HARNESSING NATURE'S TIMEKEEPER: A HISTORY OF THE PIEZOELECTRIC QUARTZ CRYSTAL TECHNOLOGICAL COMMUNITY (1880-1959)

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HARNESSING NATURE'S TIMEKEEPER: A HISTORY OF THE PIEZOELECTRIC QUARTZ CRYSTAL TECHNOLOGICAL COMMUNITY (1880-1959)

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SUMMARY

In 1880, French brothers Jacques and Pierre Curie discovered the phenomenon of piezoelectricity in naturally occurring quartz crystal, sometimes referred to as "nature's timekeeper." By 1959, tens of millions of devices that exploited quartz crystal's piezoelectric character were being used in the technologies of radio, telephony, and electronic timekeeping. This dissertation analyzes the rapid rise of quartz crystal technology in the United States by looking at the growth of its knowledge base as reflected primarily in patents and journal articles. The major finding of this analysis is that the rise of quartz crystal technology cannot be fully understood by looking only at individuals, institutions, and technological factors. Rather, this work posits that the concept of technological community is indispensible in explaining rapid technological growth and diffusion that would otherwise seem inexplicable. In the late 1920s, and again in the early 1940s, the knowledge base of quartz crystal technology experienced exponential growth, partly due to U.S. government patronage and enlightened regulation. However, as this study shows, quartz crystal engineers, scientists, and entrepreneurs could not have mobilized as quickly and effectively as they did unless a vibrant technological community already existed. Furthermore, the United States' ability to support such a thriving community depended in part on an early 20th century American culture that displayed an unmatched enthusiasm for democratic communications media, most especially broadcast radio and universal telephone service. Archival records, professional journal articles, government reports, manufacturer catalogs, and U.S. patents have been used to document this history of the quartz crystal technological community.

This dissertation contributes to the literature on technological communities and their role in facilitating technological and ecomonic growth by showing that though such communities often form spontaneously, their growth may be nurtured and stimulated through enlightened government regulation. As such, this dissertation should be of interest to scholars in the fields of history of technology, business history, management studies, and public policy.

CHAPTER 1: INTRODUCTION

This is the story of the formation and growth of a technological community – that is, a group of like-minded persons dedicated to researching, developing, using, and refining a particular technology, such as jet aircraft, gasoline-powered automobiles, or mobile telephony. Such communities are commonplace in the early 21st century. Yet this story tells of a community that has its origins in late 19th century France, began to coalesce in early 20th century America, became fully self-conscious during World War II, and reached maturity by the 1950s. This is the community of scientists, engineers and technicians dedicated to exploiting the technological potential of quartz crystal, a piezoelectric mineral found in abundance in the Earth's crust. Piezoelectricity is the property of many natural crystallized materials, including cane sugar, Rochelle Salt, and quartz, by which an applied mechanical pressure or stress yields an electric potential. The converse effect, by which an applied electric potential produces mechanical deformation, is also present in piezoelectric materials. Among all naturally-occurring piezoelectric crystals, quartz crystal is unique in the combination of technologically useful characteristics it exhibits: structural rigidity, chemical stability, a strong piezoelectric response, and a very sharp resonance point, leading some to refer to it as "nature's timekeeper." These characteristics have lured technologists into exploiting quartz crystal far more than most other piezoelectric materials.

But "nature's timekeeper" did not submit readily to technological exploitation. Engineers and scientists of the 20th century had to bring all their ingenuity to bear on quartz crystal in order to harness its unique powers. In the course of their efforts, these technologists developed and used quartz crystal devices to improve a number of well-known technological products and systems: broadcast and two-way radio, long-distance telephony, mobile telephony, SONAR, ultrasonics, precision timekeeping, and computing. Most laypersons are blissfully unaware of the importance of quartz crystal devices to each of these systems. To be sure, the quartz crystal technological community was and remains a small, niche group of technologists huddled around what most would consider an esoteric branch of electrical engineering. Yet, studying the formation and growth of this group over time yields insights that are much broader than this one area of technology. Most importantly, this study provides a rare glimpse of the creation, growth, and maturing of a technological community. It also shows this community acting – creating, revising, and preserving a distinct body of technological knowledge. In so doing, this study follows historian Edward Constant's lead in viewing the technological community (i.e., a group of technology practitioners) as the "social locus of technological knowledge."[1]

Quartz crystal invention and innovation flourished in the early to middle decades of the 20th century. Some measure of this activity can be gained by studying United States Patent and Trademark Office (USPTO) data. Figure 1 shows the number of quartz crystal-related patents filed with and issued by the USPTO in these years. Notice first that the pattern of the Patents Issued plot generally tracks the pattern of the Patents Filed plot with a delay of from three to five years. This delay reflects the processing time required by the U.S. Patent Office. Notice also that the Patents Filed plot shows only the number of patent applications that were ultimately issued. Unsuccessful patent

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[1] Edward W. Constant II, "The Social Locus of Technological Practice: Community, System, or Organization?," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (Cambridge, MA: The MIT Press, 1989), 223-42.

applications are not shown. For the purposes of this dissertation, the author considers the Patents Filed plot, rather than the Patents Issued plot, to be the most reliable indicator of the timing of quartz crystal inventive activity.

The ebb and flow of quartz crystal inventive activity must be interpreted with reference to the larger political and economic events of the early 20th century. Quartz crystal technology first blossomed at the end of World War I as a handful of inventors applied lessons learned in the crucible of wartime research. But the technology was slow to attract the interest of others. In the mid-1920s, when quartz crystal became tied to the AM broadcast radio boom, patenting activity rapidly escalated. With the stabilization of the radio market and the arrival of the Great Depression, activity declined and oscillated throughout the 1930s, kept alive by the amateur radio market and the growth of multiplex telephony. With the coming of World War II, patenting activity once again escalated as quartz crystal was applied to numerous wartime projects, from submarine detection to two-way "walkie-talkie" radios. Also acting as a spur to invention during the war was the expiration of many of the earliest, fundamental quartz patents. After the war, patenting activity dropped off to an average of thirty to forty quartz crystal patents per year for the remainder of the period shown.

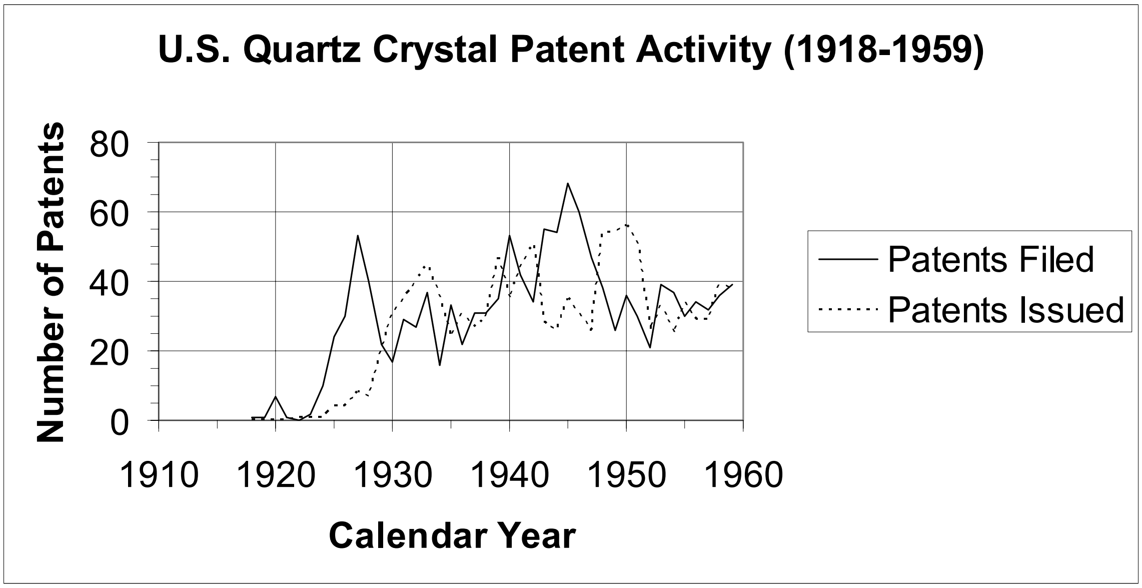

Figure 1: Numbers of Piezoelectric Quartz Crystal Patents Filed and Issued Between 1918 and 1959
(Note: Only successful patent applications are shown. That is, patent applications that were filed but never issued are not included. (Source: Google Advanced Patent Search performed by the author. Search parameters: quartz AND crystal AND (piezo OR piezoelectric)) Figure created by author.)

The pattern of inventive activity illustrated in Figure 1 must also be interpreted in light of overall U.S. patenting activity. Figure 2 compares quartz crystal patenting activity with all U.S. utility patenting activity.[2] As shown, once quartz crystal patenting ramped up in the mid-1920s, its pattern did not differ much from that of all utility patents. There are, however, a couple of notable exceptions. First, the late 1920s decline of quartz crystal applications anticipated by a few years the precipitous decline of all utility patent applications. This later decline clearly reflected the Great Depression, during which companies were less able to invest in patent-generating research and development. But, as mentioned above, the decline of quartz crystal patents more likely represented the stabilization of AM broadcast radio growth and a tapping out of AM radio-related quartz

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[2] "Utility" is the class of patents generally thought of as inventions. The other common patent classes are design and plant. Design patents cover ornamental, non-utilitarian designs, while plant patents cover new breeds of botanical plant.

crystal technology rather than any economic downturn in the quartz crystal business. Second, quartz crystal patenting activity during WWII didn't quite track overall utility patenting activity. The later experienced a significant trough in the early 1940s, due to the large-scale mobilization of the American economy, while the former experienced only a slight and temporary downturn. The rapid rebound in quartz crystal patenting activity reflected the importance of quartz crystal technology to the war effort. The patterns of patenting activity in Figures 1 and 2 are further explored and interpreted in Chapter 3.

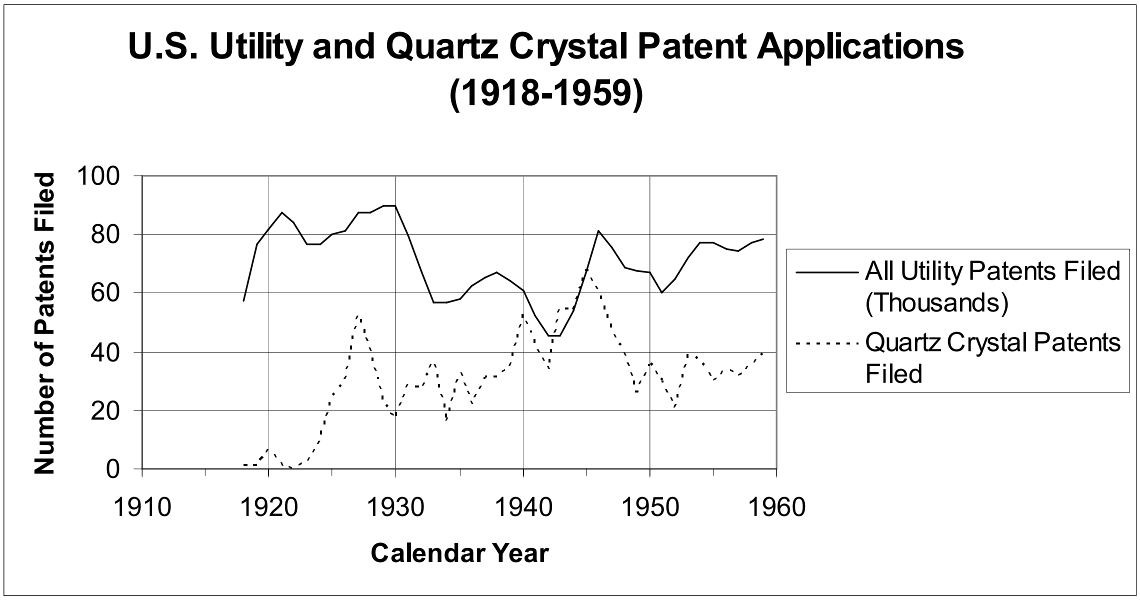

Figure 2: Number of All Successful Patent Applications Filed Vs. Number of Successful Quartz Crystal Patent Applications Filed Between 1918 and 1959
(Note that the All Utility Patents Filed line denotes thousands of patents, while the Quartz Crystal Patents Filed line does not. (Source: Google Advanced Patent Search performed by the author. Search parameters: quartz AND crystal AND (piezo OR piezoelectric)) Figure created by author.)

Taken as a whole, the intensity of quartz crystal patenting activity observed between 1918 and 1959 suggests the historically significant rise of a new and economically important area of technology. During this forty year period, inventors filed for nearly 1200 quartz crystal-related U.S. patents, and around 1000 of these were issued by the end of this period. By way of comparison, in the forty years following Lee DeForest's invention of the "Audion," inventors filed for roughly 1600 patents related to the vacuum tube triode, and nearly 1000 were issued during this period.[3] Thus, judged strictly by the number of patents it spawned, quartz crystal technology was nearly as significant as one of the most influential technological devices of the 20th century.

The economic significance of quartz crystal technology is hinted at by Figure 3, which lists the top owners of quartz crystal patents issued during this period. The Bell System, which encompasses AT&T, Western Electric, and Bell Telephone Laboratories, owned nearly twice as many patents as the next largest owner, the Radio Corporation of America (RCA). Together, the Bell System and RCA, two of the largest and most powerful American corporations of the 20th century, owned nearly a third of all quartz crystal-related patents issued. Given the core businesses of these corporate giants, it's not surprising that quartz crystal devices were used extensively in radio, television, and telephony equipment. But overall ownership of quartz crystal patents can hardly be said to have been concentrated. Figure 3 shows that the top six patent owners owned only 38% of all quartz patents, suggesting that quartz crystal invention and innovation didn't occur only in large corporate R&D laboratories. As further shown in Chapter 3, quartz crystal inventors included university professors, engineers for small firms that catered to amateur radio operators, and independent professional inventors.

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[3] Results of a Google Advance Patent Search performed by the author. Search parameters: "vacuum tube" AND (audion OR triode).

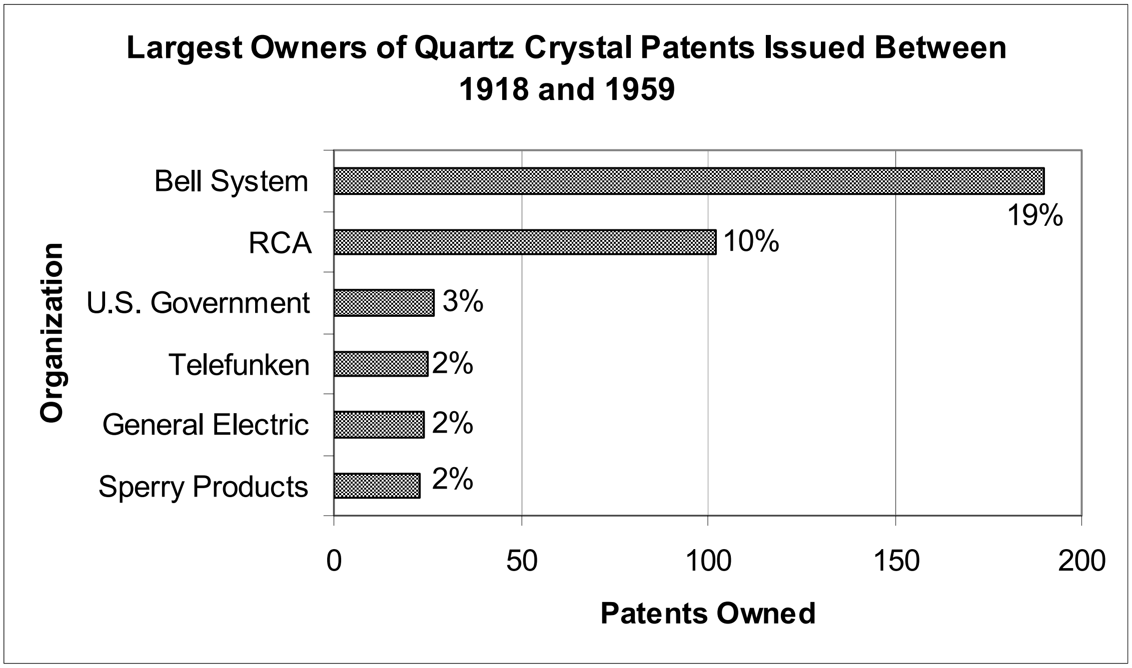

Figure 3: Largest Owners of Quartz Crystal Patents Issued Between 1918 and 1959
(Note: The percentage numbers indicate the percentage of total quartz crystal-related patents issued by the U.S. Patent Office between 1918 and 1959. (Source: Google Advanced Patent Search performed by the author. Search parameters: quartz AND crystal AND (piezo OR piezoelectric)). All patents with the Assignee listed as one of the six organizations shown in this chart were included. Figure created by author.)

The technological context of quartz crystal technology cannot properly be understood without considering the hierarchical nature of modern, large-scale technological systems. These systems display a remarkable degree of organizational complexity, beginning with single components and ending with massive super-systems that incorporate millions of components and require the support of large corporations to run smoothly.[4] Figure 4 presents a simple, four-level hierarchy of technological scale, each level progressively more complex than the previous. The operation of each level depends on the proper functioning of all lower levels. Thus, a malfunction in level II will

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[4] See Thomas Parke Hughes, "The Evolution of Large Technological Systems," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Thomas P. Hughes Wiebe E. Bijker, and Trevor Pinch (Cambridge, MA: The MIT Press, 1989), 51-82.

lead to failure of levels III and IV. The lay public generally recognizes levels III and IV technology; level III comprises most consumer products, and level IV is often the subject of government regulatory action. But levels I and II technology are usually hidden to the public. Quartz crystal technology, as primarily a level I and II technology, is not widely known to non-technologists. Yet the level III and IV technologies that depend on quartz crystal – radio, telephony, computing, and timepieces – are ubiquitous in modern life. Hence, there is a hidden aspect to quartz crystal technology that has kept it from being widely appreciated.

Level	**Name**	**Examples (Radio, Housing, Transportation)**
I	Component	Quartz Crystal Unit, Wall Stud, Piston
II	Sub-system or Circuit	Quartz Oscillator, Wall, Engine
III	System	Radio transmitter, House, Automobile
IV	Super-System	Broadcast radio network, Housing development, National transportation system

Figure 4: Hierarchy of Scale for Large Technological Systems
(Figure created by author.)

In examining quartz crystal technology, this study will focus primarily on its engineering knowledge base, though other factors such as economics and raw material procurement will not be ignored. This focus on knowledge is in keeping with much of the recent literature in both economic history and history of technology.[5] One reason for this focus is that it goes hand in hand with the study of technological communities. This is because, as Edward Constant has noted, technology as knowledge finds its home in

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[5] For example, see Jr. Layton, Edwin T., "Technology As Knowledge," *Technology and Culture* 15, no. 1 (January 1974): 31-41. See also Edward W. Constant II, "The Social Locus of Technological Practice: Community, System, or Organization?," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (Cambridge, MA: The MIT Press, 1989), 223-42. For a dated but still useful overview of the "technology as knowledge" literature, see Chapter 3 of John M. Staudenmaier, *Technology's Storytellers: Reweaving the Human Fabric* (Cambridge, MA: The MIT Press, 1985).

communities of practitioners. As he puts it, the technological community is the "social locus of technological knowledge."[6] And as Edwin Layton, Jr. has stated, "the ideas of technologists (i.e., engineering knowledge) cannot be understood in isolation; they must be seen in the context of a community of technologists and of the relations of this community to other social agencies."[7] Put simply, without a technological community to nourish, protect, and add to it, engineering knowledge stagnates and dies.

Another reason for focusing on knowledge – engineering knowledge in particular – is its relation to technological change and economic growth (or decline). Significant economic shifts can often be traced to changes in technological practice, which themselves can usually be traced to either the creation of new engineering knowledge or the revision of the existing engineering knowledge base. Economic historian Joel Mokyr, in studying the relationship between technology and economic growth, has argued persuasively that a society's economic growth is dependent on and proportional to that society's ability to continuously generate and accumulate new "useful knowledge," the two largest components of which are scientific knowledge and engineering knowledge.[8] Scientific and engineering knowledge, says Mokyr, are mutually reinforcing; they must constantly feed into and reinforce one another in order to generate sustained economic growth.

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[6] Edward W. Constant II, "The Social Locus of Technological Practice: Community, System, or Organization?," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (Cambridge, MA: The MIT Press, 1989), 223-42, cited: 240.

[7] Jr. Layton, Edwin T., "Technology As Knowledge," *Technology and Culture* 15, no. 1 (January 1974): 31-41, cited: 41.

[8] Joel Mokyr, *The Gifts of Athena: Historical Origins of the Knowledge Economy* (Princeton, NJ: Princeton University Press, 2002). Mokyr acknowledges his borrowing of the "useful knowledge" concept from Nobel Prize-winning economist Simon Kuznets.

But just what is engineering knowledge, and what does it look like? Figure 5 summarizes the following discussion and shows the relationship of engineering knowledge to other types of useful knowledge. To begin with, engineering knowledge must be clearly distinguished from scientific knowledge. As engineer-historian Walter Vincenti and others have argued, and this study will confirm, engineering knowledge is quite distinct from scientific knowledge.[9] While the activities that produce these knowledge bases sometimes appear the same, the ends toward which the knowledge bases aim is very different. For one, scientific knowledge is generally propositional while engineering knowledge is usually prescriptive. That is, science, in its purest form, says, “This is the way the world is.” Engineering says, “This is how we’d like the world to be, and here’s how we can get there.” Put crudely, scientific knowledge is “know what;” engineering knowledge is “know how.” Furthermore, scientific and engineering knowledge generally differ in their levels of specificity and context dependence. Engineers often develop highly contextualized knowledge that applies only to specific class of devices or systems. For example, an engineer may develop a vacuum tube-based amplifier circuit along with an equation that defines the amplifier’s gain. This gain equation applies only to this particular amplifier circuit; a new circuit configuration will require a new gain equation. In contrast, scientists usually aim for universal truths about nature that are assumed to be true in all times and places.

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[9] Walter Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*, ed. Merritt Roe Smith, Johns Hopkins Studies in the History of Technology (Baltimore: Johns Hopkins University Press, 1990).

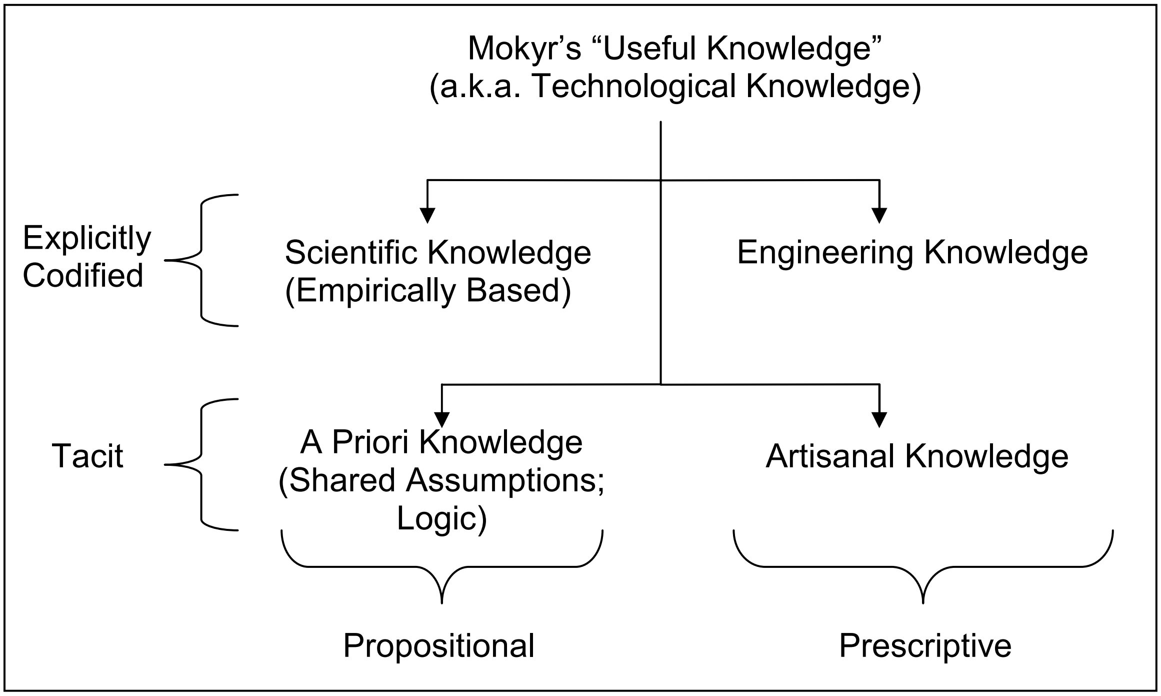

Figure 5: Four Forms of Joel Mokyr's "Useful Knowledge"
(Figure created by author.)

Engineering knowledge must also be distinguished from another type of non-scientific useful knowledge – artisanal, craft-based knowledge. The later is a form of so-called "tacit" knowledge in that it is not easily codified and communicated to others without personal, face-to-face contact.[10] Engineering knowledge, on the other hand, is explicitly codified and communicated through documents such as journal articles, patent applications, and test procedures. This study's eschewal of artisanal knowledge is not due to its lack of relevance or importance. To the contrary, artisanal knowledge has been vital to the development of quartz crystal technology, such as during World War I when the technology first crossed the Atlantic from Europe to America. But a detailed study of artisanal knowledge is beyond the present capabilities of the author. Moreover, the study

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[10] The scientist-philosopher Michael Polanyi first coined the concept of "tacit knowing." Sociologist of science Harry Collins later described the characteristics of "tacit knowledge" within a scientific community. Harry M. Collins, "The TEA Set: Tacit Knowledge and Scientific Networks," *Science Studies of Science* 4, no. 2 (1974): 165-85.

of engineering knowledge is more conducive to historical inquiry given the rich array of written documents available.

Engineering knowledge displays another characteristic that was vital to this study. In most countries, engineering knowledge, or at least the parts of it that can be classified as "invention," is subject to limited-term private ownership in the form of patents. The vital connection between patents, technological change, and economic growth has been observed by many, including the framers of the U.S. Constitution, who instituted the American patent system in order "to promote the Progress of Science and useful Arts."[11] Walter Vincenti, in his classic study of aeronautical design, deliberately downplayed this aspect of engineering knowledge, for his concern was primarily with what he called the process of "normal design," in which invention plays a relatively small role.[12] This study, however, will bring the ownership aspect of engineering knowledge to the fore, exploring the role of engineering knowledge in the patenting process and the competition that often arises between inventive organizations over the control of patents.

Finally, engineering knowledge often appears in several easily recognizable forms. Among these are the following: (1) device or system configurations, (2) fabrication or manufacturing procedures, (3) chemical composition of materials, (4) design criteria, (5) performance specifications, and (6) empirical performance data. Items (1) through (3) are patentable and thus subject to exclusive monopoly control by the inventor for a period of time. The remaining items in the list above, though not patentable, are nevertheless important for the creation, verification, and revision of items

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[11] U.S. Constitution, Article 1, Section 8.

[12] Walter Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*, ed. Merritt Roe Smith, Johns Hopkins Studies in the History of Technology (Baltimore: Johns Hopkins University Press, 1990), 230.

(1), (2), and (3). Items (4) and (5) are often placed in the public domain and can play an important role in the process of industry-wide standardization. And item (6), often held closely by firms, plays an important role in the testing and verification of engineering designs.

The story of quartz crystal technology suggests that useful knowledge, and engineering knowledge in particular, is not continuously generated and accumulated unless a technological community forms. More specifically, the formation of a technological community is a necessary but not always sufficient condition for the sustained generation and accumulation of engineering knowledge. Of course, such a community must also have adequate resources and training for pursuing knowledge generation. Additionally, the technology in question must be ripe for development, regardless of its scale. That is, the scientific principles underlying the technology, what Mokyr calls propositional knowledge, should be understood well enough such that engineering work will be productive of useful improvements; but the technology should not be so highly developed that its knowledge base has become entrenched and the technology considered routine.

All of this begs the question, “What constitutes a technological community?” For my purposes here, a technological community is simply a group, small or large, of technological practitioners (engineers, scientists, technicians, inventors, technology regulators or policy-makers) who both contribute to advances and stay abreast of the latest developments in a particular area of technology over a period of time.[14] This area of technology may be of any scale, from the component level to the mega-system level. The practitioners may be amateur or professional technologists, and they may or may not work directly with each other; in fact, they often compete directly with one another. Furthermore, they may work in other technological fields, beyond their work on the shared technology in question; that is, their work on the common technology (quartz crystal technology in this case) may constitute only a small part of their total technical work. More importantly, to the extent that a technological community draws members from a diversity of other technological fields, members are able to make important connections between seemingly different fields. For example, the quartz crystal technological community examined in this study brought together engineers interested in standards of measure, broadcast radio, multiplex telephony, precision timekeeping, and even stress analysis of materials. Such cross-fertilization is made possible by a characteristic of all technological systems. Namely, different technologies at a given level of scale (see Figure 3) often share in common technologies at a lower scale. For example, both radio and telephone mega-systems, level IV technologies, use oscillator circuitry, a level II technology. Thus, radio and telephone engineers have often shared an interest in oscillator design, leading them to share a sustained commitment to developing and advancing quartz crystal technology and its associated knowledge base.

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[14] In defining "technological community" in this way, I am broadening Edwin Constant's use of the term. He has defined "technological community" as a group of technological practitioners who adhere to a particular tradition of technological practice. (Edward W. Constant II, "The Social Locus of Technological Practice: Community, System, or Organization?," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (Cambridge, MA: The MIT Press, 1989), 223-42.) In the time period covered in this story, quartz crystal technology drew practitioners from a variety of traditions. Thus, it is more useful for me to center my definition of community on quartz crystal rather than on particular traditions of practice.

The formation and growth of the quartz crystal technological community in early 20th century America is a rich topic of study for at least three reasons. First, it sheds light on the ways in which the institutional structures of research and development during this era affected the formation of technological communities. Second, it illuminates the influence of materials science on communications technologies between Lee DeForest's invention of the Audion and Bell Labs' invention of the transistor. And third, it illustrates the growth and maturation of engineering knowledge in a particular field of technology, illustrating as well the nature of the work required to produce this knowledge.

The story of the quartz crystal technological community cannot be considered apart from the early 20th century creation and growth of science-based research and development laboratories both in industry and in government. American businessmen created the modern multiunit business enterprise in the second half of the 19th century to manage the large and complex operations involved in industries such as railroads, steel, oil, telephony, and electric lighting.[15] In the first two decades of the twentieth century, many large firms, in imitation of pioneering German firms such as Bayer, BASF, Hoechst, and Siemens, began conducting science-based research and development in order to accomplish a number of objectives: to explore and develop new markets; to improve existing products and manufacturing processes; to enhance the enterprise's competitive position vis-à-vis competitor firms; and to extend the enterprise's market control as key patents, such as Edison's incandescent electric light patent or Alexander Graham Bell's telephone patent, approached expiration. Five pioneering companies

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[15] Alfred D. Chandler, *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, MA: Belknap Press of Harvard University Press, 1977).

played important roles in giving birth to quartz crystal technology. Three of them, American Telephone & Telegraph (AT&T), General Electric (G.E.), and Westinghouse, were among the earliest American firms to form in-house R&D organizations. The fourth, the Federal Telegraph Company, was formed in California in 1909 and developed its R&D capabilities in the teens. The fifth and final, the Radio Corporation of America (R.C.A.), formed in 1919 through an agreement between the U.S. Navy and G.E., initiated its in-house R&D program in the mid-1920s.

Competition among these firms for control of radio technology was fierce, and quartz crystal patents were an important currency in this competition. Examining the ways that quartz crystal patents were used by firms adds an important dimension to the well-known history of radio and the crucial role played by patents there.[16] Most histories of broadcast radio focus on receiver technology because this was where the largest market and financial stakes were. Consequently, competition for receiver patents, such as those for the super-regenerative and superheterodyne circuits, was intense and long-lasting. But by looking at quartz crystal patents, this study shows that competition was also present in transmitter technology, even though this element of radio was far more heavily regulated than receiver technology. In fact, government regulation of radio transmission actually intensified the competition for quartz crystal patents.

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[16] On the growth of formalized research and development laboratories in early 20th century America, see, for example, Encyclopedia of the United States in the Twentieth Century, 1996, s.v. "Industrial Research and Manufacturing Technology." by David A. Hounshell. David Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (Cambridge, UK: Cambridge University Press, 1989), Chapters 2-4. Leonard Reich, *The Making of American Industrial Research: Science and Business at G.E. and Bell, 1876-1926* (New York: Cambridge University Press, 1985). George Wise, *Willis R. Whitney, General Electric, and the Origins of U. S. Industrial Research* (New York: Columbia University Press, 1985). For the fierce competition over control of key radio patents, see Leonard Reich, "Research, Patents, and the Struggle to Control Radio: A Study of Big Business and the Uses of Industrial Research," *Business History Review* 51, no. 2 (1977): 208-35.

In addition to considering the business climate of early 20th century America, the growth of the quartz crystal technological community cannot be understood apart from the general growth of materials science research in the late 19th and early 20th centuries. Much research in this field was focused upon construction materials – iron, steel, concrete, and wood – but some was also directed toward materials that altered communications technologies.[17] Between 1870 and 1950, a number of advances in materials science revolutionized electrically mediated communication. These advances included not only the creation and synthesis of entirely new artificial materials, but also the discovery and exploitation of hitherto unknown properties of natural materials. Among the most important research efforts were those of Ferdinand Braun, Thomas Edison, Ambrose Fleming, and General Electric's Irving Langmuir on semiconductor materials and the phenomenon of thermionic emission. This work established the base of engineering knowledge necessary for the invention and refinement of the vacuum tube triode amplifier. In 1915, AT&T produced over 3200 such amplifiers for its long-distance telephony system.[18] And during World War I, with the U.S. government temporarily suspending radio patent rights for the duration of the war, G.E. produced roughly 200,000 vacuum tube devices.[19] After the war, both G.E. and AT&T improved the materials out of which triode filaments were made, significantly extending their lifetime and establishing the technological foundation for the radio broadcasting boom of

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[17] David Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (Cambridge, UK: Cambridge University Press, 1989). Chapter 3 – The beginnings of the commercial exploitation of science by U.S. industry.

[18] Leonard Reich, *The Making of American Industrial Research: Science and Business at G.E. and Bell, 1876-1926* (New York: Cambridge University Press, 1985), 164.

[19] Ibid., 88.

the early 1920s.[20] Finally, in the 1930s and 1940s, Bell Labs researchers performed pioneering work in semiconductor physics that famously led to the invention of the solid-state transistor by John Bardeen, Walter Brattain, and William Shockley in 1948.[21] The transistor enabled electronic communications devices to become smaller, faster, and cheaper than would have likely ever been possible with vacuum tube technology.

An important material has been omitted from this brief chronology. Quartz crystal and the devices fashioned from it greatly influenced the evolution of two communications technologies, radio and telephony. In radio, quartz crystal devices impacted radio transmitters in two ways; they enabled operators to measure radio frequencies with unprecedented precision, and they enabled operators to adhere to specified transmit frequencies with unprecedented stability over time. In telephony, quartz crystal devices allowed AT&T to squeeze an increasing number of simultaneous phone conversations onto a single communications cable. These developments were possible only because a vast amount of engineering knowledge concerning quartz crystal was discovered, created, and accumulated between the two World Wars. After World War II, materials science research continued as the U.S. Army Signal Corps desired to find a synthetic replacement for natural quartz crystal. Research funded by the Corps and performed by the Bell Telephone Laboratories and the Bush Development Company led to an economical method for growing quartz crystal in high pressure chambers, thereby obviating the need for large, flawless natural quartz crystals.

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[20] Hugh Aitken, *The Continuous Wave: Technology and American Radio, 1900-1932* (Princeton, NJ: Princeton University Press, 1985), 511.
[21] Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age*, First ed., Sloan Technology Series (New York: W.W. Norton & Company, 1997).

In viewing quartz crystal technology from the vantage point of materials science, this study follows the lead of recent historical studies of steel, semiconductors, plastics, radioactive materials, indigo, and pulp and paper.[22] These studies, including this one, emphasize a key characteristic of technology in all times and places. Namely, the known properties of available materials often define and delimit the technological possibilities of a given time. The real question of interest then is this. What are the factors that drive scientists and engineers to either better understand the properties of existing materials or to develop altogether new materials? This study yields several answers to this question, which are presented in the Conclusions chapter.

One further consideration is important for understanding the growth of the quartz crystal technological community. This is the nature of the work required to produce engineering knowledge within this field of technology. The first thing to be noted is that the technological work dealing with quartz crystal devices did not require large amounts of capital. The raw material, quartz crystal, was not especially expensive or hard to obtain, and the tools needed to turn it into a useful artifact were generally available in any well-equipped machine shop. Economists would say that the field of quartz crystal technology exhibited low barriers to entry. Thus, barring patent restrictions, firms both large and small were relatively free to enter the field.

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[22] On steel see Thomas J. Misa, *A Nation of Steel: The Making of Modern America, 1865-1925* (Baltimore: Johns Hopkins University Press, 1995). On semiconductors, see Christopher Lecuyer and David C. Brock, "The Materiality of Microelectronics," *History and Technology* 22, no. 3 (September 2006): 301-25. On plastics, see Wiebe E. Bijker, *Of Bicycles, Bakelites, and Bulbs: Toward a Theory of Sociotechnical Change* (Cambridge, MA: MIT Press, 1995). On radioactive materials, see Bettyann Holtzmann Kevles, *Naked To The Bone* (New York: Addison Wesley, 1997). See also Gabrielle Hecht, *The Radiance of France: Nuclear Power and National Identity after World War 2* (Cambridge, MA: MIT Press, 1998). On indigo, see Prakash Kumar, "Facing Competition: The History of Indigo Experiments in Colonial India, 1897-1920" (Ph.D. diss., Georgia Institute of Technology, 2004). On pulp and paper, see Hannes Toivanen, "Learning and Corporate Strategy: The Dynamic Evolution of the North American Pulp and Paper Industry, 1860-1960" (Ph.D. diss., Georgia Institute of Technology, 2004).

Second, the technological work described in this study centered on devices, the principal one being the quartz crystal unit (QCU). Invented in its basic form by a university physicist just after World War I, the QCU took decades of engineering work to refine and perfect. Much of this work fell into a few general categories: improving the QCU's power efficiency, increasing the QCU's useful operating life, neutralizing the harmful effect of environmental change or extreme environmental conditions on QCU performance, increasing the yield of the QCU fabrication process, economizing on the raw quartz crystal used in QCU manufacture, and replacing the natural quartz crystal used in QCUs up through World War II with artificially grown quartz. Achieving some of these goals required scientific research aiming for a better understanding of quartz crystal. Others required mechanical ingenuity. Still others required a deep familiarity with the methods and practices of radio engineering. Thus, the effort to improve the QCU's performance was cross-disciplinary. It brought together engineers and scientists from a variety of backgrounds. In this way, the QCU was not unlike the incandescent lamp or the triode vacuum tube.

Finally, the technological work of quartz crystal technology was stimulated and shaped by the fact that much, though not all, of the associated engineering knowledge was patentable. The initial developments within the field were based on non-patentable scientific discoveries, but, beginning with World War I, many quartz crystal developments were both patentable and cumulative. A handful of key quartz crystal patents (also called basic or fundamental patents) were issued in the early and mid 1920s. The owners of these patents, who happened to be independent inventors, were thus in a position to exercise a great deal of control over the evolution of quartz crystal devices, at least up until World War II. For a number of reasons, however, this never happened. Instead, a wide range of inventors, firms, and research institutions contributed to the growth and accumulation of quartz crystal knowledge. The reasons for this diversity of research sites, as well as for the rich variety of quartz crystal patents issued, is one of the key points of interest in this study.

This study is organized into nine chapters. Chapters 1 through 8 are roughly chronological, with the exceptions of Chapters 3 and 5. Chapter 3 breaks from the narrative to provide a broad overview of quartz crystal technology based on extensive patent data, and Chapter 5 overlaps considerably with Chapter 4 but presents the narrative from a regulatory rather than an industry perspective. The conclusions of Chapter 9 draw from all preceding chapters. What follows is a very brief synopsis of the chapter contents.

Chapter 2 provides a pre-history of quartz crystal technology, beginning in France before the turn of the century with the Curie brothers' discovery of piezoelectricity and ending in the U.S. in the immediate post-World War I years. For most of this period, piezoelectricity remained an area of purely academic interest for a handful of European scientists. In terms of knowledge, much of the foundational propositional knowledge of piezoelectricity was discovered at this time. With the coming of World War I, however, piezoelectric technology was born. The Allied countries, united in their efforts to combat the German submarine menace, developed the first piezoelectric SONAR systems. This work began in France and England but was quickly transferred across the Atlantic, where American physicists and engineers picked up the work. The American anti-submarine work brought together many individuals that would greatly influence the course of quartz crystal technology for decades to come. This chapter ends by introducing the post-war work of one of these individuals, Walter Guyton Cady. In the early 1920s, Cady filed for and was issued two patents, one for the piezoelectric resonator and the other for the piezoelectric oscillator. These patents provided the technological foundation for all subsequent work in quartz crystal technology.

Chapter 3 departs from the narrative structure of Chapter 2 and presents a long view of subsequent developments in quartz crystal technology. Based heavily on a detailed evaluation of quartz crystal patents filed between 1918 and 1959, this chapter identifies the essential knowledge and knowledge producers and surveys the entire scope of quartz crystal devices and accessories. It provides a baseline technical background useful for understanding the narrative of Chapters 4 through 8 and helpful in exploring the thematic issues raised earlier in this introduction. In addition, this chapter tracks the inventive activity of quartz crystal knowledge producers – private firms, government labs, and independent inventors – over four decades. Many of these producers have prominent roles in the ensuing narrative.

Chapter 4 picks up the narrative begun in Chapter 2, beginning with Walter Cady's attempts to find a licensee or buyer for his piezoelectric resonator and oscillator patents. The earliest organizations to express interest were the U.S. Bureau of Standards and the newly opened U.S. Naval Research Laboratory (NRL). The Bureau was interested in using Cady's resonator as a new reference standard for measuring high-frequency radio waves, while the NRL viewed Cady's oscillator as a means of achieving greater frequency stability for its high-powered radio transmitters. Radio amateurs also adopted Cady's oscillator, which allowed them to communicate in the newly discovered shortwave radio band. It wasn't long, however, before Cady's inventions attracted commercial interest. The early 1920s boom in AM radio broadcasting created an enormous consumer market for affordable radio receivers, but the many stations crowding the airwaves created a thorny interference problem. Once it became clear that Cady's quartz crystal oscillator could ameliorate this problem, inventors began building on Cady's foundational patents with scores of improvement patents. Radio transmitter manufacturers – principally RCA and AT&T – began purchasing sizeable portfolios of these patents, as well as developing their own through their in-house R&D programs. Thus, this chapter presents the initial formation of the quartz crystal technological community, comprised largely of radio engineers in the largest American radio companies, but also of enterprising radio amateurs. At this point, quartz crystal engineering knowledge was for the most part considered a small subset of radio engineering knowledge, interesting as far as it went, but not broad enough to merit study apart from the context of radio.

Chapter 5 examines the same historical period as Chapter 4, yet from the perspective of broadcast radio regulation. This chapter argues that the Radio Section of the U.S. Bureau of Standards greatly accelerated the broadcast industry's adoption of quartz crystal technology by developing design criteria and performance specifications for broadcast transmitters and by lobbying for strict frequency adherence legislation. The principal figure at the Radio Section was John Dellinger, a prominent radio engineer and member of the Institute of Radio Engineers (I.R.E.), from whom he received much technical assistance in his regulatory work. Also assisting Dellinger in his work was the

General Radio Company of Cambridge, MA. This small but influential firm helped the Bureau realize its strict frequency adherence guidelines by pioneering the manufacture of quartz crystal-based frequency standards for use by broadcast stations, industrial R&D labs, government standards agencies, and manufacturers of high precision radio equipment. Without General Radio's affordable, portable, and highly accurate frequency standards, quartz crystal engineering knowledge would have likely reached a plateau by the mid-1920s.

Chapter 6 relates developments in quartz crystal technology from the late 1920s up to just before World War II. During this period, AT&T's Bell Telephone Laboratories developed quartz crystal wave filters, which, along with its newly developed coaxial cable, enabled the company to greatly increase the capacity of its multiplex long-distance telephony network. This period also saw the rise of many small, privately owned manufacturing firms that specialized in the production of quartz crystal units (QCUs) for the thriving amateur radio market. By the end of the 1930s, a sizeable and diverse quartz crystal technological community existed. This community had created and accumulated a great deal of scientific and engineering knowledge pertaining to quartz crystal, and it had established the centrality of that knowledge to the two most significant communications systems of the day – radio and telephony. Yet one significant area of quartz crystal technology – QCU fabrication and manufacture – remained relatively undeveloped, for most QCU production remained small-scale and craft-based.

Chapter 7 chronicles the rapid escalation of QCU production from small-scale batch production to mass production, brought on by the urgency of World War II. With the U.S. mobilizing for war, all private QCU production was placed under centralized management and optimized for satisfying the needs of the Army Signal Corps. The effort to rapidly scale-up QCU production revealed two potentially fatal weaknesses in quartz crystal technology. First, the rigorous demands of mass production exposed areas of insufficient engineering knowledge that had gone unnoticed as long as small-scale, craft-based QCU production methods reigned. Consequently, engineers and inventors developed much new engineering knowledge throughout the course of the war. Second, the vast amounts of raw quartz crystal needed to supply the Army Signal Corps during the war made quartz crystal a critical national resource. But virtually all of the quartz used in the war was imported from Brazil. If quartz crystal technology was to have any future in the U.S., one of two things had to happen. The U.S. would need to either discover a significant new domestic source of natural quartz crystal or develop a synthetic substitute for natural quartz. With the former option failing to materialize, the latter was the quartz crystal industry's only hope for the future.

Chapter 8 tells the story of the decade long Army Signal Corps-sponsored research effort to develop a substitute for natural Brazilian quartz crystal. As part of this effort, the Corps created and sponsored an annual Frequency Control Symposium, which had the effect of consolidating the scattered quartz crystal technological community and imparting to it a self-consciousness that had never quite existed. The search for a quartz substitute was conducted in the U.S. by two firms, Cleveland-based Brush Development Company and AT&T's Bell Telephone Laboratories. These firms pursued similar but distinct paths in which flawless quartz crystals would be artificially grown (i.e., cultured) in a laboratory from crushed natural quartz. By the mid-1950s, two distinct quartz culturing processes had been developed, and a new industry – the cultured quartz industry

– had been formed. Now the U.S. quartz crystal industry, after nearly four decades of evolution, was finally freed from its dependence on natural Brazilian quartz crystal. Furthermore, QCU manufacturers could now tailor the growth of cultured quartz to suit certain applications. In the beginning, Walter Cady harnessed nature's timekeeper; by the late 1950s, engineers could tamper with nature to design and fabricate improved timekeepers.

Chapter 9 closes the study by analyzing the narrative of the preceding chapters along with the patent data of Chapter 3, arriving at a number of conclusions regarding the conception, growth, and maturation of the quartz crystal technological community and its creation, revision, and preservation of a distinct body of engineering knowledge.

CHAPTER 2: THE PRE-HISTORY OF QUARTZ CRYSTAL TECHNOLOGY (1880-1923)

2.1 Introduction

The scientific study of the phenomenon of piezoelectricity began in 1880, but technologies exploiting the piezoelectric property of quartz crystal did not appear until World War I. Thus, the story of the quartz crystal technological community has a nearly four decade pre-history. This chapter tells this pre-history as well as the history of World War I piezoelectric research and the beginnings of the post-war quartz crystal technological community. In doing so, this chapter shows that, prior to the war, piezoelectricity remained merely an esoteric area of crystal physics due primarily to technological limitations of the time. During the war, these limitations were removed, and piezoelectric technology soon appeared. This chapter also shows that the National Research Council, formed in the U.S. during the war, was instrumental in creating the beginnings of a piezoelectric technological community. In the course of the war, quartz crystal proved itself to be among the most useful of piezoelectric crystals, leading many researchers to focus on it to the exclusion of other crystals, such as Rochelle Salt. After the war, Wesleyan University professor Walter Guyton Cady continued the work begun during the war, ultimately developing and patenting the foundational engineering knowledge of quartz crystal technology – the piezo-resonator and the piezo-oscillator. The originality of Cady’s work was soon contested, leading to a prolonged battle between the two giant American radio companies of the time – RCA and AT&T – over the ownership of quartz crystal patents. This rivalry is shown to have established a fruitful dynamic that would lead to a proliferation of quartz crystal engineering knowledge in the years to come.

2.2 The Curie brothers discover piezoelectricity

The year was 1880; the place, Paris, France.[23] Brothers Jacques and Pierre Curie were young physicists, both interested in exploring the properties of crystals under changing environmental conditions. Jacques, age 24, served as assistant to a professor of mineralogy at the Sorbonne. 3 ½ years his junior, Jacque's brother Pierre was still a novice experimentalist; his only experimental work prior to 1880 was a determination of the lengths of heat waves, performed with the help of a professor. The brothers' interest in crystals was not surprising given the pioneering history of mineralogy and crystallography in France. In 1745, the Jardin du Roi (Garden of the King) established a chair of mineralogy, and the French government founded the Ecole des Mines (School of Mines) in 1783, dedicated exclusively to the fields of mineralogy and metallurgy.[24] Upon the founding of the French Academy of Sciences in 1795, one of the ten original sections was dedicated to mineralogy. And in 1772, Frenchman Rome de l'Isle (1736-1790) published one of the first books on crystallography, *Essai de Cristallographie*, which laid the foundation for the highly influential work of Rene-Just Hauy (1743-1822), one of two founding members of the Academy's mineralogy section and regarded today as one of the founders of the science of crystallography.[25] More recently, Frenchmen

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[23] What follows is a brief summary of the Curie brothers' discovery of the piezoelectric effect. For a thorough account of this discovery, written from a history of science perspective, see Shaul Katzir, "The Discovery of the Piezoelectric Effect," *Archive for History of the Exact Sciences* 57, no. 1 (January 2003): 61-91.

[24] Maurice Crosland, *Science Under Control: The French Academy of Sciences 1795-1914* (Cambridge, England: Cambridge University Press, 1992).

[25] Ibid. Note: The other founding member of the Academy's mineralogy section was D'Arcet.

Charles Friedel (1832-1899) and John Mothee Gaugain had studied the pyroelectric properties of crystals, pyroelectricity being the phenomenon in which a crystal generates an electric polarity when subjected to changes in temperature.[26] The Curie brothers had acquainted themselves with these works. In 1880, based upon their knowledge of pyroelectricity and furthered by their own studies, the brothers postulated the existence of a similar phenomenon - piezoelectricity, in which the application of pressure on the faces of a crystal would produce an electric polarity.

To test their hypothesis, the Curie brothers took a crystal and cut it in such a way that two of its faces were perfectly parallel as well as perpendicular to one of the crystal's three natural axes.[27] Next, they took two tin sheets, placed them in contact with each of the two faces, and electrically isolated the two tin sheets from each other; these sheets were to serve as electrodes. The entire device was then placed in a vise such that pressure could be applied to the two parallel faces. Finally, the brothers connected the two electrodes of an electrometer to the two tin sheets in order to measure the electrical potential between them. Upon tightening the vise, the electrometer's needle jumped, clearly showing the presence of an electric charge. The greater the pressure applied, the higher the needle jumped, indicating that the electrical potential generated was proportional to the intensity of the applied pressure. The Curies observed this effect in ten types of crystal, including quartz, cane sugar, and Rochelle salt (potassium sodium tartrate).[28]

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[26] Jacques Curie and Pierre Curie, "Development, by pressure, of polar electricity in hemihedral crystals with inclined faces," *Comptes Rendus* 91 (2 August 1880): 294.

[27] One of the defining characteristics of a crystal is that its molecules are arranged in a lattice structure, making it easy for scientists to impose a set of three axes, similar to those used in a Cartesian coordinate system, onto the crystal.

[28] Jacques Curie and Pierre Curie, "Development, by pressure, of polar electricity in hemihedral crystals with inclined faces," *Comptes Rendus* 91 (2 August 1880): 294.

At the time of the Curie brothers' discovery, quartz crystal was valued primarily for its aesthetic beauty, optical clarity, and hardness. The sparkling clearness of pure quartz coupled with its hardness had long inspired people to fashion jewelry, optical lenses, and, most famously, crystal balls from it. The 1911 Encyclopedia Britannica listed a number of common applications for quartz crystal, including gems and ornaments, balance weights, "pivot supports for delicate instruments," engraving tools, spectacles, and as a grinding and polishing material.[29]

Because of its chemical composition (silicon dioxide), quartz was and remains the most common mineral in the earth's crust, often found mixed with other minerals. But despite its ubiquity, large deposits of pure, high-quality quartz crystal are relatively rare throughout the world. Though large single crystals are not uncommon, they often contain defects, such as twinning[30] and discoloration, which compromise their aesthetic as well as their piezoelectric value.

When the Curies made their discovery, the Dauphine region of France, near the Italian border, was known to contain some of the finest deposits of quartz crystal in all of Europe. In fact, this was likely the source of the samples with which the Curies experimented. Across the Atlantic, the U. S. Geological Survey had already noted several deposits of high quality quartz. Its 1882 Annual Survey of U. S. mineral resources noted that quartz could be found in New York, the Hot Springs region of Arkansas, Colorado, the New Jersey coast, and part of North Carolina. Most of the

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[29] *The Wikisource 1911 Encyclopedia Project.* (Accessed 17 July 2006) available from http://en.wikisource.org/wiki/Main_Page; Internet.

[30] Twinning is a phenomenon in which a crystal possesses two or more distinct orientations. It is often difficult to ascertain from a crystal's external appearance. The presence of twinning seriously compromises a crystal's piezoelectric usefulness. See Walter Guyton Cady, *Piezoelectricity; An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals* (New York: McGraw-Hill, 1946), 31-33.

specimens collected in these regions, the Survey noted, were sold as souvenirs or occasionally turned into jewelry. Despite these numerous domestic sources, quartz crystal used for optical purposes were typically imported from Brazil, “not that the American is not fine enough, but the good material found here rarely reaches the proper channels, and the Brazilian is cheap.”[31] Thus, by the 1880’s, Brazil had gained a reputation as having some of the highest quality and least expensive quartz crystal in the world. As will be seen in later chapters, Brazil maintained this reputation well into the 20th century.

The Curies published their discovery of piezoelectricity in the August 2, 1880 issue of the French journal *Comptes Rendus*, known for its rapid publication of research presented before weekly meetings of the French National Academy of Sciences.[32,33] The particular form of piezoelectricity observed by the brothers in these first experiments, in which the crystal converts applied physical pressure into electrical energy, came to be called the “direct” piezoelectric effect. Upon learning of their work, French physicist and mathematician Gabriel Lippmann (1845-1921), arguing from theoretical assumptions, hypothesized the existence of a converse piezoelectric effect, in which the application of an electric charge to a piezoelectric crystal would produce physical deformation of the crystal**.** Though the existence of this converse effect was much more difficult to verify experimentally than was the direct effect, the Curie brothers succeeded in doing so, publishing their results in December of 1881.[34]

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[31] U.S. Geological Survey, *Mineral Resources of the United States*, (Washington, D. C., 1883).

[32] Jacques Curie and Pierre Curie, "Development, by pressure, of polar electricity in hemihedral crystals with inclined faces," *Comptes Rendus* 91 (2 August 1880): 294.

[33] Maurice Crosland, *Science Under Control: The French Academy of Sciences 1795-1914* (Cambridge, England: Cambridge University Press, 1992).

[34] Jacques Curie and Pierre Curie, "Contractions and dilations produced by electric voltages in hemihedral crystals with inclined faces," *Comptes Rendus* 93 (26 December 1881): 1137.

What the Curie brothers had in fact discovered was that all piezoelectric crystals, including quartz, are natural transducers, converters of energy from one form to another. That is, these crystals can convert physical or mechanical energy into electrical energy. Furthermore, the energy conversion process is reversible, allowing electrical energy to be converted into mechanical energy. As later researchers would learn, much energy is lost in each conversion[35]; nevertheless, the fact that quartz is a transducer in its natural state made it unique among electromechanical transducers of the time. Other transducers, such as carbon microphones, electromagnets, and DC electric motors were and are very much artifacts that require a great deal of human design and fabrication to realize. By contrast, quartz simply requires some cutting and polishing, as well as encasing it such that it can be easily interfaced with other electrical components. Of course, the cutting, polishing, and encasing tasks are not always easy to achieve in practice, but they are not conceptually difficult.

2.3 Discovery of piezoelectricity fails to yield any immediate technological applications

Given all the practical applications to which piezoelectric materials were put in the 20th century (microphones, frequency stabilizers, phonograph pickups, ultrasonic transducers, loudspeakers), it may seem surprising at first glance to see that the Curie brothers' discovery resulted immediately in only one practical application. The brothers developed and patented the piezo-electric quartz electrometer, a device for measuring small DC electric potentials.[36] This was a fairly straightforward application of the converse piezoelectric effect. Pierre actually used the quartz electrometer years later in

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[35] It is this fact that makes the perpetual motion machine an impossibility.

[36] Jacques Curie and Pierre Curie, *Electrometer System*, French Patent Office, Patent No. 183,851, Issue Date: 27 May 1887.

his experiments with Marie Curie on radio-activity.[37] However, no further patents for piezoelectric devices would appear until after World War I.[38]

Surprising as the nearly four decade gap between the discovery of piezoelectricity and the birth of piezoelectric technology may seem, there are at least two solid reasons for it. First and most importantly, full exploitation of piezoelectric quartz crystal had to await the development of auxiliary technologies, most notably technologies for generating and sustaining continuous radiofrequency electrical oscillations.[39,40] Unbeknownst to the Curie brothers, the true technological value of quartz crystal was to lie in its ability to operate at radiofrequencies, ranging from the tens of kilohertz (kHz) to hundreds of Megahertz (MHz).[41] In the 1880s, electrical oscillators were limited to alternating current generators, which generated frequencies no higher than several hundred Hertz. In the 1890s, alternators capable of producing oscillations up to 15 kHz were developed.[42] The first decade and a half of the 20th century saw the development of

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[37] Marie Curie, *Pierre Curie. With the autobiographical notes of Marie Curie* (New York: Dover Publications, 1963).

[38] According to an exhaustive bibliography of piezoelectricity published by Walter Cady in 1928, the next piezoelectric-related patent to be awarded was to R.W. Moore of the General Electric Company in 1920 for a method of growing piezoelectric crystals from solution. (U.S. Patent 1,347,350) For a complete bibliography of patents up to 1928, see Walter Guyton Cady, "Bibliography on Piezo-Electricity," *Proceedings Of The Institute Of Radio Engineers* 16, no. 4 (April 1928): 521-35.

[39] Two words are crucial here – "continuous" and "radiofrequency." "Continuous" designates undamped sinusoidal waves of the kind that are required for the transmission of voice, music, and other audible information. Methods of producing high-frequency *damped* waves were developed as early as the 1860s, but these waves required the use of Morse code or other forms of pulsed modulation. (See Chapter 3 of Hugh Aitken, *Syntony and Spark: The Origins of Radio* (New York: Wiley, 1976).) "Radiofrequency" designates frequencies ranging from 10 kHz to 300 GHz. One GHz is equal to 1,000,000,000 cycles per second.

[40] Shaul Katzir has made this point in Shaul Katzir, "Technological and scientific study in the discovery and application of the piezoelectric resonance" (paper presented at the The Applied-Science Problem - A Workshop, Stevens Institute of Technology, Hoboken, NJ, 6-8 May 2005). Katzir notes that the development of the electronic vacuum tube amplifier was a technological pre-condition for the invention of the piezoelectric resonator.

[41] One kilohertz (kHz) is 1000 cycles per second; one Megahertz is 1,000,000 cycles per second.

[42] See Nikola Tesla, *Alternating Electric Current Generator*, U. S. Patent Office, Patent No. 447,921, Filing Date: 15 November 1890; Issue Date: 10 March 1891. See also Hugh Aitken, *The Continuous Wave: Technology and American Radio, 1900-1932* (Princeton, NJ: Princeton University Press, 1985), 53.

several methods of radiofrequency oscillation. Canadian Reginald Fessenden, working with General Electric engineer Ernst Alexanderson, developed radiofrequency alternators capable of producing frequencies as high as 100 kHz, but these devices were very heavy and bulky. Valdemar Poulsen of Denmark developed an arc oscillator capable of generating frequencies up to 150 kHz, but this was also heavy and bulky. Without question the most important device for practically producing high frequency oscillations was the triode vacuum tube, an extension of Ambrose Fleming's diode and Lee De Forest's audion. This device, which had the advantage of being relatively small and operating on low power, was perfected as an oscillator by G.E., Westinghouse, and AT&T in the mid-teens. The vacuum tube would allow quartz crystals to be used in compact and inexpensive electronic oscillator circuits. Thus, by the mid to late teens, auxiliary technologies had developed to the point where the high frequency capabilities of piezoelectric quartz crystal could begin to be explored.[43]

A second reason for the nearly four decade gap between the discovery of piezoelectricity and the appearance of piezoelectric applications concerns the Curies themselves. The Curie brothers were much more scientists than engineers, and the late 19th century was a time when the scientist/engineer distinction was still observed by many, even though engineers were already beginning to adopt scientific methods in their work.[44] Both Curie brothers were much more interested in discovering and exploring fundamental properties of nature than in developing useful devices or instruments. Pierre would go on to explore the principle of symmetry in nature as well as the behavior of

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[43] The development of the radiofrequency alternator, the Poulsen arc, and the audion are well-documented in Hugh Aitken, *The Continuous Wave: Technology and American Radio, 1900-1932* (Princeton, NJ: Princeton University Press, 1985).

[44] Jr. Layton, Edwin T., "Mirror-Image Twins: The Communities of Science and Technology in 19th-Century America," *Technology and Culture* 12, no. 4 (1971): 562-80.

magnetic materials, while Jacques became head lecturer in mineralogy at the University of Montpelier, where he served for over thirty years.[45] For his individual work, as well as for his work with wife Marie on radioactivity, Pierre was elected into the prestigious French Academy of Sciences in 1905, just one year before his untimely death.[46]

It's easy to see why the Curies didn't have a more technological bent, given the society in which they lived. French government and culture of the late 19th century did not exactly encourage cooperation between science and industry. Science was viewed more as an intellectual endeavor and as an aspect of the national culture than as a practical means to assisting industry.[47] Most of France's universities, where the Curies spent their lives, did not have close ties to French industry. Surely this explains, at least in part, the failure of the Curies and other French scientists to more fully exploit the practical potential of piezoelectricity.

2.4 The scientific study of piezoelectricity

The immediate impact of the Curie's discovery was felt not in the world of technology, but in the rarefied world of academic scientific research.[48] Notable scientists across Europe, including Lord Kelvin of Scotland, Woldemar Voigt of Germany, and two future Nobel Prize winners, Wilhelm Rontgen, discoverer of X-rays, and Gabriel Lippmann, studied and advanced the new field of piezoelectricity. Numerous articles on the phenomenon appeared in several European scientific journals, most of them French or

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[45] Walter Guyton Cady, *Piezoelectricity; An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals* (New York: McGraw-Hill, 1946), footnote on page 2.

[46] Maurice Crosland, *Science Under Control: The French Academy of Sciences 1795-1914* (Cambridge, England: Cambridge University Press, 1992).

[47] Ibid.

[48] For an exhaustive and authoritative study of the first two decades of piezoelectric research from a history of science perspective, see Shaul Katzir, *The beginnings of piezoelectricity: a study in mundane physics*, vol. 246, Boston studies in the philosophy of science (Dordrecht, Holland: Springer, 2006).

German, during the three decades following the Curies' discovery. A select bibliography of piezoelectricity compiled in 1928 listed twenty-four journal publications appearing between 1880 and 1916, but noted that these were only the most important of the early literature, which was described as being "very voluminous."[49] Even so, piezoelectric research as a field was miniscule compared with the study of phenomena such as X-rays, cathode rays, and black-body radiation. One prominent physicist of the time described research in crystal physics, of which piezoelectricity was only a small part, as "hermit's work" because of the small number of scientists interested in it.[50]

Notable among the scientific works on piezoelectricity appearing before World War I was German physicist Woldemar Voigt's mathematically rigorous and exhaustive 964-page *Lehrbuch der Kristallphysik* (Textbook on Crystal Physics).[51] It stands out as a testament to the thoroughness with which the scientific theory of piezoelectricity had been studied prior to the war. Voigt's work is representative of all piezoelectric work done during this period in that he treats piezoelectricity as a window onto his primary interest – the molecular structure and dynamics of crystals. He investigated crystals only for the light that they could shed on fundamental questions regarding the constitution of matter at the molecular level. Voigt was interested in all phenomena exhibited by crystals – piezo- and pyroelectricity, piezo- and pyromagnetism – because, for him, crystals displayed the properties of molecules "in their purest and most complete form."[52] Furthermore, Voigt displayed the "pure" scientist's disdain for practical application of

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[49] Walter Guyton Cady, "Bibliography on Piezo-Electricity," *Proceedings Of The Institute Of Radio Engineers* 16, no. 4 (April 1928): 521-35.
[50] The physicist was Woldemar Voigt, as cited in Christa Jungnickel and Russell McCormmach, *Intellectual Mastery of Nature: Theoretical Physics from Ohm to Einstein*, 2 vols., vol. 2 (Chicago: University of Chicago Press, 1986).
[51] Woldemar Voigt, *Lehrbuch der Kristallphysik* (Leipzig: B. G. Teuner, 1910).
[52] Ibid., 4.

physical phenomena. He considered crystal physics to be “old-fashioned physics in the strictest sense,” by which he meant that physicists pursued it for pure understanding apart from any possible useful application.[53]

Perhaps the most striking aspect of the piezoelectric research done between 1880 and World War I was that all of it was done in Europe, and most of it published in non-English journals. Of the significant piezoelectric research done in this period, only Lord Kelvin published in English.[54] Also striking is that American physicists seem to have completely ignored piezoelectricity. *Physics Review*, the premier publication for American physicists, published its first research article on piezoelectricity only in 1927![55] This lag was more likely due to the generally backwards state of pre-WWI American physics than to any particular avoidance of piezoelectricity.

Between 1880 and World War I, virtually no technological or engineering work exploited the piezoelectric property. But these years did see the development of technologies, especially radiotelephony and the triode vacuum tube, that would later allow piezoelectric quartz crystal to be harnessed to great effect. Also important was the submarine or U-boat, not because it was necessary for the full development of piezoelectric technology, but because it provided the stimulus that led to the first high-frequency, piezoelectric application of quartz.

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[53] Christa Jungnickel and Russell McCormmach, *Intellectual Mastery of Nature: Theoretical Physics from Ohm to Einstein*, 2 vols., vol. 2 (Chicago: University of Chicago Press, 1986). For description of the pure science ideal, see David A. Hounshell, "Edison and the Pure Science Ideal in 19th-Century America," *Science* 207 (8 February 1980): 612-17.

[54] Lord Kelvin, *Baltimore Lectures on molecular dynamics and the wave theory of light* (London: C. J. Clay, 1904). ———, "On the piezo-electric property of quartz," *Philosophical Magazine and Journal of Science* 36 (1893): 331, 42, 84, 453.

[55] L. H. Dawson, "Piezoelectricity of Quartz Crystal," *Physics Review* 29 (1927): 532-41. Dawson was a researcher with the Heat and Light Division of the Naval Research Laboratory.

2.5 SONAR – the first technological application of piezoelectricity

In the Spring of 1915, two physicists began working on a new device in a Paris laboratory. The two men, Russian émigré Constantin Chilowsky and French physicist Paul Langevin, hoped to develop a device that would help the French and British navies combat the menace of German U-boat (i.e., submarine) warfare. Chilowsky, upon hearing of the need for a countermeasure to the U-boat, had conceived of an echo-ranging system based on high-frequency underwater pressure waves.[56] Pressure waves would be needed because they propagate through water far better than most radio waves. Moreover, Chilowsky figured that the frequencies of these pressure waves would have to lie in the ultrasonic band, above the range of human hearing (>20 kHz). These high frequencies would allow the waves to be directed with great precision, permitting them to be used for locating distant objects.

Not knowing how to physically realize such an idea, Chilowsky sought out Langevin, then a physics professor at the Ecole Municipale de Physique et Chimie Industrielles in Paris. Langevin, who had received his Ph.D. working under Pierre Curie at the Sorbonne, was more familiar than most with the phenomenon of piezoelectricity. He speculated that piezoelectricity could be exploited to create Chilowsky's echo-ranging system. Since piezoelectric quartz crystal was a natural transducer converting electric waves into mechanical waves, applying a high frequency electric wave to quartz would theoretically produce a corresponding high frequency mechanical wave. When placed underwater, this mechanical wave would translate into a propagating pressure wave. But there was a problem. The minute amplitudes of the electrical signals involved would

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[56] A pressure wave sets up alternating regions of compression and rarefaction in the transmitting medium. When this medium is air, the pressure wave is called a sound wave. The pressure wave is a kind of mechanical wave in that it requires a transmitting medium; pressure waves cannot propagate in a vacuum.

require powerful, low-noise amplifiers. Unfortunately, the primitive vacuum tube amplifiers available to Langevin at the time were simply not up to the task.

In early 1917, the situation suddenly changed. Physicists and engineers with the French agency Radiotelegraphie Militaire had earlier acquired one of American Lee DeForest's Audion amplifiers. Using the Audion as a starting point, the engineers made tremendous improvements to the device, similar to those made by Irving Langmuir of G.E. In early 1917, Langevin convinced the French Signal Corps to loan him several of its improved vacuum tube amplifiers.[57] He then managed to obtain large slices (10 x 10 x 1.6 cm) of pure quartz crystal from a Parisian optician. With all the necessary pieces in place, Langevin constructed a novel condenser, known as a "sandwich" transducer, by employing a mosaic of thin quartz plates as the dielectric. When inserted into an oscillating circuit, one of the condenser's plates would vibrate at the driving frequency, generating pressure waves in whatever medium the unit was placed – water in this case. Conversely, pressure waves traveling toward the condenser's exposed plate would set up electrical oscillations within the connected circuit, thus acting as a receiver rather than a transmitter of underwater pressure waves. Langevin and Chilowsky had built the world's first ultrasonic echo-ranging system, known today as SONAR (SOund Navigation And Ranging).

Langevin's work with quartz "sandwich" transducers represented a radical extension of the way in which piezoelectric quartz had been used up to that time. The Curie brothers, when verifying the existence of the converse piezoelectric effect, had only applied static, direct current (DC) voltages to a quartz crystal. These voltages produced a

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[57] Willem Dirk Hackmann, *Seek and Strike: Sonar, Anti-Submarine Warfare, and the Royal Navy, 1914-54* (London: H.M.S.O., 1984).

physical displacement, or flexure, in the crystal slab, much as the DC current through a D'Arsonval meter movement would produce movement of the meter's needle.[58] Little did the Curies know that applying an oscillating or alternating current (AC) voltage to quartz crystal would open up entirely new applications.

Langevin discovered that quartz slabs vibrated in resonance when certain frequencies of oscillating voltage were applied to the slab, and that these frequencies varied with the physical dimensions of the slab. (Langevin emphasized that the ensemble of quartz plate and condenser armatures should possess "une periode proper de vibration elastique" (a characteristic period of elastic vibration) equal to those of the excited electric oscillations. He later described this condition as one of elastic resonance.) If the crystal slab was cut such that the resonance frequency lay in the tens of kilohertz, above the audible range, then, when submerged in water, the excited slab would generate pressure waves that could be easily focused and directed toward particular objects. These were exactly the kind of waves needed to detect submarines at a distance; they could be directed with precision and were strong enough to generate detectable echoes.

2.6 U.S. Anti-Submarine Warfare research during World War I

In April 1917, the U.S. joined the Allied powers in the war against Germany. In preparation, the Americans had already formed two organizations to bring technology and science to bear on the problems of warfare. The Naval Consulting Board (NCB), chaired by Thomas Edison and staffed by civilian experts from the business and

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[58] A D'Arsenval meter movement operates on the principle of electromagnetism, whereby the current flowing through an electromagnet sets up a temporary magnetic field. If the electromagnet is suspended between the poles of a permanent magnet, the interaction of the two magnetic fields will produce rotational displacement. A piezoelectric quartz crystal utilizes a completely different mechanism when subjected to a DC voltage; yet, the result is similar to that of the D'Arsenval meter movement.

engineering worlds, solicited new technology proposals from the nation at large. In contrast, the National Research Council (NRC), organized by George Ellery Hale of the National Academy of Sciences, sought to coordinate the research efforts of several universities and other research institutions. Upon the U.S. entry into the war, these organizations quickly mobilized themselves to address the ongoing threat of U-boat warfare, forming anti-submarine warfare (ASW) research efforts.[59]

The NCB and NRC ASW research efforts operated largely independently of one another, not the least reason for which was the tension between the NCB's "industrial" culture and the NRC's "academic" culture. The NCB established a research facility at Nahant, MA, under the direction of General Electric's Willis Whitney, to develop and test passive sound-detection systems. Contributing to the effort were industrial scientists and engineers from G.E., Western Electric, and the Submarine Signal Company (today known as Raytheon). For its part, the NRC appointed an anti-submarine committee, led by Robert Millikan, then Professor of Physics at the University of Chicago. Millikan established a research facility in New London, CT, where he gathered many academic as well as industry scientists to develop and test active echo-detection systems, including Paul Langevin's proposed system. The firms that contributed to the NCB effort also contributed to the NRC effort.[60]

On June 1, the NRC held a conference in Washington, D. C. with British, French, and American scientists as well as U.S. Navy officers to discuss ASW research goals.[61]

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[59] Willem Dirk Hackmann, *Seek and Strike: Sonar, Anti-Submarine Warfare, and the Royal Navy, 1914-54* (London: H.M.S.O., 1984). See chapter entitled, "Organizing Science for the War at Sea." See also 89-95.
[60] Ibid.
[61] Scientists attending the June 1 conference included Ernest Rutherford of Great Britain, Ch. Fabry, H. Abraham, Due de Guiche, and M. Paternot of France, and G. E. Hale, E. Merritt, W. E. Durand, R. W. Wood, I. Langmuir, F. B. Jewett, C. E. Mendenhall, Henry Fay, H. D. Arnold, and E. H. Colpitts of the

This meeting was followed by a much larger meeting on June 14-16. Attendees of this meeting included representatives of Western Electric, G. E., and Westinghouse, the three largest American manufacturers of electrical apparatus at the time and the firms that would come together after the war to form the Radio Company of America (RCA). Also present were forty to fifty scientists and engineers, including Walter Guyton Cady, then a Professor of Physics at Wesleyan University, a small, mostly undergraduate school in Middletown, CT.

Prior to the NRC conference, Cady had considered the submarine detection problem and determined that, among the variety of methods being investigated, a method of ultrasonic signal generation and echo detection held the most promise. As he recalled some forty-five years later, “I had been thinking of the submarine problems before the meeting in Washington… and came to the conclusion that if I could only think of a good way to generate powerful ultrasonic-waves underwater with a frequency high enough for the beam to be directed, that would be a good way to pick up the submarine. Then came the call to Washington and immediately I grabbed hold of the piezoelectric idea because it seemed to be just what I wanted.”[62] The call Cady was referring to came from renowned physicist Robert Millikan, who had been appointed to head the NRC’s ASW research effort.

United States. Source: Walter Guyton Cady, "Piezoelectricity and Ultrasonics," *Sound* 2, no. 1 (January-February 1963): 46-52.

[62] R. Bruce Lindsay and W. J. King, "Walter G. Cady Oral History Interview" 28-9 August 1963, Center for History and Philosophy of Physics. Available at Box 2, Walter G. Cady Papers, Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT.

2.7 Walter Guyton Cady

Walter Guyton Cady was born on December 19, 1874 in Providence, Rhode Island, one of three sons to John Hamlin and Mary Tabitha Cady. His family had been in the shipping business for several generations, doing well enough to move into a large and fashionable house near the campus of Brown University. As a child, Walter showed an interest in tools and knew by the time of high school that he wanted to be either an engineer or a physicist. All the Cady boys attended nearby Brown University, where Walter graduated with a Master of Arts degree in 1896. During his senior year there, Professor Carl Barus, originally from Germany, encouraged Walter to go to Germany to study for his Ph.D. in physics. Armed with several letters of introduction written for him by Dr. Barus, Walter crossed the Atlantic and enrolled at the University of Berlin in 1897.[63]

In pursuing his graduate studies in Germany, Cady was fairly typical of aspiring American physicists of his day.[64] Most of America's top physicists of the late 19th century, including Henry Rowland, Albert Michelson, Josiah Gibbs, Robert Millikan and Michael Pupin had spent time studying in Europe, particularly in Germany.[65] In fact, Pupin had studied at the University of Berlin just ten years prior to Cady.[66] Despite growing opportunities for graduate study in the U.S., the options were still limited to a handful of institutions, such as Johns Hopkins, Yale, Columbia, Cornell, and the University of Chicago. Between 1873 and 1890, American universities granted only

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[63] Sidney B. Lang, "A Conversation with Professor W. G. Cady," *Ferroelectrics* 9 (1975): 141-49. This article is a transcript of an interview held a Cady's home in Providence on September 28, 1972, when Cady was nearly 98 years old.

[64] Encyclopedia of the United States in the Twentieth Century, 1996, s.v. "Industrial Research and Manufacturing Technology." by David A. Hounshell, 834.

[65] Daniel J. Kevles, *The Physicists* (New York: Alfred A. Knopf, 1978).

[66] Michael Pupin, *From Immigrant To Inventor* (New York: Charles Scribner's Sons, 1923).

twenty-two Ph.D.s in Physics.[67] Furthermore, there weren't many active physicists in the U.S. in the 1890s. Historian Daniel Kevles has noted that "by the early 1890s only some 200 Americans were practicing the discipline of physics."[68] Only about 20% of these, he notes, published research regularly. The only American scientific journal dedicated exclusively to physics at the time, *The Physics Review*, wasn't founded until 1893.[69] By all accounts, American physics research was still in its infancy when compared with European research.

When Walter Cady arrived at the University of Berlin in 1897, he entered an institution with a second-to-none reputation in electromagnetic research, having been the university home of pioneering physicists Gustav Kirchhoff (1824-1887) and Hermann von Helmholtz (1821-1894). The Physics faculty at the time included, among others, a mid-career theoretical physicist named Max Planck (1858-1947) and the experimental physicist Emil Warburg, who was head of the department as well as Cady's principal examiner in physics.[70] The late 1890s was an exciting time in the world of physics. German physicist William Roentgen had recently discovered a powerful new form of radiation, the X-ray. In Britain, physicist J. J. Thomson, through his study of cathode rays, had just announced his discovery of the first subatomic particles, which he called corpuscles, but which soon were dubbed electrons. And many physicists, including Planck, were investigating the nature of so-called black-body radiation (i.e., the light given off by an opaque and non-reflective body as its temperature increases). By contrast, piezoelectricity was not of particularly great interest to most of the physics

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[67] Daniel J. Kevles, *The Physicists* (New York: Alfred A. Knopf, 1978), 39.

[68] Ibid., 26.

[69] Edward L. Nichols of Cornell founded *The Physical Review* in 1893. See page 76 of Ibid.

[70] Christa Jungnickel and Russell McCormmach, *Intellectual Mastery of Nature: Theoretical Physics from Ohm to Einstein*, 2 vols., vol. 2 (Chicago: University of Chicago Press, 1986).

community. Since the Curies' discovery in 1880, only a handful of European physicists had published significant papers on the subject.[71] Piezoelectricity was generally considered to be a scientific curiosity, but not deserving of much research attention. Some researchers considered the phenomenon to be a window into molecular-level dynamics, but this was not a major interest to the physics community at large.

For his dissertation, Cady developed a new method of measuring the energy of cathode rays. The topic was not a novel one; many physicists at the time were investigating the characteristics of cathode rays. The popularity of this research was largely due to the prevalence of a laboratory device called the Crookes tube, named after English chemist William Crookes. In 1876, Crookes had developed a glass tube in which he placed two metal plates at opposite ends; one plate was called the cathode, the other the anode. After evacuating the tube of air, creating a near vacuum, Crookes set up an electric potential between the two plates. The result was that the tube glowed and turned green. The rays generated in Crookes' tube were soon dubbed cathode rays.[72] Roentgen's discovery in 1896 that Crookes tubes were capable of generating X-rays as well as cathode rays only increased their popularity. In early 1897, the periodical *Electrical World* announced that Crookes tubes were so popular in Philadelphia that all local suppliers had sold out.[73] Thus, Cady did not choose a little-known, esoteric subject for his dissertation; by contrast, cathode rays were quite the rage, even outside the rarefied world of academic physics.

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[71] A comprehensive bibliography of piezoelectricity published by Walter Cady in 1928 lists just six physicists having published piezoelectric-related papers prior to 1897: the Frenchmen Jacques and Pierre Curie and G. Lippmann; the Germans Woldemar Voigt and P. Czermak; the Scotsman Lord Kelvin.

[72] Bettyann Holtzmann Kevles, *Naked To The Bone* (New York: Addison Wesley, 1997), 16-17.

[73] Ibid., 22-23.

The University of Berlin awarded Cady his Ph.D. in 1900, after which he returned to the U.S. Job prospects for a newly-minted Ph.D. physicist at this time were generally limited. Most became professors in colleges or universities, and many of these supplemented their modest salaries by offering consulting services to industry. Another option was to take a government post at one of the scientific bureaus. The time had yet to arrive in America when a large percentage of the nation's Ph.D. scientists were hired by industry as industrial researchers; in fact, such a position did not even exist in 1900. As historian George Wise has shown, General Electric was the first company, in 1900, to begin creating such positions.[74] But Cady did not have this option when he returned to the States.

Cady chose to take a position in Washington, D.C. as a magnetic observer for the U.S. Coast Guard and Geodetic Survey (USCGGS). His supervisor at the Survey was Louis Agricola Bauer. Like Cady, Bauer had earned his Ph.D. in physics in Berlin. While there, he had become interested in terrestrial magnetism, a field that was wide open for investigation.[75] Upon returning to the U.S., Bauer became convinced that the mysterious variation of the earth's magnetic field could be explained only by collecting and analyzing a vast amount of observational data. As head of the USCGGS, Bauer was now in a position to organize the collection of this data.[76] Cady, as a member of Bauer's staff, was charged with collecting and analyzing field measurements of terrestrial magnetism. After doing this work for a short time, Cady decided to look for a teaching position at a small college or university. As he would recall many years later, he wrote

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[74] George Wise, "A new role for professional scientists in industry: industrial research at General Electric, 1900-1916," *Technology and Culture* 21 (1980): 408-29.

[75] "Terrestrial magnetism" is today referred to as geomagnetism.

[76] *Dictionary of Scientific Biography* (1974), s.v. "Louis Agricola Bauer."

letters to six colleges,[77] receiving a response only from Wesleyan College in Middletown, CT, which offered him a position in 1902. Cady accepted the offer and spent the next forty-six years on the Wesleyan faculty. Though Cady's formal contact with Bauer ended in 1902, the two men would stay in touch over the next decade and a half.

During his early career at Wesleyan, Cady revealed himself to be what historian Shaul Katzir has called a "technologically oriented scientist."[78] At first, this was perhaps due simply to Cady's desire to supplement Wesleyan's modest budget for research. Early on, he secured several research grants for the school, including one from the Elizabeth Thompson Science Fund and another from the American Association for the Advancement of Science (AAAS).[79] But over time, Cady demonstrated a predilection for instrumentation and a real talent for invention. One of his first publications concerned an original machine for computing and plotting compound sine waves.[80] The machine's primary purpose was for instruction, yet it was an early sign of Cady's capacity for practical invention.

Cady's first serious research project investigated the poorly understood phenomenon of arc discharge-glow discharge oscillations occurring between metallic electrodes, particularly those made of iron. Lasting for several years, this research

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[77] Sidney B. Lang, "A Conversation with Professor W. G. Cady," *Ferroelectrics* 9 (1975): 141-49.

[78] Shaul Katzir, "Technological and scientific study in the discovery and application of the piezoelectric resonance" (paper presented at the The Applied-Science Problem - A Workshop, Stevens Institute of Technology, Hoboken, NJ, 6-8 May 2005).

[79] Walter Guyton Cady, "Saving Ancestors" [Unpublished Autobiography] 1963, cited: 209. Available at Walter G. Cady Papers, Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT. This is an unpublished autobiographical manuscript that Cady wrote for his grandchildren after retiring. The Elizabeth Thompson Science Fund award of $200 came in 1906 or 1907 and helped to fund Cady's multi-year study of electric arcs. Thompson was a Boston widow and philanthropist who established her fund in 1884 with an endowment of $25,000. As for the AAAS research grant, I've been unable to identify the research project that was supported.

[80] Walter Guyton Cady, "A machine for compounding sine curves," *Science* 23 (January-June 1906): 877-81.

yielded seven significant publications in both American and German scientific journals.[81] One of these papers was co-written with a promising young student, Harold Arnold, who would go on to become an influential research manager with AT&T.[82] Cady's research in this area demonstrated his deep interest in oscillatory phenomena and gave him his first chance to develop a working scientific theory from the ground up. Furthermore, it showed his predilection for topics that were rich in technological potential, for arc phenomena had already been exploited in numerous technologies, including illumination and continuous-wave radio transmission. Cady then went on from this project to investigate a number of topics, including the magnetic behavior of copper and the properties of "insulated double connectors."[83] Thus, his pre-war work stayed firmly within the realm of electromagnetic phenomena.

Cady also demonstrated a practical bent in his teaching and extracurricular activities. According to one former student, Cady stayed away from cutting-edge areas of theoretical physics, such as quantum mechanics and Einstein's relativity,[84] preferring more settled areas of physics theory. Perhaps this was because these theoretical concepts were not yet ripe for being reduced to practice in the form of practical devices. Not that Cady shied away from new and unexplored areas. Rather, the areas he chose to investigate were ones that could be profitably explored using existing theoretical frameworks. Cady was also an amateur radio operator, helping to found Wesleyan's

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[81] Cady's facility with the German language allowed him to publish many of his research findings in both American and German scientific journals. The German journal Cady's articles most often appeared in was *Physikalische Zeitschrift*.

[82] Walter Guyton Cady and Harold D. Arnold, "On the electric arc between metallic electrodes," *American Journal Of Science* 24, no. 143 (1907): 383-411.

[83] Walter Guyton Cady, "Insulated double connectors," *Physikalische Zeitschrift* 12 (1911): 1254-55.

[84] Phillip Goodman, E-mail to the author, 19 January 2006. Mr. Goodman earned his M.S. degree under Professor Cady in 1948, just as Cady was retiring from Wesleyan.

Radio Club in the fall of 1914.[85] He regularly attended the Club's monthly meetings and kept up with the latest developments in radio technology. By no means did Cady fit the stereotype of the "pure" scientist, aloof from using science in the service of industry or other utilitarian pursuits.

From Cady's fifteen scientific publications prior to World War I can be discerned four related interests. First is his persistent interest in oscillatory phenomena, as evidenced by his compound sine wave machine and his investigation of arc oscillations. Next is Cady's interest in the properties of materials, particularly metals, but also dielectrics (i.e. insulators). Third, virtually all of Cady's pre-World War I research could be classified in the general category of electromagnetic phenomena: cathodes rays, electric arcs, insulators, and magnetism. Finally, Cady displayed a strong interest in instrumentation and precision measurement, as borne out especially by his doctoral research. These four interests and the experience and knowledge Cady gained in pursuing them gave him a distinct and somewhat atypical identity within the world of academic physics.

2.8 Cady's introduction to piezoelectric technology

In early June of 1917, Cady received a telegram from Robert Millikan asking him to report to Washington for a June 14-16 anti-submarine research conference, sponsored by the NRC. Louis Bauer, aware that his former colleague had given the anti-submarine problem some thought, had suggested to Millikan that Cady might contribute much to the conference, the primary purpose of which was to give British and French delegates a

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[85] Walter G. Cady Papers, Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT.

forum for presenting the results of their anti-submarine research, as well as to appeal to the U.S. research community to join the ASW research effort. The French delegation consisted of physicist Charles Fabry, radio expert Le Duc de Guiche, and Nobel Prize-winning chemist Victor Grignard, while the British delegation featured Nobel Prize-winning physicist Ernest Rutherford. The combined delegations presented test results obtained with two passive sound-detection devices and one active echo-ranging device, Paul Langevin's "sandwich" transducer.[86] For most attendees, the passive devices attracted the most attention, for they seemed closer to actually working in the field. But Cady was drawn to Langevin's work, which, despite its promise, was much less developed than the passive device work.

The three-day NRC conference was the initial catalyst for American piezoelectric engineering research. The response of NRC members was quick and energetic. Teams from G.E., Western Electric, the Bureau of Standards, Leland Stanford University (now Stanford University), and Columbia University all agreed to work on various aspects of Langevin's proposed underwater echo-ranging system. Stanford and Columbia agreed to work on quartz transmitters, while Western Electric investigated the possibility of replacing quartz with Rochelle Salt, a crystal known to exhibit a much stronger piezoelectric effect than quartz, but which was also highly water soluble. General Electric was to pursue research on both quartz and Rochelle Salt, and the Bureau of Standards agreed to inspect incoming shipments, most of them from Brazil, of raw quartz crystal.[87]

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[86] Robert A. Millikan, *The Autobiography of Robert A. Millikan* (New York: Prentice-Hall, 1950), 152.

[87] Walter Guyton Cady, "Piezoelectricity and Ultrasonics," *Sound* 2, no. 1 (January-February 1963): 46-52.

Walter Cady quickly involved himself with the NRC's underwater echo-ranging research. Just four days after the June conference, Cady noted in his personal diary that he had begun to work in his lab with piezoelectric crystals.[88] Then, at the suggestion of long-time friend and G.E. researcher A. W. Hull, Cady traveled to Schenectady, N.Y., a 140 mile journey, to talk with G.E. scientists regarding the company's development of Rochelle Salt and quartz crystal anti-submarine devices.[89] Upon President Wilson's declaration of war on Germany, the G.E. Research Lab, under the leadership of Willis Whitney, had suspended its usual activities to focus on war-related research, and no research project ranked higher in importance than that aimed at improving submarine detection.

Willis Whitney had established a policy at G.E. of hiring summer research associates.[90] Those who performed satisfactorily during this short stint were often asked to join the Research Lab on a permanent basis. Whitney's initial impressions of Cady must have been favorable, for he asked the Wesleyan professor to work for the lab until classes resumed in the fall. Though Cady was certainly paid by G.E., money was not likely a dominant factor in his deciding to work for the lab that summer. More than anything, Cady probably saw this as a practical way to contribute to the war effort. Over forty and raising a son by himself, Cady was in no position to serve militarily.[91] Furthermore, he had no real responsibilities at Wesleyan until the beginning of fall

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[88] Walter G. Cady, Personal Diary entry for 20 June 1917, Folder 24, Box 3, Walter G. Cady Papers (Subgroup 3), Cady Family Papers (MSS 326), Rhode Island Historical Society Library, Providence, RI.

[89] Walter G. Cady, Personal Diary entry for 30 June 1917, Folder 24, Box 3, Ibid. "Talk at GE Co. with Whitney, Hull, Langmuir."

[90] George Wise, *Willis R. Whitney, General Electric, and the Origins of U. S. Industrial Research* (New York: Columbia University Press, 1985).

[91] Walter G. Cady, Various diary entries, Folders 22-26, Box 3, Walter G. Cady Papers (Subgroup 3), Cady Family Papers (MSS 326), Rhode Island Historical Society Library, Providence, RI. Cady's wife died from unknown illness in 1909. He raised his only child, son Willoughby, by himself, never remarrying.

semester. From Whitney's standpoint, it seems likely that he saw Cady as little more than a temporary research consultant who could assist with the urgent war effort. It was rare for Whitney to hire any full-time researchers at Cady's age; he preferred to hire men (and women) when they were young and more flexible.[92]

As he recalled years later, Cady felt that he was the only "outsider" in G.E.'s crystal laboratory.[93] Being completely new to the field of piezoelectricity, he spent his spare moments in his first month acquainting himself with the existing literature. Other than the Curie brothers' foundational papers, most work on the topic was in German. This included Voigt's mammoth *Lehrbuch der Kristallphysik* (1910).[94] Cady's fluency in German certainly made this a much easier task than it would otherwise have been. Most of the laboratory work done during this summer seems to have aimed at familiarizing the researchers with methods for cutting and shaping bars and plates from large, unformed pieces of Rochelle Salt and quartz.[95] Cady and the team learned that the most effective tool for cutting quartz was a diamond-tipped saw, while the best tool for Rochelle Salt, which is water soluble, was nothing more than a wet thread kept in constant motion.[96]

Once Cady returned to his teaching duties that fall, he became involved with Michael Pupin's research group at Columbia University. New York City was only a 90 minute train ride from Middletown, so Cady could visit Columbia often. By February 1918, Pupin's group had progressed to the point where it was ready to test an apparatus in

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[92] Kendall Birr, *Pioneering in Industrial Research: The Story of the General Electric Research Laboratory* (Washington, D. C.: Public Affairs Press, 1957), 76.

[93] R. Bruce Lindsay and W. J. King, "Walter G. Cady Oral History Interview" 28-9 August 1963, Center for History and Philosophy of Physics. Available at Box 2, Walter G. Cady Papers, Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT.

[94] Walter G. Cady, Personal Diary entry for 29 July 1917, Folder 24, Box 3, Walter G. Cady Papers (Subgroup 3), Cady Family Papers (MSS 326), Rhode Island Historical Society Library, Providence, RI.

[95] Walter Guyton Cady, "Piezoelectricity and Ultrasonics," *Sound* 2, no. 1 (January-February 1963): 46-52.

[96] Sidney B. Lang, "A Conversation with Professor W. G. Cady," *Ferroelectrics* 9 (1975): 141-49.

an actual field setting. Traveling to the Navy yard in Key West, FL, the group, including Cady, successfully tested a quartz transmitter in the Gulf of Mexico. Buoyed by these results, the group returned north to continue tests at the newly opened Naval Experiment Station at New London, Connecticut. Here, in the summer of 1918, Cady worked closely with George Washington Pierce, a Harvard electrical engineering professor whom he had met a year or two earlier through their mutual involvement in the Institute of Radio Engineers (I.R.E.).[97]

2.9 The legacy of World War I-era Anti-Submarine Warfare research

Despite the rapid progress made by the Columbia group, the fruits of their labor never made it onto actual ships during the war. At best, the group's quartz crystal device prototypes could detect an approaching submarine up to a distance of about one mile. This was much inferior to the performance of the passive sounding devices developed by other research groups.[98] Even so, the American effort to improve on Paul Langevin's quartz "sandwich" transducer was tremendously important for the far-reaching influence it would have on the future of piezoelectric and ultrasonic technology.

The lasting influence of the wartime NRC and NRB-sponsored research efforts on piezoelectric technology lies in at least two areas. First and most importantly, the NRC and the NRB had created a network of scientists and engineers interested in piezoelectric devices. This network spanned academic institutions (Columbia and Stanford), industrial R&D labs (Western Electric, Westinghouse, and G.E.), and government bureaus (Bureau

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[97] Walter G. Cady, Personal Diary entry for 18 January 1917, Folder 24, Box 3, Walter G. Cady Papers (Subgroup 3), Cady Family Papers (MSS 326), Rhode Island Historical Society Library, Providence, RI. Cady mentions attending an I.R.E. meeting at Harvard, where he spoke with G. W. Pierce.

[98] See Daniel J. Kevles, *The Physicists* (New York: Alfred A. Knopf, 1978), 121-26. for a discussion of the "MB listener," developed by Max Mason of the University of Wisconsin.

of Standards, the Army Signal Corps, the Navy). Among the American scientists and engineers involved in the wartime ASW research effort who would later contribute much to quartz crystal technology were Walter Cady, George Washington Pierce, Harold Arnold, and Joseph Warren Horton.[99] For its part, AT&T, through its manufacturing arm Western Electric, immediately began developing commercial devices that exploited the piezoelectric effect of Rochelle Salt. This work was based on a patent filed by Western Electric researcher Alexander Nicolson in April 1918 for using Rochelle Salt "in telephone transmitters and receivers, repeaters, loudspeakers, generators and modulators of alternating currents and the like."[100] On the government end, the Navy was anxious to further apply piezoelectric technology to submarine warfare and ship-to-ship communications, but work would be delayed until the opening of the new Naval Research Laboratory (NRL) in 1923. Second, the war research effort had helped to identify obstacles to piezoelectric devices becoming practical; in this way, it had helped to define a piezoelectric research agenda. Some aspects of this agenda including increasing the driving power, and thus the effective range, of quartz transmitters, increasing their operating frequency beyond 200 kHz, and improving the sensitivity and bearing-detection abilities of hydrophones (i.e. receivers of ultrasonic echoes). The outlines of an engineering knowledge base for piezoelectric technology were beginning to take shape.

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[99] For a brief biography of Harold Arnold, see James E. Brittain, "Scanning the Past: Harold D. Arnold," *Proceedings of the IEEE* 86, no. 9 (September 1998): 1895-96. For a brief biography of Joseph Warren Horton, see ———, "Scanning the Past: Joseph Warren Horton," *Proceedings of the IEEE* 82, no. 9 (September 1994). Available at http://ieee.cincinnati.fuse.net/reiman/11_2006.html.

[100] Alexander Nicolson, *Piezophony*, U. S. Patent Office, Patent No. 1,495,429, Filing Date: 10 April 1918; Issue Date: 27 May 1924.

2.10 Cady invents the quartz crystal piezoelectric resonator

Of the scientists who carried their piezoelectric investigations into the post-war period, Walter Cady quickly emerged as the most prominent because of his keen and persistent observation of piezoelectric device behavior. Throughout 1918, as part of the New London research effort, Cady had been assigned the task of developing and improving Rochelle Salt (RS) hydrophones. While attempting to measure the capacitance of RS plates at various frequencies, Cady observed erratic results. Finally, he realized in early January of 1919, after the war's end, the cause of his problems: RS had an unusually sharp resonance curve. That is, as Cady applied an AC voltage over a wide range of frequencies to an RS plate, he observed that the plate reached a maximum amplitude oscillation (i.e. resonance) over an extremely narrow band of frequencies. Furthermore, the resonant oscillations exhibited extremely low damping.[101]

Cady soon noticed that quartz plates behaved in a similar manner, but that their resonance curves were even sharper than those of RS plates. As an added benefit, though quartz's elastic constant was much lower than that of Rochelle Salt, it was also much more stable chemically than RS.[102] As Cady recalled years later, while getting ready for bed one night in 1919, he realized that the sharpness of quartz's resonance curve was on par with that of a standard tuning fork, which served as a frequency standard for acoustic waves in the audible region. Cady suspected that quartz could serve as a highly precise and accurate frequency standard for much higher frequencies – and not just for acoustic

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[101] Damping refers to the time rate at which a transient oscillation attenuates. For example, a tuning fork with a very low damping factor would continue to vibrate for quite some time (perhaps several minutes) after being initially struck.

[102] The elastic constant is an indication of the amplitude of mechanical vibrations produced for a given applied voltage. Materials with higher constants produce more prominent vibrations for a given voltage than do materials with lower constants. The constant for Rochelle Salt is from 4 to 5 times as great as the constant for quartz. Source: Walter Guyton Cady, *Piezoelectricity; An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals* (New York: McGraw-Hill, 1946), Chapter 6.

waves. Since quartz was a natural transducer, converting mechanical into electrical waves and vice-versa, it could serve as a standard for high-frequency electrical waves (i.e., radio waves).

Realizing the potential scientific value of a new frequency standard, Cady set about constructing several quartz resonator prototypes. Each prototype involved a carefully-cut quartz bar sandwiched between brass plates. When an electrical excitation was applied to the brass plates, the entire unit would vibrate. As the unit's resonance frequency was approached, the magnitude of the vibrations would increase, reaching a very prominent maximum at precisely the resonance frequency. The unit's resonance point was, for the most part, a function of the physical dimensions of the quartz bar and brass plates, and thus would not vary unless these were varied.[103]

Cady was well-positioned in two respects for fabricating his resonator prototypes. First, because of his summer employment with General Electric, he had access to the company's supply of high-quality quartz crystal. Such crystal was not easy to come by; one had to have connections. Second, Cady was blessed at Wesleyan to have access to a well-equipped machine shop, known as the Scott Lab. The shop was outfitted with several lathes, a shaper, planer, drill press, milling machine, grinder, blower, and a circular saw, equipment that was needed for precisely cutting and shaping raw quartz crystal into thin wafers. Furthermore, the lab was staffed with an expert "mechanician," as Cady referred to him.[104] Apparently, Cady focused on physics and left the actual cutting and polishing of crystals to someone more experienced in this type of work.

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[103] Ibid. Section 343, Resonator Mountings and Holders.

[104] ———, "Saving Ancestors" [Unpublished Autobiography] 1963, cited: 207. Available at Walter G. Cady Papers, Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT.

After completing several resonator prototypes, Cady began showing them to colleagues and shopping for a customer. Among the first to see them was Harold Arnold of Western Electric. Arnold, a former student of Cady's, was now director of research for Western Electric and was thus always on the lookout for useful new techniques, materials, and devices. Arnold had earned both a Bachelor's degree and an M.S. at Wesleyan before pursing his Ph.D. at the University of Chicago. As mentioned previously, Arnold's M.S. work had led to a jointly authored paper with Cady in the *American Journal of Science* on electric arcs.[105] The events of World War I brought teacher and student together again when both men became involved in the anti-submarine research effort. In February 1919, Arnold visited Cady in Middletown and was treated to a demonstration of his resonator prototypes.[106] When Cady asked if Western Electric might have some commercial use for the resonator, Arnold said he would think it over, only later to say that he saw no use for it at the present time.

Not deterred by Arnold's lack of interest, Cady, a year later, sent several prototypes to the Bureau of Standards in Washington for demonstration as well as for calibration.[107] At the Bureau, the prototypes fell into the hands of John Dellinger, head of the Bureau's frequency measurement and standardization efforts. Dellinger's measurements indicated that Cady's piezoelectric resonator was capable of an accuracy of 1 or 2 parts per 10,000 (i.e. 0.01%) at radio frequencies.[108] This was roughly one-hundred times more accurate than the Bureau's existing frequency standard – the

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[105] See page 20 of this chapter.
[106] Walter G. Cady, "Chief Dates on the Piezo-resonator and Oscillator," 9 March 1945. Walter G. Cady Papers, Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT.
[107] Walter G. Cady, Personal Diary entry for 23 April 1920, Folder 25, Box 3, Walter G. Cady Papers (Subgroup 3), Cady Family Papers (MSS 326), Rhode Island Historical Society Library, Providence, RI.
[108] See Walter Guyton Cady, "The piezo-electric resonator," *Proceedings Of The Institute Of Radio Engineers* 10, no. 2 (April 1922): 83-114.

"standard wavemeter," which consisted of the series combination of a variable condenser (i.e., capacitor), a standard coil (i.e., inductor), and an ammeter.[109] Not surprisingly, this one test of the resonator did nothing to make the Bureau change its primary frequency standard. Standards of measure are never changed overnight. The Bureau would continue using its standard wavemeter for several more years before retiring it.

2.11 Cady invents the quartz crystal piezoelectric oscillator

Harold Arnold was back to visit Cady's lab on Dec. 17, 1920, showing renewed interest in the prototypes. Cady presented his first public talk on the resonator at the Physical Society in New York on February 26, 1921. Afterwards, Arnold approached Cady and suggested the possibility that the device might be used not only as a frequency standard but also as a means of precisely controlling an oscillating circuit's frequency. The implication was that Western Electric would have many uses for such a device. Cady immediately went to work on the idea and soon achieved success, noting in his personal diary for February 28, 1921, "Made quartz rod serve as master oscillator."[110] He did so by inserting a quartz crystal in the feedback loop of a vacuum tube oscillator circuit. Cady called the device the "piezo-oscillator." The specific dimensions of the crystal governed the frequency at which the entire circuit would oscillate. When Cady notified Arnold of his success, he was still told that Western Electric did not yet have a use for such a device.

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[109] R. T. Cox, "Standard Radio Wavemeter - Bureau of Standards Type R 70B," *Journal Of The Optical Society Of America And Review Of Scientific Instruments* 6, no. 2 (March 1922): 162-68.
[110] Walter G. Cady, Personal Diary entry for 28 February 1921, Folder 25, Box 3, Walter G. Cady Papers (Subgroup 3), Cady Family Papers (MSS 326), Rhode Island Historical Society Library, Providence, RI.

In the midst of his work, Cady submitted patent applications for both the piezo-resonator and the piezo-oscillator, both of which were issued in 1923.[111] Undaunted by Western Electric's apparent lack of interest, Cady continued to demonstrate his devices and shop for potential licensees. Among those to whom he showed his inventions were the U.S. Bureau of Standards, Westinghouse, General Radio Company, and American Radio and Research.[112] But before Cady could find a taker, he received notice from Western Electric that he was being sued for patent infringement. The company claimed that Cady's patents fell within the claims of Alexander Nicolson's patent for Rochelle Salt devices, thus invalidating Cady's patent claims.[113] Thus began an ugly patent infringement case between Cady and Western Electric, one that Cady could not sustain for long because of his limited financial resources. In the mid-1920s, the Wesleyan physics professor ended up selling his resonator and oscillator patents to RCA for $50,000, a handsome sum at the time, and RCA continued the legal battle with Western Electric.[114] In 1953, the courts upheld Cady's precedence, but by this time the issue had become one of merely academic interest.[115]

By the late 1920s, Cady's resonator and oscillator patents had acquired tremendous economic value. The worldwide explosion of radio broadcasting that had begun in 1922 gave Cady's piezo-oscillator a value that could not have been foreseen

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[111] Walter Guyton Cady, *Piezo Electric Resonator*, U. S. Patent Office, Patent No. 1,450,246, Filing Date: 28 January 1920; Issue Date: 3 April 1923. ———, *Method of Maintaining Electric Currents of Constant Frequency*, U. S. Patent Office, Patent No. 1472583, Filing Date: 28 May 1921; Issue Date: 30 October 1923.

[112] Walter G. Cady, "The Story of My Patent Litigation," 30 June 1967, Box 2, Walter G. Cady Papers, Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT.

[113] Alexander Nicolson, *Piezophony*, U. S. Patent Office, Patent No. 1,495,429, Filing Date: 10 April 1918; Issue Date: 27 May 1924.

[114] Adjusting for inflation, $50,000 in 1925 roughly corresponds to $1/2 million in 2005.

[115] Walter G. Cady, "The Story of My Patent Litigation," 30 June 1967, Box 2, Walter G. Cady Papers, Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT.

earlier.[116] Unfortunately, Cady did not share in much of the wealth that flowed from his inventions. In time, however, he was universally recognized by scientists and engineers as being the world's foremost expert on resonant applications of piezoelectric quartz.

2.12 Conclusions

This chapter has related the nearly four decade pre-history of piezoelectric quartz crystal technology, beginning with the discovery of piezoelectricity by the Curie brothers in 1880 and ending with Wesleyan physics professor Walter Cady's invention of the quartz piezo-resonator and piezo-oscillator. For most of this period, piezoelectricity was nothing more than a curious natural phenomenon to a handful of European scientists interested in crystal physics. These scientists developed a considerable body of knowledge that explained the source of piezoelectricity, catalogued the types of crystal in which it occurred, and described with mathematical precision the piezoelectric effect. This knowledge was what economic historian Joel Mokyr would call propositional knowledge, as opposed to prescriptive knowledge.[117] Its basic goal was to describe and understand piezoelectricity. This knowledge did not, however, aim to exploit the piezoelectric effect for human purposes.

The scientists who developed the theory of piezoelectricity prior to World War I failed to thoroughly investigate the response of piezoelectric crystals to high-frequency oscillatory signals. Had they done so, quartz crystal technology would have likely been born before the war. But, of course, these scientists were incapable of exploring the high-

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[116] The boom in radio broadcasting and the subsequent increase in the value of Cady's patents is discussed further in Chapters 4 and 5.

[117] Joel Mokyr, *The Gifts of Athena: Historical Origins of the Knowledge Economy* (Princeton, NJ: Princeton University Press, 2002).

frequency response of crystals because high-frequency electrical oscillators had yet to be invented. Thus, as has always been true, the scientific knowledge of the time was limited by the technological capabilities of the time.[118]

With the invention of high-frequency vacuum tube oscillators in the second decade of the 20th century, a whole new world of scientific inquiry opened up. For the first time, continuous, undamped radio waves could now be generated, studied, and exploited without great expense or large, cumbersome equipment. Realizing this, Constantin Chilowsky and Paul Langevin ingeniously used piezoelectric quartz crystal to convert a high frequency alternating electric current into a high frequency mechanical wave. That is, an applied AC voltage caused a slab of quartz crystal to alternately flex and relax (i.e. vibrate) at a high frequency. When placed underwater, the mechanical waves generated by the quartz slab spawned high frequency pressure waves that could travel long distances through water with little attenuation and great directional precision. Chilowsky and Langevin found that quartz crystal, of all piezoelectric crystals, was uniquely suited to this task because of its chemical stability, its ability to handle relatively high-powered signals without cracking, and its ability to resonate at ultrasonic frequencies. Quartz crystal technology had been born.

World War I saw not only the birth of quartz crystal technology; it also provided the context for the birth of the quartz crystal technological community, without which the technology itself would have stagnated. The wartime NRC-sponsored ASW research effort brought together a group of scientists and exposed them for the first time to piezoelectric crystals, primarily quartz crystal and Rochelle Salt. Many of these scientists

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[118] Incidentally, the converse of this statement is only partially true. The technological capabilities of a time are only partially limited by the scientific knowledge of a time. In all times have there existed working technologies that are not fully understood in light of contemporary science.

abandoned the study of piezoelectricity after the war, but some, including Wesleyan professor Walter Cady, Harvard professor George Washington Pierce, and Western Electric research manager Harold Arnold, maintained their interest in this new area for years. These individuals formed the core of what would eventually become a large and passionate group of technologists dedicated to nurturing and advancing quartz crystal technology.

Without question, Walter Cady contributed the most to the emerging knowledge base of quartz crystal technology. His first contribution was the discovery that piezoelectric quartz crystal, when subjected to a continuous spectrum of AC electric signal frequencies, displays an extremely selective resonance curve. If Cady had stopped here, his primary contribution would have been scientific. But he went further to show that quartz crystal's unique resonance characteristic could be exploited to serve as a frequency standard for very high frequencies. Furthermore, he showed that a quartz crystal wafer's characteristic resonance frequency was a function of its physical dimensions. By varying a wafer's thickness, width, and depth, different resonance frequencies could be obtained.[119] With a little prodding by his former student Harold Arnold, Cady then went on to show that a quartz crystal wafer could be harnessed to precisely control and maintain the frequency of a vacuum tube oscillator.[120] In two foundational patent applications (U.S. Patents #1,450,246 and #1,472,583), Cady presented this prescriptive knowledge and was granted, in essence, a legal twenty-year monopoly over its use.

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[119] Cady's invention of the "piezo-resonator" is discussed in greater detail in Chapter 5.

[120] Cady's invention of the "piezo-oscillator" is discussed in greater detail in Chapter 4.

No sooner had Cady been granted patents for the piezo-resonator and piezo-oscillator than AT&T began contesting them, suggesting that the giant telecommunications firm saw much commercial potential in quartz crystal technology. Not willing to give in easily, Cady fought AT&T's legal action until the cost became too great for him. He then outright sold the patents for a lump sum to RCA, then AT&T's biggest competitor in radio. Thus began a decades-long battle between AT&T and RCA to control the patents of quartz crystal technology. This patent battle, though at times acrimonious, provided the technology with a profit motive that proved to be healthy for its long-term future.

In the early 1920s, the future of quartz crystal technology was uncertain. A small community of quartz technologists had begun to form, but the utility of piezoelectric quartz was still in doubt. It seemed to provide great promise as a frequency standard, but this was a niche application that would appeal primarily to scientific laboratories, manufacturers of precision radio equipment, and government standards agencies. Quartz crystal had also shown itself capable of stabilizing the frequencies of radio oscillators, but the usefulness of this application had not yet been demonstrated. Not until Cady's piezo-oscillator became coupled to the survival of AM broadcast radio would the future of quartz crystal technology be assured.

CHAPTER 3: QUARTZ CRYSTAL TECHNOLOGY AND INTELLECTUAL PROPERTY

Departing from the narrative form of Chapter 2, this chapter presents and interprets the results of a qualitative and quantitative study of quartz crystal technology patents filed between 1918 and 1959. The numerous devices, circuits, and manufacturing processes that constitute quartz crystal technology are identified and classified into major and minor categories. This classification provides a technical "lay of the land" for understanding the technical content of subsequent chapters. The quartz crystal unit, or QCU, is shown to have been the dominant device or component for resonant applications of piezoelectric quartz crystal. Many QCU-related patents cover processes used in the manufacture of the QCU, while others cover new variants to the QCU itself. This chapter also shows that ownership of quartz crystal patents was dominated by private firms, particularly AT&T and RCA, who engaged in something of a battle for control of quartz patents during the 1920s and 1930s. Nevertheless, quartz crystal invention, because of its low cost and the many opportunities available for novel variation of quartz devices, consistently attracted a significant number of independent inventors. The patent data suggests that, particularly in the 1920s and to a lesser extent throughout the remaining decades of this study, there existed a healthy open market for the selling and licensing of quartz crystal patents. As the technology matured and those in the business established in-house R&D labs, this market shrank but never dried up completely. Finally, this chapter shows that foreign quartz crystal inventors, particularly Germans, were active in filing for U.S. patents. Thus, for the period 1918-1959, quartz crystal invention was primarily an American and Western European activity, though Russia and Japan exerted a growing influence on the technology beginning after World War II.

The history of inventive and innovative technological activity can be told in a variety of ways. Chapter 2 and Chapters 4 through 8 give a narrative history that focuses on actors, individual and collective, acting and reacting over time to effect change in the technological use of quartz crystal. The social and economic contexts of these actors are shown to exert a strong influence on the decisions they make and the courses they take. This chapter, however, steps away from this detailed narrative to give a different and complementary view of quartz crystal technological innovation. The view taken here is from a higher level and spans decades. The method used entails the careful study of aggregate patent records, but the details of individual patents were also studied in many cases. In seeking to broadly characterize inventive activity through the study of patents in the aggregate, this study follows a trail blazed by many others, including, for example, the U.S. Temporary National Economic Committee (T.N.E.C.), Jacob Schmookler, David Noble, Leonard Reich, Robert Merges and Richard Nelson, and Naomi Lamoreaux and Kenneth Sokoloff.[121] The high-level, somewhat impersonal view of quartz crystal invention offered by this chapter complements the nuanced, actor-driven narrative of the remaining chapters.

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[121] George E. Folk, *Patents and industrial progress; a summary, analysis, and evaluation of the record on patents of the Temporary National Economic Committee* (New York: Harper & Brothers, 1942). David F. Noble, *America By Design: Science, Technology, and the Rise of Corporate Capitalism* (Oxford, England: Oxford University Press, 1977), Chapter 6. Leonard Reich, "Research, Patents, and the Struggle to Control Radio: A Study of Big Business and the Uses of Industrial Research," *Business History Review* 51, no. 2 (1977): 208-35. Robert P. Merges and Richard R. Nelson, "On the Complex Economics of Patent Scope," *Columbia Law Review* 90 (May 1990). Naomi Lamoreaux and Kenneth L. Sokoloff, "Long-term Change in the Organization of Inventive Activity," *Proceedings of the National Academy of Sciences of the United States of America* 93, no. 23 (12 November 1996): 12686-92.

The patent search methods used in this study were reliable but not immune to the occasional error. Therefore, the patent data used here is comprehensive in scope but not exhaustive in depth. There are surely a handful of quartz crystal related patents from the period studied that were overlooked. Similarly, some of the patents included in the study are related only tangentially to piezoelectric quartz crystal technology. Nevertheless, the author is confident that the patent data used sketches a reliable broad outline of quartz crystal invention over the four decades studied.

The patent search method used here can be described as follows. Google Advanced Patent Search was the primary search tool used. Google has scanned the entire database of approximately seven million U.S. patents. In the process of scanning, character recognition algorithms were used to make the patent documents text-searchable. These algorithms, while very good, are not perfect, particularly when the document being scanned is old and possibly faded. Thus, some of the text in Google's patent database has been misread. This is the primary error source in this study.

A two stage patent search process was used for this study. Stage one involved performing a search for every patent filed between 1918 and 1959 containing the following search terms: ((“piezo” OR “piezoelectric”) AND “quartz crystal”).[122] The patent filing date rather than the patent issue date was used because the former gives a more accurate indication of what year the inventive activity occurred. Patent applications that were filed but never issued are not included in Google's patent database and were thus not used. The stage one search, the results of which are shown in Figure 1 of the Introduction, yielded a total database size of 1280 quartz crystal patents. The stage two

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[122] Google's Advanced Patent Search allows for searches by global key words, patent number, patent title, name of inventor, name of assignee, date of filing, and date of issue.

search consisted in selecting six local maxima in Figure 1 for detailed study. The years selected were 1927, 1933, 1940, 1945, 1953, and 1959. This selection yielded a total sample size of 285 patents, or roughly 1/5 of all quartz crystal patents filed between 1918 and 1959. The charts shown in this chapter were derived from this sample.

Each of the 285 patents in the sample was studied individually. In order to make some sense of the patents, a typological scheme was devised consisting of five categories: QCU Design and Fabrication, Oscillator and Transmitter Circuits, Wave Filter Circuits, Transducers, and Other. Each of the 285 patents was then placed in one of these categories. Several other aspects of the patents were also noted: the patent number, the inventor, the inventor's location or residence, the assignee, the assignee's location, and the type of assignment. The analysis method used on this patent database was designed to illuminate both the epistemological and the social aspects of quartz crystal innovation.

This chapter is organized into two parts. The first focuses on the "what" of quartz crystal technology – the technical content of the patents studied. A typology of the technology is presented and patent data analyzed to show the distribution of patenting activity across a number of basic categories. The data is also analyzed across time to illustrate how this distribution changed. A fundamental distinction is made between patents that present a physical apparatus or device and those that present a manufacturing process. Quartz crystal patents covered both categories, sometimes within the same patent. The second part of this chapter focuses on the "who" of quartz crystal technology – the inventors and assignees specified on the 285 patents studied. All of the inventors were either individuals or small groups, while the majority of assignees were companies. While studying separately the inventors and assignees allows us to see who was doing the inventing and who cared enough about this technology to either sponsor its development or purchase it afterwards, studying the relationships between inventors and assignees is even more enlightening. The inventor-assignee relationships observed in this study were classified into seven categories, and changes in the distribution of these categories were tracked over the selected years. The results yield insight into the organizational context of quartz crystal technological innovation between 1918 and 1959.

With his invention of the quartz "sandwich" transducer during World War I, Frenchman Paul Langevin laid the groundwork for using quartz crystal as a piezoelectric transducer. Over the following decades, engineers and inventors patented hundreds of quartz transducer devices based on his work. The American Walter Cady created an entirely new class of quartz devices with his inventions of the piezoelectric resonator and oscillator. These inventions exploited the unique resonant properties of quartz crystal in a manner that paved the way for the invention of highly stable oscillators and wave filters with sharp cutoff bands. Together, transducer and resonant applications of quartz crystal made up roughly four out of every five quartz patents applied for between 1918 and 1959.

Figure 6 presents a simple five category typology of quartz crystal technology and illustrates the distribution of quartz crystal patents across the categories. Three of the categories – QCU Design and Fabrication, Oscillator and Transmitter Circuits, and Wave Filter Circuits – cover resonant applications of quartz crystal. The remaining two categories – Transducers and Other – exploit non-resonant properties of quartz crystal. What follows is a brief description of each category. (1) The QCU in "QCU design and fabrication" refers to Quartz Crystal Unit; this is the fundamental device or system component around which all oscillator, transmitter, and wave filter circuits are built. QCU's, however, are not used in transducers or "Other" applications. QCU engineering is an area all its own and includes crystal cutting and polishing, crystal holders, mountings, cases, and methods of attaching electrodes to crystals. (2) Oscillator and transmitter circuits are grouped together in one category because of their similarity. Transmitters may be considered systems in which the oscillator is an important sub-system. Other important transmitter sub-systems include the modulator, the amplifier, and the antenna or transmission line. All of the transmitter and oscillator circuits represented in Figure 6 employ the QCU as a crucial component. (3) The wave filter circuits of the next category also employ the QCU as a crucial component. These circuits often served as important sub-systems in multiplex telephony systems. (4) The "Transducers" category includes applications in which the quartz crystal transducer rather than the QCU is the fundamental device or system component. Such applications include SONAR, ultrasonic medical imaging, phonograph needles, loudspeakers, vibration sensors, and modulators. Modulators are included here rather than in the previous category because the quartz crystal functions in a modulator as a transducer and not as an oscillator. (5) Finally, the "Other" category in Figure 6 includes applications such as optical relays, accelerometers, delay lines, light valves, and microwave detectors. At their base, these atypical applications rely on either the transducer or resonant characteristics of quartz crystal, but they are difficult to categorize without more detailed study.

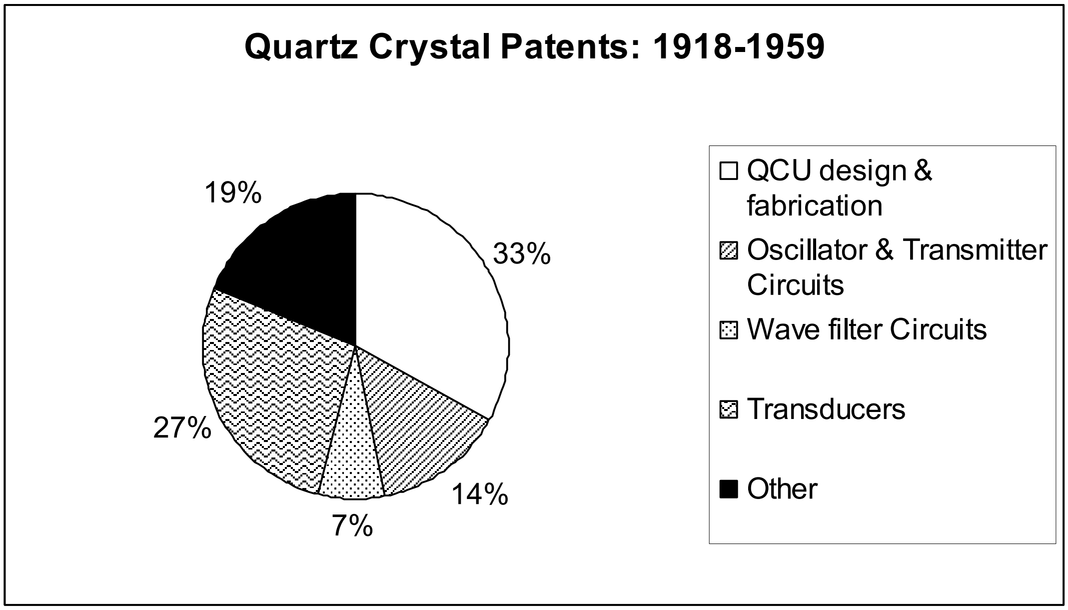

Figure 6: Types and Average Distribution of All Quartz Crystal Patents Issued Between 1918 and 1959

(Note: The approximate total number of successful quartz crystal patent applications filed between 1918 and 1959 is 1280. This chart is based on a sampling of these patents. Sample size for the data presented is 285 patents, or just over 22% of the total. Data on unsuccessful patent applications (i.e., those that are never issued) are not readily available from the USPTO. Figure created by author.)

The distribution portrayed in Figure 6 did not remain static between 1918 and 1959. Figures 7 and 8 show how the distribution of quartz crystal patents fluctuated for the selected years. Note firstly that the areas covering resonant applications of quartz crystal – QCU Design and Fabrication, Oscillator and Transmitter Circuits, and Wave Filter Circuits – always comprised from 50 to 60 percent of all quartz crystal patenting activity. The remaining 40 to 50 percent consisted of transducers and other applications. This is noteworthy because the focus of this work is the resonant applications of quartz crystal. Adding transducers and other applications to this work would have lengthened it considerably; a later work may focus on these.

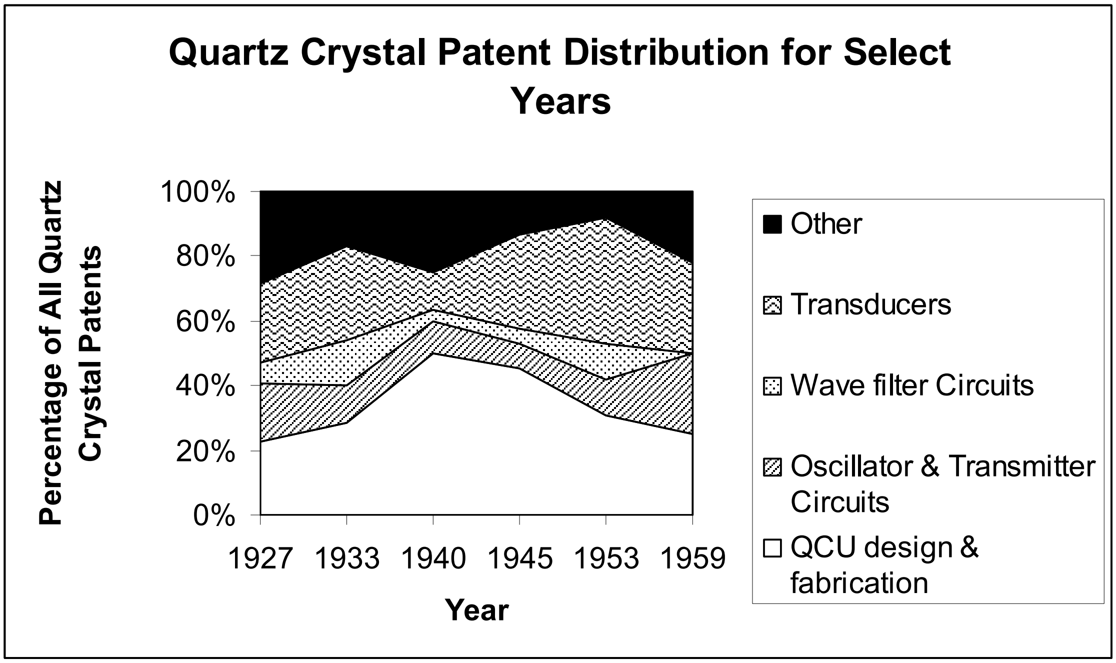

Figure 7: Types and Percentage of Quartz Crystal Patents for Select Years between 1927 and 1959

(It should be noted that the total number of quartz crystal patents (i.e., the number represented by 100%) varied significantly across these years. See Figure 2.3 for these numbers. Figure created by author.)

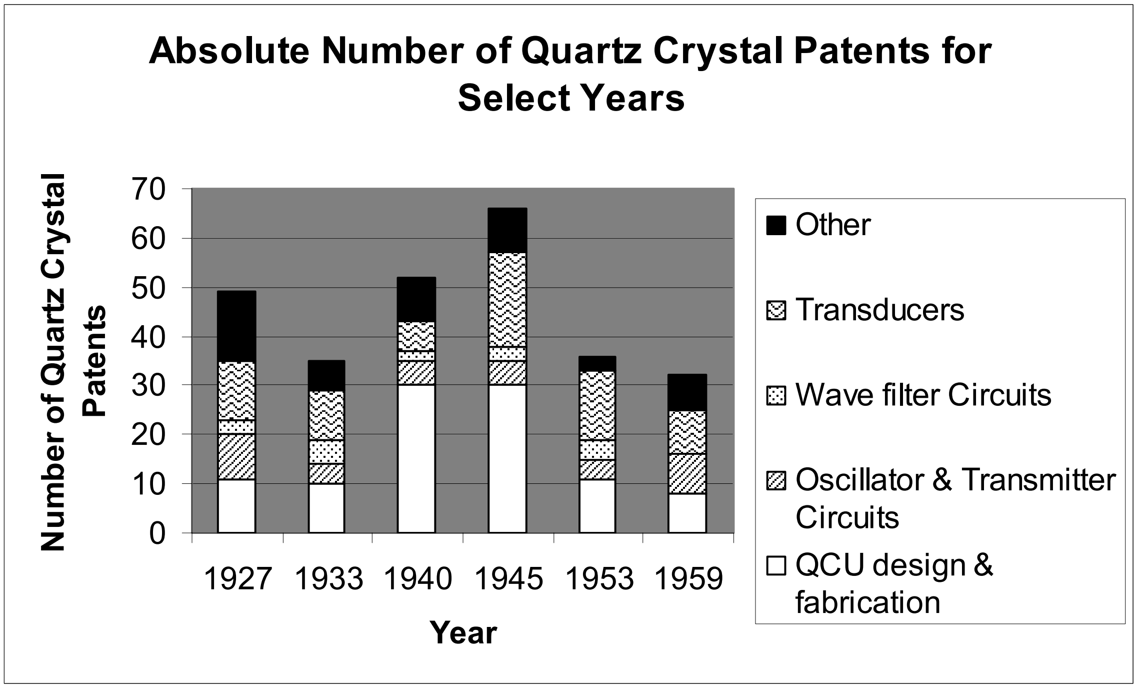

Figure 8: Types and Numbers of Quartz Crystal Patents for Select Years between 1927 and 1959
(Figure created by author.)

Figures 7 and 8 show also that patenting activity in QCU design and fabrication peaked in 1940 and 1945, both as a percentage of all quartz patenting activity and in absolute numbers. This is not surprising given that, as described in Chapter 7, military contractors faced numerous production challenges in producing the millions of QCU's required by the Army Signal Corps during the war. Also note that though the percentage of transducer patents peaked in 1953, the absolute number of transducer patents peaked in 1945. This reflects the great amount of anti-submarine warfare research conducted during WWII. Wave filter patents peaked in 1933 both as a percentage and in absolute numbers, reflecting the extensive work Bell Labs did in the 1930s to refine this branch of quartz crystal technology and apply it to its expanding multiplex telephony system. This work is discussed in detail in Chapter 6.

Quartz crystal devices – QCU's, transducers, and other – are typically embedded within large technological systems.[123] As such, quartz crystal technology is hierarchical in nature. The hierarchical structure of Figure 9 illustrates how the two fundamental components of quartz crystal technology – the QCU and the quartz transducer – are related to higher and lower levels of organization. It should be noted in passing that Figure 9 is merely meant to be representative, and not exhaustive, of quartz crystal-based systems and sub-systems. Furthermore, the figure is historical, characterizing quartz crystal technology during the period studied. Updating Figure 9 to represent post-1960 developments would alter it significantly.

Most obvious from Figure 9 are the two separate branches of quartz applications, one stemming from the exploitation of quartz's resonant property, and the other from the exploitation of quartz's transducer property. Notice also that the QCU and the quartz transducer have only one sub-component in common – the quartz blank. This is a thin, polished wafer of quartz whose thickness has been carefully set such that the wafer will resonate at a specific frequency. Some early transducers, such as those made by Langevin that used a rough mosaic of quartz slices, did not share even this with the QCU.

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[123] Thomas Parke Hughes, "The Evolution of Large Technological Systems," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Thomas P. Hughes Wiebe E. Bijker, and Trevor Pinch (Cambridge, MA: The MIT Press, 1989), 51-82.

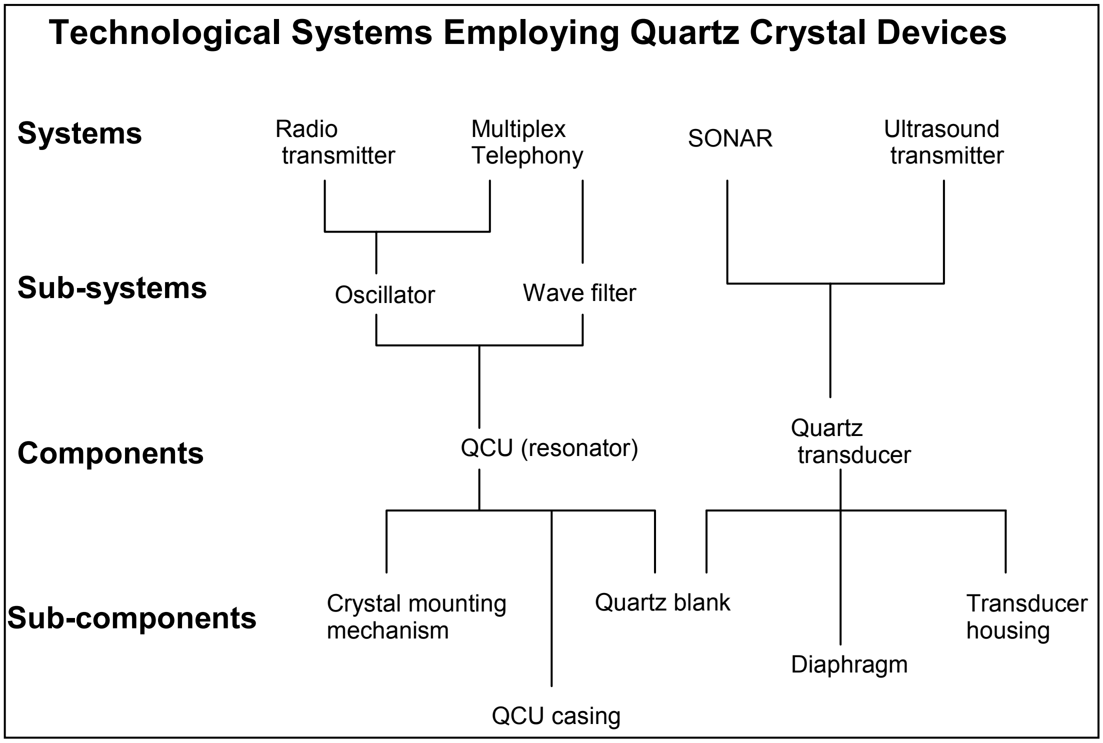

Figure 9: The Hierarchical Structure of Quartz Crystal Technology
(Figure created by author.)

While Figure 9 shows the patentable physical apparatus associated with quartz crystal technology, patents may be obtained also on methods or processes. Specifically, many manufacturing processes are required to take sub-components and turn them into an operational QCU. These processes are shown in Figure 10. Work in several of these processes yielded a great many patents. The processes yielding the most patents in the time period covered here were 3, 4, 7, 8, and 9. Figure 11 shows the distribution of patents among these processes, while Figure 12 shows how this distribution varied for select years.

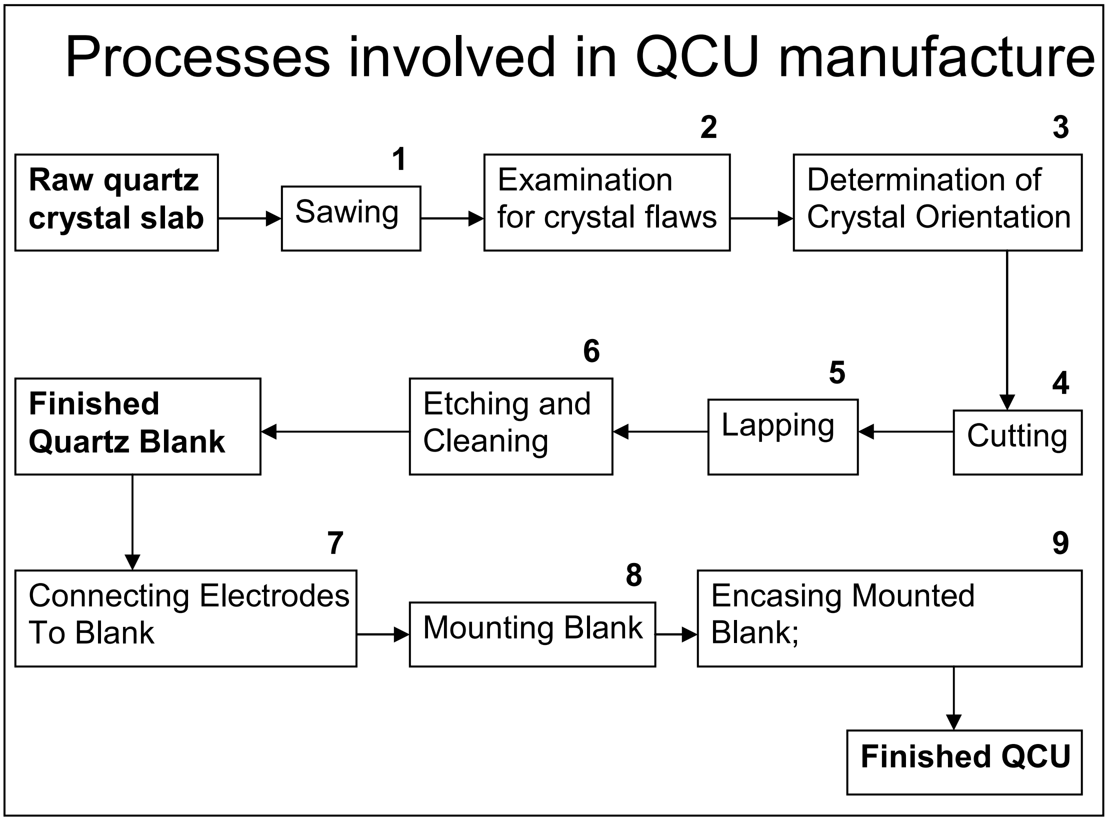

Figure 10: Manufacturing Processes of Quartz Crystal Unit (QCU) Production
(Figure created by author.)

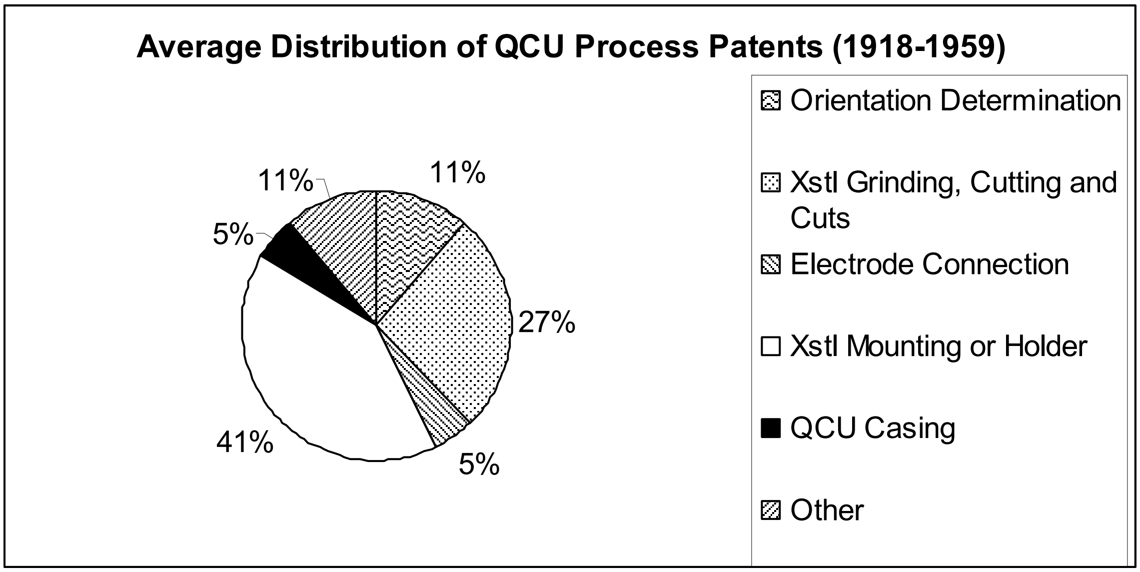

Figure 11: Average Distribution of Quartz Crystal Unit (QCU) Process Patents Filed between 1918 and 1959
(Like Figure 6, this figure is based on a sampling of all quartz crystal patents during this period. The sample size is 285 patents of a total of 1280 patents. Only successful patent applications were considered. Figure created by author.)

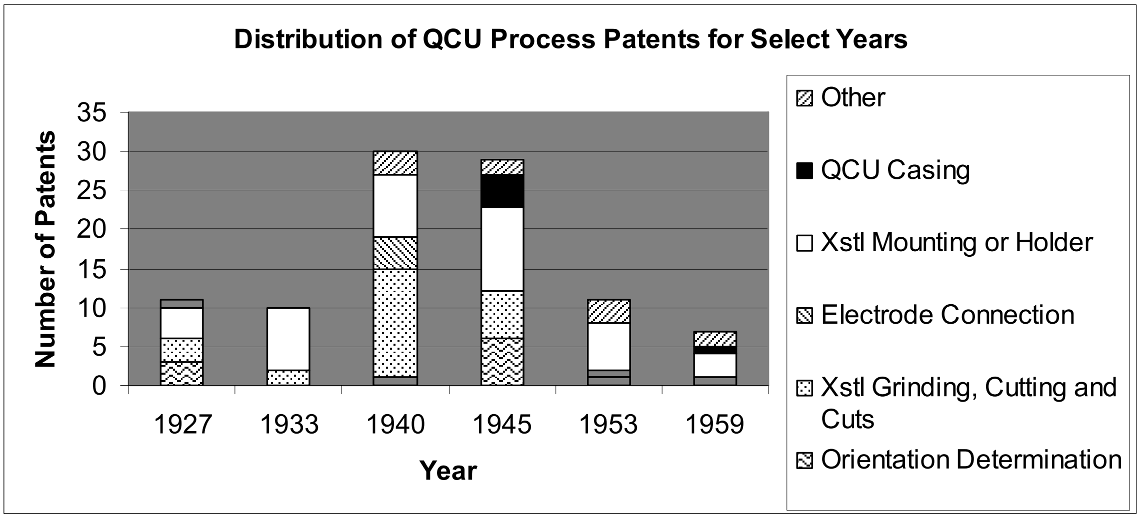

Figure 12: Distribution of Quartz Crystal Unit (QCU) Process Patents Filed for Select Years between 1927 and 1959
(Figure created by author.)

A brief description of QCU manufacture processes 3, 4, 7, 8, and 9 will heighten appreciation of their importance and aid the reader in interpreting Figures 11 and 12.

Process 3, determining the crystal lattice orientation, is crucial in that a raw quartz crystal slab cannot be properly cut into wafers without it. Ignoring a crystal's lattice orientation may produce wafers that are not strongly piezoelectric. This process was once performed by various methods, including submerging a crystal in a special oil bath and shining light through it. During World War II, however, an orientation method using X-rays was developed which surpassed all previous methods in convenience and accuracy. As can be seen in Figure 12, the large amount of effort invested in improving process 3 during WWII is reflected in the number of Orientation Determination patents filed in 1945.

Process 4, cutting of the crystal, has also yielded many patents, most relating to the angle at which a crystal should be cut relative to its electrical axis in order to achieve certain temperature coefficient properties. If a crystal is cut to certain angles, it can exhibit essentially a zero temperature coefficient, neutralizing the tendency of temperature changes to alter a QCU's resonant frequency. Figure 11 shows that process 4, Crystal Grinding, Cutting and Cuts, received just over one-quarter of all QCU process patents during the years studied. This reflects both the importance of this process as well as the large variety of useful angles at which quartz crystal may be cut. Figure 12 shows that patenting activity on this process peaked in 1940. This was largely due to the work of one man, Warren Mason of Bell Telephone Laboratories. The most prolific inventor in the history of BTL, Mason was granted a total of nearly 200 patents, over 40 of which concerned piezoelectric crystal apparatus.[124] His work on quartz crystal temperature coefficients in the 1930s and early 1940s, which is covered in more depth in Chapter 6, yielded many innovative and important crystal cuts.

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[124] Robert N. Thurston, "Warren P. Mason, 1900-1986," *Journal of the Acoustical Society of America* 81 (1987): 570-71. ———, "Warren P. Mason (1900-1986) Physicist, Engineer, Inventor, Author, Teacher," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 41, no. 4 (July 1994): 425-34.

Process 7, connecting electrodes to the quartz blank, is a mundane but clearly important process in manufacturing a QCU. Electrodes that become detached in hot weather or when jostled in a shipping truck can ruin an otherwise good QCU. Bell Telephone Laboratories patented several methods for securing metallic electrodes to quartz wafers in 1940, as can be seen in Figure 12. The other years covered in this study saw very little patenting activity on process 7.

As shown in Figure 11, process 8, the mounting of the quartz blank onto a crystal holder, produced over 40% of all QCU process patents between 1918 and 1959. This was primarily due to the wide variety of QCU mounting schemes that are possible. Two of the most common schemes are illustrated in Figure 13. Note that the two-pin scheme has a smaller circuit board footprint, while the three-pin scheme is capable of a lower vertical profile. Many “anti-shock” mounting schemes were developed to enable QCU’s to operate in vibration-intensive environments such as aircraft. As Figure 12 shows, work in this process area yielded a consistently high number of patents throughout the period studied.

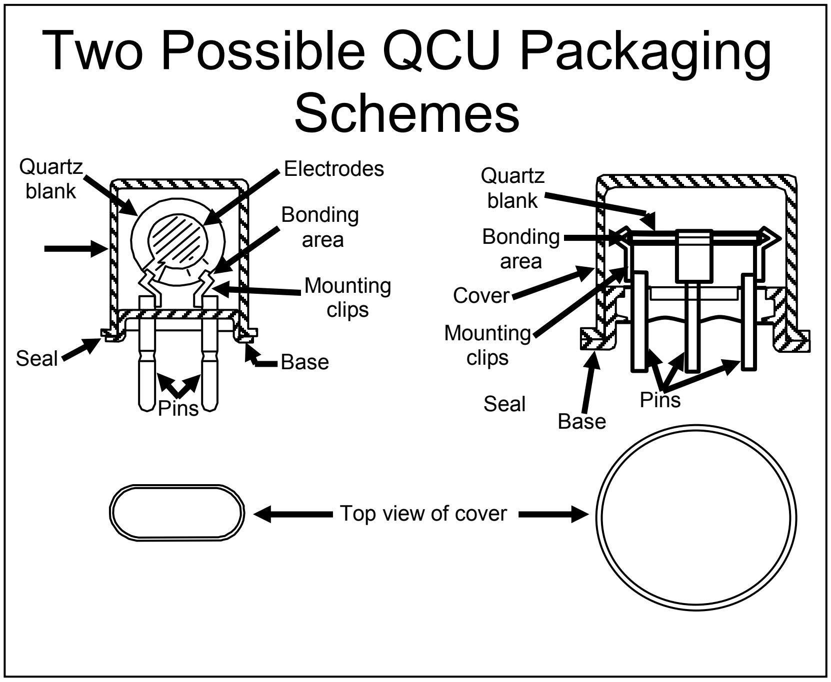

Figure 13: Two Popular Quartz Crystal Unit (QCU) Packaging Schemes
(Reprinted, by permission, from John R. Vig, "Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications – A Tutorial," Rev. 8.5.3.8, March 2008. J.Vig@IEEE.org)

Finally, process 9, the encasing of the mounted crystal blank, yields the finished QCU. One of the primary aims of this process is to create a hermetic seal around the mounted crystal so that moisture and dirt are kept out. Figure 12 shows that this process reached a peak in patenting activity in 1945, suggesting that QCU casing was vital to ensuring that the U.S. Army's radios worked in harsh environment around the world.

Figure 10, shown earlier, displayed the general order of work involved in manufacturing QCU's up through the mid-1950s. However, as explained in Chapter 8, research conducted after World War II yielded a method for growing perfect quartz crystals from crushed quartz. This method, referred to as the culturing of quartz, essentially replaced steps 1 through 3 of Figure 10 and freed the United States from dependence on Brazilian quartz mines. Thus, new patents on processes 1-3 of Figure 10 became almost non-existent from the 1950s on.

Just as understanding the physical apparatus and manufacturing processes of quartz crystal technology is crucial to grasping the technical content of the following chapters, knowing the patentees behind quartz crystal inventions is essential to appreciating the social nature of quartz crystal innovation. Two types of patentee are specified on most patent applications: the inventor, or assignor, and the assignee. The inventor, typically an individual and sometimes a group, is the person or persons who first conceived of the invention and reduced it to practice in the form of a working device or manufacturing process. When an assignee is designated on a patent application, the inventor is legally assigning the property rights of the patent to the assignee. That is, the assignee, and not the inventor, now owns the patent and may license or sell it to others. The assignee may also sue for infringement if another party manufactures, uses, or sells the patented invention without the consent of the assignee. Assignees are typically private companies but may also be individuals or the government. When no assignee is designated on a patent application, the de facto assignee is the inventor.

Figure 2 of the Introduction showed that the Bell System, comprising AT&T, Western Electric, and Bell Telephone Laboratories, was assigned far more quartz crystal patents than any other single organization during the period 1918-1959. In second place was RCA, holding about half as many patents. Though the Bell System consistently ranked among the most active quartz crystal patent assignees during this period, little else remained stable. Tables 1 and 2 give two ways of looking at changing patent ownership for select years. Table 1 categorizes patents by type of assignee – private sector firm, government, or individual – while Table 2 focuses exclusively on private sector firms, showing all firms that were assigned two or more quartz crystal patents in the select years. Table 2 shows that private sector firms represented by far the most common type of assignee, followed by individuals. The government did not appear as an assignee before 1940, during which year the government seized several quartz crystal patents from Germans, assigning them to Alien Property Custodian. From there on, the government appeared as the assignee for patents invented by employees of military R&D laboratories, such as the U.S. Army Signal Corp's laboratories in and around Fort Monmouth, New Jersey. Chapter 6 tells of the Army Signal Corps' quartz crystal activity during World War II. Table 2 gives a comprehensive list of private sector firms assigned at least two quartz crystal patents during the years of interest. Note that the Bell System is the only firm to be assigned patents in all six years of interest. RCA appears five times, and General Electric and the Submarine Signal Company, later Raytheon, both appear four times. The most patents assigned in any one year to a single firm was eighteen, assigned to the Bell System in 1940 and representing an amazing 43% of all quartz crystal patents filed that year. In fact, the Bell System led with the most patents for every year of interest except for 1927, when Bell ranked third behind the Federal Telegraph Company and RCA.

Table 1: Number of Patents Assigned to Private Sector Firms, Government, and Individuals for Select Years

Type of Patent Assignee	**1927**	**1933**	**1940**	**1945**	**1953**	**1959**	**Total**
Firms (Private Sector)	47 (89%)	29 (81%)	44 (84%)	44 (64%)	29 (74%)	30 (81%)	**223 (78%)**
Government (Public Sector)*	0	0	4 (8%)	8 (12%)	2 (5%)	3 (8%)	**17 (6%)**
Individuals**	6 (11%)	7 (19%)	4 (8%)	16 (24%)	8 (21%)	4 (11%)	**45 (16%)**

* - Includes patents assigned to Alien Property Custodian.

** - Includes patents that do not specify an assignee.

(Table created by author.)

Table 2: Number of Patents Assigned to Private Sector Companies for Select Years

Company	**1927**	**1933**	**1940**	**1945**	**1953**	**1959**	**Total**
American Bosch Arma Corp.	--	--	--	--	--	2	**2**
Bell System	6	8	18	11	4	4	**51**
Bliley Electric Co.	--	--	5	--	--	1	**6**
Brush Development Co. (Clevite)	3	--	--	1	3	--	**7**
Cambridge Thermionic Corp.	--	--	--	2	--	--	**2**
Collins Radio Co.	--	--	--	1	1	--	**2**
Communication Patents, Inc.	2	--	--	--	--	--	**2**
Compagnie Generale de Telegraphie sans Fil	--	1	--	--	2	--	**3**
Crystal Research Laboratories	--	--	--	3	--	--	**3**
Endevo Corp.	--	--	--	--	--	2	**2**
Federal Telegraph Co.	10	--	--	--	--	--	**10**
Federal Telephone and Radio Corp.	--	--	--	2	--	--	**2**
Galvin Manufacturing Corp. (Motorola)	--	--	--	5	3	--	**8**
General Dynamics Corp.	--	--	--	--	1	1	**2**
General Electric	2	--	1	2	--	2	**7**
Midland Manufacturing Co.	--	--	--	--	1	2	**3**
Radio Corporation of America (RCA)	7	6	10	3	3	--	**29**
Radio Patents Corp.	--	--	2	--	--	--	**2**
Reeves-Hoffman Corp.	--	--	--	1	1	--	**2**
Research Corp.	--	--	2	--	--	--	**2**
Sperry Products, Inc.	--	--	--	2	2	--	**4**
Submarine Signal Co. (Raytheon)	--	4	2	3	--	1	**10**
Telefunken	5	6	2	--	--	--	**13**
Westinghouse	5	--	--	--	--	--	**5**
Wired Radio, Inc.	5	--	--	--	--	--	**5**
Totals	**45**	**26**	**42**	**36**	**20**	**15**	**184**

(Note: Only Companies assigned a total of two or more crystal patents during this period are shown. Table created by author.)

An important question not answered by Table 2 is whether each firm purchased its patents from an inventor outside its organization or whether it patents were developed in-house by an employee-inventor. This question is difficult to answer with absolute certainty from just the information contained in a patent, but an educated guess can usually be made by comparing the address of the inventor's residence with the addresses of known R&D facilities for each company. For inventors for whom biographical information exists, more certain decisions can be made regarding the inventor-assignee relationship. Lastly, some patent applications give further assignment information, such as the designation “mesne assignment.” This legal term, which signifies that intermediate assignments occurred prior to the final assignment, strongly suggests that the inventor was not an employee of the assignee. Thus, using these guidelines, Figure 14 was constructed to show the various types of inventor-assignee relationships occurring in the world of quartz crystal patents over the years of interest.

The seven categories of Figure 14 require some explanation. The categories represent the types of inventor-assignee relationships observed in this study, and they are defined as follows.

(1) Employee-employer: The inventor is an employee of the assignee, a private firm. Thus, the assignee is sponsoring in-house R&D rather than purchasing patents from others. In this scenario, the inventor has usually agreed, as part of the terms of employment, to assign all inventions developed on company time and with company equipment to the company.

(2) Non-employee: The assignee is a private firm or occasionally an individual, but the inventor is not an employee of this firm or individual. The inventor is typically an independent inventor, a university researcher, or a government laboratory employee. In this scenario, the assignee is purchasing patents from outside its organization. The inventor is not necessarily independent, particularly if working for a government laboratory. That is, the inventor may have no say over who the assignee is.

(3) Unknown: The assignee is a private firm, but it is unknown from available data whether or not the inventor is an employee of this firm. Thus, both categories (1) and (2), but no other categories, are possibilities here.

(4) Inventor-Broker: The assignee is in the business of buying and selling patents and manufactures no products. An example is Communication Patents, Inc. In this scenario, the inventor may or may not be independent. Thus, as far as the inventor is concerned, this scenario is similar to category (2).

(5) Government assignee: The inventor assigns the patented invention directly to the U.S. government for governmental or military use. Many of these patents were invented by researchers and engineers for the Army Signal Corps' laboratories in and around Fort Monmouth, New Jersey. Thus, the inventor is more often than not a government employee.

(6) Government Seizure: The assignee here is always listed as Alien Property Custodian. The invention is seized from an enemy nation, typically during time of war. This practice was common during the two world wars.[125]

(7) Non-assignment: The inventor doesn't assign his or her patent to anyone, choosing instead to retain ownership. The inventor may then license the patent or choose to sell it outright. Inventors that are employees rarely have this option. This is the only scenario in which the inventor is always independent. Some of these inventors founded their own companies to manufacture and market their inventions.

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[125] *Records of the Office of Alien Property, Record Group 131, U.S. National Archives*, (Accessed 20 December 2007) available from http://www.archives.gov/research/guide-fed-records/groups/131.html; Internet.

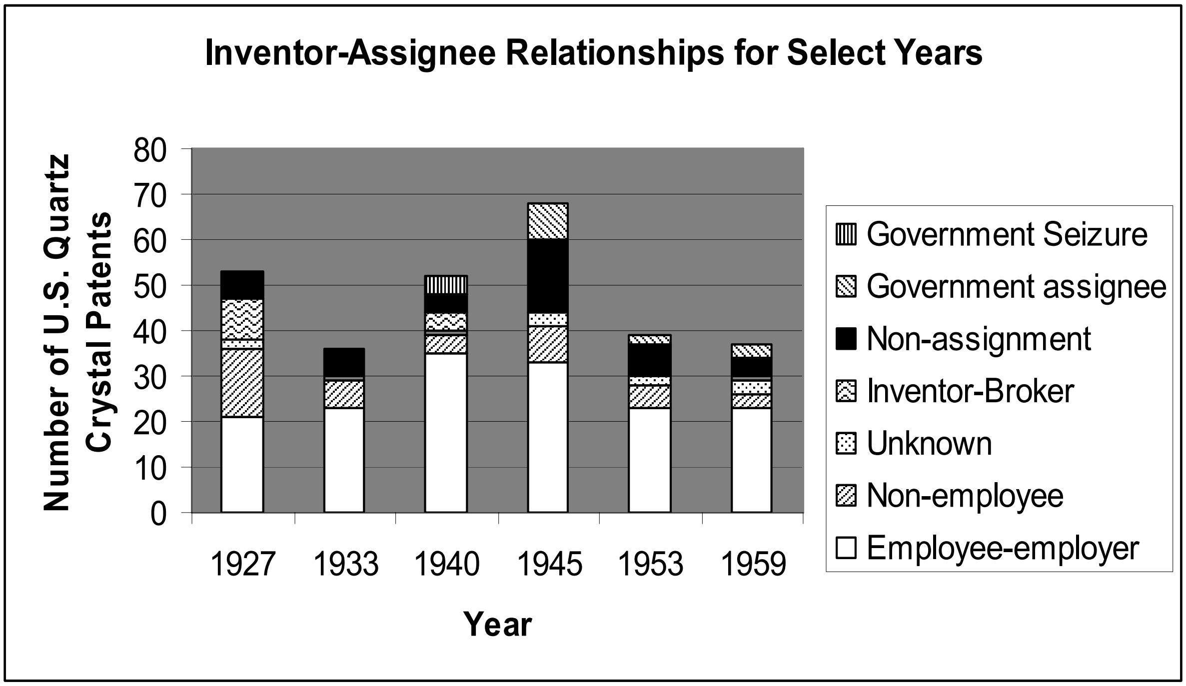

Figure 14: Inventor-Assignee Relationships for Select Years between 1927 and 1959
(Figure created by author.)

Figure 14 illustrates several important trends in quartz crystal technological innovation over the four decades studied. First, employee-employer relationships characterize more than one-half but less than three-fourths of the patents for every year except 1927 and 1945. Given the increasing visibility of in-house industrial R&D laboratories during these years, one might expect nearly all patents to have been developed by employees.[126] Yet the "Non-employee" and "Inventor-Broker" sections of Figure 14 clearly show the persistent presence of a market for purchasing patents. 1927 is especially noteworthy for its large percentage of non-employee and inventor-broker patents. During this year, the Federal Telegraph Company purchased all of its quartz

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[126] As documented by David Mowery, between 1919 and 1936 1150 industrial R&D labs were established by U.S. firms, and from 1921 to 1940, the number of scientists and research engineers employed in industrial R&D establishments increased tenfold. David Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (Cambridge, UK: Cambridge University Press, 1989).

crystal patents from two sources: independent inventor and former Western Electric engineer Alexander McLean Nicolson, and the Naval Research Laboratory. Also during this year, RCA purchased five of its seven patents from British or German inventors. At the risk of over-generalizing, these observations suggest the following general rule. When a new technology is first emerging, established companies wishing to enter the field will attempt to buy their way in by purchasing important patents from others. If this strategy succeeds in helping the company get its foot in the door, it may then go on to develop its own patents in-house.[127] This was the road taken by RCA. In 1933, four of the company's six quartz crystal patents were invented by RCA employees. For the remaining years studied, all of RCA's patents were developed in-house at one of three R&D facilities, located at Rocky Point, New York (Long Island); Camden, New Jersey; and Harrison, New Jersey.[128]

Other than RCA and Federal Telegraph Company, two other companies bought significant numbers of quartz crystal patents. Wired Radio, Inc., a company launched by Army General George Owen Squier in 1922 to exploit Squier's invention of techniques for transmitting music over power lines, bought all five of its quartz crystal patents in 1927. The company was transformed in 1934 into the well-known Muzak Corporation. Boston-based Submarine Signal Company, later becoming Raytheon, also purchased many quartz crystal patents. By the end of the period studied, however, Raytheon had begun developing most patents in-house.

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[127] For an thorough discussion of the various incentives that led companies to establish in-house R&D programs in the early 20th century, see ———, *Paths of Innovation: Technological Change in 20th Century America* (New York: Cambridge University Press, 1998).

[128] See the entries for RCA Communications, Inc., RCA Victor Company, and RCA Radiotron Company in U.S. National Research Council, *Research Laboratories in Industrial Establishments of the United States*, 4 ed., Bulletin of the National Research Council (New York: Bowker, 1933).

Several companies included in this study demonstrated a consistent pattern of developing their own patents through in-house research and development. Among these firms were the Bell System (primarily Bell Telephone Laboratories), General Electric, Westinghouse, Brush Development Company, the German firm Telefunken, Motorola, and the Bliley Electric Company. These firms consciously adopted a strategy of hiring engineers and scientists and giving them the resources necessary to innovate. Among the most prolific quartz crystal employee-inventors were Warren Marrison (8) and Warren Mason (44) of BTL, Paul D. Gerber (7) and Henry Hawk (6) of RCA, and John Wolfskill (17) of Bliley Electric.[129] Warren Mason of BTL holds the distinction of being the most prolific of all quartz crystal patentees during the period studied, as well as the most prolific of all BTL researchers.[130]

Another interesting aspect of Figure 14 is the persistent presence of non-assigned patents. The inventors behind these patents generally fell into one of three categories: independent professional inventors, university researchers, and business owners. One of the most prolific independent inventors covered in this study was Alexander McLean Nicolson. Nicolson was born in England but moved to New York at a young age. He worked for Western Electric from around 1914 to 1925, after which he worked professionally as an independent inventor. Between 1914 and 1943, he was granted 93 patents, 24 of which were piezoelectric-related.[131] Then there were the university researchers. Among these were Walter Cady of Wesleyan University and George

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[129] The numbers in parentheses are the total numbers of piezoelectric crystal-related patents granted to each inventor between 1918 and 1959.

[130] Robert N. Thurston, "Warren P. Mason, 1900-1986," *Journal of the Acoustical Society of America* 81 (1987): 570-71.

[131] All of the information presented here on Nicolson has been gathered from his patents. Very little, if anything, seems to have been written about him or his career.

Washington Pierce of Harvard. Both of these men figure prominently in Chapters 2, 4, and 5. Finally, there were the quartz crystal inventors who started their own companies to develop their inventions. Representative of this group is Kurt Klingsporn, a German physicist who worked for Telefunken for many years before launching his own firm, KVG, which specialized in piezoelectric quartz crystal devices.[132]

Finally, what can the patents studied tell us about the inventors themselves? The employment status of many inventors is difficult to ascertain with any certainty. The inventor's residence, however, is clearly indicated on every patent application. Table 3 compares the residence, U.S. or foreign, of quartz crystal patentees with the residence for all utility patentees for the years studied.[133] The largest differences occur in 1927 and 1933, when the percentage of foreign quartz crystal inventors was much larger than the percentage of all foreign utility patent inventors. This indicates that, more than many other areas of technology, early quartz crystal technology was an international endeavor. A closer look at the patents from 1927 and 1933 reveals that a plurality of these foreign-inventor patents was assigned by German inventors to the Telefunken Company. The French and the British had much smaller numbers of quartz inventors. Also noteworthy in Table 3 is the unusually small percentage of foreign quartz crystal inventors in 1945. A closer look shows that all of these inventors were British. This is not surprising given that German inventors would have been prohibited from applying for U.S. patents during wartime. Finally, we see the percentage of foreign quartz crystal inventors drop once again in 1959. This drop is hard to fully explain. One possible reason for it is that some

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[132] KVG continues manufacturing quartz crystal products to this day. *K.V.G. Quartz Crystal Technology*, (Accessed 20 December 2007) available from http://www.kvg-gmbh.com/; Internet.

[133] The utility patent is that class of patent typically recognized as an invention. (The others classes of patent are the plant patent and the design patent, the later referring to ornamental design.) All quartz crystal patents are utility patents.

talented German quartz crystal engineers, such as Rudolf Bechmann, who is discussed in Chapter 8, left Germany during the war and later settled in the U.S., where they went to work for private firms or the Army Signals Corps.

Table 3: Comparison of the Percentage of U.S. Quartz Crystal Patent Holders Having a Foreign Residence With the Percentage of All U.S. Patent Holders Having a Foreign Residence

	1927	**1933**	**1940**	**1945**	**1953**	**1959**	**Average**
% Foreign (quartz crystal patents)	23	31	15	3	15	8	16
% Foreign (all utility patents)	12	15	15	8	11	16	13
Difference	**+11%**	**+16%**	**---**	**-5%**	**+4%**	**-8%**	**+3%**

(Table created by author.)

This chapter has presented the results of a study of quartz crystal technology patents filed between 1918 and 1959. These results point to a number of important conclusions. First, the body of technological knowledge examined can be divided into three broad categories: components and systems that exploit primarily the uniquely stable resonant properties of quartz crystal, components and systems that exploit primarily the natural transducing property of piezoelectric quartz crystal, and other components and systems that do not fit neatly into either of these broad categories. During the period studied, the first of these three categories accounted for 50 to 60 percent of all quartz crystal-related patents. It is partly for this reason that this dissertation focuses on resonant applications of quartz crystal, leaving transducer and other applications for a future study.

Furthermore, this study has shown that the knowledge surrounding resonant applications of piezoelectric quartz crystal can be further divided into three more specialized categories: quartz crystal unit (QCU) design and fabrication, radio oscillator and transmitter circuitry, and wave filter circuitry. Quartz crystal technology has been shown to be hierarchical and system-based, with the QCU serving as the principal component in resonant applications. As such, the QCU has attracted a significant amount of inventive effort. This effort peaked during World War II, corresponding with the important role played by QCU's in making possible the U.S. Army Signal Corps' wartime mobile communications.

This study has also highlighted the distinction between product and process patents. Many QCU patents, particularly those filed during World War II, covered processes useful in QCU manufacturing. Among the processes that have allowed for much creative latitude, and that therefore have yielded large numbers of patents, have been the grinding and cutting of crystals into wafers and the mounting of crystal wafers onto crystal holders. For the companies involved in QCU manufacture, many of these process patents would have been visible to competitors only through the improved performance characteristics of their products. That is, two QCU's manufactured using identical materials but different manufacturing processes might have looked the same. The only noticeable difference would have been their performance within a radio or telephony system. Thus, for the companies holding them, process patents may have been more difficult to protect against infringement than product patents.

In addition to providing insight into the knowledge structure of quartz crystal technology, this patent study has also shed light on the social nature of quartz crystal invention. Private sector firms, led by the various parts of the Bell System, were shown to be the assignees on nearly four of every five quartz crystal patents issued between

1918 and 1959. The remaining patents either specified the U.S. government as the assignee or indicated no assignee at all, resulting in a de factor assignment to the inventor. This dominance of private firms in the ownership of patents is not surprising in light of the well-documented rise in intrafirm research and development during the first half of the 20th century.[134] What is surprising, however, is the persistent presence in quartz crystal technology of unassigned patents. On average, roughly one of every six patents filed during the period studied specified no assignee as of the date of issue. This fact, when coupled with the persistent presence of patents for which the inventor was not an employee of the assignee, suggests that, for the period studied, there was a healthy open market for the selling and licensing of quartz crystal patents. The patent data examined here also suggests that this market was most active in the early years of the technology, when large firms such as AT&T, Federal Telegraph Company, and RCA were struggling to acquire dominant patent positions. In particular, RCA and Federal Telegraph sought during the 1920s to buy their way into quartz crystal technology by purchasing patents developed outside their organizations. By contrast, AT&T, through its Bell Telephone Laboratories, developed an early pattern of developing quartz crystal inventions in-house. As quartz crystal technology matured, most firms that remained in the business developed their own in-house R&D capabilities rather than choosing to purchase patents from others.[135]

Lastly, this chapter has shown that U.S. quartz crystal inventors were not solely American. As indicated by the patent data, quartz crystal technology was an international

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[134] David Mowery, "Industrial Research and Firm Size, Survival, and Growth in American Manufacturing, 1921-46: An Assessment," *Journal of Economic History* 43 (December 1983): 953-80.

[135] This was consistent with the general trend during the interwar years for manufacturing firms to develop in-house R&D capabilities. See David Mowery and Nathan Rosenberg, *Paths of Innovation: Technological Change in 20th Century America* (New York: Cambridge University Press, 1998).

endeavor, especially in the 1920s and 1930s. The Germans, and the firm of Telefunken in particular, were engaged more than any other foreign people in developing new quartz crystal devices and processes. During World War II, when Germans were prohibited from filing for U.S. patents, the percentage of quartz crystals patents filed by foreign inventors fell precipitously. By the early 1950s, this percentage had returned to pre-war levels. British and French inventors filed for a modest number of quartz crystal patents during the period studied. But, on the whole, quartz crystal technology between 1918 and 1959 was driven by American and German firms.

CHAPTER 4: THE 1920s – QUARTZ CRYSTAL AND FREQUENCY CONTROL

It is indeed most fortunate that just when extremely accurate frequency control is becoming so necessary to radio, the instrumentalities for it should become available. It may be that this is putting the cart before the horse and explaining how remarkable it is that great rivers always flow past large cities. Perhaps the modern desire and need and application of constant frequency is the result of the crystal oscillator and similar high precision frequency control devices.[136]

Alfred N. Goldsmith, R.C.A. Chief Broadcast Engineer, 1928

4.1 Introduction

By 1921, Walter Cady had invented the two foundational devices of resonant quartz crystal technology, the piezo-resonator and the piezo-oscillator.[137] Yet, the application of these devices to the technology of radio awaited further developments, such as the growth of medium-wave broadcasting and the rise of shortwave relaying as a means of linking distant stations together. Furthermore, Cady's piezo-oscillator, an important breakthrough invention in its own right, was too fragile and finicky a device to be used in radio. It required simplification.

This chapter traces the beginning of the first quartz crystal technology boom to early 1924, when George Washington Pierce invented a simplified piezo-oscillator. Pierce's invention found use quickly in shortwave experiments and later in medium-wave broadcasting, where it enabled engineers to construct "crystal-controlled" transmitters. The highly stable frequencies generated by the Pierce oscillator greatly improved the reception characteristics of both shortwave and medium-wave radio signals. Beginning in 1924, quartz crystal technology progressed on several fronts. The U.S. Naval

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[136] "Discussions on Harrison Paper," *Proceedings of the Institute of Radio Engineers* 16, no. 11 (1928): 1470.

[137] The term "resonant quartz crystal technology" is used here to distinguish those quartz crystal devices and systems that exploit primarily the unique resonance property of quartz crystal from those that exploit primarily the electro-mechanical transducer property of quartz crystal. See Figure 9 of Chapter 3.

Research Laboratory began applying crystal control to high-powered shortwave transmitters. The so-called Radio Group companies began conducting shortwave relaying experiments using crystal-controlled transmitters, while AT&T applied crystal control to medium-wave transmission, these experiments leading to a number of patentable inventions. Those companies that lacked established R&D facilities, such as R.C.A., began purchasing quartz crystal patents on the open market. Finally, the U.S. radio amateur community, which had already made many substantial contributions to radio technology, also began adopting the technique of crystal control, creating a large and growing market for precisely ground quartz crystals.

In relating the experimental and inventive activity following the 1924 invention of the Pierce oscillator, this chapter illuminates the growth of a technological community and its creation and maintenance of a new engineering knowledge base. Prior to 1924, the quartz crystal technological community comprised alumni of the World War I anti-submarine warfare research effort and a handful of well-connected radio amateurs. By the late 1920s, this community had grown to include small R&D groups at AT&T, G.E., Westinghouse, and the Naval Research Laboratory, as well as increasing numbers of radio amateurs. Forces driving the growth of this community included technological and scientific curiosity, competition between AT&T and the Radio Group over the future of chain (i.e., network) broadcasting, patent competition between AT&T and R.C.A., and the desire to find a technical solution to the problem of radio interference in the U.S. The engineering knowledge base created by this community was disseminated through a number of channels, including patents, journal publications, conference presentations, and even amateur radio magazines.

4.2 Walter Cady's piezoelectric oscillator is without a practical application

When Walter Cady filed his piezo-oscillator patent in May of 1921, its field of application was uncertain at best. The piezo-oscillator's primary function was to generate a single and highly stable radio frequency. As Cady had proposed, such a device could serve as a frequency standard, but this was a niche application for which a few hundred, or at most a few thousand, devices would ever be needed.[138] Other possible applications for the piezo-oscillator were radio transmission and multiplex telephony, but non-quartz based master-oscillator transmitters were performing adequately enough in these areas. In radio, most transmissions were still of the point-to-point variety; broadcasting had yet to take hold in the U.S., or anywhere else for that matter. The potential value of what is now called the shortwave band (1500-30,000 kHz) had yet to be recognized; most observers considered the useful portions of the spectrum to be limited to the low-frequency (30-300 kHz) and medium-frequency (300-1500 kHz) bands. At these frequencies, broadcasters, amateurs, and the military considered master-oscillator transmitters to be more than adequate for maintaining a stable transmit frequency. For the lowest radio frequencies ($\leq$ 100 kHz), the Alexanderson alternator, developed by Ernst Alexanderson of General Electric and used by the U.S. Navy for land-based transmitters, enabled high-power, continuous wave radio transmission.[139] In telephony, AT&T had introduced small-scale multiplexing into its long-distance network

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[138] The use of the piezo-resonator and piezo-oscillator as a frequency standard is discussed in Chapter 5.

[139] Susan J. Douglas, *Inventing American Broadcasting, 1899-1922*, ed. Thomas P. Hughes, Johns Hopkins Studies in the History of Technology (Baltimore, MD: Johns Hopkins University Press, 1987), 155-56. For a thorough study of Ernst Alexanderson, see James E. Brittain, *Alexanderson: Pioneer in American Electrical Engineering*, Johns Hopkins Studies in the History of Technology (Baltimore: Johns Hopkins University Press, 1992).

in the late teens. Stable carrier frequencies were needed to prevent simultaneous phone conversations from bleeding into each other. But again, as with radio, non-quartz vacuum tube oscillators proved sufficient for this job. The piezo-oscillator seemed to be a device for which a clear need, other than possibly as a frequency standard, did not yet exist.

4.3 The birth of shortwave and medium-wave radio broadcasting

In 1921, a new type of radio transmission – shortwave – was just emerging for which non-quartz vacuum-tube oscillators would prove insufficient. Enterprising radio amateurs were the first to demonstrate the value of the shortwave band for long-distance, low-power transmissions.[140] Among the earliest to experiment with shortwave transmission was Westinghouse engineer Frank Conrad, famous for orchestrating Westinghouse station KDKA's radio broadcast of the 1920 presidential election results.[141] Throughout 1921 and 1922, Conrad, who was an avid radio amateur in his spare time, used his personal "ham" station to relay KDKA's broadcast signal on frequencies ranging from 2,000 to 5,000 kHz, much higher than most transmissions of the time. Conrad and others quickly came to realize that the sensitivity of a radio transmitter's frequency to small variations in transmitter components increased linearly with increasing frequency. In other words, as transmitter frequency increased through the shortwave band, it became more and more difficult to maintain a stable frequency to which listeners could easily tune in. But of course, in 1922 there were hardly any

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[140] Hugh Aitken, *The Continuous Wave: Technology and American Radio, 1900-1932* (Princeton, NJ: Princeton University Press, 1985), 512.

[141] Jerome S. Berg, *On the Short Wave, 1923-1945: Broadcast Listening in the Pioneer Days of Radio* (Jefferson, N. C.: McFarland & Co., 1999), 14, 48, 50.

shortwave receivers with which listeners could tune in, so the problem was not considered acute. Nevertheless, by 1922, the radio amateur community had identified improved frequency stability as one of the technical goals that must be achieved if shortwave radio was to have a future.

1922 was also the year that radio broadcasting took America by storm. This so-called radio boom was not completely unanticipated; General Electric and Westinghouse had begun ramping up production of affordable home radio receivers throughout 1921.[142] At the end of that year, there were fewer than thirty broadcast stations in the U. S.[143] By March of 1922, this number had grown to sixty-seven.[144] Then, in the late spring and summer months, the U. S. Department of Commerce was inundated with hundreds of broadcast license applications. By August, 253 stations had been licensed, and by October, 546.[145] The exuberant enthusiasm with which Americans greeted radio broadcasting over the course of a few months in 1922 has few parallels in the nation's history. As Herbert Hoover would say in 1925, "There have been few developments in

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[142] At the 1st Radio Conference, Herbert Hoover estimated that the number of radio receivers in public use in Feb. 1921 was 50,000; by Feb. 1922, he estimated that this number had grown to 600,000. See page 15 of Hugh Slotten, *Radio and Television Regulation: Broadcast Technology in the United States, 1920-1960* (Baltimore, MD: Johns Hopkins University Press, 2000). RCA introduced its Radiola Super-Heterodyne, the first receiver housed in a "handsome cabinet," in 1923. By 1924, it has been estimated that 10.1% of American families owned radio receivers. See page 69 of Philip T. Rosen, *The Modern Stentors: Radio Broadcasters and the Federal Government, 1920-1934* (Westport, CT: Greenwood Press, 1980).

[143] 5 stations are listed as being licensed on Jan. 1, 1922 by Christopher H. Sterling and John Michael Kittross, *Stay Tuned: A History of American Broadcasting*, 3rd ed. (Mahwah, NJ: Laurence Erlbaum Associates, 2002). 8 stations are listed in Captain Linwood S. Howeth, *History of Communications-Electronics in the United States Navy*, 1 ed. (Washington, D.C.: U. S. Government Printing Office, 1963), 382-3. 28 stations are listed in Hugh Slotten, *Radio and Television Regulation: Broadcast Technology in the United States, 1920-1960* (Baltimore, MD: Johns Hopkins University Press, 2000).

[144] See the list of broadcast stations in "List of stations broadcasting market or weather reports (435 meters) and music, concerts, lectures, etc. (360 meters)," *Radio Service Bulletin*, no. 59 (1 March 1922): 13-14.

[145] See "Broadcasting Still Increasing," *Radio News* (August 1922): 237. See also "Broadcasting Increases 500-Fold in One Year," *Radio News* (December 1922): 1156.

industrial history to equal the speed and efficiency with which genius and capital have joined to meet radio needs."[146]

The 1922 radio boom brought a number of permanent changes in the ways that Americans communicated, entertained themselves, and received their news. For one, Americans no longer viewed radio as a means of point-to-point communication only, used mostly by the military, big business, and radio amateurs. Radio was now a means of bringing the latest news and the most popular forms of entertainment into the home. But the radio boom also changed forever the way that the radio spectrum was used. The increasing demand for broadcast station licenses, the willingness of the Dept. of Commerce to grant them, and the finite size of the usable radio spectrum all combined to ensure that spectrum would quickly become a scarce resource. By 1923, Secretary of Commerce Herbert Hoover declared that radio interference, caused by broadcasters crowding the airwaves, had become "simply intolerable."[147]

One source of the severe radio interference problem was the difficulty most broadcast stations experienced in holding their transmitters to their assigned frequencies. The non-crystal vacuum tube master-oscillator transmitters used by stations of the day were quite sensitive to small changes in temperature. As vacuum tubes heated up, a transmitter's frequency tended to drift. One way to remedy this was to have a technician vigilantly monitor the station's outgoing frequency, resetting the transmitter's frequency dial when necessary. The master-oscillator transmitter was the state-of-the-art in early 1920s radio technology. If taken care of, its performance was admirable. But broadcast

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[146] U.S. Department of Commerce, *Proceedings of the 4th National Radio Conference*, by U. S. Department of Commerce, (Washington, D.C., 1925).
[147] Herbert Hoover, "The Urgent Need for Radio Legislation," *Radio Broadcast* (January 1923): 211.

engineers would have welcomed a way to automatically control the station's frequency without having to check it every few hours.

Theoretically, broadcast engineers could have used Walter Cady's piezo-oscillator to hold a transmitter's frequency constant. Practically, however, there were many problems with the device. For one, it was somewhat finicky and required careful selection of circuit component values in order for oscillation to occur. Furthermore, the use of Cady's device essentially locked a station in to one and only one frequency. Precise tweaking of the frequency would no longer be an option, as it was with master oscillators. Thus, in 1923, no serious broadcast engineer would have considered using Cady's oscillator in a medium-wave broadcast transmitter.

Meanwhile, experimentation with shortwave radio transmission continued. In 1923, Westinghouse began using shortwave to extend the reach of its flagship medium-wave station, KDKA.[148] Transmitting on a wavelength of 64 meters, equal to a frequency of 4687 kHz, Westinghouse shortwave station 8XS had a much broader geographic reach than KDKA.[149] The company built station KFKX in Hastings, Nebraska to receive the signals from 8XS and re-transmit them on a medium-wave frequency for local reception, making KFKX the first shortwave relay station in the U.S.[150] In the same year, General Electric and the Crosley Corporation also built

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[148] KDKA's initial broadcast wavelength was 360 meters, corresponding to a frequency of 833 kHz. All commercially available receivers could pick up this frequency, but few at this time could pick up shortwave frequencies higher than 1500 kHz. Source: Susan J. Douglas, *Inventing American Broadcasting, 1899-1922*, ed. Thomas P. Hughes, Johns Hopkins Studies in the History of Technology (Baltimore, MD: Johns Hopkins University Press, 1987), 300.

[149] See Erik Barnouw, *A History of Broadcasting in the United States. A Tower In Babel*, 3 vols., vol. 1 (New York: Oxford University Press, 1966), 151. See also "Important Events in Radio - 1923," *Radio Service Bulletin*, no. 141 (31 December 1928): 22.

[150] Jerome S. Berg, *On the Short Wave, 1923-1945: Broadcast Listening in the Pioneer Days of Radio* (Jefferson, N. C.: McFarland & Co., 1999), 49. Alice Brannigan, "KFKX: A Most Historic Broadcast Station," *Popular Communications* (October 1998): 14.

shortwave transmitters for relaying their medium-wave broadcasts, G.E.'s signal being strong and clear enough to be regularly picked up in England. None of these early shortwave relay stations, however, used Cady's piezo-oscillator, making the signals moderately difficult to receive as the transmit frequencies drifted. Nevertheless, these experimental stations established the feasibility of using shortwave to instantaneously link broadcast stations separated by hundreds and even thousands of miles, a practice that ultimately came to be known as interconnection.

What driving motive lay behind these early shortwave experiments? Were radio engineers driven solely by curiosity to explore the communications potential of higher frequencies, or was there something more strategic going on? Curiosity certainly played a role, for shortwave was poorly understood at this time, but fierce competition between AT&T and the so-called Radio Group, comprising R.C.A., G.E., Westinghouse, and United Fruit, also drove shortwave experimentation.[151]

For the first two decades of radio, AT&T saw the new technology, which was used primarily for point-to-point communication, as a potential threat to its wired telephone network. Thus, the company invested heavily in radio technology throughout the first two decades of the 20th century. With the rise of broadcasting in the early 1920s, AT&T stayed in radio, establishing station WEAF in Manhattan.[152] Then, attempting to parlay its nationwide network of telephone wires, over which it had exclusive control, into a competitive advantage over the Radio Group, the company began experimenting

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[151] Susan J. Douglas, *Inventing American Broadcasting, 1899-1922*, ed. Thomas P. Hughes, Johns Hopkins Studies in the History of Technology (Baltimore, MD: Johns Hopkins University Press, 1987), 290.

[152] See Chapters 5 and 6 of William Peck Banning, *Commercial Broadcasting Pioneer: The WEAF Experiment (1922-1926)* (Cambridge, MA: Harvard University Press, 1946).

with "chain broadcasting" in the summer of 1923.[153] Chain broadcasting involved simultaneous broadcasts over multiple geographically-dispersed stations, each connected to the chain via dedicated telephone wires. The first chain in the summer of 1923 included only three stations, WEAF plus two New England stations, one in Providence, RI and the other in South Dartmouth, MA. Three more stations were added by the end of 1923, and by the end of 1924 AT&T could boast of a 26-station coast-to-coast radio network, all connected by the company's proprietary telephone wires.[154]

These developments seriously threatened R.C.A.'s position in the growing broadcast industry, for neither R.C.A. nor any other member of the Radio Group had access to AT&T's telephone wires. The Group would have to find another way to interconnect its stations. Between 1923 and 1926, R.C.A., G.E., and Westinghouse experimented with three interconnection techniques: Western Union telegraph lines, superpower transmitters, and, as already described, shortwave relays. Western Union telegraph lines provided adequate geographic coverage but were found wanting in sound quality.[155] Superpower transmitters, which aimed to make interconnection unnecessary by building stations powerful enough to reach the entire nation, produced unacceptable levels of interference with smaller stations. Lastly, shortwave relays proved much more effective than telegraph lines, but were plagued by a couple of technical problems – the variable propagation characteristics of shortwave frequencies at different times of day, and the difficulty of maintaining a shortwave transmitter at a constant frequency. Radio

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[153] Erik Barnouw, *A History of Broadcasting in the United States. A Tower In Babel*, 3 vols., vol. 1 (New York: Oxford University Press, 1966), 144. See also Chapters 9, 15, and 17 of William Peck Banning, *Commercial Broadcasting Pioneer: The WEAF Experiment (1922-1926)* (Cambridge, MA: Harvard University Press, 1946).
[154] Erik Barnouw, *A History of Broadcasting in the United States. A Tower In Babel*, 3 vols., vol. 1 (New York: Oxford University Press, 1966), 145.
[155] Ibid., 143-4.

Group engineers saw these problems as difficult but not insurmountable. Shortwave thus seemed to give the Radio Group the best chance of constructing a nationwide chain of broadcast stations to rival that of AT&T.

While the Radio Group was experimenting with shortwave relays, amateur interest in shortwave was increasing. This interest intensified when, in November of 1923, amateurs in the U.S. and France conducted the first trans-Atlantic two-way conversation via shortwave.[156] One amateur attracted to the possibilities of shortwave radio made evident by this remarkable demonstration was George Washington Pierce, a professor of electrical engineering at Harvard. Pierce had been acquainted with Walter Cady, another radio amateur, since at least 1917, when the two met at a regional meeting of Institute of Radio Engineers (I.R.E.) members.[157] On the basis of their friendship and mutual interest in radio, Cady disclosed his piezo-resonator and piezo-oscillator inventions to Pierce after filing patent applications.[158] Pierce was immediately attracted to the possibilities of the piezo-oscillator.

4.4 George Washington Pierce improves on Cady's piezoelectric oscillator

Walter Cady's invention of the piezo-oscillator had occurred before anyone quite knew what to do with such a device. In early 1920, Cady had invented the piezo-resonator, a passive device consisting of a thin quartz crystal wafer, a pair of conducting electrodes, and a mechanical holder, the combination which served as a highly frequency-

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[156] See Bob Raide and Ed Gable, *Celebrating the First Transatlantic QSO* (1998, Accessed 2 January 2007) available from http://www.arrl.org/news/features/1998/1102/2/?nc=1; Internet.

[157] Walter G. Cady, Personal Diary entry for 18 January 1917, Folder 24, Box 3, Walter G. Cady Papers (Subgroup 3), Cady Family Papers (MSS 326), Rhode Island Historical Society Library, Providence, RI.

[158] Frederick A. Saunders and Frederick V. Hunt, "George Washington Pierce," in *Biographical Memoirs. National Academy of Sciences* (Washington, D.C.: National Academy Press, 1959), 351-80, cited: 361.

selective electrical resonator.[159] At this time, America's radio broadcasting boom was still in the future, and the utility of the shortwave radio band for long-distance communication had yet to be demonstrated. Cady was giving public talks on the topic of using the piezo-resonator as a frequency standard. After one such talk at Columbia University in early 1921, Harold Arnold, director of research for the Western Electric Research Laboratories and a former student of Cady's, approached Cady with a novel suggestion. Perhaps the piezo-resonator could be used, Arnold conjectured, to precisely control the frequency of a vacuum tube oscillator.[160] Within days, Cady had confirmed in his laboratory that the idea was indeed feasible.[161] After presenting these exciting results at a Physical Society meeting held at the U.S. Bureau of Standards in April of 1921, Cady filed a patent application for his "piezo-electric oscillator." The title of the application, "Method of Maintaining Electric Currents of Constant Frequency," hints at the uncertainty as to utility with which the patent was drafted.[162] Nowhere in text of the patent did Cady explicitly propose that his "method" be used to control the frequency of a radio transmitter; the closest he came was stating that the method "may be employed in the transmission or the reception of intelligence by means of high frequency currents."[163] Precisely what Cady meant by the term "high frequency" is not entirely clear, but in using such general language, he and his patent attorneys were seeking to keep the scope of the patent claims as broad as possible.

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[159] See Chapter 5 for more on the piezo-resonator.

[160] R. Bruce Lindsay and W. J. King, "Walter G. Cady Oral History Interview" 28-9 August 1963, Center for History and Philosophy of Physics. Available at Box 2, Walter G. Cady Papers, Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT.

[161] Walter G. Cady, Personal Diary entry for 28 February 1921, Folder 25, Box 3, Walter G. Cady Papers (Subgroup 3), Cady Family Papers (MSS 326), Rhode Island Historical Society Library, Providence, RI.

[162] Walter Guyton Cady, *Method of Maintaining Electric Currents of Constant Frequency*, U. S. Patent Office, Patent No. 1472583, Filing Date: 28 May 1921; Issue Date: 30 October 1923.

[163] Ibid.

Though no one was sure how to use Cady's piezo-oscillator, word of it spread rapidly through the scientific and engineering communities. In August 1921, *Physical Review* published a summary of Cady's Physical Society talk.[164] Then, in November of the same year, Cady presented a talk before a New York meeting of the Institute of Radio Engineers (I.R.E.) entitled "The Piezo-Electric Resonator," the text of which was re-printed in the April 1922 issue of *Proceedings of the I.R.E.*[165] In this talk, Cady explicitly proposed using the piezo-resonator as a frequency stabilizer, but never suggested the utility of this for radio transmission. In fact, despite the wide dissemination of Cady's ideas and inventions, no public record exists of anyone using quartz crystal to control the frequency of a radio transmitter until Pierce's work in early 1924.[166]

Pierce, much more the electrical engineer than Cady, felt that the Wesleyan professor's piezo-oscillator could be substantially improved. The Harvard professor first devised a way to used Cady's oscillator to calibrate the university's frequency meters.[167] Then, working from his home amateur station as well as from his university lab, Pierce conducted shortwave transmission experiments in which the piezo-oscillator was used to stabilize the transmitter's frequency. The resulting device came to be known as the crystal-controlled transmitter. Within a few months, Pierce had developed significant modifications to Cady's piezo-oscillator. These modifications, embodied in a circuit that came to be known as the Pierce oscillator, produced a device that was simpler and more

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[164] See ———, "New Methods For Maintaining Constant Frequency in High-Frequency Circuits," *Physical Review* 18, no. 2 (August 1921): 142-43.

[165] ———, "The piezo-electric resonator," *Proceedings Of The Institute Of Radio Engineers* 10, no. 2 (April 1922): 83-114.

[166] "Pubic record" in this sentence is intended to refer to patents as well as journal (both amateur and professional) articles.

[167] George Washington Pierce, "Piezoelectric Crystal Resonators and Crystal Oscillators Applied to the Precision Calibration of Wavemeters," *Proceedings of the Amercian Academy of Arts and Sciences* 59, no. 4 (October 1923).

reliable than Cady's. The Pierce oscillator still employed a quartz crystal wafer to regulate the oscillating frequency, but it required fewer passive components and used only two electrodes rather than the piezo-oscillator's four. Furthermore, unlike Cady's circuit, Pierce's circuit would not oscillate without the crystal inserted, making it more stable and robust in operation. Finally, the Pierce oscillator was capable of oscillating at frequencies well into the shortwave band, beyond the operational range of the piezo-oscillator.[168] In sum, the Pierce oscillator represented a material advance in quartz crystal technology. Cady's piezo-oscillator had demonstrated the feasibility of using a quartz crystal wafer to control the oscillating frequency of a vacuum tube oscillator, but the circuit itself was difficult to use in practice. In contrast, the Pierce oscillator could easily be built into a radio transmitter, medium-wave or shortwave, to reliably control the transmitted frequency. In modern engineering terms, Cady's contribution to crystal-control oscillation was proof-of-concept; Pierce's contribution was reduction of concept to practice in the form of a practical, robust, and easy-to-use circuit.

In February of 1924, Pierce filed a patent application for his new invention (U.S. Patent 2,133,642), initiating a period of frenzied activity in the realm of quartz crystal technology. Within a matter of months, experimental shortwave stations began using crystal-controlled transmitters, R&D organizations intensified their work in quartz crystal

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[168] See ———, *Electrical System*, U. S. Patent Office, Patent No. 2,133,642, Filing Date: 25 February 1924; Issue Date: 18 October 1938. The following statements are of special importance. Page 2, Column 1, lines 27-34 state, "I have constructed apparatus, according to the present invention, for fundamental frequencies ranging from 35 kilocycles per second to 3000 kilocycles per second. I have utilized harmonics of the device at frequencies of 20,000 kilocycles per second." Page 6, Column 1, lines 45-56 state, "A tunable transmitting system … and a tunable receiving system … may the one transmit, and the other receive, constant oscillations of very high frequency. This has been done by me over considerable distances. The constancy of the beat note and the consequent certainty of being always in adjustment to receive the given signals was found to be of great value, rendering possible the use of very high frequencies." Finally, page 6, Column 2, lines 2-7 state, "The master oscillator, which may be of, say, 5 watts, controls, through power amplification, the tube of much higher power, say 50 watts, and so forth. Such a system has been successfully operated by me in practice over a considerable distance."

technology, and the U.S. Patent Office began receiving unprecedented numbers of quartz crystal patent applications. In 1924 alone, the Patent Office received ten quartz crystal-related applications that resulted in issue, more than all quartz crystal-related patents issued prior to 1924. As shown in Figure 1 of the Introduction, this number increased to twenty-three in 1925, thirty in 1926, and fifty-three in 1927. Many of these inventions were modest extensions of the Pierce oscillator, but some, such as a multiplex telephony system employing crystal-controlled oscillators, were altogether new.[169] The relationship between the appearance of the Pierce oscillator and the creative burst in quartz crystal technology beginning in 1924 is of course impossible to determine definitively. Perhaps the Pierce oscillator itself stimulated this creative outpouring. Maybe the Pierce oscillator just happened to be the first response among many to the merging of Cady's work and developments in shortwave radio. Whatever the case may be, the appearance of the Pierce oscillator marked the beginning of a remarkably fruitful five-year period in quartz crystal technology.

4.5 Quartz crystal research and development at the Naval Research Laboratory

Among the R&D organizations most active in researching quartz crystal technology in 1924 was the newly opened U.S. Naval Research Laboratory (NRL). In the spring of that year, NRL researchers Albert Hoyt Talyor, head of the Lab's radio division, and Alfred Crossley were attempting to replicate and improve on Pierce's experiments with crystal-controlled shortwave transmission. The two men wanted to

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[169] For a modest extension of the Pierce oscillator, see Joseph W. Horton, *Oscillation Generator*, U.S. Patent Office, Patent No. 1,606,791, Filing Date: 18 July 1924; Issue Date: 16 November 1926. For a multiplex telephony patent, see Charles H. Fetter, *Multiplex System*, U.S. Patent Office, Patent No. 1,833,966, Filing Date: 3 December 1924; Issue Date: 1 December 1931.

increase transmission power beyond the meager 50 Watts used by Pierce. Their first success came in May 1924 with a 100 Watt experimental unit.[170] Throughout the summer, the NRL researchers received help from Walter Cady and his protégé, Karl Van Dyke, in producing crystal-controlled units of higher power.[171] This led to the group constructing, by early 1925, a 10 kW transmitter operating at 4015 kHz. At the time, this was a unique combination of high power and high frequency. Used for Naval communications between Washington and Australia, this unit was likely the first crystal-controlled transmitter to be used by anyone for routine communications work.[172] The NRL's work on crystal-controlled shortwave transmitters led to nearly twenty quartz crystal patents before the decade was out.[173]

The NRL's 1924 experiments with crystal-controlled shortwave transmission were motivated by the Navy's desire to expand the radio bandwidth available to it for ship-to-shore and ship-to-ship communications. In the spring of 1923, Congress had chosen to reserve the 500-1350 kHz medium-wave band for AM broadcasting, effectively restricting Naval communications to the long waves below 500 kHz. The Navy, feeling the need for more bandwidth, was given permission to experiment at frequencies greater than 3000 kHz, well into the then mysterious shortwave, or high frequency (HF), band. Several senior officials expressed misgivings about basing the future of Navy

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[170] See John M. Clayton, "Navy Developments in Crystal-Controlled Transmitters," *QST* 9, no. 11 (November 1925): 41-44.

[171] See page 24 of Albert Hoyt Taylor, *The First Twenty-Five Years of the Naval Research Laboratory* (Washington, D.C.: U.S. Department of Navy, 1948).

[172] See page 43 of John M. Clayton, "Navy Developments in Crystal-Controlled Transmitters," *QST* 9, no. 11 (November 1925): 41-44. See also page 52 of Louis A. Gebhard, *Evolution of Naval Radio-Electronics and Contributions of the Naval Research Laboratory* (Washington, D.C.: Naval Research Laboratory, 1979).

[173] Between 1924 and 1928, N.R.L. engineers filed for 19 quartz crystal patents that were eventually issued. The assignee on all of the patents was Wired Radio, Inc., a company begun by Army General George Owen Squier for transmitting music over power lines. In 1934, Wired Radio became the well-known Muzak Corporation. Source: *Muzak, Inc.: Company History*, (Accessed 7 January 2008) available from http://www.fundinguniverse.com/company-histories/Muzak-Inc-Company-History.html; Internet.

communications on such a poorly understood phenomenon as shortwave radio. Still, others suspected that the move to shortwave might bring many benefits. By arguing, rightfully so, that its existing radio equipment would not operate at the higher frequencies, the Navy could easily justify new appropriations for developing shortwave radio equipment. This is precisely what happened.[174] Upon the opening of the NRL in the summer of 1923, one of the Lab's first charges was to develop equipment for exploring and exploiting the shortwave band.[175] Taylor, Crossley, and other NRL researchers quickly learned what the radio amateur community already knew – reliable shortwave communications required extremely stable carrier frequencies. After the invention of the Pierce oscillator in early 1924, the way to achieve such stable frequencies was obvious to the NRL staff.[176]

Nevertheless, despite its advantages, crystal-control was seen by some Navy officials, including the head of the Navy's Radio Division, Stanford C. Hooper, as having several serious drawbacks, particularly since crystal-control was being advocated not only for transmitters but also for receivers, allowing for pushbutton reception .[177] First and most importantly, Hooper was concerned about the supply and cost of quartz crystal.

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[174] Some authors (see Gebhardt – page 44 and Howeth) have stressed the Navy's reluctance to yield the 500-1350 kHz band to broadcasters. Others (see Rosen – pages 58-59 and Slotten – page 22) have portrayed the Navy as more compliant, knowing that, in the long run, the change would work to its advantage.

[175] Hugh Aitken has effectively argued that spectrum scarcity has been a recurrent feature of radio history, one that has served to push technological development toward higher and higher frequencies. In the 1920s, the spectral frontier was the HF band (3,000-30,000 kHz). In the 1930s and '40s, the frontier moved to the VHF (above 30,000 kHz) and UHF (above 300,000 kHz). Finally, in the 1950s and '60, the frontier moved into the microwave region. See Hugh Aitken, "Allocating the Spectrum: The Origins of Radio Regulation," *Technology and Culture* 35, no. 4 (October 1994): 686-716, cited: 687.

[176] See Captain Linwood S. Howeth, *History of Communications-Electronics in the United States Navy*, 1 ed. (Washington, D.C.: U. S. Government Printing Office, 1963). See also Louis A. Gebhard, *Evolution of Naval Radio-Electronics and Contributions of the Naval Research Laboratory* (Washington, D.C.: Naval Research Laboratory, 1979).

[177] Captain Linwood S. Howeth, *History of Communications-Electronics in the United States Navy*, 1 ed. (Washington, D.C.: U. S. Government Printing Office, 1963). Howeth cites a letter from Hooper to Commander H. P. LeClair, dated July 20, 1926, in which he advises that the Navy not adopt crystal-control.

Outfitting all of the Navy's HF transmitters and receivers with crystal-control would require an enormous quantity of quartz. He was concerned that Brazilian mines were the only known adequate source of electronics-grade quartz and that, in the event of this source being blocked, the cost of quartz would become prohibitive. Furthermore, he was concerned with the ability of crystal-controlled transmitters and receivers to be precisely tuned with one another. A failure in this regard would, he believed, "endanger the reliability of communications by increasing the likelihood of unit and force commanders losing contact with their ships." Thirdly, Hooper worried that building radio equipment at very high frequencies (> 9 MHz) would subject on-board radio receivers to "internally generated disturbances," preventing clear reception. Lastly, Hooper worried that high-frequency radio equipment would be inherently more susceptible than lower frequency equipment to jamming by the enemy. This concern was based partly on the ability of low-power HF transmitters to transmit their signals over very long distances, and partly on the relatively low cost and ease of construction of HF transmitters. Thus, an enemy would theoretically be capable of assembling and positioning a jamming HF transmitter very quickly and at little cost. Hooper's objections eventually carried the day, keeping the Navy from adopting crystal control on a large scale. In the early 1930s, the Navy developed and adopted a moderately successful non-crystal technique of frequency stabilization.[178] In the end, the Navy's rejection of crystal control did little to dissuade the radio industry and the amateur radio community from adopting the technique.

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[178] This technique, employing a device called the Dow electron-coupled oscillator, is described in J. B. Dow, "A Recent Development in Vacuum Tube Oscillator Circuits," *Proceedings Of The Institute Of Radio Engineers* 19, no. 12 (December 1931): 2095-108.

4.6 The radio industry begins investing in quartz crystal technology

The appearance of the Pierce oscillator led all the major radio companies of the day to invest in quartz crystal technology. At least three visible developments manifested this investment: radio stations owned by these companies began transmitting with crystal-controlled transmitters, companies with internal R&D organizations began developing and patenting new quartz crystal devices, and companies without internal R&D organizations began purchasing quartz crystal patents on the open market. Each of these developments marked a permanent change to the radio landscape. From 1924 on, the number of stations broadcasting with crystal-controlled transmitters would only grow with each year, while non-crystal-controlled transmitters would gradually become antiquated. Furthermore, 1924 marks the point at which radio companies began caring about their patent positions in quartz crystal technology. A strong position meant independence and freedom from having to license the technology from others. A weak position meant the payment of licensing fees or, worse yet, being shut out of the latest radio technology.

Starting in 1924, the Radio Group companies (R.C.A., G.E., and Westinghouse) began equipping their shortwave relay transmitters with Pierce oscillators. This technique, called “crystal control,” aimed to stabilize the very high frequencies being generated, resulting in more reliable communications. The most successful of these experiments were conducted by Westinghouse. In April of 1925, the Supervisor of Radio for the Great Lakes region wrote to his superior in Washington, “At the present time the short wave transmitter at Pittsburgh is controlled, experimentally of course, by a piezo-crystal oscillator, and from observations I have made I am convinced that the

Westinghouse engineers have met with considerable success along this line."[179] Later that year at an I.R.E. meeting in New York, Westinghouse engineers described the results achieved with their 5100 kHz crystal-controlled transmitter as follows. "The results have been very gratifying. Our transmissions have been relayed in England, France, Germany, South Africa and Australia. The use of the quartz crystal as a frequency stabilizer has gone a long way in improving the quality of transmission at short wavelengths."[180]

AT&T was also experimenting with crystal-controlled transmitters, but its motive had nothing to do with shortwave communication. The telephone giant's extensive network of telephone wires interconnected its broadcast stations, and international radio, made possible by shortwave, wasn't of particular interest to the company. AT&T rather grew interested in crystal-control out of concerns over the quality of its AM medium-wave broadcast transmissions. Throughout 1923 and 1924, the company's Development and Research arm conducted field strength studies in WEAF's listening area. These studies revealed several spots of highly localized nighttime distortion and fading which could not be explained with reference to the terrain or the positioning of buildings and other man-made structures. Through experiments performed with experimental stations 2XB and 2XY, the company discovered that its standard AM broadcast transmitters produced a small amount of frequency modulation; in other words, the transmitter frequency would waver slightly over a small range during the course of a broadcast. While usually unnoticeable, after dark this frequency modulation was contributing significantly to spotty reception and, in some areas, severe distortion. As reported in the

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[179] S. W. Edwards to Commissioner of Navigation, 8 April 1925, Box 59, File 933, Records of the FCC and Predecessor Agencies, Record Group 173, U.S. National Archives, College Park, MD.

[180] D. G. Little and R. L. Davis, "KDKA," *Proceedings Of The Institute Of Radio Engineers* 14, no. 4 (August 1926): 479-506.

February 1926 issue of the *Proceedings of the I.R.E.*, the use of a crystal-controlled transmitter almost completely removed the distortion, thereby increasing the station's effective listening area.[181]

AT&T's finding proved highly influential to the radio broadcast industry. Up to 1926, broadcast engineers generally believed that medium-wave stations could maintain adequate frequency stability by using a non-crystal, master-oscillator transmitter.[182] But with the publication of AT&T's findings in February of that year, it became clear that the lack of crystal control in an AM broadcast transmitter could potentially limit a station's good-service area. From this point on, broadcast stations throughout the U.S. rapidly began converting master-oscillator transmitters to crystal control. By early 1927 nine stations in the Chicago area alone had adopted crystal control, and by 1932 the Federal Radio Commission was mandating crystal control for all licensed broadcast stations.[183] The reasons for the rapid adoption of crystal control are more fully explored in Chapter 5. The important point here is that the application of crystal control to AM medium-wave broadcasting began with AT&T's demonstration of its technical utility.

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[181] Ralph Bown, DeLoss K. Martin, and Ralph K. Potter, "Some Studies in Radio Broadcast Transmission," *Proceedings Of The Institute Of Radio Engineers* 14, no. 1 (February 1926): 57-130. See also William Peck Banning, *Commercial Broadcasting Pioneer: The WEAF Experiment (1922-1926)* (Cambridge, MA: Harvard University Press, 1946). On page 186, Banning says of WEAF, "Thus there came into being in 1924 … the first crystal-controlled broadcast transmitter, employing a technique that was to set the pace thereafter in broadcast transmission generally."

[182] At the Fourth National Radio Conference, held in November 1925, no mention was made of the need for crystal-controlled transmitters in AM medium-wave broadcasting. Source: U.S. Department of Commerce, *Proceedings of the 4th National Radio Conference*, (Washington, D.C., 1925). Section 3, Report of Committee No. 7.

[183] "List of broadcasting stations in Chicago and vicinity equipped with piezo crystal oscillators calibrated to their designed frequency," *Radio Service Bulletin*, no. 107 (27 February 1926): 12. The statement regarding crystal control in 1932 was surmised from a 1932 Application for Radio Broadcast Station Construction Permit Or Modification Thereof found in the archives of Atlanta station WGST. The application asks the applicant to "state what apparatus is included as an integral part of the transmitter that will automatically hold frequency within the required limits." Source: "Application for Radio Broadcast Station Construction Permit Or Modification Thereof ," Folder 5, Box 6, WGST Radio Station Records, 1928-1975 (MS 8), Special Collections and Archives, Library and Information Center, Georgia Institute of Technology, Atlanta, GA.

As the use of crystal control for AM medium-wave broadcasting increased, the use of crystal control for shortwave relaying declined. Ironically, shortly after AT&T engineers convinced the radio community of the value of crystal control, the company withdrew from broadcasting, selling off station WEAF and agreeing to lease its telephone lines to a newly formed company – the National Broadcasting Company (NBC). Jointly owned by the members of the Radio Group, NBC used AT&T's phone lines to realize chain broadcasting on a national scale, thus setting the technical pattern for the creation of America's two other broadcasting networks, ABC and CBS. Never again would American broadcasters use shortwave relays to form networks of independent stations.

The appearance of the Pierce oscillator not only stimulated the major radio companies to experiment with crystal-controlled transmission; it also encouraged those companies with internal R&D organizations to invent new quartz crystal devices. The earliest and most active company here was AT&T, acting initially through the Western Electric Research Laboratories and, after 1925, through the Bell Telephone Laboratories (BTL).[184] Between 1924 and 1928, AT&T engineers filed thirty-one quartz crystal patent applications that were ultimately issued, more than twice as many as the next most active industrial R&D lab, that of General Electric.[185] Among the most prolific AT&T inventors at this time were Canadian-born Warren Marrison and Joseph Warren Horton, who play a prominent role in Chapter 6 as inventors of the quartz crystal clock. In 1924 alone, Marrison filed for four piezo-oscillator related patents. But, though AT&T was both the earliest and the most prolific generator of quartz crystal patents, it was not alone.

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[184] Western Electric was the wholly owned manufacturing subsidiary of AT&T. Leonard Reich, "Industrial Research and the Pursuit of Corporate Security, Early Years of Bell Labs," *Business History Review* 54, no. 4 (1980): 504-29.

[185] During this five year period, G.E. engineers filed for fourteen quartz crystal patents that were ultimately issued.

General Electric and Westinghouse, both pioneers of industrial R&D, also focused on developing new quartz crystal technology.[186] These companies, however, gradually withdrew from quartz crystal development once R.C.A. began fortifying its in-house R&D in the late 1920s and 1930s.[187]

Radio companies also began purchasing quartz crystal patents in 1924. The five years following the appearance of the Pierce oscillator (1924-1928) saw over 150 quartz crystal patents filed with the U.S. Patent Office that were eventually issued, and a large percentage of these were sold through a thriving market for radio patents. R.C.A., Wired Radio, and Federal Telegraph, all companies that lacked a well-established internal R&D lab during this period, purchased many quartz crystal patents.[188] Of these firms, only R.C.A. survived as a radio firm. It did so largely because it developed its own in-house R&D facilities. Continual purchase of quartz crystal patents on the open market was not a strategy consistent with long-term competitiveness.

4.7 The radio amateur community learns to use quartz crystal

Quartz crystal activity after Pierce's oscillator was not restricted to the Naval Research Laboratory and the large radio companies; the radio amateur community was also eagerly experimenting with crystal control. In July of 1924, just five month's after Pierce filed for his oscillator patent, H.S. Shaw, Treasurer of the General Radio Company of Cambridge, MA, published an article in the magazine *QST* entitled, "Oscillating

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[186] Between 1924 and 1928, Westinghouse engineers filed for eight quartz crystal patents that were ultimately issued.

[187] Before it began conducting its own quartz crystal research and development, R.C.A. had access to all quartz crystal patents of G.E. and Westinghouse, both which were part owners of R.C.A.

[188] Between 1924 and 1928, RCA purchased 14 quartz crystal patents and developed 2 in-house. In the same period, Wired Radio purchased 24 patents, and Federal Telegraph purchased 15 patents.

Crystals."[189] In the course of the article, Shaw, who lived in Newton Center, MA, announced that on May 20, 1924 he had succeeded in sending a message from a crystal-controlled transmitter, tuned to 3150 kHz, over a distance of approximately 85 miles. The recipient was one S. Kruse of Hartford, CT. Shaw, an active radio amateur, had built the transmitter himself. The article gave a schematic of the transmitter, but was short on details of construction and operation; its main purpose was to establish precedence rather than to instruct the reader in how to build an actual crystal-controlled transmitter. Shaw in fact said as much himself in the article's last sentence. "From a technical point of view, this article is, perhaps, premature, but I have written it in self-defense to protect myself from the onslaughts of the Technical Editor who has been on my trail for some time for the story."[190] The Technical Editor referred to was none other than Kruse, recipient of Shaw's crystal-controlled transmission.

Shaw's *QST* article may have been a bit premature for those amateurs wanting to construct their own crystal-controlled transmitters, but they didn't have to wait long. In 1925, ads began appearing in *QST*'s classifieds section for companies offering to grind raw quartz crystals to a specified frequency.[191] Additionally, *QST* and other publications ran articles explaining in detail how to grind one's own crystals and assemble a crystal-controlled oscillator.[192] As Chapter 6 shows, the coming years would see the radio

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[189] See H. S. Shaw, "Oscillating Crystals," *QST* 7, no. 12 (July 1924).
[190] Ibid. (cited: 33.
[191] Patrick R. J. Brown, "The Influence of Amateur Radio on the Development of the Commercial Market for Quartz Piezoelectric Resonators in the United States" (*Proceedings of the 50th Annual IEEE Frequency Control Symposium*, U.S. Army Research Laboratory, Forth Monmouth, NJ, 5-7 June 1996), 58-65. According to Brown, QST ran 2 quartz crystal ads in 1925, 2 in 1926, and 3 in 1927. After this, the number of ads grew every year through 1931.
[192] For example, see John M. Clayton, "Crystal Control For Amateur Transmitters," *QST* 9, no. 11 (November 1925): 8-13.

amateur community grow to become one of the largest markets for precisely ground quartz crystals, with a handful of them even developing patented inventions.[193]

4.8 The geography of quartz crystal invention in the 1920s

The development of quartz crystal technology in the 1920s, particularly as it relates to crystal-controlled radio transmission, began in and was largely confined to the United States, with one major exception. Berlin, Germany was a hot spot during this time for radio technology in general and quartz crystal technology in particular. The Berlin-based Telefunken Company, founded in 1903, was the premier German radio company, but there were also a number of independent inventors at work in the city. Between 1924 and 1929, German inventors filed for a total of twenty-three U.S. quartz crystal patents that were eventually issued. Of these, nine were assigned to Telefunken, nine to R.C.A., and five to the inventors themselves. No other European country came close to this level of activity in quartz crystal technology.[194]

The reasons for the concentration of early quartz crystal inventive activity in the U.S. to the exclusion of most other industrialized nations are many and complex. One major reason is that American radio companies pioneered in the area of shortwave relaying and broadcasting. Non-amateur use of shortwave didn't begin in other nations until 1927.[195] Another factor was the size and strength of the radio amateur community

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[193] Patrick R. J. Brown, "The Influence of Amateur Radio on the Development of the Commercial Market for Quartz Piezoelectric Resonators in the United States" (*Proceedings of the 50th Annual IEEE Frequency Control Symposium*, U.S. Army Research Laboratory, Forth Monmouth, NJ, 5-7 June 1996), 58-65. An example of a quartz crystal patent developed by an amateur is James J. Lamb, *Piezoelectric Filter*, U.S. Patent Office, Patent No. 2,054,757, Filing Date: 24 August 1933; Issue Date: 15 September 1936.

[194] As shown in Chapter 3, English and French inventors filed for a very few U.S. quartz crystal patents during this period.

[195] Jerome S. Berg, *On the Short Wave, 1923-1945: Broadcast Listening in the Pioneer Days of Radio* (Jefferson, N. C.: McFarland & Co., 1999), 52.

in the U.S.; no other nation could boast of amateurs who were as knowledgeable or as well equipped as American amateurs. Yet another reason, the severity of the broadcast radio interference problem in the U.S., is discussed in Chapter 5.

Before concluding this chapter, let us consider the following two questions in order. First, what accounts for the nearly three-year time lag between Cady's invention of the piezo-electric oscillator and Pierce's experiments with crystal-controlled transmitters? Second, what is the significance of the fact that, during a time when radio was quickly coming to be controlled and directed by large corporate interests, the three fundamental patents of quartz crystal technology – Cady's piezo-resonator, Cady's piezo-oscillator, and the Pierce oscillator – were held by independent inventors?

4.9 Explaining the time lag between the Cady and Pierce piezoelectric oscillators

The technical leap from Cady's piezo-oscillator to Pierce's oscillator seems small, but the time gap between these two events is not difficult to explain when a few factors are considered. First, Pierce's oscillator circuit was much easier to construct and operate than Cady's, and it was capable of higher frequency operation. Second, the ability to hold one's radio transmitter precisely to one frequency was not of particular interest to most radio operators in 1921, before medium-wave broadcasting or shortwave relaying had become popular. By 1924, this ability had become a crucial interest, especially for Radio Group companies that were trying to achieve chain broadcasting by using shortwave relays. Third, in mid-1921, the potential value of the shortwave band had yet to be recognized. At long-wave and medium-wave frequencies, broadcasters, amateurs, and the military considered the master-oscillator method of maintaining a stable transmitter frequency to be adequate. Fourth and finally, Cady was, by and large, an experimental physicist, while Pierce was an electrical engineer. Factors one and three above may be seen as technological reasons for the delayed introduction of crystal-controlled transmitters; that is, these reasons lay within radio technology itself rather than with external factors. Factor two, on the other hand, lay more in the social realm, having to do with popular practice and legislation, factor four lies within the realm of personal psychology and socially-defined roles. Each factor is discussed in order.

First, Cady's piezo-electric oscillator was not easy to construct and operate. One version of Cady's oscillator circuit contained a vacuum tube, an inductive coil, and a variable condenser, meaning that the circuit had to be tuned until resonance was achieved.[196] Cady also presented a circuit that didn't require tuning, but this version required at least three vacuum tubes. In both versions, the circuit was capable of oscillating without the crystal inserted; the crystal simply acted as a stabilizer of frequency. If any circuit parameters were varied slightly, including the voltage of the power supply, the circuit could begin oscillating at a frequency other than that determined by the quartz crystal. In engineering terms, Cady's circuit was not particularly stable. Furthermore, because Cady's oscillator utilized lengthwise vibrations of a quartz crystal wafer, high frequency oscillations in the shortwave band were difficult to achieve.[197] By contrast, Pierce's oscillator circuit was much simpler, consisting of a quartz crystal, a single vacuum tube, and a load resistance, and was more robust, the frequency of the

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[196] See Walter Guyton Cady, *Method of Maintaining Electric Currents of Constant Frequency*, U. S. Patent Office, Patent No. 1472583, Filing Date: 28 May 1921; Issue Date: 30 October 1923.

[197] See George Washington Pierce, *Electrical System*, U. S. Patent Office, Patent No. 2,133,642, Filing Date: 25 February 1924; Issue Date: 18 October 1938, cited: 2, Column 1, lines 3-16.

oscillator being determined entirely by the dimensions of the quartz crystal. The frequency of oscillation was nearly constant over changes in temperature, vacuum tube plate voltage, and circuit resistance. Absolutely no tuning was required, and because Pierce's oscillator utilized thickness rather than lengthwise vibrations of the quartz crystal, it was capable of frequencies as low as 35 kHz and as high as 3,000 kHz.[198] Furthermore, it was impossible for Pierce's circuit to oscillate with the crystal removed; in Pierce's words, the circuit was "stably non-oscillatory in the absence of the crystal."[199] In summary, the Pierce oscillator was more practical, robust, and versatile than Cady's, making it far more likely to be adopted by amateurs and radio engineers.

Second, crystal control meant different things to radio operators in 1921 and in 1924. To fully understand this difference requires a brief discussion of one of quartz crystal technology's fundamental characteristics. The chief technological value of piezoelectric quartz crystal, whether used as a resonator or an oscillator, lies in four characteristics: the extremely high selectivity or sharpness of its resonant frequency[200], the remarkable stability of this resonant frequency over time, the possibility of cutting quartz crystal in such a way that the effects of temperature change upon its resonant frequency is almost completely neutralized, and the chemical stability of quartz crystal.[201] Other minerals, such as Rochelle salt, demonstrate a much more pronounced piezoelectric effect, but none can come close to matching quartz in all four areas. The chief drawback of quartz crystal, or for that matter any piezoelectric material, when used as a

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[198] Ibid., cited: 2, Column 1, lines 24-30.

[199] Ibid., cited: 4, Column 2, line 39.

[200] Engineers refer to this as the quality factor, or Q, of the crystal. Graphically, it is represented as the sharpness of a resonance curve, where the abscissa is frequency and the ordinate is the amplitude of oscillations.

[201] 9th ed., 2002, s.v. "Piezoelectricity." Piezoelectricity.

resonator or oscillator, is its lack of flexibility. Generally speaking, a piezoelectric quartz crystal will oscillate at one frequency and any harmonic of that frequency; no other frequencies are readily attainable unless the crystal is re-cut and/or re-mounted in its holder.[202] Thus, fine-tuning of a quartz crystal's resonant frequency is ruled out once it has been cut and mounted. The continuously-variable tuning available with standard LC and master-oscillator tuning circuits is not possible with a crystal-controlled oscillator circuit. This is the price paid for the crystal's stability. Of course, a transmitter may be outfitted with an array of crystals having different resonant frequencies, but this still leaves one with discrete rather than continuous frequency selection.

By and large, radio operators in 1921 wanted continuous rather than discrete frequency selection. To begin with, most stations at the time were not required by the Department of Commerce to restrict operation to one frequency. The station licenses issued by the Department of Commerce at the time allowed each station to transmit on multiple wavelengths, even though they required one particular wavelength to be designated as the "normal sending and receiving wavelength."[203] When the Department created the broadcast class of station license in December, 1921, stations operating under this license were authorized to operate on only two wavelengths: 360 meters for music and entertainment programming, and 485 meters for crop and weather reports. Months later, in August 1922, Commerce created the Class B broadcast license, which allowed a station only one transmit wavelength – 400 meters (750 kHz).[204] But even broadcast station operators restricted to one, or at most two, transmitter frequencies typically

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[202] One exception to this is the variable frequency quartz crystal units developed by Bliley Electric in the 1930s. These variable units were a commercial failure.

[203] See *Radio Communication Law of the United States. License for Radio Station*, (15 August 1919).

[204] "The wavelength of 400 meters only will be assigned for the use of stations of this class …" See "Amendments to Regulations," *Radio Service Bulletin*, no. 65 (1 September 1922): 10-11.

strayed from their assignments. Their refusal to stay on frequency was only an attempt to avoid a very real problem of the time – destructive interference among broadcast stations. This problem of interference is discussed further in Chapter 5.

The third reason for the delayed appearance of crystal-controlled transmitters has to do not with medium-wave broadcast radio, but with shortwave radio. Crystal-control was used first with shortwave transmitters because of the difficulty of holding the transmitter's frequency stable at high frequencies. The earliest experiments with shortwave transmission began only in December 1921; before this time, the frequencies above 1500 kHz were thought to be almost useless. But as the value of the shortwave band for long-distance communication became evident throughout 1922 and 1923, amateurs and radio engineers began looking for a way to achieve more stable transmitter frequencies. This was what led Pierce to his pioneering experiments in early 1924. Thus, it was clearly the development of short-wave radio, and not AM broadcast radio, that initially pushed the development of crystal-controlled transmitters. As Stanford engineering professor Fred Terman noted in his classic text *Radio Engineering*, standard master-oscillator radio transmitters (i.e. without crystal-control) were capable of maintaining their frequency constant "to better than 0.1 per cent over long periods of time if the ambient temperature is constant."[205] Thus, within the medium-wave broadcast band (500-1500 kHz), the stability of non-crystal-controlled oscillator circuits was more than sufficient for keeping stations close to their assigned frequencies. Had short-wave radio not developed when it did, it may have been a while before anyone questioned the adequacy of existing oscillator techniques for AM broadcasting.

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[205] Frederick Emmons Terman, *Radio Engineering*, 1st ed. (New York: McGraw-Hill, 1932), 253.

The final possible reason for the delay of crystal-control has to do with the differing aims of Walter Cady and George Washington Pierce as evidenced by their selection of technical problems and approach to solving them. On the surface, Cady and Pierce appear to have been remarkably similar. Cady authored or co-authored thirty-four peer-reviewed journal articles and was issued between fifty and sixty patents, while Pierce authored or co-authored thirty-eight papers and was issued fifty-three patents.[206] Both men were university professors, Cady at Connecticut's Wesleyan University and Pierce at Harvard, and both were, to some extent, independent inventors. That is, they enjoyed a large degree of freedom in choosing the technical problems on which they worked, and they both patented and profited from their inventions.[207] But neither was a professional inventor a la Thomas Edison or Elmer Sperry; neither man's primary source of income derived from their inventive activities. Both were quite content to remain university professors, where they were assured a steady income and the freedom to follow their own inventive muses. Finally, both Cady and Pierce were amateur radio enthusiasts, or "hams," involved in the amateur radio clubs at their respective institutions. But despite these similarities, these two men approached quartz crystal technology in fundamentally different ways, leading to distinctive contributions for each.

In a nutshell, the differences between Walter Cady and George Washington Pierce can be summarized as follows. Cady, in his selection of problems and approach to solving them, was what Shaul Katzir has called a "technologically oriented scientist."[208]

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[206] "Obituary - Walter G. Cady," *Wesleyan University News Bureau* 1974. *Dictionary of Scientific Biography* (1974), s.v. "Pierce, George Washington."

[207] Thomas Parke Hughes, *American Genesis: a century of invention and technological enthusiasm, 1870-1970* (New York: Viking, 1989), 20-21.

[208] Shaul Katzir, "Technological and scientific study in the discovery and application of the piezoelectric resonance" (paper presented at the The Applied-Science Problem - A Workshop, Stevens Institute of Technology, Hoboken, NJ, 6-8 May 2005).

He looked for natural phenomena that were poorly understood and thus not subject to human control, his goal being to develop just enough knowledge of a phenomenon such that it could be harnessed for human ends. But Cady usually stopped short of developing fully formed technological devices. The piezo-resonator and piezo-oscillator are cases in point. With the later, he did just enough to show that a quartz crystal could be used to control an oscillator's frequency. Later in his life, Cady described himself as follows. "I've never really considered myself an inventor. It was just a big hobby because a research laboratory happened to have some devices that looked as though they might be practical."[209] On the other hand, Pierce was an inventor and an engineer's engineer. Starting with a practical problem, such as that of keeping a shortwave transmitter's frequency stable enough for reliable communications, he would use his knowledge of science and engineering techniques to systematically develop a solution, drawing from whatever fields of knowledge were necessary. Furthermore, Pierce was concerned that the devices he developed satisfy engineering standards of performance, such as simplicity, efficiency, and robust operation under a variety of operating conditions. Pierce's contribution to quartz crystal technology was thus practical, workable devices, some of which are still used by engineers today. Cady's contribution was more fundamental and less practice-oriented. Not only did he prove that devices such as the Pierce oscillator were feasible, but he also, throughout his later career, constructed a large

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[209] R. Bruce Lindsay and W. J. King, "Walter G. Cady Oral History Interview" 28-9 August 1963, Center for History and Philosophy of Physics. Available at Box 2, Walter G. Cady Papers, Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT.

body of engineering knowledge that laid the foundation for all subsequent quartz crystal technology.[210]

4.10 Quartz crystal technology and independent inventors

Our second question is the following. What is the significance of the fact that, during a time when radio was quickly coming to be controlled and directed by large corporate interests, the three fundamental patents of quartz crystal technology – Cady's piezo-resonator, Cady's piezo-oscillator, and the Pierce oscillator – were held by independent inventors?[211] Three things are of note here. First, it was possible for Cady and Pierce to develop their inventions independently only because early quartz crystal inventions did not require great investments in capital or manpower. The only material resources needed for these inventions were access to an electronics laboratory, with its associated instrumentation, and access to a machine shop for grinding and polishing crystals. As professors at colleges with well-endowed science departments, both men had these resources. Furthermore, a professorship gave them the time and the freedom to pursue this line of research before any private firms were willing to invest in it.

Second, corporate interests did not foresee the eventual importance of either the piezo-resonator or the piezo-oscillator. This is evident in the fact that Cady tried in vain to license or sell these patents after filing the applications. Among the companies that turned down a chance to buy his piezo-oscillator was AT&T, which began to see the light in 1923. This brings us to our third and last point.

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[210] Walter Guyton Cady, *Piezoelectricity; An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals* (New York: McGraw-Hill, 1946).

[211] This question is explored in more depth in Chapter 9.

The experiences of Cady and Pierce in the 1920s show us that corporate interests of that time fought tooth and nail against the right of independent inventors to license their inventions to whomever they chose.[212] When AT&T began to see the importance of crystal control, it sued both Cady and Pierce, claiming the two men's patents interfered with one of its own pending patents. With the assistance of Boston-based patent attorney David Rines, both men initially fought the claims. Cady eventually tired of the legal proceedings, selling his patents to R.C.A. in 1925 for a $50,000 lump sum.[213] Pierce was more successful. Throughout his long career, Pierce became a millionaire through licensing fees paid by AT&T, R.C.A., the Navy, and others.[214]

As independent inventors, Cady and Pierce appeared at the tail end of what Thomas Hughes has referred to as the "era of the independent inventors," a period, beginning in the mid-1870s, of extraordinary inventive activity in the U.S.[215] Hughes sees this period ending due, in part, to the rise of industrial R&D laboratories at companies such as G.E., Dupont, and AT&T. With the rise of large technological systems and companies for managing them, the nature of invention began to change. So-called "radical invention," the kind that establishes new and upsets old technological systems, was gradually being replaced by "conservative invention," which was characterized by the incremental improvement of existing technological systems.[216] Independent inventors excelled at radical invention, as demonstrated by Bell's telephone, Edison's light bulb, and the Wright brothers' airplane. But, once a new technological system was established

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[212] Under U.S. patent law, compulsory licensing does not exist. That is, the assignee of any patent is not compelled by law to license that patent to others.
[213] This is roughly equivalent to $571 million in 2006 dollars.
[214] Frederick A. Saunders and Frederick V. Hunt, "George Washington Pierce," in *Biographical Memoirs. National Academy of Sciences* (Washington, D.C.: National Academy Press, 1959), 351-80.
[215] Thomas Parke Hughes, *American Genesis: a century of invention and technological enthusiasm, 1870-1970* (New York: Viking, 1989), 15.
[216] Ibid., 53.

and had begun growing, a new type of invention (and inventor) was called for. These conservative inventions often depended upon proprietary knowledge that was held closely within private firms, thus making it very difficult if not impossible for independent inventors, not privy to the inside knowledge of these firms, to contribute. Many independent inventors, unable to find markets for their radical inventions and unable to participate in conservative invention, resorted to joining the engineering staffs of large industrial R&D labs (e.g., General Electric, AT&T, Westinghouse, etc.).

So how did Cady and Pierce manage to make fundamental contributions to quartz crystal technology as independent inventors? There are at least two answers to this. First, piezoelectric engineering was a completely new field in the late teens and early 1920s. In fact, both men's primary quartz inventions were "radical" in the sense that they essentially helped to found this new field. Second, the radio broadcasting industry, where quartz crystal had such a large impact, was still in its infancy. The enormous technological system that would soon form around broadcast radio did not yet exist. As Hughes has shown, it is in the formation of a new technological system where independent inventors can have the most influence. As systems grow and acquire momentum, the influence of business structures formed to tend the system grows while the influence of those outside of these business structures diminishes. Cady and Pierce were fortunate enough to be professionally active during a period in American history when an unusually high number of large technological systems (and accompanying business structures) were still being formed. Examples given by Hughes include electric light and power systems, the automotive and airline industries, telephony, and radio.[217]

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[217] Ibid., 5.

Though Walter Cady's timing was fortunate in the sense of his being in a position to found a new technical field, he was not immune to the pressures sometimes exerted by large, powerful corporations. Cady had an invention that would ultimately prove to be of enormous economic value to radio firms; initially, however, it seemed to have little value. AT&T eventually realized the potential value of the piezo-oscillator but didn't want to be bothered with licensing fees. With its unmatched financial and legal resources, the initiated patent infringement proceedings against Cady, claiming that a prior and similar, but different, AT&T patent was being infringed. Cady, though confident that he would ultimately win the case, had limited financial resources for defending his patents. Unable to afford a lengthy legal battle, he was forced to sell off his patents to RCA, letting its legal department continue the battle. Here we see that companies with deep pockets could initiate patent infringement cases of doubtful merit against independent inventors. With such legal pitfalls awaiting the independent inventor, it's not surprising that many of them found it difficult to remain free from organizational allegiances.

Cady's story is similar to, though not nearly as tragic as, Edwin's Armstrong's well-known battle with RCA over frequency-modulation (FM) technology.[218] A big, powerful corporation leverages its influence to expropriate valuable technology from independent inventors. Yet, Cady's story also shows that in industries where oligopolistic competition prevailed, a fairly lucrative market still existed for the patents of independent inventors. Had RCA not been in competition with AT&T in the radio transmitter market, this would indeed have been a tale of the triumph of a powerful monopoly over an independent inventor. Instead, RCA's purchase of Cady's patents represented a partial victory for Cady. Pierce was, however, even more successful with

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[218] Lawrence Lessing, *Man of High Fidelity: Edwin Howard Armstrong* (Philadelphia: Lippincott, 1956).

his Pierce oscillator circuit. When AT&T brought an infringement suit against him, Pierce fought back and won a decisive victory. Consequently, he was able to maintain ownership of his patent and license its use out to AT&T and others. These two examples show that the independent inventor was not completely dead after World War I, but the terrain in which he/she operated had become much more treacherous.

While some may mourn the declining influence of the independent inventor in the early 20th century, this development can in no way be said to have hurt the development of quartz crystal technology. To the contrary, just the opposite seems to have been the case. As we've seen, the laboratories of firms such as General Electric and AT&T were establishing quartz crystal research groups staffed by highly-trained scientists and engineers. These men, who would likely have been independent inventors in earlier decades, now worked for and had to assign all their patentable inventions to their employers.[219] As shown in Chapters 6 through 8, this change in the inventor-society relationship would have many salutary effects on the subsequent growth of quartz crystal technology.

4.11 Summary

This chapter has briefly chronicled the development of the first popular application of quartz crystal technology – the crystal-controlled radio transmitter. The dominant circumstances providing the demand for this application were the rapid rise of shortwave radio and the growing popularity of AM medium-wave broadcasting. The technique of crystal control stabilized the transmit frequency of radio transmitters,

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[219] The word "men" is used here because there were in fact very few women inventors in the world of early radio R&D.

making feasible reliable shortwave communications and improving the sound quality of medium-wave broadcasting. Crystal-controlled transmitters first appeared following George Washington Pierce's invention of an improved piezo-oscillator in early 1924. The technique spread rapidly in shortwave radio, where its utility was obvious, but it spread in medium-wave broadcasting only after AT&T engineers demonstrated its benefits. By the late 1920s, crystal control had become common in both shortwave and medium-wave transmitters, and large numbers of radio amateurs had begun experimenting with the technique, creating a market for precisely ground quartz crystals.

An important factor in the rise of crystal-controlled transmitters in the 1920s has been underemphasized in this chapter. This is the issue of radio interference, particularly a type of interference known as heterodyne. Because of the severity of this problem in the early and mid-1920s, the U.S. Bureau of Standards began advocating in 1926 the mandatory adoption of crystal control for all licensed medium-wave broadcast stations. The subsequent actions of the Bureau of Standards, and later the Federal Radio Commission, were instrumental in accelerating the adoption of crystal-controlled transmitters in the U.S. This important story is related in Chapter 5.

CHAPTER 5: THE 1920s – QUARTZ CRYSTAL AND FREQUENCY STANDARDIZATION

When you can measure what you are speaking about, and express it in numbers, you know something about it: but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science.

Lord Kelvin, *Popular Lectures and Addresses (1891-1894)*

5.1 Introduction

Chapter 4 showed the efforts of radio amateurs and professional radio engineers of the 1920s to apply quartz crystal technology to radio transmitters. The primary advantage of the resulting technique of “crystal control” was that it greatly improved the frequency stability of both medium-wave and shortwave radio transmitters. This improved stability made shortwave communications more reliable and medium-wave communications clearer. A related and no less important development was the application of quartz crystal technology to radiofrequency measurement and standardization. This chapter recounts the efforts of independent inventors, government institutions, private firms, and a professional engineering society to develop and widely disseminate quartz-based radiofrequency standards and measurement instruments.

By the end of the 1920s, the efforts of these individuals and groups had led indirectly to the formation of a distinct quartz crystal technological community. A real commercial demand for quartz crystal technology now existed, and this demand helped support a growing commercial radio testing industry. Greatly helpful to the process of community formation were the Radio Division of the U.S. Bureau of Standards and the Institute of Radio Engineers. Through their publications and meetings, these organizations allowed piezoelectric engineers scatters across many institutions – private firms, universities, and government research labs – to communicate with one another and steadily advance the base of engineering knowledge undergirding quartz crystal technology.

5.2 The Status of Frequency Standardization in the Early 1920s

When Walter Cady filed a patent application for the piezo-electric resonator in January 1920, he suggested a number of uses for it. "The piezo-electric resonator may be used in various ways, as for example, to produce a large reactance in an alternating circuit at a certain particular frequency or frequencies, to serve as a standard of frequency or wave length in high frequency circuits, or even for such purposes as coupling one high frequency circuit to another, in order to transmit energy from one to the other circuit at a certain particular frequency."[220] The second suggested application – "to serve as a standard of frequency or wave length in high frequency circuits" – hinted at Cady's conviction that existing frequency standards were inadequate. As head of the physics department at Wesleyan University and an active radio amateur, Cady would have known that the dominant frequency standard of the day for high frequency circuits was the standard wavemeter, maintained by the U.S. Bureau of Standards. With the piezo-electric resonator, he had stumbled upon a device that he suspected might one day replace the wavemeter.[221]

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[220] Walter Guyton Cady, *Piezo Electric Resonator*, U. S. Patent Office, Patent No. 1,450,246, Filing Date: 28 January 1920; Issue Date: 3 April 1923.

[221] "Stumbled upon" is an accurate description of Cady's invention of the piezo-resonator, for he was certainly not actively looking to develop an improved frequency standard. Source: Shaul Katzir, "Technological and scientific study in the discovery and application of the piezoelectric resonance" (paper presented at the The Applied-Science Problem - A Workshop, Stevens Institute of Technology, Hoboken,

The wavemeter, which could measure frequencies as low as 3.5 kHz and up to nearly 5000 kHz, had been the principal instrument of frequency measurement and standardization since the U.S. Bureau of Standards (BOS) had begun its frequency studies in 1911. Limited in 1920 to an accuracy of approximately 1%, the wavemeter was a fairly simple device, comprising a variable condenser (i.e. capacitor) connected in series with a fixed coil (i.e. inductor). An ammeter or galvanometer was used to indicate the current flowing through the circuit.[222] The series condenser and coil combination formed a "tank" circuit that would resonate at a particular frequency; that is, the magnitude of electrical current flowing through the circuit would reach a maximum at a certain frequency. Adjusting the value of the variable condenser would change the value of this frequency. Thus, with a source signal of unknown frequency applied to one of the wavemeter's terminals and with the wavemeter's second terminal connected to electrical ground, the variable condenser could be adjusted until the ammeter or galvanometer indicated maximum current flow. The setting of the variable condenser, if properly calibrated, would then indicate the unknown signal's frequency.

As with any measurement instrument, the accuracy of a wavemeter in 1920 was limited by the accuracy of the primary standard with which it was calibrated. The Bureau of Standard's primary frequency standard at this time was the "standard wavemeter," shown in Figure 15. The capacitance (*C*) of the condenser and the inductance (*L*) of the coil shown in Figure 15 were known with a high degree of accuracy. These two values

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NJ, 6-8 May 2005), cited: 5. "[Cady's] finding that the piezo-resonator can be used as a standard of frequency did not originate in a search for such a standard." Also see §2.10 of this dissertation.

[222] See R. T. Cox, "Standard Radio Wavemeter - Bureau of Standards Type R 70B," *Journal Of The Optical Society Of America And Review Of Scientific Instruments* 6, no. 2 (March 1922): 162-68.

were then used to calculate the wavemeter's resonant frequency (*f*) with the following formula.

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad \text{(Equation 1)}$$

Thus, if one desired a standard frequency of 100 kHz, one would adjust the value of the variable condenser such that Equation 1 yielded $f = 100$ kHz. If one wanted to go a step further and actually generate a pure 100 kHz radio frequency, one would need a continuously variable master-oscillator circuit. Connecting this circuit to the standard wavemeter, one would then adjust the master-oscillator's tuning dial until the standard wavemeter's ammeter indicated maximum current flow.

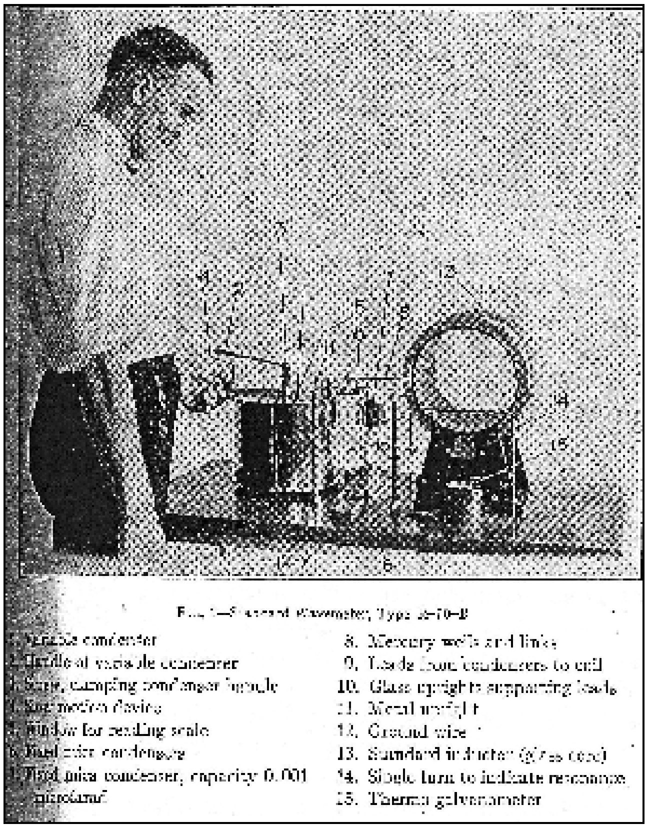

Figure 15: The Bureau of Standards' Standard Wavemeter, Circa 1922
(Source: R.T. Cox, "Standard Radio Wavemeter Bureau of Standards Type R 70B," *Journal of the Optical Society of America*, Vol. 6, No. 2, March 1922. Public Domain.)

With the accuracy of the BOS's standard wavemeter limited to approximately +/- 1%, radio wave frequencies in what are now known as the low-frequency (30 kHz – 300 kHz) and medium-frequency (300 kHz – 3000 kHz) bands could be only loosely measured. Based on his early experiments, Cady suspected that the piezo-resonator, when used as a frequency standard, was capable of much greater accuracy than this. Yet, as described in Chapter 2, he was initially unable to convince others of the need for a more accurate frequency standard. In 1920, the low-frequency radio band was not densely populated with stations, and the occupancy of the medium-frequency band was even sparser. As for the high-frequency or short-wave band (3000 – 30,000 kHz), its value for long-distance communications had yet to be shown. The need to measure frequencies in any of these bands with extreme accuracy simply did not exist.

5.3 The Broadcasting Boom forces the Bureau of Standards to update its primary frequency standard

In 1922, America's so-called "radio boom" changed forever the occupancy of the medium-frequency (MF) band. At the end of 1921, there were fewer than thirty MF stations broadcasting in the U. S.[223] By October of 1922, there were 546 stations on the air.[224] Predictably, radio interference in the MF band quickly became a severe problem. Exacerbating this problem was the fact that in 1922 only two frequencies were available to American radio broadcasters – 618.6 kHz (485 meters) and 833.3 kHz (360 meters). The former was reserved by the Department of Agriculture for crop and weather reports, while the latter could be used for entertainment and news programming.[225] In cities where multiple stations were licensed to broadcast on 360 meters, the stations had to work out time-sharing arrangements to prevent the frequency from becoming a garbled mess. Even with such arrangements, interference was often intolerable, leading broadcast executives and listeners alike to call for government regulatory action.

Anticipating the interference problem, Secretary of Commerce Herbert Hoover convened the First National Radio Conference in Washington, D.C. in February of 1922. In his opening address, Hoover observed, "The comparative cheapness … of receiving sets … bids fair to make them almost universal in the American home." "The time has

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[223] Hugh Slotten lists twenty-eight stations in Hugh Slotten, *Radio and Television Regulation: Broadcast Technology in the United States, 1920-1960* (Baltimore, MD: Johns Hopkins University Press, 2000).
[224] See "Broadcasting Increases 500-Fold in One Year," *Radio News* (December 1922): 1156.
[225] In mid-1922, the Dept. of Commerce reserved a third frequency – 750 kHz (400 meters) – for radio broadcasters.

arrived … when there must be measures to stop the interferences … between even the limited number of sending stations … The problem is one of most intensely technical character … Even if we use all the ingenuity possible I do not believe there are enough permutations to allow unlimited numbers of sending stations."[226] Thus, Hoover characterized radio interference as largely a technical problem, implying that ingenious radio engineers could develop techniques to remedy the situation. But he also felt that some type of regulation, imposed either by the broadcasting industry itself or by the government, should supplement engineering technique. Radio bandwidth, limited at the time to the low-frequency and medium-frequency bands, was not an infinite resource and could therefore not support an unlimited number of broadcasting stations.

Qualitatively, radio interference circa 1922 came in many forms. Perhaps the most common form, crosstalk, resulted from two or more stations broadcasting on the same frequency within each other's geographic listening areas. The straightforward solution to crosstalk was to keep same-frequency stations separated by enough distance such that they lay outside each other's listening areas. A much more insidious form of radio interference was known as heterodyne interference. Manifesting itself in superheterodyne receivers in the form of an audible whistling or howling, heterodyne interference resulted partly from the transmitter frequencies of two of more stations differing by only 0.2 – 3 kHz. This frequency difference would produce an audible tone loud enough at times to drown out regular station programming. The insidious aspect of heterodyne interference was that its ill effects were detectable over a much wider geographic region than the standard listening areas of each station. Thus, two stations

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[226] Herbert Hoover, *The Memoirs of Herbert Hoover: The Cabinet and the Presidency, 1920-1933*, 3 vols., vol. 2 (New York: Macmillan, 1952), 140-41.

separated by enough distance such that crosstalk was not present could still produce heterodyne interference over a large portion of the station's listening areas. In 1922, the accuracy limits of the BOS's standard wavemeter and the difficulty of achieving a high level of frequency stability with non-crystal controlled transmitters (see Chapter 4) combined to make heterodyne interference a widespread problem.[227]

In response to the interference problem, attendees at the 1922 Radio Conference recommended that the BOS develop technical methods of interference reduction, including "the study and standardization of wavemeters."[228] The "wavemeters" referred to here were those used by radio transmitter operators to set their carrier frequencies.[229] This worked roughly as follows. A station operator would first adjust his wavemeter's variable condenser such that the instrument was tuned to resonate at the desired frequency. The operator would then electrically connect his radio transmitter in series with the wavemeter. Finally, he would adjust the transmitter tuning dial until the wavemeter was in maximum resonance, indicating that the transmitter was set to the desired frequency. When used in this manner, the wavemeter was serving as a secondary frequency standard, just as a yardstick serves as a secondary standard of length every time it is used to measure an unknown length.[230] In calling for the standardization of

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[227] C. B. Jolliffe, "When Broadcast Stations Interfere," *Radio Broadcast* 7, no. 5 (September 1925): 586-90.

[228] U. S. Department of Commerce, "Report of the Department of Commerce Conference on Radio Telephony," *Radio Service Bulletin* (1 May 1922): 23-30. See Section V – Technical methods for the reduction of interference. Recommendation C9.

[229] A carrier frequency is the frequency that "carries" the information signal. This is equal to a broadcast station's transmit frequency.

[230] A secondary frequency standard is one that "does not have inherent accuracy, and therefore must be calibrated against a primary frequency standard." A primary frequency standard is "a frequency source that meets national standards for accuracy and operates without the need for calibration against an external standard." Source: National Communications System Technology and Standards Division. "Telecommunications: Glossary of Telecommunication Terms (Federal Standard 1037C)." General Services Administration Information Technology Service, 1996), Available at http://www.its.bldrdoc.gov/fs-1037/, Accessed 13 June 2008. See entries for "secondary frequency standard" and "primary frequency standard."

wavemeters, the radio conference attendees were essentially calling for better and more frequent calibration of wavemeters. Indirectly, this was also a call to improve the accuracy of the BOS's primary frequency standard, since all wavemeters used as secondary frequency standards had to be calibrated with reference to a primary standard.

One of the most prominent American manufacturers of high-quality wavemeters in the early 1920s was the General Radio Company (GR), based in technologically-progressive Cambridge, MA. GR had been founded with an initial capitalization of only $9000 by Melville Eastham in 1915 as the first U.S. firm expressly devoted to supplying test equipment for the nascent wireless telephony (i.e., radio) industry. Prior to this time, the most well-known manufacturer of wavemeters and other frequency measurement equipment was Germany's Telefunken. With the escalating tensions of World War I, the British had blockaded all German ships in 1915, creating the need for the U.S. to domestically produce many manufactures that it had formerly imported from Germany. Eastham and GR quickly stepped in to fill the niche for frequency measurement equipment, becoming the U.S. marketplace leader in this field for decades to come.[231]

Among GR's first products was the Model 105B Universal Wavemeter, shown in Figure 16 and capable of measuring radio frequencies between 33 and 2,000 kHz. Selling for $105, the 105B was by far the most expensive device in the firm's 1916 product catalog. With U.S. entry into WWI, GR began producing a much less expensive ($34 in 1918) portable wavemeter; the U.S. military purchased many of these for field use during the war. By 1923, the firm was offering four models of wavemeter: the "Type 224 Precision" for close to $200, the "Universal" for $133, the "Type 174 Direct-

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[231] Arthur E. Theissen, *A History of the General Radio Company, 1915-1965* (West Concord, MA: General Radio Company, 1965).

Reading" for \$60, and the "Type 145B Direct-Reading" for \$38. While the latter three instruments were capable of frequency accuracy around +/-1%, the Precision was capable of +/-0.25% accuracy. On the strength of these and other precision radio instruments, GR became the undisputed U.S. leader in commercial frequency measurement equipment, a position it would hold for most of the 20th century.[232]

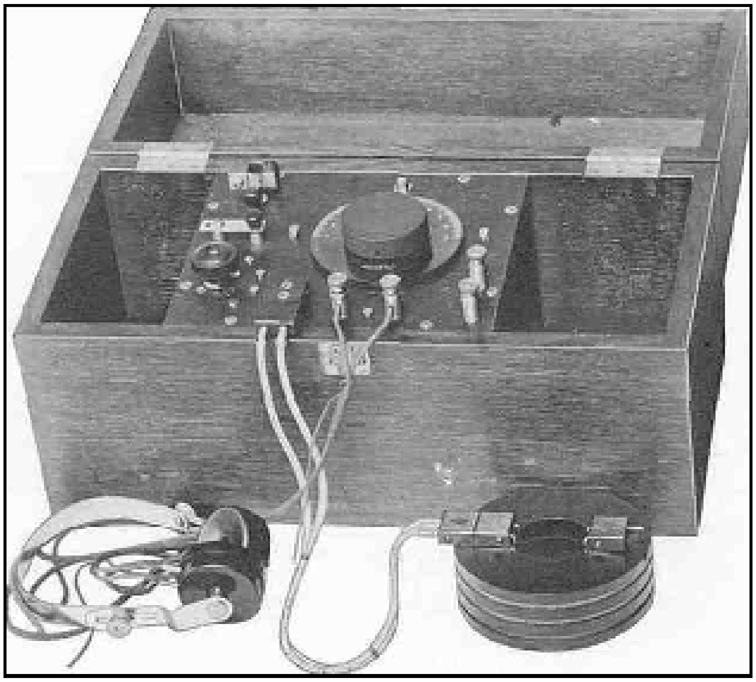

Figure 16: The General Radio Company's Universal Wavemeter (Model 105 B), which sold in 1916 for \$105
(Reprinted, by permission of the General Radio Historical Society, from General Radio Company, *Radio Laboratory Apparatus: Catalogue A*, 1916. http://www.teradyne.com/corp/grhs/)

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[232] See General Radio Company. "Catalog A." (Cambridge, MA, 1916), Available at http://www.teradyne.com/corp/grhs/, Accessed 14 August 2006. ———. "Catalog B." (Cambridge, MA, 1918), Available at http://www.teradyne.com/corp/grhs/, Accessed 14 August 2006. ———. "Catalog C." (Cambridge, MA, 1919), Available at http://www.teradyne.com/corp/grhs/, Accessed 14 August 2006. ———. "Catalog E." (Cambridge, MA, 1928), Available at http://www.teradyne.com/corp/grhs/, Accessed 14 August 2006. Available from the General Radio Historical Society.

The call issued by the 1922 Radio Conference for “the study and standardization of wavemeters” reflected the hope that more accurate wavemeters in the hands of radio operators would materially reduce the amount of heterodyne interference on the airwaves, but it also reflected the direction in which radio spectrum management was moving. Though broadcast stations at the time were given only two frequencies (618.6 kHz and 833.3 kHz), regulators wanted to move to a system whereby scores of channels (i.e., fixed frequency bands) would be available for broadcasting, with any given station licensed to broadcast on just one of these channels. To maximize usage of the available radio spectrum, the spectral distance (D) between two broadcast channels adjacent in frequency would need to be as small as possible without producing crosstalk interference.

In general, three technical factors govern the minimum possible spectral distance (*D*) between adjacent AM broadcast channels. First, the spectral width, or bandwidth (*BW*), required for an AM broadcast signal sets the absolute minimum possible value for *D*. Thus, in an ideal radio transmission system, *D* is equal to *BW*. In all non-ideal, real-world systems, however, two other factors inflate the value of *D*. First is the accuracy with which radio frequencies may be measured, and second is the stability with which AM signal carrier frequencies may be maintained. Thus,

$$D = BW + FrequencyAccuracy + FrequencyStability\ . \qquad \text{(Equation 2)}$$

The 1922 Radio Conference identified frequency accuracy as the primary technical bottleneck preventing more efficient use of the radio spectrum. The task before the Bureau of Standards was thus twofold: to improve the ± 1 % accuracy of its standard wavemeter, and to improve the procedures for calibration of wavemeters used as secondary frequency standards.

5.4 John Dellinger and the Bureau of Standards

The Chief of the Radio Section of the Bureau of Standards in the early 1920s was John Howard Dellinger. A native of Cleveland, Ohio and a Ph.D. physicist, Dellinger had received his training from Western Reserve University, George Washington University, and Princeton. The Bureau of Standards was his first and only employer throughout his long and fruitful career. Beginning work at the Bureau in 1907 at the age of 21, Dellinger showed early signs of the initiative and foresight that would come to mark his career. In 1911, because of his recent training in electromagnetic theory, he was assigned a novel project. Someone had submitted a wavemeter to the Bureau requesting that it be calibrated and “standardized.” Dellinger impressed his superiors by the skill with which he handled the project. Soon he began working on high-frequency ammeters, which became the topic for a doctoral dissertation that he completed at Princeton in 1913.[233] In 1921, at the age of 35, Dellinger was promoted to Chief of the Radio Section, a position which he held for the next 25 years. Throughout his career at the Bureau, he wrote numerous important articles for both the technical community and the general public, and was involved in the processing of nearly 50 patents.[234]

In response to the 1922 Radio Conference’s call for study and standardization of wavemeters, Dellinger initiated two new BOS programs. The first aimed to improve the ± 1% accuracy of the Bureau’s primary frequency standard. The second program

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[233] Dellinger resigned from the Bureau in 1912 to work on his Ph.D.; he was re-hired by the Bureau in 1913 after its completion.

[234] For the most extensive biography of Dellinger, see Appendix D of Wilbert F. Snyder and Charles L. Bragaw, *Achievement In Radio: Seventy Years of Radio Science, Technology, Standards, and Measurement at the National Bureau of Standards* (Boulder, CO: National Bureau of Standards, 1986). See also "Obituary: John Howard Dellinger," *Proceedings Of The Institute Of Radio Engineers* 51, no. 83 (March 1963): 20A. The most accessible biography of Dellinger is James E. Brittain, "Scanning Our Past: John H. Dellinger," *Proceedings of the IEEE* 95, no. 9 (September 2007): 1884-87.

involved a novel scheme to disseminate the primary frequency standard over the airwaves via “standard frequency transmissions.” This would allow wavemeter owners to calibrate their instruments without having to send them to Washington for direct calibration with the standard wavemeter.

Dellinger’s first program aimed to improve the accuracy of the primary frequency standard from ± 1% to ± 0.1%. He was keenly aware of the importance of this task, stating, “The whole success of American broadcasting is tied up with the placing of broadcasting stations on the correct frequencies to an accuracy approaching 99.9 per cent.”[235] To accomplish this goal, Dellinger decided to place the Bureau’s primary frequency standard on a four instrument basis. Prior to this time, the standard had been based on a single instrument – the standard wavemeter. The three new and independent bases were the tuning fork, a device called the multi-vibrator, and a pair of parallel wires that could be used to directly measure radio waves of very short wavelength. With four independent bases, the Bureau could now use any one of them as a self-check on the other three. As Dellinger put it in 1923, “When the present series of measurements is completed, the Bureau of Standards frequency basis will be certainly accurate well within 0.1 per cent.”[236] Furthermore, the accuracy of ± 0.1 % would apply to frequencies as low as 3.5 kHz or as high as 33,000 kHz, extending the range of the old Bureau standard (3.5 – 5000 kHz) more than six times.

Dellinger’s decision to exclude the piezoelectric resonator as one of the new bases for the Bureau’s primary frequency standard reflected the still immature status of Cady’s invention in 1922. Dellinger likely suspected that the invention would undergo many

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[235] John Howard Dellinger, "Reducing the Guesswork in Tuning," *Radio Broadcast* 3, no. 4 (July 1923): 241-45.

[236] Ibid. (

improvements before stabilizing. He didn’t want to make the resonator the new basis for the frequency standard, only to have to change it a year later. Furthermore, though Cady had filed for his resonator patent in early 1920, the patent had yet to issue.[237] The invention might still encounter interference with a prior patent. Lastly, Cady knew that the resonator would have to be subjected to more extensive and rigorous testing before Dellinger would consider adding it as a frequency standard basis. To this end, Cady began making plans to travel to some of the great physical laboratories of Europe with his resonator in the summer of 1923. In the meantime, he continued giving talks and publishing papers on the resonator, including a *Proceedings of the I.R.E.* paper in which he presented five methods by which the device could serve as a frequency standard.[238] One of these methods was noteworthy in that it mentioned the possibility of using the resonator to calibrate a wavemeter. Cady did not elaborate, however, stating, “… the method is difficult and not generally to be recommended.”[239]

Dellinger’s second program initiated in response to the 1922 Radio Conference aimed to use the Bureau’s radio station WWV to disseminate the primary frequency standard over a large portion of the nation. Those able to receive the so-called “standard frequency transmissions” could use them to precisely and frequently calibrate their wavemeters. Dellinger realized the uniqueness of a standard of measurement that could be disseminated wirelessly and without physically transporting anything. As he was to put it some eight years later before a hearing of the Federal Radio Commission, “Frequency is a unique physical quantity, in that the standard can, by transmission of

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[237] Cady’s piezoelectric resonator patent issued on April 3, 1923. U.S. Patent #1,450,246.

[238] Walter Guyton Cady, "The piezo-electric resonator," *Proceedings Of The Institute Of Radio Engineers* 10, no. 2 (April 1922): 83-114, cited: 109-11.

[239] Ibid. (cited: 111.

radio signals, be made available everywhere at once. It is the only super-portable standard in existence."[240]

On January 29 and 30, 1923, Dellinger oversaw the first tests of standard frequency transmissions from BOS station WWV in Washington, D. C. The stated purpose of these tests was "to show the degree of agreement between wave frequency standards used in this country, and the need for more frequent standardization of such instruments." Several different frequencies between 200 and 545 kHz were transmitted from WWV, while eighteen radio laboratories throughout the East, South, and Midwest measured the transmitted frequencies. Showing early cooperation between academia, industry and government, the measurements were made at both industrial R&D labs (e.g., AT&T, General Radio Co., Westinghouse) and university labs (e.g., Harvard, Georgia Tech, University of Illinois). Results showed that 1/3 of the measurements fell within +/- 0.5 % of the actual transmitted frequency, but some measurements differed from the actual transmitted frequency by as much as 4.2%. Dellinger was not discouraged by the mixed results. In fact, he found them good enough to state, "The results of the measurements as reported were quire satisfactory when all points are considered." This comment probably referred more to the performance of the WWV transmitter and the strength of its signal at the various measurement locations rather than the performance of the various measuring instruments used by participants. As for the latter, the test results

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[240] Testimony of Dr. J.H. Dellinger given at a hearing before the FRC on "Proposed Modification of General Order No. 7," 20 April 1931, Box 4, Records of the National Institute of Standards and Technology, General Records of J. Howard Dellinger, Record Group 167, U.S. National Archives, College Park, MD.

clearly showed that much room remained for improvement in the accuracy of wavemeters used as secondary frequency standards.[241]

Dellinger was satisfied enough with the tests of Jan. 29-30 that he decided to inaugurate a periodic standard frequency transmission service on March 6, 1923. Transmitting at a power of 1 kW from WWV and guaranteeing its frequency accuracy within +/- 0.3 %, the Bureau hoped with this service to "make it possible for any person having suitable apparatus to use these signals for calibrating his own wave meter and transmitting and receiving equipment." Furthermore, the Bureau hoped "that the system of standard wave transmission will have as a result the more accurate measurement and adjustment of radio apparatus of all kinds."[242]

The initiation of WWV standard frequency transmissions provided easy and efficient dissemination of standard frequencies to radio stations throughout the eastern United States, meaning that station operators in receiving range of WWV's signal no longer had to ship their wavemeters off to Washington or elsewhere for calibration. Since a range of frequencies (from 200 to 550 kHz) were included in the transmission, the operator simply chose a calibration frequency and adjusted his wavemeter accordingly. Dellinger's hopes were high that this single act – the establishment of standard frequency transmissions – would go a long way toward addressing the 1922 Radio Conference's concerns over wavemeter standardization.

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[241] See "Results of Measurements in Preliminary Tests of Standards Wave Transmission," 16 April 1923, Folder "Frequency – Absolute Measurement (1920-1925)," Box 21, Ibid.

[242] See "Bureau of Standards to Transmit Standard Radio Wave Signals," *Radio Service Bulletin*, no. 70 (1 February 1923): 20-21.

5.5 The 2nd National Radio Conference pushes for stricter frequency adherence

On March 20, 1923, Herbert Hoover convened the Second National Radio Conference in Washington. At the top of the agenda was radio interference, which had worsened considerably over the preceding year. The WWV standard frequency transmissions had been in place for less than a month, not long enough to make a noticeable difference in interference. Still, there were other interference-related actions the Conference could take to improve the situation. With more than five-hundred licensed stations in operation throughout the country, most broadcasting on 360 meters (833.3 kHz), interference had become, in Hoover's words, "simply intolerable." The Conference produced three interference-related recommendations. The first was to open for broadcasting the entire 222-545 meter (550-1350 kHz) band, which had previously been reserved for Navy fleet tactical communications.[243] The second, in accordance with BOS studies, was to set the frequency separation between adjacent broadcast stations, *D*, to 10 kHz. This meant that there would now be eighty-six distinct channels by which broadcast stations could be organized. Lastly, the Conference recommended that licensed broadcasting stations be equipped with a frequency-indicating instrument "for the purpose of maintaining the operating wave frequency within 2 kilocycles of the assigned wave frequency."[244]

The 1923 Conference's recommendations did not carry the force of law, but they did lead to Congress passing legislation implementing the first two aforementioned recommendations. The third, concerning frequency-indicating instrumentation, was

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[243] Hugh Aitken, "Allocating the Spectrum: The Origins of Radio Regulation," *Technology and Culture* 35, no. 4 (October 1994): 686-716, cited: footnote 27.

[244] Resolution No. 2"Recommendations of the National Radio Committee," *Radio Service Bulletin*, no. 72 (2 April 1923): 9-13.

actually impossible to meet at the time of the Conference. At the upper end of the AM broadcast band (1350 kHz), the +/-2 kHz accuracy recommended by the Conference was equivalent to +/-0.15%. Given that the BOS guaranteed the accuracy of its new standard frequency transmissions to only +/-0.3%, stations placed in the upper end of the AM broadcasting band would have found it impossible to meet the Conference's recommendation.

The Conference's attendees didn't make a mistake in issuing the +/-2 kHz recommendation. They were simply setting a technical goal for the radio industry. This is very similar to what in the late 20th century came to be called "technology-forcing regulation." This type of regulation "specifies a standard that cannot be met with existing technology," the hope being that the regulation will stimulate technological innovation.[245] The Conference's attendees wanted the BOS and the radio industry to develop instruments and techniques that would enable all broadcast stations to stay within +/-2 kHz of their assigned frequencies.

Meanwhile, Walter Cady was certain that in his piezoelectric resonator lay at least a partial answer to the radio interference problem. In the summer of 1923, he traveled to Europe with several of his quartz resonators. At laboratories in Italy, France, and England, Cady compared the +/-0.01% accuracy of his resonators with those of various European frequency standards.[246] He was encouraged to find that the European standards agreed to within 0.1% of each other, but his primary objective was to gather solid

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[245] David Gerard and Lester B. Lave, "Implementing technology-forcing policies: The 1970 Clean Air Act Amendments and the introduction of advance automotive emissions controls in the United States," *Technological Forecasting and Social Change* 72, no. 7 (September 2005): 761-78.

[246] See Walter Guyton Cady, "An international comparison of radio wavelength standards by means of piezo-electric resonators," *Proceedings Of The Institute Of Radio Engineers* 12, no. 6 (December 1924): 805-16.

evidence with which he could demonstrate the superiority of the quartz resonator as a frequency standard. Writing of his findings in the *Proceedings of the I.R.E.*, Cady stated, "In constancy and sharpness of tuning, as well as in simplicity, the piezo-electric standards are already superior to any type of wave-meter in use at present, except for the multi-vibrator."[247, 248]

While Cady was touring the laboratories of Europe, John Dellinger was feeling pressure from multiple sources to increase the accuracy of the Bureau's primary frequency standard. The 1923 Radio Conference had made it clear that the broadcasting industry needed the BOS to improve the +/-0.3 % accuracy of its WWV standard frequency transmissions. But the broadcasting industry was not alone in needing a more accurate frequency standard. Dellinger learned later that year that the Navy wanted an even higher standard of frequency accuracy, +/-0.01 %, than did broadcasters. The Navy's reason for wanting this was related to the 1923 Radio Conference's decision to reserve the 500-1350 kHz band for commercial broadcasting. This decision effectively pushed the Navy into experimenting with the higher shortwave band, where the BOS's current +/-0.1 % frequency standard simply did not permit efficient use of the spectrum.

Dellinger was confident that the Bureau could satisfy the needs of both broadcasting and the Navy. Writing to Dr. J. M. Miller of the newly opened Naval Research Laboratory (NRL) in June of 1923, Dellinger stated, "The establishment of a frequency basis which shall be accurate to 0.3 kilocycle, or say 1/100 per cent over the radio range, is a definite part of the program of the radio laboratory of this Bureau."

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[247] Ibid.

[248] The "multi-vibrator" was an electronic amplifier used to generate harmonics from the fundamental frequency of a tuning fork. In 1923, it served as the primary frequency standard of England, held at the National Physical Laboratory. At the time, the Bureau of Standards also used the multi-vibrator method as one of its four independent bases of frequency measurement.

Dellinger went on, however, to request the financial support of the NRL.[249] The Bureau, he argued, needed this support to research the feasibility of including Cady's quartz resonator in its frequency standardization activities.

5.6 The Piezo-Electric Oscillator as a Portable Secondary Frequency Standard

Around this time, a third individual in addition to Walter Cady and John Dellinger joined the effort to improve frequency standardization through the use of piezoelectric quartz crystal. George Washington Pierce, a professor of electrical engineering at Harvard, had come across Cady's 1922 *Proceedings of the I.R.E.* paper, "The Piezoelectric Resonator," while attempting to calibrate the university's wavemeters. Finding Cady's resonator not ideally suited for performing calibrations, Pierce developed a simple calibration method that instead used Cady's piezoelectric oscillator.[250] In October 1923, the method was disseminated in a widely read *Proceedings of the A.A.A.S.* article descriptively entitled, "Peizoelectric Crystal Resonators and Crystal Oscillators Applied to the Precision Calibration of Wavemeters."[251]

The appearance of Pierce's article quickly galvanized the frequency standardization community. Within nine months of its publication, two independent development efforts, one at the BOS and the other at the General Radio Company (GR), yielded the first practical quartz crystal-based secondary frequency standards. The goal in both cases was not to make the wavemeter obsolete, but to supplement it in a way that

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[249] Dellinger to Miller, 21 June 1923, Folder "Frequency – Absolute Measurement," Box 21, Records of the National Institute of Standards and Technology, General Records of J. Howard Dellinger, Record Group 167, U.S. National Archives, College Park, MD.

[250] While doing so, Pierce also altered Cady's oscillator circuit, resulting in a much simpler and more robust crystal oscillator. See Chapter 4 for more on the Pierce oscillator.

[251] George Washington Pierce, "Piezoelectric Crystal Resonators and Crystal Oscillators Applied to the Precision Calibration of Wavemeters," *Proceedings of the Amercian Academy of Arts and Sciences* 59, no. 4 (October 1923).

would better enable broadcast transmitter operators to closely adhere to their assigned frequencies. In mid-1924, the Bureau announced that it had completed development of the Type C Frequency Indicator. When used by a broadcast station, the passive Indicator, equipped with a quartz crystal ground to resonate precisely at the station's assigned frequency, would indicate whether or not the station's transmitter was operating within 2 kHz of this frequency. Essentially, the Indicator was Cady's piezo-electric resonator adapted for broadcast station use. Dellinger summarized the new instrument's advantages as follows. "This frequency indicator eliminates all the possibilities of error due to the change of coil or condenser constants, requires no shielding, is much less expensive, and is much more accurate."[252] Intended primarily for the use of BOS personnel and regional Radio Supervisors, the Type C was not produced in quantity or sold on the open market, but the Bureau did make available detailed specifications and schematics so that station operators could build their own.[253]

Also in mid-1924, GR released its Type 275 Piezo-Electric Oscillator, an active quartz-based instrument that the company had developed with the assistance of Drs. Cady and Pierce.[254] Intended to be used as a portable secondary frequency standard for precisely calibrating wavemeters, the Type 275 generated a single radiofrequency tone at a frequency specified by the customer. As its name indicated, the instrument was in

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[252] See Dellinger handwritten notes, 12 July 1924, Box 3, Records of the National Institute of Standards and Technology, General Records of J. Howard Dellinger, Record Group 167, U.S. National Archives, College Park, MD.

[253] "Improved Apparatus for Frequency Measurement," *Radio Service Bulletin*, no. 103 (2 November 1925).

[254] See Bulletin 715 of the General Radio Company, November 1925, Box 3, Records of the National Institute of Standards and Technology, General Records of J. Howard Dellinger, Record Group 167, U.S. National Archives, College Park, MD. (Note: Eastham had met Cady and Pierce at an I.R.E. meeting at Harvard's Cruft Laboratory in January, 1917.) Source: Walter G. Cady, Personal Diary entry for 18 January 1917, Folder 24, Box 3, Walter G. Cady Papers (Subgroup 3), Cady Family Papers (MSS 326), Rhode Island Historical Society Library, Providence, RI.

essence one of the circuits included in Pierce's 1924 patent for the piezo-electric oscillator. The instrument, shown in Figure 17, was similar in size, weight (9.75 lbs.), and price ($135) to GR's Universal Wavemeter.[255] Capable of holding to its specified frequency with an accuracy of +/- 0.05 %, the Type 275 was clearly an improvement over WWV transmissions, accurate only to +/- 0.3%.[256] GR felt that the instrument would contribute significantly to ending the interference problem, stating, "The development of a small, reliable frequency standard, suggests the possibility of uniform frequency standards, provided by a central laboratory, ending the present interference between stations due to a difference in standards."[257]

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[255] Records of the National Institute of Standards and Technology, General Records of J. Howard Dellinger, Record Group 167, U.S. National Archives, College Park, MD.

[256] See "Test of General Radio Company's Piezo-Electric Oscillator," *Bureau of Standards Report*, July 1924, Box 3, Ibid.

[257] Bulletin 715.

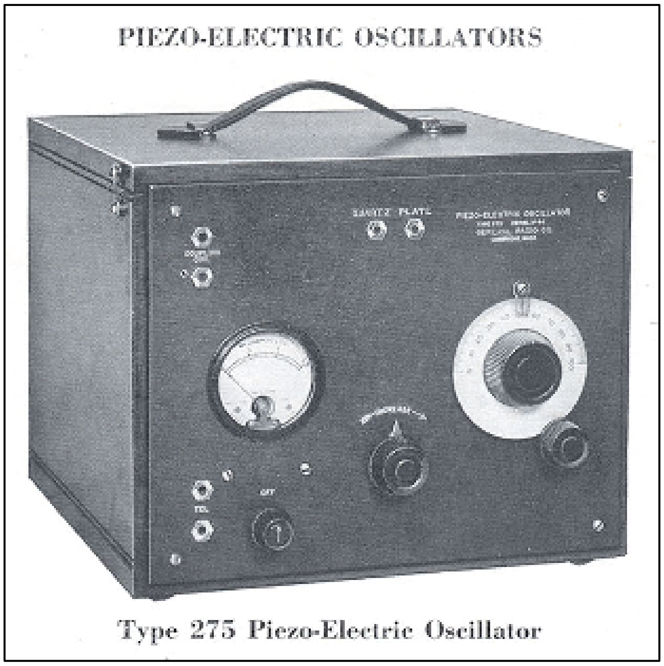

Figure 17: The General Radio Company's Type 275 Piezo-Electric Oscillator, which sold in 1928 for $60
(Reprinted, by permission of the General Radio Historical Society, from General Radio Company, *Catalog E*, September 1928. http://www.teradyne.com/corp/grhs/)

The appearance of GR's Piezo-Electric Oscillator did more than any journal article or technical conference presentation could do to advance the case for quartz crystal as frequency standard. In October of 1924, the Department of Commerce's *Radio Service Bulletin*, read by all broadcast station operators, printed its first article dedicated to quartz crystal. Entitled "Piezoelectric Crystals as Radio Standards," the article stated that quartz crystal "appears to be a standard of greater constancy than the best wavemeters."[258] In the same issue and for the first time, the Bulletin's monthly list of "standard frequency stations," which included broadcast stations demonstrating exceptional frequency stability, showed that all listed stations were maintaining a

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[258] "Peizoelectric Crystals As Radio Standards," *Radio Service Bulletin*, no. 90 (1 October 1924): 8-9.

frequency constancy of +/- 2 kHz, indicating that many if not most of these stations were already using either the GR Type 275 or the BOS's Type C frequency indicator.[259]

GR's Piezo-Electric Oscillator also made a splash among radio regulators. In late 1924, the BOS's August Hund traveled to San Francisco with a Type 275. A Colonel Dillon, the Supervisor of Radio for the West Coast, was intrigued by the oscillator and requested to keep it for a trial period; Hund complied. In January 1925, Dillon wrote enthusiastically to Washington, "The quartz crystal oscillator was brought here by Dr. August Hund of the BOS, and is really the most convenient and accurate means of checking the wave lengths or frequencies of instruments that we have yet found. Therefore, if it can consistently be arranged, we are very anxious to keep the same."[260] In response, the Bureau, wishing to have enough piezo-oscillators for all twelve Supervisors of Radio, began taking bids from several manufacturers for delivery of eighteen oscillators - six for BOS personnel and the remaining twelve for the Supervisors.

General Radio was the first and largest but not the only manufacturer of piezo-electric oscillators. Walter Cady, who owned the fundamental patents to the device and had assisted GR with the Type 275's design, granted the company a non-exclusive license to use his patents.[261] He was equally willing to license other manufacturers. Among these was the D.C.-based American Instrument Company, which won the BOS contract with a low bid of $61.50 per oscillator.[262] Writing in December of 1925 to the Bureau, Arthur Batcheller, Supervisor of Radio for New York and New Jersey, was

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[259] "Standard Frequency Stations," *Radio Service Bulletin*, no. 90 (1 October 1924): 11.

[260] Letter dated 15 January 1925, Box 2, File 19, Records of the FCC and Predecessor Agencies, Record Group 173, U.S. National Archives, College Park, MD.

[261] General Radio Company. "Catalog E." (Cambridge, MA, 1928), Available at http://www.teradyne.com/corp/grhs/, Accessed 14 August 2006, cited: 64.

[262] Letter dated 20 April 1925, Box 2, File 19, Records of the FCC and Predecessor Agencies, Record Group 173, U.S. National Archives, College Park, MD.

delighted with the performance of his American Instrument piezo-electric oscillator. "I believe the utilization of the new crystal oscillator for checking our wave meters is most ideal and that the conditions in the future as regards uniform settings of the stations throughout the various districts will more closely approximate true settings than any practice we have heretofore carried out. … The use of Piezo crystal oscillators for checking our wave meters is a big step forward and should materially aid in standardizing the frequency settings of all the stations throughout the U.S."[263]

In early 1926, the BOS began publicly endorsing the piezo-electric oscillator for use by broadcast stations. An article in the *Radio Service Bulletin* read as follows. "Experience has shown that the use of an ordinary frequency meter (wave meter) is not a satisfactory means of fulfilling this requirement [that broadcast stations maintain a constant station frequency]. The most satisfactory constancy of frequency has been attained by stations which use a special frequency standard adjusted to the licensed frequency of the particular station."[264] The article went on to state that the best such frequency standard was a piezo-electric oscillator and that the oscillator could be used "either as a master oscillator controlling the frequency of a station's output or as a frequency indicator."[265]

5.7 Developing a Quartz Crystal-based Primary Frequency Standard

The piezo-electric oscillator provided radio transmitter operators a very accurate and constant secondary frequency standard, one that could be used to calibrate any

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[263] Arthur Batcheller to Commissioner of Navigation, 8 December 1925, Ibid.

[264] "New Method of Maintaining Constant Station Frequency," *Radio Service Bulletin*, no. 106 (30 January 1926): 23.

[265] Ibid., (

continuous frequency measuring instrument, such as a wavemeter. But commercially available piezo-oscillators did nothing to improve the fundamental accuracy of the nation's primary frequency standard. John Dellinger's 1923 promise to increase the accuracy of the Bureau's primary frequency standard to 0.01 % was fulfilled not with the piezo-oscillator but by coupling a multi-vibrator (i.e., harmonic amplifier) to a tube-driven 1025-cycle tuning fork.[266] The multi-vibrator generated precise multiples of the tuning fork's frequency. Thus, the standard frequencies available with this setup were $N \cdot 1025$ Hz, with N being any positive integer. By using wave filters on the multi-vibrator's output signal, particular values of N could be selected to produce any desired multiple of the tuning fork's frequency.

The tuning fork/multi-vibrator provided the BOS with a primary frequency standard accurate to +/- 0.01 %, but Dellinger knew that quartz crystal, if harnessed properly, could provide much greater accuracy. Not only was greater accuracy possible; it was becoming necessary for the further stabilization of broadcasting and for the further development of the shortwave band. Among the technical obstacles preventing the Bureau from devising a quartz-based primary standard were the adverse effects of temperature and humidity changes on the frequency stability of the piezo-oscillator. By 1926, General Radio had developed a non-temperature-controlled piezo-oscillator accurate to +/- 0.03 %, but this was felt to be the technology's limit.[267] Further improvement in accuracy would require precise temperature control.

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[266] "Establishment of Radio Standards of Frequency by the Use of a Harmonic Amplifier," *Radio Service Bulletin*, no. 114 (30 September 1926).

[267] "A Review of Twenty Years of Progress in Communication-Frequency Measurements," *The General Radio Experimenter* 10, no. 1 (1935): 1-20. See also ———. "Catalog E." (Cambridge, MA, 1928), Available at http://www.teradyne.com/corp/grhs/, Accessed 14 August 2006.

John Dellinger knew that any effort to improve the accuracy of the national primary frequency standard beyond +/- 0.01 % would likely require many months of concentrated research involving not only the Bureau, but also the Naval Research Laboratory and private industry. Organizing such a cooperative effort during peacetime would be no easy task. Dellinger needed some type of external stimulus to convince others of the urgency of this task. Just such a stimulus presented itself when the U.S. State Department invited representatives from seventy-nine countries to participate in the Third International Radiotelegraph Conference, the first since 1912.[268] The Conference was to be held in Washington during October and November of 1927.

The stated purpose of the 1927 Radiotelegraph Conference was to update the international radio agreements last set forth in London in 1912, long before AM broadcasting and short-wave transmission had appeared. The rising popularity of shortwave radio in the early and mid-1920s made the Conference especially crucial because of the worldwide range of shortwave signals. Dellinger saw the Conference as the perfect opportunity for showcasing U.S. progress in the standardization of frequency, but he also knew that a more precise frequency standard was critical in the international allocation of shortwave frequencies. Using the approaching Conference as a prod, he sent a letter in January of 1927 to representatives of the following organizations: Bell Telephone Labs, AT&T, Westinghouse, General Radio Company, RCA, G.E., the U.S. War Department, and the Naval Research Laboratory. In the letter, Dellinger invited the

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[268] Marvin R. Bensman, *The Beginning of Broadcast Regulation in the 20th Century* (Jefferson, N.C.: McFarland & Co., 2000), 203.

recipients to a special conference on the status of frequency standardization, to be held at the Bureau of Standards.[269]

On February 7, 1927, twenty-three men and one woman met at the Bureau to devise a plan for increasing the accuracy of the nation's primary frequency standard. The meeting seems to have been remarkably productive; its chief resolution was stated by the NRL's Dr. Albert H. Taylor as follows. "It was resolved that … the several organizations join in a cooperative endeavor, centered at the Bureau of Standards, to develop concrete standard (sic) in terms of which radio frequencies may be measured to an absolute accuracy not poorer than one part in one hundred thousand (0.001%)."[270] This level of accuracy represented an improvement of ten times over the present accuracy of 0.01%. Moreover, it was recommended that this work be expedited so that "maximum progress" could be made in "securing a unified world basis of frequency measurement" by the time of the International Conference.

To accomplish the February meeting's ambitious goal, the attendees decided that seven complete temperature-controlled piezo-oscillators were to be constructed: two by the NRL, two by G.E., two by Westinghouse, and one by the Bureau of Standards. The oscillators would all be sent to the Bureau for testing, after which they would be sent to the NRL and the Bell Telephone Laboratories for inter-comparison. The method of "temperature control," in which piezo-oscillators were placed in thermostatically-controlled temperature chambers to avoid temperature-related frequency variations, was

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[269] "Report of Conference of February 7 on Frequency Standardization," Folder "Misc. International Comparisons," Box 22, Records of the National Institute of Standards and Technology, General Records of J. Howard Dellinger, Record Group 167, U.S. National Archives, College Park, MD.
[270] Ibid.

still new in early 1927, but hopes were high that this technique alone would go a long way toward reaching the accuracy goal of 0.001%.

When the International Radiotelegraph Conference convened in Washington in October, 1927, the seven experimental piezo-oscillators had yet to be completed. What had been completed, however, was an important demonstration of the technique of precision temperature control as well as the close degree of agreement between international frequency standards. During the summer of 1927, Dellinger had personally traveled to several European countries with a temperature-controlled piezo-oscillator for the purpose of performing laboratory comparisons with each country's frequency standard.[271] Understanding the importance of these tests requires a brief review of the Bureau's earlier efforts at international frequency comparison.

The Bureau's first attempt at comparing various national frequency standards had been in 1924, when it had coordinated the simultaneous measurement in several countries of a number of high-power short-wave transmissions. The results had been somewhat disheartening, indicating an agreement of only ~0.2%, much less than the known degree of certainty of each national standard. The second attempt was a series of measurements begun in 1925 and not fully completed until late 1927; six countries had participated – England, France, Germany, Italy, Canada, Japan, and the U.S. Dellinger had chosen to use a different method for these tests than was used for the 1924 tests; a number of piezo-oscillators, not temperature-controlled, would be carefully packaged and shipped to the participating countries for direct laboratory comparison with each nation's standard. This series of tests were far more accurate than the earlier one, showing an agreement to

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[271] "International Comparison of Frequency Standards," *Radio Service Bulletin*, no. 130 (31 January 1928).

within 0.03%. Dellinger saw these results as proof of the superiority of the piezo-oscillator method of international frequency comparison.[272]

When Dellinger performed his European frequency tests during the summer of 1927, he hoped that the addition of temperature-control to the piezo-oscillator used in the comparisons would allow for improvement over the +/-0.03% accuracy of non-temperature-controlled oscillators. To his delight, the addition of temperature-control allowed for a 10-fold increase in accuracy, moving Dellinger to state that “it has been demonstrated that the several national laboratories are measuring frequencies with an accuracy satisfactorily in advance of the immediate requirements of radio practice.”[273] Continuing, “The standards of frequency of the larger countries agree sufficiently well to insure against interference provided the transmitting stations are accurately adjusted according to their national standards.” Even so, Dellinger observed that “the accuracy attained in these comparisons is not by any means the limit attainable.”[274] He still hoped that the Bureau’s program of reaching 0.001% accuracy would succeed.

The 1927 International Radiotelegraph Conference had acted as a spur to kick-start teamwork on developing a more accurate primary frequency standard, but the research team assembled by Dellinger ended up going much farther than originally planned. This was likely the result of at least a couple of factors. First, once the research team and a suitable division of labor had been organized, remarkable progress was made. Considering how difficult it was to put the team together in the first place, it is unlikely

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[272] J. H. Dellinger, “The Status of Frequency Standardization,” presented at a meeting of the I.R.E. in New York, 9 January 1928, Folder “Frequency Standardization,” Box 21, Records of the National Institute of Standards and Technology, General Records of J. Howard Dellinger, Record Group 167, U.S. National Archives, College Park, MD.
[273] Ibid.
[274] Ibid.

that anyone was willing to disband the group immediately after the Conference ended, particularly since one of the team's key deliverables – seven temperature-controlled piezo-oscillators – had yet to be completed. Second, early test results indicated that the promise of temperature-control was much greater than the team had initially expected. Full realization of the potential of temperature-control required a significant extension of the research effort.

In January of 1928, Dellinger's frequency standard research group began disseminating monthly status reports to all group members.[275] The reports continued to be written through December of 1929, by which time a remarkable new primary frequency standard had been installed at the Bureau. The standard, assembled at Bell Telephone Laboratories, comprised four temperature-controlled piezo-oscillators which were compared daily and averaged to give the actual standard. Its accuracy of 0.00001%, or one part in 10 million, was a remarkable hundred-fold improvement over the group's original goal of 0.001%.[276]

The accuracy of the Bureau's new primary frequency standard was much higher than needed for full development of the medium-wave and shortwave radio bands, but the significance of the new standard lay in the much higher, unexplored regions of the electromagnetic spectrum, such as the microwave band that would become important during the Second World War. The new primary frequency standard, the very first one of the Bureau's to be quartz based, served the nation's radio needs for thirty years. In 1959, the quartz standard was replaced with one based on the oscillations of a cesium atom. During its thirty year reign, the Bureau's quartz standard was modified and refined

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[275] These reports, twenty-four in all, may be found in Folder "Frequency Measurement – Monthly Reports," Box 22, Ibid.

[276] "New Fundamental Frequency Standard," *Radio Service Bulletin*, no. 157 (30 April 1930): 23-24.

several times. Nevertheless, the frequency standard installed in late 1929 established the paradigm of quartz crystal frequency standardization until atomic-based standardization replaced it.[277]

5.8 Birth of the Commercial Radiofrequency Testing Industry

In early 1927, as Dellinger and the BOS were developing plans for improving the nation's primary frequency standard, the Bureau was beginning to grapple with a serious problem related to the increasingly popular use of piezo-oscillators as secondary frequency standards. Once an initial calibration was performed, these instruments held to their calibrated frequency remarkably well over time. However, the initial calibration required a very precise reference standard with which to compare the piezo-oscillator. Furthermore, if the instrument's user ever wanted to increase its oscillating frequency, a completely new calibration was required.[278] For both initial calibrations and recalibrations, many users began sending their piezo-oscillators to the Bureau's Washington office so that calibrations with respect to the primary frequency standard could be performed. The Bureau was happy to perform these calibrations for a nominal fee.

Until mid-1927, the Bureau did not find the job of calibrating piezo-oscillators too burdensome. Then the U.S. Congress passed the Radio Act of 1927, part of which contained a new frequency adherence measure for broadcast stations. General Order No.

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[277] Wilbert F. Snyder and Charles L. Bragaw, *Achievement In Radio: Seventy Years of Radio Science, Technology, Standards, and Measurement at the National Bureau of Standards* (Boulder, CO: National Bureau of Standards, 1986), 253-302.

[278] Lowering a piezo-oscillator's frequency required increasing the physical dimensions of the instrument's quartz crystal wafer. The only way to do this was to scrap the old wafer and cut a new one to the desired dimensions. On the other hand, increasing the instrument's frequency required only further cutting on the current quartz wafer.

7, issue by the newly formed Federal Radio Commission (FRC) on April 17, ordered all licensed broadcast stations to stay within +/- 0.5 kHz of their assigned frequencies. Following a short grace period, violators of the order were to be fined $500 a day, and repeated violation would result in license revocation. The only possible way for station operators to consistently comply with General Order 7 was to use a piezo-oscillator for checking station frequency. Thus, those stations that didn't already own a piezo-oscillator quickly ordered one or attempted to make their own. Of course, all of these piezo-oscillators required calibration, so the BOS began seeing a rapid rise in the number of instruments it received for calibration.

In 1928 the calibration situation reached a crisis state. In January, the Bureau reported, "There is just at present an exceptional demand for radio tests of this kind [i.e. crystal calibration] which is greatly in excess of the capacity of the bureau for immediate service. For this reason it has been necessary to schedule pending tests. … Tests already scheduled will require about 2 months to complete." The Bureau also announced the discontinuation of its monthly publication of a "Standard Frequency Stations" list, citing "the demands on the bureau for testing and other urgent work."[279]

What the Bureau really needed and desired was the creation of a commercial radiofrequency testing industry, one which would be able to perform piezo-oscillator calibrations as well as many other types of routine radio tests. The beginnings of such an industry were already in place, but the quality of testing was not sufficient to assist stations in complying with General Order No. 7. In an FRC internal memo dated February 8, 1928, nine testing laboratories were identified as offering, for a nominal fee, some types of radiofrequency tests; six of these were located at universities or technical

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[279] "Standard Frequency Stations," *Radio Service Bulletin*, no. 130 (31 January 1928).

institutes.[280] Yet, in a February 23, 1928 letter to Radio Chief William Dandrige Terrell, BOS Director George Kimball Burgess made it clear that none of these labs were yet qualified to perform frequency measurements and calibrations with sufficient accuracy. "At the present time commercial testing laboratories are farther than ever from being able to measure station frequency standards with the necessary accuracy. … The Bureau will be glad to have the routine testing of frequency standards taken over, when possible, by laboratories which can handle this business on a commercial basis. In fact, we have been trying for several years to get such laboratories to take up the work of accurate calibration of wavemeters."[281]

The situation described by Burgess continued for several years. By the early 1930s, however, a commercial radio testing industry capable of the same level of frequency accuracy as the BOS had been established. Perhaps the major factor enabling this development was the proliferation of quartz-based primary frequency standards beyond the walls of the BOS's Washington headquarters. In testimony before the FRC on April 20, 1931, John Dellinger testified that there were currently three laboratories in addition to the BOS that maintained a quartz-based primary frequency standard to an accuracy of at least one part per million, or +/- 0.0001%.[282] These laboratories, located at the General Radio Company, the Naval Research Laboratory, and the Bell Telephone

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[280] FRC memo, 8 February 1928, Entry 1, Box 3 (19-28), Records of the FCC and Predecessor Agencies, Record Group 173, U.S. National Archives, College Park, MD. The laboratories were as follows: the Harvard Cruft High Tension Electric Lab, the General Radio Company, Electrical Testing Laboratories, J. H. Morecroft (NY), Dartmouth College, the Cornell School of Electrical Engineering, the University of Tennessee Engineering Experiment Station, the University of Wisconsin, and the Armour Institute of Technology (Chicago).

[281] Burgess to Terrell, 23 February 1928.

[282] "Testimony of Dr. J. H. Dellinger given at the hearing before the FRC on Proposed Modification of General Order No. 7, held Monday, 20 April 1931," Box 4, Records of the National Institute of Standards and Technology, General Records of J. Howard Dellinger, Record Group 167, U.S. National Archives, College Park, MD.

Laboratories, lightened the BOS's calibration load and allowed the Bureau to focus on non-routine standardization issues.

Of these three laboratories, only General Radio manufactured primary frequency standards for sale on the open market. The company's Class C21-H Standard Frequency Assembly, released in 1930 and selling for $1860, gave anyone who could afford it a primary frequency standard accurate to at least one part per million.[283] By 1932, GR could state in its catalog, "Once developed for use in our own calibration work, this assembly has since been installed by more than fifteen universities, communication companies, and government agencies in the U.S. and abroad."[284] And by 1935, the company could boast, "More than thirty-eight [C21-H] units have been installed and are operating in all parts of the world in industrial organizations, research laboratories, observatories, and frequency monitoring stations. Many of them are used as national standards of frequency by communications administrations in North American, European, and Asiatic countries."[285] More than any other single company, the General Radio Company facilitated the spread of quartz-based primary frequency standards not only throughout the U.S. but throughout the world.

5.9 The Institute of Radio Engineers encourages adoption of quartz crystal frequency standards

Thus far this narrative has shown quartz crystal-based frequency standardization as being influenced and implemented by independent inventors (Walter Cady, George

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[283] General Radio Company. "Catalog F: Instruments for Electrical Measurements at Communication Frequencies." (Cambridge, MA, 1930), Available at http://www.teradyne.com/corp/grhs/, Accessed 14 August 2006, cited: 51-56.

[284] ———. "Catalog G." (Cambridge, MA, 1932), Available at http://www.teradyne.com/corp/grhs/, Accessed 14 August 2006, cited: 46-48.

[285] ———. "Catalog H." (Cambridge, MA, 1935), Available at http://www.teradyne.com/corp/grhs/, Accessed 14 August 2006, cited: 34.

Washington Pierce), government institutions (Bureau of Standards, Naval Research Laboratory, Federal Radio Commission), and private firms (General Radio Company, Bell Telephone Laboratories, General Electric, Westinghouse). One other group that was instrumental in promoting quartz standards has yet to be mentioned. Most of the individuals mentioned in the narrative thus far were members of the Institute of Radio Engineers (I.R.E.), a professional engineering society that played a prominent role in influencing early broadcast radio policy.[286] In mid-1927, just after the formation of the F.R.C., the I.R.E. offered its technical consulting services to the Commission; the Commission soon accepted. In 1928, the I.R.E. leadership formed the Committee on Broadcasting "as a means by which the Institute might assist the government as well as the Institute membership in the solution of some of the technical problems involved in the development of broadcasting."[287]

Shortly after its formation, the I.R.E. Committee on Broadcasting received a request from John Dellinger, the then Chief Engineer of the Federal Radio Commission. Dellinger asked the Commission to study certain broadcasting subjects of urgent concern, including the matter of "permissible deviation of carrier frequency from licensed frequency."[288] Within a few months, the Committee had issued a report on the topic. Beginning with the acknowledgement that the primary purpose of precise carrier frequency stability was the elimination of heterodyne (or "beat-note") interference, the report confessed that the complete elimination of such interference "is not believed to be

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[286] Hugh Slotten, "Radio Engineers, the Federal Radio Commission, and the Social Shaping of Broadcast Technology: 'Creating Radio Paradise,' 1927-1934," *Technology and Culture* 36, no. 3 (October 1995): 950-86.
[287] I.R.E. Committee on Broadcasting, "Reports of I.R.E. Committee on Broadcasting," *Proceedings of the Institute of Radio Engineers* 18, no. 1 (January 1930): 15-37.
[288] Ibid. (, 15.

a practical possibility at the present stage of the art. It can be achieved only by highly refined apparatus, which is yet beyond the resources of many of the smaller stations that occupy the channels under discussion."[289] Nevertheless, noting that even partial elimination of heterodyne interference would improve broadcasting quality, the Committee recommended a new frequency adherence requirement of +/-0.05 kHz. "An effort on the part of the industry to meet a plus or minus 50-cycle requirement, while it may not be a complete solution, and while its effect may only be temporary, will nevertheless serve as a powerful stimulus to the development of the more refined apparatus and improved technique ultimately required."[290]

As earlier, we see again here an example of legislation very close to what it today known as "technology-forcing regulation."[291] Yet, the +/-0.05 kHz recommendation was not impossible to meet. As the Committee's report noted, "the maintenance of frequencies in the broadcast band with a maximum permissible deviation of plus or minus 50 cycles is believed to be both technically and economically feasible, at the present state of the art." The report went on to suggest means for meeting the new recommendation. "The required degree of accuracy and stability can hardly be attained, however, without resorting to automatic frequency control by means of tuning forks, piezo crystals, and similar devices. Such devices must not only be accurately adjusted to the required frequency but should be enclosed in constant temperature chambers."[292] Clearly, the Committee chose not to mandate that quartz crystal equipment be used.

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[289] Ibid. (, 25.
[290] Ibid. (, 26.
[291] David Gerard and Lester B. Lave, "Implementing technology-forcing policies: The 1970 Clean Air Act Amendments and the introduction of advance automotive emissions controls in the United States," *Technological Forecasting and Social Change* 72, no. 7 (September 2005): 761-78.
[292] I.R.E. Committee on Broadcasting, "Reports of I.R.E. Committee on Broadcasting," *Proceedings of the Institute of Radio Engineers* 18, no. 1 (January 1930): 15-37, cited: 27.

Practically speaking, however, this was the most feasible way for most stations to comply with the +/-0.05 kHz recommendation.

The I.R.E. Committee on Broadcasting's recommendation was eventually put into law as General Order No. 116. Passed in 1931 and taking effect in 1932, this Order tightened the F.R.C.'s frequency adherence regulation from +/- 0.5 kHz to +/- 0.05 kHz. As predicted by the Committee, broadcast station operators found it necessary to use not only a well-calibrated piezo-oscillator, but also a crystal-controlled transmitter equipped with precision temperature control in order to comply with the order.[293] Thus, by directly influencing frequency adherence legislation, the I.R.E. Committee on Broadcasting effected the widespread adoption of quartz crystal technology among American broadcasters.

By the mid-1930s, a small but healthy industry had formed to help broadcast stations comply with F.C.C. (formerly F.R.C.) frequency adherence regulations. At least five American manufacturers made F.C.C.-approved quartz-based frequency monitors.[294] Furthermore, in 1936 thirteen manufacturers were producing F.C.C.-approved automatic frequency control units, eleven manufacturers were producing F.C.C.-approved crystal-controlled transmitters, and five manufacturers were making F.C.C.-approved automatic

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[293] An *F.R.C. Application for Radio Broadcast Station Construction Permit or Modification Thereof* from 1932 asked the applicant to "state what apparatus is included as an integral part of the transmitter that will automatically hold frequency within the required limits" and to "state whether or not frequency control apparatus is automatically maintained at constant temperature." Source: Folder 5, Box 6, WGST Radio Station Records, 1928-1975 (MS 8), Special Collections and Archives, Library and Information Center, Georgia Institute of Technology, Atlanta, GA. Also, see Chapter 4 of this dissertation for more on the development of the crystal-controlled transmitter.

[294] FRC Secretary James W. Baldwin to "All Broadcast Stations," 26 April 1932, Box 4, Records of the National Institute of Standards and Technology, General Records of J. Howard Dellinger, Record Group 167, U.S. National Archives, College Park, MD. The five manufacturers were RCA Victor, Western Electric, General Radio, DeForest Radio, and Doolittle & Falknor.

temperature control units.[295] The BOS worked closely with some of these manufacturers in determining the feasibility of new F.C.C. frequency adherence regulations as the radio art moved into higher frequencies. For example, in 1936 the acting secretary of the BOS wrote the following to the General Radio Company. "The F.C.C. is interested in frequency measurement equipment suitable for measuring any frequency in the range from 1 cycle to 500 megacycles." What followed were some proposed specifications pertaining to frequency accuracy and stability in the higher frequencies. The letter then continued, "Progress in the design of equipment for higher frequencies has been less rapid with the result that the question of the best method to be used and the feasibility of manufacturing components having the required electrical performance cannot be easily answered. It is desired that your engineering department give this matter some consideration and advise the Commission whether the tentative specifications enumerated above can be successfully approached and submit information covering a practical apparatus layout, together with the performance that can be anticipated."[296] Ten years earlier, in 1926, the BOS would have hardly approached private industry with such a request, for industry was simply not producing quartz-based frequency measurement equipment in large numbers. By 1936, however, the Bureau could boast of a highly skilled and knowledgeable American radiofrequency testing industry, one that the Bureau routinely consulted when the F.C.C. wanted to update radio spectrum regulations.

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[295] An "automatic frequency control unit" was a unit that, when installed, added crystal-control to a non-crystal-controlled radio transmitter. See FCC Memorandum, 22 January 1936, Entry 2, Box 308, File 75-2 (Apparatus – Transmitting), Records of the FCC and Predecessor Agencies, Record Group 173, U.S. National Archives, College Park, MD.

[296] John B. Reynolds to the General Radio Co., 31 August 1936, Entry 2, Box 308, File 122-1 (Frequency, Radio Measurements and Standardization – Miscellandous), Ibid.

5.11 Conclusions

During the 1920s, the Radio Division of the U.S. Bureau of Standards and the Institute of Radio Engineers, moved to action by the growth of shortwave band radio, the growing presence of destructive interference in the broadcast band, and the communications requirements of the U.S. Navy, endeavored successfully to encourage widespread adoption of quartz crystal-based frequency standards and measurement instruments. The efforts of these two organizations culminated in the passage of frequency adherence legislation in 1927 and 1931. These laws required licensed broadcast stations to employ a quartz-based frequency measurement device (General Order No. 7 – 1927) as well as a crystal-controlled transmitter (General Order No. 116 – 1931). Consequently, a small but technologically vital industry grew up around the manufacture and calibration of precision quartz crystal radio instruments. The earliest and most influential American firm to emerge in this industry was the General Radio Company of Cambridge, Massachusetts. Over time, General Radio developed a close consultant-like relationship with the Bureau, advising it on the feasibility of proposed frequency adherence legislation.

The relationship between the Bureau of Standards and the General Radio Company embodied the kind of public sector/private sector partnership encouraged in the 1920s by Secretary of Commerce Herbert Hoover. Hoover's regulatory philosophy, which has since come to be labeled "associationalism," encouraged industry self-regulation.[297] In the absence of self-regulation, however, Hoover had no qualms about

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[297] David M. Hart, *Forged Consensus: Science, Technology, and Economic Policy in the United States, 1921-1953* (Princeton, NJ: Princeton University Press, 1998). Ellis W. Hawley, "Herbert Hoover, the Commerce Secretariat, and the Vision of an 'Associative State,' 1921-1928," *Journal of American History* 61 (1974): 116-40.

stepping in with government regulation, as he had to do when radio broadcasting interference became intolerable. In the wake of the 1927 Radio Act and General Order No. 7, which imposed a strict frequency adherence regulation on broadcasters, the Bureau of Standards, which was part of the Department of Commerce, found that many broadcasters found it difficult to comply with the order because of the lack of a commercial radio testing industry. In countries less committed than the U.S. to private sector ownership of capital, the government itself would have probably stepped in to produce the needed instrumentation and perform much needed calibrations. The Bureau, however, agreed to provide calibrations only until private industry proved itself up to the task. Over several years, in accordance with Hoover's associationalism, the Bureau patiently nurtured the growth of a private radio testing industry. By the mid-1930s, a flourishing and competitive U.S. commercial radio testing industry, of which General Radio was only one player among many, existed.

The commercial radio testing industry was an important sector of a growing quartz crystal technological community. Some of the firms in this industry, such as General Radio, did not generate many quartz-related patents.[298] The importance of these firms was not as inventors, but as innovators. They brought inventions into the marketplace and consequently into widespread use in the form of commercial products, such as the revolutionary GR Type 275 Piezo-Electric Oscillator. These products then made it possible for others to continue inventing in the area of quartz crystal technology, creating a self-reinforcing cycle of invention-innovation-invention.

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[298] GR did not file for its first quartz-related patent until 1931. James Kilton Clapp, *Electric System and Method*, U. S. Patent Office, Patent No. 1,944,315, Filing Date: 22 October 1931; Issue Date: 23 January 1934. In the 1930s, GR was assigned only five quartz-related patents, all of them invented by Clapp, a GR employee.

While firms such as General Radio turned quartz crystal engineering knowledge into quartz crystal commercial products, the Institute of Radio Engineers, a professional engineering society formed in 1912 in New York, served as a crucial nexus linking piezoelectric engineers from private industry, independent inventors such as Cady and Pierce, government engineers such as John Dellinger, and military researchers from the NRL. The I.R.E.'s meetings allowed engineers from all of these institutions to meet and collaborate, while the I.R.E.'s principal publication, *Proceedings of the I.R.E.*, facilitated the broad dissemination of quartz crystal engineering knowledge.

Also serving in the 1920s as a nexus for the growing quartz crystal technological community was the Radio Division of the Bureau of Standards. By virtue of its twin mandate to both maintain the nation's primary radiofrequency standard and to standardize frequency measurement equipment, the Bureau necessarily worked closely with all of the individuals and groups that were at the forefront of quartz crystal technology. The best example of this was the Bureau's initiating and organizing the three year research and development effort to develop a quartz crystal-based national primary frequency standard. Through the monthly *Radio Service Bulletin*, the Bureau also effectively disseminated quartz crystal engineering knowledge to broadcast station operators who were primarily interested in keeping their stations on the air. Notable among Bureau employees was John Dellinger, whose passionate pursuit of ever more accurate frequency standards involved the relentless promotion of quartz crystal-based standards. Like the General Radio Company, Dellinger's legacy to quartz crystal technology is one of innovation, bringing quartz crystal instruments and standards into widespread use.

The great quartz crystal independent inventors that we have seen in previous chapters, Walter Guyton Cady and George Washington Pierce, appeared also in this chapter. Chapter 4 showed that the engineering contributions of these two men were conceptually distinct. Cady was fundamentally a technologically oriented scientist, while Pierce was an inventive electrical engineer. These distinctions appear once again in this chapter. Cady first demonstrated that piezoelectric quartz crystal could serve as the basis of a radiofrequency standard, but his idea of using the quartz piezo-electric resonator as a frequency standard never gained much traction in practice. Pierce first proposed that Cady's piezo-electric oscillator rather than his resonator be used as a practical frequency standard. This idea quickly took hold and led within a few years to the piezo-electric oscillator replacing the wavemeter as a portable secondary frequency standard. Pierce's familiarity with the needs of working engineers and technicians allowed him to refine Cady's initial ideas, making them more usable by the radio industry.

By the early 1930s, quartz crystal technology had come to pervade the transmission side of radio technology, particularly among licensed broadcasters. The new decade, one that would bring the Great Depression but that has also been called "the most technologically progressive decade of the century," saw the widespread application of piezoelectric quartz crystal to telephony as well as the birth of an industry that catered to the quartz crystal needs of radio amateurs.[299] The following chapter relates these stories.

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[299] Alexander J. Field, "The Most Technologically Progressive Decade of the Century," *The American Economic Review* 93, no. 4 (November 2003): 1399-413.

CHAPTER 6: EXPANSION – THE AMATEUR RADIO AND TELEPHONY MARKETS FOR QUARTZ CRYSTAL

…the division of labour is limited by the extent of the market.
Adam Smith, 1776[300]

In the past the man has been first. In the future the System must be first.
Frederick Winslow Taylor, 1911[301]

6.1 Introduction

The late 1920s and 1930s witnessed the tremendous expansion of the nascent quartz crystal technological community as well as the significant extension of quartz crystal engineering knowledge. This growth proceeded, as the two quotes above suggest, along two very different paths. The first path, made possible by the growing number of radio amateurs in the U.S., was characterized by increasing specialization in quartz crystal device production. The second path, supported by the growing American demand for accessible and affordable long-distance telephony service, was characterized by centralized planning and organization of telephony research. This research was possible only because of AT&T's government-regulated monopoly over U.S. telephony. Though these two paths were distinct, they did not work against each other. Rather, they both contributed to the technological and economic growth of quartz crystal technology during the decade that economic historian Alex Field has recently called "the most technologically progressive … of the century."[302]

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[300] Adam Smith, *The Wealth of Nations*, Fifth ed. (New York: Bantam Classics, 2003), Chapter 3.

[301] Frederick Winslow Taylor, *The Principles of Scientific Management: and Shop Management* (London: Routledge/Thoemmes Press, 1993), Chapter 1.

[302] Alexander J. Field, "The Most Technologically Progressive Decade of the Century," *The American Economic Review* 93, no. 4 (November 2003): 1399-413.

While much of the American economy became mired in depression after 1929, the quartz crystal industry actually grew. In numbers, the largest addition to the quartz crystal community during this time was the swelling ranks of American radio amateurs, most of whom began adopting the technique of crystal control for their transmitters. The growth of this market led to the formation of many small firms specializing in the manufacture of quartz crystal units, or QCU's. By the end of the 1930s, specialized QCU firms were producing a total of as many as 100,000 QCU's a year, far more than the broadcast radio industry alone could have supported. By and large, these firms were strictly manufacturing outfits, not research and development organizations. Nevertheless, at least one firm – Bliley Electric of Erie, Pennsylvania – made important contributions to quartz crystal engineering knowledge by developing innovative QCU designs and labor-saving manufacturing processes.

Despite the contributions of Bliley Electric and other specialized QCU manufacturers, the most significant additions to quartz crystal engineering knowledge during the late 1920s and 1930s were made by Bell Telephone Laboratories (BTL), the research division of American Telephone and Telegraph (AT&T). In the course of a long-range effort to expand the company's long-distance telephony network, BTL engineers developed two new technologies – quartz crystal wave filters and coaxial cable – that allowed AT&T to develop and deploy a high-capacity, multiplex carrier telephony system. Additionally, BTL engineers developed important quartz crystal temperature compensation techniques as well as the quartz crystal clock. Consonant with Alex Field's aforementioned assessment of the 1930s, the body of quartz crystal engineering knowledge expanded greatly during this time, largely due to the efforts of BTL engineers.[303]

For most of the 1920s, as Chapters 4 and 5 have shown, the growth of the emerging quartz crystal technological community was centrally orchestrated by the U.S. Bureau of Standards and, to a lesser extent, the Institute of Radio Engineers. In contrast, this chapter shows that growth of the amateur radio community and the concurrent rise of dedicated QCU manufacturing firms was largely a decentralized, grass roots phenomenon. There were no government regulations forcing radio amateurs to adopt quartz crystal control.

The growth of quartz crystal engineering knowledge during the 1930s tells a different story. The significant advances made by BTL engineers would likely not have been possible had not AT&T enjoyed a government-regulated monopoly over long-distance telephony in the U.S. The company's large and secure profits allowed it to fund one of the world's most advanced industrial research and development labs. The quartz crystal work performed at BTL was not undirected, blue sky research; rather, it was carefully planned to fit the needs of the Bell System and its customers. BTL managers were trained to focus on the needs of the system above the needs of particular scientific or engineering disciplines. The invention and refinement of quartz crystal wave filters, as well as the work on temperature compensation, functioned first and foremost to expand and economize Bell's telephony infrastructure, but this work also expanded quartz crystal engineering knowledge far beyond what it had been in the late 1920s.

By the late 1930s, the quartz crystal technological community was much larger than it had been a decade earlier, but it was still quite fragmented. Most quartz crystal

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[303] Ibid.

inventors and engineers focused primarily on their company's needs or the needs of their customers. That is, they were not self-consciously advancing the body of quartz crystal engineering knowledge. This was the legacy of a decade in which quartz crystal technology grew in two very different contexts: the free-market, entrepreneurial capitalism of radio amateurs and the QCU manufacturing industry; and the world-class research and development laboratory of BTL, supported by AT&T's government-regulated monopoly of telephony.

6.2 Review of quartz crystal technology during the 1920s

For most of the 1920s, piezoelectric applications of quartz crystal remained limited in large measure to two areas: frequency standards, both primary and secondary; and precise frequency control of radio transmitters. The principal devices employed in these applications were the piezoelectric resonator and the piezoelectric oscillator, invented by Wesleyan University professor Walter Cady, and the Pierce oscillator, invented by Harvard University professor George Washington Pierce.[304] These inventions, their areas of technological application, and the popular names of these applications are summarized in Figure 18. This table includes two applications, wave filters and crystal clocks, that have yet to appear in this dissertation. The present chapter introduces these two applications.

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[304] Walter Guyton Cady, *Piezo Electric Resonator*, U. S. Patent Office, Patent No. 1,450,246, Filing Date: 28 January 1920; Issue Date: 3 April 1923. ———, *Method of Maintaining Electric Currents of Constant Frequency*, U. S. Patent Office, Patent No. 1472583, Filing Date: 28 May 1921; Issue Date: 30 October 1923.

Invention	Inventor(s)	Fundamental Patents (U.S.)	Applications	Popular or Brand Names
Piezoelectric Resonator	Walter Cady	1,450,246	Frequency Standards	- Quartz Plate - Crystal - Quartz Crystal Unit (QCU)
			Wave filters	
Piezoelectric Oscillator	Walter Cady G. W. Pierce	1,472,583 2,133,642	Frequency Standards	Piezo-oscillator
			Frequency stabilization of radio transmitters	Automatic Frequency Control Unit (AFCU)
			Crystal Clocks	Syncro-Clock

Figure 18: The Piezoelectric Resonator and Oscillator: Inventors, Patent Numbers, Applications, and Popular Names
(Figure created by author.)

The quartz resonator is the more basic device, consisting essentially of a thin slice of quartz crystal sandwiched between two conducting electrodes, such that the combination might be inserted in an electrical circuit. As such, the piezoelectric resonator is a passive electrical component, akin to a capacitor, inductor, or resistor. In fact, a very helpful way of thinking of the resonator is as a capacitor with a quartz crystal dielectric.

The quartz crystal of the piezoelectric resonator is cut to physical dimensions that would allow it to resonate mechanically at its so-called natural frequency. Because of quartz's piezoelectric property, this mechanical resonance simultaneously produces electrical resonance. In the 1920s, a common demonstration of the resonator's operation was to connect it in series with a variable frequency alternating current (AC) source and an AC ammeter, as shown in Figure 19. As the frequency of the AC source was allowed to increase gradually, it would pass through the piezoelectric resonator's natural frequency, at which point the circuit's AC series current would drop to a sharp minimum, represented in Figure 20. The distinctive technological value of the resonator in the

1920s lay in the sharpness of this curve and the stability of its natural frequency. No other existing passive electrical component exhibited such a sharp resonance curve or such a stable natural frequency. Indeed, because of these two characteristics, the quartz piezoelectric resonator could serve as a stable and reliable standard of frequency.

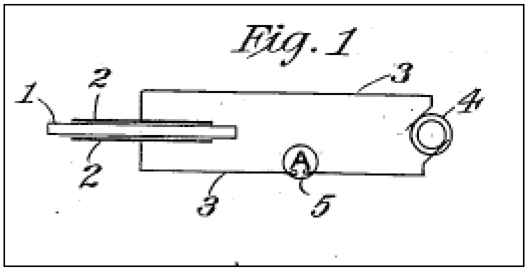

Figure 19: Circuit Demonstrating Operation of the Piezoelectric Resonator
1 - Quartz Crystal Plate; 2 - Conductive coating for electrically connected crystal plate to rest of circuit; 3 - Conducting wires; 4 - High-Frequency AC Current Source; 5 – AC Ammeter. (Source: Walter Cady, U.S. Patent 1,450,246)

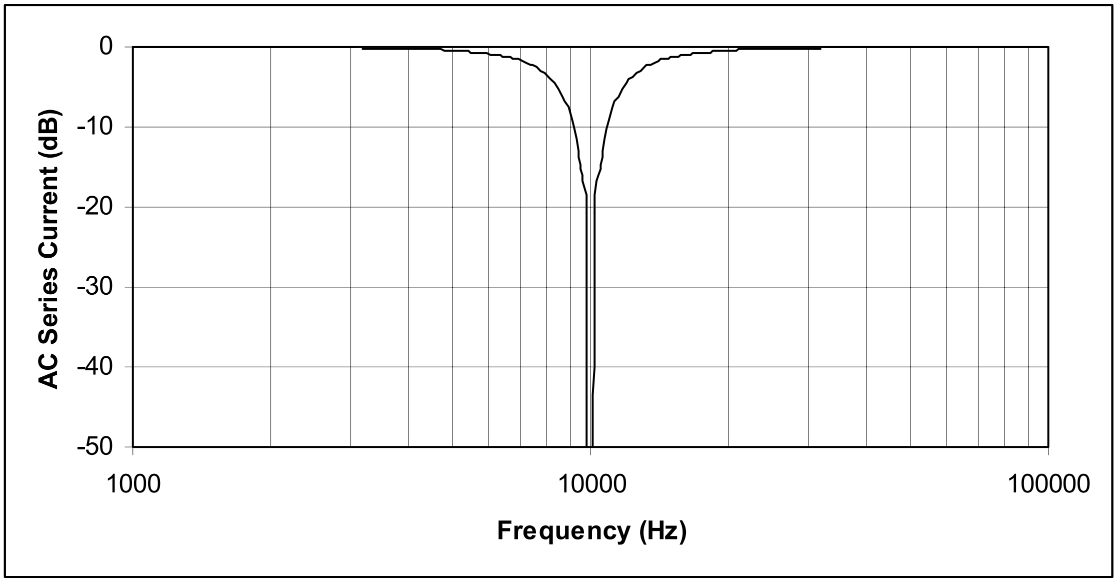

Figure 20: Characteristic Frequency Response of Piezoelectric Resonator Circuit
(Figure created by author.)

The quartz piezoelectric oscillator was a cumulative invention that built on and added to the piezoelectric resonator. An electrical circuit rather than a simple component, the oscillator embeds the resonator in the feedback loop of any one of many well-known oscillator circuits employing one or more triode vacuum tubes as amplifiers. (See Figure 21 for a commonly-used quartz oscillator circuit.) By doing so, the embedded resonator prevents the circuit from oscillating at any frequency other than the resonator's natural frequency. Moreover, because of the stability of this natural frequency, the piezoelectric oscillator produces extremely stable electric oscillations at one and only one frequency.

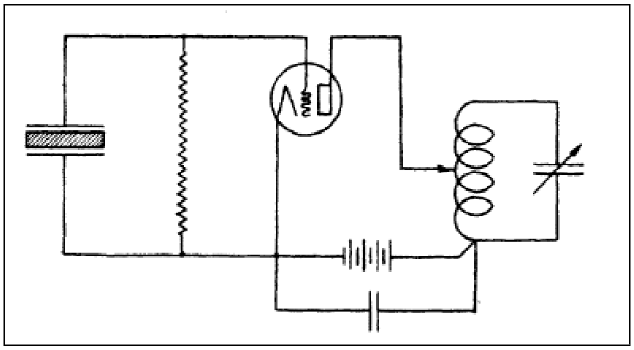

Figure 21: Quartz Crystal Oscillator Circuit Used by the U.S. Navy, Circa 1927
(Reprinted, by permission of the IEEE, from A. Crossley, "Piezo-Electric Crystal-Controlled Transmitters," *Proceedings of the I.R.E.* 15, no. 1 (January 1927): 19, Figure 11. ©1927 IEEE)

Like the piezoelectric resonator, the oscillator can easily serve as a standard of frequency, but it has another use as well. When used in the oscillator circuit of a radio transmitter, it stabilizes the transmitter's carrier frequency. In practice, the piezoelectric oscillator was used in the 1920s for both frequency standards and precision frequency control of radio transmitters, while the piezoelectric resonator saw very limited use. This disparity was largely due to George Washington Pierce's development in 1924 of a simplified and robust crystal oscillator circuit.[305] The piezoelectric oscillator was known by different names depending on its application. When used as a frequency standard, the device came to be known simply as the piezo-oscillator. The U.S. Bureau of Standards played a crucial role in developing this application, and the General Radio Company was the first to manufacture and sell piezo-oscillators intended for use as primary or secondary frequency standards. When used to precisely control the frequency of radio transmitters, the piezoelectric oscillator went by the name of the Automatic Frequency Control Unit, or AFCU. This application was developed extensively in the 1920s by the Naval Research Laboratory and commercialized by many firms, including Western Electric, RCA, General Electric, and Westinghouse.

As Chapters 4 and 5 have shown, a small community formed around the technological use of piezoelectric quartz crystal in the 1920s. This community consisted of three classes of participants: users, producers, and regulators. The users of quartz crystal technology included licensed broadcast stations, the U.S. Navy, radio networks or chains, the Department of Commerce's Radio Inspection Service, the Bureau of Standards, scientific and engineering laboratories conducting radiofrequency research, and radio amateurs. The producers of quartz crystal technology in the 1920s were, in many cases, also the users. That is, many users had to make their own quartz crystal devices and instruments, because the quartz crystal technology industry did not exist for most of the decade. This was especially true for amateurs on limited budgets.

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[305] George Washington Pierce, *Electrical System*, U. S. Patent Office, Patent No. 2,133,642, Filing Date: 25 February 1924; Issue Date: 18 October 1938.

There was, however, at least one dedicated producer of quartz-based instruments during the 1920s – the General Radio Company (GR). The Company produced piezoelectric oscillators, plug-in quartz plates, and, by 1930, quartz-based primary frequency standards. GR sold these quartz crystal instruments on the open market. Their customers included the U.S. Bureau of Standards, radio broadcast stations, industrial research and development laboratories, and probably a handful of affluent radio amateurs. Most of the large radio firms of the 1920s (AT&T, G.E., Westinghouse, R.C.A.) also produced quartz crystal equipment, but primarily for internal use only. In other words, they were user-producers rather than dedicated producers.

Regulation of 1920s quartz crystal technology was the principal focus of Chapter 5. Before 1927, regulation was in the hands of the Radio Division of the U.S. Department of Commerce. Through a series of national radio conferences, the Department made recommendations concerning wavemeter standardization and carrier frequency adherence, but it lacked the authority to turn these recommendations in binding law. In 1927, the Federal Radio Commission (F.R.C.) became the principal regulator of quartz crystal technology. The Commission regulated the use of quartz devices, leaving production to the private sector. With General Order No. 7 (1927), the F.R.C. effectively forced licensed broadcasters to employ piezoelectric oscillators as secondary frequency standards. In 1931, General Order No. 116 forced broadcasters to employ quartz crystal-control in their transmitters. In developing these technical regulations, the F.R.C. was heavily influenced by the expert advice of the Bureau of Standards and the I.R.E. Committee on Broadcasting. Engineers with these two organizations did much to effect the widespread adoption of quartz crystal technology throughout the broadcast radio industry.

6.3 Overview of quartz crystal developments during the 1930s

Some economic historians have recently argued that the label typically ascribed to the 1930s – the Great Depression – belies the great technological advances that were made during that decade.[306] This study confirms this argument by showing that great advances were made in piezoelectric quartz crystal technology in the 1930s. These advances were stimulated by two significant developments in American society occurring in the late 1920s. First, the number of radio amateurs increased rapidly. From 1925 to 1935, the number of licensed radio amateurs in the U.S. trebled.[307] This stimulated the growth of a new industry that catered to radio amateur needs. In particular, many small firms formed in the late 1920s and early 1930s that specialized in the production of quartz crystal units (QCU's) for amateur use. The General Radio Company had developed the standardized QCU, a hermetically sealed, plug-in quartz resonator, in the mid-1920s for use with its piezoelectric oscillators. The QCU quickly became the most popular form of quartz resonator. Some of the QCU manufacturing firms forming during this time proved to be highly innovative, developing devices and methods that catered to budget-minded amateurs. By World War II, radio amateurs represented the single largest commercial market for QCU's.

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[306] For example, see Alexander J. Field, "The Most Technologically Progressive Decade of the Century," *The American Economic Review* 93, no. 4 (November 2003): 1399-413.

[307] Patrick R. J. Brown, "The Influence of Amateur Radio on the Development of the Commercial Market for Quartz Piezoelectric Resonators in the United States" (*Proceedings of the 50th Annual IEEE Frequency Control Symposium*, U.S. Army Research Laboratory, Forth Monmouth, NJ, 5-7 June 1996), 58-65.

The second significant development occurring during the late 1920s was AT&T's withdrawal from broadcast radio and the company's subsequent focus on expanding the capacity of its long-distance telephony network. Bell Telephone Laboratory (BTL) engineers soon learned how to use quartz crystal technology to achieve the desired network expansion. The solution lay in using quartz resonators to construct highly selective wave filters. These quartz wave filters allowed AT&T to develop on paper a highly efficient multiplex carrier telephony distribution system. The development in the mid 1930s of high bandwidth coaxial cable allowed this system to be implemented in practice. The quartz filters Western Electric manufactured during the 1930s were for Bell System use only, so the marketplace never saw them. Nevertheless, the size of this internal market was enormous, requiring a vast amount of quartz crystal.

One additional change occurring in the late 1920s and early 1930s was BTL's invention of the quartz crystal clock. This technology quickly made the pendulum clock obsolete, a change which affected only the scientific and military communities for the next several decades. In the late 1960s, however, the technical groundwork laid by the crystal clock made possible the development of the affordable quartz wristwatch. Developments in miniaturization and integrated circuitry were necessary to make the quartz wristwatch a practical reality, but the original crystal clock proved the feasibility of quartz-based timekeeping.

6.4 General Radio develops the plug-in quartz plate, preparing the way for dedicated QCU companies

It didn't take long for designers of the piezoelectric resonator in the 1920s to realize the utility of offering it in a hermetically sealed case with standardized plugs. By designing it as an easy-to-use plug-in component, engineers at the General Radio Company transformed the resonator from an experimental curiosity into a reliable, off-the-shelf component. Electronics research labs desiring a reliable local frequency standard could now purchase a piezo-oscillator having a standard plug-in slot for inserting the quartz resonator. If one resonator went bad or cracked, a new one could easily be inserted. And radio broadcast stations could similarly purchase transmitters having a standard plug-in slot for the resonator; all stations routinely kept a backup resonator on hand so that a cracked resonator wouldn't keep the station off the air.

The General Radio Company (GR) of Cambridge, MA pioneered the manufacture of standardized piezoelectric resonators in 1925, the same year that the company released the first commercially available piezoelectric oscillator.[308] Calling them "quartz plates," GR's product, shown in Figure 22, consisted of a carefully cut, grounded and polished quartz crystal wafer, a crystal holder or mounting, and a pair of electrical plugs for inserting the unit into the desired device, whether that be a piezo-oscillator or a broadcast transmitter. For the remainder of the 1920s, GR dominated the U.S. market for quartz plates; most were used in broadcast radio or in primary and secondary frequency standards. One mark of this dominance was the establishment of the General Radio quartz plate plug style as a de facto industry standard. By the early 1930s, all quartz plate manufacturers were conforming to this standard, using GR plugs spaced ¾" apart, as shown in Figure 23. Yet, the markets that GR catered to – broadcast radio stations and scientific and engineering laboratories - were never large. Most radio stations needed only two plates, the one in use and a backup. The same held for laboratories that used

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[308] Bulletin 715 of the General Radio Company, November 1925, Box 3, Records of the National Institute of Standards and Technology, General Records of J. Howard Dellinger, Record Group 167, U.S. National Archives, College Park, MD.

piezo-oscillators as frequency standards. By 1926, however, a market for quartz plates had begun to emerge that would, for a time, dwarf these and all others. The size of this market, consisting of amateur radio operators, would allow for a greater division of labor among producers of quartz crystal technology.

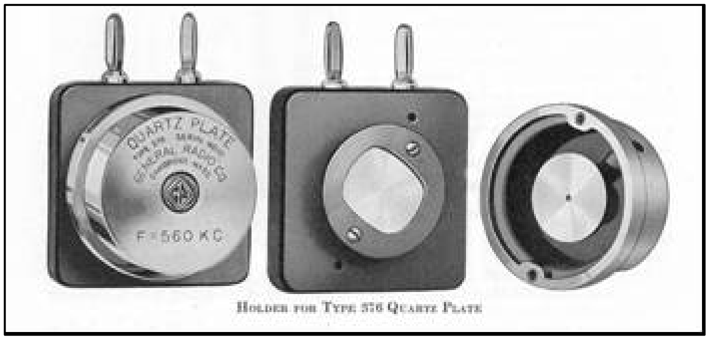

Figure 22: Exploded View of General Radio Co. Quartz Crystal Unit, Circa 1930
(Reprinted, by permission of the General Radio Historical Society, from General Radio Company, *Catalog F*, 1930. http://www.teradyne.com/corp/grhs/)

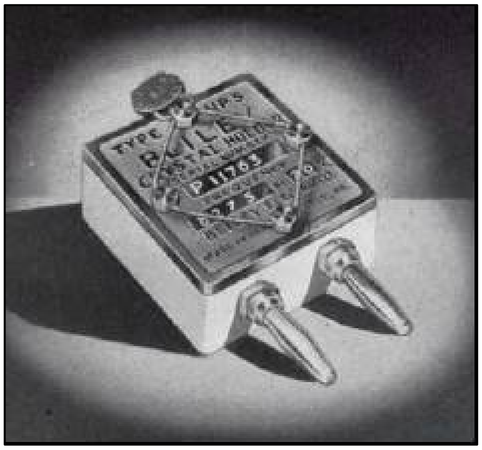

Figure 23: Bliley Electric Co. VP5 QCU with Standard G.R. Plugs Spaced ¾” Apart, Circa 1936
(Reprinted, by permission of C. Bliley, from Bliley Electric Catalog G-9, 1936, ©2009, C. Bliley, Bliley.net/XTAL)

6.5 Radio amateurs and the rise of dedicated QCU manufacturers

In 1926, American amateur radio was already well over a decade old, with the American Radio Relay League (ARRL), the premier organization for amateur radio operators, having been established in 1914.[309] The number of licensed operators had since grown to over 15,000. In 1926, the number of U.S. licensed broadcast stations was just over 600.[310] Thus, the potential amateur market for quartz plates was roughly twenty-five times that of the broadcast market, and growing. Yet amateurs were slow to purchase manufactured plates. The prevailing ethic among amateurs of the time was experimentation and do-it-yourself. When faced with the option of purchasing a ready-made plate or making one's own, many amateurs opted for the latter, not the least reason for which was the high cost of early quartz plates (as high as $50 for a crystal ground to within +/- 0.1% of a specified frequency) and the limited budgets of most amateurs.[311]

Adventurous amateurs were aided in making their own plates by a number of articles appearing in amateur-focused magazines. These articles showed how to cut and finish a crystal plate, how to construct a crystal holder, and how to design and build crystal-controlled transmitter circuits.[312] But GR guessed that not all amateurs were patient enough to build their own plates from scratch. For these users, GR began offering in 1926 quartz plates ground to approximate frequencies in the 160 meter (1715-2000

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[309] *American Radio Relay League Home Page*, (Accessed 10 June 2007) available from http://www.arrl.org/aarrl.html; Internet.

[310] ———, "The Influence of Amateur Radio on the Development of the Commercial Market for Quartz Piezoelectric Resonators in the United States" (*Proceedings of the 50th Annual IEEE Frequency Control Symposium*, U.S. Army Research Laboratory, Forth Monmouth, NJ, 5-7 June 1996), 58-65.

[311] General Radio Company. "Catalog E." (Cambridge, MA, 1928), Available at http://www.teradyne.com/corp/grhs/, Accessed 14 August 2006.

[312] Patrick R. J. Brown, "The Influence of Amateur Radio on the Development of the Commercial Market for Quartz Piezoelectric Resonators in the United States" (*Proceedings of the 50th Annual IEEE Frequency Control Symposium*, U.S. Army Research Laboratory, Forth Monmouth, NJ, 5-7 June 1996), 58-65.

kHz) amateur band. At $15 each, the GR Type 276-A quartz plate was not ready to use.[313] The amateur still had to mount the plate in a suitable holder. Nevertheless, the purchase of a pre-ground plate saved the amateur the considerable hassle of cutting and grinding his or her own plate from a chunk of raw quartz.

General Radio found a sizeable and growing market among amateurs for pre-ground quartz plates. It had this market to itself for a few years, but in the late 1920s and early 1930s numerous specialty firms formed to meet the growing demand for inexpensive quartz crystal units (QCU's), as quartz plates had come to be called. These firms were scattered throughout the country, and many of them were started by entrepreneurial radio amateurs grinding crystals for their friends. Among the more successful of these firms were A.E. Miller Laboratories (est. 1928), Monitor Piezo Company (est. 1928), Bliley Electric (est. 1930), Valpey-Fisher (est. 1931), and Standard Piezo Company (est. 1938), most of which remain in business in the early 21st century.[314]

Among the most successful of the dedicated QCU manufacturers was Bliley Electric, established in 1930 by F. Dawson Bliley, himself an amateur radio operator.[315] Though the U.S. had just entered the most severe economic depression in its history, amateurs still wanted crystals, and often more than one. In contrast to broadcast stations, amateur operators were not limited to only one transmitter frequency. Thus, the more

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[313] "Quartz Plates Available to Amateurs," *The General Radio Experimenter* 1, no. 3 (December 1926).

[314] ———, "The Influence of Amateur Radio on the Development of the Commercial Market for Quartz Piezoelectric Resonators in the United States" (*Proceedings of the 50th Annual IEEE Frequency Control Symposium*, U.S. Army Research Laboratory, Forth Monmouth, NJ, 5-7 June 1996), 58-65. Also, see Chapter 4 of Richard J. Thompson Jr., *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006). According to company websites, Bliley Electric and Valpey Fisher are still in business today. Standard Piezo is now Hoffman Materials, and Monitor Piezo was purchased in 2002 by MMD Components. No current information can be found on A.E. Miller Laboratories.

[315] Charles A. Bliley, *The Bliley Electric Company: The Early Years 1930-1955 (2001).* [Web site] (Accessed 28 May 2007) available from http://www.bliley.net/XTAL/; Internet.

experience an amateur had, the more crystals he or she was likely to own. A Bliley survey of amateur operators in 1936 indicated that most amateurs owned between three and five QCU's.[316]

Through the early 1930s, Bliley's business thrived, and in 1935 the company hired a staff engineer by the name of John Martin Wolfskill. A former BTL engineer who had been laid off as the Depression worsened, Wolfskill was already familiar with QCU design when he came to work for Bliley.[317] Over the next several years, this talented and creative engineer invented a number of devices and techniques that would come to strongly influence the art of QCU design and manufacture. Most of these inventions aimed at either giving amateurs more value for their money or at economizing the QCU production process. Thus, it is easy to see why organizations not focused on the budget-minded amateur market – the Bureau of Standards, the Naval Research Laboratory, or Bell Telephone Laboratories – failed to innovate in these areas.

Perhaps Wolfskill's single most influential invention was the overtone crystal, so named because it was cut in such a way that the crystal could be operated at an overtone or harmonic of its fundamental frequency.[318] This permitted operation of the QCU in the then-popular 20 meter (~15 MHz) amateur band without the need for a costly and cumbersome frequency doubler or multiplier. The commercial value of this patent was suggested by an interference suit that R.C.A. filed against Wolfskill.[319] The suit was

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[316] ———, *A Survey of the Use of Quartz Crystals in the Amateur Radio Service, Produced July 1936 by The Bliley Electric Company.* (Accessed 28 May 2007) available from http://www.bliley.net/XTAL/; Internet.

[317] Sallie Wolfskill Smith, *The Life of John Martin Wolfskill (2002).* [Web site] (Accessed 28 May 2007) available from http://www.bliley.net/XTAL/; Internet.

[318] John M. Wolfskill, *Piezoelectric Crystal*, U.S. Patent Office, Patent No. 2,157,808, Filing Date: 27 August 1935; Issue Date: 9 May 1939.

[319] Sallie Wolfskill Smith, *The Life of John Martin Wolfskill (2002).* [Web site] (Accessed 28 May 2007) available from http://www.bliley.net/XTAL/; Internet.

eventually decided in Wolfskill's favor, but the issuing of the patent was delayed by at least two years.

Among other of Wolfskill's inventions was a series of variable frequency QCU's, which allowed the user to combine crystal-controlled precision with the freedom to vary the unit's natural frequency over a pre-determined range.[320] These units showed some commercial promise in the late 1930s, but failed to take hold within the amateur market before the onset of World War II. After the war, single-frequency surplus military QCU's glutted the amateur market, effectively dooming Bliley's variable frequency QCU.

One other Wolfskill invention, the acid etch-to-frequency process for setting a quartz crystal wafer to a specified frequency, achieved widespread use during the Second World War.[321] Referred to by Bliley in late 1930s marketing campaigns as the mysterious-sounding "X-Lap" process, the company attributed the high reliability, long life, and high accuracy of its QCU's to the etch-to-frequency process. But the process had another very practical benefit for the company. It reduced the number of persons hired to hand polish, or lap, quartz plates, thereby reducing Bliley's labor costs. Wolfskill was working within a highly competitive, relatively high volume, and budget-minded industry – providing affordable QCU's to tens of thousands of amateur radio operators. The pressures to economize acting upon Wolfskill created a favorable environment under which labor-saving techniques were likely to develop. Talented

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[320] See U.S. patents (2,079,540), (2,224,700), (2,240,449), and (2,240,450).

[321] John M. Wolfskill, *Piezoelectric Crystal Apparatus*, U.S. Patent Office, Patent No. 2,364,501, Filing Date: 4 April 1941; Issue Date: 5 December 1944. The use of this patent during World War II is discussed further in Chapter 7 of this dissertation.

engineers such as Wolfskill were perfectly positioned to respond creatively to these pressures.

The experience of Bliley Electric in the 1930s shows that invention and innovation in the quartz crystal industry was not limited to government laboratories or lavishly funded industrial R&D labs. Important innovation occurred among small producers catering to the amateur radio market. Not surprisingly, however, innovation also occurred in large R&D labs, most notably AT&T's Bell Telephone Laboratories (BTL). Toward the end of the 1920s, BTL engineers began experimenting with a new quartz application – wave filters – that by the 1940s would come to consume nearly as much raw quartz as all other piezoelectric quartz applications combined.

6.6 Walter Cady's invention of the narrowband quartz wave filter

To appreciate the use of quartz in electric wave filters, it is necessary to first give a brief and highly simplified introduction to wave filter technology. Electric wave filters are two-port, frequency-selective electrical circuits. One port is referred to as the input port; the other is the output port. If a complex electrical signal containing multiple frequencies is applied to the input port, then the signal available at the output port is a filtered version of the original signal. That is, the frequency content of the output signal will generally be more restricted than that of the input signal. A common example is the use of a low-pass filter (i.e., a filter that passes low frequencies while blocking high frequencies) to remove the high-frequency hiss produced by magnetic audio cassette tapes, as illustrated later in Figure 33. Another common example is the bandpass filter, shown earlier in Figure 29, which passes frequencies lying in a given band but blocks all frequencies lower and higher than this band. In general, the band of frequencies passed by a wave filter is referred to as the passband, while the band or bands of frequencies blocked by a filter are known as stopbands.

Before the invention of the quartz wave filter, most electric wave filters were constructed using only capacitors (a.k.a. condensers) and inductors (a.k.a. coils). As shorthand, electrical engineers represented a capacitor with the letter “C” and an inductor with the letter “L.” Thus, these filters were known as L-C filters. For many applications, L-C filters worked well, but the physical limitations of inductor construction made it very difficult for engineers to design and build filters exhibiting sharp transitions between the passband and stopband. Wave filters constructed with quartz crystals promised to remove this difficulty.

Walter Cady was the first, in 1920, to conceive of using piezoelectric crystals as wave filters. In his patent application for the piezo-electric resonator, he suggested that it could be used “for such purposes as coupling one high frequency circuit to another, in order to transmit energy from one to the other circuit at a certain particular frequency.”[322] A year later, in a presentation before the New York meeting of the Institute of Radio Engineers (I.R.E.), Cady referred to this application as a “tuned mechanical coupling between two circuits.”[323] Radio engineers of Cady’s time referred to this use as a “single signal” filter.[324] Today’s engineers would use the term narrowband filter, meaning that it passes only a very narrow range of signal frequencies while blocking all others, as shown

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[322] Walter Guyton Cady, *Piezo Electric Resonator*, U. S. Patent Office, Patent No. 1,450,246, Filing Date: 28 January 1920; Issue Date: 3 April 1923.

[323] ———, "The piezo-electric resonator," *Proceedings Of The Institute Of Radio Engineers* 10, no. 2 (April 1922): 83-114.

[324] Bliley Electric Company, *General Catalog G9 (1939).* [JPEG File] (Bliley Electric Company, Accessed 28 May 2007) available from http://www.bliley.net/XTAL/; Internet.

in Figures 24-26. The degree to which a bandpass filter selects out one frequency while rejecting others (i.e., its frequency selectivity) is measured by a parameter known as the quality factor, or Q. While the filters in Figures 24-26 have Q values of 1, 10, and 100 respectively, the Q of a quartz crystal wave filter can be one million or higher. Such a highly selective bandpass filter had some uses (e.g., as a "single signal" intermediate frequency filter in a super-heterodyne radio receiver) in the 1920s, but most applications required filters having a wider bandwidth. Even so, Cady's idea was intriguing, for if the bandwidth of the quartz filter could somehow be widened while still preserving sharp frequency cutoffs, the potential uses would be many.

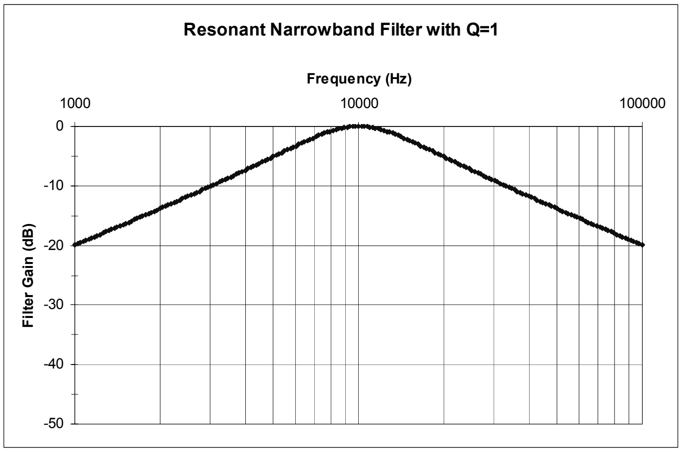

Figure 24: Narrowband Filter: Resonant Frequency = 10 kHz, Quality Factor = 1
(Figure created by author.)

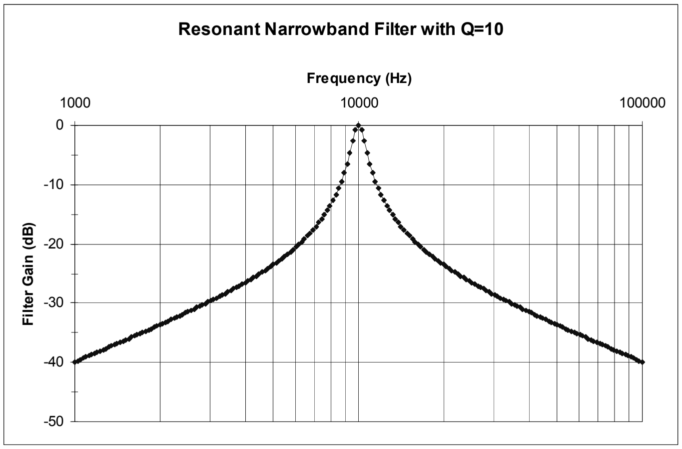

Figure 25: Narrowband Filter: Resonant Frequency = 10 kHz, Quality Factor = 10
(Figure created by author.)

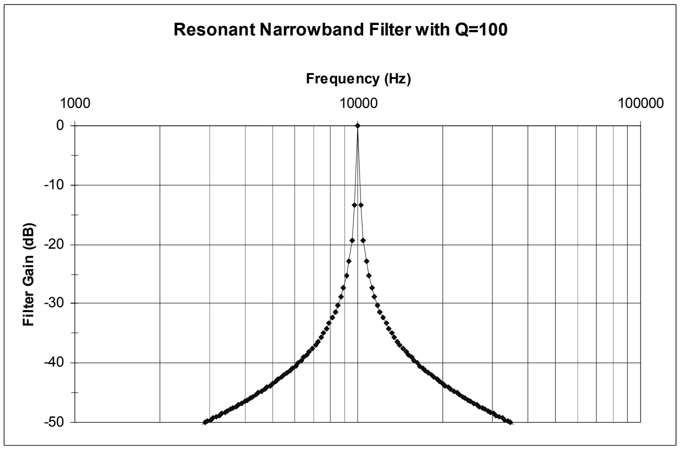

Figure 26: Narrowband Filter: Resonant Frequency = 10 kHz, Quality Factor = 100
(Figure created by author.)

6.7 Bell Telephone Labs (BTL) engineers develop the wideband quartz wave filter

The value of bandpass wave filters with extremely sharp cutoffs was well-known to Bell System engineers in the 1920s. During World War I, AT&T had developed the concept of the carrier multiplex telephony system, in which multiple and independent telephone messages were sent simultaneously over a single wire or cable. The system worked as follows. At the transmitting end of a cable, a number of messages (e.g., conversations, music, data, etc.) were brought together and each message assigned its own communications channel. To be placed on its channel, a particular message was used to modulate that channel's carrier frequency (e.g., 60 kHz). The channel's carrier frequency was designated as such because it, in a sense, carried its message safely to the reception end of the cable. To prevent crosstalk between adjacent channels, each channel was separated in frequency from its two neighbors by a guard band, as illustrated in Figure 27, where a message bandwidth of 3.2 kHz and a guard bandwidth of 0.8 kHz (i.e., 0.4 kHz on either side of the message band) have been assumed. This method of bringing multiple messages together, assigning each its own carrier frequency, and placing them all on a common transmission medium is today called frequency division multiplexing (FDM).[325] In theory, this method was identical to the way that broadcast radio stations came to be allocated in the radio spectrum, the only difference being the transmission medium. In radio, the medium was free space; in multiplex telephony, the medium was an electric wire or cable.

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[325] Dennis Roddy and John Coolen, *Electronic Communications*, Third ed. (Reston, VA: Reston Publishing Company, 1984), 311-13.

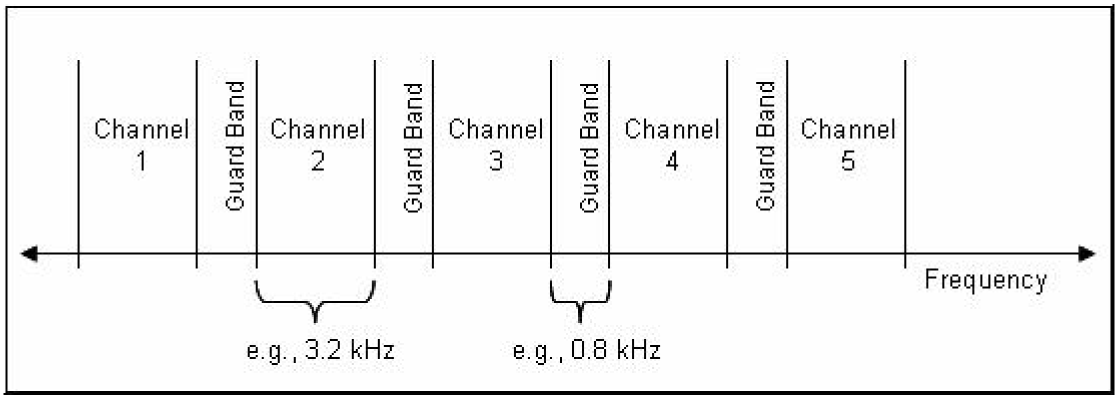

Figure 27: Frequency Division Multiplexed Telephony Signal
(Figure created by author.)

At the receiving end of the transmission cable, the composite FDM signal, comprised of many message channels, was de-multiplexed. That is, each channel was separated out from the composite signal so that it could be received and listened to independently of the others. The crucial component that performed this separating function was the bandpass filter. If this filter exhibited a gradual transition from passband to stopband, as illustrated in Figure 28, valuable bandwidth was wasted because the width of the guard band between adjacent channels had to increase in order to prevent crosstalk. Such was the case with most L-C filters. By contrast, sharp transitions between the passband and stopband, as illustrated in Figure 29, conserved bandwidth by permitting narrower guard bands. Consequently, channels could be packed more tightly together, allowing more simultaneous telephone conversations to be transmitted over a given spectral band. Herein lay the value of the quartz wave filter for AT&T. By making possible the design of sharp cutoff bandpass filters, this small, inconspicuous device had the power to significantly increase the capacity, and hence lower the cost, of the company's long-distance telephony service.

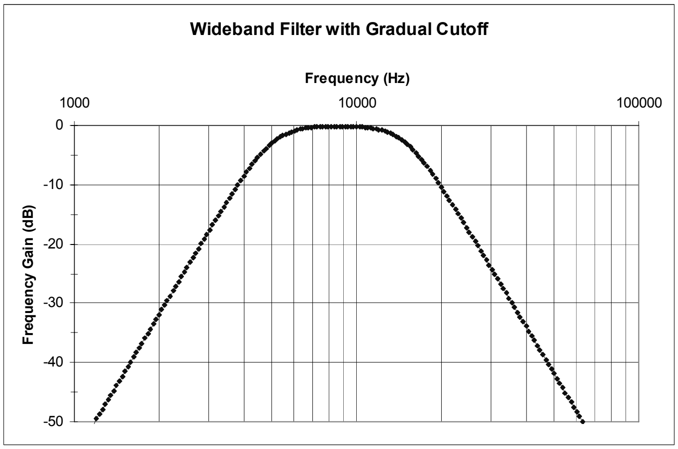

Figure 28: Frequency Response of a Gradual-Cutoff Wideband Filter Not Employing Quartz Crystal Wave Filters
(Figure created by author.)

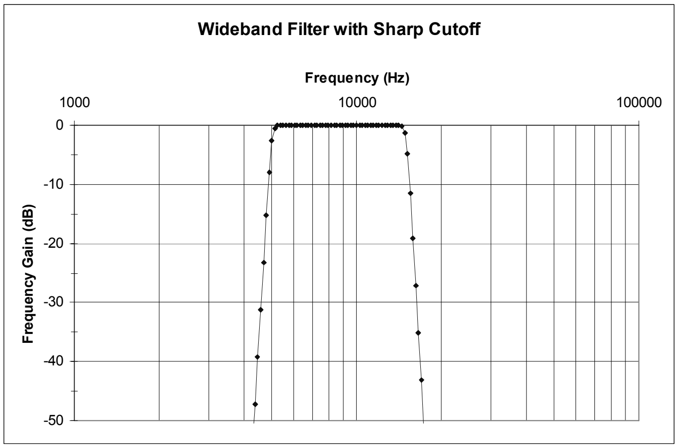

Figure 29: Frequency Response of a Sharp-Cutoff Wideband Filter Employing Quartz Crystal Wave Filters
(Figure created by author.)

AT&T built the first successful carrier multiplex system between Pittsburgh and Baltimore during the First World War.[326] It employed open wire transmission lines,

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[326] E. H. Colpitts and O. B. Blackwell, "Carrier Current Telephony and Telegraphy," *Transactions of the American Institute of Electrical Engineering* (1921): 205-300.

which could accommodate up to four simultaneous voice channels.[327] Prior to this development, long-distance telephony had been, in many cases, prohibitively expensive, as each long-distance telephone call had to reserve an entire transmission line to itself for the duration of the call. The development of carrier multiplex telephony made long-distance service more economical, but AT&T's long-distance capacity was still quite limited.

In the 1920s, AT&T engineers began investigating technical strategies for increasing the capacity of its long-distance transmission lines beyond three or four voice channels. Engineers faced two major technical hurdles. First, they needed to find a higher bandwidth and more electrically secure replacement for open wire transmission lines, which exhibited moderate bandwidth and were susceptible to electrical interference. Second, engineers had to develop means for more efficiently using the spectrum available on their transmission lines; in others words, they had to find a way to more tightly pack voice channels into the available bandwidth. One means for achieving this was to employ bandpass wave filters having very sharp cutoffs. At the time, however, no one knew how physically to realize such filters.

In 1927, two men, one working for AT&T and the other for R.C.A., independently developed bandpass wave filter circuits having very sharp cutoffs similar to those shown in Figure 29. Lloyd Espenschied of AT&T developed circuits employing multiple quartz crystals as well as standard capacitors and inductors, as shown in Figure 30. These circuits exhibited much wider bandwidths than those of Cady and were thus

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[327] Lloyd Espenschied and Herman A. Affel, *Concentric Conducting System*, U. S. Patent Office, Patent No. 1,835,031, Filing Date: 23 May 1929; Issue Date: 8 December 1931. See lines 36-59.

more practical for telephony circuits.[328] Clarence Hansell of R.C.A. had a different idea. Working in the context of radio rather than telephony, Hansell placed several quartz crystals in parallel, as illustrated in Figure 31, each crystal having slightly different natural frequencies, such that the total effect was that a range of frequencies were passed rather than a single frequency.[329] Whether used in telephony or in radio, these quartz filters helped to increase the message capacity of transmission media. Though the transmission media differed in the two cases, both systems employed FDM to simultaneously transmit multiple messages.

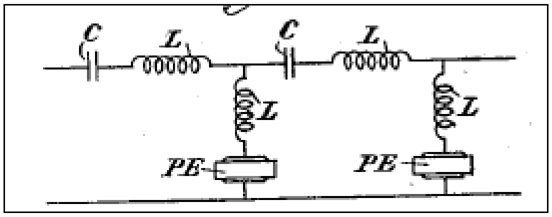

Figure 30: Bandpass Wave Filter Circuit Employing Quartz Crystals (PE), Inductors (L), and Capacitors (C)
(Source: Lloyd Espenschied, U.S. Patent 1,795,204; "Electric Wave Filter"; March 3, 1931.)

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[328] Lloyd Espenschied, *Electrical Wave Filter*, U. S. Patent Office, Patent No. 1,795,204, Filing Date: 3 January 1927; Issue Date: 3 March 1931.

[329] Clarence W. Hansell, *Filter*, U. S. Patent Office, Patent No. 2,005,083, Filing Date: 7 July 1927; Issue Date: 18 June 1935.

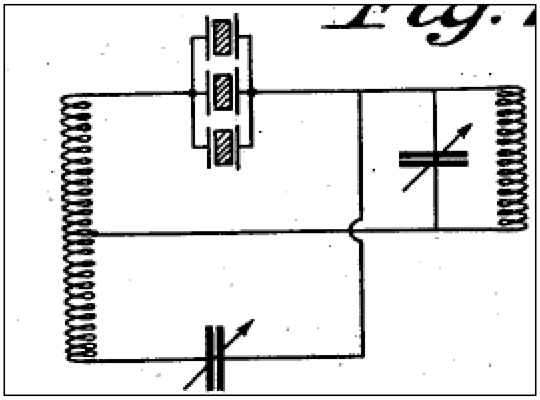

Figure 31: Bandpass Wave Filter Circuit Employing 3 Parallel Quartz Crystals, Each Having Slightly Different Natural Frequencies
(Source: Clarence W. Hansell, U.S. Patent 2,005,083; "Filter"; June 18, 1935.)

The work of these two men showed that their employers – AT&T and R.C.A. – were investing significant R&D dollars into quartz crystal. In fact, AT&T had begun investing in quartz and other piezoelectric crystals just after World War I, when Alexander Nicolson developed his pioneering Rochelle Salt devices. By the early 1920s, Bell Labs had established an independent department dedicated to piezoelectric research.[330] The early interest of these two firms in quartz crystal was tied to their heavy investments in broadcast radio, as shown in Chapter 4. But AT&T sensed that quartz might also prove of value to its telephony business. Thus, when AT&T withdrew from the broadcast radio business in 1926, the company continued its R&D investment in piezoelectric materials.

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[330] Virgil E. Bottom, "A History of the Quartz Crystal Industry in the USA" (*Proceedings of the 35th Annual Frequency Control Symposium*, Philadelphia, PA, 27-29 May 1981), 3-12.

6.8 BTL engineers fundamentally advance quartz crystal engineering knowledge

Over the next decade and a half, numerous Bell Labs researchers made important contributions to quartz crystal technology. Warren P. Mason developed high-pass and low-pass quartz wave filters, whose frequency responses are shown in Figures 32 and 33, adding flexibility to the company's multiplex carrier telephony systems.[331] The company's quartz innovations also influenced applications other than telephony. For example, researcher George Thurston tackled the problem of quartz crystal units (QCU's) changing their frequency as they were shipped from factory to place of installation. This problem stemmed from the fact that a QCU's frequency was partly a function of the electrical coupling between the crystal and the electric circuit in which it was used. This coupling was governed largely by the QCU's mounting mechanism. If the crystal shifted in its mounting while being transported, its frequency would change. Thurston developed a shock-resistant crystal mounting, shown in Figure 34, in which the crystal plate was firmly clamped along its edges.[332] This mounting turned out to be effective enough to allow QCU's to be used for the first time in high-vibration environments such as airplanes.[333] Consequently, Thurston's invention proved enormously important to the nascent commercial airline industry.

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[331] W. P. Mason, *Wave Filter*, U. S. Patent Office, Patent No. 1,921,035, Filing Date: 30 September 1931; Issue Date: 8 August 1933.

[332] George M. Thurston, *Piezo-Electric Crystal Mounting*, U. S. Patent Office, Patent No. 1,883,111, Filing Date: 14 August 1929; Issue Date: 18 October 1932.

[333] Raymond A. Heising, ed., *Quartz Crystals for Electrical Circuits, Their Design and Manufacture* (New York: Van Nostrand Company, 1946), 5.

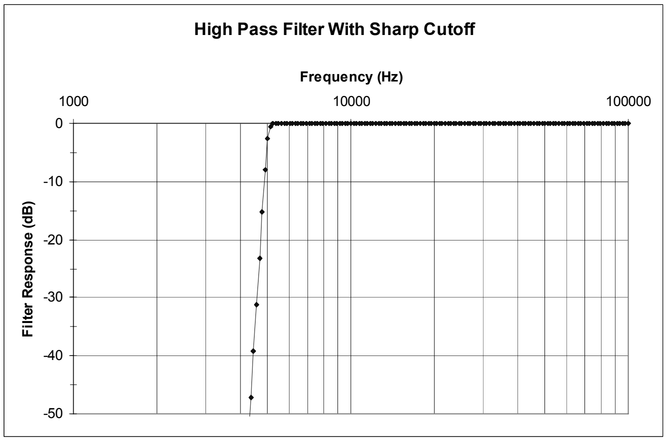

Figure 32: Frequency Response of a Sharp-Cutoff High-Pass Filter Employing a Quartz Crystal Wave Filter

(Figure created by author.)

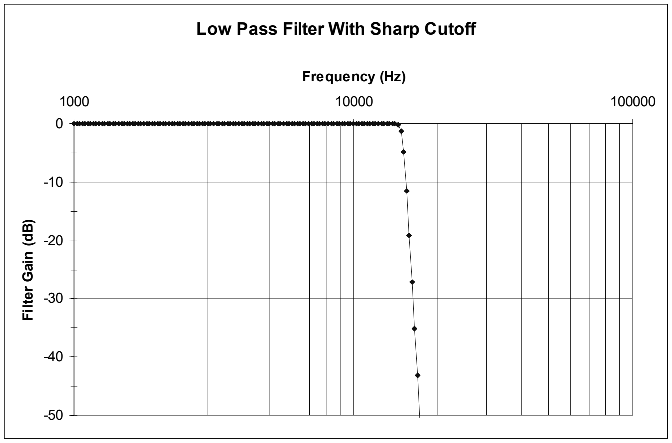

Figure 33: Frequency Response of a Sharp-Cutoff Low-Pass Filter Employing a Quartz Crystal Wave Filter

(Figure created by author.)

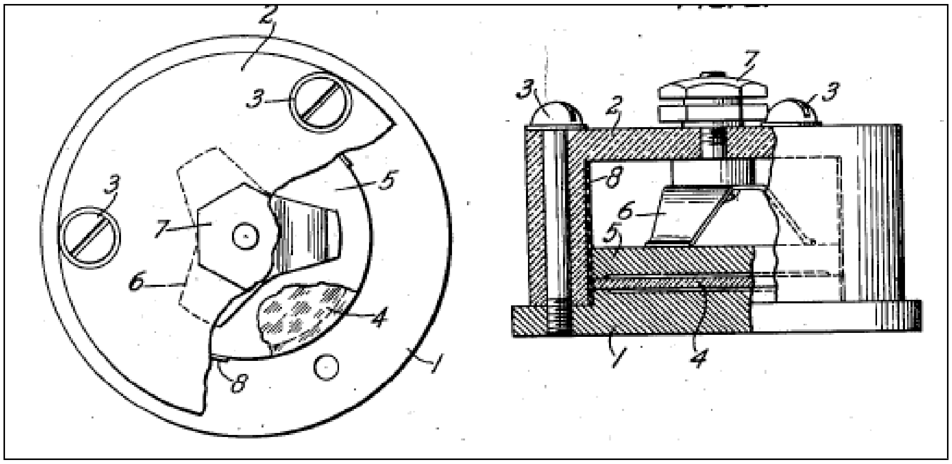

Figure 34: Piezo-Electric Shock-Resistant Crystal Mounting, Top View (L) and Side View (R)
(The circular crystal (4) is clamped at its edges by conducting electrodes 1 and 5. Electrodes do not make physical contact with crystal other than at its edges. The pressure of clamping is set by spring retainer (6) and screw (7). Source: George M. Thurston, U.S. Patent 1,883,111, "Piezo-Electric Crystal Mounting," October 18, 1932.)

Probably the single most consequential Bell Labs quartz breakthrough of the 1920s occurred in 1928. Engineer Warren Marrison was drawn to the problem of a quartz crystal wafer's temperature coefficient of frequency. Measured in Hertz per degree Celsius, the temperature coefficient of frequency quantitatively characterized the drifting of a quartz wafer's natural resonant frequency as its ambient temperature changed. Because of this drift, applications requiring highly stable frequencies, such as broadcast radio, required that the QCU controlling the frequency be placed in a costly thermostatic temperature control chamber. If a wafer's temperature coefficient of frequency could somehow be made very close to zero, then the need for such a chamber would diminish. This would have the effect of both lowering the cost and increasing the mobility of crystal-controlled radio transmitters. Marrison found that he could do precisely this by cutting crystal wafers from a raw quartz slab in a way that achieved certain angles with respect to the quartz slab's intrinsic crystal lattice orientation.[334] Furthering Marrison's research, several researchers, including Raymond Heising, F. R. Lack, G. W. Willard, I. E. Fair, Roger Sykes, and Warren Mason developed new crystal orientations, or "cuts," throughout the 1930s that progressively lowered crystal wafer temperature coefficients.[335] This line of research culminated in 1940 with the development of the GT-cut crystal, a zero-temperature coefficient cut which altogether eliminated the need for thermostatic temperature control of QCU's.[336]

AT&T's focused piezoelectric quartz research efforts thus yielded tremendous returns. More than any other single organization, AT&T, and specifically its Bell Telephone Laboratories, advanced the art of piezoelectric quartz technology during the interwar years. One major reason for this is that few, if any, organizations had either an R&D budget or a cadre of scientific and technical personnel equal to those of AT&T during these years. As Lillian Hoddeson and Michael Riordan have noted, "nothing on the scientific landscape at the time compared with Bell Labs. It combined intellectual power equal to that of the nation's best science departments with technical resources and manpower that none of them could come close to matching."[337] While Hoddeson and Riordan were speaking specifically of the late 1940s, their characterization also applies in

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[334] Warren A. Marrison, *Piezo Electric Crystal*, U. S. Patent Office, Patent No. 1,899,163, Filing Date: 19 December 1928; Issue Date: 28 February 1933. This method of cutting quartz wafers was used in the construction of the primary frequency standard that Bell Labs developed for the Bureau of Standards. See Chapter 5 of this dissertation. See also Marrison patents 1,907,425-1,907,426.

[335] Raymond A. Heising, *Piezo-electric Crystals having low temperature coefficients of frequency*, U. S. Patent Office, Patent No. 1,958,620, Filing Date: 2 April 1929; Issue Date: 15 May 1934. F. R. Lack, G. W. Willard, and I. E. Fair, "Some Improvements in Quartz Crystal Circuit Elements," *Bell System Technical Journal* 13 (1934): 453-63. W. P. Mason and R. A. Sykes, *Piezoelectric Apparatus*, U. S. Patent Office, Patent No. 2,173,589, Filing Date: 14 December 1933; Issue Date: 19 September 1939.

[336] W. P. Mason, "New Quartz Crystal Plate, Designated the GT, Which Produces a Very Constant Frequency Over a Wide Temperature Range," *Proceedings Of The Institute Of Radio Engineers* 28 (May 1940): 220-23.

[337] Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age*, First ed., Sloan Technology Series (New York: W.W. Norton & Company, 1997), 280.

large extent to the 1930s. AT&T's "lucrative monopoly on the nation's telephone services," which was in place by the second decade of the 20th century, was largely responsible for the generous funding received by BTL.[338]

Yet, just as important as AT&T's unparalleled resources was its commercial motivation to develop quartz technology. BTL engineers found an application of quartz wave filters that contributed directly to expanding the capacity of AT&T's long-distance telephony system. Other firms, such as G.E., Dupont, and Westinghouse, had scientific and technical resources that, while not equal to those of AT&T, were formidable nonetheless. Yet none of these firms had a similar commercial motivation for developing quartz technology.[339] Furthermore, in conducting its quartz research, Bell Labs succeeded in converting the fruits of fundamental scientific research into technological development and the expansion of AT&T's telephony network. The design and development of quartz wave filters exemplified this conversion process. Other firms of the time, such as Westinghouse, were less successful in linking fundamental and applied scientific research.[340]

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[338] Ibid., 281.

[339] General Electric began large-scale production of QCU's in 1935. As most of these were likely used for frequency stability in radio transmitters, an application that was fairly mature by this time, quartz innovation was not as strong at G.E. as at Bell Labs. Source: Virgil E. Bottom, "A History of the Quartz Crystal Industry in the USA" (*Proceedings of the 35th Annual Frequency Control Symposium*, Philadelphia, PA, 27-29 May 1981), 3-12.

[340] See Leonard Reich, *The Making of American Industrial Research: Science and Business at G.E. and Bell, 1876-1926* (New York: Cambridge University Press, 1985). On research and development at Westinghouse during the interwar period, see Thomas C. Lassman, "Industrial Research Transformed: Edward Condon at the Westinghouse Electric and Manufacturing Company, 1935-1942," *Technology and Culture* 44, no. 2 (April 2003): 306-39.

6.9 AT&T deploys high-capacity multiplex carrier telephony infrastructure

After its invention by Espenschied and Hansell, the quartz crystal wave filter languished for roughly a decade before AT&T integrated it into its existing multiplex carrier telephony system. In order to fully exploit the gains in capacity made possible by the filters, AT&T needed to develop transmission lines of higher bandwidth and more electrical security. The approach upon which the company placed its money and hopes was a new transmission system, patented by Espenschied and Herman Affel in 1931, that featured coaxial cable.[341] The bandwidth of coaxial cable was, at minimum, many Megahertz (i.e., thousands of kilohertz), ensuring that hundreds of simultaneous voice channels could be transmitted. Furthermore, coaxial cable carried the added advantage of being immune to ambient electrical interference.

The combination of quartz crystal wave filters and coaxial cables promised to make high-capacity multiplex carrier telephony a commercial reality for AT&T. But it took several years before practical systems could be built and operated. In the meantime, quartz wave filter technology found its way into the amateur radio community. In 1932, an article appeared in QST magazine written by James Lamb, the magazine's technical editor.[342] This article described how to use a highly frequency-selective quartz wave filter in the intermediate frequency (IF) stage of a super-heterodyne receiver. Serving as a narrowband wave filter, the quartz device allowed the receiver to pick up only one coded station (i.e., the signal was in Morse code rather than voice) at a time and to filter out all others. In 1934, Bliley Electric began offering its BC3-SSF 525 kHz single signal

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[341] Lloyd Espenschied and Herman A. Affel, *Concentric Conducting System*, U. S. Patent Office, Patent No. 1,835,031, Filing Date: 23 May 1929; Issue Date: 8 December 1931.

[342] James J. Lamb, "Short-Wave Receiver Selectivity to Match Present Conditions: Constructional and Operating Features of the Signel-Signal Superhet," *QST* 16, no. 8 (1932).

filter for $5.90, allowing average amateurs to replicate Lamb's receiver design.[343] The BC3 was a success, leading many amateurs to use quartz crystals not only in their transmitters, but also in their receivers.

As AT&T engineers continued developing multiplex carrier telephony in the 1930s, they realized that, in addition to using quartz wave filters on the reception end of the transmission system, it would be necessary to use highly-stable quartz oscillators, identical to the ones used in broadcast radio transmitters, for generating the high-frequency carrier waves at the transmitting end of the system. Throughout the 1930s, AT&T conducted experimental trials with the new system, including a highly publicized trial linking the cities of New York and Philadelphia in 1936. This system, employing coaxial cable as well as quartz filters at both transmission and reception ends, proved capable of transmitting 240 simultaneous telephone conversations.[344]

Bolstered by the success of the New York-Philadelphia trial, AT&T proceeded to implement multiplex carrier telephony on a massive scale. In 1938, Western Electric (W.E.) began the full-scale manufacture of twelve different quartz wave filter designs.[345] These filters were used to construct channel banks, systems for multiplexing twelve voice channels and using them to modulate carrier frequencies. Tens of thousands of such channel banks were installed throughout the Bell system to bring long-distance multiplex carrier telephony online. W.E.'s quartz wave filters did not employ QCU's as used in piezo-oscillators and AFCU's. One reason for this was that there would have been little point in providing a standardized plug-in connection for the filter's crystals. Wave filters

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[343] November 20, 1934 Bliley Electric Company catalog. http://www.bliley.net/XTAL

[344] "Radio Progress during 1936: Part IV – Report by the Technical Committee on Television and Facsimile," *Proceedings of the Institute of Radio Engineers* 25, no. 2 (February 1937): 203-4.

[345] Thomas H. Simmonds Jr., "The Evolution of the Discrete Crystal Single-Sideband Selection Filter in the Bell System," *Proceedings of the IEEE* 67, no. 1 (January 1979): 109-14.

were installed in channel banks and placed in operation in the field. The units were designed to be very low maintenance. Barring a malfunction, there would have been no need to insert new crystals having different natural frequencies. Another reason why W.E.'s wave filters didn't employ QCU's was the degree of vertical integration that the company employed. With the exception of the mining of raw materials, W.E. built everything in its system, from the channel bank down to the quartz wafers used in the wave filters. There was no incentive for the company to use QCU's whose plug style conformed to a de facto industry standard (i.e., General Radio plugs spaced ¼" apart).

In June 1941, AT&T placed into commercial service a permanent coaxial cable telephony service linking Stevens Point, Wisconsin with Minneapolis, Minnesota. Called the type L-1 carrier system, the service was the first of its kind in the United States and featured a capacity of 480 simultaneous voice channels.[346] The service was quickly replicated throughout the U.S. Such a system would have been inconceivable without both highly-stable quartz oscillators and quartz crystal wave filters, which allowed for dense packing of voice channels into coaxial cable's available bandwidth.

By the time of America's entry into World War II, the amount of piezoelectric quartz crystal used in AT&T's telephony system was on par with that used for frequency stabilizers in broadcast and amateur radio. Furthermore, the numbers of quartz wave filters produced was approaching parity with the number of quartz oscillators, estimated to be 100,000 units in 1939.[347] One Bell Labs engineer noted in 1946 that "at the time of the entry of this country [U.S.A.] into the war, the use of crystal filters in the telephone

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[346] K. C. Black, "Stevens Point and Minneapolis Linked by Coaxial System," *Bell Laboratories Record* (January 1942): 127-40.

[347] Virgil E. Bottom, "A History of the Quartz Crystal Industry in the USA" (*Proceedings of the 35th Annual Frequency Control Symposium*, Philadelphia, PA, 27-29 May 1981), 3-12.

plant was growing so that the rate of manufacture of quartz plates for the filters was about the same as for radio oscillators."[348]

6.10 BTL engineers apply quartz crystal technology to precision timekeeping

Until the late 1920s, the piezoelectric oscillator's only applications were frequency standards and the precise and stable control of radio transmitter carrier frequencies. But engineers, particularly those at Bell Telephone Laboratories, knew that if quartz could be used as a highly precise standard of frequency, then it should theoretically be possible to use it also as a highly precise timekeeper. The fundamental unit of frequency, the Hertz, is simply the number of cycles of an oscillatory phenomenon per second. Thus, the piezoelectric oscillator's ability to hold with remarkable stability to one frequency could be exploited to serve as a standard for the fundamental unit of time, the second. When used as a timekeeper, the piezoelectric oscillator would exhibit marked advantages over the pendulum clock, heretofore recognized as the most accurate and reliable standard of time. One problem with the pendulum clock was that its period (i.e., the time required for one oscillation) was a function of both elevation above sea level as well as latitudinal distance from the equator.[349] Because of this, the pendulum clock had to be re-calibrated every time it was physically moved. In contrast, the piezoelectric oscillator's period was only a function of the quartz wafer's physical dimensions. Thus, if the oscillator's crystal were mounted securely, it was relatively mobile.

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[348] Raymond A. Heising, ed., *Quartz Crystals for Electrical Circuits, Their Design and Manufacture* (New York: Van Nostrand Company, 1946), 5.

[349] Warren A. Marrison, "The Evolution of the Quartz Crystal Clock," *The Bell System Technical Journal* 27 (1948): 510-88.

The two inventors of the piezoelectric oscillator, Walter Cady and G. W. Pierce, were almost certainly aware of quartz's timekeeping potential but were stymied from realizing it by a technical obstacle. Quartz crystal wafers cut to practical sizes of 1" or less usually resonate at frequencies ranging from several kilohertz to several Megahertz. In order to be useful in a clock, however, these high frequencies have to be subdivided low enough to drive a mechanism oscillating at 1 Hertz (i.e., one cycle per second). For Cady and Pierce, ways of accomplishing this were neither intuitive nor simple.

As early as 1924, two researchers at the newly established Bell Telephone Laboratories, Warren Marrison and Joseph W. Horton, were just beginning to work in the area of quartz-based frequency standards.[350] Realizing that a highly accurate and stable frequency standard could also serve as a time standard, the two men identified and set out to solve the frequency subdivision problem. By 1927, they had done so. Their solution employed a current-controlled variable low-frequency oscillator, a harmonic generator and amplifier, and a temperature-controlled piezoelectric oscillator designed to produce a precise 50 kHz output. These elements were arranged in a feedback control loop, shown in Figure 35, such that the piezoelectric oscillator acted to control the frequency of the low-frequency oscillator, ensuring that it operated at a pre-determined sub-multiple, usually 1/50th, of 50 kHz. Marrison designed this feedback control circuit, for which he filed a patent application in 1927.[351] The output of the low-frequency oscillator, typically a 1 kHz pure sine wave, was then used to control the speed of a synchronous electric motor, which drove the clock's train of gears. Marrison and Horton presented their results at the 1927 annual meeting of the International Union of Scientific Radio

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[350] Ibid. (

[351] ———, *Frequency-Control System*, U. S. Patent Office, Patent No. 1,788,533, Filing Date: 28 March 1927; Issue Date: 13 January 1931.

Telegraphy.[352] Three years later, in 1930, Marrison disseminated a refined version of his and Horton's work, shown in Figure 36, to a much broader audience by presenting a paper before the National Academy of Sciences entitled "The Crystal Clock."[353]

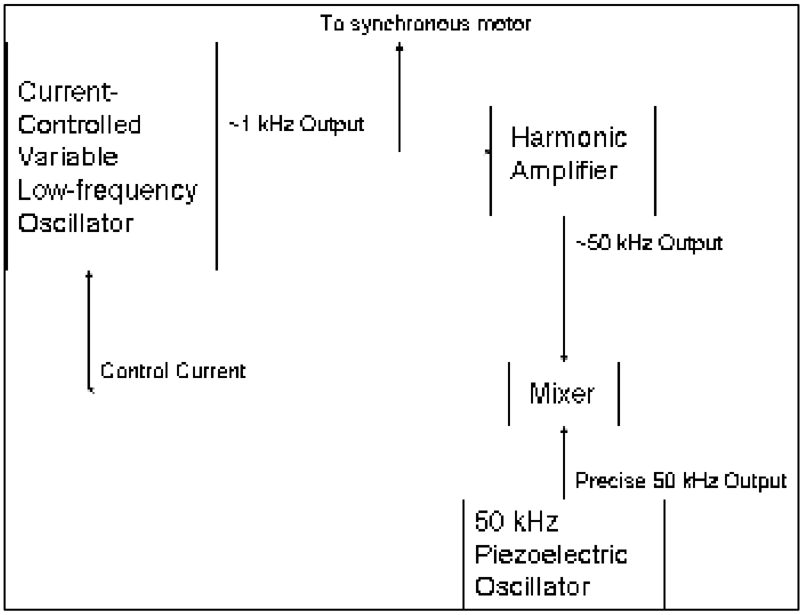

Figure 35: Original Crystal Clock Mechanism, Invented by Joseph Horton and Warren Marrison of Bell Telephone Laboratories in 1927
(Figure created by author.)

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[352] Joseph W. Horton and Warren A. Marrison, "Precision Determination of Frequency," *Proceedings of the Institute of Radio Engineers* 16, no. 2 (February 1928): 137-54.
[353] Warren A. Marrison, "The Crystal Clock," *Proceedings of the National Academy of Sciences of the United States of America* 16, no. 7 (15 July 1930): 496-507.

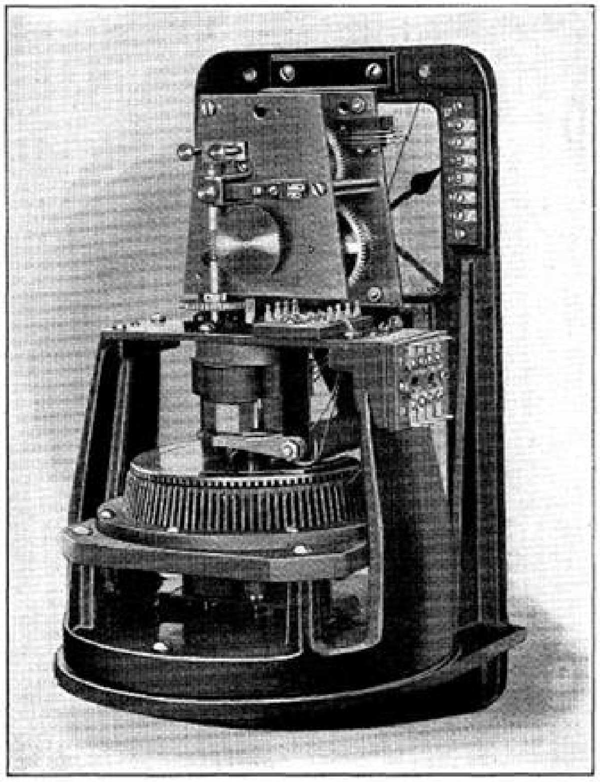

Figure 36: William Marrison's Refined Crystal Clock, Circa 1930
(Source: W. A. Marrison, "The Crystal Clock," *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 16, No. 7. July 15, 1930. Public Domain)

6.11 General Radio releases a line of quartz crystal clocks

Though Horton and Marrison's ultra-precise clock may have at first seemed little more than a scientific curiosity, a variant of it was soon being manufactured and sold on the open market. The clock was not manufactured by AT&T or its manufacturing subsidiary, Western Electric, but by the same firm that had first commercialized the piezoelectric oscillator. In its Catalog F, published in 1930, the General Radio Company (GR) made available a series of quartz-controlled "syncro-clocks," shown in Figure 37 and ranging in price from $160 to $400, not including the quartz plate or special amplifiers that were needed to drive the clock. According to the company's catalog, syncro-clocks were particularly useful for those wishing to precisely measure short time intervals, as might be required in many types of laboratory experiments.

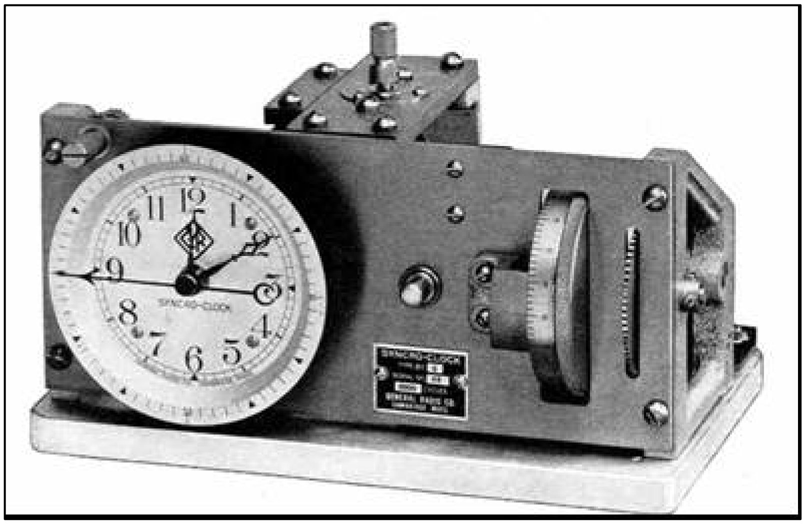

Figure 37: General Radio Company's Type 611 Syncro-Clock, Circa 1935
(Reprinted, by permission of the General Radio Historical Society, from General Radio Company, *Catalog H*, 1935. http://www.teradyne.com/corp/grhs/)

The migration of crystal clock technology from BTL to GR was greatly facilitated through a single person. In 1928, Joseph Horton, who had worked for the Bell System since 1916, left BTL to become GR's Chief Engineer. Horton was originally from Ipswich, Massachusetts, located about twenty-five miles northeast of Cambridge, and he was a graduate of M.I.T. Thus, he was returning home by going to work for General Radio.[354] Horton's experience with quartz crystals began in the same manner as with several other quartz technology pioneers; he had been involved with the World War I anti-submarine warfare research in Nahant, Massachusetts. Because of this experience,

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[354] James E. Brittain, "Scanning the Past: Joseph Warren Horton," *Proceedings of the IEEE* 82, no. 9 (September 1994).

Horton was assigned to work on quartz crystal devices when BTL was founded in 1925. During the 3 ½ years that Horton and Marrison worked together there, Horton was Marrison's supervisor.[355]

In designing the company's syncro-clocks., Horton managed to avoid patent infringement with Marrison's earlier patent by designing a different circuit, shown in Figure 38. GR's syncro-clocks were designed to keep true time when driven by a precise 1 kHz signal; the more accurate and stable this drive signal, the more accurate and stable would be the clock's time. The 1 kHz drive signal was derived by sending a 100 kHz piezoelectric oscillator's output through two or more multivibrators, each which could effectively divide the input frequency by an integer factor of up to ten.[356]

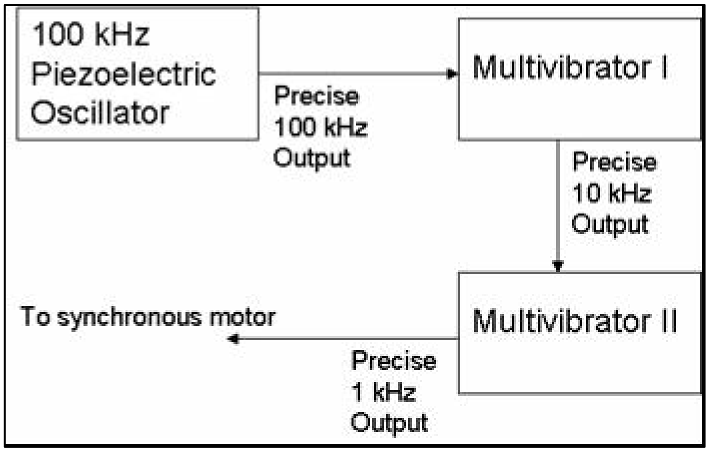

Figure 38: General Radio Company's Crystal Clock Design, Circa 1930
(Reprinted, by permission of the General Radio Historical Society, from General Radio Company, *Catalog F*, 1930. http://www.teradyne.com/corp/grhs/)

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[355] Carlene Stephens, "Reinventing Accuracy: The First Quartz Clock of 1927" (paper presented at the Furtwangen Conference, Germany, 11 October 2007). Unpublished conference presentation.
[356] General Radio Company. "Catalog H." (Cambridge, MA, 1935), Available at http://www.teradyne.com/corp/grhs/, Accessed 14 August 2006.

For those desiring the highest possible standard of precision timekeeping, GR offered its C-21-H standard frequency assembly, which included a 1 kHz synchro-clock and had a remarkable frequency accuracy of "better than +/-5 parts in 10 million over periods of several months."[357] Shown in Figure 39, the C-21-H was the first commercial unit that could be used not only as a highly precise primary standard of frequency, but also as a crystal-controlled clock of high precision. At $1860, the unit was relatively high-ticket and low-volume, but by 1935, GR had sold more than thirty-eight C-21-H units, mostly to large industrial R&D laboratories, observatories, and government standards organizations in North America, Europe, and Asia.[358]

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[357] Ibid.
[358] Ibid.

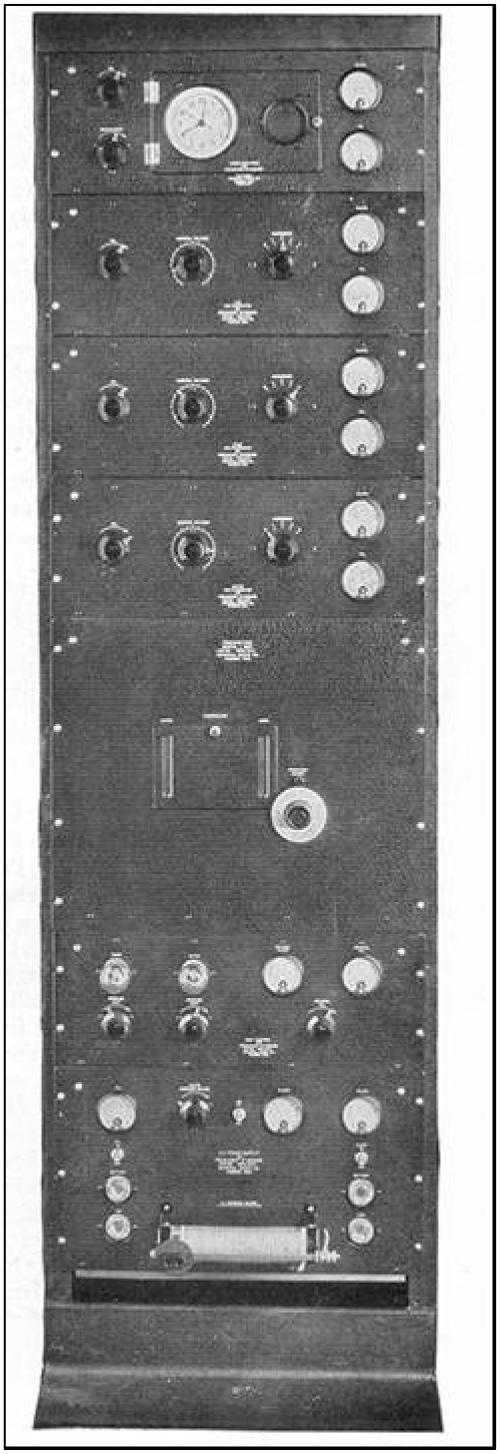

Figure 39: General Radio Company’s C-21-H Standard-Frequency Assembly, Circa 1930
(Reprinted, by permission of the General Radio Historical Society, from General Radio Company, *Catalog F*, 1930. http://www.teradyne.com/corp/grhs/)

One of GR's customers for the C-21-H was the U. S. Naval Observatory. In 1931, the Observatory, located in Washington, D. C., was concerned with the stability of the pendulum clock that it used to control time signals transmitted to vessels at sea. Engineers at the Naval Research Laboratory (NRL) had convinced the Observatory that it could do better than its pendulum clock, which had an estimated deviation from its average rate ranging from two to five parts in 100 million over a period of several months.[359] Captain J. F. Hellweg, Superintendent of the Observatory, stated in a May 7, 1931 letter to the NRL that it was "the earnest desire of the Observatory to obtain a crystal clock at the earliest practicable date."[360] Initially, the NRL agreed to develop and construct the desired clock in-house for an estimated cost of $5,000.[361] By the summer of 1933, however, with construction still ongoing, the NRL began lowering expectations for the clock.[362] It appeared that its final accuracy was going to far fall short of the original specifications. Furthermore, the NRL was working on so many simultaneous projects that it was unable to devote the resources necessary to finish the clock on schedule.

By December of 1933, Captain Hellweg's patience with the NRL had run out. On the 13th of that month, in a letter to the General Radio Company (GR), he stated, "I cannot afford to permit their [i.e., the Naval Research Laboratory's] procrastination to be continued further."[363] He proceeded to inquire as to GR's ability to construct quickly the desired crystal clock, which would need to be considerably more accurate than its standard C-21-H. He inquired the same of Bell Telephone Laboratories (BTL). Both GR

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[359] J. F. Hellweg to Director of the NRL, 25 July 1933, Historical Records of the Naval Research Laboratory, Record Group 19, U.S. National Archives, Washington, D.C.
[360] J. F. Hellweg to Director of the NRL, 7 May 1931, Ibid.
[361] Captain E. G. Oberlin to Superintendant of the Naval Observatory, 15 May 1931, Ibid.
[362] J. F. Hellweg to Director of the NRL, 25 July 1933, Ibid.
[363] J. F. Hellweg to General Radio Company, 13 December 1933, Ibid.

and BTL claimed to be capable of constructing the clock to the desired accuracy, but BTL was not prepared to deliver the clock to the Observatory within the specified time of 120 days. GR, on the other hand, agreed to the strict deadline and was awarded the clock contract on January 6, 1934. By May 1 of that year, the Observatory had received a customized GR C-21-H crystal clock and placed it into operation. Buoyed by this success, General Radio continued for years selling its C-21-H crystal clock and primary frequency standard to demanding customers throughout the world.

6.12 Other quartz crystal developments (and non-developments) during the 1930s

As has been suggested by the contents of this chapter thus far, the most consequential quartz crystal developments in the late 1920s and 1930s were made by small QCU manufacturing firms catering to the amateur market, Bell Telephone Laboratories, and the General Radio Company. Nevertheless, some development did occur elsewhere, particularly in the radio broadcast industry and among broadcast regulators, such as the Bureau of Standards and the Federal Communications Commission (F.C.C.). Conspicuously absent for most of the 1930s were military use or development of resonant quartz crystal technology as well as any effort by the Institute of Radio Engineers (I.R.E.) to organize the growing quartz crystal technological community.

Other than the Bell System, comprising AT&T, Western Electric, and BTL, the large corporations most actively involved in advancing quartz crystal technology during the 1930s were R.C.A. and German radio giant Telefunken. The patent data presented in Chapter 3 shows that these firms developed a substantial number of quartz patents during these years. Upon closer inspection, almost all of them can be seen to be refinements of quartz crystal devices that were already in use in the 1920s. Among the most common of these inventions were improved quartz oscillators and improved crystal holders or mountings. The only fundamentally new patents related to synchronous broadcasting, which is discussed below. The continued involvement of Telefunken in quartz technology would come to play an important role in World War II, as discussed in Chapter 7.

Chapter 5 discussed the role of quartz crystal technology in the regulation of broadcast radio throughout the 1920s and into the early 1930s. This was a period of great activity in which the level of frequency accuracy and stability available with quartz crystal oscillators was improving dramatically every one or two years, requiring frequency adherence regulations to be updated often. General Order No. 116, passed by the F.R.C. in 1931 and requiring broadcast stations to stay within 50 Hz of their assigned frequencies, held throughout the 1930s. Thus, there was virtually no regulatory activity during the decade related to frequency adherence. The F.R.C. became the F.C.C. in 1933, and the Commission continued to compile approved equipment lists containing commercial quartz crystal instruments and devices that met federal frequency standards.

There was, however, one regulatory development occurring during the late 1920s and early 1930s that has yet to be mentioned. Synchronous broadcasting, also known as common-frequency broadcasting, was a technique developed in the late 1920s by which all stations broadcasting the programming of a particular network (e.g., NBC, CBS) would transmit on a single carrier frequency. If all participating stations adhered to this frequency with extreme precision, no heterodyne interference would result and the network's programming would be available in an unbroken chain across the country. The purpose of the scheme, which was technically impossible before the development of thermostatic quartz crystal-controlled transmitters, was to free up the crowded radio spectrum and to simplify channel allocation. Despite receiving the support of many prominent radio engineers, including the BOS's John Dellinger, synchronous broadcasting was consistently opposed by the major radio networks because of the serious disruption it would cause their existing affiliates. Thus, while several European countries ended up adopting synchronous broadcasting in the 1930s, it was dead in the U.S. by 1932.[364]

The U.S. military was conspicuously absent from quartz crystal development for most of the 1930s. As Chapters 4 and 5 showed, the U.S. Navy's Naval Research Laboratory (N.R.L.) was very active in quartz crystal patenting in the mid 1920s, and the N.R.L. participated in the BOS's 3 year effort to develop a quartz-based primary frequency standard. By 1930, however, the Navy had decided not to adopt crystal control for either its land-based or its fleet radio transmitters. The decisive factor was the uncertain supply of raw quartz crystal imported from Brazil. Were the U.S. to become engaged in another war, the Navy didn't want to be dependent on Brazil for a vital raw material. An extensive search for domestic quartz deposits was conducted throughout the 1920s, but no adequate replacement for Brazilian quartz was found.[365] Thus, the Navy looked to alternate frequency stabilization techniques for its fleet transmitters.[366] In the

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[364] Michael J. Socolow, "A Wavelength for Every Network: Synchronous Broadcasting and National Radio in the United States, 1926-1932," *Technology and Culture* 49, no. 1 (January 2008): 89-113.

[365] See Folder "Quartz – Supply of in U.S. (1925-1926)," Box 81, Historical Records of the Naval Research Laboratory, Record Group 19, U.S. National Archives, Washington, D.C. See also Folder "Quartz – Supply of in U.S. (1927)" and Folder "Quartz – Supply of in U.S. (1928)."

[366] Louis A. Gebhard, *Evolution of Naval Radio-Electronics and Contributions of the Naval Research Laboratory* (Washington, D.C.: Naval Research Laboratory, 1979). Captain Linwood S. Howeth, *History*

late 1930s, the U.S. Army began investigating quartz crystal technology. This story is told in Chapter 7.

Also conspicuously absent from quartz crystal developments in the 1930s was the Institute of Radio Engineers (I.R.E.), one of two premier professional societies for electrical engineers, the other being the American Institute of Electrical Engineers (A.I.E.E.). The organization's flagship journal, *Proceedings of the I.R.E.*, continued to publish articles on the latest quartz crystal devices or techniques. However, there were no formal acts by the Institute in the 1930s to promote quartz technology, as there had been by the Committee on Broadcasting in the late 1920s and as there would be in the early 1940s as the U.S. entered World War II. (See Chapter 7.) Thus, electrical engineers interested in quartz crystal technology during the 1930s remained somewhat fragmented, bound largely to the firms or organizations for which they worked and with little opportunity to network with like-minded engineers across the country.

6.13 Summary and Conclusions

The 1930s witnessed dramatic changes in quartz crystal technology, both in the size and composition of its technological community as well as in its engineering knowledge base. Before the decade began, a quartz crystal industry catering to the frequency control and standardization needs of radio amateurs can hardly be said to have existed. General Radio sold a few quartz products aimed at amateurs, but most amateurs made their own crystal resonators. By the end of the 1930s, a true industry existed, comprising scores of specialized QCU firms. The telephony industry also saw

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of Communications-Electronics in the United States Navy, 1 ed. (Washington, D.C.: U. S. Government Printing Office, 1963).

tremendous strides made during the 1930s. According to data compiled by economic historian John Kendrick, between 1929 and 1941 the U.S. telephone industry experienced a compound annual average growth rate in multi-factor productivity of 2.01, higher than either the period preceding it (1919-1929) or after it (1941-1948).[367] As this chapter has shown, a large portion of this growth was likely due to AT&T's development and expansion of its multiplex carrier telephony infrastructure, a system that relied heavily on quartz crystal wave filters. By the end of the 1930s, the technological groundwork had been laid for the post-war explosion of affordable long-distance telephony.

The quartz crystal engineering knowledge base was expanded during this decade primarily by the Bell Telephone Laboratories, but also by the small QCU manufacturer Bliley Electric. The technical goals driving BTL engineers were to widen the bandwidth of quartz wave filters and to make wave filters environmentally robust by neutralizing the harmful effects of temperature change and mechanical vibration. Achievement of the first goal allowed AT&T to integrate quartz wave filters into its multiplex carrier telephony system, while achievement of the last two goals allowed the company to dispense with expensive temperature chambers and elaborate anti-vibration measures. The technical goals driving Bliley Electric's QCU work were to expand the possible frequency range of QCU's, to make them user-tunable within a narrow range around the nominal resonant frequency, and to reduce the amount of skilled labor required in QCU production. The first and third goals were lasting additions to quartz crystal engineering knowledge, while the second goal was a commercial failure.

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[367] This data is summarized in Alexander J. Field, "The Most Technologically Progressive Decade of the Century," *The American Economic Review* 93, no. 4 (November 2003): 1399-413. The corresponding number for the period 1919-1929 was 1.60. For the period 1941-1948, the number was 0.53.

The advances made by BTL and Bliley Electric in the 1930s were made in very different economic contexts. BTL was the research arm for AT&T, a government-regulated monopoly. Had the telephone giant been subject to free market competition for telephone customers, it is uncertain whether or not it could have supported a world-class research and development laboratory. Within its protected sphere, BTL managers and engineers were able to rationally organize a systematic research program aimed at making long-distance telephony more accessible and more affordable for the American public. By contrast, Bliley Electric operated in a free market environment that was relatively unregulated. The company, which had many competitors in the QCU business, sought to distinguish itself through the high quality of its products and by developing innovative variations on the standard QCU. Also, competitive pressures forced Bliley to search for labor-saving production techniques, such as the "X-lap" process. These developments would profoundly influence QCU production during World War II, as discussed in Chapter 7.

By the end of the 1930s, a sizeable and diverse, though fragmented, quartz crystal technological community existed. This community had created and accumulated a great deal of scientific and engineering knowledge pertaining to quartz crystal, and it had established the centrality of that knowledge to the two most significant communications systems of the day, radio and telephony. Yet one significant area of quartz crystal technology, high-volume fabrication and manufacture, remained relatively undeveloped. Most quartz crystal production remained small-scale and craft-based. Chapter 7 recounts the U.S. struggle to achieve mass production of QCU's during World War II.

CHAPTER 7: MASS PRODUCTION – THE QUARTZ CRYSTAL UNIT IN WORLD WAR II

Quantity production must rely for its success upon quantity consumption; and nothing ensures replacement like organized destruction. In this sense, war is not only, as it has been called, the health of the State: it is the health of the machine, too.[368]

The army is in fact the ideal form toward which a purely mechanical system of industry must tend.[369]

Lewis Mumford, *Technics and Civilization* (1934)

7.1 Introduction

Some fifteen months before the U.S. entered World War II, one of the great discontinuities in the history of quartz crystal technology occurred. Counter to the U.S. Navy's experience with quartz crystal, the Army Signal Corps chose to officially adopt the technique of crystal control for two types of Armored Force mobile radios. By December 1941, this decision had been extended to most of the Army's mobile radios. Each radio set was to be equipped with anywhere from ten up to one hundred QCUs, each having a different resonant frequency. Almost overnight, an enormous new market had opened up to QCU manufacturers. The fifteen or so QCU manufacturers existing before the war, which together had never produced more than 100,000 units per year, were now swamped with orders that they couldn't meet.[370] In response, the Signal Corps formed a Washington-based committee called the Quartz Crystal Section (QCS), whose job was "to expedite the production of quartz crystal units to meet the requirements of

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[368] Lewis Mumford, *Technics and Civilization* (New York: Harcourt Brace and Company, 1934). Chapter 2, Section 7 – Military Mass-Production.

[369] Ibid. Chapter 2, Section 6 – Warfare and Invention.

[370] "Institute News and Radio Notes: Winter Technical Meeting, New York, New York," *Proceedings of the Institute of Radio Engineers* 33, no. 1 (January 1945): 49-59. See Item 14, Quartz-Crystal Supply Program, by Major Edward W. Johnson.

our Armed Services and those of the Allies."[371] Largely due to the efforts of the QCS, roughly one hundred U.S. firms began manufacturing QCU's, producing at the peak of the war some 30 million QCU's per year.[372] Most of these firms, entirely new to the field of quartz crystal technology, had to climb a steep learning curve in a very short time.

The process of ramping up QCU production presented many opportunities for disseminating as well as expanding the existing quartz crystal engineering knowledge base. First, there was the difficult problem of standardizing QCU production practices across some one-hundred and fifteen manufacturing firms. Before doing this, however, what are now called "best practices" had to be identified and disseminated. Most of these practices related to specialized QCU fabrication methods, such as chemical etching of crystal wafers or electrode coating. Just as important were improvements to the procedures for inspecting raw quartz. Because of the severe shortage of natural quartz experienced during the war, raw quartz had to be economized, leading to efficient inspection procedures. Finally, there were the technical problems encountered in mass producing an item that had heretofore been produced on a relatively small scale by skilled technicians. The solving of these problems led to a significant growth of quartz crystal engineering knowledge, similar to the rapid growth in metallurgical knowledge that resulted once the scale of steel production, catalyzed by the introduction of the Bessemer and open hearth processes, accelerated in the latter 19th century.[373] The rigorous demands of mass production tend to expose areas of insufficient technical or scientific knowledge,

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[371] Virgil E. Bottom, "A History of the Quartz Crystal Industry in the USA" (*Proceedings of the 35th Annual Frequency Control Symposium*, Philadelphia, PA, 27-29 May 1981), 3-12.

[372] "Institute News and Radio Notes: Winter Technical Meeting, New York, New York," *Proceedings of the Institute of Radio Engineers* 33, no. 1 (January 1945): 49-59.

[373] David Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (Cambridge, UK: Cambridge University Press, 1989). Chapter 3.

while simultaneously creating the economic incentive to generate or refine the needed knowledge.

World War II also witnessed a new phase in the growth of the quartz crystal technological community. Many of the hundred-odd firms that began manufacturing QCU's during the war were temporary additions to the community, reverting back to their pre-war line of business after the war ended. Some firms, however, such as Motorola, became permanent additions to the community. In the military, the Army Signal Corps Electronics Laboratory (S.C.E.L.), based in Fort Monmouth, New Jersey, became the epicenter of quartz crystal engineering during the war. After the war, the S.C.E.L. continued to play a very important role in facilitating a broad-based and centrally organized quartz crystal research program. In the private sector, the Institute of Radio Engineers (I.R.E.) formed a technical committee dedicated to piezoelectric crystals in 1941. By publishing comprehensive yearly progress reports for the quartz crystal field, this committee provided direction and unity to the quartz crystal community. Also, for the first time, members of the community received recognition from the broader community of radio engineers.

The Army Signal Corps' decision to adopt crystal control on a massive scale changed forever the field of quartz crystal technology. Because of the undisputed success of crystal-controlled FM mobile radio on the battlefield, crystal control became a permanent feature in the two-way radios that were produced in large numbers for the civilian market after the war. Also, the Corps' unprecedented demand for high-quality raw quartz crystal exposed the greatest weakness in quartz crystal technology – the uncertain supply of Brazilian quartz. After the war, the most active area of quartz research for at least a decade was the chemical synthesis of artificial quartz crystal. Had this research failed, piezoelectric engineers would have had to abandon quartz crystal for most applications. Thus, World War II placed quartz crystal technology in something of a crisis state that would remain unresolved until the mid-1950s.

The economic and technological forces driving quartz crystal technology during World War II broke sharply from the forces that had been prevalent during the 1930s. For much of that decade, engineers and inventors had advanced quartz crystal technology in response to free-market capitalist forces. The growing markets of radio amateurs and long-distance telephone users stimulated talented engineers to innovate in the areas of economical QCU design and manufacture, as well as quartz wave filters. During World War II, however, free market forces were replaced by a war economy characterized by centralized planning and control. One market, the market for military QCU's, now prevailed above all others. Consequently, engineers during the war focused almost exclusively on QCU mass production techniques. Inter-firm competition and the pursuit of market share were replaced by cooperation and centralized planning in pursuit of Allied victory. Indeed, this was probably the only way at the time that American industry could have produced tens of millions of standardized QCU's. In the immediate post-war years, the wartime forces driving quartz crystal technology did not disappear. Rather, they persisted as the nation's scientific and technological communities were permanently mobilized in preparation for the Cold War.

7.2 The U.S. Army Signal Corps' decision to adopt crystal control

Because of the significant historical ramifications of the Army Signal Corps' decision to adopt quartz crystal control, the way in which the decision was made is worth a close look. Before the mid-1930s, both the U.S. Navy and, to a lesser extent, the U.S. Army had experimented with crystal-control of radio transmitters. The Navy saw great potential in quartz crystal for providing reliable communication with ships at sea. Among the first projects undertaken at the Naval Research Laboratory when it opened in 1923 was the design and construction of high-powered crystal-controlled radio transmitters. However, primarily because of concerns over Brazil being the only known abundant source for natural electronics-grade quartz crystal, the Navy had abandoned crystal-control on a large scale by the early 1930s.[374] For its part, the Army, in the late 1920s, included crystal-control in a limited number of transmitting stations built as part of the nationwide War Department Radio Net.[375] However, the Army couldn't do much more with crystal at this time without using expensive thermostatic temperature chambers.

By the mid-1930s, however, quartz crystal technology had fundamentally changed with Bell Labs' development of the zero temperature coefficient quartz crystal plates.[376] Prior to this development, quartz plates had to be kept in a controlled environment, often by means of a thermostatic temperature chamber, to ensure stable operation. Such elaborate temperature control equipment was impractical for field radio units. Zero temperature coefficient plates, however, enabled the development of mobile

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[374] See §6.12.

[375] Richard J. Thompson Jr., *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006), 19.

[376] See Chapter 6.

crystal-controlled radio sets capable of operating in the harsh environmental conditions typical of combat.

In 1936, attempting to exploit this development, the Signal Corps began investigating the possible inclusion of crystal-control in its field radio units.[377] Legislators had recently boosted the budget of the Corps, which had been scraping by on scant resources since the end of World War I.[378] In February of that year, the Army's Chief Signal Officer, Major General James B. Allison (CSigO from 1935-1937), issued a general policy calling for all field radio equipment to be equipped with both master-oscillator and crystal-control capabilities whenever weight and space limitations permitted.[379] Master-oscillator operation – then the dominant method of frequency selection for radio transmitters required to operate at multiple frequencies – provided continuous frequency variation via tuning dials, while crystal control quantized the frequency spectrum, limiting communication to a discrete number of pre-determined frequencies. The relative merits and drawbacks of these two techniques soon became the topic of vigorous discussions between senior Signal Corps personnel and Signal Corps Laboratory engineering staff.

One of the first branches of the Army to consider designing crystal-control into its radio sets was the Air Corps. In December 1938, the Sub-Committee of the Air Corps Technical Committee thoroughly investigated the possibility of outfitting many of its

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[377] Signal Corps Director Roger B. Colton to Chief Signal Officer, War Dept., 15 January 1940, Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C.

[378] SCEL Annual Report for Fiscal Year 1942, SCEL Annual Reports, Signal Corps Engineering Laboratories Collection, Historical Files of Fort Monmouth, Fort Monmouth, NJ. See particularly Chapter 7 – General Development.

[379] Signal Corps Director Roger B. Colton to Chief Signal Officer, War Dept., 15 January 1940, Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C.

aircraft with exclusively crystal-controlled radio sets. Weight and space limitations prevented these sets from containing both crystal-control and master-oscillator circuitry. The committee eventually decided to adopt crystal-control on a very limited basis, agreeing to outfit two types of radio sets with four crystals per set. The reasoning for such a tentative commitment to crystal-control was summarized in a report as follows. "Crystal controlled radio equipment is too inflexible to meet war-time demands and even if it could be made flexible enough by procurement of sufficient crystals it would be exceedingly costly for tactical purposes."[380] This statement contains three important objections to the large-scale adoption of exclusive crystal-control. Each is worth examining in detail.

First, the Air Corps committee criticized crystal-control for its inflexibility. This argument can be intuitively understood by considering that master-oscillator operation theoretically provides for infinite frequency flexibility since it permits continuous variation over the frequency spectrum, while crystal-control, by breaking the spectrum into a discrete number of frequencies, limits communication to these frequencies. The distinction has a couple of important ramifications. First, consider a master-oscillator transmitter that, while attempting to transmit at a carrier frequency of 2400 kHz, encounters unintentional interference (i.e., interference not deliberately caused by the enemy). The radio operator can then change the transmitter's carrier frequency slightly to, say, 2405 kHz, which might be enough to escape the harmful interference and allow communication to proceed. On the receiver side, a continuously variable frequency unit allows the listener to shift with the transmitter, though the operator must guess in which direction to shift frequency. By contrast, a system in which both transmitter and receiver

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[380] Colonel Clyde L. Eastman to Chief of the Air Corps, 12 June 1940, Ibid.

are crystal-controlled is incapable of side-stepping the interference at 2400 kHz. The only valid option is to change the communications channel altogether. In summary, a master-oscillator system in which both transmitter and receiver are capable of continuous frequency variation allows for fine-tuning; a crystal-controlled system does not. With crystal-control, both the transmitter and receiver crystals must be ground to precisely the same frequency; there is precious little room for error. If a receiver's crystal having a nominal frequency of 2400 kHz is actually ground to a frequency of 2399 kHz, while the transmitter's crystal is ground to 2401 kHz, the two units will likely find communicating difficult, especially as the distance between them increases. And, unless these units are also equipped with master-oscillator operation that allows for fine tuning, this communications channel (2400 kHz) has limited or no utility when interference is present. Some Signal Corps officials, such as Colonel Clyde Eastman, doubted the ability of crystal manufacturers to achieve in practice the high level of manufacturing precision and accuracy required by crystal-controlled operation.

The inflexibility of crystal-control is also seen when we consider intentional interference, commonly referred to as enemy jamming. At the time of the Signal Corps debates, some argued that crystal-controlled sets would be more susceptible to jamming.[381] To see this, consider the following two cases. In the first case, the Air Corps chooses to conduct its radio communications in the spectral band covering 2000 to 3000 kHz with master-oscillator sets. An enemy wishing to jam the Corps' communications must blanket the entire 2000-3000 kHz band with wideband interference. Such an act would make this radio band just as unusable to the enemy as to the Air Corps; thus, though the Corps has lost its communications, the enemy has not

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[381] "Routing and Work Sheet," 19 August 1940, Subject "Crystal for Tactical Radio Sets," Ibid.

gained a net advantage. On the other hand, consider a second case. The Air Corps uses crystal-controlled sets, which effectively subdivide the 2000-3000 kHz band into one hundred distinct channels, with adjacent channels separated by 10 kHz. Furthermore, let's assume that the Corps has purchased aircraft radio sets that can accommodate ten crystals at a time. In other words, at any given time, an operator can select between only ten of one hundred total channels. This is a realistic assumption, since sets that can accommodate one hundred crystals would have been far too heavy to place in aircraft. (In fact, the greatest number of crystals included in any aircraft radio set during the war was seven.)[382] In this case, it is theoretically much easier for an enemy to determine which 10 channels are in use and to jam them, leaving the rest of the band open for its own communications. The most obvious and direct way for the Air Corps to counter this jamming would have been to increase the total width of the communications band and hence the total number of channels requiring monitoring by the enemy. This tactic, however, becomes quite costly as the increase in channels means a commensurate increase in the number of different crystal plates that must be produced. Since jamming was (and remains today) one of the principal concerns of battlefield communications, this argument against crystal-controlled operation was of great concern to the Army.[383] During and after WWII, many other counter-jamming methods, such as spread spectrum modulation, were developed.[384] But prior to 1942, jamming was a very real vulnerability of crystal-controlled communications systems.

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[382] Richard J. Thompson Jr., *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006). Appendix 1 – Crystal-Controlled Equipment, 175-177.

[383] Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C.

[384] Hollywood actress Hedy Lamarr and American composer George Antheil received U. S. patent 2,292,387 for the first spread spectrum modulation technique. Known as frequency-hopping, the technique

The Air Corps' second criticism of crystal-control was its doubt over the U. S. government's ability to procure a sufficient number of crystals for making crystal-control a standard feature in Air Corps radio units. The issue of the scarcity of electronics-grade quartz crystal was not a new one. The U. S. Navy, after discovering the value of quartz for frequency control in the mid-1920s, conducted an extensive search for domestic sources of quartz. Possible sources in Arkansas, Colorado, and California were examined but found to be insufficient even for the Navy's peacetime needs.[385] In the late 1920s, the Navy concluded that Brazil was the only viable source for large amounts of high-quality quartz, leading it to largely abandon crystal-control in favor of master-oscillator operation. Yet crystal-control continued to have supporters, some of who persuaded the Naval Research Laboratory to begin research into the artificial production of quartz crystals in 1931.[386] This research had not yielded any tangible results by the late 1930s, leaving Brazil as the only known source of large quantities of electronics-grade quartz crystal. Thus, the Air Corps had every right to question the U.S. government's ability to procure a sufficient quantity of quartz crystals for its radio units, particularly since the Air Corps depended upon radio far more than any other individual Corps within the Army.[387] Though Brazil was at the time a U.S. ally, no one could guarantee that friendly trade relations would continue, particularly in time of war.

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involved the message signal modulating a pre-determined sequence of rapid carrier frequency hops. The exact sequence was known only by the transmitter and the intended receiver. No other receiver would be able to demodulate the signal.

[385] Box 81, Historical Records of the Naval Research Laboratory, Record Group 19, U.S. National Archives, Washington, D.C. The documents in this box trace the NRL's search for a domestic supply of electronics-grade raw quartz from 1925 to 1928.

[386] C. S. Barrett to the NRL Director, 25 February 1931, Subject "Artificial production of quartz crystals," Folder "S67/40 Quartz Research B," Box 79, Ibid.

[387] Richard J. Thompson Jr., *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006), 33.

Finally, the Air Corps committee had concerns over the potential cost of supplying every aircraft with a set of crystals. If purchased in very large quantities, the per-unit cost of crystal plates could be quite low. But in the event of a shortage in crystals, this cost could escalate quickly. The bottom line was that crystal cost was an unknown quantity, depending upon a very uncertain supply. By contrast, the cost of master-oscillator circuitry was known and depended upon no scarce materials. Thus, master-oscillator designs promised a degree of predictability and reliability not possible with crystal designs.

Despite the Air Corp's hesitant stance toward crystal control, the technique was enthusiastically endorsed by others. Perhaps the technology's most effective advocate at this time was the Director of the Signal Corps Engineering Laboratories (S.C.E.L.), Roger B. Colton. Colton, who held electrical engineering degrees from Yale and M.I.T., had long been a believer in the strategic value of wireless communications for the armed forces. As SCEL Director, he was in a position to introduce new technologies to the forces from time to time. In October 1939, upon a visit to Fort Knox, Kentucky, headquarters of the Mechanized Cavalry Board, Colton oversaw testing of a modified SCR-245 radio set that incorporated crystal-control as well as a set utilizing frequency modulation (FM), still a relatively new technique at the time.[388] Colton had obtained both sets with the assistance of Dr. Edwin H. Armstrong, then a professor of electrical engineering at New York's Columbia University and the world-renowned inventor of the

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[388] Ibid., 23.

regenerative feedback circuit, the superheterodyne radio receiver, and frequency modulation.[389]

Armstrong had patented frequency modulation in 1933 and, against the opposition of RCA and others with a vested interest in preserving the dominance of AM radio, championed its adoption for the remainder of the 1930s.[390] Because FM required more radio bandwidth than AM, Armstrong was forced to conduct his early experiments in what we today call the VHF (Very High Frequency) band, consisting of frequencies above 30 MHz. Practically speaking, the only possible way to achieve the necessary frequency stability at these frequencies was through crystal-control. Thus, FM radio transmitters quickly became associated with crystal-control. Though crystal-control was much broader than FM, FM could not exist in practice without crystal-control. By the late 1930s, the Federal Communication Commission (FCC) had reserved the 42-50 MHz band for FM broadcasting.[391] Thus, the FM radio unit that Armstrong provided Colton in 1939 likely operated somewhere in this vicinity of the radio spectrum.

Upon introducing FM and crystal-control to the Mechanized Cavalry at Fort Knox, Colton learned that radio enthusiasts within the Cavalry were already well-acquainted with these two technologies.[392] Apparently, these enthusiasts had recently heard of a pioneering radio experiment being conducted by the Connecticut State Police. The Link Radio Corporation of New York had begun supplying the department with two-

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[389] Edwin Armstrong to Major General Roger B. Colton, 6 May 1946, Edwin Armstrong Correspondence, Signal Corps Engineering Laboratories Collection, Historical Files of Fort Monmouth, Fort Monmouth, NJ.

[390] Thomas Parke Hughes, *American Genesis: a century of invention and technological enthusiasm, 1870-1970* (New York: Viking, 1989), 146. See also James E. Brittain, "Scanning the Past: Edwin Howard Armstrong," *Proceedings of the IEEE* 79, no. 2 (February 1991).

[391] After WWII and heavily influenced by RCA, the FCC would move the FM broadcast band to 88-108 MHz, making 42-50 MHz part of the television band. See American Genesis, 149.

[392] Richard J. Thompson Jr., *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006), 25.

way, crystal-controlled FM radio sets for use in an innovative statewide two-way mobile radio system.[393] The radio sets and the system were the brainchild of Dr. Daniel Noble, a professor of electrical engineering at the University of Connecticut. Noble had been keenly interested in FM for several years and had obtained Edwin Armstrong's approval before recommending the statewide system to the Connecticut police.[394] The system Noble proposed was to be the first practical two-way FM radiotelephone mobile network in the world, and it received widespread recognition at the time – so much so, apparently, that the Mechanized Cavalry had heard of it. When contacted by Cavalry radio enthusiasts, Link Radio agreed to lend them a few experimental sets similar to the Connecticut police units. The enthusiasts found these new sets so vastly superior to their old, master-oscillator AM sets that they didn't need much persuading by Colton at Fort Knox. In fact, it wasn't long before the Mechanized Cavalry began requesting of the SCL at Fort Monmouth, New Jersey that all future radio set designs contain both crystal-control and frequency-modulation.[395]

In late 1939 and early 1940, both the Infantry and the Mechanized Cavalry, soon to be consolidated as the Armored Force, requested crystal-controlled FM sets for field testing. Having either witnessed firsthand or heard of the Fort Knox demonstration, these divisions were anxious to try crystal-control for themselves. Though there was some opposition to one of the requests from within the Signal Corps, Chief Signal Officer Joseph Mauborgne (CSigO from 1937-1941) ended up approving both requests. The new

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[393] *I.E.E.E. History Center: F.M. Police Radio Communication, 1940.* [Web site] (Accessed 2 August 2006) available from http://www.ieee.org/web/aboutus/history_center/police_radio.html; Internet.

[394] Man from Mars Productions, *Daniel E. Noble* (2006, Accessed) available from http://www.wdrcobg.com/noble2.html; Internet.

[395] Signal Corps Director Roger B. Colton to Major David E. Washburn, 13 August 1940, Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C.

sets would be engineered and produced by the SCEL, but, since this involved modification of existing AM sets rather than a complete re-design, the divisions had the sets in hand in a matter of weeks.

The response of the Infantry and Mechanized Cavalry forces to the new crystal-controlled sets was swift and predictable; they loved them. As Colton observed this response, he became convinced that crystal-control was the way to go, but only if every set could be equipped with a full complement of crystals covering all communication channels for which that set was designed. Otherwise, the sets would be hampered by the inflexibility that the Air Corps had noted. This was a bold proposal, as some sets would require one hundred or more crystals each. In January 1940, anticipating the troops' positive response to crystal-control, Colton had ordered the SCL to prepare a detailed report comparing master-oscillator to crystal-control for field radio sets.[396]

The resulting report highlighted three advantages of crystal-control. First was its superior frequency accuracy, which was estimated to be ten to twenty times that of a master-oscillator set. This allowed there to be no ambiguity as to where a particular communication channel would be found in the spectrum. With master-oscillator sets, a certain amount of searching or fine tuning was almost always necessary to locate a channel at full-strength. In the midst of an intense armed conflict, the time spent fine-tuning could be just the time needed for an enemy to gain the upper hand. With crystal-control, instant push-button tuning of transmitters and receivers was possible. The second advantage of crystal-control was a direct consequence of the first. The superior frequency accuracy of crystal-control allowed communications channels to be packed

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[396] "Comparison of Master Oscillator and Crystal Control for Field Radio Sets," Signal Corps Laboratories Report, 11 January 1940, Ibid.

more tightly into a limited portion of the frequency spectrum, making possible an increase in the total number of channels. Because of the built-in ambiguity of a master-oscillator set's frequency setting, the minimum acceptable frequency separation between adjacent AM voice channels was estimated to be 50 kHz. By contrast, the report asserted that crystal-control allowed channel separation of "as little as 6 kHz," which, for a given frequency spectrum, would allow a crystal-controlled set to have roughly eight times as many voice channels as a master-oscillator set. In reality, this analysis proved to be overly optimistic. Crystal-control did allow for more channels, but only about 2 ½ times as many as a master-oscillator system. Even so, this represented a significantly more efficient use of the radio spectrum. Third, crystal-controlled sets were ready to operate immediately upon being powered up while master-oscillator sets required as much as twenty minutes of warm-up time before adequate frequency stability was achieved. The latter would work fine for planned maneuvers, but in the event of an enemy surprise attack, only crystal-controlled sets would do the job.

In its summary, the SCL concisely stated the advantages of crystal-control in its report as follows. "Generally speaking, approximately 5 to 10 times as much communication, quality and quantity considered, or a corresponding reduction of transmission time, can be obtained with crystal-operated field sets as compared to master oscillator-operated field sets, but this increase in communication efficiency is not obtainable in the field unless an adequate number of crystals is issued with each set."[397]

Colton's advocacy for crystal-control, though well-considered and based for the most part on solid field data and supply estimates, was nevertheless bold and somewhat risky. Those opposing large-scale crystal-control, such as Colonel Clyde L. Eastman,

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[397] Ibid.

often pointed to the troubles that the Air Corps had experienced since adopting small-scale crystal-control (four crystals per set) in two of its radio sets. The Air Corps had apparently experienced significant difficulties with the distribution, supply and maintenance of quartz crystals.[398] Colton, while acknowledging these difficulties, argued that they could be overcome and, more importantly, that the radio needs of the new Armored Force, combining the Infantry and the Mechanized Cavalry, should be considered separate from those of the Air Corps. He was also highly critical of the Air Corp's meager allocation of four crystals per set, arguing that such sets were "substantially useless for military combat purposes, except in very special situations."[399] Furthermore, he argued that the cost of crystal-controlled sets should be considered only in relation to the cost of master-oscillator sets designed for an equivalent number of communication channels. With such a comparison, Colton demonstrated that a one hundred channel crystal-controlled set would, at $1600, cost only $300 more than a one hundred channel master-oscillator set ($1300). The added performance gained with crystal-control was, he argued, well worth the 23% cost increase. Finally, Colton noted that crystal-controlled sets, because of their push-button operation and their ability to operate at a stable frequency immediately upon powering up, would be much easier for personnel without special radio training to operate. As he put it, "If we are trying to get practically automatic radio sets at the present time, only crystals fill the bill."[400]

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[398] Clyde L. Eastman to Chief of the Air Corps, 5th Ind., 12 June 1940, Ibid.

[399] Roger Colton to Major David E. Washburn, Subject "Crystal Controlled Radio Sets," 13 August 1940, Ibid.

[400] Ibid.

7.3 Procurement of quartz crystal

Colton's arguments for crystal-control were persuasive to Chief Signal Officer Mauborgne, but the Air Corp's chief criticism still worried him. Before committing to Army-wide adoption of crystal-control, Mauborgne insisted that the quartz procurement issue be addressed. In an attempt to do this, Colton organized and convened in August 1940 two meetings of the Committee for the Procurement of Quartz Crystal, composed of representatives from industry and government. The companies represented were Western Electric, Bendix Radio, R.C.A., Bausch & Lomb, and Bliley Electric. Also present were representatives of the Bureau of Mines, the Army Signal Corps, the Navy, the Army and Navy Munitions Board, and the Treasury Department's Procurement Division.[401] The major outcome of these meetings was the decision to loosen the existing specification governing raw quartz crystal purchase and inspection. The attendees generally agreed that the existing spec was considerably stricter than necessary and was thus exacerbating the quartz supply problem. They determined therefore that a more lenient spec, with regard to crystal size and the number of natural exposed faces, would allow many heretofore rejected crystals to be profitably used. The new spec allowed for the purchase of crystals much smaller than those previously accepted and permitted many crystals with just one natural face and some with no faces to pass inspection. One important aspect of the new specification – the definition of the "usability" of a raw quartz sample – did not change. This definition stated that samples judged by the inspector to contain less than 60% usable material be rejected.

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[401] "Minutes of the Meeting of the Committee for the Procurement of Quartz Crystal," 12 and 16 August 1940, Ibid.

While the official minutes of these two meetings highlight consensus and downplay disagreements or disputes, the subsequent correspondence of one committee member, C. B. Hamilton of the Treasury Department, reveals a suspicious attitude toward several of the industrial representatives. Hamilton felt that four of the firms present – Western Electric, RCA, Bendix Radio, and Bausch & Lomb – had attempted to slant the new quartz specification in their favor. These firms, referred to by Hamilton as "the Big Four," allegedly possessed cutting equipment that allowed them to process very large crystals; Bliley and other smaller manufacturers did not have such equipment. Hamilton argued that, by seeking to include an item in the new specification defining crystal samples smaller than a certain size as unusable, these four firms were attempting to squeeze smaller firms out of lucrative wartime crystal contracts.[402]

Whether or not "the Big Four" were actually conspiring to keep valuable government contracts away from the smaller quartz manufacturers may likely never be known. If they were conspiring, they failed, for the new quartz specification allowed for the purchase of crystals as small as 0.88 lbs.; all manufacturers agreed that crystals smaller than this were unusable. Nevertheless, this incident emphasizes the inherently political nature of procurement specifications in a nation where the military routinely contracts with private firms for supplies and munitions.[403] Assuming that there are a number of firms wishing to win a contract, the final form taken by a procurement specification can and often does favor one or a number of firms to the exclusion of others. Of course, this may be because some firms are much more qualified to perform

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[402] C. B. Hamilton, "Tentative Specification for Quartz Crystals," 15 April 1941, Ibid.

[403] See the following for more on military contracting and the setting of specifications. Alex Roland, *The Military-Industrial Complex*, ed. Pamela O. Long and Robert C. Post, Historical Perspectives on Technology, Society, and Culture (Washington, D.C.: American Historical Association, 2001).

the contract than others. But, in the event that a specification ends up being far more strict or rigorous than called for by the ultimate use or application, the possibility exists that the spec has been crafted to favor the wealthiest and/or best-equipped firm or firms. The term "specification inflation" is perhaps a helpful name for this phenomenon. To the U. S. Army's credit, "specification inflation" did not happen with quartz crystal, one reason being that a smaller crystal manufacturer, Bliley Electrical, was invited onto the Procurement Committee. The Signal Corps had probably already realized that it would need the contributions of both large and small crystal manufacturers if it was to have any chance of supplying the military's enormous quartz needs. Had Bliley and C. B. Hamilton not been present at the two committee meetings, it's possible that "the Big Four" and perhaps a few other large firms would have gotten most of the wartime crystal business.

Questions of "specification inflation" notwithstanding, the most important outcome of these meetings was that the quartz procurement specification was relaxed and that this served to somewhat ease the concerns of many over the quartz shortage problem. Another concurrent development acted to even further ease these concerns. Colton and Major J. D. O'Connell of the SCEL arranged a meeting with representatives of Western Electric in early August to discuss possible means of expediting quartz procurement.[404] The two men, fully confident in the SCEL's ability to develop crystal-controlled FM radio set prototypes and produce them in small numbers, nevertheless knew that the Army would need a very large and well-established manufacturing firm to help produce vast quantities of crystal plates if the U. S. was to ever enter the war. Western Electric's

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[404] Roger B. Colton and J. D. O'Connell, "Conference with representatives of the Western Electric Company," 10 August 1940, Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C.

Hawthorne Works, an enormous manufacturing facility in suburban Chicago, was ideally suited to this type of large-scale production. Moreover, Western Electric, as the manufacturing arm of AT&T, had roughly two decades of experience with piezoelectric crystals and nearly as much experience with quartz. The company had first worked with piezoelectric materials through its involvement in the anti-submarine warfare research effort of World War I. (See Chapter 2) In the 1920s and 1930s, AT&T pioneered the use of quartz for frequency control in both broadcast radio and carrier multiplex telephony. Furthermore, the company had a well-established trade relationship with Brazilian mines. Thus, Colton and O'Connell were confident in the Company's ability to assess and address the quartz supply problem.

Upon meeting with Fred Lack, manger of Western Electric's Specialty Products Division, Colton and O'Connell learned that the company had already been supplying the U.S. Coast Guard with crystal plates for frequency stabilization. They were disappointed to learn that these plates were quite large (1 ½ square inches rather than the usual 1 square inch) and sold for $100 a piece. Furthermore, prior to this meeting, Western Electric's projections of quantities and prices for supplying the Army with quartz plates were based on these large plate sizes. Colton and O'Connell informed Lack that SCEL engineers had already worked out a method for greatly reducing plate size, thereby conserving quartz. The Lab's engineers had discovered that quartz plates of only ¼ square inch could be used in transmitters if an extra radio-frequency amplification stage was added. With the old 1 square inch plates, roughly ten plates could be extracted per pound of raw quartz; the new ¼ square inch plates allowed as many as forty plates to be extracted. After demonstrating the feasibility of this method to skeptical Western

Electric representatives, the Company agreed to shrink its standard quartz plates. Moreover, taking into account the shrinking of plate size as well as the large number of crystals that the Army would need, Company representatives agreed that the per-unit price could drop to as low as $5.[405] Years later, Fred Lack wrote, "If it had not been for [the Signal Corps'] experience with the small crystals purchased from other companies, we [Western Electric] would have never persuaded the Bell Laboratories that the large crystal slab of the Coast Guard type was not essential."[406]

Contrary to the Bell System's justified reputation as a technological innovator, here is a case of Western Electric and BTL learning directly from its smaller competitors in the quartz business. One probable reason for this was the different customer bases served by Western Electric and smaller crystal manufacturers, such as Bliley Electric of Erie, PA or the Monitor Piezo Company of Los Angeles. Western Electric was selling to the Coast Guard, which was likely willing and able to pay top dollar for reliable, high-performance quartz plates. By contrast, Bliley and Monitor sold mostly to amateur radio enthusiasts (a.k.a. "hams") who were often working from a limited budget and were willing, unlike the Coast Guard, to experiment with novel and untested designs. Another probable reason is that Western Electric, with its vast resources and the backing of AT&T, could purchase the larger Brazilian raw crystals from which it cut its 1 ¼ square inch wafers. Bliley and other small firms often had to make do with smaller raw crystals, many of which would have been too small for cutting wafers of 1 square inch, much less

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[405] Roger Colton to Major David E. Washburn, Subject "Cyrstal Controlled Radio Sets," 13 August 1940, Ibid. In particular, see Item 6b. A conservative estimate at the time put the Army's crystal needs at well over one million QCUs.

[406] Western Electric Vice President Fred Lack to Major General Roger B. Colton, 4 December 1951, Miscellaneous Correspondence, Signal Corps Engineering Laboratories Collection, Historical Files of Fort Monmouth, Fort Monmouth, NJ.

1 ¼ square inch.[407] In fact, during the war Monitor owner Herbert Blasier made it a point to purchase the smaller raw crystals that were rejected by the larger manufacturers.[408] Thus, it was the smaller QCU manufacturers, rather than Western Electric, who innovatively developed ¼ square inch quartz plates out of sheer necessity and their customers' willingness to experiment with new designs. It was only later that this technique was seen as a valuable strategy for coping with the wartime shortage of Brazilian quartz. In fact, had it not been for this reduction in standard plate size, it is questionable whether or not the Signal Corps would have eventually committed to crystal-control.

The combination of these two developments in August 1940 – the relaxation of the government's quartz procurement specification and Western Electric's adoption of ¼ square inch quartz plates – acted to convince Mauborgne and other Signal Corps officials that quartz procurement was not the insurmountable problem that it had appeared earlier that year. In September, with his concerns eased and with Colton's persuasive arguments for crystal-control in mind, Chief Signal Officer Mauborgne gave his approval for incorporating crystal-control in two types of Armored Force sets.[409] One type was to be equipped with one hundred crystals per set, and the other with fifty. The primary justification given for crystal-control was its ability to provide "accurate frequency selectability and stability instantly on any one of the preset channels." At this time, Mauborgne's approval only extended to these two Armored Force sets, not to all military

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[407] C. B. Hamilton, "Tentative Specification for Quartz Crystal," 15 April 1941, Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C.

[408] Richard J. Thompson Jr., *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006), 58-59.

[409] "Report of conference held at the Signal Corps Laboratories on September 18 and 19, 1940 on radio equipment for the Armored Force," 30 September 1940, Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C.

radio sets. Nevertheless, many felt that the die had been cast; there was no turning back now. Once other divisions began to see the enhanced performance of Armored Force radio sets, there would be no stopping all divisions from demanding them.

Signal Corps officials estimated in early September 1940 that roughly 800,000 crystals, the equivalent of approximately 87,200 pounds of raw quartz, would be needed over the coming two years if the U. S. were to enter the war, and Colton, partly based upon data received from Western Electric, estimated this amount to be only 10 % of the total number of crystals then available in the United States. The 800,000 crystal estimate not only turned out to be far lower than the number of crystals needed in the coming two years, but, more importantly, American involvement in the war lasted 3 ½ years rather than 2. Inaccurate forecasts aside, Mauborgne's September 1940 decision committed the SCEL to begin designing crystal-controlled FM radio sets for the Armored Forces. How these sets would actually be produced in the quantities needed was another problem altogether, one that will be briefly recounted below, but which has been much more thoroughly researched and written on by Richard Thompson, Jr.[410]

The new quartz specification crafted by the Committee for the Procurement of Quartz Crystal in August 1940, though a considerable improvement over the old specification, did not stand long. In December 1940, Major General Mauborgne reassessed the military's wartime requirements for quartz. Many changes had occurred over the previous four months, including a request from the Air Corps, in a reversal of its former position, that crystal-control be incorporated into its new UHF (Ultra-High

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[410] ———, *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006).

Frequency) command radio set.[411] This was an enormous development, for it was well-known that the Air Corps' radio needs were and would likely remain vastly larger than the Armored Force needs.[412] In fact, the Air Corps' demand for quartz crystal would come to swamp all other force demands during the war. With this in mind, Mauborgne's reassessment increased the estimated quartz need for the coming two years from 87,200 pounds to 309,103 pounds, a staggering increase of over 300%.[413] At the time, the Assistant Secretary of War bluntly and pessimistically declared that this requirement would be impossible to meet prior to about 1950. In response, C. B. Hamilton went to work once again crafting a new quartz procurement specification. The new spec, which he proposed in April of 1941, dropped the quartz "usability" definition from 60% down to 40%, increasing tremendously the sheer volume of raw quartz accepted by government inspectors. The risk of this action was that the U.S. government would end up with a great deal of scrap quartz not usable in radio oscillators. It was decided, however, that this outcome was preferable to running short of quartz radios for troops.

After the U. S. officially entered the war in December 1941, the need for crystal-controlled radio sets, and thus raw quartz, only increased. By this time, new Chief Signal Officer Dawson Olmstead (CSigO from 1941-1943), motivated in part by a dramatic Fort Knox field test of crystal-controlled radios in January 1941, had committed the SCEL to incorporating crystal-control in almost all new tactical radio sets. The Fort Knox test had demonstrated beyond all doubt the tactical advantages of crystal-controlled sets over master-oscillator sets, leading Mauborgne and then Olmstead to commit the Army to

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[411] Ibid., 27.
[412] Ibid., 33.
[413] Brigadier General H. K. Rutherford to the Chief Signal Officer, Subject "Stock Reserve of Quartz Crystal," 23 December 1940, Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C.

high-volume use of quartz.[414] Vastly more raw quartz was now needed than the initial 1940 forecasts had indicated. Consequently, further steps were taken to make the most of the quartz that the U. S. could get from Brazil. These steps won't be recounted in detail here.

Ultimately, the success of the U. S. quartz crystal procurement effort can be attributed to four actions. First was the loosening of the overly strict initial quartz procurement specification, allowing many Brazilian quartz samples to be purchased that would have previously been rejected. It is unlikely that an adequate amount of quartz could have ever been purchased from Brazil had this change not been made. Second was the reduction of the standard crystal plate size from 1 square inch to ¼ square inch, essentially quadrupling the number of plates that could be cut from a given amount of raw quartz. The remaining two actions, though important, are only briefly mentioned here. Third was the widespread adoption of X-ray crystallography for inspecting crystals. This technique, which Western Electric began employing early in the war, enabled crystal cutters to quickly and reliably ascertain a raw crystal's lattice orientation before beginning cutting. This single step saved enormously on the amount of scrap quartz discarded during the quartz plate production process.[415] Fourth and last was the U. S. government's decision to allow the Reconstruction Finance Corporation, through its subsidiary, the Metals Reserve Corporation, to pay Brazilian mining companies a premium for the quartz that had been going to the Axis powers.[416] Though much of this

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[414] For details on the January 1941 Fort Knox demonstration, see Thompson, 27.

[415] J. D. O'Connell to Walter Cady, 14 May 1942, Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C. See also President of Western Electric C. G. Stoll to the Chief Signal Officer, 25 May 1942.

[416] Richard J. Thompson Jr., *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006), 100.

quartz was of questionable quality, the MRC's actions both ensured a larger supply of raw quartz for the U. S. and limited the amount of quartz available to Germany and Japan.

7.4 Alternatives to crystal control

Neither Major General Mauborgne's September 1940 decision nor the persuasive Fort Knox demonstration of January 1941 ended the Army's search for alternatives to crystal-control. The fragile quartz procurement situation still had many officials worried, and rightfully so. Any reasonable equivalent to crystal-control itself or to Brazilian quartz would have been quickly adopted by the Signal Corps. The search for alternatives proceeded along two parallel paths: finding ways to improve the frequency stability of traditional master-oscillator sets, and finding a substitute material for natural quartz crystal.

The SCEL's effort to improve the frequency stability of master-oscillator sets drew a number of unsolicited proposals from radio manufacturers. One such proposal came from the Jefferson-Travis Manufacturing Corporation, which, in February 1941, sent the Corps a proposal for a "method for the elimination of crystal control in radio transmitters."[417] The central aim of the method, which employed "electron coupling" of a master oscillator to a power amplifier, temperature control, and precision tuning mechanisms, was to eliminate the tendency of master-oscillator circuits to drift in

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[417] Edward J. Hefele, "Proposed Method for the Elimination of Crystal Control in Radio Transmitters," 28 January 1941, Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C.

frequency over time.[418] The method, while reasonably successful on a technical level, received a cool reception from the Roger Colton, who knew that no matter how stable a master oscillator circuit could be made, it still required manual tuning. It could never provide the push-button tuning made possible by crystal-control.

As for the Army's other option, finding an equivalent material substitute for natural quartz crystal, prospects appeared dim. The Navy had begun such a search in 1931 but had abandoned it in favor of master-oscillator sets.[419] The Army, unsatisfied with the Navy's outcome, began its own search by visiting companies such as the Corning Glass Works to query their chemists on the feasibility of developing a synthetic quartz substitute.[420] Responses were negative and timeframe projections for finding or developing a substitute were usually in years rather than months. The Army wisely decided to sideline its synthetic quartz project for the time being, focusing instead on improving the procurement and efficient use of natural quartz. After the war, the search for a quartz substitute would become a central focus of the SCL's research efforts. (See §7.9 as well as Chapter 8.)

For the duration of the war, these two alternatives, as well as others, failed to supplant crystal-control as the dominant method of radio frequency control or Brazilian mines as the primary source for radio-grade quartz crystal. In spite of the grave quartz procurement risk, troops in both the Armored Force and the Air Corps championed

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[418] The "electron-coupling" method had been developed by Navy engineer J. B. Dow in 1931. See J. B. Dow, "A Recent Development in Vacuum Tube Oscillator Circuits," *Proceedings Of The Institute Of Radio Engineers* 19, no. 12 (December 1931): 2095-108.

[419] C. S. Barrett to the NRL Director, Subject "Artificial production of quartz crystals," 25 February 1931, Folder "S67/40 Quartz Research B," Box 79, Historical Records of the Naval Research Laboratory, Record Group 19, U.S. National Archives, Washington, D.C.

[420] Memorandum to J. D. O'Connell, Subject "Report of Visit to Corning Glass Works, Corning, New York," 3 October 1942, Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C.

crystal-controlled sets for a simple reason. Crystal-controlled sets provided entirely new capabilities that could be achieved in no other way at the time. They allowed for push-button tuning of both transmitter and receiver, rapid and precise switching between channels, and an overall increase in the number of channels available for a given portion of radio spectrum. Furthermore, they required no warm-up period; frequency stability was achieved immediately after switching on the power. Master-oscillator sets, though having an advantage in scenarios where fine-tuning would be an asset, simply could not duplicate the capabilities of the crystal-controlled set, capabilities that, once the forces experienced them in the field, could not be resisted. The only problem now, other than the quartz procurement dilemma, was how to produce enough crystal-controlled radios for satisfying the military's enormous demand.

7.5 Mass Production of quartz crystal plates during World War II

Up until around mid-1942, the principal bottleneck to supplying the American military with adequate numbers of crystal-controlled radios was the supply of electronics-grade quartz crystal.[421] In late 1942, with the supply situation relieved by the actions discussed above, the enormous challenge of manufacturing millions of quartz crystal units (QCUs) became the military's most pressing quartz-related problem. The effort to ramp up production has been discussed extensively by others and will thus be covered here in only a summary fashion.

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[421] Ensuring an adequate supply of electronic-grade quartz crystal encompassed many sub-tasks, including procuring raw quartz from Brazil, inspecting raw quartz for its quality, and cutting raw quartz in wafers that could be used in quartz crystal units. Each of these sub-tasks proved to be more challenging than anticipated by Signal Corps officials.

The quartz production effort involved the coordination of at least one hundred American QCU manufacturers, both large and small and spread across the U.S.[422] Since Congress had banned amateur radio for the duration of the war, these manufacturers were concerned with satisfying only one customer, the U.S. military. Most of the new QCU manufacturers were complete novices in quartz crystal technology, requiring extensive training before production could begin. Among the largest firms to take up QCU production during the war were Chicago-based Motorola and Baltimore-based Bendix Radio. Unlike many of the new wartime producers, these firms continued producing QCU's after the war.

The tasks of coordinating QCU producers and disseminating crucial engineering and manufacturing knowledge fell to the Washington-based Quartz Crystal Section (QCS), formed in late 1941 by the Office of the Chief Signal Officer. One member of the QCS, physicist Virgil Bottom, later described the Section's mission as follows: "to expedite the production of quartz crystal units to meet the requirements of our Armed Services and those of the Allies."[423] The logistics of fulfilling this mission were daunting. Many severe problems arising during the production effort were tackled. Among the more crucial of these were the problem of standardizing the QCU production process across manufacturers and the so-called "ageing problem," in which QCU's placed in tropical climates began drifting in frequency after only a few days. Both problems were eventually solved through the diligence and cooperation of thousands of

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[422] Richard J. Thompson Jr., *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006). See Appendix 2, in which Thompson lists 139 wartime American QCU manufacturers.
[423] Virgil E. Bottom, "A History of the Quartz Crystal Industry in the USA" (*Proceedings of the 35th Annual Frequency Control Symposium*, Philadelphia, PA, 27-29 May 1981), 3-12.

civilian workers and military personnel. For extensive discussion of the entire quartz production effort, see works by Virgil Bottom and Richard J. Thompson.[424]

From the standpoint of numbers alone, the swift ramping up of QCU production during the war was quite remarkable. During 1941, the average production rate was only a few thousand QCU's per month.[425] By May 1942, the rate had increased to roughly six thousand QCU's per day.[426] Finally, by late 1943 or early 1944, the production rate was approximately 2 ½ million QCU's per month – an increase of roughly one thousand times over 1941 levels.[427] By the end of the war, Western Electric had produced nearly 10 million of one crystal type alone – the FT-241A, which was used in most tanks and in many field sets.[428] The total number of QCU's produced by all manufacturers during the war is difficult to ascertain; estimates have ranged from 30 million to over 70 million QCUs produced by American manufacturers between 1941 and 1945.[429]

Whatever the exact number of QCU's produced, the wartime QCU production effort represented a huge investment for the Signal Corps. One Signal Corps official estimated in early 1945, before the war was over, that the Corps had already spent "in

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[424] Ibid. See also Richard J. Thompson Jr., "The Development of the Quartz Crystal Oscillator Industry of World War 2," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 52, no. 5 (May 2005). ———, *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006).

[425] SCEL Annual Report for FY 1945, SCEL Annual Reports, Signal Corps Engineering Laboratories Collection, Historical Files of Fort Monmouth, Fort Monmouth, NJ. See particularly page 2 of the section entitled, Frequency Control Units.

[426] O'Connell to Walter Cady, 14 May 1942, Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files], Record Group 111, U.S. National Archives, Washington, D.C.

[427] SCEL Annual Report for FY 1945, SCEL Annual Reports, Signal Corps Engineering Laboratories Collection, Historical Files of Fort Monmouth, Fort Monmouth, NJ. See page 2 of the section entitled, Frequency Control Units.

[428] M. D. Fagen, *A History of Engineering and Science in the Bell System*, 7 vols. (New York: Bell Telephone Laboratories, 1985). Volume II., 325.

[429] Virgil E. Bottom, "A History of the Quartz Crystal Industry in the USA" (*Proceedings of the 35th Annual Frequency Control Symposium*, Philadelphia, PA, 27-29 May 1981), 3-12. Richard J. Thompson Jr., *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006), 163-4.

excess of $200 million for crystals alone since the outbreak of the war."[430] Based on this number, the Corps paid, on average, anywhere from $3 to $7 per QCU. This was a very reasonable price, given that Bliley Electric, in 1936, had been charging a minimum of $25 for a single QCU ground exactly to a specified frequency.[431] The low per unit prices were made possible by the industry-wide standardization of QCU types as well as the very high production runs for the various QCU resonant frequencies required by the Corps. As the size of a given production run increased, economies of scale allowed the per-unit cost to drop. Thus, entire factories could afford to tool their manufacturing operations to produce QCU's having a single resonant frequency, saving the time and expense required to retool their equipment for a variety of frequencies.

Another significant wartime concern for the Signal Corps was the area of QCU patent rights. The Corps wanted any company using a superior manufacturing process or technique to make it available to all QCU manufacturers for the duration of the war. This was in the spirit of broadly disseminating best practices so that QCU production could be performed as efficiently as possible. One of the best examples of this was an acid etching technique used by Bliley Electric to perform the final calibration of a crystal wafer. The technique, labeled cryptically by Bliley personnel as the "X-Lap" process, allowed the company to produce higher quality QCU's than most other manufacturers.[432] When Signal Corps officials noticed, they demanded the process be made available to all

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[430] "Institute News and Radio Notes: Winter Technical Meeting, New York, New York," *Proceedings of the Institute of Radio Engineers* 33, no. 1 (January 1945): 49-59. See item 14, "Quartz-Crystal Supply Program," by Major Edward W. Johnson.

[431] Bliley Electric Company, *General Catalog G9 (1939).* [JPEG File] (Bliley Electric Company, Accessed 28 May 2007) available from http://www.bliley.net/XTAL/; Internet.

[432] John M. Wolfskill, *Piezoelectric Crystal Apparatus*, U.S. Patent Office, Patent No. 2,364,501, Filing Date: 4 April 1941; Issue Date: 5 December 1944.

manufacturers.[433] Unfortunately, it is not known whether Bliley and the other manufacturers offering patented processes were justly compensated for their intellectual property. It is likely that many firms or individuals, out of a sense of patriotism and duty, offered their patented inventions free of charge to the government. This was true of at least one independent inventor, Edwin Armstrong, who allowed the government to use frequency modulation free of charge for the duration of the war.[434] Whether important quartz crystal patents were freely donated out of patriotism or were commandeered by the Signal Corps, the result was the same. The state of the art in quartz crystal engineering knowledge was disseminated much more widely during the war years than it had ever been.

The General Radio Company, the pioneer of commercial piezo-oscillators, primary quartz frequency standards, and quartz clocks, was quite active during the war, but not making QCU's. The company continued manufacturing frequency measurement instruments and standards, many of which were used by the more than one hundred dedicated QCU manufacturers. General Radio's official history notes that the company saw a more than four-fold increase in output during the war, with annual sales increasing from \$1.2 million is 1940 to \$5.3 million in 1944. Moreover, the company's permanent staff increased from about 220 to 440.[435] Without the quartz-based instruments provided by GR, the Signal Corps QCU production effort would have quickly ground to a halt.

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[433] This story is told in detail in a couple of places. Charles A. Bliley, *The Bliley Electric Company: The Early Years 1930-1955 (2001).* [Web site] (Accessed 28 May 2007) available from http://www.bliley.net/XTAL/; Internet. Richard J. Thompson Jr., *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006), 70-72.

[434] Tom Lewis, *Empire of the Air: The Men Who Made Radio* (New York: Harper Collins, 1991).

[435] Arthur E. Theissen, *A History of the General Radio Company, 1915-1965* (West Concord, MA: General Radio Company, 1965), 51.

7.6 Quartz crystal patents during the war

In the process of realizing mass production of QCUs, wartime engineers developed many patentable inventions.[436] Most of these related in some way to QCU production, including the inspection of raw quartz, determining the electrical orientation of a piece of quartz, the cutting of quartz wafers, the final calibrating of a wafer to the desired frequency, the attachment of electrodes to the quartz wafer, and the mounting of the wafer within a holder or housing. The most active large firm in patenting new inventions was the Bell Telephone Laboratories, but R.C.A. was also quite active at the beginning of the war. Among small firms, Bliley Electric was by far the most inventive, filing at least six QCU-related patents during the war years. By the end of the war, new players had entered the picture and quartz crystal invention had become less concentrated in a few large firms. Among the most important of the new firms were Motorola and the Signal Corps Engineering Laboratories, based in Fort Monmouth, New Jersey. In 1945 alone, sixteen quartz crystal patents were filed by independent inventors. This was almost certainly due to the broad dissemination of quartz crystal engineering knowledge during the war. Many more people with inventive tendencies became aware of the technical problems to be solved.

7.7 I.R.E. activity during the war

As shown in Chapter 6, the Institute of Radio Engineers (I.R.E.) made no deliberate effort to organize the growing quartz crystal technological community during the 1930s. This changed with the approach of war. In 1941, with war clouds on the horizon and the Army Signal Corps already having committed itself to crystal control for

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[436] This section is based on the patent data examined for Chapter 3.

mobile radio units, the I.R.E. formed a Piezoelectric Crystals technical committee. The Institute already had eight technical committees, covering areas such as electronics, transmitters and antennas, television, and radio wave propagation. The addition of a ninth committee indicated the perceived importance of piezoelectric crystals to both the radio engineering community and the Army Signal Corps. Walter Cady, still professor of Physics at Wesleyan University, was named chairman of the new committee. Committee membership included between ten and fifteen engineers drawn mostly from BTL, General Radio, Bliley Electric, and Wesleyan University.

The creation of the I.R.E. Technical Committee on Piezoelectric Crystals did two things that helped to formally organize the quartz crystal technological community and give technical direction to its work. For one, the *Proceedings of the I.R.E.* began devoting a section of its annual feature, “Radio Progress During 19--,” to piezoelectric research. Important papers published during the prior year were listed, and a summary of developments in each specialized area of piezoelectric technology, including quartz crystal technology, was provided. Second, the Institute began paper sessions on quartz crystal technology at its semi-annual technical meetings, as it did at its 1945 Winter Technical Meeting.[437] At this meeting, a technical session featured six papers on various aspects of quartz crystal technology. These two actions laid the groundwork for the post-war consolidation of the quartz crystal technological community that will be discussed in Chapter 8.

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[437] "Institute News and Radio Notes: Winter Technical Meeting, New York, New York," *Proceedings of the Institute of Radio Engineers* 33, no. 1 (January 1945): 49-59, cited: 51.

7.8 The Unqualified Success of Crystal-Control During the War

In the summer of 1944, Roger Colton, now Chief of the Engineering and Technical Service within the Office of the Chief Signal Officer, made the following assessment of the Signal Corp's decision to adopt crystal-control. "Our decision to go into crystal controlled radios for widespread tactical use has been more than justified by the results obtained. The Army had radio before they had crystal. Now the Army has communications. That's the difference. Crystals gave us communications. The advantage of precise and constant frequency control, together with the ease of reading, have given a reliability to our radio communications, which make them second to none in the World."[438] Crystal-control was unquestionably an important factor in the Allied forces' ultimate victory, but just how large a role quartz crystal played is quite difficult to determine and not the primary goal here. A persuasive case can be made that the D-Day invasion of June 6, 1944 would have been a disaster for the Allies without crystal-controlled radios.[439] Whatever the case, it can reliably be said that crystal-controlled radio contributed crucially to ensuring reliable communications for the U. S. military throughout the war. Without it, an Allied victory, though still conceivable, would have been considerably more difficult to achieve.

7.9 The Move to Cultured Quartz

With the conclusion of the war, American manufacturers had successfully produced tens of millions of QCUs and Allied soldiers had become accustomed to the quick, reliable, simple and static-free operation of FM crystal-controlled mobile radio

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[438] Roger B. Colton, "Introductory Remarks" (*Chicago Crystal Conference*, Chicago, IL, 11-12 July 1944).

[439] Richard J. Thompson Jr., *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2* (New York: Wiley-IEEE Press, 2006), 167.

sets. There was clearly no going back to the old days of master-oscillator AM units, but the Brazilian supply of quartz crystal remained a serious concern. Now, with the pressure to keep producing millions of QCU's every month gone, the Signal Corps Engineering Laboratories decided to resume its earlier effort to find a synthetic substitute for natural quartz. Beginning in 1946, the SCEL began investing millions of taxpayer dollars in an intensive R&D effort aimed at solving this problem. As will be recounted in Chapter 8, the ultimate results of this effort stand as one of the most lasting and consequential outcomes of the Signal Corp's decision to adopt crystal-control in 1940.

7.10 Conclusions

World War II represented a watershed for quartz crystal technology. Before the war, its two largest markets were QCU's for the amateur radio market and quartz wave filters for AT&T's carrier multiplex telephony network. Relatively small-scale, batch production techniques were sufficient for supplying these markets. The quartz crystal technological community, to the extent that it could be said to exist, was fragmented. Quartz engineers had little opportunity to network with like-minded engineers outside their own organizations. Quartz crystal engineering knowledge diffused through the community primarily via articles in *Proceedings of the I.R.E.* and the amateur journal *QST*, as well as personal contacts. A few well-connected individuals were particularly important for spreading the quartz crystal gospel. These included Walter Cady, George Washington Pierce, John Dellinger of the Bureau of Standards, Joseph Horton of the Bell Telephone Labs and later General Radio, Melville Eastham of General Radio, and John Wolfskill of BTL and later Bliley Electric.

After the war, the landscape of quartz crystal technology had almost completely changed. The war had required the development of QCU mass production techniques. Before the war, quartz technology had been developed mostly by private industry. Now the U.S. military was committed to advancing the technology. The War saw the beginnings of what came to be called the "military-industrial complex," characterized by a tight coupling between private industry and military needs. During the War, the I.R.E. had formed a Piezoelectric Crystals technical committee, providing the quartz crystal community with its first official recognition by the wider radio engineering community. Quartz engineers now had their own technical sessions at I.R.E. conferences. In many ways, the quartz crystal technological community was beginning to look like a scientific community. Community members were beginning to talk of advancing the field and the state of quartz engineering knowledge rather than simply advancing the interests of the firm or organization for which they worked. The importance of key individuals in disseminating knowledge was diminishing, while the importance of formal institutional structures was increasing. The body of quartz crystal engineers was becoming a self-conscious technological community driven by a collectively agreed upon research agenda.

However, quartz crystal technology faced a crisis at the end of the Second World War. The War had highlighted the scarcity of Brazilian quartz. If the field was to have any future, either new sources of natural quartz would have to be found, or a substitute for natural quartz would have to be developed. Chapter 8 relates the story of the birth of the cultured quartz industry and its ramifications for quartz crystal technology.

CHAPTER 8: REPLICATING NATURE – THE ARTIFICIAL GROWTH OF QUARTZ CRYSTAL

8.1 Introduction

American industry produced massive quantities of supplies and munitions during the years of World War II. Indeed, some observers have even attributed the ultimate Allied victory primarily to American industrial might. No single production effort was more impressive than the one that turned out thirty million or more quartz crystal units (QCUs) between 1942 and 1945. These QCUs, when installed in Allied two-way radios, made tactical communications far quicker, more reliable, and less reliant on trained radio operators than would have otherwise been the case, thus setting the stage for the rapid post-war growth of the commercial mobile two-way radio market.

Yet, the wartime QCU production feat also revealed an Achilles' heel in the quartz crystal industry. The very material used to fabricate QCUs – high quality Brazilian quartz crystal – became the limiting factor in the industry's growth. The Brazilian quartz mining industry proved resistant to rationalization, meaning uncertain quantities and long delivery times.[440] After the war, the U.S. Army Signal Corps and private industry invested millions of dollars in a research effort aimed at finding a substitute for natural quartz. Aided by industrial intelligence gathered from post-war Germany, this effort yielded fruit in the 1950s. The result, called cultured quartz, was grown from natural quartz "seeds" in high-pressure chambers called autoclaves. The Signal Corps generously nurtured this new technology for ten years, culminating in the

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[440] Ibid. Chapter 7.

construction of a pilot plant. At this point, in the late 1950s, the Corps handed over the commercialization and further production of cultured quartz to private industry.

The story of the transformation of the post-war quartz crystal industry from sole reliance upon natural Brazilian quartz to the controlled production of cultured quartz illustrates a number of important themes in the history of 20th century American technological practice. The most far-reaching of these is the centrality of the U.S. military in helping to rationalize post-war American industry and transform it from full-time mobilization to joint civilian-military production, thus laying the foundation for what Eisenhower would later ominously call the "military-industrial complex." Another theme is the important role played by post-war industrial intelligence efforts, notably the Technical Industrial Intelligence Committee, in exploiting the Allied victory and stimulating American research and development in the late 1940s and early 1950s. Thirdly, this story gives a detailed view of a decade-long R&D effort whose aim was the substitution of a naturally occurring substance with an artificially produced one. The efforts of scientists and engineers to convince users that the later was equivalent and even superior to the former shed light on engineering views of "nature" and the criteria that engineers use to assess technical performance. Finally, this chapter illustrates the maturation of the body of resonant quartz crystal engineering knowledge and the consolidation of a vibrant quartz crystal technology research community. This community was something of a prototype for the many technological communities that would be formed during the early years of the Cold War.

8.2 Industrial intelligence in post-war Germany

During World War II, the U.S. government secured enough raw quartz for meeting wartime radio needs only by developing quartz conservation techniques and by paying the Brazilian government to divert quartz shipments bound for Germany and Japan to U.S. ports. As the U.S. emerged from the war, the unreliable supply of Brazilian raw quartz threatened both to restrict the Army's continued use of crystal-controlled radio and to impede the growth of the nascent commercial two-way radio market. In most observers' eyes, the U.S. had to find a reliable and equivalent substitute for Brazilian quartz. Some suspected that a solution might lie in the hands of German scientists and engineers.

In 1945, as Nazi Germany fell and Allied forces occupied the country, America and Great Britain viewed Germany as a potential bonanza of valuable scientific and technical knowledge. Even before Germany's surrender, Allied powers began forming intelligence teams, such as the Combined Intelligence Objectives Subcommittee (CIOS), to move into German states as they fell. Great Britain and the U.S. formed their own teams, the British Intelligence Objectives Subcommittee (BIOS) and the Technical Industrial Intelligence Committee (TIIC), respectively. The early purpose of these organizations was essentially two-fold: to gather scientific, technological, and industrial intelligence that might be of military value, and to interrogate and possibly even intern German scientists and technicians who might try to escape and continue their wartime work elsewhere.[441] Conducting this work for the TIIC were some three hundred and eighty "Scientific Consultants," civilians representing seventeen U.S. industries and

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[441] John Gimbel, "U.S. Policy and German Scientists: The Early Cold War," *Political Science Quarterly* 101, no. 3 (1986): 433-51.

possessing special scientific or technical training as well as competency in the German language.[442] After the German surrender, Britain and the U.S. consolidated their teams to form the Field Information Agency, Technical (FIAT), an organization which existed until mid-1947.[443] Over its two-year lifespan, FIAT's work gradually assumed more of an industrial and less of a military character as the agency's workers realized the potential commercial value of the German "secrets" they were uncovering.

Even before TIIC teams first entered Germany, it was no secret to American scientists that Germany had a strong scientific tradition of augmenting or replacing natural resources with synthetic or artificially grown ones. In the late 19th century, the German firm BASF had developed a synthetic blue dye to replace the expensive natural indigo dye cultivated in British-controlled India.[444] During World War I, the German chemists Fritz Haber and Carl Bosch, motivated by a British blockade of natural nitrate imports from Chile, had developed an industrial process for synthesizing nitrogen compounds.[445] And after the war, the formation of the German conglomerate I.G. Farben had made Germany a global leader in synthetic chemistry. Thus, the TIIC teams entering Germany in the early summer of 1945 fully expected to find new materials and production processes developed in response to the country's wartime trade disruptions.

One of the seventeen U.S. industries chosen for the TIIC's initial investigations was the quartz crystal industry. Researchers in the field of crystallography were aware of

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[442] C. Lester Walker, "Secrets By The Thousands," *Harper's*, October 1946. See also page 435 of John Gimbel, "U.S. Policy and German Scientists: The Early Cold War," *Political Science Quarterly* 101, no. 3 (1986): 433-51.

[443] John Gimbel, "U.S. Policy and German Scientists: The Early Cold War," *Political Science Quarterly* 101, no. 3 (1986): 433-51.

[444] Prakash Kumar, "Facing Competition: The History of Indigo Experiments in Colonial India, 1897-1920" (Ph.D. diss., Georgia Institute of Technology, 2004).

[445] Thomas Parke Hughes, "Technological Momentum in History: Hydrogenation in Germany 1898-1933," *Past & Present*, no. 44 (August 1969): 106-32.

German research in the field of artificial crystal growth, and some suspected that wartime pressures had provided German scientists with the incentive and urgency needed to develop a process for mass producing artificial quartz crystal. To lead this investigation, the TIIC selected Charles Baldwin Sawyer, a Ph.D. physicist with expertise in the fields of crystal growth and beryllium production.

Charles B. Sawyer, not to be confused with Charles W. Sawyer, Secretary of Commerce in the Truman administration, came to the TIIC with over twenty years of industrial experience. Having earned his Ph.D. from MIT at the age of twenty-six, Sawyer moved to the great industrial city of Cleveland, Ohio in 1921 to co-found Brush Laboratories with Charles F. Brush, Jr., son of the famous inventor of the arc lamp and founder of the Brush Electric Company. Brush Laboratories quickly established itself as the leading American manufacturer of microphones, phonograph pickups and loudspeakers made from piezoelectric Rochelle Salt crystals.[446] Sawyer published a handful of technical papers here and there, but his primary interests laid in patenting inventions and building companies for developing and commercializing them.[447] In the 1920s and early 1930s, he published two technical articles on Rochelle Salt, one of which was eventually cited more than five-hundred times, an indication of its great influence within the scientific and technical communities.[448] Then in 1930, Sawyer played a prominent role in establishing two new organizations, the Brush Development Company, formed to commercialize the inventions of Brush Laboratories, and the Brush Beryllium

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[446] Charles Baldwin Sawyer, "The Use of Rochelle Salt Crystals for Electrical Reproducers and Microphones," *Proceedings of the Institute of Radio Engineers* 19, no. 11 (November 1931): 220-29.

[447] The Science Citation Index Expanded database lists five per-WWII publications for Charles B. Sawyer, covering the years 1923 to 1938. In contrast, Sawyer had been issued, either individually or jointly, some 24 patents before beginning his TIIC service. Most of these patents relate to Rochelle Salt devices or beryllium.

[448] Charles Baldwin Sawyer, "Rochelle Salt As A Dielectric," *Physical Review* 35, no. 3 (February 1930): 269-73. According to the Science Citation Index Expanded, this article has been cited 537 times.

Company. Beryllium, a somewhat obscure chemical element, may be mixed with copper to make it both stronger and more tensile, similar to the manner in which carbon may be added to or removed from iron to create steel.[449] As such, the nascent aircraft and electronics industries quickly came to value beryllium, generating a sizeable market for the element. Because of his extensive experience with both piezoelectric crystals and beryllium, the TIIC was essentially getting two "Scientific Consultants" for the price of one in Charles Sawyer.

The TIIC arranged as one of Sawyer's first tasks in Germany a visit with Professor Richard Nacken of the University of Frankfurt am Main. As director of the university's Mineralische and Petrographische Institut (Institute of Mineralogy and Petrography), Nacken was as likely as anyone to be acquainted with recent German developments in artificial quartz crystal production.[450] As it turned out, he was more than acquainted with such work. Sawyer learned that the Nazi government had appointed Nacken in late 1943 to head up a research effort aimed at developing an economical and scalable method for growing quartz crystal. The effort had nearly succeeded when the Nazi regime fell in May 1945. Furthermore, Sawyer learned of the events that led to Germany's quartz crisis.

Prior to 1939, ten private German firms produced a total of roughly ten thousand QCUs per year, many of which were probably sold internationally for commercial use.[451] The two largest of these, Telefunken and Zeiss, obtained the vast majority of their raw

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[449] Charles Baldwin Sawyer and B. R. Kjellgren, "Newer Developments in Beryllium," *Industrial and Engineering Chemistry* 30, no. 5 (May 1938): 501-05.

[450] Petrography is "the description and systematic classification of rocks." *Merriam-Webster's Collegiate Dictionary* (2008), s.v. "Petrography."

[451] Technical (U.S Army) Field Information Agency, Office of the Military Government for Germany (US), *FIAT Final Report on the Interrogation of German Scientists Regarding Quartz Crystals and Other Piezoelectric Materials*, Report 641, by Allyn C. Swinnerton, (1945).

quartz from Brazil. With the start of the war, these firms and others mobilized their plants for wartime production; all manufactured QCUs now went into radios for use by Nazi troops. Over the first two years of the war, Germany's Brazilian source of quartz crystal evaporated as the U.S.-backed Metals Reserve Company paid Brazil to divert quartz shipments bound for Germany to U.S. ports. For a time, the Nazis turned to the Ukraine for raw quartz, but soon discovered that both the quantity and quality of this quartz was insufficient. Even given these severe limitations, German firms managed to produce in the neighborhood of one million QCUs during the war years, including 400,000 units in 1944 alone, all using natural quartz.[452] They did this by taking a number of measures: reducing the size of their quartz wafers, as did the U.S.; using low-grade raw quartz, as evidenced by some German radio sets captured by the U.S.; and working from quartz stockpiles built up prior to the war.[453] But by 1943, with their stockpile of natural quartz dwindling, Nazi officials saw no choice other than to find a natural quartz substitute. With his knowledge of artificial crystal growth, Richard Nacken seemed the best hope for rescuing Germany's QCU producers from their dire predicament.[454]

Prior to 1943, little is known of Richard Nacken other than that he had published a number of scientific papers on crystals and had been experimenting with the artificial

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[452] Ibid.

[453] A consultant deemed the crystal in a captured German QCU to be "much inferior to American-made crystals." U.S. Department of Commerce, Office of the Publication Board, *Report PB 1565. Foreign Crystals (Captured Enemy Equipment Report, 63, compiled by Camp Coles Signal Laboratory)*, by U.S. Army Signal Corps, (Washington, D.C., 1945).

[454] See Charles Baldwin Sawyer Collection, Department of Special Collections, Kelvin Smith Library, Case Western Reserve University, Cleveland, OH. See also Technical (U.S Army) Field Information Agency, Office of the Military Government for Germany (US), *FIAT Final Report on the Interrogation of German Scientists Regarding Quartz Crystals and Other Piezoelectric Materials*, Report 641, by Allyn C. Swinnerton, (1945).

growth of quartz crystal since the mid-1930s.[455] In late 1943, government officials provided generous funding to move the scientist out of his cramped university laboratory and into a space once used by the Nungens Watch Company. Equipped with a machine shop, a furnace, a diamond saw, two x-ray cameras, a darkroom and several microscopes, Nacken's new lab spanned at least six rooms and opened in early 1944.[456]

The artificial growth of quartz crystal, referred to by scientists as the culturing of quartz, was hardly uncharted scientific territory in the early 1940s. At least thirty researchers had published on the topic since the early 19th century.[457] Most notably, between 1898 and 1908 Giorgio Spezia, a mineralogist at the University of Turin, Italy, pioneered a technique of quartz crystal growth called the hydrothermal method, which he believed was quite similar to the process occurring in the Earth's mantle to produce natural quartz crystals. At a very basic level, this method consisted of the following: a hermetically sealed metal chamber, called a bomb or, less ambiguously, an autoclave; a heating element for raising the autoclave's internal temperature; a tiny "seed" of flawless quartz crystal; a solid nutrient, typically crushed quartz or glass, which provided the raw material for seed growth; and an alkaline solvent solution for dissolving the nutrient (Figures 40 and 41.). Before beginning the growth process, the crystal seed was suspended in the solvent solution. After being sealed, the autoclave was heated to a pre-determined temperature. As the temperature and internal pressure of the autoclave rose, the solid nutrient dissolved in the solvent solution. Once the desired temperature-

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[455] Ernest Buehler and A.C. Walker, "Growing Quartz Crystals," *The Scientific Monthly* 69, no. 3 (September 1949): 148-55. The authors state that Nacken had been working with cultured quartz crystal for "about 12 years" when the war ended.

[456] Technical (U.S Army) Field Information Agency, Office of the Military Government for Germany (US), *FIAT Final Report on the Interrogation of German Scientists Regarding Quartz Crystals and Other Piezoelectric Materials*, Report 641, by Allyn C. Swinnerton, (1945).

[457] P.F. Kerr and E. Armstrong, "Restricted Supplement 1," *Geological Society of America, Bulletin* 54 (1943): 1-34.

pressure level had been reached, the autoclave was held in steady state while the solvent solution, now enriched with dissolved nutrient, slowly deposited crystallized silica onto the crystal seed, gradually producing a large and defect-free quartz crystal. By using this method, Spezia succeeded in growing several quartz crystals, each about ¼-inch in length. Because the growth rate was excruciatingly slow (about 0.001 inches per day), Spezia had to sustain his process for six or more months to get crystals of this size.[458]

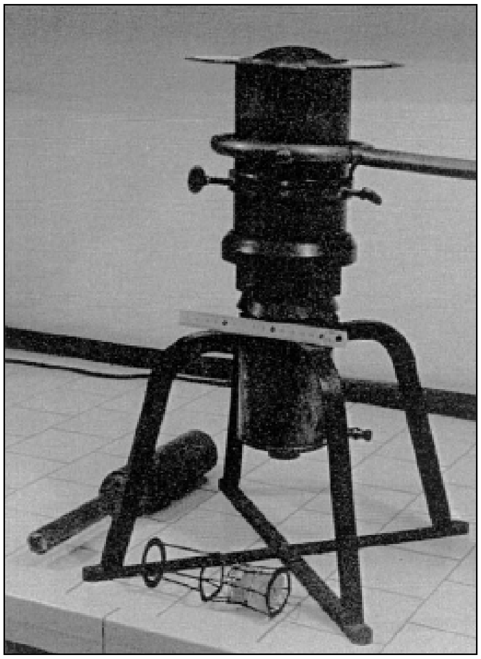

Figure 40: Giorgio Spezia's Autoclave, Photograph of
(Reprinted, by permission of Elsevier, from Fumiko Iwasaki and Hideo Iwasaki, "Historical Review of Quartz Crystal Growth," *Journal of Crystal Growth* 237-239 (2002): 820-827, Figure 1. ©2002 Elsevier)

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[458] Ernest Buehler, *Method of Growing Quartz Crystals*, U. S. Patent Office, Patent No. 2,785,058, Filing Date: 28 April 1952; Issue Date: 12 March 1957. See also Danforth R. Hale, "The Laboratory Growing of Quartz," *Science* 107, no. 2781 (16 April 1948): 393-94.

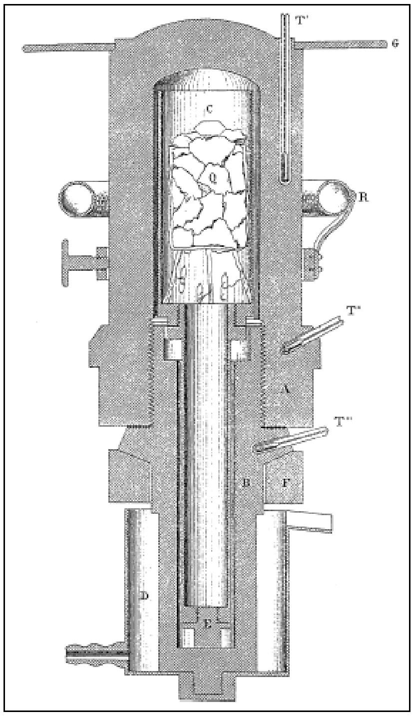

Figure 41: Cross-Section of Spezia's Autoclave for Implementing the Hydrothermal Method of Crystal Growth
(Reprinted, by permission of Elsevier, from Fumiko Iwasaki and Hideo Iwasaki, "Historical Review of Quartz Crystal Growth," Journal of Crystal Growth 237-239 (2002): 820-827, Figure 2. ©2002 Elsevier).

Nacken, beginning his cultured quartz research in 1930s Germany, also chose the hydrothermal method. However, he introduced some important modifications to Spezia's process that allowed him to grow perfect crystals of one inch diameter, far larger than any that had ever been grown artificially, in less time than it took Spezia to grow his ¼-inch crystals. Nacken's growth process was very fast, but it was not continuous, requiring a recharging of the autoclave every twenty-four hours. Nevertheless, many saw the process as holding great promise. Most importantly, it seemed capable of producing crystals of sufficient size for use in the manufacture of QCU wafers. Wagering that further research would improve Nacken's new process, the Nazi government allocated funds in 1943 for the creation of a National Hydrothermal Institute. Also, Germany's Telefunken Company applied for patents on Nacken's refined hydrothermal method and began constructing a plant for the large-scale production of artificial quartz.[459] Only Germany's defeat in May 1945 prevented the fulfillment of these plans.

Upon meeting with Nacken in the summer of 1945, Sawyer was deeply impressed with his growth of one inch diameter crystals. Yet, he also realized that Nacken's process was not yet to the point where cultured quartz could compete commercially with natural quartz. In his estimation, "at least one year" would be required to bring the process to commercial viability.[460] Unhampered by intellectual property concerns, Charles Sawyer and another Scientific Consultant, Dr. Allyn Swinnerton, gathered all the patent applications and other technical documentation they could find related to German artificial quartz growth. Swinnerton, a geology professor at Ohio's Antioch College and cross-state neighbor of Sawyer's, possessed valuable scientific knowledge of quartz that dovetailed nicely with Sawyer's industrial knowledge. Armed with German quartz documents and detailed notes of interviews with Nacken and other scientists, the two men returned home convinced that their findings would ensure the U.S. quartz crystal industry's continued growth.

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[459] Technical (U.S Army) Field Information Agency, Office of the Military Government for Germany (US), *FIAT Final Report on the Interrogation of German Scientists Regarding Quartz Crystals and Other Piezoelectric Materials*, Report 641, by Allyn C. Swinnerton, (1945).

[460] Folder 4, Box 10, Series II, Charles Baldwin Sawyer Collection, Department of Special Collections, Kelvin Smith Library, Case Western Reserve University, Cleveland, OH.

8.3 Post-War organization of cultured quartz research

With German quartz crystal "secrets" now in the hands of the Allies, researchers began jockeying for position, competing for funds to extend Nacken's quartz growth research. The first group out of the box was English rather than American. The research team of N. and W.A. Wooster, with the Brooklyn Crystallographic Laboratory of Cambridge, England, had begun independently investigating hydrothermal methods of quartz growth prior to the war's end. In March 1946, the team published results showing that it had achieved quartz growth using a method very similar to Nacken's.[461] Like Nacken, this team also experienced problems with sustaining growth, but the independent replication of Nacken's results was an important first step in moving the research forward. This work led to Wooster and Wooster soon receiving the support of the British firm General Electric Company (GEC), Ltd., which continued to support their quartz growth research for a number of years.[462]

In the U.S., a group at Bell Telephone Laboratories (BTL) headed by A.C. Walker was the first to begin work on the culturing of quartz crystal. Walker, a physical chemist with a Yale Ph.D., had developed during World War II methods for growing synthetic piezoelectric crystals. One of these crystals, ethylenediamine tartrate (EDT), turned out to be a very effective replacement for natural quartz in AT&T's multiplex telephony wave filters. But, because of its unique properties, natural quartz remained essential in the production of QCU's, which Western Electric, AT&T's manufacturing arm, continued to manufacture for use in broadcast radio transmitters. With the end of the war, BTL sent some investigators to Germany as part of the TIIC post-war intelligence

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[461] Nora Wooster and W. A. Wooster, "Preparation of Synthetic Quartz," *Nature* 157, no. 3984 (9 March 1946): 297.

[462] C.S. Brown et al., "Growth of Large Quartz Crystals," *Nature* 167, no. 4258 (9 June 1951): 940-41.

effort. One of these, a Mr. J. R. Townsend, collected information on Nacken's quartz experiments independent from that of Sawyer and Swinnerton.[463] Walker used this information, as well as the government reports published by Swinnerton and Sawyer, to launch BTL's cultured quartz project in March 1946.

The U.S. Army Signal Corps, unwilling to leave American cultured quartz research solely in BTL's hands, soon established its own program, organized and managed by the Fort Monmouth, New Jersey-based Signal Corps Engineering Laboratories (SCEL). The Labs' limited research and production facilities meant that the bulk of the research would be performed by university and industry groups on a contractual basis. SCEL personnel would make funding decisions as well as coordinate the overall research effort. To this end, the Signal Corps announced at the 1946 annual meeting of the American Association for the Advancement of Science that it was launching a new frequency control research program, whereby researchers could apply for multi-year funding.[464] Designed to sponsor research related to any aspect of frequency control technology, the SCEL program supported investigations on a wide range of topics in addition to quartz crystal growth, including the fabrication of QCUs, oscillator circuitry, the chemical and physical properties of quartz crystal, and the synthesis of non-quartz piezoelectric crystal types, such as tourmaline and nepheline.[465] The last topic in this list hedged against the possible failure of the quartz crystal growth project, for despite the limited successes of Nacken in Germany and the Wooster team in England, no one was certain that further research would yield a commercially-viable

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[463] Ernest Buehler and A.C. Walker, "Growing Quartz Crystals," *The Scientific Monthly* 69, no. 3 (September 1949): 148-55.

[464] Danforth R. Hale, "The Laboratory Growing of Quartz," *Science* 107, no. 2781 (16 April 1948): 393-94.

[465] Arthur Ballato, "Introduction to the Historical Section" (*50th IEEE International Frequency Control Symposium*, U.S. Army Research Laboratory, Forth Monmouth, NJ, June 1996), 4-23. See Appendix.

production process. Considerable risk was involved, as is always the case with exploratory research.

The first organizations to apply for and receive SCEL cultured quartz research contracts were the Brush Development Company, led by Charles Sawyer, and Antioch College, Allyn Swinnerton's home institution.[466] Clearly, Sawyer and Swinnerton leveraged their Scientific Consultant positions with the TIIC to win these contracts. Antioch's task was to extend Nacken's laboratory work by determining the optimum conditions for controlled quartz growth and by developing a theory explaining the mechanism of hydrothermal crystal growth.[467] Brush was to then use this knowledge to develop a scalable and economical quartz production process.

Leading the research effort at Brush Development were two men – Hans Jaffe, a German Jew with a Ph.D. in crystal physics from the University of Goettingen, and Danforth Hale, an American whose previous positions included chemistry professor at a small college and research chemist for RCA.[468] Emigrating to the U.S. in 1935, Jaffe had the good fortune to meet Walter Cady, who agreed to hire him as a lab assistant in the Wesleyan University Physics Lab.[469] Impressed with his abilities, Cady soon promoted Jaffe to Assistant Professor, a position he held until 1940. During his five years at Wesleyan, Jaffe ably assisted Cady in generating and organizing data for his forthcoming book on piezoelectricity.[470] In 1940, he left academia to take a position with Brush

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[466] SCEL Annual Report for FY 1947, SCEL Annual Reports, Signal Corps Engineering Laboratories Collection, Historical Files of Fort Monmouth, Fort Monmouth, NJ.

[467] James F. Corwin and A.C. Swinnerton, "The Growth of Quartz in Alkali Halide Solutions," *Journal of the American Chemical Society* 73, no. 8 (19 August 1951): 3598-601.

[468] Rudolf Bechmann and Danforth R. Hale, "Electronic Grade Synthetic Quartz," *Brush Strokes* 4, no. 1 (September 1955): 1-7.

[469] See Chapters 2, 4, and 5 for more on Walter Cady.

[470] Walter Guyton Cady, *Piezoelectricity; An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals* (New York: McGraw-Hill, 1946). This book was Cady's

Development in Cleveland, where he began researching synthetic substitutes for Rochelle Salt.[471] In 1946, Brush management tapped Jaffe to head the company's new cultured quartz project. It was also at this time that Hale left RCA to join Brush. For the next ten years or so, the two men worked closely with Swinnerton at nearby Antioch College on the culturing of quartz crystal.

To help manage and coordinate the numerous frequency control projects that it sponsored, the SCEL sponsored and organized a frequency control symposium in 1947. Held at the Labs' headquarters in Fort Monmouth, this meeting brought together representatives from the War and Navy departments, universities and firms holding research contracts, and members of the new Joint Research and Development Board (JRDB), created by Vannevar Bush and Lloyd Berkner in 1946 to succeed the Office of Scientific Research and Development (OSRD).[472] This board reviewed Department of War and Navy research projects "in order to avoid duplication" as well as to "filter out and terminate mediocre or wasteful efforts."[473] Despite the heavy military representation at the first symposium, the proceedings were largely free of secrecy. In fact, SCEL research policy explicitly stipulated that "research programs be conducted with a minimum of security restrictions in order to permit interchange of information and

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magnum opus and, upon its publication in 1946, quickly became the "Bible" of piezoelectric crystal engineering.

[471] Charles F. Pulvari, "A Tribute to Dr. Hans Jaffe: From Rochelle Salt to Poled Piezoelectrics," *IEEE Transactions on Sonics and Ultrasonics* SU-25, no. 6 (November 1978): 329.

[472] Erik P. Rau, book review of *Science, Cold War, and the American State: Lloyd V. Berkner and the Balance of Professional Ideals*, by Allan A. Needell, *Technology and Culture*, Vol. 42, No. 3, October 2001. With the creation of the National Military Establishment (later Department of Defense) in September 1947, the JRDB became the Research and Development Board.

[473] SCEL Annual Report for FY 1949, 74, SCEL Annual Reports, Signal Corps Engineering Laboratories Collection, Historical Files of Fort Monmouth, Fort Monmouth, NJ.

freedom of work."[474] The stated aims of this policy were to minimize time delays in applying new technologies to military equipment and to make the new knowledge gained generally available to the research community.[475]

Over the next several years, the GEC, BTL, and SCEL cultured quartz research efforts progressed independently. The team of Wooster and Wooster continued to head the British research effort, but the financial support and resources of GEC greatly expedited their work. The BTL research team soon grew to include researchers Ernest Buehler and R. A. Laudise.[476] Along with Walker, these three men worked full-time on the culturing of quartz. As for the SCEL, the success of its first frequency control symposium persuaded the Labs to make it an annual event.

8.4 The nature of cultured quartz research

Cultured quartz research proceeded slowly through the late 1940s and early 1950s, not for lack of finances or focused effort, but simply because of the newness of the field and the enormous amount of work required. Theory was of very little help to researchers, largely because there was an insufficient base of experimental data on cultured quartz growth. Furthermore, as has already been mentioned, success was far from guaranteed. No one knew for sure that further research would yield a rapid and scalable process for culturing quartz crystal. Yet, the Zeitgeist within the scientific and technical communities just after World War II was, if anything, can-do. The remarkable

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[474] "Outline of Research Program with Compilation of Tasks Assigned Through Outside Contracts," 15 February 1947, SCEL Annual Reports, Ibid.
[475] Lt. Colonel Winfred A. Ross, "Signal Corps Research and Development Program," 24 June 1949, SCEL Annual R&D Reviews, Ibid.
[476] A.C. Walker and E. Buehler, "Growing Large Quartz Crystals," *Industrial and Engineering Chemistry* 42, no. 7 (July 1950): 1369-75.

technological achievements of the war had given many engineers the feeling that just about anything could be accomplished if enough resources were provided.

Though generous resources were certainly provided for cultured quartz research, many technical problems proved frustratingly stubborn. This was not open-ended, blue sky research; rather, it had a definite goal – to grow large, high quality quartz crystals rapidly and with high yield (i.e., the growth process would yield very little waste product). No one, however, knew just how to get there.

Because of the prior successes of Spezia and Nacken, all major post-WWII quartz research teams decided to focus their efforts on the hydrothermal method of crystal growth. Though other methods existed, this one was seen as providing the best chance of success. But the hydrothermal method, as described earlier, encompassed a bewildering array of variable process parameters, such as autoclave temperature and type of solvent solution: there was no single correct way to implement the method. Furthermore, the process parameters were interdependent, and no one knew the precise relationship between each parameter and crystal growth rate or crystal quality. Painstaking experimentation – the systematic varying of each process parameter and observation of results – was the only way to discover these relationships.

Of all the process parameters of the hydrothermal method, two stood out as particularly consequential. These were temperature variation within the autoclave, and nutrient material. Concerning temperature variation, there were basically two options available, the temperature differential method and the isothermal method. Spezia pioneered the first, in which a heating element was applied to one end of the autoclave, the other end remaining unheated. This set up a temperature differential within the autoclave, giving rise to convection currents in the solvent solution. Nacken consciously rejected Spezia's temperature variation technique, instead pioneering the isothermal method in which the entire autoclave is heated to a uniform temperature.

The choice of temperature differential or isothermal was far from arbitrary; the two scientists chose between these two based upon the nutrient material available to them. Spezia chose crushed quartz crystal, while Nacken chose fused silica, also known as vitreous quartz, fused quartz, or, most commonly, glass. These two materials are both forms of silicon dioxide (SiO_2), the only chemical difference being that the atoms of the first are organized into a single crystal lattice, while the atoms of the later are fused together in an amorphous manner. Spezia, working in Italy around the turn of the century, a time of relative peace, knew that large, flawless quartz crystals were relatively rare in nature, but he would have had no reason to question the availability in general of quartz crystal, particularly the smaller, flaw-ridden kind common in granite. Nacken, however, faced a very different circumstance. Since wartime Germany's supply of quartz crystal was quite limited, Nacken capitalized on the fact that fused quartz, which is the primary ingredient of common sand, is among the most abundant of all naturally occurring materials. Nazi Germany, even at the height of its procurement problems, would not have had trouble securing abundant quantities of fused quartz.

When performing his pioneering temperature differential experiments, Spezia placed his crushed quartz nutrient in the top of the autoclave and the crystal seed beneath this. He then applied heat to the autoclave's top, thereby dissolving the crushed quartz in the solvent solution. This dissolved quartz slowly diffused down to the crystal seed, where the slightly cooler temperatures transformed the enriched solvent into a supersaturated solution, thus facilitating the deposition of the dissolved quartz onto the seed. Essentially, this process transformed a multitude of tiny, flaw-riddled crystals into one large flawless crystal, as shown in Figure 42. It was crucial that the crystal seed be placed at the cooler end of the autoclave; otherwise, the seed itself might begin to dissolve in the solvent. As discussed earlier, Spezia achieved very slow growth rates with this process, but by sustaining it for as long as six months, he could grow sizable crystals.

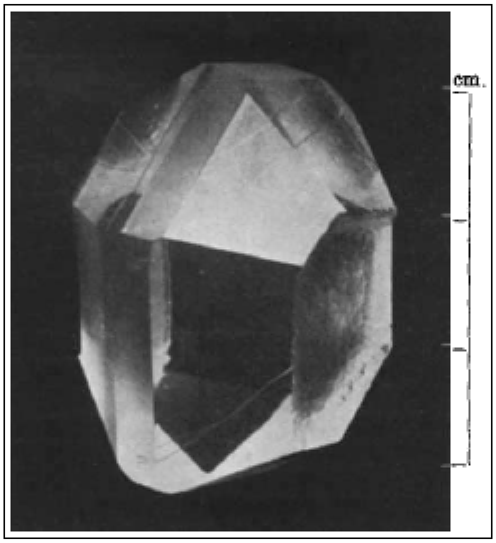

Figure 42: A Large, Flawless Cultured Quartz Crystal
(Reprinted by permission from Macmillan Publishers Ltd: *Nature*, Brown, Kell, Thomas, Wooster, and Wooster, "Growth of Large Quartz Crystals," 167, no. 4258, 9 June 1951: 940-941), ©1951)

Nacken, however, was not satisfied with Spezia's temperature differential method because of its dependence upon natural quartz crystal as the nutrient. Quartz crystal, even in crushed form, was in short supply in Nazi Germany. Nacken wanted a more accessible nutrient material. He therefore used fused silica, a substance that Germany, or any other nation for that matter, would have no trouble procuring. Yet the temperature gradient method did not work particularly well with it. Through much research, Nacken ingeniously exploited the large difference in the solubilities of quartz crystal and fused silica. He found that near the critical point of water (374.2^{o}C, 218 Atmospheres), the solubility of fused silica is much greater than that of quartz crystal. Thus, as Nacken heated his autoclave to a uniform temperature, the fused silica nutrient rapidly dissolved, creating a supersaturated solvent solution well before the quartz crystal seed itself was in danger of dissolving. As the seed was bathed in the supersaturated solution, rapid deposition (i.e., seed growth) occured.

But Nacken ran into a thorny problem with his isothermal method. As captured German reports indicated, seed growth rates within the first several hours of autoclave heating were remarkably high, but could not be sustained. In fact, all seed growth came to a virtual halt within twenty-four hours. At this point, the only thing to do was bring the autoclave back to room temperature, drain it, refill it with fresh solvent and nutrient material, and restart the process with the seed preserved from the former growth cycle. Through the laborious process of refreshing the autoclave every day for many weeks, Nacken was able to grow his one inch diameter quartz crystals.

Thus, in 1946, as the post-WWII quartz research teams began their work, the knowledge of hydrothermal quartz growth could be broadly summarized as follows. Spezia's method of using the temperature gradient technique with a nutrient of crushed quartz crystal yielded seed growth that could be sustained for months, but at an extremely slow growth rate. On the other hand, Nacken's use of the isothermal technique with a nutrient of fused silica yielded seed growth at a far faster rate, but the growth could be sustained for only a day or so. The trick, of course, was to devise a method that combined Nacken's growth rate with Spezia's sustainability of growth.

Researchers were well aware that process parameters of the hydrothermal method other than temperature variation and nutrient material also affected cultured quartz growth. Among these were autoclave size and shape, whether or not to artificially agitate the autoclave contents during crystal growth, composition and concentration of solvent solution, whether or not various impurities should be added to the solvent solution, the cut or crystal lattice orientation of the seed crystal, and the autoclave's internal temperature-pressure operating point. The precise effect of any of these parameters on crystal growth was largely an open research question in 1946.

Surveying the state of things, the Wooster and BTL teams independently decided to use Nacken's isothermal technique as a starting point, reasoning that it would be easier devising ways to sustain Nacken's process than figuring out how to accelerate Spezia's. After all, at this time no one was quite sure what halted isothermal crystal growth after only a day. Perhaps the problem would be easily identified and solved. Not far into their research, however, the teams ran into the same wall that Nacken had encountered – though initial growth rates were very rapid, all crystal growth abruptly stopped within sixteen to twenty-four hours of heating the autoclave. Neither team was able to surmount this technical barrier.

8.5 The Brush Development Company makes a breakthrough

Meanwhile, the Brush and Antioch team, which began its research in early 1947, had the benefit of learning from Wooster and BTL's difficulties. Danforth Hale of Brush decided to start with Spezia’s temperature gradient method, wagering that he could find a way to accelerate growth. Rather than simply replicate Spezia’s experimental setup, Hale made a simple but very important modification. As shown in Figure 43, he hung the crystal seed at the top, placed the nutrient material in the bottom, and applied heat only to the autoclave’s base, essentially inverting Spezia’s setup. This simple change, along with using a sodium carbonate solution and raising the autoclave’s internal temperature and pressure, resulted in a 26% increase in quartz growth rate.[477] By the end of 1948, Hale had used his method to grow a flawless 1.5” diameter quartz crystal, the largest yet produced in a laboratory.[478]

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[477] Danforth R. Hale, "The Laboratory Growing of Quartz," *Science* 107, no. 2781 (16 April 1948): 393-94.
[478] Charles Baldwin Sawyer Collection, Department of Special Collections, Kelvin Smith Library, Case Western Reserve University, Cleveland, OH.

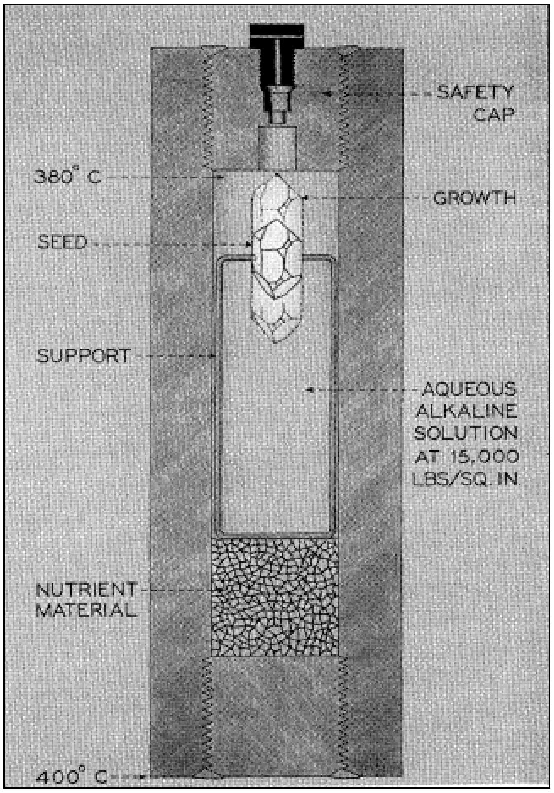

Figure 43: Autoclave Setup Similar to That Developed by Danforth Hale of Brush Development Company
(From Ernest Buehler and A.C. Walker, "Growing Quartz Crystals," *The Scientific Monthly* 69, no. 3, (September 1949): 150 pp: 148-155. Reprinted with permission from AAAS.)

Hale's simple inversion of Spezia's autoclave represented a fundamental evolution in scientific understanding. To Spezia's way of thinking, the nutrient material (i.e., crushed quartz crystal) should be held at the top of the autoclave. Once dissolved by the applied heat, the nutrient would naturally fall, via gravity, down to the crystal seed at the autoclave's base. What Spezia, along with everyone else in the scientific community, did not understand in the first decade of the 20th century were the processes of natural convection and molecular diffusion. As became evident with scientific discoveries made in the 1920s and '30s, the only natural mechanism for transporting dissolved nutrient from autoclave top to base in Spezia's setup was molecular diffusion, a tediously slow process. By the time of Hale's experiments, it was well known that heating a vertical column of fluid from the bottom makes the lower fluid less dense than the higher, creating an upward buoyancy force. The result, called natural convection, is bulk movement of the fluid from base to top, with cooled fluid returning to the base along the sides of the vertical column. Natural convection, which requires the presence of a gravitational field, is a much more rapid process than diffusion, meaning that dissolved nutrient is transported to the crystal seed at a much higher speed.[479] Developments in atomic physics and thermodynamics in the first half of the 20th century changed the way that scientists looked at the world. Hale was a beneficiary of these developments. What to him seemed a very reasonable autoclave setup probably never occurred to Spezia forty years earlier.

Hale's findings, first published in 1948 in the journal *Science*, greatly influenced the BTL and Wooster research teams, both who promptly abandoned their isothermal experiments to focus on temperature gradient crystal growth. In 1949, Walker and the BTL team replicated and then bested Hale's results by realizing three modifications: substituting sodium hydroxide for sodium carbonate as the solute; increasing the temperature differential from autoclave base to top; and raising the autoclave's internal pressure from 200-300 atmospheres to around 1000 atmospheres.[480] Realizing the last of these modifications required developing a new autoclave design that could withstand

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[479] A. F. Mills, *Heat and Mass Transfer* (Boca Raton, FL: CRC Press, 1995), 293.

[480] Ernest Buehler and A.C. Walker, "Growing Quartz Crystals," *The Scientific Monthly* 69, no. 3 (September 1949): 148-55.

high internal pressures.[481] The development of such a device proved to be a significant engineering challenge.

8.6 Bell Telephone Laboratories develops the high-pressure autoclave

If Hale's inversion of Spezia's setup represents the single most important development in post-WWII cultured quartz research, BTL's development of the high-pressure autoclave is a close second.[482] While attempting to improve on the Brush crystal growth technique, A. C. Walker learned of recent geological research on the relationship between gas solubility and gas density.[483] This research showed that the solubility of silica began progressively increasing at around 1000 atmospheres.[484] Walker reasoned that if he could raise an autoclave's internal pressure to this level, the increased solubility of silica might produce a richer nutrient solution, thus accelerating crystal growth. But higher autoclave pressures could be quite dangerous. At one point, while testing a new autoclave temperature control unit, BTL researchers accidentally allowed the chamber's internal pressure to rise above 1350 atmospheres. The device exploded, destroying the insulated furnace that held it. No researchers were injured, but the accident highlighted the urgent need for an improved autoclave design.[485]

BTL received vital help from others in developing its new autoclave. Prior to learning of Hale's success at Brush Development and while still experimenting with the

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[481] Mean sea level atmospheric pressure is approximately one atmosphere.

[482] A.C. Walker and E. Buehler, "Growing Large Quartz Crystals," *Industrial and Engineering Chemistry* 42, no. 7 (July 1950): 1369-75. "Perhaps the most important factor in the success of this work has been the engineering design and operation of steel autoclaves in which are grown such large quartz crystals."

[483] A.C. Walker, "Hydrothermal Synthesis of Quartz Crystals," *Journal of the American Ceramic Society* 36, no. 8 (August 1953): 250-56.

[484] Ibid. (

[485] A.C. Walker and E. Buehler, "Growing Large Quartz Crystals," *Industrial and Engineering Chemistry* 42, no. 7 (July 1950): 1369-75.

isothermal method, BTL had been using an autoclave with internal dimensions of only 1 inch diameter and 1 inch depth. Once the decision was made to move to the temperature gradient method, BTL received important information from Brush on its autoclaves. Namely, Brush had been using a 1 inch diameter and 12 inch deep autoclave constructed of welded steel and employing a 0.5 inch thick steel wall surrounding the growth chamber. BTL took this design, fortified it with additional features, and added a pressure release valve for safety. The resulting autoclave design, illustrated in Figure 44, could generate and maintain an internal pressure in the neighborhood of 1000 atmospheres for weeks or even months.

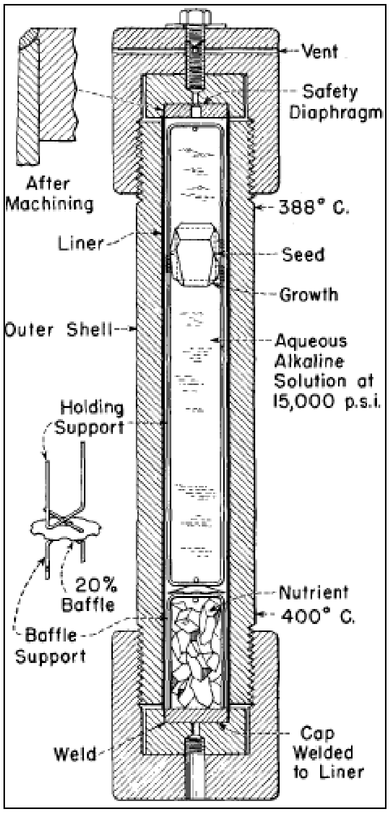

Figure 44: Cross-Section of High-Pressure Autoclave Developed at Bell Telephone Labs, Circa Late 1940s
(Reprinted, by permission of Wiley-Balckwell Publishers, from A.C. Walker, “Hydrothermal Synthesis of Quartz Crystals,” *Journal of the American Ceramic Society* 36, no. 8 (August 1953): 250-256.)

Walker considered his BTL research team's success with the high-pressure temperature gradient crystal growth method a turning point in cultured quartz research. Writing in 1949, he stated, "It is still too early in the development to quantitatively relate temperature gradient, size of nutrient material, and bomb dimensions to growth rate, but these factors can be correlated, and sufficient progress has been made so that *it is clear that large perfect quartz crystals weighing up to one pound or more may be grown at commercially practicable rates under reproducible conditions*."[486] (Italics are mine.) In other words, BTL had demonstrated the technical feasibility of cultured quartz growth. In recognition of his achieving "controlled growth of piezoelectric crystal in sizes suitable for commercial and military use," the Franklin Institute awarded its Louis Edward Levy Medal to Walker in 1951.[487] But technical feasibility was only the first step in replacing natural with cultured quartz in the marketplace. Engineers still had to work out quantitative relationships between the hydrothermal method's many process parameters. Beyond that, BTL's successful laboratory procedure had to be converted into a scalable and efficient production process. Furthermore, such a process had to be implemented on a large enough scale such that sufficient economies of scale could be realized, making cultured quartz affordable. Finally, customers had to be convinced that cultured quartz was functionally identical to natural quartz. Of course, there was no guarantee that any of these things would happen. In particular, the economic feasibility of cultured quartz remained very much in doubt. Brush and BTL's laboratory growth of

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[486] Ernest Buehler and A.C. Walker, "Growing Quartz Crystals," *The Scientific Monthly* 69, no. 3 (September 1949): 148-55.
[487] "Radio Progress During 1951," *Proceedings of the Institute of Radio Engineers* 40, no. 4 (April 1952): 388-439.

cultured quartz was essentially a scientific achievement, and a very limited one at that. The economic and social achievement of replacing natural with cultured quartz in the marketplace was another matter altogether. If possible, it would require many more years of continued Signal Corps investment and engineering research.

8.7 The Signal Corps Engineering Laboratories organizes a parallel approach to the cultured quartz problem

In 1950, the SCEL invited BTL to present its cultured quartz progress to the Fourth Annual Frequency Control Symposium. Since 1947, the symposium had continued to grow each year; by 1950, it was quickly becoming an international mecca for all things frequency control. BTL's presentation that year lasted only fifteen minutes, but it led to the Labs' receiving a cultured quartz contract. The SCEL offered this contract not because BTL needed the money to continue its research. As is well-known, BTL was at this time the premier industrial R&D lab in the U.S., generously funded through AT&T's government-protected monopoly on telephony. But the SCEL wanted to direct all U.S. cultured quartz research, eliminating duplications of effort and realizing as quickly as possible a commercially viable cultured quartz industry.

To this end, the SCEL implemented a division of labor between BTL and Brush Development, with each team working on a different variant of temperature gradient crystal growth. This was in accordance with one of the Research and Development Board's explicit policies. "Truly fundamental scientific endeavor appears to thrive best under competition, and parallel (not identical) approaches to the same problem is often most beneficial and gives a greater assurance of ultimate success."[488] Undoubtedly, this policy was based, at least in part, on the OSRD's success during WWII with this approach, particularly the multiple and simultaneous paths pursued in realizing the atomic bomb.[489]

The SCEL's cultured quartz division of labor was quite simple. Brush Development was to focus on low to medium pressure (81-340 atm) crystal growth, while BTL would investigate high pressure (816-1020 atm) growth. The logic of this division stemmed from uncertainty as to what pressure would yield the best balance between crystal growth rate, crystal quality, yield of crystal growth per quantity of nutrient, and cost. Lower pressures tended to yield high quality, clear crystals and a high yield for low to moderate cost. This was often accompanied, however, by slower growth rates. Higher pressures, though producing more rapid growth rates, were harder to control and tended to produce an effect called spurious crystallization or self-nucleation, in which tiny quartz crystals would form throughout the autoclave chamber. This effect was highly undesirable because of the low yields that resulted. Furthermore, the capital costs for high pressure crystal growth were considerably more than for low or medium pressure growth. Not only did the autoclaves have to be larger and thicker, but they often had to be given their own insulated rooms or cells in case of explosion.

The research at Brush and BTL now proceeded along parallel lines, and both teams continued to encounter difficulties. Progress was slow, in part because each trial

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[488] SCEL Annual Report for FY 1949, 74, SCEL Annual Reports, Signal Corps Engineering Laboratories Collection, Historical Files of Fort Monmouth, Fort Monmouth, NJ.

[489] The Manhattan Project involved the simultaneous pursuit of two possible fissile materials, plutonium and uranium-235, as well as two separate procedures for generating uranium-235. See, for example, pages 381-416 of Thomas Parke Hughes, *American Genesis: a century of invention and technological enthusiasm, 1870-1970* (New York: Viking, 1989).

run of crystal growth lasted anywhere from ten days to several months. Both teams ran many simultaneous trials, with a particular process parameter systematically varied across the trials. Another complicating factor was the interdependence of process parameters; it was impossible to vary one process parameter, say, solution concentration, without affecting others. General qualitative relations between any one parameter and the crystal growth rate were gradually discerned as researchers accumulated data, but precise quantitative relations – the kind that engineers need to optimize production processes – were far harder to determine.[490]

The researchers at Brush and BTL were stepping gingerly into a technological terrain in which little was known with certainty. As is always the case with exploratory research, developments that initially appeared promising were later viewed as dead ends or boondoggles. One case in point was the dual-chamber rocking autoclave, designed by Brush Development and filed with the U.S. Patent Office in 1950.[491] Illustrated in Figure 45, this apparatus, an attempt to improve on BTL's high-pressure autoclave design, divided the traditional single autoclave chamber into two separate chambers connected by two narrow channel pipes. One chamber, called the "silica-dissolving" chamber, contained raw nutrient material while the other, known as the quartz-growing chamber, contained the seed crystal. Warm nutrient-enriched solution was to pass from the silica-dissolving to the quartz-growing chamber via one channel pipe, while cooled nutrient-depleted solution would return to the silica-dissolving chamber via another pipe. By

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[490] A.C. Walker and E. Buehler, "Growing Large Quartz Crystals," *Industrial and Engineering Chemistry* 42, no. 7 (July 1950): 1369-75.

[491] Andrew R. Sobek and Danforth R. Hale, *Method and Apparatus for Growing Single Crystals of Quartz*, U. S. Patent Office, Patent No. 2,675,303, Filing Date: 11 April 1950; Issue Date: 13 April 1954.

allowing the entire apparatus to be periodically tilted or rocked in one direction and then another, a steady flow of nutrient solution throughout the autoclave was maintained.

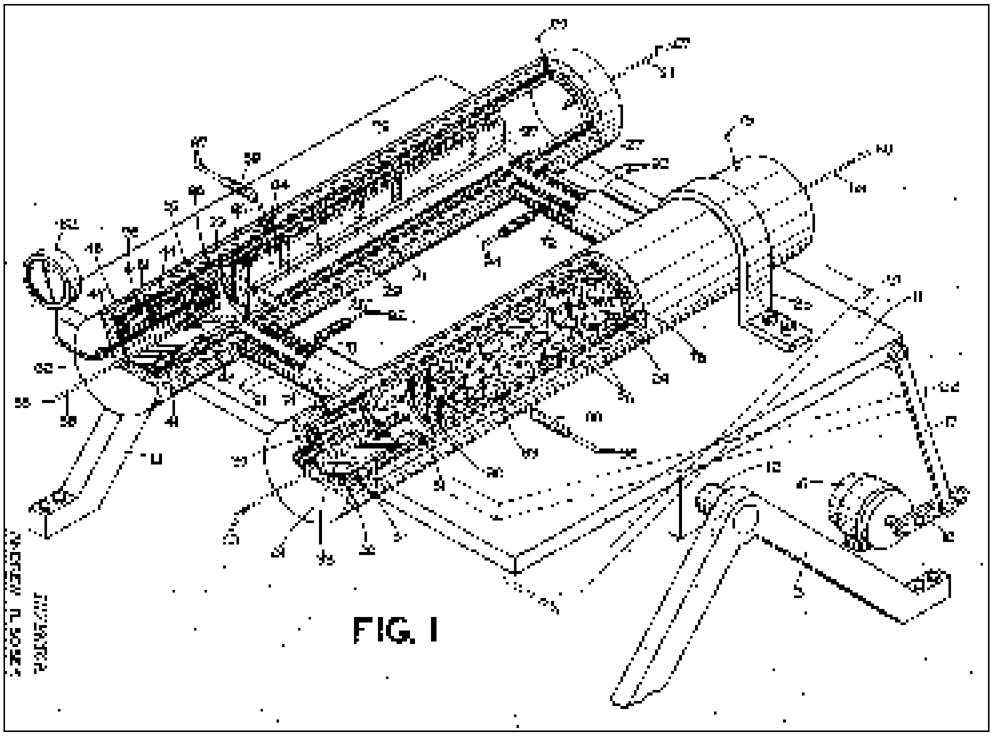

FIG. 1

Figure 45: Dual-Chamber Rocking Autoclave, Developed by Brush Development Company, Circa 1950
(Source: U.S. Patent Office, Patent No. 2,675,303)

Initial results for the dual-chamber rocking autoclave were encouraging. It accelerated crystal growth and improved yield. Yet this performance came at a high cost; the new autoclave was considerably more expensive than the single-chamber design. A cost benefit study conducted in 1955 indicated that the single-chamber autoclave, despite its slower and less efficient growth, was roughly 40% more cost-efficient than the dual-chamber rocking autoclave.[492] Brush thus abandoned the new autoclave, writing it off as a high but perhaps unavoidable cost of doing research.

8.8 SCEL selects Brush Development to construct a cultured quartz pilot plant

By 1951, the Signal Corps was confident enough in the medium-pressure research results obtained at Brush to begin funding construction of a pilot plant. While BTL's growth rates remained higher than Brush's, the former's high-pressure growth process was, as stated earlier, much more expensive than medium-pressure growth. Thus, the Signal Corps considered Brush's process the more economically feasible of the two.

Brush broke ground on its cultured quartz pilot plant near company headquarters in Bedford, Ohio, a suburb of Cleveland. Construction was completed by the fall of 1953, and the Signal Corps awarded the company a one-year "industrial preparedness study" contract, according to which Brush would deliver five hundred pounds of cultured quartz to the Corps in exchange for $120,000, or $240 per pound of quartz. Over the coming year, as the Corps received cultured quartz shipments from Brush, it forwarded them on to on to QCU manufacturers around the country for evaluation.[493] In all, fifteen firms received this experimental quartz, with more than half the total amount concentrated among five firms – the Standard Piezo Company and the Hunt Corporation,

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[492] Brush Laboratories Company, President's Report, July 1955, Folder 6, Box 2, Series III, Charles Baldwin Sawyer Collection, Department of Special Collections, Kelvin Smith Library, Case Western Reserve University, Cleveland, OH. See also Danforth R. Hale, "Optimum Methods for Quartz Synthesis" (*10th Annual Frequency Control Symposium*, 1956), 95-99.

[493] Hans Jaffe et al., "October 1953 Quartz Update," Folder "R&D Committee Minutes – 1953 (I)," Box 23, Series III, Charles Baldwin Sawyer Collection, Department of Special Collections, Kelvin Smith Library, Case Western Reserve University, Cleveland, OH.

both of Carlisle, Pennsylvania; Bliley Electric of Erie, PA; the James Knight Company of Sandwich, Illinois; and Western Electric.[494]

Brush didn't assume that all QCU manufacturers would love its cultured quartz. Anticipating that some customers might continue to prefer natural Brazilian quartz, the company hired Dr. Rudolf Bechmann in 1953 to conduct scientific comparisons of the two.[495] Bechmann, the former head of Telefunken's Crystal Laboratory in Nazi Germany, immigrated to England after the war, where he worked for several years with the British Post Office Research Station in London studying the piezoelectric properties of various synthetic materials. His coming to Brush brought the company the mathematical sophistication and theoretical brilliance for which German science had become well known. Bechmann's research findings revealed small differences in the frequency-temperature behavior of Brush's cultured versus natural quartz, but these differences would have been largely invisible to most users.[496] In confirmation of Bechmann's work, those receiving evaluation shipments from the Signal Corps were pleased, not detecting any noticeable performance difference between natural and the new quartz. The price difference was, however, another matter.

Brush's pilot plant project proceeded without any major delays, but economics continued to concern some project leaders. In early 1955, when Western Electric was paying $27.50 per pound for raw natural Brazilian quartz crystal, Brush was preparing to

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[494] Signal Corps Supply Agency memo, 25 March 1955, Folder 3, Box 5, Series III, Ibid.

[495] Charles B. Sawyer, "October 1952 Quartz Update," Folder "R&D Committee Minutes – 1952 (II)," Box 23, Series III, Ibid.

[496] Rudolf Bechmann, "Frequency-Temperature-Angle Characteristics of AT-Type Resonators Made of Natural and Synthetic Quartz," *Proceedings of the Institute of Radio Engineers* 44, no. 11 (November 1956): 1600-07.

introduce its cultured quartz into the marketplace at $52.50 per pound.[497] While the military may have been willing to purchase at such a price, the company didn't have a chance with the private commercial sector unless its salesmen could demonstrate to customers some inherent superiority of cultured over natural quartz. As it turned out, this wasn't difficult to do.

8.9 Brush sells its cultured quartz

Brush engineers and salesmen stressed to potential customers that cultured quartz had the same advantage over natural quartz that all artificially produced materials have over their natural counterparts. Namely, artificially grown quartz could be tailored to a customer's specific needs. Initially this simply meant that the quartz could be grown to a size and shape that would accommodate the customer's blanks. "Blank" was the term used for the sliced quartz wafer, shown in Figure 46, employed in making one QCU. By purchasing grown quartz crystals of varying sizes and shapes, customers were able to maximize the number of blanks that could be cut from a single crystal, thus minimizing scrap quartz. On the other hand, Brush was sure to emphasize that with natural crystals, one was never sure how many useful blanks a particular crystal would yield. In other words, pound for pound, cultured quartz could always be grown to yield more blanks than natural quartz, saving customers money and reducing unusable scrap quartz. Writing in 1948, Danforth Hale estimated that, depending upon the quality of raw quartz

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[497] Brush Laboratories Company, President's Report, May 1955, Folder 6, Box 2, Series III, Charles Baldwin Sawyer Collection, Department of Special Collections, Kelvin Smith Library, Case Western Reserve University, Cleveland, OH. See also Folder 3, Box 5, Series III.

that cultured quartz was replacing, reductions in scrap quartz of around 20% could be expected.[498]

Figure 46: Slab of Large Cultured Quartz Crystal, Shown with Rectangular and Circular Blanks
(Personal photograph of Richard J. Thompson, Jr. Reprinted by permission. thompsor@strose.edu)

But Brush also stressed that the made-to-order nature of cultured quartz could potentially mean much more than a reduction in scrap material. As Rudolf Bechmann's research from the mid-1950s showed, the addition of trace amounts of other elements, such as germanium dioxide, to the growth solution would modify the frequency-

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[498] Danforth R. Hale, "The Laboratory Growing of Quartz," *Science* 107, no. 2781 (16 April 1948): 393-94.

temperature characteristic of cultured quartz.[499] For some specialized applications, this would be desirable. Despite the promise of this technique, years of additional research would be required to perfect it. But once perfected, it would allow users to customize cultured quartz, optimizing technical performance for different uses.

By the time Brush offered its cultured quartz for sale in 1955, several QCU manufacturers, including Western Electric, Bliley Electric, and the James Knight Company were willing to buy at the initial asking price of $52.50 per pound.[500] While still more expensive than natural quartz, Brush's quartz was considerably more affordable than BTL's. No cost data is available for the latter since neither BTL nor Western Electric ever sold its quartz commercially, but BTL's high-pressure hydrothermal process was undoubtedly much more expensive than Brush's medium-pressure process. Nevertheless, AT&T began funding construction of a high-pressure pilot plant in the mid-1950s, hoping to use the resulting quartz in the Bell System's multiplex telephony wave filters (see Chapter 6). Operated by Western Electric, the plant succeeded in demonstrating large-scale, high-pressure production of cultured quartz by late 1958.[501] Perhaps more of a technical feat than Brush's accomplishment, Western Electric's quartz was nevertheless too expensive to compete with Brush's. Its chief advantage was rapid turnaround. This would have certainly been desirable for the military during wartime. But for the commercial marketplace, rapid turnaround was not enough of an advantage to justify the extra cost.

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[499] Rudolf Bechmann, "Frequency-Temperature-Angle Characteristics of AT-Type Resonators Made of Natural and Synthetic Quartz," *Proceedings of the Institute of Radio Engineers* 44, no. 11 (November 1956): 1600-07.

[500] Brush Laboratories Company, Folder 3, Box 5, Series III, Charles Baldwin Sawyer Collection, Department of Special Collections, Kelvin Smith Library, Case Western Reserve University, Cleveland, OH. See also Folder 6, Box 2, Series III.

[501] Robert A. Laudise and R. A. Sullivan, "Pilot Plant Production of Synthetic Quartz," *Chemical Engineering Progress* 55 (1959): 55-59.

The customers buying Brush's cultured quartz in the mid-1950s were for the most part using it to fabricate QCU's for civilian applications: broadcast radio transmitters and two-way radios for airline, police, emergency responder, taxi, and railroad use. The total civilian market for QCU's at this time was an estimated 750,000 units per year, with the vast majority of QCU's still using natural Brazilian quartz.[502] But a new civilian application was emerging that, according to Brush estimates, had the potential to expand the QCU market by a factor of ten.[503] This application was color television.

David Sarnoff, head of RCA, had set color television as one of his company's goals even before World War II. Delayed by the war and the subsequent Korean War, RCA finally began to realize this goal in 1953. It was in this year that the National Production Authority lifted its wartime ban on color television production. Also in this year, the FCC adopted a color TV transmission standard specifying that each television set was to internally generate a frequency of 3.579545 MHz +/- 10 Hz for separating control and color information in the received broadcast signal.[504] The only device known at this time to be capable of generating such a precise and accurate frequency was the QCU. Therefore, every color TV set produced in the U.S. would have to contain at least one QCU. This was just the kind of application – one requiring tens of thousands of identical quartz wafers – that Brush needed in order to realize economies of scale in its production of cultured quartz. Indeed, color television promised to be the "Model T" of QCU applications. But the growth rate for this new market failed to meet Sarnoff's bold

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[502] Danforth Hale to Charles B. Sawyer, 2 April 1951, Folder "Squier Signal Lab Quartz Contract: 1948-1952," Box 6, Series III, Charles Baldwin Sawyer Collection, Department of Special Collections, Kelvin Smith Library, Case Western Reserve University, Cleveland, OH.

[503] Danforth Hale to Charles Sawyer, 2 April 1951, Folder "Squier Signal Lab Quartz Contract: 1948-1952," Box 6, Series III, Ibid.

[504] W. H. Charbonnet, "Visit to Institute of Radio Engineers Convention, NTC, 22 March 1954," Folder "Quartz Synthesis – Misc. (1952-1956)," Box 6, Series III, Ibid.

prediction of five million color sets by 1958.[505] Nevertheless, once growth did take off in the 1960s, most of the QCUs in color TV sets were made from cultured rather than natural quartz.

8.10 "…the end of ten years of happy struggle with synthetic quartz"

In May of 1956, the SCEL held its 10th Annual Frequency Control Symposium at an Asbury Park, New Jersey hotel. The annual meeting had grown rapidly through the early 1950s, requiring the move from Fort Monmouth to nearby Asbury Park. Not only had it size grown, but so had the diversity of participants. The first few symposia saw a largely domestic audience. But in 1956, "representatives of governmental agencies and commercial organization from Australia, Belgium, Canada, England, France, Germany, and the Netherlands" also attended the symposium.[506] If the annual meeting had ever been cloaked in concerns for national security, that time had clearly passed. Its attendee list now comprised an international elite group of representatives from government, industry, and academia.

At the 10th Symposium, Danforth Hale of Brush Development gave a final report on his firm's quartz work. "This Symposium marks the end of ten years of happy struggle with synthetic quartz."[507] Brush's Bedford Pilot Plant had produced more than 2000 pounds of synthetic quartz under SCEL contracts. Some of the crystals produced

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[505] Thomas K. McCraw, *American Business, 1920-2000: How It Worked*, ed. John Hope Franklin and A. S. Eisenstadt, The American History Series (Wheeling, IL: Harlan Davidson, Inc., 2000).

[506] "Proceedings of the 10th Annual Frequency Control Symposium", (Asbury Park, NJ, 1956). See the Welcoming Address by Brigadier General Earle F. Cook.

[507] Danforth R. Hale, "Optimum Methods for Quartz Synthesis" (*10th Annual Frequency Control Symposium*, 1956), 95-99.

were as large as 3 pounds, and some of the crystal batches had produced as many as 190 individual crystals weighing a total of nearly 100 pounds. Never had cultured quartz been produced on such a scale. Hale went on to compare his company's quartz with natural quartz. "The total cost of the synthetic [sic] quartz produced [at Bedford] has been admittedly a little high." Indeed, the Signal Corps had invested at least $620,000, or $300 per pound, in Brush's cultured quartz program.[508] But Hale continued. "Nevertheless, because of high quality, advantageous shape, uniformity of product, freedom from twinning, … synthetic [sic] quartz is believed to be nearly competitive with natural Brazilian quartz."[509] "Nearly" competitive was correct, for cultured quartz's selling price remained significantly higher than that of natural quartz. Even so, as already mentioned, several QCU manufacturers had expressed interest in Brush's product. Hale ended his report by stating that Brush had closed its Bedford Pilot Plant in March 1956 and was awaiting disposition orders from the Signal Corps Supply Agency. The company would not be moving into full commercial production of cultured quartz.

Brush's decision to close its pilot plant and withdraw from the cultured quartz business reflected both the termination of its Signal Corps quartz contracts and recent changes in ownership at the company. In 1952, both the Brush Development Company and the Brush Beryllium Company had merged with the Cleveland Graphite Bronze Corporation to form the Clevite Corporation of Cleveland, OH. Brush Development's name was changed to Brush Electronics, which became a wholly-owned subsidiary of

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[508] Up through 1951, SCEL spent approximately $500,000 on Brush's research. Source: Brush Laboratories Company, "A Proposal For Evaluation of Synthetic Quartz," June 1952, Folder "R&D Committee Minutes – 1952 (I)," Box 23, Series III, Charles Baldwin Sawyer Collection, Department of Special Collections, Kelvin Smith Library, Case Western Reserve University, Cleveland, OH. In 1953, SCEL spent another $120,000 on Brush's industrial preparedness study.

[509] ———, "Optimum Methods for Quartz Synthesis" (*10th Annual Frequency Control Symposium*, 1956), 95-99.

Clevite. As long as SCEL contracts continued to subsidize the company's quartz research, the new Clevite leadership was happy to let the cultured quartz work continue. But in 1955, as this work was drawing to a close, the company faced a decision. It could go commercial with cultured quartz, scaling up to full production at the Bedford Pilot Plant and hoping that quartz profits would offset the loss of SCEL contracts, or it could withdraw from the business altogether, closing the Bedford plant and selling it off.

8.11 The birth of Sawyer Research Products

By the summer of 1955, some within the company had begun expressing doubts as to the profit potential of cultured quartz.[510] In addition, Charles Sawyer wasn't getting along all that well with some of the Clevite leadership. His reputation as an effective scientist-engineer was acknowledged by all, but some were questioning his managerial skills because of his "slowness in getting things through to commercialization"[511] and his occasional failure to "get along with people."[512] There was also the matter of Sawyer's age. He turned 60 in 1955; to the new Clevite management, he represented the old guard. The company wanted new ideas and fresh talent.

Charles Sawyer was not without supporters at Clevite, particularly among long-time Brush Development managers. In the spring of 1956, one manager, Harry Dodds, expressed to Sawyer his feeling that Clevite's new leadership was ruining the company's Research Center.[513] Before long, the two were looking at industrial real estate east of

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[510] Charles B. Sawyer journal entry, 4 August 1955, Folder 2, Box 5, Series II, Charles Baldwin Sawyer Collection, Department of Special Collections, Kelvin Smith Library, Case Western Reserve University, Cleveland, OH.

[511] Charles B. Sawyer journal entry, 2 August 1955, Ibid.

[512] Charles B. Sawyer journal entry, 20 September 1955, Ibid.

[513] Charles B. Sawyer journal entry, 3 April 1956, Folder 5, Box 5, Series II, Ibid.

downtown Cleveland. Very quickly, within a matter of six weeks, the two hatched a plan to buy out Clevite's quartz holdings, including all relevant patents, and start their own firm.[514] Named Sawyer Research Products (SRP), Inc., the firm's primary objective would be to commercialize cultured quartz. The plan apparently encountered little to no opposition from Clevite, for Sawyer purchased a site for his new company in late summer of that year.[515] Relieved at Clevite's response, Sawyer's new venture allowed him a graceful exit from an intractable situation. As he wrote in his personal journal, "it was my only escape."[516]

Sawyer Research Products didn't take long to get off the ground. Within two years of purchasing a site, the new company was selling cultured quartz for $27.50 per pound, a 47% drop from Clevite's 1955 price of $52.50.[517] This no doubt reflected the slow but sure growth of the color television market as well as the continued growth of the two-way radio market. Other markets for cultured quartz continued to emerge, as evidenced by the industrial diversity of attendees at the 1959 Annual Frequency Control Symposium. Among the industries represented were aircraft manufacturing, radio (broadcast and two-way), telephone, watch manufacturing, and space exploration.[518] SRP supplied cultured quartz to all of these industries, dominating the U.S. cultured quartz market.

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[514] Charles B. Sawyer journal entry, 22 May 1956, Ibid.
[515] Charles B. Sawyer journal entry, 25 August 1956, Folder 6, Box 5, Series II, Ibid.
[516] Charles B. Sawyer journal entry, 6 June 1956, Ibid.
[517] Charles Baldwin Sawyer, "Progress in Engineering Cultured Quartz For Use By The Crystal Industry" (*13th Annual Frequency Control Symposium*, 1959), cited: 466.
[518] Attendance List, "Proceedings of the 13th Annual Frequency Control Symposium", (Asbury Park, NJ, 1959).

By the late 1960s, cultured quartz had replaced natural quartz in most applications.[519] Additionally, SRP had begun supplementing crushed quartz crystal with scrap cultured quartz as the material in its production process. But still, much crushed crystal continued to come from Brazil. In the early 1970s, BTL researchers reassessed the known North American sources of quartz and determined that these were sufficient for providing nutrient material, finally bringing America's long dependence on Brazilian quartz to an end.[520]

As the popularity of consumer electronics and computers grew throughout the remainder of the 20th century, frequency control applications of quartz crystal continued to increase. Any device requiring precise control of frequency or time, be it a color television, a VCR, an electronic wristwatch, a personal computer, or a cell phone, needed at least one QCU. By the late 1990s, the annual market for quartz crystal devices had reached roughly two billion units, representing a market value of approximately $1.2 billion.[521] By 2000, cultured quartz ranked "second only to silicon in the quantity of single crystal materials produced for all electronic applications," and roughly 2500 to 3500 tons of cultured quartz crystals were being grown per year.[522] The majority of these crystals are grown in Japan and China, with only about 10% of the world's supply being

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[519] M. D. Fagen, *A History of Engineering and Science in the Bell System*, 7 vols. (New York: Bell Telephone Laboratories, 1985). Volume VI, Chapter 6, 277.

[520] Ibid. Volume IV, 532.

[521] John Vig, "Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications - A Tutorial" [PowerPoint] 1999, U.S. Army Communications-Electronics Command, Fort Monmouth, NJ. Slide 1-2.

[522] Gary R. Johnson, "History of the Industrial Production and Technical Development of Single Crystal Cultured Quartz" (*International Frequency Control Symposium and Exhibition*, Montreal, Canada, 2004). See Abstract. See also John Vig and Arthur Ballato, "Frequency Control Devices," in *Ultrasonic Instruments and Devices - Reference for Modern Instrumentation, Techniques, and Technology*, ed. Emmanuel P. Papadakis (New York: Academic Press, 1999), 638.

produced in the U.S.[523] Thus, as has happened with so many other American technological innovations, the cultured quartz industry that began in the U.S. in the 1940s and 1950s has, for the most part, moved overseas. Even so, through the later 20th century and up to the present, no American firm has ever rivaled SRP's position as the largest U.S. producer of cultured quartz.[524]

Today, the technique of cultured quartz production remains largely the same as it was in the late 1950s. Of course, certain aspects of the hydrothermal method have been refined, such as the addition of impurities to the solvent solution to slightly modify performance characteristics, techniques for accelerating the dissolution of the solid nutrient material as the autoclave heats, and the precise measurement and monitoring of internal autoclave temperatures by means of robust thermocouples. But the basic methods developed by Brush, the low and medium-pressure method, and by BTL, the high-pressure method, are still in use today. The apparatus involved have remained largely the same as well. As can be seen in Figure 47, autoclaves used by SRP today follow the basic design patented by BTL in 1950, and shown earlier in Figure 44.[525] This is evidence not so much of stagnation in the field of cultured crystal growth. To the contrary, the hydrothermal method of crystal growth has continued to evolve, albeit at a slower pace than in the pioneering post-WWII years. Rather, this is evidence of the lasting contributions made by SCEL-supported research in the 1940s and '50s.

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[523] Gary R. Johnson, "History of the Industrial Production and Technical Development of Single Crystal Cultured Quartz" (*International Frequency Control Symposium and Exhibition*, Montreal, Canada, 2004). Section IX.

[524] Ibid.

[525] Sawyer Research Products, *Technical Brief: Hydrothermal Growth of Quartz.* [PDF File] (Accessed 15 March 2007) available from http://www.sawyerresearch.com/Tech%20Brief/Quartz_growth_tech_brief.pdf; Internet.

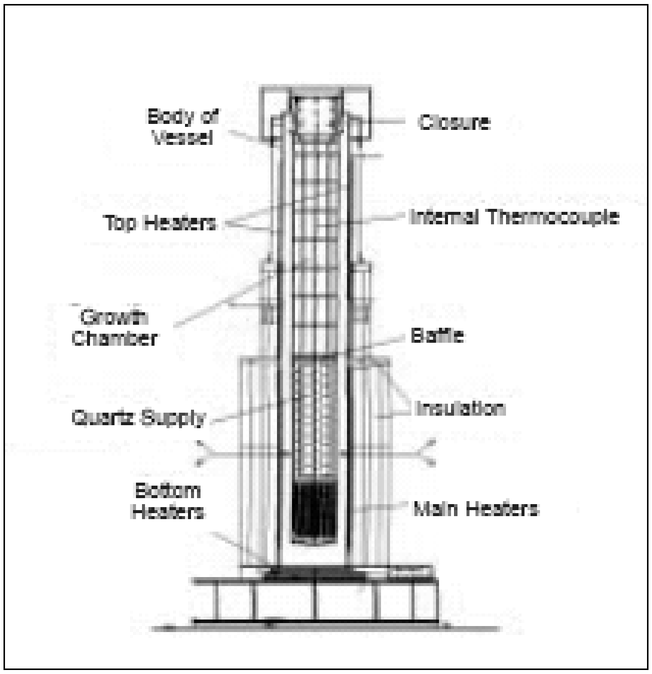

Figure 47: Cross-Sectional Diagram of Modern Autoclave, Circa 2000
(Reprinted, by permission of Sawyer Technical Meterials, from Technical Brief, http://www.sawyerresearch.com/Tech%20Brief/Quartz_growth_tech_brief.pdf. Accessed 7 February 2009.)

8.12 Conclusions

The story of the genesis and development of the cultured quartz industry is, above all, a tale of military patronage. Emerging from World War II, American leaders had become believers in the power of technology and in the might of American industry. The U.S. now looked to its technological superiority for leverage when dealing with its enemies, most notably the Communist Soviet Union. Wartime military-sponsored research had produced or greatly improved an impressive array of technologies: radar, microwaves, the atomic bomb, the digital computer, jet aircraft, and, as seen in the previous chapter, millions of quartz crystal units, each adhering to a frequency control tolerance on the order of 0.02%.[526] After the war, escalating tensions between America and the Soviet Union and America's faith in military-sponsored technology pushed the nation into a state of permanent peacetime mobilization.[527] The Army Signal Corps' sponsorship of frequency control technology in general and cultured quartz research in particular was a prime example of this mobilization.

What would have become of American quartz crystal technology had not the Signal Corps paid the bill for cultured quartz R&D? Of course, we can only speculate. Had not the Signal Corps sponsored cultured quartz R&D, Bell Labs would probably have continued its cultured quartz research, but it is very doubtful that cultured quartz would have replaced natural quartz as soon as it did. Brush would probably not have entered the cultured quartz area, given the high costs of the research and Brush's inexperience with natural quartz. This would have given Bell Labs a monopoly on cultured quartz. As with the transistor, anti-monopoly pressures would have forced Bell to make its quartz technology available to others through licensing. But again, all of this would have probably happened much slower had not the Signal Corps invested in cultured quartz.

Why did the Corps invest in cultured quartz when it did? In essence, it was the perceived urgency of national security considerations. The Army had narrowly dodged a bullet during World War II, when the supply of natural quartz almost dried up. Natural quartz had become so valuable and scarce only because of Roger Colton's bold move to

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[526] "Proceedings of the 10th Annual Frequency Control Symposium", (Asbury Park, NJ, 1956). See the Welcoming Address by Colonel C. W. James, Director of Components Department, Signal Corps Engineering Labs.

[527] Alex Roland, *The Military-Industrial Complex*, ed. Pamela O. Long and Robert C. Post, Historical Perspectives on Technology, Society, and Culture (Washington, D.C.: American Historical Association, 2001).

commit Army communications to crystal-control early in the war. Thus, we can plausibly draw a fairly direct connection between Colton's decision in 1940 to adopt crystal-control and the emergence of a commercially viable cultured quartz industry in the late 1950s.

Given the national security concerns surrounding quartz crystal during the war, the lack of secrecy around the Signals Corps' frequency control symposia begun in 1947 may strike us as odd and even a little reckless. Why were these symposia as open as they were? The SCEL was committed to openness and free flow of information when state secrets were not in danger of being disclosed. It was felt that such openness would ultimately result in more and better technology, particularly when the technology involved was "dual-use," having both military and civilian applications.[528] The scientific community had long practiced such openness, in part because the economic stakes involved were usually not nearly as great as with patentable technologies. But such openness was not usual for military-sponsored technology.

Furthermore, in the case of cultured quartz, the Army Signal Corps was primarily concerned with securing a stable and reliable supply of radio grade quartz for the U.S., not in denying this to other nations. For the U.S., this meant developing the ability to artificially grow cultured quartz. For other nations not facing a shortage of natural quartz, cultured quartz would be unnecessary. In particular, information obtained by Charles Sawyer and Allyn Swinnerton during their post-war TIIC trips suggested that the Soviet Union might have abundant supplies of natural quartz.[529] The Ukraine was known to have significant natural quartz deposits, though the quality of these deposits was in

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[528] Ibid., 23.

[529] Swinnerton learned that Germany had begun importing quartz crystal from the Ukraine once its Brazilian source was blocked.

question. Even so, there was the very real possibility that the Soviet Union had more than enough natural quartz with which to build QCUs. Thus, any effort expended in keeping cultured quartz knowledge hidden from the Soviets might have been wasted.

The story of cultured quartz also illustrates the role played by American intelligence teams at the end of World War II in stimulating American post-war industrial growth. These teams proved to be of inestimable value in certain areas of technology, such as rocketry. And immediately following the war, there was much hubbub in the American press regarding the "secrets by the thousands" that these teams had obtained from German scientists and engineers.[530] But for cultured quartz, the role was more modest. As this chapter has shown, the isothermal crystal growth method developed by Richard Nacken in Germany in the 1930s and early '40s was seriously flawed. In fact, the final methods developed by Brush and BTL bore more resemblance to Giorgio Spezia's temperature differential method than to Nacken's. Nevertheless, Nacken's work, as uncovered by TIIC consultants Charles Sawyer and Allyn Swinnerton, convinced American and British researchers that cultured quartz could be grown in volume and made commercially competitive with natural Brazilian quartz. This was important, for believing that something can be accomplished is the crucial first step toward accomplishing it. Beyond this vital contribution, Nacken's method turned out to be more of a decoy or distraction than an aid in realizing the commercial production of cultured quartz.

The story of the final replacement, in the late 1950s and 1960s, of natural Brazilian quartz by cultured quartz reveals an interesting dialogue over the benefits of artificial over naturally occurring materials. Throughout the 1930s and '40s, many

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[530] C. Lester Walker, "Secrets By The Thousands," *Harper's*, October 1946.

research teams had attempted to develop synthetic materials that could replace natural quartz as used in QCU's. None succeeded, because none was able to replicate the unique electrical characteristics of natural quartz, namely its extremely high frequency selectivity. (See Chapter 5.) Of course, this led some to speculate that man would never be able to improve on nature in this case; the long-time span, presumably thousands or even millions of years, and unique geologic conditions required to form natural quartz in the earth's crust were, some argued, the only way to realize natural quartz's electrical properties. Those who refused to buy this argument, including Richard Nacken, gave up on synthetic materials and finally resorted to attempting, as had Spezia, to replicate the earth's geologic conditions in the confines of a small, hermetically-sealed laboratory apparatus. Much to their delight, these researchers learned that the process of quartz growth could be accelerated by varying temperature, pressure, and other process parameters.

Nevertheless, cultured quartz inevitably differed slightly from natural quartz. But, as this chapter has shown, getting QCU manufacturers to accept cultured quartz was not difficult, once its technical performance was shown to be nearly identical to that of natural quartz. Moreover, manufacturers and end users began to prefer cultured quartz because of its made-to-order nature, which reduced waste, allowed customers to specify technical characteristics, and ultimately, after economies of scale had been achieved, lowered the cost of QCU's.

Finally, in closing this chapter, we can better understand the significance of the development of cultured quartz by comparing and contrasting it with another materials science innovation from the mid-20th century – single-crystal semiconductors, particularly silicon.[531] Of primary importance is the issue of patronage. As this chapter has illustrated, the development of cultured quartz in the post-war years depended heavily, but not exclusively, upon military patronage – specifically, Signal Corps contracts. The commercial promise of the nascent two-way radio and color television markets enticed BTL to undertake cultured quartz research without an SCEL contract, but even BTL eventually came under the Signal Corps' patronage as its research progressed. For semiconductor crystals, the dependence upon military patronage was less dominant. It was military funding during the war that led to the production of extremely pure ingots (i.e., polycrystalline masses) of silicon. Single-crystal silicon growth, however, which was crucial for the improvement of early transistor performance, emerged from internal Bell Labs research rather than from military contracts. Thus, silicon as a basis for semiconductor technology was developed through both public and private funding.

Also of importance are the general types of innovations represented by cultured quartz and single-crystal semiconductors – whether their influence on technology was radical or conservative; whether they provided entirely new functionalities, or simply performed an existing function more efficiently, faster, or at a higher performance level. After World War II, the scarcity of high-quality natural quartz represented the major obstacle or bottleneck to full-scale industrialization of quartz crystal technology.[532] The innovation of cultured quartz removed this bottleneck, allowing industrialization to

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[531] The information on semiconductors in this section is drawn from three sources. Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age*, First ed., Sloan Technology Series (New York: W.W. Norton & Company, 1997). Ernest Braun and Stuart MacDonald, *Revolution in Miniature: The History and Impact of Semiconductor Electronics* (Cambridge, England: Cambridge University Press, 1978). Christopher Lecuyer and David C. Brock, "The Materiality of Microelectronics," *History and Technology* 22, no. 3 (September 2006): 301-25.

[532] If we were to view the quartz crystal unit (QCU) as a technological system, then the scarcity of quartz could be characterized, in the terminology of Thomas Hughes, as a "reverse salient." It seems to me, however, that framing the QCU as a system is a misuse of the word "system." I've therefore chosen to use the metaphor of the bottleneck to characterize the scarcity of quartz.

proceed unabated. We may therefore characterize this innovation as one of natural resource replacement, cited by Nathan Rosenberg in an influential article as one of the most common "inducement mechanisms" in the history of technological change.[533] Cultured quartz was not a radical innovation in the sense of creating new capabilities that never existed before. It simply allowed a technological trend to continue in the face of changing natural resource availability. Furthermore, cultured quartz was and is, for the most part, chemically no different from natural quartz. The process of growing cultured quartz is even very similar to the geologic process that produces natural quartz, the primary difference being that the former takes place in a controlled laboratory environment. Thus, cultured quartz is not a new material, but rather a replication of an existing material. The innovation of single-crystal silicon was completely different. This was in every sense a radical innovation. To begin with, single-crystal silicon does not exist in nature. It was, when developed in the 1940s, a completely new material, not a replication of a naturally-occurring material. Second, single-crystal silicon made possible the development of solid-state devices (e.g., the field-effect transistor) that had a revolutionary impact on the world of electronics. Without them, radios, amplifiers, and computers would still depend on bulky and energy-consuming vacuum tubes.

Lastly, there are the growth trajectories of cultured quartz and single-crystal semiconductors. There is a great deal of overlap here. Since QCUs and silicon devices are amenable to miniaturization and mass production, they both helped strengthen the 20th century technological imperative toward "smaller, faster, cheaper" devices and products. Where QCUs were once used in vacuum tube radios, they have remained, the

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[533] Nathan Rosenberg, "The Direction of Technological Change: Inducement Mechanisms and Focusing Devices," *Economic Development and Cultural Change* 18, no. 1 (January 1969): 1-24.

only significant change being that they have become smaller. At the same time, bulky tubes have been replaced by tiny silicon transistors. Furthermore, the rise of digital technologies again called for both QCUs and silicon devices. In particular, personal computers and mobile telephones have made heavy use of both technologies. Thus, the demands for cultured quartz and single-crystal silicon have risen together over the past century, such that these materials are today the top two single-crystal materials produced for electronics use.

In sum, we see that cultured quartz and single-crystal semiconductors both benefited from military patronage in the middle decades of the 20th century. Furthermore, their growth trajectories through the later half of the century mirrored one another, largely due to the rise of digital electronic devices, most of which require one or more QCU's to provide precise timekeeping. But the development of single-crystal semiconductors radically transformed the world of electronics, while the development of cultured quartz played a more modest role by allowing the development of electronics to proceed along a direction established by other forces. Even so, had cultured quartz never reached the stage of commercialization, electronics in the later 20th century may well have taken a different course. What that course might have been lies more in the domain of science fiction than of history.

CHAPTER 9: SUMMARY AND CONCLUSIONS

How do we make sense of the thoroughgoing technological changes recounted in this history of quartz crystal technology, beginning with the Curie brothers' discovery of the piezoelectric effect and concluding with the establishment of the cultured quartz industry? Many large-scale social forces can be pointed to. The rise of science-based industry in late-19th century Germany and its spread to the U.S. in the early 20th century, the enormous appetite of the industrialized nations for electronic media, the competitive and vigorous business climate of early 20th century America, the tremendous productive and creative forces unleashed by two world wars in which technology played an essential role – these were undoubtedly important factors creating conditions that favored the development of quartz crystal technology. Yet one factor, often overlooked and perhaps more important than all others, helps account for the technological growth seen in the previous seven chapters. This factor is the formation of a technological community, i.e. a group of technological practitioners actively involved in developing, advancing, and refining a particular technology.[534] Such a community is bigger than any single company or corporation, bigger than any single scientific or engineering discipline, bigger than any one nation or social group. The fabric holding together a technological community is

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[534] The literature on technological communities lies mostly within the disciplines of history of technology and R&D management. What follows is a sampling. Edward W. Constant II, "The Social Locus of Technological Practice: Community, System, or Organization?," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (Cambridge, MA: The MIT Press, 1989), 223-42. Peter Weingart, "The Structure of Technological Change: Reflections on a Sociological Analysis of Technology," in *The Nature of Technological Knowledge: Are Models of Scientific Change Relevant?*, ed. Rachel Laudan, *Sociology of the Sciences Monographs* (Dordrecht, Holland: D. Reidel Publishing Company, 1984), 115-42. Andrew Van de Ven, "A community perspective on the emergence of innovations," *Journal of Engineering and Technology Management* 10 (1993): 23-51. Leonard H. Lynn, N. Mohan Reddy, and John D. Aram, "Linking technology and institutions: the innovation community framework," *Research Policy* 25 (1996): 91-106. Koenraad Debackere and Michael A. Rappa, "Technological Communities and the diffusion of knowledge: a replication and validation," *R&D Management* 24, no. 4 (1994): 355-71.

woven from personal relationships, university/corporate/government partnerships, competitive relationships between rival firms, scientific and engineering societies, amateur-based organizations and, most of all, common devotion to a particular technology, such as the automobile, radio, or in this case, resonant quartz crystal devices.

The remarkable technological changes witnessed in quartz crystal technology between the First World War and the 1950s would not have occurred without the formation of a vibrant technological community. To see this, we need to first review the growth of this technology. There are at least two metrics with which this growth can be measured. The metric emphasized throughout this study is patenting activity, the number of patents issued in a particular technological area over a given time. The second metric is market penetration, the number or percentage of potential customers for a given technological product that are actually using the product. These two metrics highlight different aspects of the growth of quartz crystal technology. By using them together, we arrive at a multi-dimensional view of technological growth.

Using patenting activity to measure technological growth reflects the fact that technology has a specialized knowledge base. The "growth" of a technology occurs when this knowledge base expands by accumulating over time. Technological knowledge can accumulate in several ways – by being passed down from generation to generation through person-to-person apprenticeships or educational institutions, by being recorded in journal articles or patent disclosures, or by simply being embodied in technological artifacts that are preserved over time. For the historian relying on written sources, journal articles and patent disclosures are particularly useful indicators of technological activity.

Journal articles tend to favor scientific discoveries rather than technological inventions since the author(s) cannot exclude others from using the disclosed knowledge once published. Patent disclosures, on the other hand, reveal patentable inventions, i.e. technological knowledge that is new, directly useful, and non-obvious in light of the existing knowledge base. Furthermore, patents, because they transfer to their owners the temporary right to exclude others from making, using, or selling the disclosed invention, act as economic instruments. Thus, patents reflect both the knowledge base and the economic incentives of a particular technology.

Some scholars of innovation have suggested that the cumulative patent numbers for a given technological area should follow a logistic curve, as shown in Figure 48, over the life cycle of that technology.[535] The notable elements of this curve are initial period of exponential growth followed by a stretch of linear, stable growth. Some scholars have referred to this linear period as "normal technology," after Thomas Kuhn's description of "normal science" in which scientists are busy working out the myriad implications of a new scientific paradigm.[536] In the case of "normal technology," technologists are engaged in refining a technology and finding new applications for it. Finally, the logistic curve of Figure 48 ends with a gradual decline in activity, presumably brought on either by the exhaustion of technological possibilities or by the appearance of an alternative, superior technology.

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[535] To the author's knowledge, the first person to use the logistic curve to describe scientific or technological growth was sociologist of science Diana Crane. See Diana Crane, *Invisible Colleges: Diffusion of Knowledge in Scientific Communities* (Chicago: University of Chicago Press, 1972).

[536] For example, see Edward W. Constant II, *The Origins of the Turbojet Revolution*, ed. Thomas P. Hughes, Johns Hopkins Studies in the History of Technology (Baltimore, MD: Johns Hopkins University Press, 1980). Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago: The University of Chicago Press, 1962).

Figure 49 shows the actual growth in quartz crystal patents measured over the forty year period covered in this study. Note that it bears only a slight resemblance to Figure 48. The first noticeable difference is that the upper bend of the S-curve is missing, indicating that quartz crystal technology, as measured by patenting activity, was still actively growing in the late 1950s. When this study was begun, 1959 was chosen as the cut-off point because it appeared on the surface that most major quartz crystal innovations, including the development of cultured quartz, had occurred by this time. Thus, it was guessed that quartz patenting activity might be in decline by 1960. Clearly, Figure 49 shows that this was not the case. Perhaps a future study will trace the evolution of quartz crystal technology from 1960 up to the present.

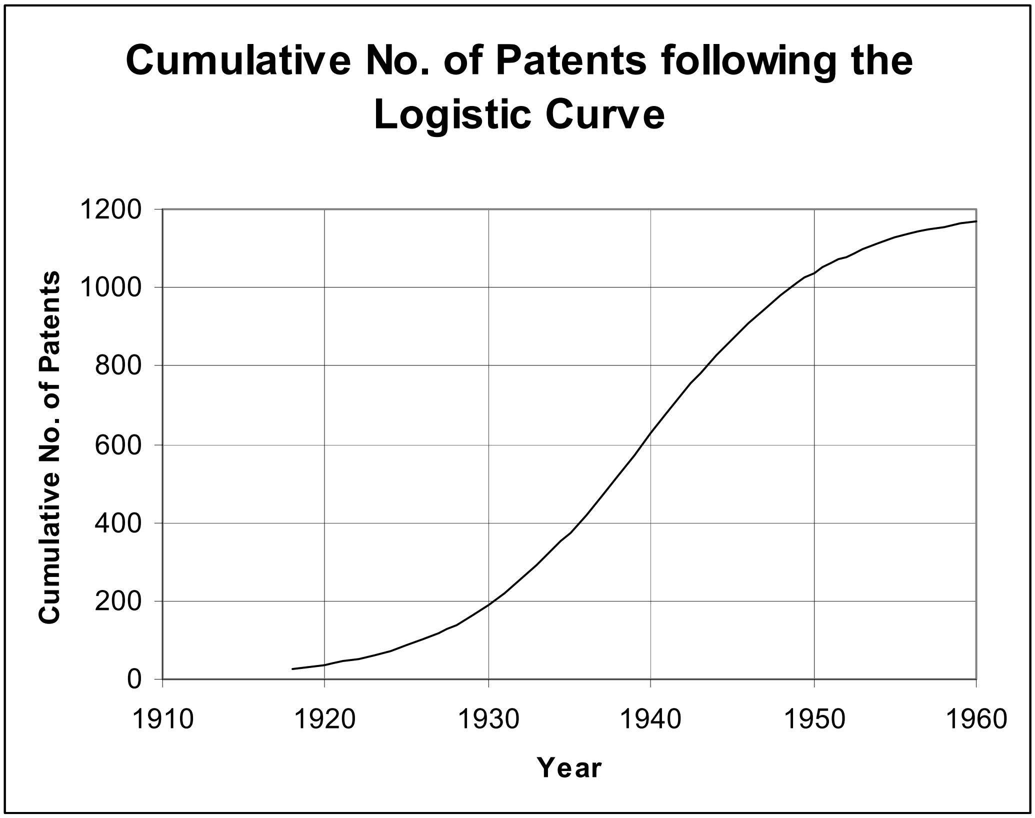

Figure 48: Ideal Logistic Curve of Cumulative Quartz Crystal Patent Growth between 1918 and 1959
(Figure created by author.)

Notice also from Figure 49 that growth spurts are present at two points in the curve, one around 1926-1927 and another around 1942-1946. These spurts in patenting activity correspond respectively to the period during which the technique of quartz crystal-control was being applied to broadcast radio transmitters and to the period during which millions of QCUs were being produced for use in Army Signal Corps field transceiver radio units. Explaining these two growth spurts is one of the principal purposes of this chapter, yet we must first look at quartz crystal technological growth from a second perspective.

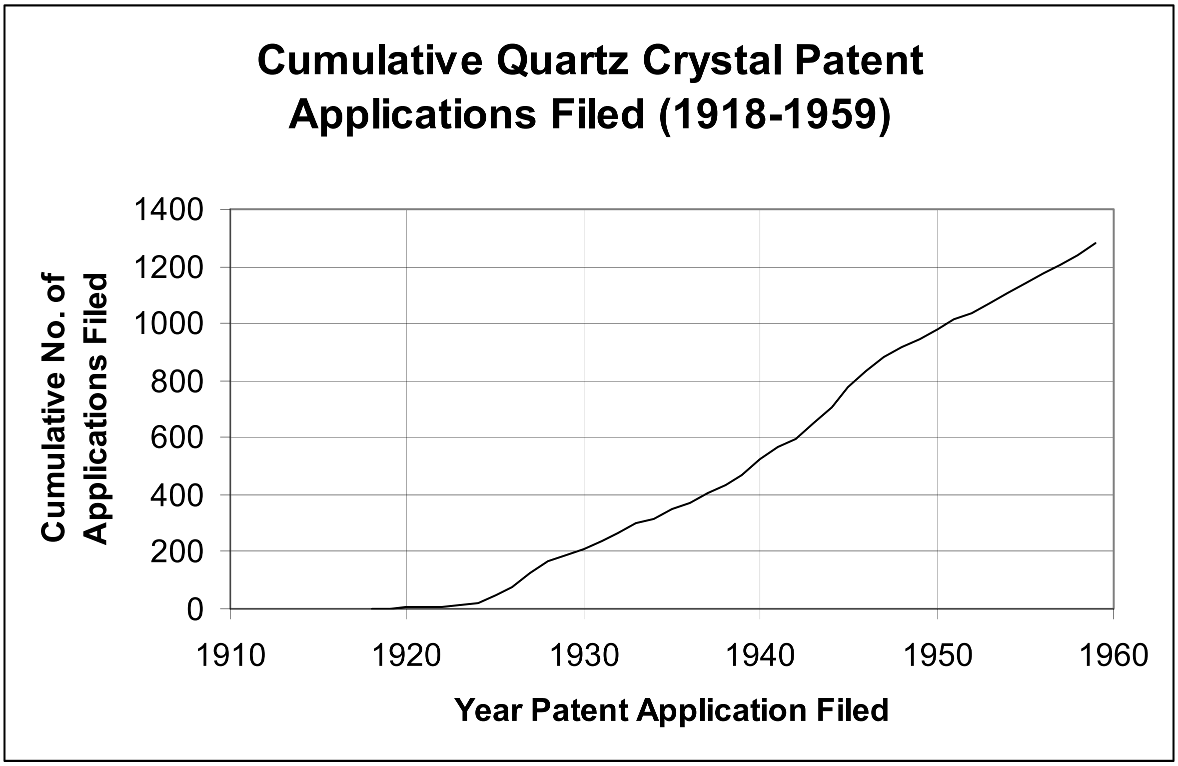

Figure 49: Actual Curve of Cumulative Quartz Crystal Patent Growth between 1918 and 1959
(Note: Only patent applications that resulted in issued patents are shown. Figure created by author.)

Technological growth may also be measured by using market penetration, i.e. the number or percentage of potential customers for a given technological product that are actually using the product. This metric is perhaps intuitively more appealing than patenting activity. After all, can a particular technology really be characterized as "growing" if no one is actually using it? However, despite its appeal, market penetration has a problem. It is difficult to measure, particularly in hindsight. Not only is measuring the number of actual users of a technology difficult, but estimating the number of *potential* users is well night impossible. Nevertheless, and in light of these difficulties, it *is* possible to use the scattered production and usage data gathered in this study to obtain an order-of-magnitude estimate for the numbers of resonant quartz crystal devices in use between 1880 and 1959. Table 4 shows these estimates and breaks the time period of this study into seven distinct phases: scientific discovery and theory-building, invention and experimentation, broadcast radio, amateur radio and telephony, wartime mass production, military surplus and artificial quartz research, and cultured quartz. Figure 50 shows this data is graphical form.

Table 4: The Approximate Number of Resonant Quartz Crystal Devices In Use Between 1880 and 1959

Year Ranges	Approximate No. of Resonant QCUs in Use	Phase
1880-1916	0	Scientific Discovery and Theory-Building
1917-24	10	Invention and Experimentation
1925-31	1,000	Broadcast Radio
1932-41	100,000	Amateur Radio and Telephony (Quartz Wave Filters)
1942-45	10,000,000	Wartime Mass Production
1946-56	10,000,000	Military Surplus and Artificial Quartz Research
1957-59	100,000,000	Cultured Quartz

(Table created by author.)

Unlike Figure 49, Figure 50 lacks detail and thus must be interpreted more cautiously. The growth spurts of the former figure are not noticeable in the latter. What we can conclude from the latter is that the absolute number of resonant quartz crystal devices in use increased exponentially while the rate of exponential growth gradually declined throughout four decades. This is not surprising, for the more widely a technology is adopted, the more difficult it is to sustain the initially high growth rates, but what is perhaps most remarkable about Figure 50 is that the number of quartz devices in use increased roughly by a factor of 10 million over four decades. This reflects some of the basic characteristics of quartz crystal devices. They are generally inexpensive, can be produced using automated mass production techniques, are used as components in larger technological products or systems, and were eventually found to be essential to three of the most important communications technologies of the 20th century – telephony, radio, and television. However, quartz crystal devices could never have been produced and adopted on such a large scale without an underlying technological knowledge base.

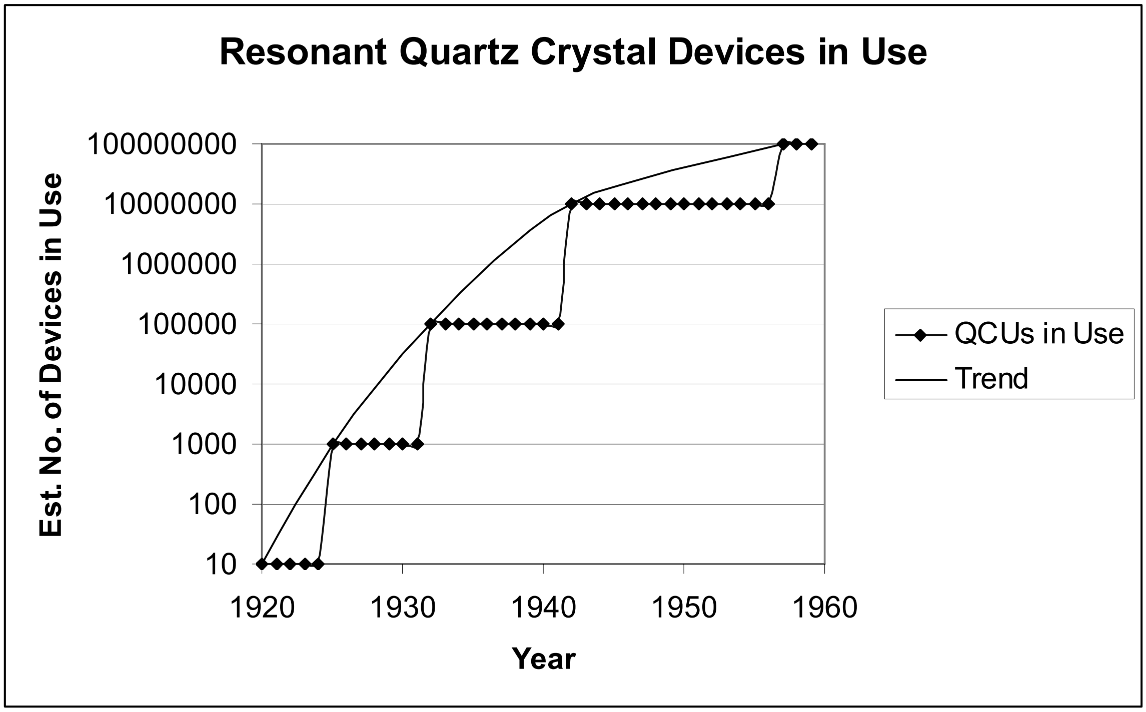

Figure 50: Estimated Number of Resonant Quartz Crystal Devices in Actual Use between 1920 and 1959
(Figure created by author.)

As evidenced by the large number of patents specifying QCU production techniques that were issued between 1920 and 1960, the massive numbers of quartz devices represented in Figure 50 could not have been produced without the technological knowledge presented in Figure 49. Yet, bodies of technological knowledge do not appear fully formed ex nihilo. They form over time, and they are created principally in the context of technological community. This is precisely why the growth of quartz crystal technology in general and the two growth spurts of Figure 49 in particular cannot be understood without understanding the role played by technological community.

The first growth spurt of Figure 49 represents the initial application of "crystal-control," the technique of using a resonant quartz crystal to control a radio transmitter's frequency, to broadcast radio. To be sure, the U.S. government played a decisive role in stimulating this burst of patenting activity by imposing frequency adherence regulations on all licensed broadcasters, but the burst could have never occurred had a foundation for quartz crystal innovation not already been laid in the preceding years. Furthermore, the germ of a quartz crystal technological community was already in place well before the 1927 appearance of FRC regulation. By the end of the "invention and experimentation" phase, Walter Cady, George Washington Pierce, the Naval Research Laboratory, the General Radio Company, Bell Telephone Laboratories, and John Dellinger of the Bureau of Standards were all actively developing resonant quartz crystal devices. Either through personal friendship, involvement in the National Research Council during World War I, business relationships, or through membership in the Institute of Radio Engineers, all were aware of each other's work, thus forming something of a nascent technological community. When the FRC announced General Order No. 7 in April 1927, this community was prepared to generate the new technical knowledge needed to make strict frequency adherence a reality, resulting in the first patenting growth spurt of Figure 49. Yes, the role played by the FRC here was critical; without it, the demand for quartz crystal devices would not have existed and quartz inventors would have acted in other areas of technology. But no less important was the small social network created by individual inventors, companies, and government researchers in the years leading up to 1927.

In the midst of the so-called "broadcast radio" phase of 1925 to 1931, the small community of engineers and scientists interested in quartz devices were quick to develop techniques and devices that allowed broadcast stations to comply with new FRC regulations. Yet, regulation exposed a major weakness in the still-young broadcasting industry. In order to make regulation work, broadcasters needed access to professional radiofrequency testing services. This need was soon filled as technically-minded entrepreneurs founded testing firms, adding at the same time another dimension to the growing quartz technological community. Also during this period, government and industry leaders such as John Dellinger, R. H. Marriott, and C. W. Horn worked through the I.R.E. to advise the FRC on radio policy. Their advice regarding crystal-controlled frequency adherence culminated in the 1931 passage of General Order No. 116, which ensured that all licensed broadcast stations would employ sophisticated quartz crystal instruments in their transmitter rooms. Here was an example of one particularly powerful segment of the growing quartz crystal community working to, as it saw it, benefit both the general public, in the form of clearer radio reception, and radio engineers, in the form of a guaranteed market for advanced radio instrumentation.

The second growth spurt of Figure 49 represents the mass production of tens of millions of QCUs in support of the Allies during World War II. These QCUs were used in both "crystal-controlled" transmitters as well as in push-button receivers, giving Allied troops reliable, instantaneous communications without the burden of tedious tuning mechanisms. As in 1927, government intervention was critical here in stimulating patenting activity. In this case, the Army Signal Corps chose to adopt quartz crystal control for many of its field transceiver radio units, creating almost overnight a level of demand for QCUs that dwarfed pre-war levels. Yet, as important as this decision was, the activities of the quartz crystal technological community over the preceding decade made the wartime growth spurt possible. During the 1930s, as tens of thousands of radio amateurs in the U.S. alone experimented with crystal control, numerous small QCU manufacturing firms such as Bliley Electric, CTS-Knights, Scientific Radio Products and Monitor Products sprang up to serve them.[537] These firms were an important addition to the quartz technological community. Among their innovative contributions was one that proved to be highly influential during the quartz shortage of the war – the use of ¼" rather than 1" quartz wafers in QCUs. Also important during the 1930s was the AT&T-sponsored research on quartz wave filters and zero temperature coefficient crystal cuts. Though no organizations existed during the 1930s that were dedicated exclusively to quartz crystal technology, most enthusiasts connected with each other through membership in either the Institute of Radio Engineers (for professional engineers) or the American Radio Relay League (for amateurs). This social network gave the Signal Corps a starting point for ramping up wartime QCU production to unprecedented levels.

During World War II, the "wartime mass production" phase of quartz crystal device history, the quartz technological community responded to the Army's demand with not only millions of QCUs, but also with new methods of QCU production. Indeed, during the war, nearly 50% of all quartz-related patents were for QCU fabrication

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[537] Patrick R. J. Brown, "The Influence of Amateur Radio on the Development of the Commercial Market for Quartz Piezoelectric Resonators in the United States" (*Proceedings of the 50th Annual IEEE Frequency Control Symposium*, U.S. Army Research Laboratory, Forth Monmouth, NJ, 5-7 June 1996), 58-65.

methods. (See Figure 7 of Chapter 3.) The war also gave the quartz crystal community visibility among the broader engineering profession. The I.R.E. formed the *Committee on Piezoelectric Devices* in recognition of the importance of quartz and other piezoelectric materials to modern technology. For the first time, an engineer or researcher interested in quartz devices could look in a special issue of the *Proceedings of the I.R.E.* each year to find all relevant peer-reviewed articles published over the preceding twelve months. What had once been an esoteric and underappreciated branch of radio engineering was now coming into its own.

The post-war years saw the quartz technological community blossom into a full-blown research community, complete with annual symposia and steady government funding. The justification for this abundance of research resources was the Brazilian quartz supply crisis of the war years. A substitute for Brazilian quartz was needed if the Army Signal Corps was to continue its reliance on the technique of quartz crystal-control. During these immediate post-war years, the quartz technological community took on a bit of the flavor of a scientific community. Though patents continued to be highly valued, journal publications increased in importance and the annual symposia tended to give the community a more collegial atmosphere than in the past. The Brush Development Company, Bell Telephone Laboratories, and many university research groups were major creative contributors during this period. During the mid-1950s, the Signal Corps-sponsored research culminated in development of a scalable method for culturing (i.e. growing) large and flawless quartz crystals from crushed quartz, but only after the Corps had spent well over $1 million supporting artificial quartz research.

This study has provided a glimpse into the growth of a technological community, from its humble beginnings as a few scattered individuals to its consolidation after World War II as a permanent fixture in the so-called “military-industrial complex.” We have seen that this community was heterogeneous in that it comprised university researchers, amateur radio enthusiasts, government bureaucrats, company presidents, and engineers working for firms both very large and very small. As such, the quartz crystal community was typical of most technological communities, which tend to be far more heterogeneous than, say, scientific communities. We’ve also seen that the quartz community was agile and flexible, responding quickly to new market incentives such as the broadcast radio market of the 1920s or the amateur radio and long-distance telephony markets of the 1930s. Yet we’ve also seen that the quartz community responded most favorably to centralized order. The most ordered periods during this study were the late 1920s period of FRC regulation, the World War II period, and the post-war cultured quartz research effort. In all three periods, and especially the first two, patenting activity was high and quartz crystal devices were finding their way into customers’ hands. Thus, we see that, in contrast to the notion that technology thrives best in an unregulated and unstructured marketplace, the quartz community benefited from what some have called “superstructure,” the organizations and institutions that coordinate the activities of “substructure” players – the individuals, companies, and government researchers that actually invent and innovate.[538]

Before closing this discussion of the role of technological community in technological growth, a consideration of the differences between Figures 48 and 49 may

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[538] For more on the superstructure/substructure framework of technological communities, see Leonard H. Lynn, N. Mohan Reddy, and John D. Aram, "Linking technology and institutions: the innovation community framework," *Research Policy* 25 (1996): 91-106.

prove insightful. These two figures are clearly different; Figure 48 is the idealized logistic curve, while Figure 49 is essentially linear with the exception of two small but noticeable growth spurts. This study was begun with the expectation that the latter figure would more or less conform to the shape of the former. But, given the a priori definitions of this study, it now appears that it would have been highly unlikely for these two figures to match. The reason for this is fairly simple.

It now appears that, as far as technological growth is concerned, the logistic curve of Figure 48 is capable of describing the growth of successful and specific technological products or techniques but *not* the growth of broad areas of technology (e.g., quartz crystal technology). In light of this interpretation, we can view the two "growth spurts" of Figure 49 as mini logistic curves, connected by the steady linear growth characteristic of "normal technology."[539] That is, the logistic curve likely comes very close to describing the application of quartz crystal-control to broadcast transmitters in the late 1920s. In 1925, no licensed broadcast transmitters utilized crystal control; by 1932, they *all* used crystal control. The growth between these two points, if examined closely, is very likely to match the logistic curve. The same analysis applies to Army Signal Corps radio sets during the Second World War. However, it now appears to have been a mistake to assume that this growth pattern would apply to all of resonant quartz crystal technology.

For the logistic curve to accurately describe growth, there has to be a saturation point (e.g., 100% market saturation) beyond which growth cannot occur. Broad areas of technology such as that chronicled in this study do not necessarily have a saturation

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[539] For more on "normal technology," see Edward W. Constant II, *The Origins of the Turbojet Revolution*, ed. Thomas P. Hughes, Johns Hopkins Studies in the History of Technology (Baltimore, MD: Johns Hopkins University Press, 1980).

point. If they prove successful in one application (e.g., radio), they will almost certainly be tried in others (e.g., telephony, television, computers). This is exactly what happened with resonant quartz crystal devices, which is why there is no downward turn toward the top of Figure 49. From this perspective, we can see that the growth of quartz crystal technology was essentially the discovery of new applications – first frequency standards, then broadcast radio, telephony, two-way radio, color television, and computers. Thus, we can generally expect the growth pattern for broad areas of technology, as measured by patenting activity, to be essentially a straight line punctuated intermittently by mini logistic curves whenever a new application of that technology or technique is found.

Though the primary conclusion of this study speaks to technological community and the growth of technological knowledge, a number of more specific conclusions have been reached. Among these is the role of independent inventors in the early 20th century. This study has clearly shown that independent inventors, most notably Walter Cady and George Washington Pierce, played a significant role in the early development of resonant quartz technology. Several factors made this possible, beginning with the fact that early quartz crystal inventions did not require great investments of capital or manpower. Both Cady and Pierce had been introduced to quartz technology through the anti-submarine warfare research of World War I. The war and this work ended, however, before the full potential of quartz could be realized. From this brief apprenticeship in quartz technology, Cady and Pierce were able, on their own and with limited resources, to develop the piezo-resonator, the piezo-oscillator, and the Pierce oscillator. As professors at colleges with well-endowed science departments, both men had access to an electronics laboratory, with its associated instrumentation, as well as a machine shop for grinding and polishing crystals. Furthermore, a professorship gave them the time and the freedom to pursue this line of research before any private firms were willing to invest in it.

Since Cady and Pierce both taught at private institutions, and since their quartz research was not supported with any government funds, the patents they took on their inventions were their own. Ironically, both men employed the legal services of the same patent attorney, a Mr. David Rines of Boston, MA, yet they obtained very different outcomes when attempting to profit from their patents. Cady, becoming mired in an infringement battle with AT&T that threatened to drag on for years and deplete him financially, sold his crystal patents to RCA for $50,000 in 1925, the equivalent of $500,000 in 2005.[540] RCA, with Mr. Rines' legal assistance, continued the case against AT&T for decades, finally vindicating Cady's original patents. Pierce was more fortunate. Able to hold on to his patent for the crystal-controlled oscillator, he reaped a handsome income through licensing fees.[541]

The difference in Cady's and Pierce's outcomes was due largely to the two men's prior patent experiences. Cady had taken out few, if any, patents prior to 1920 and could not have been considered at that time an experienced inventor. Pierce, on the other hand, had obtained thirteen patents prior to his oscillator patent. All of these were commercially viable and none were seriously contested in court.[542] In fact, Pierce had profited quite handsomely from several of these patents, enough such that his financial

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[540] Walter G. Cady, "The Story of My Patent Litigation," 30 June 1967, Box 2, Walter G. Cady Papers, Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT.

[541] *Dictionary of Scientific Biography* (1974), s.v. "Pierce, George Washington." "Less typically, Pierce became wealthy through his patents, some of which he exploited vigorously, and usually successfully, in the face of interference suits by large corporations."

[542] Frederick A. Saunders and Frederick V. Hunt, "George Washington Pierce," in *Biographical Memoirs. National Academy of Sciences* (Washington, D.C.: National Academy Press, 1959), 351-80.

situation was comfortable and secure, particularly for a college professor. Thus, Pierce didn't shirk from defending his oscillator patent when AT&T filed an infringement suit against him. After twelve long years of litigation with the communications giant, he emerged victorious. The experience, confidence, and financial security that Pierce had gained from his earlier patents were crucial contributing factors to this success.

The fact that both Cady and Pierce owned their patents and were free to either license or sell them had important consequences for the future development of quartz crystal technology. For one, it prevented AT&T from monopolizing the technology. The firm sued both inventors, but was ultimately unsuccessful in litigation. Cady, perhaps wanting to limit AT&T's power, sold his patents to AT&T's principal competitor of the time, RCA. Pierce, for his part, refused to grant AT&T an exclusive license on his oscillator patent, though the company probably entreated him to do so. The consequence was that, for at least several decades, quartz crystal technological contributions were made by many – large firms (RCA, AT&T), small firms (Bliley Electric, General Radio), government research laboratories (Naval Research Laboratory), and even individual inventors (see Chapter 3). The competition engendered by the openness of quartz technology was likely a major stimulant to inventive activity.

The inventions of Cady and Pierce were radical inventions in that they ended up launching an industry. As historian Thomas Hughes has pointed out, during the 19th and early 20th centuries, radical inventions were generally the products of independent inventors.[543] Yet, the intellectual property world inhabited by Cady and Pierce no longer exists. As the 20th century progressed, research universities began requiring their faculty

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[543] Thomas Parke Hughes, *American Genesis: a century of invention and technological enthusiasm, 1870-1970* (New York: Viking, 1989).

to sign IP agreements that yielded ownership of any patentable inventions to the university.[544] Furthermore, the trend in R&D throughout the 20th century was toward greater and greater capital investment requirements. It is difficult to imagine many areas of technology today that are as inexpensive to investigate as was early quartz crystal technology. Thus, these two developments – changes in university IP policies and the increasing costs of R&D – were among the most important factors contributing to the decline of independent inventors in the 20th century. Even so, there is still room for independent inventors, particularly in cutting-edge technologies that have not yet reached the mainstream.

Another set of conclusions reached in this study has to do with materials science, more specifically with the scenarios that encourage scientists and engineers to either better understand the properties of existing materials or to develop altogether new materials. There seem to be at least five such scenarios, all of which are drawn from the history of quartz crystal technology. The first scenario, which we can call scientific prediction, is where scientific theory predicts a previously unmeasured or undetected property of a natural or man-made material. This occurred with the Curie brothers' discovery of the piezoelectric effect, which had been suggested by previous studies of pyroelectricity. The second scenario, development of auxiliary technologies, is where the development of one or more auxiliary technologies encourages scientists and engineers to try new things with a known material. During World War I, Constantin Chilowsky and Paul Langevin, upon learning of the availability of high-frequency, low-noise amplifiers, were able to dream of using piezoelectric quartz crystal in a way that had heretofore been

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[544] Bhaven Sampat, "Patenting and U.S. academic research in the 20th century: The world before and after Bayh-Dole," *Research Policy* 35 (2006): 772-89.

impossible. The appearance of every fundamentally new technology, such as vacuum tube amplifiers, encourages technologists to re-examine assumptions about the materials with which they work.

The third scenario leading to materials science developments, which we will call the performance bottleneck or reverse salient, occurs when a device or machine built with a certain material is not performing adequately, and it is determined that the material itself is the principal factor limiting performance.[545] During the 1930s, BTL researchers dissatisfied with the performance of QCUs and quartz wave filters operating over wide temperature ranges investigated different angles at which wafers were cut from raw quartz blocks. This work resulted in the development of the breakthrough zero temperature coefficient crystal cut. Later, during WWII, the ageing problem with mass-produced QCUs led to the widespread adoption of the acid-etching process for producing quartz wafers.

A fourth scenario, identified by Nathan Rosenberg in a seminal 1969 paper, is a sudden and permanent disruption in the supply of, or a significant increase in the cost of, a natural resource or material.[546] This disruption often occurs during wartime, as normal trade routes are disrupted and supply shortages become critical to a nation's survival. As mentioned in Chapter 7, this scenario occurred several times to Germany during the 19th and 20th centuries, leading them to develop many important synthetic materials. The

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[545] For more on "reverse salients," see Thomas Parke Hughes, "The Evolution of Large Technological Systems," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Thomas P. Hughes Wiebe E. Bijker, and Trevor Pinch (Cambridge, MA: The MIT Press, 1989), 51-82. For more on bottlenecks, see Nathan Rosenberg, "The Direction of Technological Change: Inducement Mechanisms and Focusing Devices," *Economic Development and Cultural Change* 18, no. 1 (January 1969): 1-24.

[546] Nathan Rosenberg, "The Direction of Technological Change: Inducement Mechanisms and Focusing Devices," *Economic Development and Cultural Change* 18, no. 1 (January 1969): 1-24.

threatened disruption of Brazilian quartz crystal supplies during WWII provided the impetus for the post-war development of cultured quartz.

The fifth and final scenario is perhaps the simplest. This occurs when a scientists or engineer is simply driven by curiosity to better understand a strange material. Walter Cady's WWI research on Rochelle Salt and quartz crystal led him to become fascinated by the unique resonance property exhibited by quartz. He continued his research even after the conclusion of the war. His motive seems to have been nothing more than wanting to understand how this material behaved. Yet it was while conducting this research that Cady conceived of using quartz crystal as a precise frequency standard. Thus, though it may seem naïve or too simplistic, it does seem that genuine curiosity still drives at least some materials science developments.

In reviewing the rise of quartz crystal technology in the 20th century, how can we account for its remarkable success? In the time period covered by this study, we have seen that the fate of electronic communications was the fate of quartz crystal. As radio, telephony, and later television rose in importance, so rose the importance of quartz. The reason for this shared fate is easy to discern. In democratic, free market societies, as the owners of electronic communications systems sought to make them available to more and more people, the capacity of these systems had to expand. For most of the forty year period from 1918-1959, the principal technique engineers used to give multiple users access to a single communication medium, such as the airwaves for radio or a coaxial cable for telephony, was frequency division multiplexing, also known as frequency division multiple access (FDMA). Since FDMA works by assigning individual users a single frequency or band of frequencies, devices that can generate and detect frequencies with extreme precision and stability permit the frequency spectrum to be used more efficiently, allowing more users to access a communication medium. Quartz oscillators and wave filters did exactly this; they enabled the generation and detection of very high electrical frequencies such that these frequencies could be precisely known and that they would stay where they were initially set, not drifting into other frequency bands. Other techniques for giving multiple users access to a single communication medium, such as time-division and code-division multiple access (TDMA and CDMA, respectively), have been used and are still widely used today, particularly in computer networking. Nevertheless, FDMA remains the dominant multiple access technique for broadcast communications.

Since 1959, two other major technologies, affordable electronic wristwatches and digital computing, have allowed the importance of resonant quartz crystal technology to continue rising. In the late 1960s, techniques were developed that allowed engineers to affordably place tiny quartz wafers in battery-powered wristwatches, yielding unprecedented accuracy at a low price.[547] In the 1970s and early 1980s, power digital computing technology became cheap enough to begin placing computers in everything from cars to home appliances. High-speed digital technologies require precise synchronization of a variety of signals and processes, and precise synchronization requires precise timekeeping. Quartz crystals are used to provide this precise timekeeping in every digital computing device in use today, from PCs to cell phones and

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[547] Carlene Stephens and M. Dennis, "Engineering Time: Inventing the Electronic Wristwatch," *British Journal for the History of Science* 33 (2000): 477-97.

from GPS units to digital watches. Thus, the ubiquity of quartz crystal technology is not likely to change anytime soon.

In closing this study, we return to a fascinating statement made by Alfred Goldsmith, Chief Broadcast Engineer for RCA, in 1928 and quoted at the beginning of Chapter 4. “It is indeed most fortunate that just when extremely accurate frequency control is becoming so necessary to radio, the instrumentalities for it should become available. It may be that this is putting the cart before the horse and explaining how remarkable it is that great rivers always flow past large cities. Perhaps the modern desire and need and application of constant frequency is the result of the crystal oscillator and similar high precision frequency control devices.”[548] Goldsmith had it only partly right; viewing the timing of the appearance of accurate frequency instruments as a fortunate coincidence was certainly putting the cart before the horse, but the appearance of the crystal oscillator did not in any way create the “modern desire and need for application of constant frequency.”

The desire for constant frequency that first appeared in the 1920s was a consequence of several things: a national radio broadcasting system with no artificial limit on the number of broadcast stations; the large geographic size of the U.S., requiring many stations to reach all potential listeners; the decision to use frequency-division multiplexing to apportion access to the over-the-air broadcast spectrum; and, most fundamentally, the inherent instability of high-frequency vacuum tube amplifiers and oscillators of the 1920s. In fact, it was the desire for constant frequency, first recognized by Walter Cady and George Washington Pierce, that stimulated efforts to develop and

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[548] "Discussions on Harrison Paper," *Proceedings of the Institute of Radio Engineers* 16, no. 11 (1928): 1470.

refine the quartz oscillator. In the final analysis, however, these efforts, and the efforts of all quartz crystal inventors, would have been little more than the isolated actions of individual inventors without the formation and growth of a vibrant and heterogeneous technological community. Indeed, the knowledge underlying quartz crystal technology, as represented by more than a thousand related patents issued during the forty year span of this study, was as much a product of community as of the hard work and insights of individuals.

BIBLIOGRAPHY

Charles Baldwin Sawyer Collection. Department of Special Collections, Kelvin Smith Library, Case Western Reserve University, Cleveland, OH.

Historical Records of the Naval Research Laboratory. Record Group 19. U.S. National Archives, Washington, D.C.

Records of the FCC and Predecessor Agencies. Record Group 173. U.S. National Archives, College Park, MD.

Records of the National Institute of Standards and Technology, General Records of J. Howard Dellinger. Record Group 167. U.S. National Archives, College Park, MD.

Records of the Office of the Chief Signal Officer [Unclassified Central Decimal Files]. Record Group 111. U.S. National Archives, Washington, D.C.

Signal Corps Engineering Laboratories Collection. Historical Files of Fort Monmouth, Fort Monmouth, NJ.

Walter G. Cady Papers. Special Collections and Archives, Olin Library, Wesleyan University, Middletown, CT.

Walter G. Cady Papers (Subgroup 3), Cady Family Papers (MSS 326). Rhode Island Historical Society Library, Providence, RI.

WGST Radio Station Records, 1928-1975 (MS 8). Special Collections and Archives, Library and Information Center, Georgia Institute of Technology, Atlanta, GA.

Aitken, Hugh. "Allocating the Spectrum: The Origins of Radio Regulation." *Technology and Culture* 35, no. 4 (October 1994): 686-716.

———. *The Continuous Wave: Technology and American Radio, 1900-1932*. Princeton, NJ: Princeton University Press, 1985.

———. *Syntony and Spark: The Origins of Radio*. New York: Wiley, 1976.

"Amendments to Regulations." *Radio Service Bulletin*, no. 65 (1 September 1922): 10-11.

American Radio Relay League Home Page. Accessed 10 June 2007. Available from http://www.arrl.org/aarrl.html; Internet.

Ballato, Arthur. "Introduction to the Historical Section." *50th IEEE International Frequency Control Symposium*, U.S. Army Research Laboratory, Forth Monmouth, NJ, June 1996, 4-23.

Banning, William Peck. *Commercial Broadcasting Pioneer: The WEAF Experiment (1922-1926)*. Cambridge, MA: Harvard University Press, 1946.

Barnouw, Erik. *A History of Broadcasting in the United States. A Tower In Babel*. 3 vols. Vol. 1. New York: Oxford University Press, 1966.

Bechmann, Rudolf. "Frequency-Temperature-Angle Characteristics of AT-Type Resonators Made of Natural and Synthetic Quartz." *Proceedings of the Institute of Radio Engineers* 44, no. 11 (November 1956): 1600-07.

Bechmann, Rudolf, and Danforth R. Hale. "Electronic Grade Synthetic Quartz." *Brush Strokes* 4, no. 1 (September 1955): 1-7.

Bensman, Marvin R. *The Beginning of Broadcast Regulation in the 20th Century*. Jefferson, N.C.: McFarland & Co., 2000.

Berg, Jerome S. *On the Short Wave, 1923-1945: Broadcast Listening in the Pioneer Days of Radio*. Jefferson, N. C.: McFarland & Co., 1999.

Bijker, Wiebe E. *Of Bicycles, Bakelites, and Bulbs: Toward a Theory of Sociotechnical Change*. Cambridge, MA: MIT Press, 1995.

Birr, Kendall. *Pioneering in Industrial Research: The Story of the General Electric Research Laboratory*. Washington, D. C.: Public Affairs Press, 1957.

Black, K. C. "Stevens Point and Minneapolis Linked by Coaxial System." *Bell Laboratories Record* (January 1942): 127-40.

Bliley, Charles A. *The Bliley Electric Company: The Early Years 1930-1955 (2001)*. [Web site] Accessed 28 May 2007. Available from http://www.bliley.net/XTAL/; Internet.

———. *A Survey of the Use of Quartz Crystals in the Amateur Radio Service, Produced July 1936 by The Bliley Electric Company*. Accessed 28 May 2007. Available from http://www.bliley.net/XTAL/; Internet.

Bottom, Virgil E. "A History of the Quartz Crystal Industry in the USA." *Proceedings of the 35th Annual Frequency Control Symposium*, Philadelphia, PA, 27-29 May 1981, 3-12.

Bown, Ralph, DeLoss K. Martin, and Ralph K. Potter. "Some Studies in Radio Broadcast Transmission." *Proceedings Of The Institute Of Radio Engineers* 14, no. 1 (February 1926): 57-130.

Brannigan, Alice. "KFKX: A Most Historic Broadcast Station." *Popular Communications* (October 1998): 14.

Braun, Ernest, and Stuart MacDonald. *Revolution in Miniature: The History and Impact of Semiconductor Electronics*. Cambridge, England: Cambridge University Press, 1978.

Brittain, James E. *Alexanderson: Pioneer in American Electrical Engineering*, Johns Hopkins Studies in the History of Technology. Baltimore: Johns Hopkins University Press, 1992.

———. "Scanning Our Past: John H. Dellinger." *Proceedings of the IEEE* 95, no. 9 (September 2007): 1884-87.

———. "Scanning the Past: Edwin Howard Armstrong." *Proceedings of the IEEE* 79, no. 2 (February 1991).

———. "Scanning the Past: Harold D. Arnold." *Proceedings of the IEEE* 86, no. 9 (September 1998): 1895-96.

———. "Scanning the Past: Joseph Warren Horton." *Proceedings of the IEEE* 82, no. 9 (September 1994).

Broadcasting, I.R.E. Committee on. "Reports of I.R.E. Committee on Broadcasting." *Proceedings of the Institute of Radio Engineers* 18, no. 1 (January 1930): 15-37.

"Broadcasting Increases 500-Fold in One Year." *Radio News* (December 1922): 1156.

"Broadcasting Still Increasing." *Radio News* (August 1922): 237.

Brown, C.S., R.C. Kell, L.A. Thomas, N. Wooster, and W.A. Wooster. "Growth of Large Quartz Crystals." *Nature* 167, no. 4258 (9 June 1951): 940-41.

Brown, Patrick R. J. "The Influence of Amateur Radio on the Development of the Commercial Market for Quartz Piezoelectric Resonators in the United States." *Proceedings of the 50th Annual IEEE Frequency Control Symposium*, U.S. Army Research Laboratory, Forth Monmouth, NJ, 5-7 June 1996, 58-65.

Buehler, Ernest. *Method of Growing Quartz Crystals*. U. S. Patent Office. Patent No. 2,785,058, Filing Date: 28 April 1952; Issue Date: 12 March 1957.

Buehler, Ernest, and A.C. Walker. "Growing Quartz Crystals." *The Scientific Monthly* 69, no. 3 (September 1949): 148-55.

"Bureau of Standards to Transmit Standard Radio Wave Signals." *Radio Service Bulletin*, no. 70 (1 February 1923): 20-21.

Cady, Walter Guyton. "Bibliography on Piezo-Electricity." *Proceedings Of The Institute Of Radio Engineers* 16, no. 4 (April 1928): 521-35.

———. "Insulated double connectors." *Physikalische Zeitschrift* 12 (1911): 1254-55.

———. "An international comparison of radio wavelength standards by means of piezo-electric resonators." *Proceedings Of The Institute Of Radio Engineers* 12, no. 6 (December 1924): 805-16.

———. "A machine for compounding sine curves." *Science* 23 (January-June 1906): 877-81.

———. *Method of Maintaining Electric Currents of Constant Frequency*. U. S. Patent Office. Patent No. 1472583, Filing Date: 28 May 1921; Issue Date: 30 October 1923.

———. "New Methods For Maintaining Constant Frequency in High-Frequency Circuits." *Physical Review* 18, no. 2 (August 1921): 142-43.

———. "The piezo-electric resonator." *Proceedings Of The Institute Of Radio Engineers* 10, no. 2 (April 1922): 83-114.

———. *Piezo Electric Resonator*. U. S. Patent Office. Patent No. 1,450,246, Filing Date: 28 January 1920; Issue Date: 3 April 1923.

———. "Piezoelectricity and Ultrasonics." *Sound* 2, no. 1 (January-February 1963): 46-52.

———. *Piezoelectricity; An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals*. New York: McGraw-Hill, 1946.

———. "Saving Ancestors." [Unpublished Autobiography] 1963.

Cady, Walter Guyton, and Harold D. Arnold. "On the electric arc between metallic electrodes." *American Journal Of Science* 24, no. 143 (1907): 383-411.

Chandler, Alfred D. *The Visible Hand: The Managerial Revolution in American Business*. Cambridge, MA: Belknap Press of Harvard University Press, 1977.

Clapp, James Kilton. *Electric System and Method*. U. S. Patent Office. Patent No. 1,944,315, Filing Date: 22 October 1931; Issue Date: 23 January 1934.

Clayton, John M. "Crystal Control For Amateur Transmitters." *QST* 9, no. 11 (November 1925): 8-13.

———. "Navy Developments in Crystal-Controlled Transmitters." *QST* 9, no. 11 (November 1925): 41-44.

Collins, Harry M. "The TEA Set: Tacit Knowledge and Scientific Networks." *Science Studies of Science* 4, no. 2 (1974): 165-85.

Colpitts, E. H., and O. B. Blackwell. "Carrier Current Telephony and Telegraphy." *Transactions of the American Institute of Electrical Engineering* (1921): 205-300.

Colton, Roger B. "Introductory Remarks." *Chicago Crystal Conference*, Chicago, IL, 11-12 July 1944.

U.S. Department of Commerce. *Proceedings of the 4th National Radio Conference*, by Commerce, U. S. Department of. Washington, D.C., 1925.

———. "Report of the Department of Commerce Conference on Radio Telephony." *Radio Service Bulletin* (1 May 1922): 23-30.

Company, Bliley Electric. *General Catalog G9 (1939)*. [JPEG File] Bliley Electric Company, Accessed 28 May 2007. Available from http://www.bliley.net/XTAL/; Internet.

Company, General Radio. "Catalog A." Cambridge, MA, 1916. Available at http://www.teradyne.com/corp/grhs/. Accessed 14 August 2006.

———. "Catalog B." Cambridge, MA, 1918. Available at http://www.teradyne.com/corp/grhs/. Accessed 14 August 2006.

———. "Catalog C." Cambridge, MA, 1919. Available at http://www.teradyne.com/corp/grhs/. Accessed 14 August 2006.

———. "Catalog E." Cambridge, MA, 1928. Available at http://www.teradyne.com/corp/grhs/. Accessed 14 August 2006.

———. "Catalog F: Instruments for Electrical Measurements at Communication Frequencies." Cambridge, MA, 1930. Available at http://www.teradyne.com/corp/grhs/. Accessed 14 August 2006.

———. "Catalog G." Cambridge, MA, 1932. Available at http://www.teradyne.com/corp/grhs/. Accessed 14 August 2006.

———. "Catalog H." Cambridge, MA, 1935. Available at http://www.teradyne.com/corp/grhs/. Accessed 14 August 2006.

Constant II, Edward W. *The Origins of the Turbojet Revolution*. Edited by Thomas P. Hughes, Johns Hopkins Studies in the History of Technology. Baltimore, MD: Johns Hopkins University Press, 1980.

———. "The Social Locus of Technological Practice: Community, System, or Organization?" In *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, edited by Wiebe E.

Bijker, Thomas P. Hughes and Trevor Pinch, 223-42. Cambridge, MA: The MIT Press, 1989.

U.S. Department of Commerce, Office of the Publication Board. *Report PB 1565. Foreign Crystals (Captured Enemy Equipment Report, 63, compiled by Camp Coles Signal Laboratory)*, by Corps, U.S. Army Signal. Washington, D.C., 1945.

Corwin, James F., and A.C. Swinnerton. "The Growth of Quartz in Alkali Halide Solutions." *Journal of the American Chemical Society* 73, no. 8 (19 August 1951): 3598-601.

Cox, R. T. "Standard Radio Wavemeter - Bureau of Standards Type R 70B." *Journal Of The Optical Society Of America And Review Of Scientific Instruments* 6, no. 2 (March 1922): 162-68.

Crane, Diana. *Invisible Colleges: Diffusion of Knowledge in Scientific Communities*. Chicago: University of Chicago Press, 1972.

Crosland, Maurice. *Science Under Control: The French Academy of Sciences 1795-1914*. Cambridge, England: Cambridge University Press, 1992.

Curie, Jacques, and Pierre Curie. "Contractions and dilations produced by electric voltages in hemihedral crystals with inclined faces." *Comptes Rendus* 93 (26 December 1881): 1137.

———. "Development, by pressure, of polar electricity in hemihedral crystals with inclined faces." *Comptes Rendus* 91 (2 August 1880): 294.

———. *Electrometer System*. French Patent Office. Patent No. 183,851, Issue Date: 27 May 1887.

Curie, Marie. *Pierre Curie. With the autobiographical notes of Marie Curie*. New York: Dover Publications, 1963.

Dawson, L. H. "Piezoelectricity of Quartz Crystal." *Physics Review* 29 (1927): 532-41.

Debackere, Koenraad, and Michael A. Rappa. "Technological Communities and the diffusion of knowledge: a replication and validation." *R&D Management* 24, no. 4 (1994): 355-71.

Dellinger, John Howard. "Reducing the Guesswork in Tuning." *Radio Broadcast* 3, no. 4 (July 1923): 241-45.

"Discussions on Harrison Paper." *Proceedings of the Institute of Radio Engineers* 16, no. 11 (1928): 1470.

Division, National Communications System Technology and Standards. "Telecommunications: Glossary of Telecommunication Terms (Federal Standard

1037C)." General Services Administration Information Technology Service, 1996. Available at http://www.its.bldrdoc.gov/fs-1037/. Accessed 13 June 2008.

Douglas, Susan J. *Inventing American Broadcasting, 1899-1922*. Edited by Thomas P. Hughes, Johns Hopkins Studies in the History of Technology. Baltimore, MD: Johns Hopkins University Press, 1987.

Dow, J. B. "A Recent Development in Vacuum Tube Oscillator Circuits." *Proceedings Of The Institute Of Radio Engineers* 19, no. 12 (December 1931): 2095-108.

Espenschied, Lloyd. *Electrical Wave Filter*. U. S. Patent Office. Patent No. 1,795,204, Filing Date: 3 January 1927; Issue Date: 3 March 1931.

Espenschied, Lloyd, and Herman A. Affel. *Concentric Conducting System*. U. S. Patent Office. Patent No. 1,835,031, Filing Date: 23 May 1929; Issue Date: 8 December 1931.

"Establishment of Radio Standards of Frequency by the Use of a Harmonic Amplifier." *Radio Service Bulletin*, no. 114 (30 September 1926).

Fagen, M. D. *A History of Engineering and Science in the Bell System*. 7 vols. New York: Bell Telephone Laboratories, 1985.

Fetter, Charles H. *Multiplex System*. U.S. Patent Office. Patent No. 1,833,966, Filing Date: 3 December 1924; Issue Date: 1 December 1931.

Field, Alexander J. "The Most Technologically Progressive Decade of the Century." *The American Economic Review* 93, no. 4 (November 2003): 1399-413.

Folk, George E. *Patents and industrial progress; a summary, analysis, and evaluation of the record on patents of the Temporary National Economic Committee*. New York: Harper & Brothers, 1942.

Gebhard, Louis A. *Evolution of Naval Radio-Electronics and Contributions of the Naval Research Laboratory*. Washington, D.C.: Naval Research Laboratory, 1979.

Gerard, David, and Lester B. Lave. "Implementing technology-forcing policies: The 1970 Clean Air Act Amendments and the introduction of advance automotive emissions controls in the United States." *Technological Forecasting and Social Change* 72, no. 7 (September 2005): 761-78.

Gimbel, John. "U.S. Policy and German Scientists: The Early Cold War." *Political Science Quarterly* 101, no. 3 (1986): 433-51.

Goodman, Phillip. E-mail to the author, 19 January 2006.

Hackmann, Willem Dirk. *Seek and Strike: Sonar, Anti-Submarine Warfare, and the Royal Navy, 1914-54*. London: H.M.S.O., 1984.

Hale, Danforth R. "The Laboratory Growing of Quartz." *Science* 107, no. 2781 (16 April 1948): 393-94.

———. "Optimum Methods for Quartz Synthesis." *10th Annual Frequency Control Symposium*, 1956, 95-99.

Hansell, Clarence W. *Filter*. U. S. Patent Office. Patent No. 2,005,083, Filing Date: 7 July 1927; Issue Date: 18 June 1935.

Hart, David M. *Forged Consensus: Science, Technology, and Economic Policy in the United States, 1921-1953*. Princeton, NJ: Princeton University Press, 1998.

Hawley, Ellis W. "Herbert Hoover, the Commerce Secretariat, and the Vision of an 'Associative State,' 1921-1928." *Journal of American History* 61 (1974): 116-40.

Hecht, Gabrielle. *The Radiance of France: Nuclear Power and National Identity after World War 2*. Cambridge, MA: MIT Press, 1998.

Heising, Raymond A. *Piezo-electric Crystals having low temperature coefficients of frequency*. U. S. Patent Office. Patent No. 1,958,620, Filing Date: 2 April 1929; Issue Date: 15 May 1934.

———, ed. *Quartz Crystals for Electrical Circuits, Their Design and Manufacture*. New York: Van Nostrand Company, 1946.

Hoover, Herbert. *The Memoirs of Herbert Hoover: The Cabinet and the Presidency, 1920-1933*. 3 vols. Vol. 2. New York: Macmillan, 1952.

———. "The Urgent Need for Radio Legislation." *Radio Broadcast* (January 1923): 211.

Horton, Joseph W. *Oscillation Generator*. U.S. Patent Office. Patent No. 1,606,791, Filing Date: 18 July 1924; Issue Date: 16 November 1926.

Horton, Joseph W., and Warren A. Marrison. "Precision Determination of Frequency." *Proceedings of the Institute of Radio Engineers* 16, no. 2 (February 1928): 137-54.

Hounshell, David A. "Edison and the Pure Science Ideal in 19th-Century America." *Science* 207 (8 February 1980): 612-17.

———. "Industrial Research and Manufacturing Technology." In *Encyclopedia of the United States in the Twentieth Century*, edited by Kutler, 831-57. New York: Charles Scribner's Sons, 1996.

Howeth, Captain Linwood S. *History of Communications-Electronics in the United States Navy*. 1 ed. Washington, D.C.: U. S. Government Printing Office, 1963.

Hughes, Thomas Parke. *American Genesis: a century of invention and technological enthusiasm, 1870-1970*. New York: Viking, 1989.

———. "The Evolution of Large Technological Systems." In *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, edited by Thomas P. Hughes Wiebe E. Bijker, and Trevor Pinch, 51-82. Cambridge, MA: The MIT Press, 1989.

———. "Technological Momentum in History: Hydrogenation in Germany 1898-1933." *Past & Present*, no. 44 (August 1969): 106-32.

I.E.E.E. History Center: F.M. Police Radio Communication, 1940. [Web site] Accessed 2 August 2006. Available from http://www.ieee.org/web/aboutus/history_center/police_radio.html; Internet.

"Important Events in Radio - 1923." *Radio Service Bulletin*, no. 141 (31 December 1928): 22.

"Improved Apparatus for Frequency Measurement." *Radio Service Bulletin*, no. 103 (2 November 1925).

"Institute News and Radio Notes: Winter Technical Meeting, New York, New York." *Proceedings of the Institute of Radio Engineers* 33, no. 1 (January 1945): 49-59.

"International Comparison of Frequency Standards." *Radio Service Bulletin*, no. 130 (31 January 1928).

Johnson, Gary R. "History of the Industrial Production and Technical Development of Single Crystal Cultured Quartz." *International Frequency Control Symposium and Exhibition*, Montreal, Canada, 2004.

Jolliffe, C. B. "When Broadcast Stations Interfere." *Radio Broadcast* 7, no. 5 (September 1925): 586-90.

Jungnickel, Christa, and Russell McCormmach. *Intellectual Mastery of Nature: Theoretical Physics from Ohm to Einstein*. 2 vols. Vol. 2. Chicago: University of Chicago Press, 1986.

K.V.G. Quartz Crystal Technology. Accessed 20 December 2007. Available from http://www.kvg-gmbh.com/; Internet.

Katzir, Shaul. *The beginnings of piezoelectricity: a study in mundane physics*. Vol. 246, Boston studies in the philosophy of science. Dordrecht, Holland: Springer, 2006.

———. "The Discovery of the Piezoelectric Effect." *Archive for History of the Exact Sciences* 57, no. 1 (January 2003): 61-91.

———. "Technological and scientific study in the discovery and application of the piezoelectric resonance." Paper presented at the The Applied-Science Problem - A Workshop, Stevens Institute of Technology, Hoboken, NJ, 6-8 May 2005.

Kelvin, Lord. *Baltimore Lectures on molecular dynamics and the wave theory of light*. London: C. J. Clay, 1904.

———. "On the piezo-electric property of quartz." *Philosophical Magazine and Journal of Science* 36 (1893): 331, 42, 84, 453.

Kerr, P.F., and E. Armstrong. "Restricted Supplement 1." *Geological Society of America, Bulletin* 54 (1943): 1-34.

Kevles, Bettyann Holtzmann. *Naked To The Bone*. New York: Addison Wesley, 1997.

Kevles, Daniel J. *The Physicists*. New York: Alfred A. Knopf, 1978.

Kuhn, Thomas S. *The Structure of Scientific Revolutions*. Chicago: The University of Chicago Press, 1962.

Kumar, Prakash. "Facing Competition: The History of Indigo Experiments in Colonial India, 1897-1920." Ph.D. diss., Georgia Institute of Technology, 2004.

Lack, F. R., G. W. Willard, and I. E. Fair. "Some Improvements in Quartz Crystal Circuit Elements." *Bell System Technical Journal* 13 (1934): 453-63.

Lamb, James J. *Piezoelectric Filter*. U.S. Patent Office. Patent No. 2,054,757, Filing Date: 24 August 1933; Issue Date: 15 September 1936.

———. "Short-Wave Receiver Selectivity to Match Present Conditions: Constructional and Operating Features of the Signel-Signal Superhet." *QST* 16, no. 8 (1932).

Lamoreaux, Naomi, and Kenneth L. Sokoloff. "Long-term Change in the Organization of Inventive Activity." *Proceedings of the National Academy of Sciences of the United States of America* 93, no. 23 (12 November 1996): 12686-92.

Lane, C. E. "Crystal Channel Filters for the Cable Carrier System." *Bell System Technical Journal* 17 (January 1938): 125-36.

Lang, Sidney B. "A Conversation with Professor W. G. Cady." *Ferroelectrics* 9 (1975): 141-49.

Lassman, Thomas C. "Industrial Research Transformed: Edward Condon at the Westinghouse Electric and Manufacturing Company, 1935-1942." *Technology and Culture* 44, no. 2 (April 2003): 306-39.

Laudise, Robert A., and R. A. Sullivan. "Pilot Plant Production of Synthetic Quartz." *Chemical Engineering Progress* 55 (1959): 55-59.

Layton, Jr., Edwin T. "Mirror-Image Twins: The Communities of Science and Technology in 19th-Century America." *Technology and Culture* 12, no. 4 (1971): 562-80.

———. "Technology As Knowledge." *Technology and Culture* 15, no. 1 (January 1974): 31-41.

Lecuyer, Christopher, and David C. Brock. "The Materiality of Microelectronics." *History and Technology* 22, no. 3 (September 2006): 301-25.

Lessing, Lawrence. *Man of High Fidelity: Edwin Howard Armstrong*. Philadelphia: Lippincott, 1956.

Lewis, Tom. *Empire of the Air: The Men Who Made Radio*. New York: Harper Collins, 1991.

Lindsay, R. Bruce, and W. J. King. "Walter G. Cady Oral History Interview." 28-9 August 1963, Center for History and Philosophy of Physics.

"List of broadcasting stations in Chicago and vicinity equipped with piezo crystal oscillators calibrated to their designed frequency." *Radio Service Bulletin*, no. 107 (27 February 1926): 12.

"List of stations broadcasting market or weather reports (435 meters) and music, concerts, lectures, etc. (360 meters)." *Radio Service Bulletin*, no. 59 (1 March 1922): 13-14.

Little, D. G., and R. L. Davis. "KDKA." *Proceedings Of The Institute Of Radio Engineers* 14, no. 4 (August 1926): 479-506.

"Louis Agricola Bauer." In *Dictionary of Scientific Biography*, edited by Charles Coulston Gillispie. New York: Charles Scribner's Sons, 1974.

Lynn, Leonard H., N. Mohan Reddy, and John D. Aram. "Linking technology and institutions: the innovation community framework." *Research Policy* 25 (1996): 91-106.

Marrison, Warren A. "The Crystal Clock." *Proceedings of the National Academy of Sciences of the United States of America* 16, no. 7 (15 July 1930): 496-507.

———. "The Evolution of the Quartz Crystal Clock." *The Bell System Technical Journal* 27 (1948): 510-88.

———. *Frequency-Control System*. U. S. Patent Office. Patent No. 1,788,533, Filing Date: 28 March 1927; Issue Date: 13 January 1931.

———. *Piezo Electric Crystal*. U. S. Patent Office. Patent No. 1,899,163, Filing Date: 19 December 1928; Issue Date: 28 February 1933.

Mason, W. P. "New Quartz Crystal Plate, Designated the GT, Which Produces a Very Constant Frequency Over a Wide Temperature Range." *Proceedings Of The Institute Of Radio Engineers* 28 (May 1940): 220-23.

———. *Wave Filter*. U. S. Patent Office. Patent No. 1,921,035, Filing Date: 30 September 1931; Issue Date: 8 August 1933.

Mason, W. P., and R. A. Sykes. *Piezoelectric Apparatus*. U. S. Patent Office. Patent No. 2,173,589, Filing Date: 14 December 1933; Issue Date: 19 September 1939.

McCraw, Thomas K. *American Business, 1920-2000: How It Worked*. Edited by John Hope Franklin and A. S. Eisenstadt, The American History Series. Wheeling, IL: Harlan Davidson, Inc., 2000.

Merges, Robert P., and Richard R. Nelson. "On the Complex Economics of Patent Scope." *Columbia Law Review* 90 (May 1990).

Millikan, Robert A. *The Autobiography of Robert A. Millikan*. New York: Prentice-Hall, 1950.

Mills, A. F. *Heat and Mass Transfer*. Boca Raton, FL: CRC Press, 1995.

U.S. Geological Survey. *Mineral Resources of the United States*. Washington, D. C., 1883.

Misa, Thomas J. *A Nation of Steel: The Making of Modern America, 1865-1925*. Baltimore: Johns Hopkins University Press, 1995.

Mokyr, Joel. *The Gifts of Athena: Historical Origins of the Knowledge Economy*. Princeton, NJ: Princeton University Press, 2002.

Mowery, David. "Industrial Research and Firm Size, Survival, and Growth in American Manufacturing, 1921-46: An Assessment." *Journal of Economic History* 43 (December 1983): 953-80.

Mowery, David, and Nathan Rosenberg. *Paths of Innovation: Technological Change in 20th Century America*. New York: Cambridge University Press, 1998.

———. *Technology and the Pursuit of Economic Growth*. Cambridge, UK: Cambridge University Press, 1989.

Mumford, Lewis. *Technics and Civilization*. New York: Harcourt Brace and Company, 1934.

Muzak, Inc.: Company History. Accessed 7 January 2008. Available from http://www.fundinguniverse.com/company-histories/Muzak-Inc-Company-History.html; Internet.

National Research Council, U.S. *Research Laboratories in Industrial Establishments of the United States*. 4 ed, Bulletin of the National Research Council. New York: Bowker, 1933.

"New Fundamental Frequency Standard." *Radio Service Bulletin*, no. 157 (30 April 1930): 23-24.

"New Method of Maintaining Constant Station Frequency." *Radio Service Bulletin*, no. 106 (30 January 1926): 23.

Nicolson, Alexander. *Piezophony*. U. S. Patent Office. Patent No. 1,495,429, Filing Date: 10 April 1918; Issue Date: 27 May 1924.

Noble, David F. *America By Design: Science, Technology, and the Rise of Corporate Capitalism*. Oxford, England: Oxford University Press, 1977.

"Obituary - Walter G. Cady." *Wesleyan University News Bureau* 1974.

"Obituary: John Howard Dellinger." *Proceedings Of The Institute Of Radio Engineers* 51, no. 83 (March 1963): 20A.

"Peizoelectric Crystals As Radio Standards." *Radio Service Bulletin*, no. 90 (1 October 1924): 8-9.

"Petrography." In *Merriam-Webster's Collegiate Dictionary*. Springfield, MA: Merriam-Webster, 2008.

Pierce, George Washington. *Electrical System*. U. S. Patent Office. Patent No. 2,133,642, Filing Date: 25 February 1924; Issue Date: 18 October 1938.

———. "Piezoelectric Crystal Resonators and Crystal Oscillators Applied to the Precision Calibration of Wavemeters." *Proceedings of the Amercian Academy of Arts and Sciences* 59, no. 4 (October 1923).

"Pierce, George Washington." In *Dictionary of Scientific Biography*, edited by Charles Coulston Gillispie, 604-05. New York: Charles Scribner's Sons, 1974.

"Piezoelectricity." In *McGraw-Hill Encyclopedia of Science and Technology*: McGraw-Hill, 2002.

U.S. Department of Commerce. *Proceedings of the 4th National Radio Conference*. Washington, D.C., 1925.

"Proceedings of the 10th Annual Frequency Control Symposium." Asbury Park, NJ, 1956.

"Proceedings of the 13th Annual Frequency Control Symposium." Asbury Park, NJ, 1959.

Productions, Man from Mars. *Daniel E. Noble*. 2006. Accessed Available from http://www.wdrcobg.com/noble2.html; Internet.

Products, Sawyer Research. *Technical Brief: Hydrothermal Growth of Quartz*. [PDF File] Accessed 15 March 2007. Available from http://www.sawyerresearch.com/Tech%20Brief/Quartz_growth_tech_brief.pdf; Internet.

Pulvari, Charles F. "A Tribute to Dr. Hans Jaffe: From Rochelle Salt to Poled Piezoelectrics." *IEEE Transactions on Sonics and Ultrasonics* SU-25, no. 6 (November 1978): 329.

Pupin, Michael. *From Immigrant To Inventor*. New York: Charles Scribner's Sons, 1923.

"Quartz Plates Available to Amateurs." *The General Radio Experimenter* 1, no. 3 (December 1926).

Radio Communication Law of the United States. License for Radio Station. (15 August 1919).

"Radio Progress during 1936: Part IV – Report by the Technical Committee on Television and Facsimile." *Proceedings of the Institute of Radio Engineers* 25, no. 2 (February 1937): 203-4.

"Radio Progress During 1951." *Proceedings of the Institute of Radio Engineers* 40, no. 4 (April 1952): 388-439.

Raide, Bob, and Ed Gable. *Celebrating the First Transatlantic QSO*. 1998. Accessed 2 January 2007. Available from http://www.arrl.org/news/features/1998/1102/2/?nc=1; Internet.

"Recommendations of the National Radio Committee." *Radio Service Bulletin*, no. 72 (2 April 1923): 9-13.

Records of the Office of Alien Property, Record Group 131, U.S. National Archives. Accessed 20 December 2007. Available from http://www.archives.gov/research/guide-fed-records/groups/131.html; Internet.

Reich, Leonard. "Industrial Research and the Pursuit of Corporate Security, Early Years of Bell Labs." *Business History Review* 54, no. 4 (1980): 504-29.

———. *The Making of American Industrial Research: Science and Business at G.E. and Bell, 1876-1926*. New York: Cambridge University Press, 1985.

———. "Research, Patents, and the Struggle to Control Radio: A Study of Big Business and the Uses of Industrial Research." *Business History Review* 51, no. 2 (1977): 208-35.

"A Review of Twenty Years of Progress in Communication-Frequency Measurements." *The General Radio Experimenter* 10, no. 1 (1935): 1-20.

Riordan, Michael, and Lillian Hoddeson. *Crystal Fire: The Birth of the Information Age*. First ed, Sloan Technology Series. New York: W.W. Norton & Company, 1997.

Roddy, Dennis, and John Coolen. *Electronic Communications*. Third ed. Reston, VA: Reston Publishing Company, 1984.

Roland, Alex. *The Military-Industrial Complex*. Edited by Pamela O. Long and Robert C. Post, Historical Perspectives on Technology, Society, and Culture. Washington, D.C.: American Historical Association, 2001.

Rosen, Philip T. *The Modern Stentors: Radio Broadcasters and the Federal Government, 1920-1934*. Westport, CT: Greenwood Press, 1980.

Rosenberg, Nathan. "The Direction of Technological Change: Inducement Mechanisms and Focusing Devices." *Economic Development and Cultural Change* 18, no. 1 (January 1969): 1-24.

Sampat, Bhaven. "Patenting and U.S. academic research in the 20th century: The world before and after Bayh-Dole." *Research Policy* 35 (2006): 772-89.

Saunders, Frederick A., and Frederick V. Hunt. "George Washington Pierce." In *Biographical Memoirs. National Academy of Sciences*, 351-80. Washington, D.C.: National Academy Press, 1959.

Sawyer, Charles Baldwin. "Progress in Engineering Cultured Quartz For Use By The Crystal Industry." *13th Annual Frequency Control Symposium*, 1959.

———. "Rochelle Salt As A Dielectric." *Physical Review* 35, no. 3 (February 1930): 269-73.

———. "The Use of Rochelle Salt Crystals for Electrical Reproducers and Microphones." *Proceedings of the Institute of Radio Engineers* 19, no. 11 (November 1931): 220-29.

Sawyer, Charles Baldwin, and B. R. Kjellgren. "Newer Developments in Beryllium." *Industrial and Engineering Chemistry* 30, no. 5 (May 1938): 501-05.

Shaw, H. S. "Oscillating Crystals." *QST* 7, no. 12 (July 1924).

Simmonds Jr., Thomas H. "The Evolution of the Discrete Crystal Single-Sideband Selection Filter in the Bell System." *Proceedings of the IEEE* 67, no. 1 (January 1979): 109-14.

Slotten, Hugh. *Radio and Television Regulation: Broadcast Technology in the United States, 1920-1960*. Baltimore, MD: Johns Hopkins University Press, 2000.

———. "Radio Engineers, the Federal Radio Commission, and the Social Shaping of Broadcast Technology: 'Creating Radio Paradise,' 1927-1934." *Technology and Culture* 36, no. 3 (October 1995): 950-86.

Smith, Adam. *The Wealth of Nations*. Fifth ed. New York: Bantam Classics, 2003.

Smith, Sallie Wolfskill. *The Life of John Martin Wolfskill (2002)*. [Web site] Accessed 28 May 2007. Available from http://www.bliley.net/XTAL/; Internet.

Snyder, Wilbert F., and Charles L. Bragaw. *Achievement In Radio: Seventy Years of Radio Science, Technology, Standards, and Measurement at the National Bureau of Standards*. Boulder, CO: National Bureau of Standards, 1986.

Sobek, Andrew R., and Danforth R. Hale. *Method and Apparatus for Growing Single Crystals of Quartz*. U. S. Patent Office. Patent No. 2,675,303, Filing Date: 11 April 1950; Issue Date: 13 April 1954.

Socolow, Michael J. "A Wavelength for Every Network: Synchronous Broadcasting and National Radio in the United States, 1926-1932." *Technology and Culture* 49, no. 1 (January 2008): 89-113.

"Standard Frequency Stations." *Radio Service Bulletin*, no. 90 (1 October 1924): 11.

"Standard Frequency Stations." *Radio Service Bulletin*, no. 130 (31 January 1928).

Staudenmaier, John M. *Technology's Storytellers: Reweaving the Human Fabric*. Cambridge, MA: The MIT Press, 1985.

Stephens, Carlene. "Reinventing Accuracy: The First Quartz Clock of 1927." Paper presented at the Furtwangen Conference, Germany, 11 October 2007.

Stephens, Carlene, and M. Dennis. "Engineering Time: Inventing the Electronic Wristwatch." *British Journal for the History of Science* 33 (2000): 477-97.

Sterling, Christopher H., and John Michael Kittross. *Stay Tuned: A History of American Broadcasting*. 3rd ed. Mahwah, NJ: Laurence Erlbaum Associates, 2002.

Technical (U.S Army) Field Information Agency. Office of the Military Government for Germany (US). *FIAT Final Report on the Interrogation of German Scientists Regarding Quartz Crystals and Other Piezoelectric Materials*, Report 641, by Swinnerton, Allyn C. 1945.

Taylor, Albert Hoyt. *The First Twenty-Five Years of the Naval Research Laboratory*. Washington, D.C.: U.S. Department of Navy, 1948.

Taylor, Frederick Winslow. *The Principles of Scientific Management: and Shop Management*. London: Routledge/Thoemmes Press, 1993.

Terman, Frederick Emmons. *Radio Engineering*. 1st ed. New York: McGraw-Hill, 1932.

Tesla, Nikola. *Alternating Electric Current Generator*. U. S. Patent Office. Patent No. 447,921, Filing Date: 15 November 1890; Issue Date: 10 March 1891.

Theissen, Arthur E. *A History of the General Radio Company, 1915-1965*. West Concord, MA: General Radio Company, 1965.

Thompson Jr., Richard J. *Crystal Clear: The Struggle for Reliable Communications Technology in World War 2*. New York: Wiley-IEEE Press, 2006.

———. "The Development of the Quartz Crystal Oscillator Industry of World War 2." *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 52, no. 5 (May 2005).

Thurston, George M. *Piezo-Electric Crystal Mounting*. U. S. Patent Office. Patent No. 1,883,111, Filing Date: 14 August 1929; Issue Date: 18 October 1932.

Thurston, Robert N. "Warren P. Mason (1900-1986) Physicist, Engineer, Inventor, Author, Teacher." *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 41, no. 4 (July 1994): 425-34.

———. "Warren P. Mason, 1900-1986." *Journal of the Acoustical Society of America* 81 (1987): 570-71.

Toivanen, Hannes. "Learning and Corporate Strategy: The Dynamic Evolution of the North American Pulp and Paper Industry, 1860-1960." Ph.D. diss., Georgia Institute of Technology, 2004.

Ven, Andrew Van de. "A community perspective on the emergence of innovations." *Journal of Engineering and Technology Management* 10 (1993): 23-51.

Vig, John. "Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications - A Tutorial." [PowerPoint] 1999, U.S. Army Communications-Electronics Command, Fort Monmouth, NJ.

Vig, John, and Arthur Ballato. "Frequency Control Devices." In *Ultrasonic Instruments and Devices - Reference for Modern Instrumentation, Techniques, and Technology*, edited by Emmanuel P. Papadakis, 638. New York: Academic Press, 1999.

Vincenti, Walter. *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*. Edited by Merritt Roe Smith, Johns Hopkins Studies in the History of Technology. Baltimore: Johns Hopkins University Press, 1990.

Voigt, Woldemar. *Lehrbuch der Kristallphysik*. Leipzig: B. G. Teuner, 1910.

Walker, A.C. "Hydrothermal Synthesis of Quartz Crystals." *Journal of the American Ceramic Society* 36, no. 8 (August 1953): 250-56.

Walker, A.C., and E. Buehler. "Growing Large Quartz Crystals." *Industrial and Engineering Chemistry* 42, no. 7 (July 1950): 1369-75.

Walker, C. Lester. "Secrets By The Thousands." *Harper's*, October 1946.

Weingart, Peter. "The Structure of Technological Change: Reflections on a Sociological Analysis of Technology." In *The Nature of Technological Knowledge: Are Models of Scientific Change Relevant?*, edited by Rachel Laudan, 115-42. Dordrecht, Holland: D. Reidel Publishing Company, 1984.

The Wikisource 1911 Encyclopedia Project. Accessed 17 July 2006. Available from http://en.wikisource.org/wiki/Main_Page; Internet.

Wise, George. "A new role for professional scientists in industry: industrial research at General Electric, 1900-1916." *Technology and Culture* 21 (1980): 408-29.

———. *Willis R. Whitney, General Electric, and the Origins of U. S. Industrial Research*. New York: Columbia University Press, 1985.

Wolfskill, John M. *Piezoelectric Crystal*. U.S. Patent Office. Patent No. 2,157,808, Filing Date: 27 August 1935; Issue Date: 9 May 1939.

———. *Piezoelectric Crystal Apparatus*. U.S. Patent Office. Patent No. 2,364,501, Filing Date: 4 April 1941; Issue Date: 5 December 1944.

Wooster, Nora, and W. A. Wooster. "Preparation of Synthetic Quartz." *Nature* 157, no. 3984 (9 March 1946): 297.

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Sincerely,

Christopher S. McGahey, Ph.D.

Christopher S. McGahey   10 Sept. 2009