Making the Invisible Engineer Visible

DuPont and the Recognition of Nuclear Expertise

SEAN F. JOHNSTON

Between 1942 and the late 1950s, atomic piles (nuclear chain reactors) were industrialized to generate plutonium for the first atomic weapons and later to serve as copious sources of neutrons, radioisotopes, and electrical power. As nuclear aims expanded both during and after World War II, scientific expertise and engineering experience merged. Yet so-called atomic scientists were the most visible representatives of the postwar field, and American engineers increasingly sought greater recognition of their nonsubordinate role as nuclear experts. Large companies in the United States supplied the engineering labor for this new technology and played an important role in defining the nature of their nuclear expertise, repeatedly renegotiating the hierarchy of science versus engineering. The most influential was E. I. Du Pont de Nemours, responsible for the earliest plutonium-production reactors at Oak Ridge, Tennessee, and Hanford, Washington, between 1942 and 1946, and of the next generation of reactors at Savannah River, South Carolina, between 1950 and 1989. In these facilities, the company integrated technical experts to create a sustainable nuclear workforce unlike the career niches fostered at the new national laboratories. This article explores the transition of authority from scientists to nuclear engineers at those sites, and DuPont's role in shaping and consolidating this new expertise.[1]

Dr. Johnston is a reader (associate professor) in the history of science and technology at the University of Glasgow. He gratefully acknowledges the funding of this work by Economic and Social Research Council grant RES-000-22-2171, and the helpful comments of colleagues and three anonymous referees.

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[1] Other U.S. companies joined the field of reactor technology after World War II, notably via the projects to build nuclear-powered submarines and aircraft for the U.S. Navy and Air Force, respectively. These firms included General Electric, Westinghouse, and Monsanto (discussed below), plus Fairchild, Convair, Pratt-Whitney, and Electric Boat. By contrast, the early attempt by Farrington Daniels, director of the University of Chicago's Metallurgical Laboratory at the war's end, to build a pile for power generation was resisted by Oak Ridge scientists, owing in part to the project's heavy reliance on

The emergence of engineering knowledge is of considerable interest for understanding how innovation and technical practices become embedded in the working cultures of industries. While nuclear technology has generated vast scholarship, relatively little attention has been devoted to its engineering specialists. Alfred Chandler and others have characterized DuPont as a paradigm U.S. corporation and effective wartime contractor. David Hounshell has sketched the company's influence in creating the discipline of chemical engineering, but discusses the professional dimensions of nuclear technology relatively little, although nuclear-production sites and lower-tier employees have received attention from others. Andrew Abbott has defined an enduring framework for understanding the emergence of technical experts in terms of competition among professions for intellectual terrain, occupational sites, and status. Studies of twentieth-century U.S. engineers have highlighted social and political dimensions, particularly their engagement with wider corporate aims and developing themes of social responsibility.[2]

The growth of nuclear technology parallels more recent technologies in terms of the pace of its development and the nature of its organization. The field was directed and rapidly expanded by government; the urgency of its growth meant that scientists and engineers jostled, with theorization, large-scale implementation, and practical insights coexisting. Richard Hewlett,

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Monsanto engineers. See Richard G. Hewlett and Francis Duncan, *Nuclear Navy, 1946–1962* (Chicago, 1974); Stephen I. Schwartz, ed., *Atomic Audit: The Costs and Consequences of U.S. Nuclear Weapons since 1940* (Washington, D.C., 1998); Richard G. Hewlett and Jack M. Holl, *Atomic Shield, 1947–1952* (Berkeley, Calif., 1969), 68–71; Robert A. Alberty, "Farrington Daniels, March 9, 1889–June 23, 1972," *National Academy of Sciences Biographical Memoirs* 65 (1994): 106–21. Thus DuPont was unique in overseeing successful development of an integrated workforce ranging from designers and managers to reactor operators.

2. Alfred D. Chandler and Stephen Salsbury, *Pierre S. du Pont and the Making of the Modern Corporation* (New York, 1971); Harry Thayer, *Management of the Hanford Engineer Works in World War II: How the Corps, DuPont and the Metallurgical Laboratory Fast Tracked the Original Plutonium Works* (Reston, Va., 1996); David A. Hounshell and John Kenly Smith Jr., *Science and Corporate Strategy: Du Pont R&D, 1902–1980* (Cambridge, 1988), esp. 275–85; Thomas Parke Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm, 1870–1970* (New York, 1989); Gerard Colby Zilg, *DuPont: Behind the Nylon Curtain* (New York, 1974); S. L. Sanger and Robert W. Mull, *Hanford and the Bomb: An Oral History of World War II* (Seattle, 1990); Rodney Carlisle and Joan M. Zenzen, *Supplying the Nuclear Arsenal: American Production Reactors, 1942–1992* (Baltimore, 1996); Russell B. Olwell, *At Work in the Atomic City: A Labor and Social History of Oak Ridge, Tennessee* (Knoxville, Tenn., 2004); Andrew D. Abbott, *The System of Professions: An Essay on the Division of Expert Labor* (Chicago, 1988); Edwin T. Layton, *The Revolt of the Engineers: Social Responsibility and the American Engineering Profession* (Cleveland, 1971); David F. Noble, *America by Design: Science, Technology, and the Rise of Corporate Capitalism* (New York, 1977); Terry S. Reynolds, ed., *The Engineer in America* (Chicago, 1991). See also Antoine Picon, "Engineers and Engineering History: Problems and Perspectives," *History and Technology* 20 (1994): 421–36.

coauthor of the official history of the U.S. Atomic Energy Commission (AEC), provided a first overview of how nuclear engineering followed hard on the heels of science during the Manhattan Project. He noted that the wartime and postwar administrations were top-heavy with scientists while underrepresenting engineers, and Pap Ndiaye has similarly highlighted the downgrading of engineers in the historiography of the Manhattan Project. The AEC's casting of engineers as a near-invisible constituency during the early years of atomic energy complicates matters. Key participants like Walter Zinn and Alvin Weinberg, later directors of the Argonne and Oak Ridge national laboratories, respectively, were physicists by training though reactor designers by trade. While their institutions indirectly fostered the new field of nuclear engineering, the present article argues that it was more effectively prosecuted by DuPont and its senior engineer-administrators. By examining the relationships between scientific and engineering cultures at DuPont sites, we can assess how the field came to be appropriated by engineers.[3]

DuPont and the Wartime Gestation of Nuclear Specialists

Founded in Wilmington, Delaware as a gunpowder manufacturer in 1802, DuPont evolved to become an unusual American industrial company. Establishing early industrial laboratories and relying increasingly on research at the beginning of the twentieth century, it was also atypical in being relatively self-sufficient: it normally designed, constructed, and operated its plants in-house, rather than working with subcontractors. This combination of attributes, which hinted at research competence, industrial accountability, and efficient security, made the firm attractive to General Leslie Groves in the autumn of 1942 to manage one branch of the Manhattan Project.[4]

DuPont's involvement began during the autumn of 1942, when the U.S. government asked it to serve as a subcontractor to Stone & Webster, a Massachusetts consulting-engineering company. Groves asked DuPont to play a central role by liaising directly with the University of Chicago's metallurgical laboratory to design, construct, and operate chain reactors as plutonium plants. This was important in gestating a new discipline: a single, vertically integrated company assumed responsibility for collaboration with university scientists, building a burgeoning team of engineers to develop atomic piles as industrial factories.[5]

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[3] Richard G. Hewlett and Franciscus Duncan, *A History of the United States Atomic Energy Commission* (University Park, Penn., 1969); Hewlett, "Beginnings of Development in Nuclear Technology," *Technology and Culture* 17 (1976): 465–78, quotes on 477–78; Pap A. Ndiaye, *Nylon and Bombs: DuPont and the March of Modern America* (Baltimore, 2007), chap. 4; Alvin M. Weinberg, *The First Nuclear Era: The Life and Times of a Technological Fixer* (New York, 1994).

[4] Thayer.

[5] Richard G. Hewlett and Jack M. Holl, *The New World, 1939–1946* (Berkeley, Calif.,

The choice of industrial partner shaped the conception of the engineering tasks. Unlike Stone & Webster, which specialized in the physics-rich field of electrical engineering, DuPont's expertise lay in industrial chemistry. In November 1942, General Groves asked DuPont senior managers and seminal chemical engineer Warren Lewis of MIT to evaluate the feasibility of the proposed processes, all of which had been conceived by physicists. Given their role as assessors, DuPont managers understood their task to be the evaluation, refinement, and optimization of the University of Chicago's process of plutonium manufacture as an industrial routine according to established management techniques. Thus DuPont would scale up laboratory conceptions to a viable industrial process.[6]

The University of Chicago's Metallurgical Laboratory ("Met Lab") team directed by physicist Arthur Compton viewed the organization differently, defining the required expertise as a cluster of subdisciplines directed by scientists. Three groups of physicists were attacking the problem of designing a chain reactor; a separate chemistry division studied plutonium chemistry and uranium purification on a laboratory scale; and a production division, led by physicists Eugene Wigner and John Wheeler, was working on design studies to scale up this knowledge for production plants. Compton included nonscientists on his staff, appointing Thomas Moore of Humble Oil and Refining Company as chief engineer of the lab and head of an engineering council to advise the lab on plutonium-production processes. Although Compton's group was unusually proactive in incorporating engineering expertise, it was positioned as subordinate within the hierarchy.[7]

1969); Leslie R. Groves, *Now It Can Be Told: The Story of the Manhattan Project* (New York, 1962).

[6] Crawford H. Greenewalt, "Stine's Memorandum," in Hagley Library and Archives, Wilmington, Delaware (hereafter Hagley): E. I. Du Pont de Nemours Atomic Energy Division, including Clinton, Hanford, and Savannah River administrative records, 1957 series 1, box 1, 27 November 1942. The two other competing processes, which sought to manufacture uranium rather than plutonium, were the "California project" (electromagnetic separation of U-235 from U-238, pursued by Ernest Lawrence's radiation laboratory at the University of California, Berkeley) and the "New York project" (electromagnetic separation of uranium by thermal diffusion, pursued by Harold Urey's team at Columbia University). On physicists' colonization of electrical engineering, see Daniel Kevles, *The Physicists: The History of a Scientific Community in Modern America* (New York, 1977); on the relationship to chemical engineering, see William F. Furter, ed., *History of Chemical Engineering* (Pittsburgh, 1980) and Terry S. Reynolds, *Seventy-Five Years of Progress: A History of the American Institute of Chemical Engineers, 1908–1983* (New York, 1983).

[7] The council worked with Compton's nuclear physics, chemistry, and theory divisions. At the end of June, Charles C. Cooper, the assistant director of DuPont's technical division, was seconded for chemical engineering, and John Howe, from General Electric, for electrical engineering. A month later, Moore added Miles C. Leverett from Humble Oil for general engineering. That autumn Compton also appointed Martin D. Whitaker, former chair of the physics department of New York University who had worked with Enrico Fermi, to head pile design and construction.

From the standpoint of the engineers, however, the project was still decidedly academic in orientation. The problems and potential solutions of plutonium production were at this point entirely theoretical: no chain reaction had yet been demonstrated, and plutonium was available only in microgram quantities, which were too small to reveal its chemical properties or appropriate methods of separating it from other fission products. As to the reactor itself, suitable materials, designs, and properties were too uncertain to make a production unit or even a pilot plant. To varying degrees, the scientists and engineers alike viewed the project as beyond their individual expertise.

The forced marriage between Met Lab and DuPont fostered the hybrid expertise of nuclear engineering. It allowed engineers to gain an equal rather than subordinate role in defining the intellectual terrain of the new subject and in prioritizing research. This power shift, played out over the latter part of World War II and resuming in the early 1950s, began with a clash of technical cultures and ended with well-embedded occupational sites, entrenched intellectual clusters, and increasingly clear-cut professional expectations.

Engineering versus Science: Critiquing Early Pile Design

This production project was unlike DuPont's typical industrial problems and required new expertise. There were no specialists in large-scale nuclear processes akin to chemical engineers to offer a suitable background for the particular novel problems to be faced. Moreover, the science itself lacked adequate details upon which to found a factory-scale process.[8] Key DuPont participants had to rapidly absorb the fundamentals of nuclear physics, while also grappling with the problems they perceived in the already-established design practices of scientists working on nuclear piles. DuPont assigned senior manager Crawford Greenewalt to act as liaison with Met Lab scientists, and his project diary offers valuable insights into Met Lab's progress, DuPont's assessments, and their interactions with scientists.[9]

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[8] The industrialization of radioactivity did have prewar exemplars, but they incorporated few relevant technoscientific aspects. Radium, for example, had been isolated from crude ores and employed in medical treatments and commercial applications like luminous paints; see Edward Landa, *Buried Treasure to Buried Waste: The Rise and Fall of the Radium Industry* (Golden, Colo., 1987); Xavier Roqué, "Marie Curie and the Radium Industry: A Preliminary Sketch," *History and Technology* 13 (1997): 267–91; and Maria Rentetzi, "The U.S. Radium Industry: Industrial In-House Research and the Commercialization of Science," *Minerva* 46 (2008): 437–62.

[9] Crawford H. Greenewalt, "Manhattan Project Diary," 3 vols. (hereafter Greenewalt Diary), in Hagley, 1889. With an MIT degree in chemical engineering, Greenewalt (1902–1993) joined DuPont in 1922 to work successively in six departments, most importantly in managing the development of nylon. He became president of the company in 1948, and then chairman (1962–67).

Through 1942 the scientists had been building cubic piles ten feet on a side, and had found that these assemblies multiplied the radioactivity of an artificial source of neutrons. They aimed to scale up these experiments, with plans to demonstrate the feasibility of a self-sustaining chain reaction by year's end. Anticipating a successful outcome, Met Lab scientists already planned a series of reactors, including an experimental one to be built in the Argonne forest near Chicago, comprising a latticework of some twenty-five feet in diameter of uranium oxide, uranium metal, and purified graphite. A second pile—the pilot plant or semi-works—would be constructed at another site, identified as "X." Identical in form to the first, the second pile would, however, allow the chain reaction to run for weeks at a time at a sustained thermal output of some 1,000 kilowatts. To enable this the scientists envisaged the pile to be encased in a copper or steel jacket and filled with helium gas to conduct heat and contain radioactive gases and airborne materials, the exterior being sprayed with water and air-cooled by fans.[10]

DuPont managers were disconcerted by the signs of engineering naïveté in this plan. The Met Lab physicists conceived plutonium production by what they dubbed "Pile 2" as a batch process, rather than as engineers' preferred continuous-flow plant; after a month of operation, the pile was to be shut down for a week or two to allow radioactivity to decay before being dismantled to recover the uranium fuel. While batch processes were normally less complex than continuous-flow systems, radioactivity introduced novel problems, even for managers familiar with toxic chemical-production processes. As the pile would generate some 100,000 curies of radioactivity—the equivalent of 100 kilograms of radium, far in excess of the world's current supply—Met Lab planned to rotate operators "so as not to build up too much without recuperation," and to make a trade-off "between uranium danger and rapidity of construction." Thus the project's pilot plant would introduce novel health issues that were to be settled by a combination of empirical estimates and compromise.[11]

Greenewalt noted that Met Lab's scheme for obtaining plutonium ex-

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[10] Ibid., vol. 1 (1942), 2–3, 11–31. For complementary though sparse overviews, see Hewlett and Holl, *New World*, 174–80, and Arthur Holly Compton, *Atomic Quest: A Personal Narrative* (Oxford, 1956), 161–75.

[11] Greenewalt Diary, vol. 1 (1942), 28. The curie is a unit of radioactivity defined as 3.7 × 1,010 decays per second, which is approximately the decay rate of one gram of radium. The roentgen is a measure of ionizing radiation; namely, the ability of a radioactive particle or energetic ray to liberate electrons from atoms. One roentgen is defined as the radiation that will liberate one electrostatic unit (esu) of charge from a one-cubic-centimeter volume of dry air. Greenewalt's notes summarized the Met Lab's current understandings: that "humans can take 0.1 'R' [roentgen] unit per day," but the biological effects of radiation depend upon its variety (e.g., X-ray, alpha particle, or neutron); the "roentgen equivalent man" (rem) unit was later introduced to account for this. On radiation hazards in defining the identities of French nuclear workers, see Gabrielle Hecht, "Enacting Cultural Identity: Risk and Ritual in the French Nuclear Workplace," *Journal of Contemporary History* 32 (1997): 483–507.

ceeded even these tentative safety limits. The plan was to tear down the accurately machined and meticulously positioned graphite bricks via a remotely operated circular saw to cut away the copper jacket, followed by a boom crane with vacuum-operated suction cups to grasp and place each graphite block on a moving belt. The uranium blocks would be similarly directed to a hopper and a tank for chemical processing. The plutonium-extraction process, which was still sketchy, would require remote agitation and subsequent jacketing to isolate the product. The radioactive dust and oxide were hazardous, and volatile fission products would be discharged via a tall chimneystack when winds were favorable during the separation process.[12] The pile and separation facilities would be surrounded by some seven feet of concrete, and the leftover soup of products, still highly radioactive, would be stored indefinitely in shielded tanks. Scientists had planned to perform these operations remotely, with their vision restricted to a long, water-filled observation hole and periscope having a remotely adjustable mirror at its far end.

Met Lab's reliance on such hazardous and untested schemes unsettled the DuPont delegation, particularly when it learned that the lab's scientists had already moved forward in the planning for a third, full (rather than pilot) production pile. On the positive side, this third pile would enable a cyclical rather than a one-time batch-production process, thereby avoiding some of the wastage and complexity of laboriously building and remotely disassembling the pile. Yet this pile also had to be periodically unloaded of its uranium fuel by using a procedure that appeared to be complicated and dangerous. The proposed Pile 3 would generate some 100 times more plutonium, heat, and radiation, thus requiring active cooling by recirculated helium gas filtered to remove radioactive particles. The cylindrical reactor was designed for fuel rods to be withdrawn vertically by cranes and handled remotely for chemical processing.[13]

Moreover, a Met Lab group led by Wigner, Gale Young, and Leo Szilard also described its plans for a distinctly different fourth pile design, thus demonstrating the volatility of the design environment. Under considera-

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[12] By December 1942, Met Lab's plans called for each separation plant to be four miles from other facilities, with the "plant village for workers to be ten miles to windward of the nearest stack," a main highway or railroad ten miles away, and a town at least twenty miles from the nearest stack (Greenewalt Diary, vol. 1 [1942], 101). As a DuPont report later summarized, "each cubic foot of radioactive gas must be diluted with as many as 100 trillion cubic feet of atmospheric air to assure safe conditions"; see "100 Area facilities and operations," in Hagley, 1957 series 3, box 58, folder 5, September 1945. Subsequent experimental tests using oil smoke confirmed the potential dangers from inadequately dispersed stack emissions; see Peter B. Hales, *Atomic Spaces: Living on the Manhattan Project* (Urbana, Ill., 1997), 144–50. On the long-term concerns at Hanford, see Michele S. Gerber, *On the Home Front: The Cold War Legacy of the Hanford Nuclear Site* (Lincoln, Neb., 1997), chap. 4.

[13] Greenewalt Diary, vol. 1 (1942), 12–14, 32.

tion for scarcely a few weeks before DuPont came on the scene, the plans for Pile 4 were even more speculative than those for Pile 3. It would be cylindrical and use hollow uranium tubes with an aluminum lining. A fluid—possibly water, liquid bismuth, or a diphenylamine compound—would cool the individual uranium tubes. The engineers recognized that this design multiplied potential problems: water had a relatively high neutron absorption and would lower the reactivity of the pile and thus its ability to transmute plutonium; it also reacted corrosively with uranium, requiring the fuel to be encased in a protective sheath of aluminum. On the other hand, bismuth—a liquid metal at the reactor operating temperature—might be affected by high irradiation in unpredictable ways. And a diphenylamine hydrocarbon could polymerize or carbonize if overheated, thereby clogging the tubes, reducing coolant flow, and potentially causing a thermal explosion.[14]

Faced with ambitious goals, misplaced confidence, and a notable lack of engineering rigor in the existing plans, DuPont engineers were increasingly concerned and divided on the feasibility of the designs. Tom Gary, manager of DuPont's design division, and F. W. Pardee Jr., the supervising engineer of its engineering department, felt that Met Lab's planned production reactor had design flaws, questioning "whether it is even possible to build this unit—much less operate it—as designed at present." They estimated that it would require at least two years to engineer.[15] DuPont engineers were more impressed by Met Lab's ideas about a reactor based on a heavy-water moderator, at least in terms of its mechanical design and operating feasibility, and felt that it had been prematurely rejected merely because of an inadequate supply of heavy water. They informed Compton (and, at a later meeting, Groves and senior administrator James Conant, chair of the National Defense Research Committee) that the DuPont team placed its short-term confidence in a proposal by the University of California's Radiation Laboratory to design efficient *calutrons* (electromagnetic mass spectrographs to separate uranium isotopes) and argued that, for plutonium production, a heavy-water pile *designed collaboratively between physicists and engineers* was the option most likely to succeed. In the process of apportioning responsibility, DuPont proposed an intellectual shift in the balance of power, moving it away from precariously scaled-up science to an engineering discipline constructed from scratch.[16]

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[14] Ibid., 69. The specific diphenylamine compound was unidentified.

[15] Ibid., 68.

[16] The moderator (or "slow downer," as Greenewalt dubbed it [ibid., 3]) reduces the energy of neutrons to ensure their capture by a uranium nucleus and allow transmutation to plutonium. See ibid., 3, 45, 65–68, 88–91, 104; Crawford H. Greenewalt, "Stine's memorandum," in Hagley, 1957 series 1, box 1, 27 November 1942.

Wilmington Engineers versus Chicago Scientists

Despite their expectation that this unlikely project would be nipped in the bud, DuPont's managers continued to reassess their engineering conservatism in light of scientific enthusiasm. When Compton took Greenewalt to watch Fermi's prototype pile approach criticality (the operating point at which a self-sustaining nuclear reaction occurs), Greenewalt was swept along by the moment. As an engineer, he noted an amalgam of observations: how the neutron count "kept increasing by leaps and bounds"; how the pile "responds beautifully to control devices"; and how the neutron concentration in the room during the final "power flash" "rose well above the tolerable limit and the gamma radiation to just above the tolerable limit" for a daily human exposure. Overall, he recorded, it was "much better than expected. It was for me a thrilling experience."[17]

Encouraged by the demonstration, DuPont's executive committee decided to take on the Chicago project, establishing the "TNX" division in its explosives department, with chemical engineer Roger Williams assuming practical responsibility and Greenewalt's own role formalized by his appointment as technical director.[18] Within days, Greenewalt began to worry about the project's hierarchy. Groves had wanted him to serve as Compton's executive assistant, but Greenewalt opted instead to "stay in the DuPont setup" and "to 'watch' Compton and see to it that the research went in a way that would provide the right technical information at the right time." He realized, however, that without his having authority over the Chicago group, he would have to see to this through "diplomacy and pleading." Greenewalt knew he "couldn't successfully 'boss' the physicists" and thus welcomed Compton's acceptance of the relationship.[19]

The disciplinary ranking in the project had to be renegotiated. Meeting with Compton and his senior colleague Norman Hilberry, Greenewalt noted that Compton had set ideas regarding the difference between scientific and industrial research and decided to begin what he called "missionary work" to convince Compton that the difference was more a matter of terminology than otherwise. Greenewalt balked at the organization chart identifying a head of "developmental engineering," arguing that the Chicago engineering group should be small and consultative rather than experimental, and that such a project required DuPont supervision. And when he and Wilmington colleagues discussed the design of the second pilot-plant pile with Met Lab personnel, Greenewalt was exasperated to find their ideas sketchy and disorganized. He spoke privately to Compton's senior engineers Thomas Moore and Miles Leverett, deeming them to be equally discontented and dominated by the physicists. His Wilmington

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17. Greenewalt Diary, vol. 1 (1942), 111–14.
18. Ibid., vol. 2 (1942–43), 2.
19. Ibid., 3–4.

superiors agreed that DuPont must lead the engineering. This was to be an intentional colonization of engineering perspectives into a scientific stronghold: "I believe," Greenewalt recorded privately, "we must infiltrate pile design in spite of the fact we aren't very welcome."[20]

Within weeks of joining the project, the DuPont staff consequently began to make firm design decisions. Fermi's demonstration experiment had shown that even a large air- or water-cooled graphite pile would likely work as a chain reactor. Water was unappealing because of anticipated corrosion problems and helium cooling seemed worst of all, with its unsolved problems in unloading uranium fuel and the need for an airtight enclosure and efficient blowers to circulate helium, which was in short supply. Roger Williams correspondingly ordered his Wilmington pile designers to plan for an air-cooled graphite pilot pile, and to delay design of the production piles.

Even more peremptorily, Greenewalt made decisions affecting not just pile design, but locations also. Supported by Groves and Compton, he argued that Fermi's pile must be moved from the university grounds to a new location in the nearby Argonne forest—a safe distance from Chicago. He also directed that the second pilot-plant pile could not be built at Argonne, because of its much larger operating power—a thousand kilowatts rather than a handful—and the possibility of a catastrophic radiation release or sabotage.[21] Instead, the pile would be built at Clinton, Tennessee, a few miles from the Oak Ridge uranium-separation facilities being planned for the Manhattan Project. Compartmentalization of expertise offered cleaner working relationships: Greenewalt argued that Argonne should be dedicated primarily to the experimental work of physicists, while Clinton would be devoted to production. This single siting decision had enduring consequences for the division of U.S. nuclear expertise, which would henceforth be divided between Chicago/Argonne and Oak Ridge.[22]

Such bold decisions were made cautiously, however. Greenewalt was concerned that he had usurped Compton's authority, thus rendering overt the new egalitarian partnership envisaged by the engineers. As he predicted, the arrangements aggrieved many of Met Lab's physicists. The group planning the Argonne pilot plant—now to be relocated to the Tennessee hills—threatened to resign. Compton himself was upset that the Argonne site could not be used for both physics research and pilot-plant production. In February 1943 Groves and Greenewalt met with Met Lab group leaders to assuage the growing engineering–science rivalry. Greenewalt advanced his

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[20] Ibid., 5–12, quotes on 5–7.

[21] Physicist John Wheeler, a member of Compton's team, had calculated that if the control rods were pulled fully out, uranium metal could vaporize and deposit a lethal concentration of radioactivity over a five-mile-radius area, which was far too large for any feasible army evacuation plan of northern Illinois (ibid., 20, 73–75).

[22] The Argonne and Oak Ridge national laboratories became the centers of U.S. reactor expertise throughout the second half of the twentieth century.

disciplinary framework even further, casting the scientists as educators for the new field and as junior members of the production team. In effect, the roles of scientists and engineers would have to be more closely, perhaps indistinguishably, combined. He reported the atmosphere as "a bit tense."[23]

Yet the abrasive situation was not reducible simply to engineering versus science. DuPont's engineering conservatism, combined with near arrogance about project management, jarred against the more pragmatic experimental culture operating at Met Lab. Wigner, leader of Met Lab's theory group and a physicist with chemical engineering training, argued that his team's expertise was essential to guide every stage of the process: designing, constructing, testing, and operating a chain reactor to generate plutonium. As discussed by Abbott, such contestations over methodology, competence, and authority are more likely in such heterogeneous environments.[24] Wigner further argued that DuPont was too "diversified" to be able to do a good job on design and construction, and both he and Szilard threatened to resign from the project. Over the following weeks, subsequent meetings with Wigner led Greenewalt to record privately that he was "not too hopeful that he will ever see things our way."[25] To defuse potential intimidation of more junior engineers by the scientists, Greenewalt recommended segregation: DuPont engineers would stay in Wilmington, and his technical division would be the "leg men" responsible for liaison and transfer of information, thus bypassing entrenched hierarchies.[26]

The renegotiated science–engineering balance was supported by DuPont's distinctive corporate culture, which designed, constructed, and often operated its own industrial plants; most other U.S. chemical companies of the period subcontracted extensively.[27] As a result, DuPont engineers were not just a transitory nuisance for Met Lab scientists, they were in for the long haul. Through the first half of 1943 Greenewalt began to wax optimistic on piles and their possibilities. Meeting with Fermi and others about heavy-water piles, he mooted the postwar possibilities for the plutonium project, musing about piles as primary power sources for DuPont chemical plants and envisaging the design of small mobile reactors. Moreover, attending a celebratory dinner with Compton marking the six-month anniversary of the first fission, both chatted of peaceful applications, such as power generation and radioactive tracers for organic chemistry, the use of

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[23] Greenewalt Diary, vol. 2 (1942–43), quotes on 23, 85, 88; see also Hewlett and Holl, *New World* (n. 5 above), 186–88.

[24] Abbott (n. 2 above); on Wigner's assessment, see Sanger and Mull (n. 2 above), 16.

[25] Greenewalt Diary, vol. 2 (1942–43), 154, 168 (20, 31 March 1943).

[26] Ibid., 21–22. Greenewalt suggests that while Szilard was a loose cannon, Wigner was consistently a representative of the critical younger scientists; Wheeler, on the other hand, proved to be an effective intermediary between the Chicago and Wilmington teams.

[27] Thayer (n. 2 above).

the bomb for postwar peacekeeping, and the inevitability of government sponsorship. Such activities would require DuPont to expand its expertise in new directions.[28]

Hybrid Expertise: The Industrialization of Plutonium at Clinton and Hanford

The first opportunity for a genuine scientific and engineering collaboration was the pilot-plant pile at Clinton. Designed primarily by physicist Weinberg, one of Wigner's assistants, the Clinton pile, dubbed "X-10," impressed DuPont engineers as much as Met Lab scientists. Fermi's original pile at the University of Chicago had been detail-designed and procured by Stone & Webster, but had been planned and assembled by Met Lab staff. But X-10, as Greenewalt observed, showed impressive attention to details and mechanical precision. Responding to early DuPont critiques, it was the first engineered pile in existence.[29] Greenewalt's battles had ensured that a considerable number of Met Lab scientists were relocated to Tennessee to test and operate X-10, and to train a series of reactor operators for later transfer to Hanford's large production reactors. This close association sometimes relegated the scientists to subordinate or coequal roles with DuPont engineers and production workers, and provided an environment to disseminate the scientists' special expertise. Weinberg described the atmosphere as "more of a DuPont pilot plant than a University of Chicago research centre."[30]

Begun in April 1943, X-10 in Tennessee was followed by three production reactors at Hanford, with the first commencing operations in late 1944. But the planned Hanford facilities were markedly different from Clinton's pilot plant, because X-10 was air-cooled; each large Hanford pile used Columbia River water to dissipate a hundred times more heat, while generating proportionately more radiation and plutonium. In this new industrial environment DuPont specialists assumed a more senior role. Technical segregation was no longer an option: reactor technology on the industrial scale would be tackled by close association between DuPont engineers and scientists from the Met and Clinton labs.

Greenewalt, Compton, and Williams agreed that, during the start-up of the first pile, senior Chicago scientists would be needed, with Fermi "on tap." Even DuPont senior managers assumed low-status roles like shift supervisors—a model that impressed Met Lab scientists like Norman Hilberry.[31]

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[28] Greenewalt Diary, vol. 2 (1942–43), 88, 134, 239; Alice Kimball Smith, *A Peril and a Hope: The Scientists' Movement in America, 1945–47* (Chicago, 1965), 19.

[29] Greenewalt Diary, vol. 2 (1942–43), 342 (21 September 1943).

[30] Weinberg (n. 3 above), 48.

[31] Greenewalt Diary, vol. 3 (1944–45), 18 (15 January 1944); Sanger and Mull (n. 2 above), 26.

DuPont sought an integrated hierarchy, with lower-tier scientists assigned to the plants for the duration. The scientists were not eager to become industrial employees, however. The explanation of their director, Samuel Allison, to Williams illustrates the prickly status relations between the two organizations. Discussing the "considerable difficulty in finding physicists on our staff who are willing to enter the employ of the DuPont Company and thus assist in the operation of the Hanford plant," he identified three contributory factors relating to the hierarchy of engineering–science expertise. First, the physicists considered the "discovery of our process to be the greatest achievement of the science of physics," and felt that "an organization run by physicists should always have a prominent place in directing its development." By joining DuPont "as individuals in subordinate positions," he argued, "the prestige of physicists . . . is greatly diminished." Second, the younger scientists had been directed "by physicists of world-wide reputations," and they did not find any such men in prominent positions within Hanford's organization. And finally, most physicists preferred "an academic life to one on service to an industrial company," and "their chances of obtaining an academic position from that location would be distinctly poorer than they would be at the Metallurgical Laboratory which has direct University connections." Allison consequently proposed "loaning" the Chicago physicists.[32]

This encounter reveals the concerns of status and career progression in scientists' identity, and hints at more. As later recalled by one of the young Met Lab scientists, such resistance had the further aim of eliminating the salary differential between DuPont engineers and others at the same level.[33] Despite this stance, however, a growing number of scientists and engineers coexisted at Hanford, with close working relationships forged in the instrument and technical departments, whose skilled personnel came from senior staff at Wilmington's headquarters, a few directly from Argonne and Met Lab, and a large contingent from the Clinton lab. Indeed, half of the new department traced back to Compton's Met Lab, as carefully tracked by DuPont: the company was eager to ensure that experts were involved directly in identifying and solving start-up problems, and the supervisor's summary documented the hidden genealogy of scientists, engineers, and technicians who came to man the Hanford piles.[34] This "pile engineering" division also included "a stable working unit of capable physicists [as] an integral part of the plant organization."[35] Half of the physics section had

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[32] Samuel B. Allison to Roger Williams, Chicago, 13 March 1944 (Greenewalt Diary, vol. 3).

[33] Nathan Sugarman, quoted in Smith, 16–17. Indeed, Greenewalt had been instructed by Groves "not to discuss salaries with Chicago people since this brings about kicks as to disparity on salary matters" (Greenewalt Diary, vol. 2 [1942–43], 298).

[34] W. Overbeck, "Instrument Department Functions and Organization to July 1, 1945," in Hagley, 1957 series 5, box 50, folder 16, 14 August 1945, exhibit A.

[35] John Marshall, "Plant assistance (physics) to Jul 1 1945," in Hagley, 1957 series 3, box 58, folder 4, 17 September 1945.

been employees of Met Lab, with seven engaged in the construction and operation of the experimental piles at Chicago and Clinton.[36] The addition of analytical chemists and chemical engineers swelled the technical department's personnel to 1,009, including 275 engineers, 78 scientists, and 85 technologists.[37]

Despite this melting-pot environment, some divisions nevertheless remained between Met Lab scientists and DuPont engineers; for example, John Marshall recalled that physicists clustered socially, and David Hall observed that it was "kind of cliquey, with not much intermingling with DuPont." However, for Herbert Anderson, the successful working relationships were a revelation: "Friction between the DuPont people and the Met Lab scientists was always a problem [but] so many details have to be followed, and only by having a huge engineering organization can you attend to that."[38]

Scientific and engineering knowledge co-mingled at the site of the reactors. During the nine wartime months of operation, adverse physical phenomena were discovered, explained, and counteracted. The best-known example of the latent dangers in this unexplored terrain was the unanticipated drop in power from the first Hanford reactor after its first few hours of operation in November 1944. Physicists eventually ascribed the problem to a fission product, xenon-135, which proved to be a strong absorber of neutrons and so smothered the chain reaction. The reactor had been conservatively designed by DuPont engineers, with an excess of channels through the graphite for uranium fuel rods. When fully used, these compensated for the "xenon poisoning," therefore driving the chain reaction on.[39]

But this episode—an oft-told tale that vaunts scientific insight and problem-solving—was paralleled by other operational discoveries pursued by engineers. For example, the "Wigner disease" showed that the graphite bars of the reactor became distorted after intense irradiation by neutrons. After the first few months of operation there was already a perceptible bowing of the piles from expansion, and distorted fuel channels could jam fuel elements and potentially rupture. Further engineering problems with graphite continued to surface. By August 1945, just days before the drop-

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[36] S. J. Bugbee, "Technical Department Functions and Organization to 1 July 1945," in Hagley, 1957 series 3, box 58, folder 4, July 1945.

[37] "Hanford organization," in Hagley, 1957 series 1, box 2, folder 8. A handful of women—occasionally physicists themselves who joined the organization with their physicist husbands—also came to Hanford for senior technical posts. Notable among them were Leona Marshall Libby, an associate of Fermi and the only woman present at the first sustained chain reaction (see Libby, *The Uranium People* [New York, 1979]), and later an academic at the University of Chicago and New York University, and Jane Hamilton, later assistant director at Los Alamos. Some groups, such as the "instrument helpers" who assembled and repaired instruments, were entirely female.

[38] Sanger and Mull (n. 2 above), quotes on, respectively, 129, 132, 63.

[39] F. Gast and C. W. J. Wende, "Reactivity experience and control to July 1, 1945," in Hagley, 1957 series 3, box 58, folder 4, 20 September 1945. For scientists' account of the incident, see Compton (n. 10 above), 182, 191–94; and Weinberg (n. 3 above), 29–30.

ping of the atomic bombs on Japan, the supervisor of the piles, DuPont engineer Hood Worthington, was warning of a drop of 30 percent in thermal conductivity and a comparable increase in breaking strength. Both, he feared, could prove catastrophic. Worthington characterized the loss of conductivity as "the most severe heat transfer problem ever encountered," and the increase in breaking strength for the graphite suggested that brittleness might ensue, which could result in disintegration or crumbling of the graphite. For this, no curative measure seemed likely, apart from rebuilding the piles from scratch.[40]

Yet another concern was the "Szilard complication." Szilard had suggested that energy would be stored in the graphite by neutron collision in a fashion analogous to the cold working of metals. Local overheating might then release this energy suddenly with catastrophic effect, a situation that DuPont engineers avoided by higher-temperature operation to anneal the graphite. DuPont continued to operate the piles, but warned administrators that their operating lives were limited. DuPont's matter-of-fact site history, written in the house style employed for all of its industrial plants, noted that "the production facilities at Hanford that DuPont turned over to General Electric had major operational problems." These episodes identify the Hanford reactor as a large-scale experiment in which the engineers confirmed scientific hypotheses and pressed for more detailed empirical investigations.[41]

The combined actions of Met Lab and DuPont personnel, then, were seminal in defining the expert character of U.S. reactor technologists. A grudging cooperation developed at the shared worksites, breeding specialists who were unlike prewar models of physicists and industrial chemists. At these sites, expertise was acquired and disseminated through the first formal courses and on-the-job training and was segregated by security rules. From these wartime roots, U.S. nuclear engineering developed into a unique form.[42]

Nevertheless, the Hanford experience appeared unpromising as the launching pad for a new intellectual field based on reactor technology. The contingency of the enterprise was appreciated by all: meticulous industrial planning allied with uncertain physics; chronic pessimism among several of its key actors; and unsettling discoveries after just a few months of oper-

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[40] Hood Worthington, "Pile technology—effect of operation on graphite moderator (Wigner and Szilárd effects)—experience to Aug 1, 1945," in Hagley, 1957 series 3, box 58, folder 4, 13 September 1945; "100 Area facilities and operations" (n. 12 above).

[41] Greenewalt Diary, vol. 2 (1942–43), 295 (28 August 1944); "Hanford Story, chap 7, 8," in Hagley, 1957 series 5, box 50. The "Szilard complication"—not revealed to Anglo-Canadian members of the Manhattan Project—was the cause of the 1957 fire and radioactive release at Windscale, UK, which destroyed one of its two air-cooled production piles.

[42] On the influence of training, see Sean F. Johnston, "Implanting a Discipline: The Academic Trajectory of Nuclear Engineering in the USA and UK," *Minerva* 47 (2009): 51–73.

ation, revealing that the piles were aging rapidly and unpredictably. The ongoing interaction between the engineers and scientists was an abrasive hodgepodge of deep research, urgent mitigation of known problems, and fallback planning for further contingencies. DuPont engineers, as much as Met Lab scientists, were eager to end this bumpy collaboration as soon as wartime duties allowed; postwar activities, it seemed, would have to be scaled down, slowed, or abandoned.

Consolidating Postwar Expertise: DuPont's Atomic Energy Division and the Savannah River Plant

As this narrative suggests, the distinct categories of technical expertise were distributed along an industrial–academic axis. Chemical engineers had directed some aspects of the wartime nuclear work; indeed, the term "reactor" has a longer lineage in the technical culture of chemical engineering than in that of nuclear physics. The confrontations between DuPont engineers and Met Lab scientists owed more to institutional cultures than to personality conflicts; the same was true for the American companies that became associated with postwar nuclear energy. Indeed, from 1946, when the AEC assumed responsibility for what the Manhattan Project had begun, the entire field was unusually malleable and nuclear engineering continued to be shaped by the particular constellation of companies and national laboratories involved.[43]

The DuPont Company had entered into its Manhattan Project responsibilities without enthusiasm. The Chicago process required a significant fraction of its resources, but profit-making had not been pursued; the company was still sensitive to its identification in 1936 as a "merchant of death" profiteering from World War I munitions manufacturing.[44] DuPont required profits, however, and its managers carefully considered the possibilities of commercial atomic energy and the technical expertise required while making its postwar plans. Greenewalt was seduced by conversations with Met Lab scientists, encouraging him to weigh up DuPont's involvement in postwar atomic energy. On the "pro" side, he noted that "this is a new field of

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[43] Hewlett and Holl, *Atomic Shield* (n. 1 above); Allan A. Needell, "Nuclear Reactors and the Founding of Brookhaven National Laboratory," *Historical Studies in the Physical Sciences* 14 (1983): 93–122; Leland Johnson and Daniel Schaffer, *Oak Ridge National Laboratory: The First Fifty Years* (Knoxville, Tenn., 1994); Jack M. Holl, *Argonne National Laboratory, 1946–1996* (Urbana, Ill., 1997); Robert W. Seidel, "The National Laboratories of the Atomic Energy Commission in the Early Cold War," *Historical Studies in the Physical and Biological Sciences* 32 (2001): 145–62; Peter J. Westwick, *The National Labs: Science in an American System, 1947–1974* (Cambridge, Mass., 2003).

[44] The Special Committee on Investigation of the Munitions Industry, or Nye Committee (1934–36), of the U.S. Senate documented the profits of the U.S. chemical and munitions industries and led to the popular conclusion that the country's entry into World War I had been predicated on, and engineered by, commercial interests.

great scientific importance in which DuPont has some specialized knowledge which may lead to commercial or by-product developments," and that the advertising value of publications in the field could improve the company's university relationships and recruitment; on the "con" side, however, Greenewalt noted that "suitable physics personnel will be difficult, if not impossible, to get," and prospects looked better for other kinds of fundamental and applied research, because "no commercial applications can be foreseen now or even guessed at except perhaps in the field of luminous or sterilizing paints." Indeed, he judged the chance of recovering money spent to be "very remote," with patents not likely to be exploitable before they ran out. None of those possibilities included plutonium manufacture.

Greenewalt's analysis hints that he had not conceived nuclear workers as being a new kind of specialist at all ("organization might comprise a director [preferably a physicist], 1 theoretical and 5 experimental physicists and 4 chemists"). Despite enthusiasm for the novelty of the new domain, DuPont decided that other commercial fields—notably the marketing of nylon and other synthetic fibers and films—offered greater postwar profits. At the contract's completion in 1946, DuPont turned over management of the Hanford Engineering Works to the General Electric Company (GE).[45]

The contingent evolution of an industry and associated specialists is best illustrated by the experience of DuPont at the second major U.S. industrial atomic-energy project, at Savannah River. Together, the Hanford Engineering Works and Savannah River Plant were the largest U.S. reactor installations for a quarter-century. And—being designed for production, not research—they were seminal in creating a cohort of reactor designers, nuclear-process workers, and working environments based upon the DuPont model.

In late 1948 Greenewalt, now president of DuPont, was approached by the AEC to undertake a review of all chemical processes bearing on plutonium production. Unlike its Manhattan Project duties, the examination of uranium recycling, plutonium-separation chemistry, and handling of fission products and wastes appeared to fit comfortably within DuPont's organizational remit. As the DuPont survey was being completed in the summer of 1949, however, the political context shifted under the company's feet. That autumn, with the explosion of the first Soviet atomic bomb and the success of Mao Zedong's forces in China, the Truman administration and the AEC sought to recast the nuclear-energy program to ensure a larger and diversified military stockpile. In early 1950, DuPont consequently was asked to plan another plutonium facility to parallel Hanford's capacity.

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[45] Greenewalt Diary, vol. 2 (1942–43), 254 (27 July 1944). On the early GE experience, see General Electric, "Four years at Hanford," U.S. Department of Energy Declassified Document Retrieval System (online database), available at http://www5.hanford.gov/ddrs: Hanford Engineering Works archive D19803392, 1951; Richard G. Hewlett and Jack M. Holl, *Atoms for Peace and War, 1953–1961* (Berkeley, Calif., 1969).

Plans for the plant site, near Aiken, South Carolina, were announced that November as the Savannah River Plant (SRP).[46]

The company again undertook the design, construction, and operation project as a cost-plus-fixed-price contract. The project is notable in several respects: it incorporated a wide-ranging survey of the rapidly expanding state of the art, revealing the range of expertise then available; it adopted technical solutions at variance with the military projects then under way, thus expanding the U.S. state of the art in new directions; and, finally, it constructed the first postwar American model for an industrial nuclear workforce.

While responsibility for the SRP was seen more as a national duty than a commercial opportunity, DuPont laid the groundwork for future directions. The company set up an atomic energy division (AED) within its explosives department, like its wartime TNX division. DuPont's AED conformed to the company's traditional management structures, but it also established posts, administrative niches, and network nodes for the new expertise in atomic piles. This would not be a rerun of its wartime activities. As R. M. Evans, the assistant general manager of the AED, explained to the AEC manager overseeing the new facilities, DuPont would be responsible for all aspects of the project, including its science-based design. Its explosives department would have prime responsibility, defining the scope of work and specifying the process requirements, in addition to operating the functioning plant; the engineering department would occupy the role of architect-engineer and general constructor, and its design division would develop the final design and handle procurement; and the construction division would perform the field construction.[47]

This integrated management structure for the AED required, however, the nurturing of atypical DuPont personnel, of which some had had experience at the wartime Clinton and Hanford sites and others were young engineers and physicists chosen to expand company expertise in atomic energy. Worthington, the assistant manager of the technical division, had served as chief supervisor of the Hanford piles, a role involving both technical expertise and administration.[48] Worthington was to be responsible for

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[46] "Press release," in Hagley, 1957 series 1, box 2, folder 9, 22 December 1948; R. Genereaux, "Object of survey," memorandum, ibid., 29 December 1948. The wartime state of the art had been recognized by all parties privy to the secrets to have "critical process defects," including the wasteful treatment of uranium—simply by depositing slightly depleted uranium in underground storage—and production of radioactive byproducts along with plutonium, a large proportion of which accumulated in bulky and dangerous form.

[47] H. F. Brown, "Atomic Energy Division," 2 August 1950; Brown, "Atomic Energy Survey Committee," 11 July 1950; and letter, R. M. Evans to C. A. Nelson, 9 August 1950: all in Hagley, 1957 series 2, box 6.

[48] Worthington (n. 40 above). Alternately described as chemist, chemical engineer, and consulting nuclear engineer between the late 1940s and 1960, Worthington's occu-

reactor development at the SRP. Physical chemist Dale Babcock had been involved in the start-up operations of the Hanford piles. And C. W. J. Wende, a technical specialist at wartime and postwar Hanford, was to become the most active senior pile designer for the SRP. Most of those assigned to key posts were transferred from other DuPont commercial plants and laboratories, but new titles highlighted the new activities: within months, personnel called "atomic engineering managers" (more for their division association than for functional responsibilities) were recruiting new employees and identifying AEC contacts.[49]

Seeking Expertise in Pile Networks

Despite this concentration of DuPont experience, most of these senior personnel had lost contact with the growing field since 1946, when the company's responsibility for Hanford had ended and a blanket of security concealed new developments. During the years immediately following the war, a clear notion of the scope and content of nuclear engineering had not emerged at Hanford or other industrial sites, which remained almost completely obscured to public view and, indeed, to contemporary analysts. During the intervening four years, the AEC had established burgeoning projects in the research and development (R&D) of atomic piles, and also the technoscientific staff to support them. The new national laboratories more publicly took the reins, compartmentalizing R&D and reasserting the ascendancy of the scientists. For Zinn's Argonne National Laboratory, the successor to Met Lab, engineering was segregated to a separate "reactor farm" in Arco, Idaho (later known as the Idaho National Engineering and Environmental Laboratory). As Zinn put it: "the testing station will be a place to build reactors and get experience in their operation, rather than to do experiments such as will be done on the research reactor at Argonne by the physicists, chemists and biologists. The reactors at Idaho will provide space for engineering types of experiments."[50]

The SRP administrators consequently explored the institutional and intellectual networks of expertise concerned with designing piles. The AED's technical division began a flurry of activity to liaise with AEC experts to

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pational label changed more than did those of his counterparts in the national laboratories, such as Zinn's and Weinberg's.

[49] See, for example, the following letters: G. Church to E. M. Cameron (Hagley, 1957 series 3, box 12, folder 3), 13 December 1950; and R. W. Fulling to F. C. VonderLage (Hagley, 1957 series 3, box 12, folder 6), 14 May 1954.

[50] The official history of the Idaho National Engineering and Environmental Laboratory is Susan M. Stacy, "Proving the Principle," available at http://www.inl.gov/proving-the-principle/ (accessed 12 June 2009); "Minutes of Board of Governors' Meeting, ANL," University of Illinois archives, Urbana-Champaign, box 19, Board of Governors' Minutes, 2 May 1948.

channel their expertise into industrial implementation. This was, in some respects, an amplified version of the wartime model: Met Lab had served first as designers, then trainers, and finally consultants for DuPont engineers, the shifting relationships having been facilitated by staff members serving as technical liaisons—notably Greenewalt for DuPont and Wheeler for Met Lab, with dozens of personnel from both organizations gaining scientific and engineering experience, respectively. In the same way, the engineers of the AED sought the heirs of Met Lab personnel, and they found them principally at the Argonne and Oak Ridge national labs, successors to the University of Chicago's Met and Clinton labs. Unlike the wartime roles, however, the SRP was understood as a sustainable operation that would require a career workforce enrolled in an engineering perspective.[51]

The AED engineers shuttled between Wilmington and the Argonne, Oak Ridge, and Brookhaven national labs during 1950 to discuss design details of the SRP reactors, fuel elements, and plutonium separation. After a visit to the Knolls Atomic Power Laboratory, a postwar GE facility focusing on atomic-power applications, Wende was surprised at how little information was available and how much material was yet hidden. He noted that GE had conducted a training course for pile engineers several years previously that had covered "much material which is not otherwise available in coherent form." He petitioned the AEC for a selection of classified materials that addressed topics like pile physics and engineering, metallurgy, separations engineering, and separations chemistry that would cover the basic sciences and pertinent developments for the Wilmington engineers, and permission to build a classified information service for use by the DuPont designers and eventual plant personnel. Security, which cloistered information at the national labs, proved a recurring constraint on the development of facilities and expertise at the SRP.[52]

The question of knowledge transfer was a perennial one for DuPont. An early intention of SRP administrators was that a half-dozen or more DuPont designers would be educated by the most formal route then avail-

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[51] Management of Clinton lab had been transferred from Met Lab to the Monsanto Chemical Company in 1946. While Monsanto had a chemical engineering orientation like that of DuPont, its Oak Ridge National Laboratory, with Wigner serving as director of research, focused initially on reactor concepts rather than development. Following disagreements about lab remit and direction, management reverted to the University of Chicago in 1947. See Hewlett and Holl, *Atomic Shield* (n. 1 above), 68–79.

[52] C. W. J. Wende, "Meetings at Argonne, September 13–15 1950," 26 September 1950; John C. Woodhouse, "Brookhaven fuel elements," 21 September 1950; F. S. Chambers, "Manpower requirements for separation work at ORNL," 19 September 1950; C. W. J. Wende, "Visit to Argonne, September 28–29, 1950," 20 October 1950—all in Hagley, 1957 series 4, box 44, folder 1. See also C. W. J. Wende, "Visit to Schenectady, November 7 and 8, 1950," in Hagley, 1957 series 4, box 44, folder 2, 27 November 1950; and Hewlett and Holl, *Atoms for Peace and War* (n. 45 above), 184–85. On secrecy, see Sean F. Johnston, "Security and the Shaping of Identity for Nuclear Specialists," *History and Technology* 26 (forthcoming 2011).

able: at ORSORT, the newly established Oak Ridge School of Reactor Technology, populated principally with the physicists who had worked on the wartime Clinton and Hanford reactors. But as its director cautioned a prospective student, this was a demanding course: "Competition among the students is keen and generally stimulating; therefore, the advantage of prior knowledge is emphasized. In particular, a working knowledge of mathematics through the solution of boundary value problems is essential. . . . Factual knowledge and a familiarity with elementary concepts in atomic and nuclear physics are also essential."[53] Few DuPont staff members, it seemed, had the requisite skills. Only Harry Kamack, a research project manager in chemical engineering with Manhattan Project experience, was admitted to ORSORT from DuPont's first group of seven candidates. Adapting the company to a self-sufficient workforce in nuclear engineering thus required a shift to embrace the expertise of physicists.[54]

As Kamack reported to his superiors, the one-year course covered topics essential for industrial reactor design, which included an analysis course on the theory of nuclear reactors, a technology course featuring lectures on engineering problems experienced in the design of piles, and a materials course that looked at the properties of materials used in pile design. The ORSORT program featured a final project in which small groups undertook the design of a reactor.[55] Even so, he was aware of the lack of consensus in the field, with "many of the lecturers [having] decided opinions about what is the best type of reactor, or reactor material, etc for the future, and these opinions [varying] considerably from one man to another."[56]

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[53] Letter, F. C. VonderLage to H. J. Kamack, in Hagley, 1957 series 3, box 12, folder 4 ("ORSORT 1953–54"), 21 May 1953; D. F. O'Connor, "Hanford Personnel and Training Program," in Hagley, 1957 series 2, box 12, folder 3, 31 August 1950.

[54] Harry J. Kamack (1918–2009) had joined DuPont in 1942 and was assigned to its TNX design group in 1943, serving at Met and Clinton labs and then at Hanford. After his ORSORT training, he was to play a senior role in the design of the SRP reactors. From among the forty-four government-sponsored students in that cohort of eighty, he noted that twenty-nine were from twenty private companies and fifteen from six government organizations, including the Bureau of Ships, Naval Reactors Branch, Naval Research Laboratory, U.S. Air Force, U.S. Army, and the Tennessee Valley Authority. The largest industrial groups included five students from Westinghouse, three from GE, and three from the Electric Boat Division of General Dynamics. The industry students were mostly engineers—mechanical engineers being the largest single group—with a few chemists and a fairly large group of physicists. See Kamack, "Report on year of training at Oak Ridge School of Reactor Technology—1953–1954," in Hagley, 1957 series 3, box 12, folder 4 ("ORSORT 1953–54"), 8 September 1954.

[55] Harry J. Kamack, "ORSORT curriculum," in Hagley, 1957 series 3, box 12, folder 4 ("ORSORT 1953–54"), 10 June 1953.

[56] Harry J. Kamack, "Report on first term of ORSORT year," in Hagley, 1957 series 3, box 12, folder 4 ("ORSORT 1953–54"), 20 January 1954.

Shifting Hierarchies: Engineers as Research Instigators

In this urgent postwar environment DuPont engineers were again playing catch-up to physicists. Ongoing disagreements between the successors to the wartime Met Lab scientists and DuPont engineers reveal, however, the evolving nature and shifting responsibilities of the specialists who were beginning to call themselves "nuclear engineers." While reliant initially on knowledge transfer, the AED engineers challenged scientific authority in their bid for self-sufficiency.

Early in DuPont's 1950 contract to survey plutonium-production processes, it had been decided that any new reactors should be moderated by heavy water, rather than by the graphite used in the wartime Clinton and Hanford piles—as the DuPont consultants had advised in 1942. The Hanford piles had revealed the capricious properties of graphite as an engineering material, and the stockpile of heavy water could now be augmented by new production facilities.[57] Moreover, the manager of AEC operations for the SRP, Curtis Nelson, had been a colonel in the Manhattan Project. He served at Hanford and then as the AEC liaison officer at Canada's Chalk River site, where he became familiar with its heavy water–moderated reactor technology.[58] His lobbying supported DuPont's own engineering analyses.

The company's engineers accepted the design and construction of large heavy-water production plants at the SRP as a relatively routine task in industrial chemical engineering, but the challenge of heavy-water reactors was another matter. The technology was beyond their experience, and the close reliance of the SRP designers on Argonne experts mirrored, in some respects, the wartime experiences between DuPont and Met Lab; indeed, some of the same personnel were involved. The episodes reveal the distinct perspectives operating at the national labs and production facilities, and, by extension, the differentiation of what could be called "nuclear applied science" at the national labs from "nuclear engineering" as conceived at DuPont.

Wende was conscious of the scientific uncertainties underlying some of the necessary engineering choices. Four months after beginning his round of visits to the national labs, he reported to Worthington about an unexplained transient phenomenon in Argonne's heavy-water research reactor. Worthington, in turn, wrote to Zinn for further information, recalling the discovery of the suite of problems with the first Hanford reactor and not-

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[57] The heavy water plant at Trail, British Columbia—a by-product of a large electrolytic hydrogen plant—produced about six tons annually by 1950, having generated sixty tons altogether, of which thirty remained (Hagley, 1957 series 5, box 53, folder 10 ["Dana History, Startup through December 1952, 1953"]).

[58] J. Walter Joseph and Cy J. Banick, "The Genesis of the Savannah River Site Key Decisions, 1950," in *50 Years of Excellence in Science and Engineering at the Savannah River Site: Proceedings of the Symposium, May 17, 2000* (Aiken, S.C., 2000), available at http://www.c-n-t-a.com/srs50_files/001joseph.pdf.

ing his concern about the consequences for unexplained science in an industrial design. Zinn, perhaps sensing a destabilization of scientific authority akin to the wartime Met Lab troubles, telexed dismissively that the "behavior [is] probably understood but perhaps not quantitatively. In any case it is not behavior which we would expect from the equipment you have under consideration."[59]

Although he was junior in status to both Zinn and Worthington, Wende doggedly pursued the issue with Wigner, who had moved to Oak Ridge after the war, and Wheeler—both veterans of the wartime skirmishes and, with Zinn, the most senior of U.S. reactor experts. At his next trip to Argonne, Wende reiterated that DuPont engineers wanted to continue analyzing this effect, citing the experience with xenon poisoning "as a case where failure to analyze a small effect in the Clinton pile had resulted in a nearly catastrophic failure to predict a large effect in the Hanford piles." And in a separate discussion of experimental tests, Wende again admonished Zinn with historical precedent, noting the inadequate exploration of the Wigner and Szilard effects in graphite:

> The measurements so far were barely enough to begin to show us where some of the problems are; and that, rather than to terminate such experiments, it was our feeling that they should be continued and probably expanded into full-scale critical experiments. The history of exponential experiments in graphite lattices was cited as an error of omission, which should not happen again: namely, that such experiments were dropped by the Met Lab in 1944, and that much important information was not discovered about these systems until the group at Hanford undertook such work in 1949–50.[60]

The same visit generated yet another technical confrontation when Zinn asked why Wende had been advocating for graphite piles, rather than for a heavy-water version. Wende returned to the gulf between scientific explanation and engineering implementation: "While the heavy water piles have the potential advantages of greater flexibility and greater excess neutron production, these advantages are potential and not demonstrated; and Argonne's work over the past six months has certainly demonstrated that major areas of ignorance exist which will not be cleared up until many months after the first heavy water pile is started up."[61] The episode reveals

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[59] Letter, Hood Worthington to Walter H. Zinn, 21 December 1950, and telex, Walter H. Zinn to Hood Worthington, 21 December 1950, both in Hagley, 1957 series 4, box 54, folder 2.

[60] C. W. J. Wende, "Visit to Argonne, January 3 and 4, 1951," in Hagley, 1957 series 4, box 44, folder 2, 12 January 1951.

[61] Ibid.

attitudes that had been seeded during the war: Wende, an experienced though relatively junior engineer in a technologically conservative company, was prepared to challenge the most senior pile scientists in the country. His criticism did not concern scientific detail, but the manner in which Argonne personnel related ongoing exploratory research to engineering decision-making. Their science, involving the interplay of subtle physical phenomena with large-scale materials, was engineering in orientation, but not in style. Argonne's brand of applied science, claimed Wende, was not engineering and was not a viable match to DuPont's drive for industrial reliability.[62]

Conclusion

Over more than a decade DuPont found itself at odds with developing U.S. scientific practice in atomic energy. Both in 1942 and again in 1950 the company assumed responsibility as integral designer, builder, and operator of plutonium-production reactors with the diffident cooperation of physicists. The company had little corporate intent or technical expertise in nuclear technology, and its specialists were imperfectly configured to mesh with the limited training provided by the physicists either at wartime Oak Ridge or postwar ORSORT. Skirmishes nevertheless allowed the engineering perspective to advance and erode existing hierarchies of knowledge and practice.

Atomic piles forced DuPont to accommodate a new specialty. Both Hanford and the SRP demanded adaptations of DuPont's working culture. By the end of the 1950s, the SRP had a technical profile quite unlike other DuPont operations: while a typical 29 percent of its operations workforce consisted of managerial, engineering, scientific, and other professional personnel, engineers outnumbered scientists by only a factor of two. Both production sites promoted an engineer-led, physics-supported working environment—the inverse of Argonne—and the SRP evinced a dominance of the engineering perspective that had struggled to assert itself at Met Lab and Oak Ridge, and that had scarcely attained parity with science at wartime Hanford.[63]

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[62] The SRP did not acquire its own research or pilot-scale reactors, but cooperation with other sites within the nuclear establishment continued under the supervision of the AEC. As specified by DuPont, "a permanent nucleus [of SRP experts] is expected to maintain contact with other research centers within the AEC framework and to advise the plant technical forces on process improvement and development work"; see letter, R. M. Evans (assistant general manager of the atomic energy project) to Curtis A. Nelson (operations manager of the AEC), 9 August 1950, Hagley 1957 series 2, box 6, File—Adminstrative policy correspondence, general, 1950–1963.

[63] Some 12 percent of them were engineers and 6 percent were biological, medical,

These episodes suggest a relatively ponderous adaptation of DuPont to the new field of nuclear engineering, one that, as Melvin Rothbaum has argued, was more readily taken up by GE. Instead of viewing the nuclear reactor, as DuPont did, as a versatile and malleable collection of plants for producing a chemical product, GE viewed it as a product in its own right, akin to the industrial transformers and generators by which it had made its fortune.[64] Evidence suggests that this was not merely a matter of differing engineering cultures, but also of corporate reluctance. In 1956 the AEC asked DuPont to apply the expertise it had gained from the SRP to the design of heavy water–based power reactors (broadly similar in principle to Canada's evolving CANDU designs).[65] The slow progress of DuPont's AED engineers, however, required the AEC to reduce its pressure, shifting from a goal of an operating reactor by 1962 to open-ended design studies. Eventually these also were abandoned, and with them DuPont's potential influence on nuclear-power engineering.

Nevertheless, DuPont was committed to nuclear engineering as a viable profession in a way that the national laboratories at Argonne and Oak Ridge were not. Where Met Lab and postwar Argonne had compartmentalized and segregated scientific and engineering expertise, DuPont's facilities sought to integrate them during the war, and to subsume them within the new specialist field of nuclear engineering after the war. While other U.S. companies, notably GE and Westinghouse, benefited indirectly from this early appropriation of authority in reactor design, it was DuPont's organization of a reactor workforce involving engineers, technicians, and supporting scientists that shaped the U.S. nuclear environment.[66]

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or physical scientists, most with bachelor's degrees. The works technical section, combining engineers, chemists, and physicists with responsibility for technical, scientific, and safety issues, employed most of this new breed. See Atomic Energy Commission, "SRP Fact Book," in Hagley, 1957 series 5, box 54, folder 15, 25 November 1960.

[64] DuPont, with its working culture of "almost haphazard, cut-and-try methods" drawn from chemical engineering and industrial chemistry, was replaced by GE and its electrical engineering systems approach; see Melvin Rothbaum, *The Government of the Oil, Chemical, and Atomic Workers Union* (New York, 1962), 45–58, 88–90, 109–20, esp. 109. See also Ronald W. Schatz, *The Electrical Workers: A History of Labor at General Electric and Westinghouse, 1923–1960* (Urbana, Ill., 1983). On Westinghouse's adaptation to new fields, see Thomas C. Lassman, "Industrial Research Transformed: Edward Condon at the Westinghouse Electric and Manufacturing Company, 1935–1942," *Technology and Culture* 44 (2003): 306–39; and "History of the Savannah River Laboratory Volume III—Power Reactor and Fuel Technology," June 1984, in Hagley, 1957 series 5, box 54, folder 12.

[65] Robert Bothwell, *Nucleus: The History of Atomic Energy of Canada Limited* (Toronto, 1988); Wilfred Eggleston, *Canada's Nuclear Story* (Toronto, 1965); Ruth Fawcett, *Nuclear Pursuits: The Scientific Biography of Wilfrid Bennett Lewis* (Montreal, 1994).

[66] Westinghouse built the reactor of the first nuclear submarine, the USS *Nautilus*, launched in 1954, based on a design developed with the Argonne National Laboratory. In April 1989 it assumed management of the SRP from DuPont.

DuPont's Met Lab, Oak Ridge, Hanford, and SRP experiences were, then, emblematic of the shifting attitudes about nuclear-energy specialists in the United States. The "atomic scientists" so visibly representing the postwar field belied the reality of nuclear energy: U.S. engineers were claiming a position *beside*, not *subordinate* to, their scientific colleagues. Expertise was to be distributed and production would be reliant on specialist workers trained within the AEC network according to traditions emerging from the Argonne and Oak Ridge national laboratories—and DuPont.