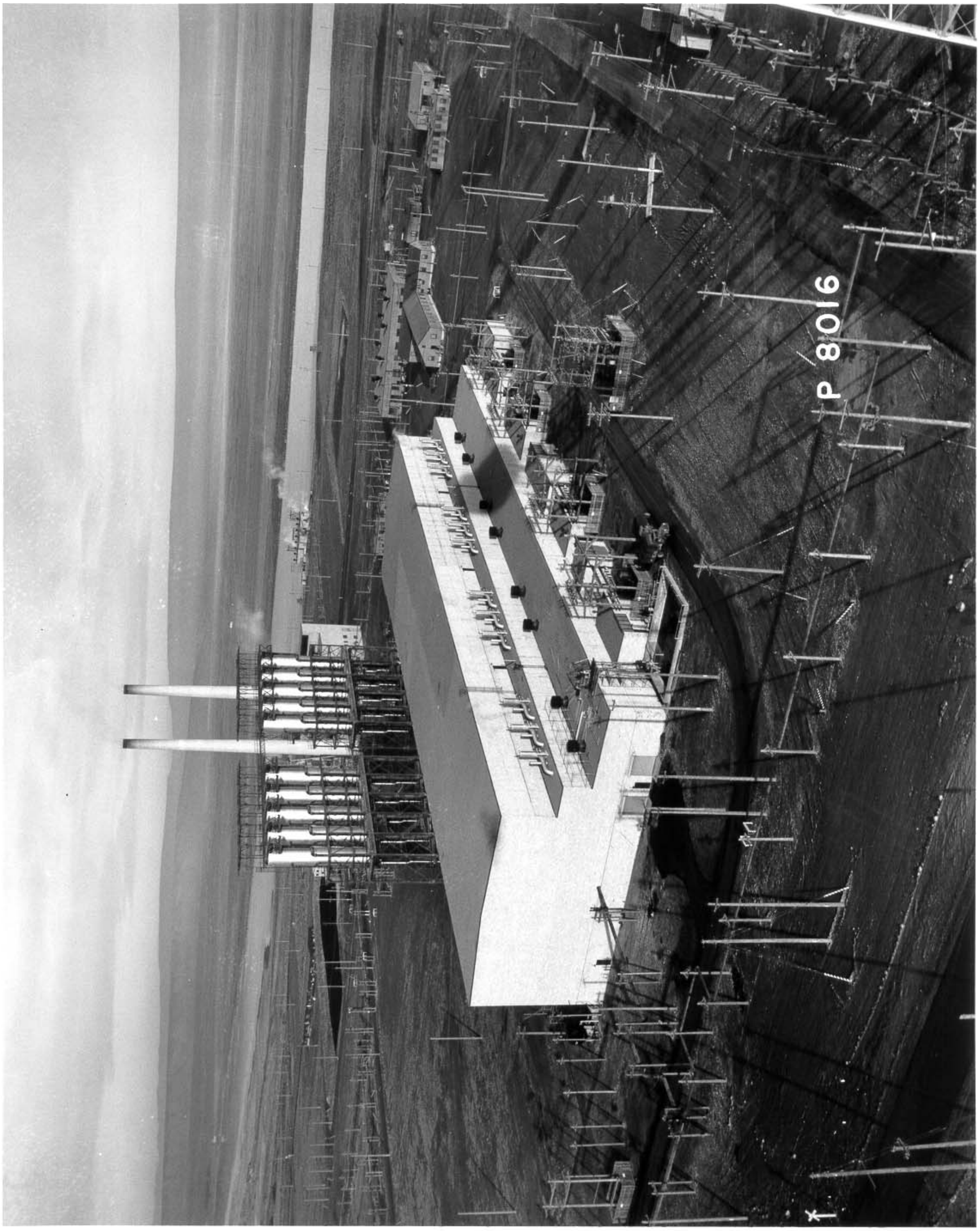
Photograph 12: The 181-B River Pump House under construction in March 1944, with the 184-B Power Plant in the background. View is to the southeast. [P-1882]

Photograph 13: The River Pump House pump room, in this case in the 100-F Area in January 1945. In the 100 Area, the pumps supplied water to the 100 Area and to the export water system that ran to D and F reactors and the 200 areas. [D-8248]

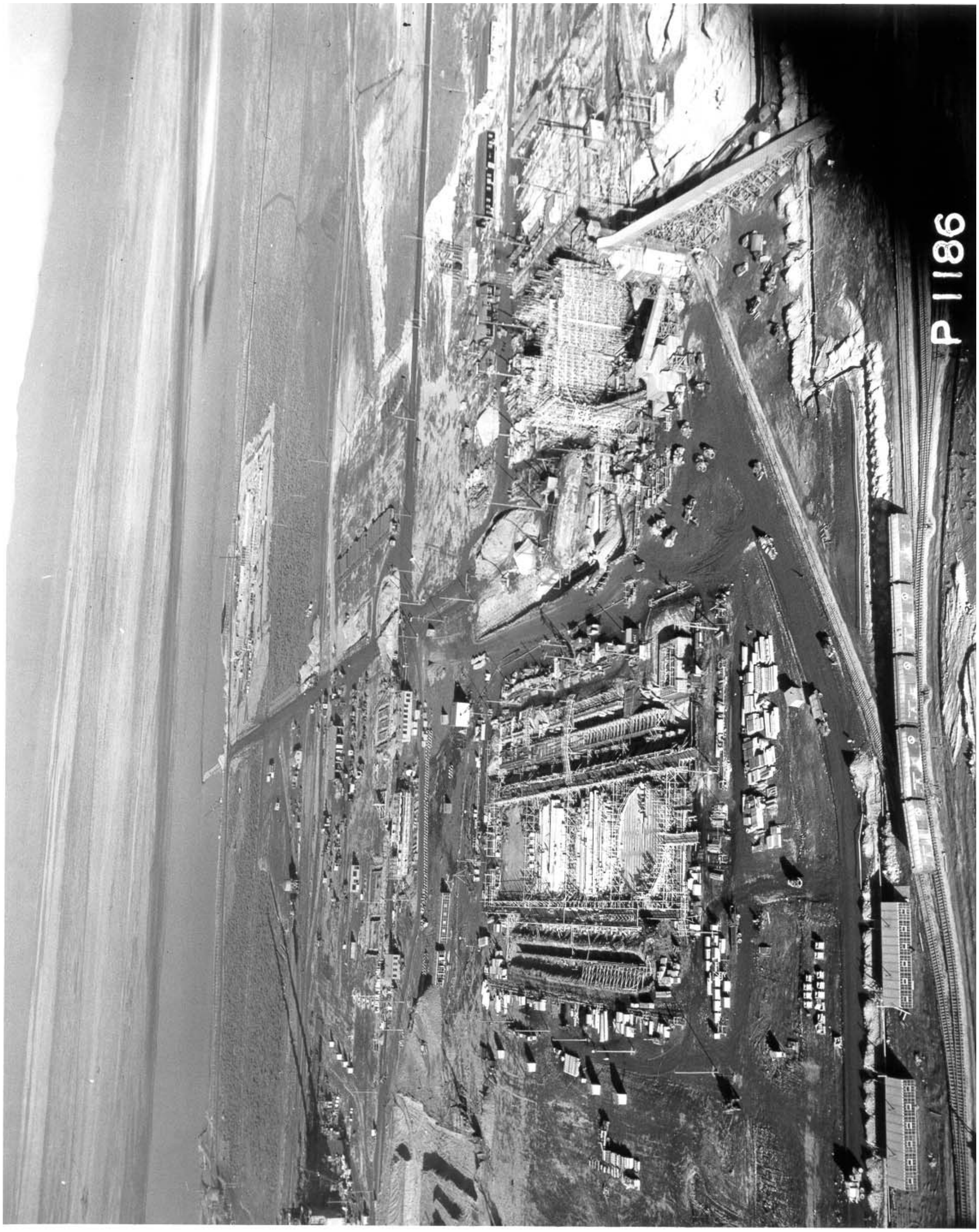
Photograph 14: The 182-B Reservoir under construction in March 1944, showing the divider which was normally covered by water. View is to the northwest. [P-1877]

Photograph 15: The 183-B Filter Plant with settling basins in January 1945. The 182-B Reservoir and Pump House is on the left in the background, and the coal storage pond for the 184-B Power House is in the upper right. View is to the northwest. [P-8012]

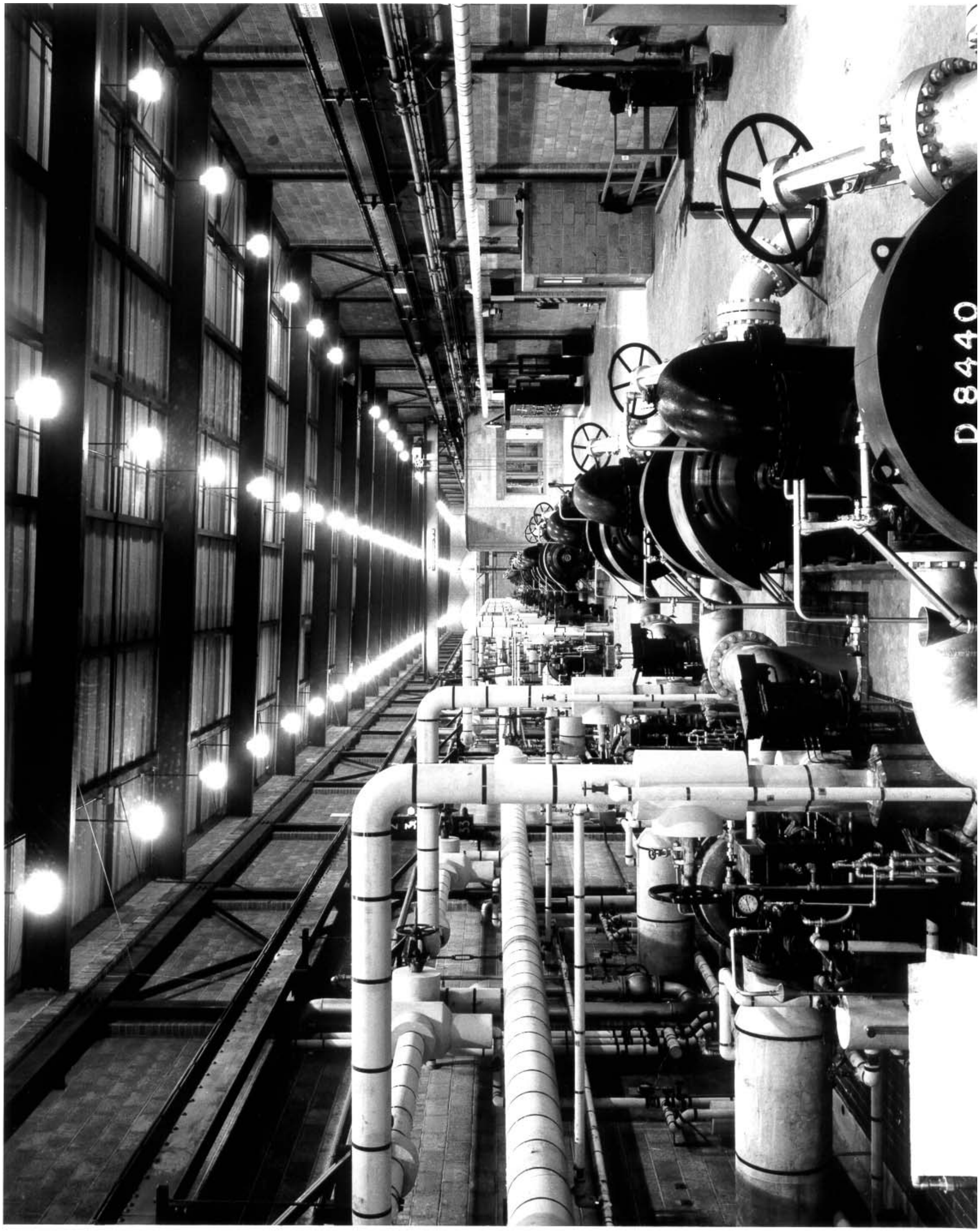
Photograph 16: Contextual view of the 100-B Area, looking toward the northeast in December 1944. The River Pump House is in the distance on the river (left of center); the 184-B Power House stands with its two tall stacks, its Coal Storage Pond (to its left), and its 188-B Ash Disposal Basin (towards the river). Also seen are the 182-B Reservoir (foreground on the left), the 183-B Filter Plant (foreground right of center), and the 107-B Retention Basin (upper right near the river). [P-7835]



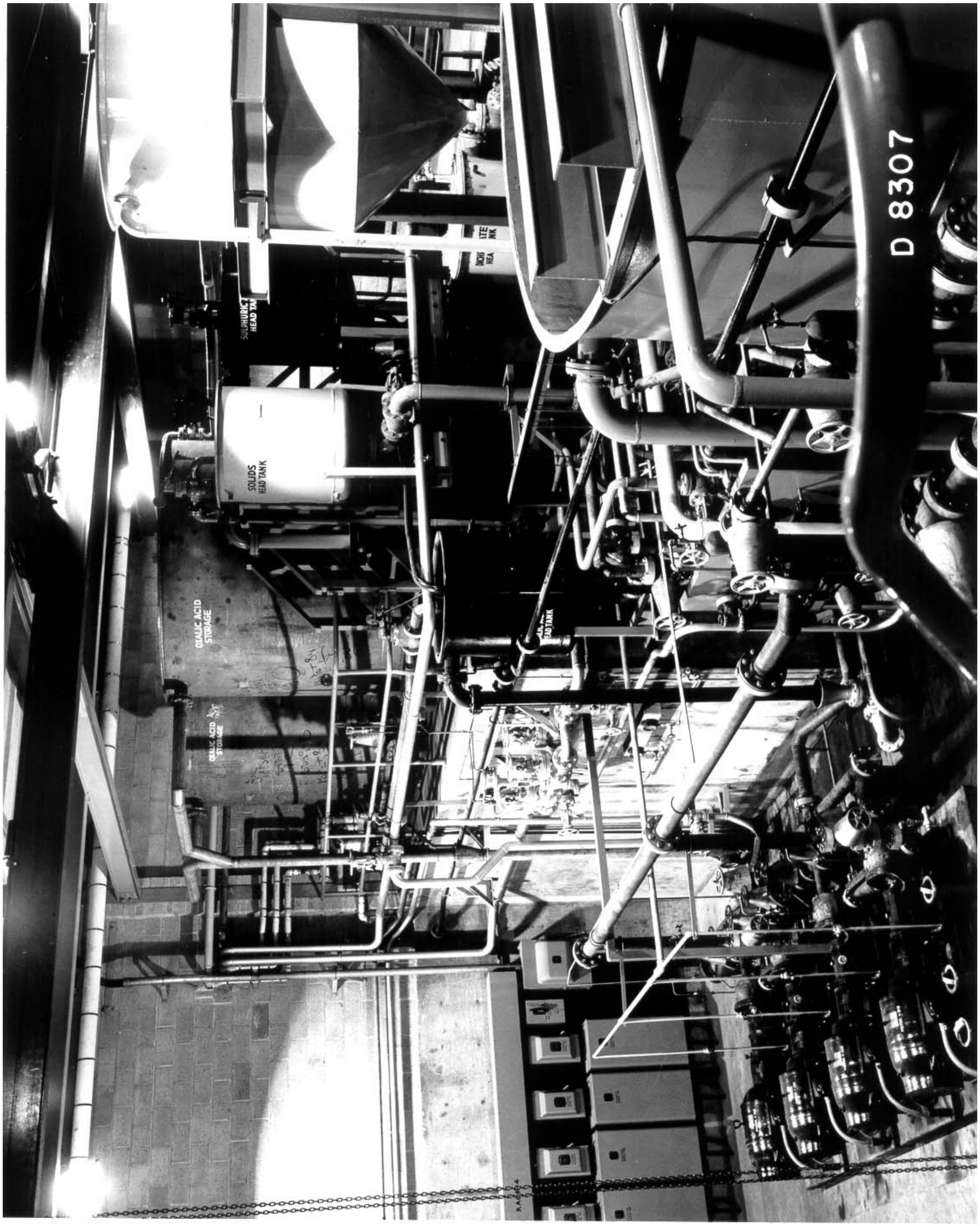
Photograph 17: The 190-B Process Pump House in January 1945, with the 185-B Deaerating Plant towers standing above the rear of the building. View is to the northwest. [P-8016]



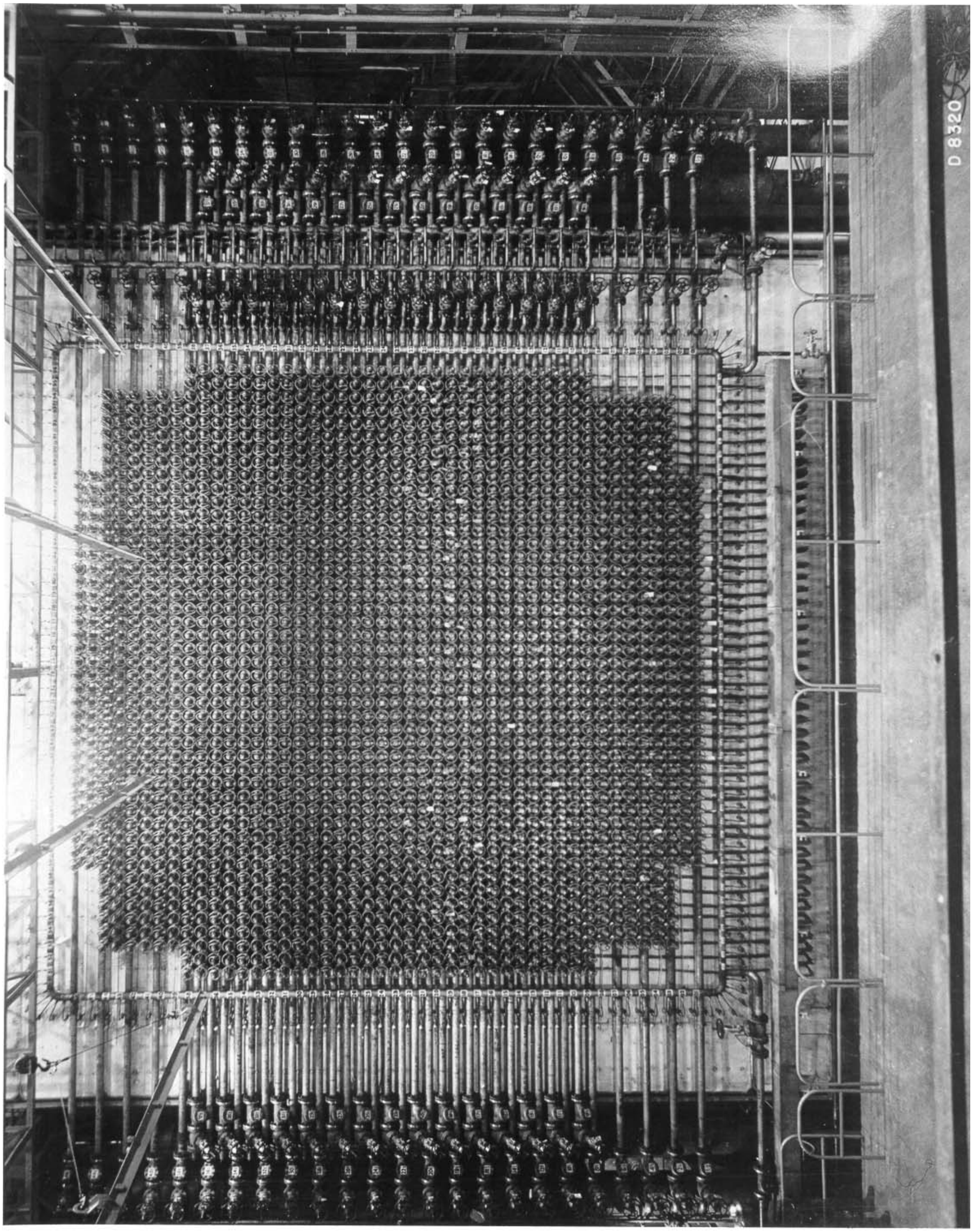
Photograph 18: Aerial view of the 100-B Area under construction in January 1944, viewed to the north. The 105-B Rector building can be seen to the right of center; the 190-B Process Pump House with its four large tanks is to the left of center; the 181-B River Pump House on the Columbia River is at the top-left side of the picture; and the 184-B Power House is just south of the River Pump House (note the shadows of its two tall stacks pointing northeast). [P-1186]



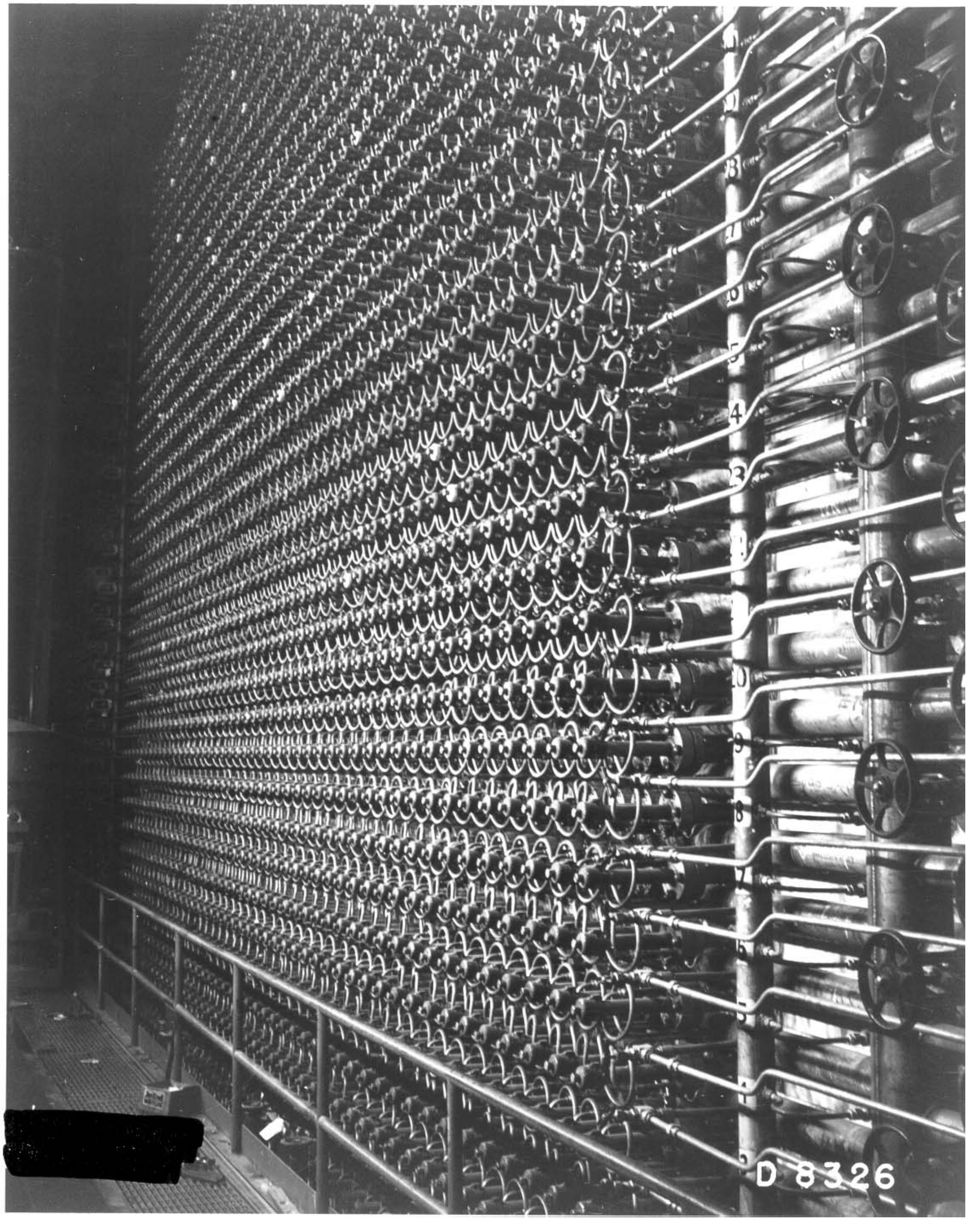
Photograph 19: Interior of the 190 Process Pump House, in this case in the 100-F Area in February 1945. Steam-driven pumps are on the left and electrically-driven pumps are on the right. [D-8440]



Photograph 20: The Valve Pit in the 105 Reactor building (F Reactor in this case), with chemical addition vats. [D-8307]

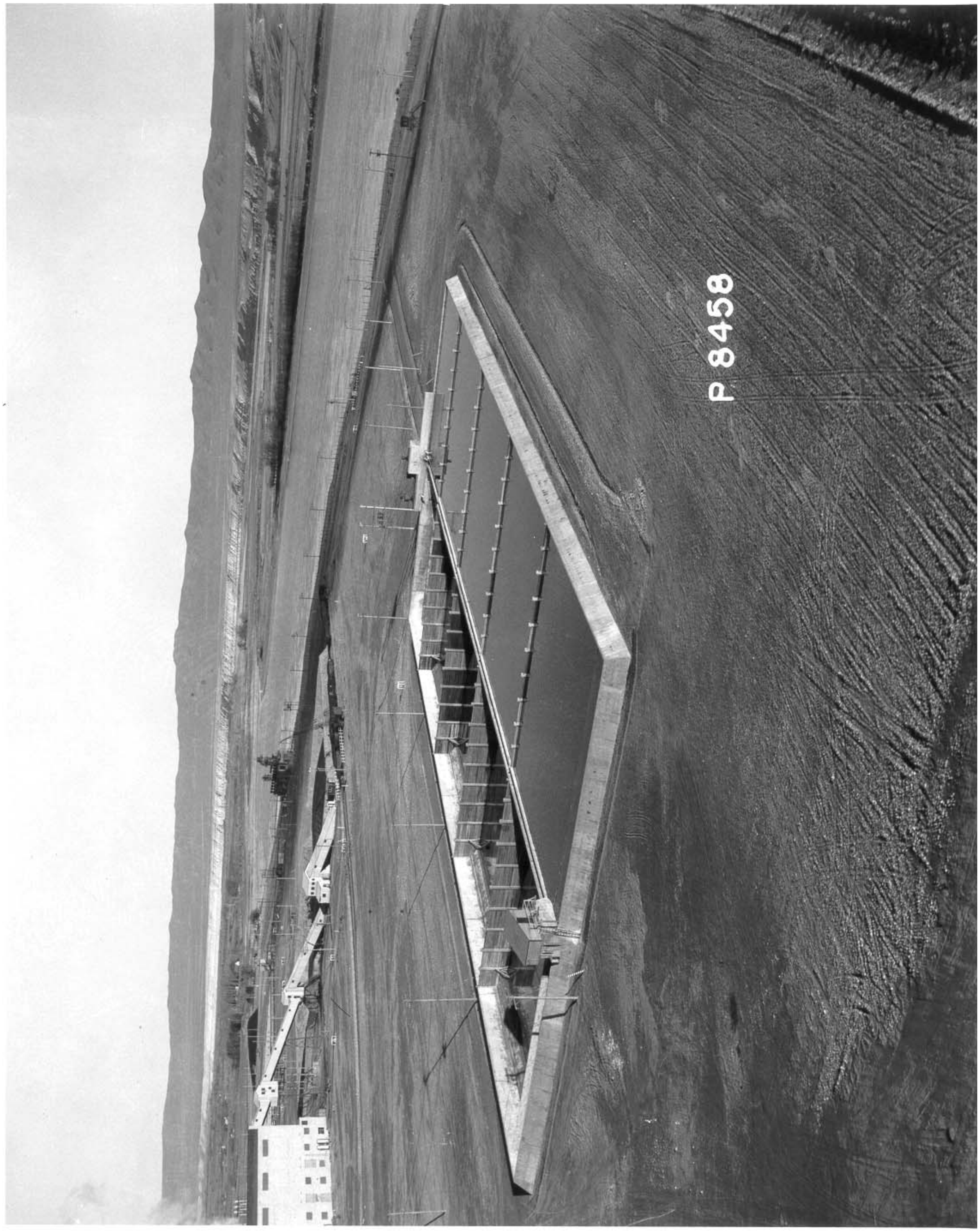


Photograph 21: View from the work area of the front face of the pile in the 105 building, in this case at the F Reactor in February 1945. The 2,004 pigtails and process tube nozzles are neatly aligned in rows and columns across the face of the pile. The cooling water risers stand at the left and right of the pile and the distribution crossheaders run across its face. The pipes running vertically at the bottom of the pile carry cooling water to the thermal shield. The low railing along the floor in front of the face prevented workers from accidentally falling into the charging elevator pit. [D-8320]



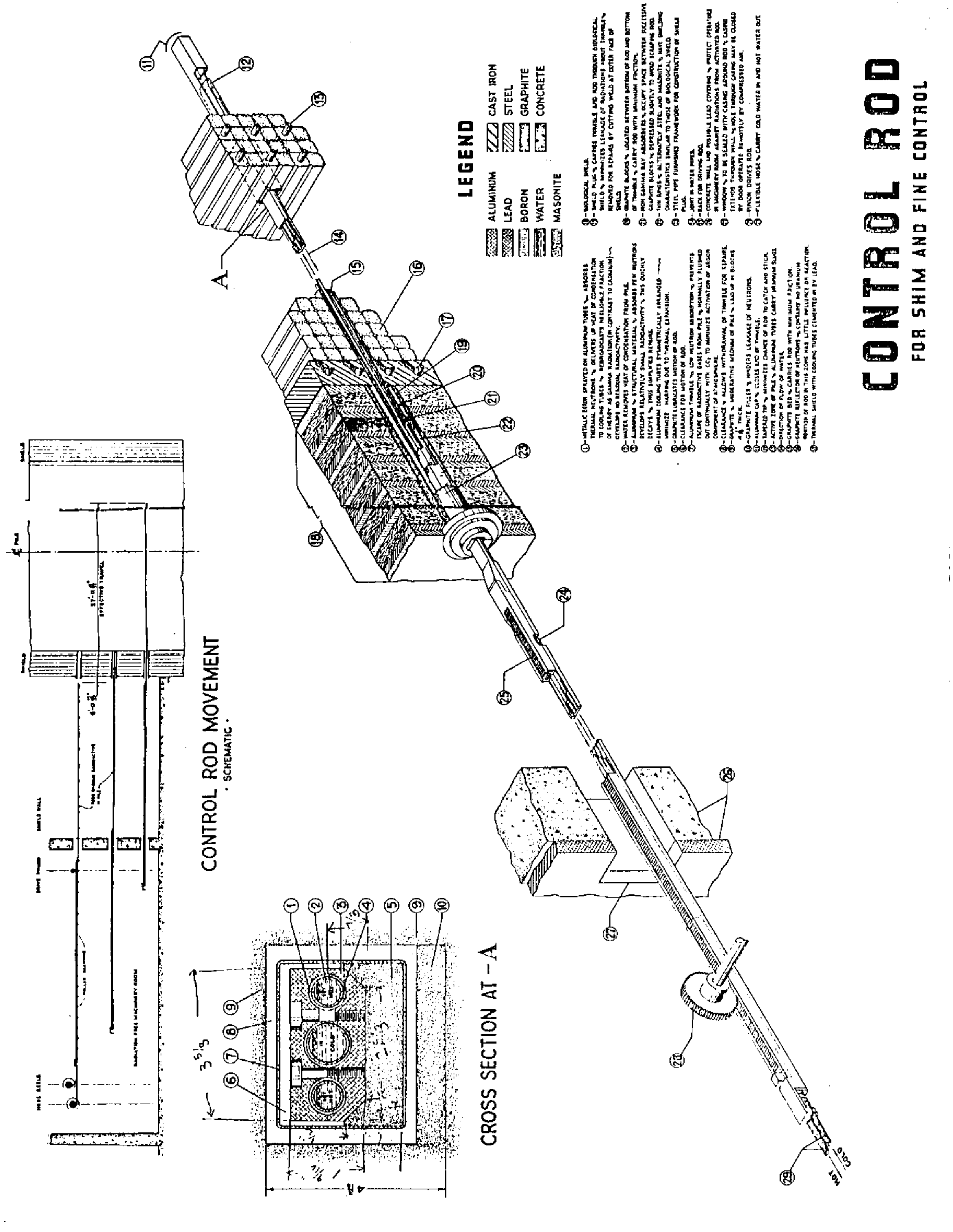
[redacted]

Photograph 22: A side-view of the rear face of a typical pile, in this case the F Reactor in February 1945. The low railing and walkway are part of the discharge elevator. Notice the vertical row of numbers on the right that identified the rows of process tubes. [D-8326]



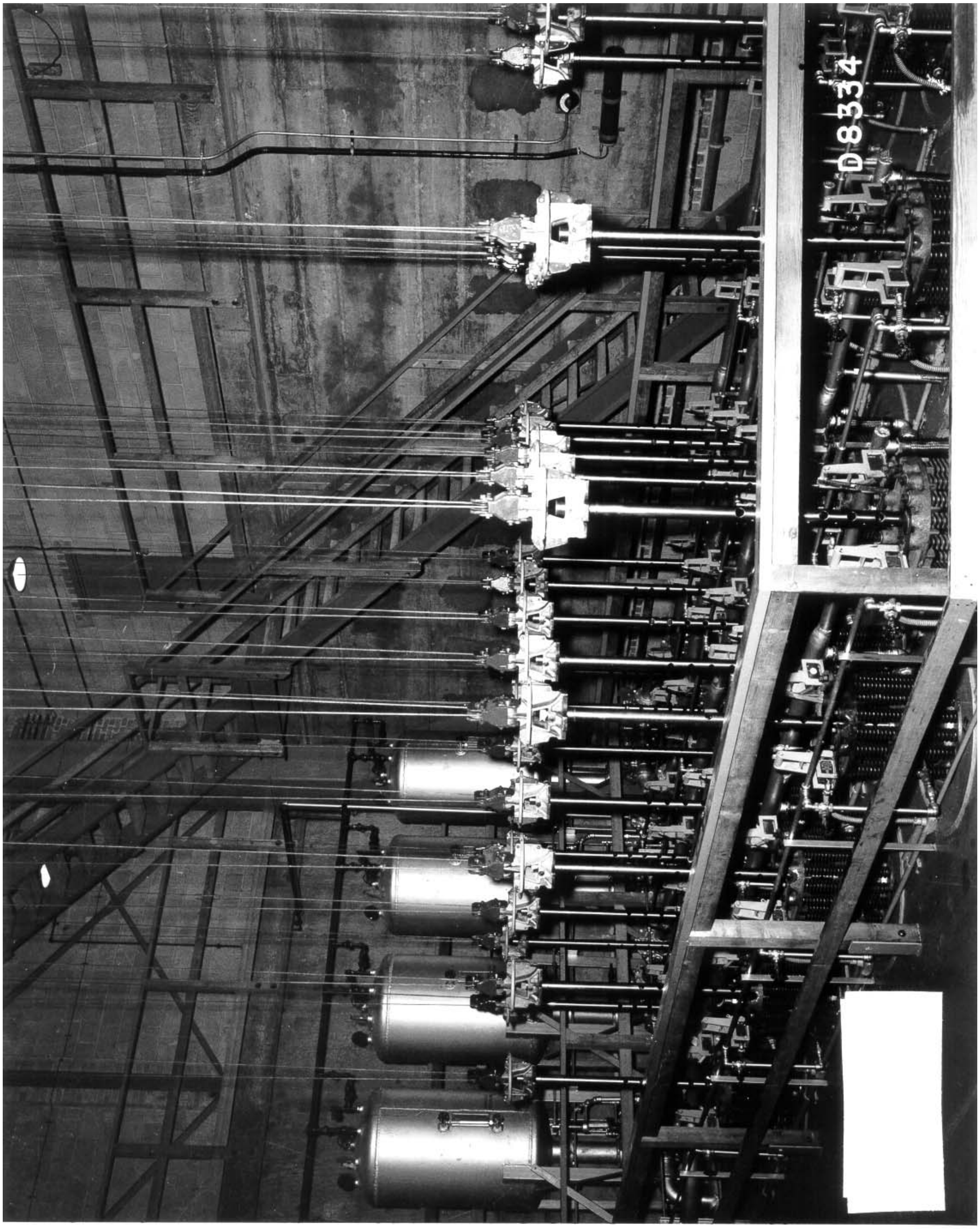
Photograph 23: A typical 107 Retention Basin, in this case in the 100-F Area in February 1945. The Columbia River is in the background and the 184 Powerhouse is at the left. [P-8458]

Photograph 24: The 184-B Power House under construction, viewed to the northeast in March 1944. The sewer line exiting to the Columbia river was used mainly for effluents from back-washing the filter basins. A separate Process Sewer Line (out of the picture to the right) for cooling water leaving the pile went to the 107-B Retention Basin, and ultimately to the river. [P-1881]

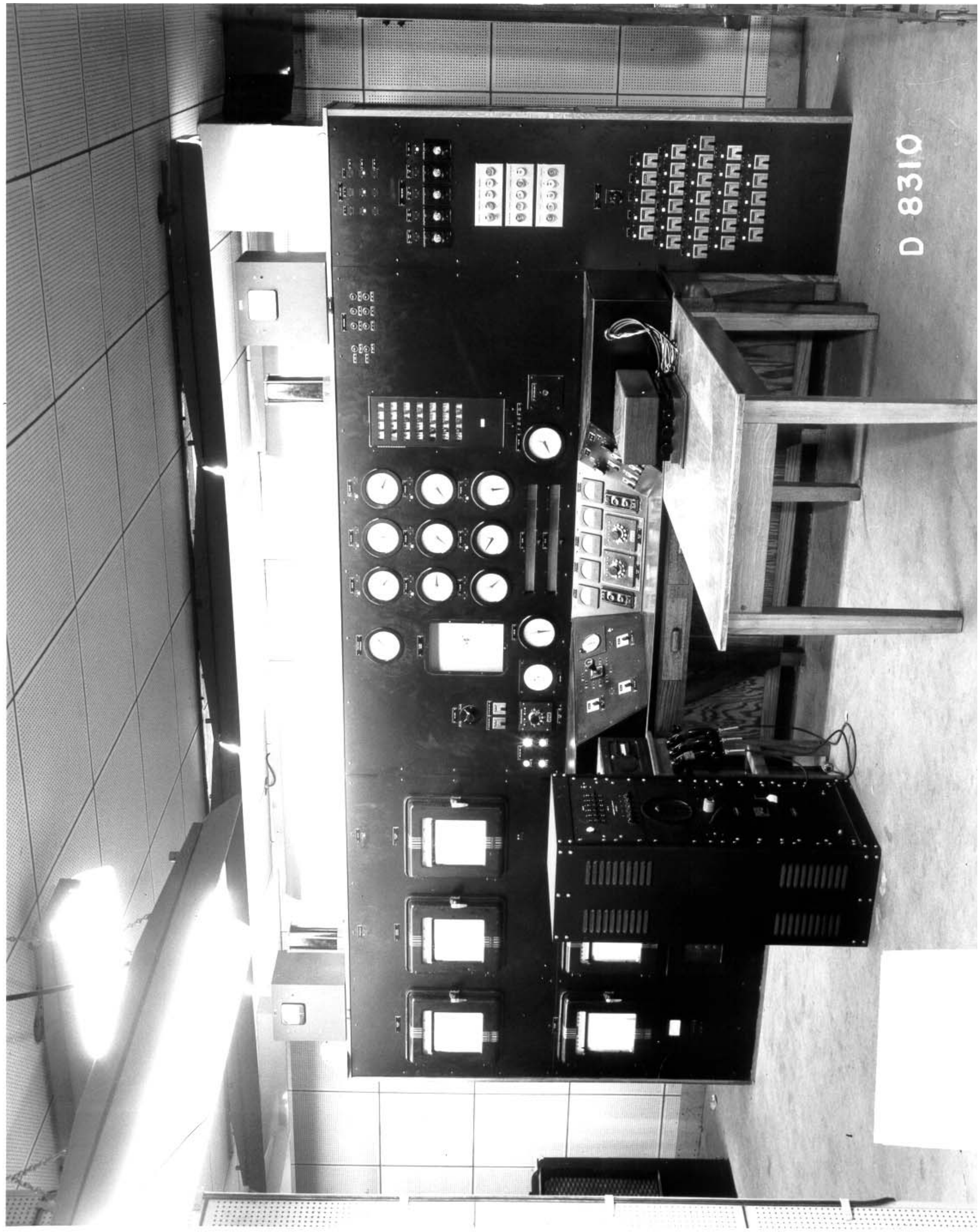


Photograph 25: A typical control rod, showing the neutron-absorbing inner end and the rack-mounted outer end.
[HTM 1945: 610]

Photograph 26: A typical outer rod room, or rack room, showing the racks for the nine horizontal control rods (HCRs) that would be inserted or withdrawn from the pile to control the rate of reaction. In this case, it is in the 105-F Reactor in February 1945. The view is looking away from the pile, which is out of the picture on the left. Several of the cooling water hose reels for the rods can be seen at the end of the racks near the wall. [D-8323]



Photograph 27: The top of a typical pile, F Reactor in February 1945 in this case, showing the vertical safety rods (VSRs) and the cables that support them. The rods could be dropped into the pile to effect a rapid shutdown. The four silver-colored drums on the left contained boron solution and are part of the last ditch safety system. Should the VSRs channels become blocked by an occurrence such as an earthquake, the solution could be dumped into the VSR channels to help shut down the reactor. [D-8334]



Photograph 28: A typical main control panel in a 105 reactor building, in this case 105-F in February 1945. A single operator sat at the controls to regulate the pile’s rate of reaction and monitor it for safety. The galvanometer screens (the two horizontal bars just below the nine round gauges that showed the positions of the control rods) showed the pile’s current power setting. With that information, the operator could set the control rod positions to increase, decrease, or maintain the power. [D-8310]

Photograph 29: An early picture of the Panellit gauges in the control room of a typical 105 reactor building, in this case 105-F in February 1945. There was one gauge for each of the pile's 2,004 process tubes. Each gauge monitored the tube's water pressure to ensure adequate cooling. Notice the wooden ladder, which operators could use when reading or adjusting the gauges. In later years, a large sign was installed across the top of the wall of gauges that read "Caution: Bumping This Panel Can Scram The Reactor." [D-8311]

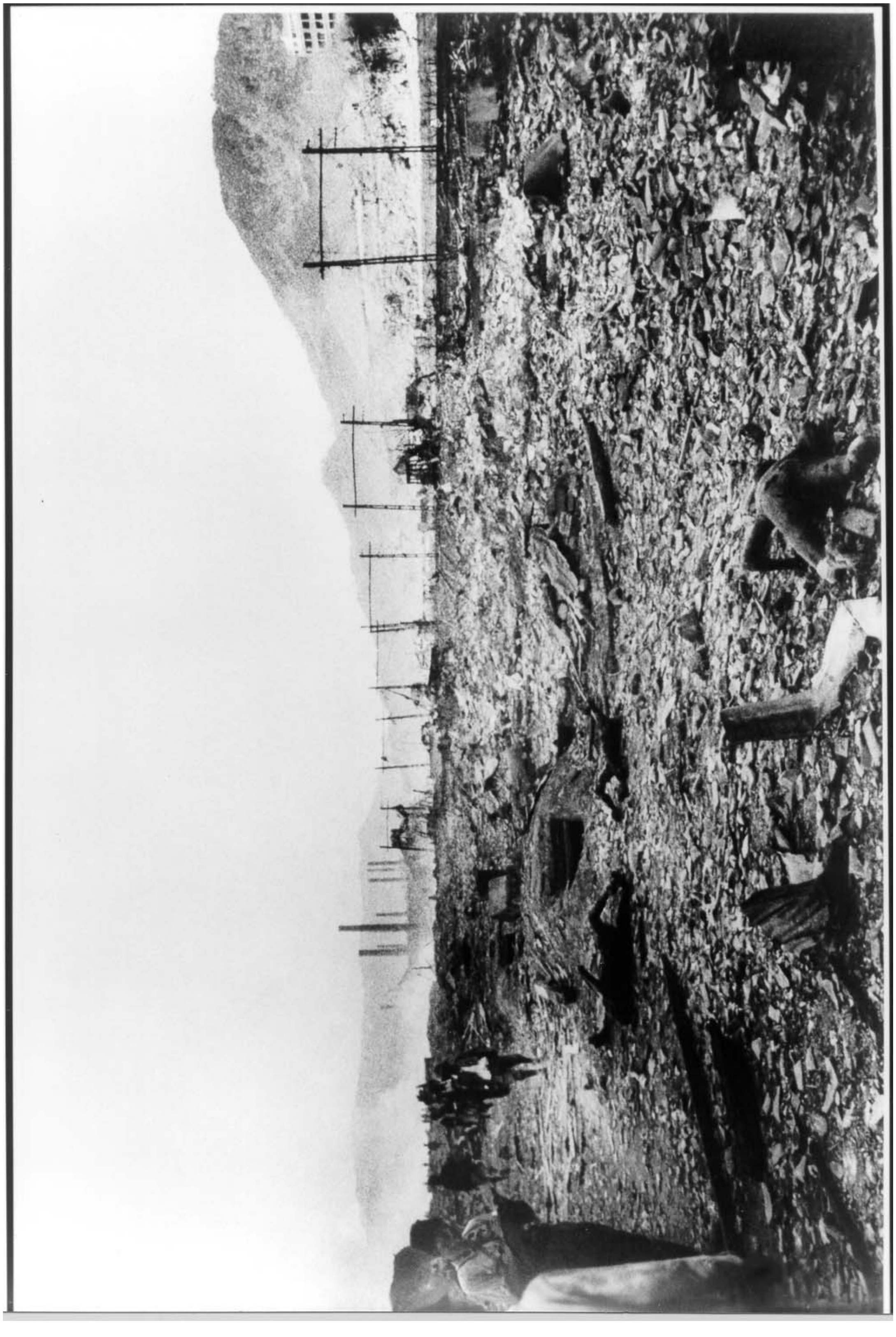
Photograph 30: Miscellaneous gauges and recorders on the wall opposite the Panellit gauges in a typical control room, 105-F Reactor in this case in February 1945. The temperature recorder for the 2,004 process tubes is at the far right side. [D-8308]

Photograph 31: The 1701-B Main Gate House in March 1944, viewed to the northwest. Its clock alley provided controlled access to the 100-B Area. The second floor was used to read radiation-detecting pencil dosimeters and to replace radiation-detecting film badges worn by employees. [P-2006]

Photograph 32: The 1704-B Supervisor’s Office and Laboratory building, which also contained the classified materials vault. This type of wooden construction was typical in the 100-B Area. Viewed from the northwest in September 1944. [P-4445]

Photograph 33: This photograph and the next (WA-164-34) form a panorama that was made from three adjacent 35 mm frames. The view is looking south across residential neighborhoods toward the center of Nagasaki, with the smokestacks of the Mitsubishi armaments factory still standing at the far right in the distance. The twisted metal framework close in at the right is the remains of a baseball field grandstand. (Copyright Shogo Yamahata)

Photograph 34: The right side of the panorama formed with photograph WA-164-33. (Copyright Shogo Yamahata)



Photograph 35: This photograph was taken from the pathway winding through the panorama (WA-164-33 and WA-164-34), which was formerly the main street of Nagasaki. Few burned bodies were generally visible in the aftermath, because many of the dead had been completely reduced to dust and ash by the heat of the fireball. The overhead crosspieces mark the tracks of the Nagasaki trolley system. The smokestacks of the Mitsubishi armaments factory can again be seen standing in the distance, somewhat closer than in the panorama. (Copyright Shogo Yamahata)

Figure Captions for Cross Referencing
DO NOT PRINT

Figure 1: The Hanford Site resides in eastern Washington state on the banks of the Columbia River. Nine graphite-moderated nuclear reactors were built during its 50 year role as one of the nation's plutonium production plants. [DOE/RL-96-29: 12]

Figure 2: The 100-B Area and its primary facilities as it was soon after completion in 1944. [DuPont 1945: 676]

Figure 3: The Plant coordinate system divided the Hanford Engineer Works into a convenient grid. [DuPont 1945: 643]

Figure 4: A cutaway view of the 105-B building.

Figure 5: The general arrangement of the pile assembly. [DOE Hanford photo, negative #7901473-1cn]

Figure 6: A cutaway view of the pile showing the graphite interior, cast iron thermal blocks, and biological shielding. [HTM 1945: 417]

Figure 7: The 2,004 process tubes were spaced 8.375 in. on center and arranged in a somewhat circular fashion when viewed from the front or rear face. [HTM 1945: 415]

Figure 8: The highest quality graphite was used in the central portions of the pile. [HTM 1945: 407]

Figure 9: A cross section through a process tube showing the surrounding graphite, the tube, and a uranium slug. [HTM 1945: 510]

Figure 10: Graphite blocks were bored out for the process tubes and beveled to provide a passage for the pile's helium atmosphere. Graphite keys helped to bind the layers together. [AEC-GE Richland, G-132-743-B]

Figure 11: The arrangement of fuel and dummy slugs in a typical process tube. [HTM 1945: 413]

Figure 12: The helium atmosphere circulated from the 115-B building, through the pile, and back again, where it was purified and dried before returning to the pile. [HTM 1945: 520]

Figure 13: The helium circulation within the pile. [HTM 1945: 521]

Figure 14: The discharged fuel slugs fell into the water-filled discharge chute, where they slid downward to the fuel storage area where they were loaded into buckets. [HTM 1945: 914]

Figure 15: A labyrinth allowed access through a thick shielding wall without the need for an equally thick door. [HTM 1945: 825]

Figure 16: Irradiated fuel slugs arranged in numerous buckets were stored safely under 20 ft of water beneath the floor of the fuel storage area. [HTM 1945: 915]

Figure 17: The water system in the 100-B Area. [Wahlen 1989: 6]

Figure 18: The influent water system at the front face of the pile. [HTM 1945: 507]

Figure 19: The effluent water system at the rear face of the pile. [HTM 1945: 512]

Figure 20: An operator regulated the pile and monitored for problems while seated at the main control panel. [HTM 1945: 706]

Figure 21: The lever-action charging machine proved to be more efficient than the original equipment, and provided a more uniform force on the slugs. [HTM 1945: 908]

Figure 22: The discharge fixture for the free-fall method of fuel discharging. [HTM 1945: 910]

Figure 23: The oil drain trough carried away the oil and water lubricant, which would have clouded the basin water and become a source of radiation contamination. [HTM 1945: 911]