GORDON TEAL

Figure 1. Gordon Teal, born 10 January 1907, is a recipient of the IEEE Medal of Honor, a member of the National Academy of Engineering, and a current resident of Dallas, Texas.

CHAPTER 4

Finding the Right Material

Gordon Teal as Inventor and Manager

In 1930 Robert Williams, the head of the chemistry department at Bell Telephone Laboratories, spelled out the role of chemistry research for AT&T: "In the Laboratories chemists act chiefly as advisors and critics. They concern themselves with such problems as the theory of chemical structure as related to dielectric properties and simultaneously attack the task of making an improved substitute for gutta-percha which renders possible a transatlantic telephone."[1] He went on to identify some of the other outstanding research projects, all of which were devoted to enhancing the durability of telephone equipment. He closed his list with a discussion of finishes for telephones and measures to extend the life of telephone poles.

In fact, chemistry was more relevant to electrical engineering than Williams suggests. Michael Faraday's interest in the subject, as well as that of Thomas Edison, speaks to the fundamental link between the two fields. Graduates of the first electrical engineering bachelors degree programs, such as the one at the University of Wisconsin designed in the late nineteenth century by noted EE educator Dugald Jackson, were required to complete one year of rigorous chemistry instruction. The early success of General Electric at the beginning of this century was due in no small part to chemical breakthroughs in filament manufacture. At Bell

Labs, however, where electrical engineering and physics were the principle activities, chemistry had only marginal status in 1930.

Thirty-two years later, scientist Richard L. Petritz, in an article entitled "Contribution of Materials Technology to Semiconductor Devices," pointed out that materials technology, the burgeoning discipline that had evolved from chemistry, was one of the basic disciplines underlying the design and development of solid-state electron devices.[2] Inasmuch as those devices were already well on their way to revolutionizing electrical engineering, Petritz's observation indicates that the relation of materials science to electrical engineering had changed dramatically from the time Williams wrote the passage above. That transformation, one of the most important in electrical engineering history, is well illustrated by the work of one of its central figures, Gordon Teal. Teal distinguished himself as the inventor of the first processes to grow germanium and silicon junction transistors, and also as a leader of scientific research and manager of science in the industrial context. His career exemplifies many important aspects of the research scientist's role in technological development in the mid twentieth century.

Early Days

Gordon Kidd Teal was born on 10 January 1907 in South Dallas, Texas. His father, Olin Allison Teal, had come to Texas in 1897 from Georgia, ready to make a go of running a five-and-dime store that Olin's uncle had established sometime earlier. The two men did well, and soon a "Duke and Teal's" could be seen in many Texas towns. Olin left that business in 1910 to begin a real estate enterprise, which also thrived. The Teals prospered, at least until the Great Depression, and the family lived free from want.[3]

The Teals lived in a simple community and were dedicated members of the First Baptist Church of Dallas. Gordon's father, who became deacon in 1905, brought his three children—Gordon, his older sister, and his younger brother—to church every week. Young Gordon accepted the church's teachings and became a faithful Baptist.

Olin Teal provided an academically stimulating atmosphere for his children. Born into humble circumstances and receiving only home instruction prior to attending high school, Olin nevertheless managed to graduate from college, distinguishing himself with high marks in Latin, French, and mathematics. He supported himself as a substitute school teacher and completed his courses in only two years and a summer session. He was not particularly scientifically inclined, but Olin's example set a standard of excellence for his children to emulate. Gordon's mother, Azelia, reinforced that message by assuring her son that he was especially capable. With hard work, she promised him, he could live up to the model of his father.

She encouraged his boyhood interest in science, and when he was in high school, told him he had the gifts to be the best at it. Teal, inspired by his mother's praise, applied himself to exceed her expectations. He graduated in 1924 from the Bryan Street public high school as valedictorian, having earned the highest marks of any student in Dallas.

With his successful high school experience, Teal hoped to attend the most prestigious school he could. He looked north, to the Massachusetts Institute of Technology. His mother, however, entreated him to remain close to home and attend a Baptist school. He agreed to try Baylor University for one year. The school appealed to Teal, and he met a woman there, an outstanding student named Lyda Smith whom he was eager to stay close to. So, without complaint, Teal agreed to finish his education at Baylor.

At Baylor, Teal concentrated on math and chemistry, two subjects he both enjoyed and excelled in. Engineering was not offered at Baylor, and Teal elected not to take physics courses so that he might better focus on his chosen fields. He studied assiduously and achieved high marks. Academic dedication did not prevent him from exploring a variety of pastimes, however. He led the Latin club and the Baylor chapter of the Kappa Epsilon Alpha Honor Scholarship Society as president, and served as vice president of his senior class. He ran on the track team and took great pleasure in being a member of the Baylor Chamber of Commerce. In 1927 Teal graduated from Baylor with a double major in math and chemistry.

MIT still tempted Teal, and in his last years at Baylor he began planning to continue his studies there. Split between his twin interests of math and chemistry, he finally selected the latter as his preferred subject. The tangibility of chemistry held greater appeal to his practical sensibilities than did math. One of his chemistry professors at Baylor recommended that Teal consider Brown University over MIT. Teal investigated, and developed a positive feeling about the program there after meeting the head of the department, Dr. Charles A. Kraus. Brown offered Teal a full scholarship to attend, and Teal, who was eager to spare his family the expense of additional schooling, again put off MIT. In the fall of 1927, he headed to Providence, Rhode Island, to begin his graduate work in chemistry as an Edger L. Marston Scholar.

The late 1920s was a dynamic time for chemistry. Advances in quantum physics offered a radically new picture of atomic processes, and chemists had an opportunity to use these to deepen their understanding of familiar atomic processes.[4] When Teal arrived at Kraus's lab at Brown, however, he found many of the students there were instead working along more traditional lines to discover the basic chemical properties of the esoteric element germanium. Teal had little experience with this metal—indeed, few outside of Kraus's lab knew very much about it—and it quickly captured his imagination. Possessed of "a strong desire to exploit discoveries for practical use," Teal was challenged by the apparent uselessness of germanium.[5] In 1931, he finished his dissertation research on certain reactions of germanium, mixing sodium germanyl and potassium germanyl with alkyl halides to prepare the methyl-, ethyl-, and propyl-germanes that standard theory predicted. The reactions Teal studied were untried cases of a well-known general reaction.[6] He explored them in an effort to find a use for a material to which he had formed an attachment that is best described as esthetic.

. . . I always have had considerable curiosity, with particular interest in new things and new ideas. This has led me over the years to a closer look at some of the basic phenomena in science and stimulated a strong desire to exploit discoveries for practical use. I also share the delight in the esthetic . . . I enjoy adventure and, in particular, I am interested in pioneering, that is, the kind of pioneering demanded by our rapidly changing and highly technical society. These interests have greatly influenced my decisions and were often crucial in the directions my career has taken.[7]

Even before Teal submitted his dissertation, he began his professional career as a chemist. In 1929, he toured Bell Laboratories, eager to investigate operations inside the esteemed facility. Teal and Bell were mutually impressed. Asked not to start work anywhere before talking to Bell, Teal ceased flirting with the idea of working at Du Pont or some other laboratory. When Bell made him an offer in the summer of 1930, he accepted. Overcoming reservations he had about living in New York City (the laboratory was located in the city, in a structure on West Street, at that time), Teal began his 22-year career at Bell Laboratories in August 1930.

Teal on TV

Almost immediately after Teal joined Bell Labs, the Depression forced AT&T, the Lab's corporate parent, to institute a hiring freeze on new scientific staff. The Lab reduced its payroll expenses by allowing the attrition of its workforce, laying off some staff, and reducing the hours of those that remained. Teal, who married Lyda on 7 March 1931, experienced deep concern about his future at Bell, but he was reassured that his low seniority posed no threat to his job security. He occupied the time that the reduced hours program had liberated for him with study of heavy hydrogen in collaboration with future Nobel laureate Dr. Harold Urey, who was at Columbia University.[8]

Shortly after establishing himself in the chemistry department, Teal began looking at ways to purify mercuric oxide at the request of Bell Labs' television division. Teal's chemical abilities had attracted the attention of Herbert E. Ives, the leader of that division. Television tubes demanded skilled chemists to prepare the light-sensitive substances and glass for the tubes. By Teal's second year at Bell, he was transferred from chemistry to television.

Bell Labs began television research in 1925 and soon became the preeminent research organization in the field. In April 1927 Ives and his colleagues transmitted pictures of a speech given in Washington, D.C., by Secretary of Commerce Herbert Hoover to an audience in New York through coaxial cable. They also broadcast the same scene over the air the considerably shorter distance between Whippany, New Jersey, and New York City. The sharpness of Bell's pictures impressed those who witnessed the demonstration. No better picture would be produced by any system for years to come.[9]

Bell's early success was achieved with a mechanical television system. In it, the camera apparatus scanned the image by the spinning action of an internal disc. Ives favored this approach to its alternative, electronic scanning of the image by a cathode ray within the camera tube. Ives experimented with an electronic system in 1926 and the results convinced him that an electronic system posed too many serious problems. Thereafter, he focused Bell's efforts to mechanical systems, rejecting the electronic idea again when it was proposed by a member of his staff in 1930.[10] By 1933, however, the announcement of an electronic scanning tube called the iconoscope by RCA engineer Vladimir Zworykin prompted Ives to soften his position. Before 1933 ended, Bell had begun its own research on iconoscope-like tubes. It was at this stage that Teal joined the television effort.

Teal worked principally on a critical element within the iconoscope, the light-sensitive target called the mosaic. The tube worked by focusing light from an object onto the mosaic and then converting the physical reaction there into an electrical signal by bombarding the mosaic with a stream of electrons from a hot cathode. The mosaic posed several difficult research challenges. Chemists needed to develop a substance that was highly sensitive to light, and they also had to develop a technique to apply it to the mosaic substrate. No less an authority than Zworykin himself conceded that "The most difficult item of construction in the image multiplier iconoscope is the mosaic."[11]

Teal's work on a variety of mosaic types exemplifies the significance of patient, technique-oriented innovation to his scientific investigations. He began in 1934 by experimenting with compounds of silver and cesium or potassium to create a substance, described as photoemissive, which reacted to light by ejecting electrons. This was the most common approach to mosaic fabrication, but Teal did not work with it long. As early as March 1935, he was exploring photoconductive mosaics, which generated voltage between illuminated spots and nearby dark spots. Later, he concentrated his efforts on still a different type of mosaic, one that responded not to incident light, but rather to electrons that were generated by light from the object focused on a photocathode and then directed toward the mosaic.[12]

One challenge with these latter mosaics was to fix the sensing material into the substrate in a regular and controlled way. Among the techniques that Teal developed was to cover a magnetic pole piece with a sticky substance and then drop tiny magnetic wires onto the piece. The magnetism of the pole piece caused the wires to stand up straight. He caught the wires' top ends in a support and then removed the sticky substance from their bottoms. He coated the wires with insulator and then filled in the space between the insulated wires with a conductor. After releasing the tops of the wires from their support and electroplating, he was left with the desired configuration of sensitive material, conductors, and insulators.[13]

Another method Teal invented was to take a metallic screen with a very fine mesh (400 holes to the linear inch) and coat the inside wall of the apertures with insulator. He then laid the screen on a porous material and poured over it a fluid that contained small particles of photosensitive material. The particles were small enough to fall through the apertures, but too large to pass through the pores of the object upon which the screen rested. With the particles each inside an aperture, lying in their pools of fluid, he used a pressure difference to force the fluid through the porous substance, leaving the particles alone to fill the apertures.[14]

One other approach to mosaic design quickened Teal's interest. W. H. Hickok, a researcher at RCA, was taking advantage of the thermoelectric properties of germanium, Teal's "pet" element, to build a pick-up that was sensitive to far-infrared radiation.[15] The germanium mosaic reacted not to the light reflected off objects but to their temperature. RCA imagined a scope that could aid navigation by televising objects through fog or other visual interferences. Teal has recalled trying to interest his superiors at Bell Labs in germanium research in the 1930s.[16] Although there is no record of what specifically he proposed, it appears probable that he was suggesting following up on the RCA experiments. Besides having a latent interest in the element itself, Teal was eager to match the accomplishments of other television research laboratories. The keen sense of competition that drove him is evidenced by his practice of pasting the press clippings of other labs' successes into his lab notebook for inspiration.[17]

Bell Labs did not share Teal's enthusiasm for general television research. From the high point of Ives's triumphant 1927 demonstration, AT&T watched Bell's leadership in television research slip away during the 1930s without much panic or concern. In 1925, AT&T president Walter Gifford decided to pull his company out of most businesses not related to telephone service in the United States. Activity in television, along with other areas such as radio broadcasting, household appliances, and foreign telephone service, declined at AT&T. The television research that continued considered TV primarily as a visual extension of the telephone—allowing pictures to accompany words in point-to-point communications.[18] Although Bell continued to spend an average of $133,000 per year on television between 1932 and 1937, and then $335,000 per year between 1938 and 1940, their commitment remained far below that of RCA, for instance, which spent upwards of $50 million developing a working television system.[19] In deciding how to spend these comparatively modest allocations, Bell's management applied their most important criterion—the relevance of the proposed research to AT&T's principal business of providing telephone service. It is little surprise that in this climate, Teal's proposal for germanium mosaics (sensitive to light outside of the visible spectrum) met with rejection.

Teal got so involved in his television work that he moved beyond the boundaries of his expertise in chemistry. Without any academic training in electrical engineering, Teal began designing electrical components and systems with a proficiency in EE he acquired solely through experience in the lab.[20] He patented several electron multipliers, assemblies of electrodes that amplified signals by augmenting beams of electrons. This work contributed to his eventual composition of an entire system for television, which he patented in 1941. Teal's system, following the "flying spot" innovation that made Ives's television transmission for Bell a success in 1927, moved a sheet of light across the subject, successively illuminating parallel linear sections of it. He also worked on a tube that could reduce the number of frames per second needed by storing images on the mosaic (as the iconoscope did) and scanning at quick rates (what would today be called "faster than real-time") in order to cut the bandwidth needed to transmit an image.[21] He worked on these ideas, and shared many of his patents, with the small group of men he directed, including A. W. Treptow, R. L. Rulison, and B. A. Diggory.

Semiconductor Days . . . and Nights

Television research at Bell ended abruptly with the US entry into World War II and much of the electronic expertise in the department was reassigned to radar systems.[22] Teal, a chemist foremost, despite his work with electronics, was set to work developing materials crucial for military equipment. Teal moved suddenly from engineering complete television systems to investigating molybdenum carbide coatings for gun barrels, dies, and rocket nozzles. If the change to a less glamorous assignment saddened him, his feelings are largely hidden behind the stiff formality of his 10 February 1942 notebook entry: "On Friday morning, Feb 6, 1942, Mr. S. O. Morgan [Stanley Morgan, who later headed Bell's chemistry department] informed me that I am to work on the silicon detector problem in collaboration with Mr. Shive."[23]

Any remorse Teal felt over the end of television work was balanced by the excitement of the new opportunity that war-related research offered him to work with semiconductors. The war stimulated an unprecedented interest in those metals of which Teal was so fond. Silicon, germanium's sister element on the periodic chart, proved particularly valuable for radar systems. AT&T began using the material to make rectifiers, components that turn alternating current into direct current, in early 1942. By 1944, Western Electric, the manufacturing division of AT&T, was turning out over 50,000 units per month.[24]

Teal saw a chance, once again, to try to interest his superiors in research on germanium. He hoped that rectifiers made of germanium would outperform the silicon rectifiers that Bell was already exploring. Early in 1942 he fabricated some germanium rectifiers, the first germanium devices made at Bell Labs, and in June, the director of research at Bell Labs, Mervin J. Kelly, authorized Teal to continue his work.[25] Within a few months, however, Teal found his laboratory assistance for the project disappearing. Sensing that he was being discouraged from germanium research, Teal dropped the project and turned to radar attenuators. Soon after, his germanium rectifier program was revived under a contract from the MIT Radiation Laboratory, but Teal was unable to participate in the work because he had contracted pneumonia in a work-related accident. The germanium research proceeded without him.

Teal spent much of the war studying attenuators, the elements in microwave systems, such as radar, that function as resistors do in electric circuits. Attenuators control the power of microwave signals traveling within the wave guides that make up microwave circuits, allowing operators greater control of their systems. Teal experimented with ceramics, plastics, films, and rubbers in an effort to optimize properties such as power handling, sensitivity to temperature, moisture absorption, heat conductivity, energy reflectivity, and physical size.[26] The work involved consideration of the physical properties of the materials under study and the effect of the attenuator's shape on its performance.

The war disrupted the course of Teal's career, but his new research areas represented only a temporary interlude, not a permanent change. The tasks he undertook were selected more on the basis of wartime expediency than personal interest, and he did not directly continue any of them after Bell demobilized. Still, some of his war work helped prepare him for the next, most important, phase of his career.

After the war, Bell took advantage of the familiarity that Teal had gained with silicon by assigning him responsibility to manage the materials development for two new, inexpensive, silicon-carbide varistors. The varistor, an electrical component that changes resistance when the applied voltage changes, is an essential element in the telephone handset. Western Electric planned to manufacture four to eight million varistors per year. The design requirements included close tolerance (±10 percent), 20-year reliability, and low cost (about five cents per varistor.) The assignment had satisfactions for Teal. It was an important project—Western Electric would come to manufacture over 100,000,000 varistors—and he was able not only to contribute to the materials side, but also to work closely with electrical engineers on the device's design. Judged within the context of AT&T's priorities, the job was as significant as any other at Bell.[27] At the same time, however, developments elsewhere in the lab would steal Teal's most ardent interest away from the varistor project. In 1948 Teal heard that germanium was being used in a new solid-state amplifier called the transistor.

By 1948 transistor research already had a substantial history at Bell Labs. The development effort began with the reign of Mervin Kelly as director of research. Kelly had directed the vacuum tube division between 1928 and 1934 and was sensitive to the limitations of the components that AT&T relied upon to switch and amplify the electrical signals that traveled along its phone lines. The company used relays to switch calls from one line to another, but relays worked slowly and were prone to fail when dirt accumulated on their metal contacts. Kelly sought an electronic replacement for the electromechanical relays, but electronic devices were not free of problems either. Tubes were fragile and expensive. They generated heat while doing nothing but standing ready. This wasted power and shortened life span, which diminished the tubes' reliability. When Kelly was promoted to director of research in 1936, he initiated measures to exploit the nonlinear electrical properties of semiconductors as an alternative to tubes and relays.

Kelly's research program was interrupted by the war, but even before the fighting ended, he began to reorganize a solid state amplifier research effort at Bell Labs. He created a multidisciplinary group, which he placed under the charge of theoretical physicist William Shockley and chemist Stanley Morgan. Shockley began by focusing his team's efforts on silicon and germanium, two semiconducting elements that had become quite familiar to scientists, if not Shockley himself, through wartime research. Of the two, germanium was the simpler material. Working steadily with germanium, two members of Shockley's team, Walter Brattain and John Bardeen, built a working amplifier on 23 December 1947. It was soon after named the "transistor" and word about the breakthrough spread throughout the laboratory.[28]

Teal recognized the enormous potential of the solid state amplifier when he first heard about it informally in early 1948. Intrigued by the germanium composition of the device, he resolved not to let this rewarding research opportunity slip by him, as the germanium rectifier project had. He pressed for a new line of germanium research, stressing in several memos to research management that a deep understanding of, and control over, the properties of germanium were crucial to satisfactory transistor performance.[29] He hoped to improve the germanium refining techniques and, more importantly, to grow single crystals of germanium to use for transistors as a replacement for the polycrystalline samples that the Lab was using. He argued that just as superior vacuum resulted in improved performance of vacuum tubes, so would transistors benefit from purer, more uniform germanium. Teal likened the unwanted impurities in germanium and the grain boundaries of the multiple crystals to poor vacuums in tubes.[30]

Teal's proposals were greeted with indifference. As with the germanium in the iconoscope mosaics episode, Bell management did not agree with Teal about the value of the research he proposed. In the case of crystals for transistors, however, it was not a matter of intriguing research losing to the pragmatic need for useful products. Teal promoted the single crystals from the most practical standpoint, offering improved predictability of transistor behavior. Bell management disagreed, but on a strictly scientific basis. Shockley believed that the germanium the lab used was adequate and that single crystal germanium would offer no advantage.[31] Bell's research management, accepting Shockley's opinion, regarded Teal's offer of single crystal germanium as irrelevant to the transistor project and refused to support it.

In the pursuit of new knowledge bearing on rather deep questions and useful concepts of natural phenomena, the scientist has learned that certain attitudes are helpful. He has learned to suspend his prejudices, to stop and take a fresh look. He finds it a helpful exercise to decide what are the relevant and the irrelevant facts. He is interested in an economy of conceptual symbols and relations in which to express his observations. He has found in this economy an expression of principles that are often a more permanent part of accepted science than are the facts which gave rise to the principles. He has found it useful to make precise measurements under known conditions in order to check the correctness of his conjectures and to add precision and clarity to his views. He finds it a good habit to be logical but also, paradoxically, personal knowledge of major advances made in science in which logic was not the dominant feature has made him an enemy of categorical imperatives and authoritarianism in views. He is relentless, dissatisfied with current views and driven by a fierce curiosity.[32]

Teal soon found a chance to grow single crystals of germanium, however. In late September 1948, Teal learned that a colleague of his, John Little, needed a thin rod of germanium fabricated. Teal offered to prepare it, adding as a bonus that the germanium would be a single crystal. By December Teal and Little succeeded in creating a monocrystal rod of germanium by adapting a technique developed in 1918 known as the Czochralski method. (See Figure 2.) They dropped a small seed of germanium into a molten pool of the purified element. As they slowly withdrew the seed, the liquid germanium, called the "melt," solidified uniformly, extending the crystal of germanium along the pattern established by the seed. Teal showed his crystals to Jack Morton, who directed the transistor development effort. Morton was interested in what Teal was doing, but would not take Teal off the important varistor project, nor would he provide Teal with extra laboratory space. Morton did agree to purchase equipment for Teal to continue his experiments and allowed him to use the metallurgical shop after normal working hours. With that opportunity, Teal began a maverick program of "bootleg" research.[33] He would roll his crystal pulling equipment into the lab in the late afternoon as the staff there prepared to depart and would experiment when the room was unoccupied. When he would finish working, usually at two or three in the morning, he had to disconnect his machinery and stow it before the metallurgical staff arrived at work the following morning. For most of 1949, Teal occupied his nights and weekends growing progressively superior crystals.

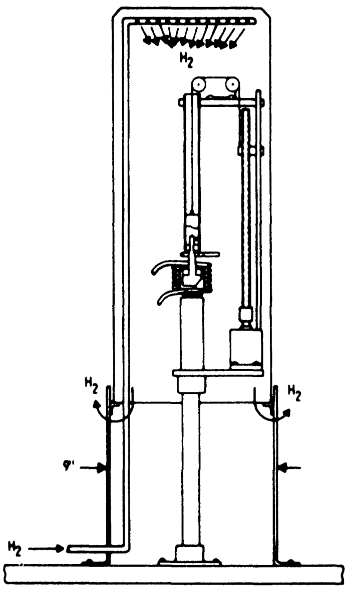

Figure 2. Schematic drawing of the machine designed by Teal and Little to grow monocrystals of geranium.

This uncomfortable situation improved when it was recognized that Teal's work might have some bearing on the progress of a different transistor project managed by Shockley. Soon after Brattain and Bardeen's breakthrough, Shockley began theoretical work on a new type of amplifying semiconductor device, which he called the "junction transistor." This transistor differed from the first sort in that it exploited semiconducting properties in the bulk of its germanium base. Bardeen and Brattain's transistor was active only at the points where metal leads touched the semiconducting crystal.

Any semiconductor can be one of two sorts, p-type or n-type. Impurities in the semiconductor crystal determine whether the material conducts electricity primarily by the movement of excess electrons (n-type) or, conversely, by the shuffling of electrons through vacant spots, called "holes," where a deficiency of electrons leaves an effective positive charge (p-type). The operation of all semiconductor devices depends on the reaction of electrons and holes to electromagnetic fields applied at interfaces of n- and p-type regions. At the interface, when electrons migrate into the p-type region, where conduction is primarily by holes, they are said to be minority carriers. The same term is used for holes in an n-type region, where electrons carry most of the current. Shockley's junction transistor featured alternate layers of semiconductors that are intrinsically n- and p-type sandwiched together. Bardeen and Brattain's transistor, called the "point-contact" model, used the electric activity of the metal leads that connected the crystal to the circuit to induce only small regions of n- or p-type conductivity in a single semiconductor of one intrinsic type. The junction transistor boasted a larger interface between n- and p-type semiconducting crystals.

After thinking and experimenting for over a year, Shockley published his theory of the junction transistor in June 1949.[34] His paper made it clear that the action of the junction transistor, unlike the point contact type, depended heavily on the flow of minority carriers. Shockley saw this confirmed experimentally in an "existence proof" junction transistor made for Shockley by Bell chemists Morgan Sparks and R. M. Mikulyak in April 1949. The lifetime of minority carriers was quite limited, however, in this trial device made of polycrystalline germanium. By contrast, measurements showed that in Teal and Little's single crystal germanium, minority-carrier lifetimes exceeded that of their polycrystal counterparts by 20 to 100 times.[35] This characteristic gave single crystals an obvious advantage over polycrystals in achieving Shockley's design. Teal and Sparks began collaborating, and for the first time, Teal's research came out from underground. Once Bell's perspective on single crystals matched Teal's own, the crystals' applicability to the junction transistor was recognized. Bell dedicated a laboratory for crystal growing at the end of 1949, and Teal's communication with the transistor development team increased.[36]

Working with Morgan Sparks, Teal began his first work explicitly on the transistor, trying to produce the crystals needed for Shockley's proposed junction device. To create crystals that had alternating n- and p-type layers, as demanded by Shockley's design, Teal modified his crystal-pulling machine to accept impurity pellets into the melt while the single crystal was growing. This enabled him to "dope" the germanium crystal, that is, add impurities to change the germanium crystal's conductivity from n-type to p-type and then back to n-type, in precisely controlled stages. With this improvement, Shockley, Sparks, and Teal were able to grow the first n-p-n junction transistor on 20 April 1950.[37] One year later, Shockley, Sparks, and Teal achieved a useful and reliable junction transistor.[38]

Shockley and Teal disagree when recalling the intensity of the transistor development effort during this period. Shockley's claim that "The efforts to improve junction transistors were practically negligible at the Laboratories" is opposed by Teal's impression that "At no time did the enthusiasm for the double doping program lag."[39] The disparity between the two scientists' perceptions most likely stems from the difference in the roles they played in the development process. Shockley, the theoretical physicist, might not have understood the formidable technical challenges Teal faced in refining his crystal pulling procedure. The deceptively simple concept underlying Teal's technique hides a great number of practical complications that made crystal pulling a difficult enterprise: Precise temperature control was critical; to achieve the necessary crystal uniformity, Teal had to determine how much agitation of the melt and vibration of the seed were required; nonuniformities in the distribution of the impurity in the melt and the tendency of the crystal to change resistivity as it grew added further considerations; and so on. Only through painstaking experimentation was Teal able to successfully pull crystals suitable for junction transistors.[40] (See Figure 3.)

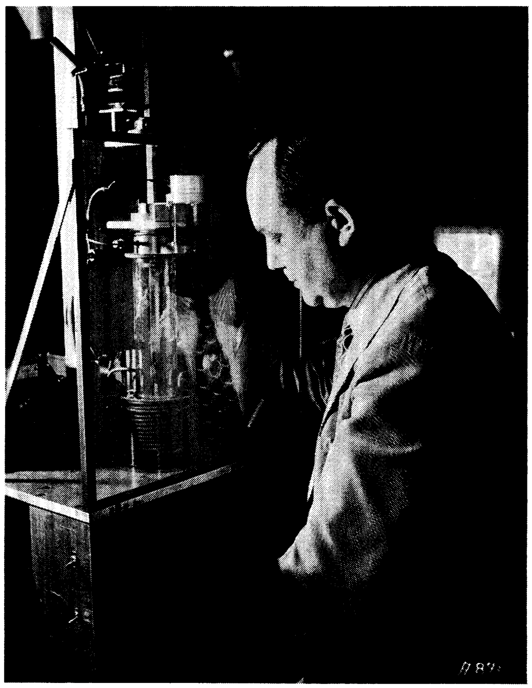

Figure 3. Teal at his crystal-pulling apparatus.

Back to Texas

Manufacture of transistors as circuit components began slowly in the 1950s. Of the eight companies making transistors in 1952, the largest was AT&T's own Western Electric, which began making transistors of the point contact type at its Allentown plant the year before.[41] Western Electric produced most of the 90,000 transistors made in 1952, but all of these were for internal use by AT&T. AT&T made no attempt to expand into other electronic enterprises by marketing transistors or selling transistorized products. Efforts along those lines would not only have violated a long-standing company tradition to stay out of such markets, but might also have drawn unwanted attention to the company. AT&T had good reason to seek a low profile with regard to new solid state technology. In 1949 the US Government began antitrust proceedings against the telephone giant. AT&T, which was eager to maintain its monopoly and integrated structure, may have been willing to sacrifice fully exploiting the transistor's potential to avoid hurting its position either in a court of law or in the court of public opinion.[42] The company decided its best strategy was to collect royalties from electronics companies that it would license to use the transistor patent. In the fall of 1951, AT&T offered nonexclusive licenses for a nominal fee, $25,000 advance against future royalties.

An early respondent to AT&T's offer was Geophysical Service Incorporated (GSI), a Texas-based manufacturer of seismic equipment. This firm, which had almost no experience in manufacturing electronics, took an interest in transistors as the cornerstone of a comprehensive program to redefine itself for the post-war era. GSI had specialized in oil-exploration services and equipment since its founding in 1930. It developed a strong reputation within its field, making contracts with the major oil companies and eventually expanding into the oil business itself. This growth pattern was altered, however, by World War II. The company's technologies for remote sensing and location were useful to the military for applications such as finding land mines. GSI became a supplier of military equipment, selling $1.1 million of equipment to the armed forces during the war years.[43] The turn to military contracting not only expanded GSI sales, but also appealed to the business sense of its principal management. Company President Erik Jonsson and General Manager Pat Haggerty predicted that postwar geopolitics would compel the US to maintain a high level of military procurement. They decided to capitalize on this by expanding GSI's regular enterprise to include military hardware.

Jonsson and Haggerty's foresight rewarded the company well. GSI vigorously courted the military market, adding to its product line such electronic technologies as submarine detection equipment, radar-controlled bomb sights, and airborne and ground radar. Spurred by the Korean War, sales for GSI were over $15 million in 1951, up from $2.3 million in

1946. Most of the income resulted from military contracts.[44] With this success pointing the way for the future direction of the company, Haggerty and Jonsson began the 1950s looking for new opportunities for GSI.

Bell Lab's development of the transistor provided a special opportunity for GSI. The transistor, which promised great miniaturization and ruggedness, seemed ideal for meeting the military's desiderata for the hardware it purchased.[45] Haggerty's vision, however, called for GSI to do more than simply employ transistors. He believed that in order for his company to become an important electronics firm, it would have to be involved at the component level and not merely assemble systems. Jonsson's desire that GSI start large-scale manufacturing primed Haggerty's interest in obtaining a license to produce the new solid state amplifiers invented at Bell. In 1951 Haggerty had one of his engineers, Bob Olson, test several sample transistors. Olson's investigations convinced Haggerty to pursue transistor manufacture. He met with AT&T representatives and, by the fall of 1951, submitted his $25,000 advance for the right to get into the transistor business. Haggerty, Jonsson, and the other GSI executives reorganized their company to better suit its new interests. They lowered GSI, with its tradition of seismic exploration equipment, to subsidiary status, and created above it, on 1 January 1952, a new parent company named Texas Instruments.

Texas Instruments (TI) faced significant obstacles in its route to become a large company based on transistor manufacture. In 1952 the transistor still ran a poor second to vacuum tubes in almost every measure of performance.[46] Transistors could not approach the frequency response or power output of tubes. The solid state device was more expensive than tubes and transistors were only slightly smaller than the subminiature-type tubes that were readily available. In some cases, tubes held the edge over transistors in size also. In 1955 General Electric made a dramatic show of the small size of its ceramic tubes by placing one inside the casing of a standard transistor.[47] It was clear that a major R&D effort awaited any firm that planned to make money in semiconductors. Haggerty planned a two-pronged approach to overcome these problems: research and development to improve the transistor's characteristics and a high-visibility showcase product to promote the transistor's acceptance.

Texas Instruments began by attending a landmark symposium organized by AT&T in the spring of 1952. The symposium provided a complete disclosure of AT&T's experience with transistor theory, design, and manufacture. For eight days representatives from each of AT&T's transistor licensees, a total of forty firms (twenty-six of them American) heard lectures on solid state physics and toured the Murray Hill and Allentown facilities.[48] Each participant received a detailed exposition of the information covered in the seminar in a multivolume set of books entitled *Transistor Technology*. The symposium was intended "to enable qualified engineers to set up equipment, procedures, and methods for the manufacture of these [transistor] products," but Haggerty knew that he had to do better than this.[49] Certain that transistor technology could not, at its present state, dent the tube business, Haggerty was looking for inroads to improving the state-of-the-art.

Haggerty found the opportunity he sought when he met with Teal at the New Jersey symposium. Teal, who had authored one of the chapters in *Transistor Technology* on pulling crystals, made a presentation on his topic to the symposium attendees. Haggerty was impressed with Teal, and later met with him to offer him the chance to return to his native Texas and found his own research laboratory at TI. The offer appealed to Teal for both professional and personal reasons. Professionally, it presented Teal with the opportunity not only to do research, but also to manage it. The difficulties he had experienced at Bell must have made this seem an attractive prospect. Fondness for his native state and an illness in his family also favored a return to Texas. At the end of 1952, he relocated in Dallas and began to build a research laboratory.

Teal's responsibility, phrased by Haggerty in the corporate language of "goals" and "ambitions," included such imperatives as the following: pioneer the development of technology; integrate diverse scientific disciplines and advanced technologies to create projects of great potential impact on TI's future; create new ideas and concepts through bold research.[50] In practical terms, that meant pulling together a diverse and highly competent staff of research scientists and providing them with sure direction. Teal visited other companies and universities with strong programs to entice talented researchers to follow him back to the small Texas company. Teal's transistor work had bestowed him with a reputation that aided his recruitment efforts. He was able to attract top talent to his fledgling lab, including a chemist from Standard Oil, Willis Adcock, and a recent Oxford graduate in physics, J. Ross Macdonald.[51]

Transistor research was a wide-open field in 1953. The outstanding problems confronting investigators included the chemical composition of the semiconductor material to be used, the purity of semiconducting crystals, and the method for fabricating the transistor. There were at least as many different ideas on how to proceed as there were laboratories to pursue them. At Bell Labs important progress had been made in purifying germanium with the zone-refinement process developed by W. G. Pfann in 1951. The following year J. E. Saby at General Electric developed an entirely new way to prepare junction transistors that allowed one to eschew the crystal-pulling apparatus entirely. Saby composed alternate n and p layers by alloying dots of indium to a base of germanium. This technique, which offered greater frequency range and current handling (provided the germanium base was thin), was adopted by RCA and Raytheon. Philco, a Philadelphia electronics firm, mastered a jet-etching technique for machining exceptionally thin germanium bases in 1953, giving their alloy transistors the highest frequency response yet.[52] These companies avidly researched the alloy technique because they believed it held promise for making transistors that were not only superior but also cheaper—the pulling process for the grown-junction transistor was notoriously slow.

At Texas Instruments, however, Teal's presence led the company toward the crystal-pulling technique that he had pioneered, a fact that proved decisive in moving that firm ahead of the other transistor licensees. Under the direction of Mark Shepherd, chief engineer for semiconductor design, TI began pulling crystals immediately after the Bell symposium. Working on a machine dubbed "Old Betsy," Shepherd's group made their first transistor in June. By the end of the year they had found a customer for their product: The Gruen watch company purchased ten of these point-contact transistors. In 1953, production increased to 7,500, spurred by an order from the Sonotone hearing aid company. These transistors were expensive, costing between $10 and $16 each, but this did not concern Haggerty excessively. At such small production volumes, competitive edge from superior technique was an almost meaningless concept. The critical issue for Haggerty was generating a demand for transistors. He cared little about optimizing the performance of transistors as laboratory devices; he wanted to create the impression that transistors were a proven technology and simultaneously establish Texas Instruments as the preeminent company to fill the ensuing demand. It was vital, then, that Texas Instruments act quickly.

In the spring of 1954, Haggerty set his engineers on a breakneck development project to design a transistor radio that would fit in a shirt pocket and cost no more than $50. After extraordinary effort Haggerty's engineers met his target of a Christmas release date. The radio, the TR-1, manufactured by the Regency division of the IDEA Company of Indiana, sold 100,000 units in its first year. At four transistors per radio, the phenomenal sales of the TR-1 achieved the market breakthrough for transistors that Haggerty sought.[53]

The TR-1 played an important role in fixing the transistor in the mind of the consumer and the commercial manufacturer, but Texas Instruments had been, from the beginning, more interested in the military market. Here, too, the company's commitment to Teal's crystal-pulling technique for growing junction transistors gave it a crucial advantage over its competitors. Certain military applications, the sort of high-performance weaponry emphasized by Eisenhower's "New Look" at military strategy, demanded transistors that functioned reliably at high temperatures.[54] This requirement pointed to silicon, with its high melting point. Eager to include the military on their list of customers, most semiconductor manufacturers began working at developing a silicon transistor.[55] Most research laboratories approached the problem using the alloy method of fabrication, an unfortunate choice since alloyed silicon transistors proved exceptionally difficult to develop. However, by working with the grown junction technique, Texas Instruments was able to market a working silicon transistor well in advance of any other company, effectively monopolizing this large military market for four years.

Possessing a familiarity with silicon from wartime work, Teal had been interested in silicon crystals since his early days working with Little at Bell Labs. In experiments conducted in the late 1940s, Teal found silicon less manageable than germanium. The higher temperature necessary to melt silicon made it prone to react with atoms in its environment, spoiling the perfection of the crystal. Patient work with the element paid off slowly. In 1952 Teal, still at Bell, worked with Ernie Buehler to grow silicon junctions.[56] Functioning transistors had remained elusive, however. By 1953 most research on the silicon transistor involved alloying techniques. Others sought instead to "leapfrog" silicon entirely and make high-temperature transistors out of intermetallic compounds, such as gallium-arsenide. Teal rejected both of these approaches as introducing additional complex practical problems. He placed Willis Adcock in charge of developing a grown junction silicon transistor. By the spring of 1954, Adcock, together with Morton Jones, J. W. Thornhill, E. D. Jackson, Ray Sangster, and Boyd Cornelison, solved the purification problems and mastered the pulling technique.

Teal announced his team's success at the Institute of Radio Engineers national conference on 10 May 1954 with a paper titled "Some recent developments in silicon and germanium materials and devices." The session in which Teal gave the paper was marked by a succession of grim-faced scientists solemnly confessing that the silicon transistor was still years away. Indulging a flair for drama encouraged by Haggerty, Teal ended his modestly titled paper by announcing that "contrary to the opinions expressed in this morning's session, this [the production of the silicon transistor] will begin immediately" and then reached into his pocket exclaiming, "I happen to have some here." (See Figure 4.) The excitement that ensued among the audience foreshadowed the heady growth that Texas Instruments enjoyed over the rest of the decade. Texas Instruments saw sales rise overall from $27 million in 1953 to $233 million in 1960. This environment of expansion was ideal for a director of research.

As Haggerty predicted, military sales were valuable for Texas Instruments, but they were not the sole cause of the company's spectacular growth. Commercial sales of germanium transistors were significant. Texas Instruments entered into an agreement with IBM in 1957 whereby they sold 41,000 transistors for each model 7070 computer. Sales of semiconductor rectifiers also were profitable. Targeting all semiconductor markets, Texas Instruments diversified its product line by maintaining a steady pace of incremental improvements in products, processes, and testing equipment. In 1958, for example, the company announced over 100 new semiconductor products—57 of them meeting military specifications—which improved on past offerings with a wider range of operating parameters and enhanced reliability. Funding for research, development, and engineering that year equaled $16.25 million, half of which was derived from contracts, principally from the federal government.[57]

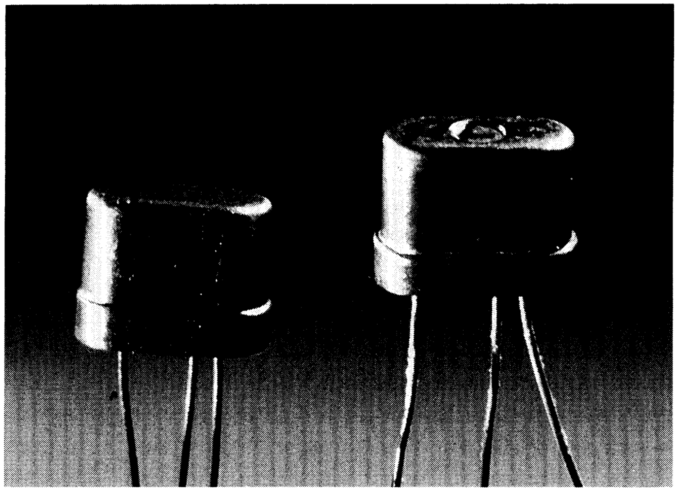

Figure 4. Two of Texas Instruments' first silicon transistors.

Texas Instruments' marketing triumphs of the 1950s reflect a corresponding string of research successes in Teal's Central Research Lab (CRL). In addition to transistors, TI manufactured silicon components such as a cell to convert solar energy to electricity (introduced in 1955) and the sensitor, a silicon resistor, made in 1957. Refinement of the procedures that CRL developed to attain ultrahigh-purity silicon enabled TI to market the material in bulk form to other electronics firms, as TI joined Du Pont in 1957 as the only suppliers of this high-grade substance. The need for exact control in this chemical process stimulated development at CRL of high-precision test and measurement equipment. The lab invested heavily in research with intermetallic compounds such as gallium-arsenide and indium-antimonide, materials that found use in diodes, transistors, and infrared detectors. Other CRL projects included work on fuel cells and the automation of electric power systems.

Teal's success at running the Central Research Laboratory emboldened him to seek a larger role in the management of Texas Instruments. According to Howard Sorrows, CRL's director of new product development, Teal contributed significantly during the 1950s to the development of OST (Operations, Strategies, and Tactics), a rigorous company-wide management system that Texas Instuments instituted in the early 1960s. OST required certain preliminary planning operations before work on a new project began, such as identification of the clients for a proposed product, drafting of a detailed plan of development, and securing written agreements between the internal divisions that planned to participate in the development effort. Sorrows recalls that Haggerty derived these aspects of OST, along with other features such as zero-based budgeting, from the system that Teal implemented at CRL.[58]

Teal downplays his management efforts at Texas Instruments, perhaps because they generated some tension among the company's principals. Haggerty and Shepherd received Teal's management recommendations only coolly. They preferred that he concentrate his labor on scientific matters and take a more passive role in general management. The pair regarded those qualities that they respected in Teal as a scientist, namely, his analytic abilities and his thorough methodology, as liabilities in corporate management. Haggerty had concluded early on that executive responsibility often demanded that managers make decisions based on only incomplete information and imperfect comprehension. He worried that Teal was not inclined to operate in this mode.[59]

An organizational dispute over the development of the integrated circuit exemplifies this conflict over Teal's proper role within TI. The integrated circuit, Texas Instruments' most important product since the silicon transistor, emerged not from Teal's CRL but from another unit within TI called the Semiconductor Products Division (SPD). This unit, which was organized in 1954 under Shepherd to oversee the refinement of semiconductor products for the marketplace, was the development counterpart to Teal's research laboratory. Although the two divisions worked closely, they were operationally quite distinct.[60] When Haggerty and Shepherd assigned the responsibility for the integrated circuit (IC) to the SPD, they shut out Teal's unit from the project.

The decision dismayed Teal. He felt that the IC project belonged in the CRL. He traced its origin back to research that Richard Stewart performed at CRL in 1956. Stewart, working under Adcock, created arrays of diodes in single wafers of silicon for use in microwave detectors. In 1957 Adcock transferred to the SPD to work on microminiaturization and shortly thereafter hired Jack Kilby. Kilby, in 1958, built the first integrated circuit, fabricating multiple electrical components, such as resistors, capacitors, and conductive connectors, out of a single crystal of silicon.[61] Although Adcock has emphasized the differences between Stewart's work and Kilby's—the key one being that Stewart never attempted to form different electrical components out of the single crystal—Teal felt that integrated circuit research began at the CRL.[62] Moreover, he believed that the project would benefit from a sounder scientific understanding. Haggerty and Shepherd, however, were eager to push development of the IC. They overrode Teal's desire to put CRL staff on the project.

These developments frustrated Teal. It discomforted him to be positioned on the pure science side of the basic-versus-applied research debate that is so frequently an issue for high-tech firms. Teal fully comprehended Haggerty and Shepherd's desire to market the integrated circuit as soon as possible (their haste notwithstanding, Texas Instruments' innovation collided in patent court with similar work done by Robert Noyce at Fairchild Camera's electronics department). Teal was a pragmatic individual. Indeed, his own inclination, the spur that drove his interest in germanium, was to find uses for things. It surprised Teal, then, to find that, despite his own inclination toward pragmatism, he was seen by Texas Instruments as being, as Shepherd expressed it, "sort of Bell Labs-like. A little on the academic side."[63] If at Bell, Teal was held back for a time by the scientific myopia of his superiors, at Texas Instruments he could chafe against the explicit business perspective that underlay crucial organizational decisions. He took the event as a lesson; his writings and activities of the late 1950s reflect a heightened attention to corporate interests.

Teal had to undergo several educations to learn the subtleties of his position as a research manager in a commercial enterprise. He was acutely aware of the differences in his responsibilities at Texas Instruments as compared with Bell and undertook to equip himself for his new duties as best as possible. He remembers, "When I got to be a boss instead of a scientist working mostly by himself . . . I began communicating, being interested to hear what everybody else was doing. . . . So that got me involved with working in the Dallas-area scientific organizations."[64] Teal joined the American Management Association, Research Division in 1953. That same year, he joined the Dallas chapter of the Institute of Radio Engineers (IRE). He quickly took a leadership role in that organization and in 1956 was named chairman. As a local leader for the IRE, Teal organized regular meetings, started a local magazine called *Direction,* and planned social occasions that gave him opportunities to meet and trade concerns with the growing community of Texas electrical engineers.[65]

Teal had belonged to the American Chemical Society since 1927; his involvement with the IRE was an acknowledgment of his new relationship to electronics. His close association with Haggerty reinforced his desire to become active in the IRE. (See Figure 5.) Haggerty was named president of the Institute in 1962, the year preceding its merger with the American Institute of Electrical Engineers to form the present-day Institute of Electrical and Electronics Engineers. Teal favored the merger, expecting that the consolidation would expand the interests of members of each society. He participated by serving on a two-man study committee on the merging of the sections, considering the finances, geographical boundaries, and sectional publications.

In addition to these activities, Teal was enlisted as a member of the editorial board for the IRE, a national position that he held between 1958 and 1961. He also joined SWIRECO, the IRE convention organization for

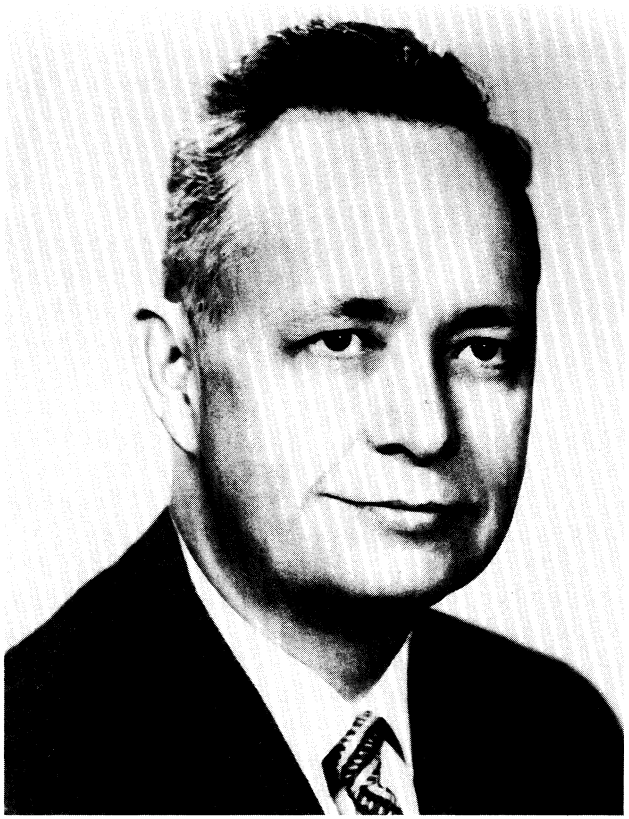

Figure 5. Patrick E. Haggerty (1914–1980), President of Texas Instruments and President of the IRE for 1962.

the Southwest, in 1955. Four years later, he was vice chairman. That same year, Teal was appointed director-at-large of the IRE, a position he reclaimed by election in 1962.

Teal found that his professional society affiliations presented him with an opportunity to express his opinion on issues that were becoming more important to him. One of these was education. At the 1958 IRE National Convention, he presented a paper entitled "Broadening the horizons of the engineer." This lecture stressed not only the changes in physics and chemistry that were transforming the world of the engineer, but also the general political and economic forces in the world scene, the growing importance of industrial research, changing technology and corporate needs, and societal needs. He elaborated on the value of education for American industrial growth and stability.[66]

The present dilemma in education indicates clearly the need for the engineer to be effective not only on a specific technical job but also in society. One of the major needs of our times is to make science an integral part of our culture just as it is an integral part of present day technology. Failure of our educational system to achieve this no doubt accounts largely for the unfortunate fact that the public as a whole has little understanding of science. This offers the engineer a unique opportunity. Since his work is better understood by the public than that of the pure scientist, he is ideally suited to interpret society's dependence on pure science as well as applied science. In doing this the engineer will be rendering a service to his community and nation. This could lead the average citizen to have a clearer understanding of decisions of state involving complex scientific knowledge. The engineer himself, however, to have the interest in such activity, must be educated broadly.[67]

The zeal in America to prioritize education, particularly in science, that followed the Soviet Union's successful launch of Sputnik focused some of Teal's ideas on education. In 1958 he spearheaded the creation of a body called the Council of Scientific and Engineering Societies and served as the chairman of the executive committee of its board of directors in 1961 to 1962. The Council provided service by assisting teachers in extending their education, advocating higher teacher qualifications and salaries, sponsoring scientific lectures for the general public, and promoting student interest in science through activities such as science fairs and science-oriented TV programs. Writing of the Council's purpose, Teal asserted "the value of learning is an end in itself, worthy of great effort," but conceded also that "national security and material wealth as objectives must be of concern to all of us. These are increasingly dependent on activities of the intellect."[68] This social motivation, in contrast to a purely intellectual one, is apparent in activities such as the Council's cosponsorship with the Council on World Affairs of a civil defense symposium, held on 7 and 8 December 1961, at which Edward Teller, the physicist known for his strong political views, spoke.

Teal on Assignment

The concern for large social issues demonstrated by these activities underscored the variety of ways in which Teal could be valuable to Texas Instruments. In the 1960s Haggerty had an opportunity to use some of these extra-scientific talents. The company's explosive growth during the 1950s came to an abrupt halt in 1961. The Kennedy administration, fresh in office, ordered a slowdown of military procurement while it reassessed US strategy. This decrease in the demand for semiconductors exacerbated the problem of overproduction (20 percent in 1961) and led to a brutal price war. For the first time since the appearance of the silicon transistor, Texas Instruments profits were off from the previous year, $9.4 million compared with $15.5 million. The company did not panic—they were still the top supplier of semiconductors and they still made a profit. But the semiconductor recession of 1961 alerted Texas Instruments to the fact that as a large, mature company, it faced an entirely different set of problems that innovation through scientific research could not solve alone.

One of these problems was its overseas operations. Texas Instruments began production outside the US in 1957, when it built a plant in Bedford, England, to manufacture semiconductors. Texas Instruments, Ltd., the TI subsidiary operating the Bedford plant, was a success. By the end of 1960, Texas Instruments made 12 percent of its sales outside the US and operated seven manufacturing plants in England, France, Italy, Germany, and Holland.

With so much activity outside the United States, Haggerty began to wonder if the Dallas Central Research Laboratory was adequate for all of the firm's interests. Thinking that better ties might be established with European scientific talent if Texas Instruments operated a research lab on that continent, Haggerty asked Teal to investigate whether a branch lab should be built, and if so, where. In 1963 Teal, named International Division technical director, left with his family for an extended tour in Europe. He worked in London, Paris, and Rome, visiting government laboratories, industries, and universities to discuss research with officials, managers, scientists, and professors. Teal ultimately decided that the logistical complications of managing research in two sites so distant from one another outweighed any possible advantages a European research lab would offer. Even with the negative decision, the trip had great value for Teal (apart from the cultural exposure that he thirstily absorbed). Teal shined in the opportunity to display his sensitivity to the complex interactions between science, technology, and industry.

Teal's sophisticated grasp of these issues was not lost on Haggerty, or on certain other keen observers. Late in 1964, when Teal was still in Europe, the director of the National Bureau of Standards, Allen Astin, and his deputy director, Irl Schoonover, approached Haggerty, asking if TI could "loan" Teal to the Bureau for a two-year stint as director of a new Bureau division called the Institute for Materials Research (IMR). The Institute was to be "the principle focal point in the federal government for assuring maximum application of materials sciences to the advancement of technology in industry and commerce."[69] Its head was to be responsible for the stimulation of industrial capacity through rationalization of the production and distribution of scientific data about materials. Bureau officials sought an astute materials scientist with experience at organizing a research laboratory and an understanding of the needs of the industrial community.

Astin and Schoonover recognized Teal as an ideal candidate. Haggerty, agreeing with their judgement, telephoned Teal in Rome and put the request to him. Teal quickly assented, excited by the challenge of organizing a new research institution. In January 1965 he went to Gaithersburg, Maryland, to begin work at the National Bureau of Standards. (See Figure 6.)

Figure 6. The National Bureau of Standards buildings in Gaithersburg, Maryland.

The Bureau had a long tradition of assisting industry through scientific research. It was formed in 1901 under the Department of the Treasury, principally to deliver accurate measurements, and was moved under the auspices of the Department of Commerce when that agency was created in 1903. The change in parent administration encouraged the Bureau to pursue functions beneficial to industry, such as standardization of parts and products or promotion of new and improved materials.[70] The rapid growth of science during World War II and the subsequent Cold War expanded the Bureau's activities even further. This trend continued into the 1960s, but tight budgets in those years prevented the Bureau from growing in proportion to its responsibilities. The Bureau needed to take steps to improve the effectiveness of its operation.[71]

In the drive for a more cost-effective agency, Astin heeded the recommendation of a National Research Council advisory committee to take a new approach to organization.[72] He identified the missions that were shared by the numerous different divisions of the Bureau and regrouped these divisions along the lines of these common objectives. In 1964 all research within the Bureau was divided into four decentralized units: the Institute for Basic Standards, the Institute for Applied Technology, the Central Radio Propagation Laboratory, and the Institute for Materials Research.

Astin formed the last of these, the Institute for Materials Research, by pulling together six distinct divisions within NBS: the laboratories for analytic chemistry, polymers, metallurgy, inorganic materials, reactor radiation, and cryogenics. In each of these six areas, the Institute offered valuable services to its industrial clients and other government agencies. Its program included the development of techniques for the study and manufacture of materials; identification and measurement of meaningful physical and chemical properties of materials; on-site calibration services to scientific and industrial institutions; consultation services on materials; and identification of critical materials problems that obstructed major national goals.

Teal thrived in his position as the first director of the IMR.[73] His initial task was to execute the internal changes that would bind the formally independent divisions of the Institute into a coordinated research organization. Initially Teal did not need to do any recruiting, because the Institute, unlike the Central Research Laboratory at Texas Instruments, had a staff of over 600 when he arrived, 370 of whom were professionally trained, including 160 Ph.D.s. Still, his skills in evaluating scientists' abilities and matching them to the jobs proved critical in launching the Institute.[74]

As leader of the Institute, Teal attacked the problem of how to maximize the value of his laboratory's resources to industry with the same spirit he had shown on more scientific problems earlier in his career. He held a five-year management planning review on 4 April 1966. Proceeding methodically, Teal first outlined national needs and goals, then identified customers and program outputs, assessed the impact of Institute programs on national goals, and pointed out the strengths and weaknesses of the available resources and plans for achieving their objectives. The review was a huge success. Within a year the entire Bureau was conducting similar sessions.[75]

Teal developed his assessment of national research goals through consultation with leading U.S. industrial firms. From these meetings, he decided which materials studies were most crucial by considering impact evaluations prepared by a staff of technical economists that he brought to the Institute. Directed by this input, IMR developed techniques to prepare such materials as hyperpure copper and crystals of other metals, new silicon compounds, superconducting ceramics, and vinyl-like polymers.[76] Other techniques developed there helped scientists determine the physical characteristics of materials. Examples include an assembly to rotate a sample of steel in a neutron environment in order to sense the presence of oxygen in steel, and a method to identify trace elements in substances by measuring the ratio of residual current and thermoelectric power in materials at high and low temperatures. The sort of practical objectives underlying the work of the IMR is revealed by the report of one success in the Bureau's 1965 annual survey of technical highlights: "IMR scientists desired an improved spectroscopic technique for chemically analyzing the high-temperature alloys being used in increasing quantities in modern technology. The technique [which combined the principle of isotope dilution with electrolytic separation and determination by a spark source mass spectrometer] is readily adapted to existing instrumentation and can save industry time and money because the number of primary standards needed to calibrate the analytical equipment is reduced."

One of the Institute's most important contributions was the preparation and distribution of standard reference materials. These were samples of substances, each carefully prepared, that laboratories could use as a reference for precision adjustment of their instruments. The Bureau sold these materials (known as standard samples before Teal's arrival) to academic and industrial laboratories. Ownership of a reference material enabled a laboratory to calibrate its equipment itself, on-site, sparing it the trouble and expense of seeking an outside contractor. By using an NBS reference material, customers were assured that their processes conformed to a national standard, clearly valuable for its reproducibility and uniformity. When Teal surveyed reference materials buyers in 1965 for reactions to a proposed downscaling of the reference materials program, he was inundated with pleas to reconsider. The emphatic responses stressed how much industry appreciated the service and suggested that any shortfall in funding should be met by raising prices.

The references sold briskly. In 1965, the Institute sold over 70,000 samples to more than 2000 different companies.[77] Clients included the metal, petroleum, automotive, cement, chemical, rubber, plastic, pharmaceutical, and transportation industries. Other materials, which set standards for radioactivity, were useful in calibrating civil defense equipment. A study Teal conducted to assess the demand for new types of reference samples indicated that industry, to develop all the products and processes made possible by present technology, urgently needed over 150 new reference materials.[78] With budgets tight, this job was beyond the Institute's capacity. Teal responded by prioritizing critical needs and focusing limited resources where they would benefit most. In 1966 the Institute offered 91 new reference materials, swelling the total available to more than 600.[79] Sales in 1967 exceeded $1.2 million, representing more than 70,000 samples sold to over 8,000 customers.[80]

The Standard Reference Materials were just one method by which the Institute disseminated scientific information. In addition, the Institute published papers and books and also organized conferences and symposia on topics such as ceramics, corrosion, and the growth of crystals. Teal organized an annual series of IMR symposia as a focused effort to transfer knowledge about a particular subject among different scientific groups from around the world. The first symposium, held in 1967, considered the characterization of trace elements in materials.

Teal regarded these measures to offer quality scientific results to laboratories that needed them as simply the first step toward the Institute's goal. He envisioned the Institute as the progenitor of a vast, international, and intercorporate system of coordinated research activity, and he spoke of consolidating all research results into an international bank of scientific data. Citing a cost of $40,000 for every good technical research paper, Teal pointed out that eliminating worldwide research redundancy would relieve industry of an expensive burden that was a drag on productivity. He called on all interests to collaborate in this mutually beneficial mission and went on to suggest that underdeveloped nations could be granted access to the data network, offering them a chance for industrial growth and economic stability.

These suggestions, which he offered to members of the Industrial Research Institute (IRI) at a meeting in Detroit on 11 October 1966, were Teal at his most idealistic. Though he found the task of rationalizing the activity of competing companies and nations along lines of enlightened self-interest too much to accomplish in his two years as head of the IMR, he nevertheless did take a few modest steps toward his brave new world. After his talk to the IRI, representatives of the group came to Maryland to observe the Institute's program. Teal was also able to visit India, Pakistan, and Israel as part of an IMR delegation to instruct those countries in developing standard reference materials and other engineering standards.

. . . We will make faster progress in solving our national problems by recognizing that they are fundamentally different from the many problems solved by science and technology during the last few decades. The essential difference is that such magnificent achievements as penicillin and radar and supersonic flight were problems that could be solved by the biological and physical sciences alone. . . . In contrast, today's problems demand not only technological decisions, but the simultaneous application of many diverse disciplines and nondisciplines; in this regard, the new problems are terribly complex. . . . It seems to me that there are four keys to each of the complex problems that face us—four basic conditions that, taken together, will assure our success: First, we must articulate our national prime objective and measure progress toward it. Second, our approaches to subsidiary goals that serve this prime objective must be both interdisciplinary and extradisciplinary. Third, we must take systems approaches and avoid piecemeal solutions. And fourth, we must make the problems attractive to private industry so that industry will take the lead under government direction.[81]

Teal's tenure at the National Bureau of Standards ended in 1968, half a year after he was scheduled to depart. Having set the IMR off to a strong start, Teal left Maryland and returned to Dallas for his final years with Texas Instruments. He assumed the office of vice president and chief scientist for corporate development, which he held until his retirement in 1972. He enjoyed the responsibility of his position, plotting the technological course of a company he was instrumental in building.

Teal stayed active with the company after his retirement, consulting for another five years. He also consulted occasionally for the National Academy of Science, the National Academy of Engineering, the National Bureau of Standards, the Department of Defense, NASA, and the National Science Foundation between 1972 and 1978.

Over the years Teal has been much honored for his achievements. In 1968 he received the highest award of the IEEE, the Medal of Honor. Teal won the Patent, Trademark and Copyright Research Institute's Inventor of the Year Award for 1966, was elected Member of the National Academy of Engineering in 1969, was awarded the Academy of Achievement's Gold Plate Award in 1967, received honorary degrees from both Baylor (L.L.D., 1969) and Brown (Sc.D., 1969), was named an Omicron Delta Kappa Outstanding Baylor University Alumnus, received the American Chemical Society Award for Creative Invention (1970), and an IEEE Centennial Award (1984), to name just the most prestigious of Teal's citations.[82] It is a long, varied, and distinguished list—matching the career of the man who earned it.

Conclusion

Gordon Teal's contribution to solid state electronics, the monocrystals of germanium and silicon that opened up the field to practical use and commercial viability, guarantees him a high place in the history of technology. His story is interesting also for what it shows about science and engineering.

Historian of technology Edwin Layton has written of a nineteenth century "scientific revolution of technology" in which "technological problems could be treated as scientific ones; traditional [craft] methods and cut-and-try empiricism could be supplemented by powerful tools borrowed from science."[83] He alludes to a convergence of scientific and technological research, one that is commonly taken to be a matter of engineers "upgrading" themselves to the more "scientific" methods of mathematization and controlled experimentation. Teal's career suggests that this convergence was not necessarily as unidirectional as is generally assumed.

Teal started as a scientist. His studies at Brown were straightforward chemistry, and his early work—at Bell Labs and at Columbia with Harold Urey—bore the same unmistakable scent. He was, however, possessed of certain values and characteristics—a pragmatic enthusiasm for utility, an appreciation for the physicality of objects that sat above the desire to understand them theoretically, and a commitment to invent techniques to create perfect specimens—which fit the profile of an engineer. Guided in his work by an irrepressible inventiveness, superlative experimental skill, and an educated instinct, Teal was a scientist who thought and functioned as an engineer. He represents one important example where scientific practice absorbed the advantages of engineering practice.

Teal's style was particularly striking in the context of solid state research. Most interpretations of the development of the transistor emphasize the significance of theoretical advances to this science-based technology. Theory was a potent tool, but at the same time Teal's practice of employing dexterous technique in patient experimentation guided by extra-theoretical instincts was not irrelevant. Even as theory-rich physical chemistry was increasing in importance to the electronics industry, the work of one leader in the movement echoed the engineering traditions of an earlier age.

In his later career Teal continued to work as an engineer. His management of the research enterprises at Texas Instruments and the National Bureau of Standards offered him the chance to design and build in a way that was more abstract, but no less real, than he had experienced as a scientist. Then, as before, he sought to collect and perfect. Making the most of the resources available to him, Teal was always looking for the right material.

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[1] Robert R. Williams, "Chemistry in the telephone industry," *The Bell System Technical Journal*, vol. 9, 1930, p. 603.

[2] Richard L. Petritz, "Contributions of materials technology to semiconductor devices," *Proceedings of the IRE*, vol. 50, 1962, pp. 1025–1038.

[3] Most of the information about Teal's background comes from an extended oral history interview with Teal conducted by the author 17 to 20 December 1991. This interview is the basis for much of the content of this article. It is supplemented, as noted in the footnotes, by various published and unpublished materials. An edited transcript of the interview is deposited in the archives of the Center for the History of Electrical Engineering.

[4] See, for example, Michael Eckert and Helmut Schubert, *Crystals, Electronics, Transistors*, translated by Thomas Hughes (New York: American Institute of Physics, 1986), p. 65.

[5] Interview 1991, p. 29.

[6] See G. K. Teal and C. A. Kraus, "Compounds of germanium and hydrogen. III. Monoalkylgermanes. IV. Potassium germanyl. V. Electrolysis of sodium germanyl," *Journal of the American Chemical Society*, vol. 72, 1950, pp. 4706–4709.

[7] From "Patterns of creative action in a research career," a speech given at a meeting of the American Academy of Achievement in Dallas, Texas, 15–17 June 1967, to 350 high school students from 48 states.

[8] Harold C. Urey and Gordon Teal, "The hydrogen isotope of atomic weight two," *Reviews of Modern Physics*, vol. 7, 1935, pp. 34–94.

[9] Albert Abramson, *The History of Television, 1880 to 1941,* (Jefferson NC: McFarland & Company, 1987), p. 101.

[10] R. W. Burns, "The contributions of the Bell Telephone Laboratories to the

early development of television," *History of Technology*, vol. 13, 1991, pp. 181–213.

[11] V. Zworykin et al., "Theory and performance of the iconoscope," *Proceedings of the IRE*, vol. 25, 1937, p. 1091.

[12] Teal lab notebook 13106, AT&T Archives, Warren NJ. See also patent numbers 2,641,533; 2,598,317; 2,681,886; 2,650,191; 2,682,501; 2,662,852; 2,598,318; 2,596,617; and 2,662,274.

[13] Patent number 2,650,191.

[14] Patent number 2,641,553.

[15] Harley Iams and Albert Rose, "Television pickup tubes with cathode-ray beam scanning," *Proceedings of the IRE*, vol. 25, 1937, pp. 1066–1067.

[16] Michael Wolff, "The R&D 'Bootleggers': Inventing against the odds," *IEEE Spectrum*, vol. 13, no. 7, 1975, p. 39.

[17] Teal's lab notebook 15202, AT&T Archives, Warren NJ.

[18] S. Millman, ed., *A History of Engineering and Science in the Bell System: Communications Sciences (1925–1980)* (AT&T Bell Labs, 1984), p. 142.

[19] The figures for Bell are from Burns, "The contributions of the Bell Telephone Laboratories . . . ," p. 209. The RCA figure is quoted from David Sarnoff in Andrew F. Inglis, *Behind the Tube: A History of Broadcasting Technology and Business* (Boston: Focal Press, 1990), p. 171.

[20] Interview 1991, p. 50.

[21] Teal's lab notebook 15202, AT&T Archives, Warren NJ. See also patent number 2,408,108.

[22] Millman, *A History of Engineering and Science*, p. 145.

[23] Teal's lab notebook 18414.

[24] J. H. Scaff and R. S. Ohl, "Silicon crystal rectifiers," *Bell System Technical Journal*, vol. 26, 1947, p. 28.

[25] Teal, "Single crystals of germanium and silicon—basic to the transistor and integrated circuit," *IEEE Transactions on Electron Devices*, vol. ED-23, 1976, p. 621.

[26] G. K. Teal, M. D. Rigterink, and C. J. Frosch, "Attenuator materials, attenuators, and terminations for microwaves," *AIEE Transactions*, vol. 67, 1948, pp. 419–428.

[27] For an exposition of Bell's results, see Frank R. Stansel, "The characteristics and some applications of varistors," *Proceedings of the IRE*, vol. 39, 1951, pp. 342–359.

[28] For a more detailed account of the story of the transistor's development, see especially Lillian Hoddeson, "The discovery of the point-contact transistor," *Historical Studies in the Physical Sciences*, vol. 12, 1981, pp. 42–76; S. Millman, ed., *A History of Engineering and Science in the Bell System: Physical Sciences (1925–1980)* (Murray Hill NJ: Bell Laboratories, 1983), pp. 71–107; William Shockley, "The path to the conception of the junction transistor," *IEEE Transactions on Electron Devices*, vol. ED-23, 1976, pp. 597–620; F. M. Smits, ed., *A History of Engineering and Science in the Bell System: Electronics Technology (1925–1975)* (Murray Hill NJ: Bell Laboratories, 1985), pp. 1–100; and Charles Weiner, "How the transistor emerged," *IEEE Spectrum*, vol. 11, no. 1, 1973, pp. 24–33.

[29] Teal, "Single crystals of germanium and silicon . . . ," p. 622.

[30] Ibid., p. 623.

[31] William Shockley, "How we invented the transistor," *New Scientist*, vol. 56, 1972, p. 690.

[32] "The creative individual in modern society," presented by Teal on 2 December 1960 as Presidential Address to the General Assembly of the Texas Academy of Science at its annual meeting at Texas Christian University in Ft. Worth, Texas.

[33] Michael Wolff, "The R&D 'Bootleggers' . . . ."

[34] William Shockley, "The theory of p-n junctions in semiconductors and p-n junction transistors," *Bell Systems Technical Journal*, vol. 28, 1949, pp. 435–489.

[35] Gordon K. Teal and John Little, "Growth of germanium single crystals," *Physical Review*, vol. 78, 1950, p. 647.

[36] Teal, "Single crystals of germanium and silicon . . . ," p. 628.

[37] Shockley, "The path to the conception of the junction transistor," p. 616.

[38] William Shockley, Morgan Sparks, and Gordon Teal, "p-n junction transistors," *Physical Review*, vol. 83, 1951, pp. 151–162.

[39] The two quotations are from, respectively, Shockley, "The path to the conception of the junction transistor," p. 616, and Teal, "Single crystals of germanium and silicon . . . ," p. 630.

[40] See chapters 4, 7, and 8 of H. E. Bridgers et al., eds., *Transistor Technology* (Princeton NJ: D. Van Nostrand, 1958) for details on the difficulties of pulling crystals.

[41] Ernest Braun and Stuart Macdonald, *Revolution in Miniature* (Cambridge UK: Cambridge University Press, 1978), p. 59.

[42] I am indebted to AT&T historian Sheldon Hochheiser for this insight into AT&T's business strategy.

[43] "Biography of Pat Haggerty," TI Archives, p. 11.

[44] "Biography of Pat Haggerty," pp. 12–17.

[45] See Thomas J. Misa, "Military needs, commercial realities, and the development of the transistor, 1948–1958," in Merritt Roe Smith, ed., *Military Enterprise and Technological Change* (Cambridge MA: MIT Press, 1985), pp. 253–287.

[46] Ernest Braun and Stuart Macdonald, *Revolution in Miniature* (Cambridge UK: Cambridge University Press, 1978), p. 54.

[47] George Wise, "Research and results: A history of R&D at General Electric, 1946–1978," unpublished manuscript, 1980, pp. 12–13.

[48] Smits, *A History of Engineering and Science* . . . , p. 29.

[49] The quotation is from Smits, p. 29.

[50] "Technical highlights of TI, 1952–1964," a speech presented by Teal to the fall TI Technical Seminar, Semiconductor-Components Auditorium, 12 November 1962.

[51] Mark Shepherd, then TI's Chief Engineer for Semiconductor Design, discusses the importance of Teal's personal reputation in recruiting in an interview conducted with the author by phone on 3 November 1992 (inter-

view held at the IEEE Center for the History of Electrical Engineering archives).

[52] See chapter 6 of Braun and Macdonald, *Revolution in Miniature* for an extended treatment of these developments.

[53] The story of the TI's transistor radio is well told in Michael F. Wolff, "The secret six-month project," *IEEE Spectrum*, vol. 23, no. 12, 1985, pp. 64–69.

[54] See Misa, "Military needs . . . ," and P. R. Morris, *A History of the World Semiconductor Industry* (London: Peter Peregrinus Ltd., 1990).

[55] For example, Philco announced a silicon transistor in January 1954 but also declared that the commercial production was hampered by problems in obtaining enough pure silicon crystals (*Wall Street Journal*, Monday, 10 May 1954). RCA's efforts are described in Herbert Nelson, "A silicon n-p-n junction transistor by the alloy process," presented at the Semiconductor Research Conference of the IRE, June 1954, Minneapolis MN.

[56] G. K. Teal and E. Buehler, "Growth of silicon single crystals and of single crystal p-n junctions," *Physical Review*, vol. 87, 1952, p. 190.

[57] Texas Instruments Annual Report, 1958, pp. 3–5.

[58] Personal communication with Harold Sorrows, 2 February 1993.

[59] Personal communication with Harold Sorrows, 2 February 1993.

[60] The close cooperation of the two divisions reflects the permeable boundary between basic and applied research. When the SPD launched a series of reliability studies they found the precision they required was beyond their capabilities, and so they prevailed on Teal's staff to help them with the sophisticated test instruments that he had in his laboratory. In the other direction, the Semiconductor Products Division provided important assistance for the CRL's own research. For example, in 1954 Boyd Cornelison of the Semiconductor Products Division designed and built an improved crystal-puller for Adcock and his team to study silicon transistors.

[61] See Michael Wolff, "The genesis of the integrated circuit," *IEEE Spectrum*, vol. 14, no. 8, 1976, pp. 45–53.

[62] Adcock's view was presented to the author during phone conversation on 2 February 1993.

[63] Shepherd interview 1992.

[64] Interview 1991, pp. 152–153.

[65] Interview 1991, pp. 160–165.

[66] Teal, "Broadening the horizons of the engineer," *1958 IRE National Convention Record*, Part 10, 24–27 March 1958, pp. 42–45.

[67] Ibid.

[68] Teal, "Report of the Chairman of the Executive Committee of the Board of Directors," 5 June 1962.

[69] Annual Report, Institute for Materials Research, 1965, p. 79. These same words were used by the Department of Commerce to describe their hope for the whole of NBS in Department of Commerce, Department Order No. 90, "National Bureau of Standards" (30 January 1964). The repetition suggests how central the Institute of Material Research was to the NBS mission.

[70] Rexmond C. Cochrane, *Measures for Progress* (Gaithersburg MD: National Bureau of Standards, 1966), p. 69.

[71] See Annual Report, Institute for Materials Research, 1965.

[72] See "Presentation by Dr. Gordon K. Teal before Secretary of Commerce John T. Conner," 8 March 1965, p. 2. Copy of original from files of Gordon Teal held in the archives of the IEEE Center for the History of Electrical Engineering.

[73] Teal cites his time there as one of his most enjoyable experiences [Interview 1991, p. 121].

[74] Interview 1991, pp. 124–127.

[75] "Gordon Teal's achievements while in Washington" copy of original from files of Gordon Teal held in the archives of the IEEE Center for the History of Electrical Engineering.

[76] The examples and quotation to follow are from Annual Reports of the Institute of Materials Research, 1965 through 1967.

[77] Annual Report, Institute for Materials Research, 1965, p. 85.

[78] Teal, "The NBS Matter & Materials Data & Standards Program," talk to Industrial Research Institute, Detroit MI, 11 October 1966, p. 9.

[79] Annual Report, Institute for Materials Research, 1966, p. 69.

[80] Teal, "Summary of G. K. Teal's Washington activities and accomplishments."

[81] Teal, "Technology and human potential," AAAS Retiring Vice-Presidential Address, delivered in Chicago on 28 December 1970.

[82] In addition to these, Teal is a Fellow of the Texas Academy of Science (1954), the American Association for the Advancement of Science (1959), the Institute of Electrical Engineers (1966), the Washington Academy of Science (1966), and the American Institute of Chemists (1968).

[83] Edwin Layton, "Mirror-image twins: The communities of science and technology in 19th century America," *Technology and Culture*, vol. 12, 1971, pp. 562–580.