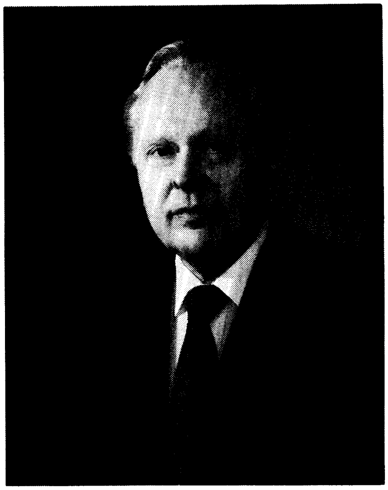


HERMAN P. SCHWAN

Figure 1. Herman P. Schwan, winner of the IEEE Edison Medal, member of the National Academy of Engineering, recipient of an honorary doctorate from the University of Pennsylvania, and current resident of Radnor, Pennsylvania.

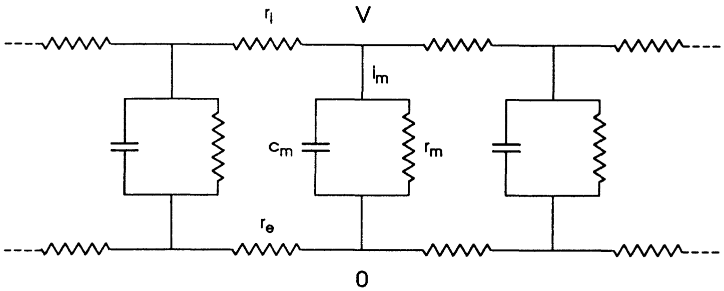
CHAPTER 2

Working to Establish a New Discipline

Herman P. Schwan and the Roots of Biomedical Engineering

Biomedical engineering—the use of the principles and techniques of engineering to solve problems in biology and medicine—has roots deep in history. Luigi Galvani's investigations in the 1780s of "animal electricity" began a line of research, called electrophysiology, that before the end of the nineteenth century had established the electrical nature of the nerve impulse and revealed much about electrolytic conduction in animal tissues. Here concepts of electrical engineering—such as resistivity, capacitance, and polarization—were obviously applicable. Indeed, the mathematical model William Thomson (later Lord Kelvin) proposed in 1855 for understanding the Atlantic telegraph cable was imported intact (see Figure 2).

Where electrical engineering had a much greater effect on biology and medicine was in instrumentation. By 1910 thermocouples, capillary electrometers, string galvanometers, and many other electrical devices were commonly used in biomedical research.[1] Electronic devices also found early application: x-ray imaging dates from 1895; both cathode-ray tubes



$$\frac{\partial^2 V}{\partial x^2} = \frac{r_e + r_i}{r_m} V + (r_e + r_i)\, c_m \frac{\partial V}{\partial t}$$

Figure 2. A schematic representation of a cable and an equation describing its electrical behavior, based on William Thomson's 1855 analysis of an underwater telegraph cable. By 1905 this analysis was being used to describe conduction along a nerve fiber.[2] (*V* is electrical potential difference across the membrane (or insulating sheath), x is distance, R_e is external resistance per unit length, R_i is internal resistance per unit length, R_m is membrane resistance per unit length, C_m is membrane capacitance per unit length, and t is time.)

and vacuum-tube amplifiers were being used to study nerve impulses in the 1920s; and the electron microscope, invented in 1931, was being used in biology by 1934.[3]

Not only research, but also medical practice was changed. Many research instruments, such as x-ray machines, electrocardiographs, and electroencephalographs, came to be regularly used in diagnosis. Throughout the nineteenth century there were attempts to use electrical technology in treatment but only a few (such as cardiorespiratory resuscitation by electrical stimulation) were of much effectiveness.[4] In the early decades of this century, a few techniques of obvious utility were introduced: x-ray therapy, electrosurgery, and diathermy (the generation of heat in animal tissues by electromagnetic or ultrasonic radiation). In the late 1920s, the vacuum tubes developed for radio led to short-wave diathermy, electrosurgery, and medical applications of telemetry.[5]

In the 1920s and 1930s, as more and more investigators used the concepts and techniques of physics and engineering in biological and medical research, a few institutions were established to promote this approach. In the United States in the 1920s, the Johnson Foundation for Medical Physics at the University of Pennsylvania and the Biophysics

Department of the Cleveland Clinic were founded. Siemens, a major supplier of x-ray and diathermy equipment, maintained a biophysical laboratory at Erlangen.[6]

Also in the 1920s the Oswalts, a Frankfurt family that had become wealthy through banking, provided the money for an Institute for the Physical Foundations of Medicine (*Institut für physikalische Grundlagen der Medizin*). The founding director was Friedrich Dessauer, who is best known for his theory of x-ray damage. In 1934 Boris Rajewsky became director of the institute; he studied the biological effects of both ionizing and nonionizing radiation.[7] In 1938 Rajewsky gained the sponsorship of the Kaiser Wilhelm Society, and the Oswalt Institute for the Physical Foundations of Medicine was attached to the larger, newly formed Kaiser Wilhelm Institute for Biophysics (*Kaiser Wilhelm Institut für Biophysik*, later the *Max Planck Institut für Biophysik*). Both biomedical engineering and biophysics—indeed, it is often difficult to distinguish between these disciplines—advanced at the Institute, where the main areas of research were the biological effects of electromagnetic radiation, both ionizing and nonionizing, and dosimetry of x-rays. With the new funding from the Kaiser Wilhelm Society, the Institute increased its staff to about twenty employees. Among those hired as a technician in 1937 was a young engineer who reached that position by a tortuous path.

Growing Up in Weimar and Nazi Germany

Herman Schwan was born 7 August 1915, in the summer of the Second Battle of Ypres, the Gallipoli Campaign, and US protests over the sinking of the *Lusitania*.[8] His father, Wilhelm Schwan, having recovered from a serious injury suffered early in the war, was teaching mathematics and physics in the high school of Aachen, a city near the border to Belgium and Holland. His mother, Meta née Pattberg, was from a well-to-do family: Her father was director of the railway system in Westphalia. In 1918 the Schwans moved to Bad Kreuznach, a town near Mainz, where the Main River joins the Rhine. Wilhelm Schwan taught at the high school, wrote a widely used geometry text, and edited a volume of mathematics lectures.[9] He became affiliated with the mathematics faculty of the University of Frankfurt and received his doctorate there.

Wilhelm Schwan, a supporter of the Social Democrats, was outspoken in his opposition to the militant nationalism then finding expression, and he strenuously objected to the view that force should be used to correct the "injustice" of the Versailles Treaty that ended the World War. As time passed, his political views became increasingly unpopular. He and three other teachers with liberal views were socially ostracized, and the atmosphere became intensely unpleasant for them. One of the teachers committed suicide. Another emigrated to France. Wilhelm Schwan was helped out of this situation by friends who, in 1926, arranged for his transfer to the high school in Düsseldorf. Three years later, however, Wilhelm was again transferred, this time to Meseritz in eastern Germany.

On 30 January 1933 Hitler was appointed Chancellor, and on 7 April the Nazi government enacted the "Law for Restoration of the Professional Civil Service," which led to the dismissal from government employment of Jews and of people not holding "proper" political beliefs. Among them was Wilhelm Schwan, and he was unable to find other employment. He became severely depressed and had periods of imagining that the Gestapo had placed microphones in the walls of the family's apartment. He moved to Berlin.[10]

Several years before this, Wilhelm and Meta Schwan had separated, though they were reunited briefly in Göttingen, where Meta, with 15-year-old Herman, had taken up residence. She had selected Göttingen primarily because of its excellent high school and university. In the years Herman attended the high school (1930 to 1934), the children of Hermann Weyl, Max Born, and Richard Courant were also students. According to Herman Schwan, ". . . the Göttingen years were very, very important to me. I had an excellent school with excellent teachers. There was a very intellectual environment. . . ."[11] The influence of his father was no doubt partly responsible for Schwan's strong interest in mathematics and physics. Equally strong was his interest in history; besides taking many history courses, Schwan avidly read ancient and Russian history as well as the history of the World War.

In 1934 Schwan received his *Abitur*, graduating summa cum laude. At that time entry into a university required not only the *Abitur*, but also a certificate of political maturity (*Reifezeugnis*). The latter was conferred by Nazi officials, and Schwan, whose political views were known to teachers from discussions in history classes, did not receive the certificate. Much against his inclination, Schwan then entered the Reich Labor Service (*Reichsarbeitsdienst*) as a way of proving "political maturity." The Labor Service provided quasimilitary training to large numbers of Germans without contravening the restriction on the size of the military mandated by the Versailles Treaty, and it soon became obligatory for all young men.

Schwan describes the "slave labor camp" he found himself in: "Getting up at four in the morning for exercising and singing patriotic songs.... Then we had to march to where we were building an airfield which became a Stuka base."[12] There it was backbreaking work until two in the afternoon, followed by the march back to the main camp and two hours of military exercises. After the evening meal, political indoctrination lasted until lights-out at ten. He soon developed major health problems: "I just couldn't take that physical punishment."[13] So just six weeks after entering the Labor Service, Schwan was granted a discharge by the camp doctor and received the political maturity certificate.

This was not, however, the last hindrance to university study, as it was necessary for Schwan to receive a tuition waiver. Advised that because of his political views he had no chance of receiving such an award at Göttingen, Schwan applied to the University of Frankfurt (where his father was well known to the math faculty) and was granted the tuition waiver. The award, however, required his membership in the "Comradeship House," which was Nazi dominated. Because of persecution at the House (see quotation below), he asked to leave it, and this meant loss of his tuition waiver. So Schwan returned to Göttingen, where his mother was still living, for his second year of study. She and he saved and borrowed all they could to pay the tuition at the university there. "Somehow we did it . . . but after one year there it was all out. There was no chance to continue [at Göttingen]."[14]

. . . I fell in disgrace, unfortunately, fairly rapidly with the people in the so-called Comradeship House. It must have been that I was not too careful about expressing myself politically, even though I tried to be careful. It became known that I was invited to Sunday dinners several times by some of my professors who were Jewish. I interacted with them, of course, strongly.

. . . It just happened that I was the best in my class. When they asked a question of the class, I raised my hand first. I did some things which others didn't. For example, sometimes before class started when the blackboards were all dirty, I wiped them clean before the professor came. Well, they called me "Der Judenjüngling." *How can I translate that? It means "the Jew boy." I became known as a Jew boy. One night they beat me up. It was a gruesome experience which led again to my heart deficiencies. I was surrounded by a blanket or sack, and they beat on me with sticks. It was an awful experience. I was deep in sleep when it started. It was one of the most miserable things in my life. In the morning I had all sorts of heart problems. I was permitted to leave the Comradeship House. That meant the next year I couldn't get free tuition.*[15]

Schwan soon devised a way to continue his education. First, he would earn money at a summer job as an engineer, then he would study at a university in the eastern part of the country where, he had heard, scholarships were easier to obtain because the government wanted to encourage ethnic Germans to live in areas where there were large Polish-speaking populations.

The first step went as planned. Schwan had done very well in course work, both in Frankfurt and in Göttingen. In addition to mathematics and physics, he studied engineering, a subject his hobby of building radios had made attractive to him. So he was able to get a summer job at the renowned firm of Siemens and Halske in Berlin, where he worked on developing electric hygrometers.

The second step failed. Schwan did move to Breslau (today part of Poland and called Wroclaw) in Lower Silesia and began attending the university. It took some time to learn if he would receive a scholarship, and after one semester he learned he would not. "I remember . . . I was in my room sick. I had a vicious flu. I hadn't paid my rent for two months, and the owner of the apartment was threatening to evict me. . . . I got a note from the university that I was thrown out for not paying tuition."[16]

His hopes for a university degree seemingly come to naught, Schwan took a job as engineer at Telefunken, which was the largest German manufacturer of radio receivers and the principal German center for research in high-frequency techniques. In the main Telefunken facilities in Berlin he tested radio receivers; he recalls evaluating an RCA receiver, comparing it to Telefunken receivers.

One day, about half a year after starting at Telefunken, Schwan had a chance encounter in the company cafeteria with one of his physics professors at Frankfurt. Schwan explained what he was doing there and why he had stopped his studies. The professor said it was a shame that so promising a student was not continuing his education and, without Schwan's knowledge, contacted H. Daenzer, another professor who knew Schwan well. Daenzer made inquiries at Frankfurt, and some weeks later Schwan received an offer of a job at the Institute for the Physical Foundations of Medicine. He would be hired as a technician at a low salary, but he would be allowed to take courses at the university and tuition would be paid.

Though delighted to be able to continue his studies, Schwan was also reluctant to leave Telefunken. He decided to maintain ties with the company so that after completing his Ph.D. he might return to work there. He therefore arranged with the director of the Institute in Frankfurt to be given a quarter of the year free in order to work at Telefunken. Indeed, the following summer (1938) Schwan did return to Telefunken and was assigned to the high-frequency laboratory where he worked on high-frequency power transmission. (In the same laboratory was a magnetron development group, which was disbanded by government order in 1939 as being inessential to the war effort. In 1943, as the importance of radar and the relative backwardness of the Germans in this area became clear to Nazi authorities, the group was reestablished.)

It was in October 1937 that Schwan moved to Frankfurt and joined the Institute. There he worked with a small group, led by the director of the institute, Boris Rajewsky, studying the electrical properties of biological tissues and the technique of diathermy. Schwan saw immediately that the Institute's electrical and electronic instruments—oscillators, Wheatstone bridges, and other devices—were at quite a primitive level, and knew that one could achieve greatly increased accuracy. Rajewsky quickly recognized Schwan's abilities and supported his research initiatives. At the same time Schwan was taking courses, including several on biophysics taught by Rajewsky, several physics laboratory courses, and a demanding course in analytic techniques taught by the famous mathematician Carl Ludwig Siegel (who shortly thereafter emigrated to the United States).

World War II and Project Paperclip

The German invasion of Poland in September 1939 brought on world war, but for about two years Schwan's situation changed little. Living conditions in Frankfurt were not greatly affected—there was rationing of basic foodstuffs, but this had begun before the war in accord with Hermann Göring's slogan "guns before butter"—and research at the Institute and teaching at the University continued much as before. Schwan gave most of his time to what he had selected as his dissertation research: deciding between two alternative theories to explain the high-frequency properties of biological tissues. He also collaborated with H. Schaefer, also at the Institute, to disprove a theory proposed by the Russian researcher N. N. Malov to use electric fields to obtain large, localized elevations of temperature (which might be used to destroy infectious bacteria selectively).[17]

Though scientific research and scholarly communication (especially across German borders) became increasingly difficult, the young field of biomedical engineering and biophysics continued its growth. Indeed, what may be the world's first biophysical conference took place in Germany in 1941. The site was Oberschlema, in Saxony, near the Czech border, and Schwan attended.[18] The leading figures were Boris Rajewsky and Nikolai V. Timofeeff-Ressovsky (famous for his genetic studies of fruit flies through radiologically induced mutation). The main topic was the biological effects of ionizing radiation, but the effect and medical application of nonionizing radiation were also discussed. Two years later the German Biophysical Society was formally established in Berlin. (This society was dissolved at the end of the war, but a few years later a new biophysical society was formed in West Germany.)[19]

One day in the late fall of 1941, Rajewsky unexpectedly told Schwan that he was ready to receive his Ph.D. and that he would have to take his math exam that very day. Expeditiousness was called for because the examining math professor had been drafted and was about to leave the university. The result was that Schwan completed his Ph.D. before his research had reached a conclusion. The research, though, continued and was eventually completed.

The winter of 1942–1943, which saw the German army's disaster at Stalingrad, brought a marked worsening of conditions in Frankfurt. Meat, fish, butter, and many other ordinary goods became hard to obtain, travel became more difficult, and the bombing of the city began. Until then Schwan was able to avoid military service because of his medical condition, but exemptions from military service became much harder to obtain and he would have been drafted except for the determined efforts of Rajewsky, the

Director of the Institute. (Rajewsky had joined the Nazi Party, but this was, in Schwan's view, an indication of opportunism rather than conviction; Rajewsky knew of Schwan's anti-Nazi feelings, but supported him nevertheless.)

Until 1943 Schwan was permitted to continue his research into the electrical properties of biological materials, but then, like everyone else at the Institute, he was compelled to work on military projects. At first he worked on a device to measure water droplets that was to be placed in a radiosonde (a combination of meteorological instrumentation and radio transmitter carried aloft by a balloon). This he did only part time, but in the summer of 1943 Rajewsky came back from a meeting in Berlin with word that henceforth all work must contribute to the war effort. Schwan was told to work full time on Project Chimney Sweeper, whose objective was a countermeasure to radar detection of submarines.

Shipborne and, especially, airborne radar became so effective in detecting surfaced submarines that in the summer of 1943 the German Admiral Doenitz conceded, "The method of radio location which the Allies have introduced has conquered the U-boat menace."[20] The Germans countered with a retractable air intake, called *Schnorkel*, that allowed a submarine to travel submerged, though at a shallow depth, while running on the diesel engines and recharging batteries. In January 1944 German submarines began to be equipped with *Schnorkel*.[21] The Allies responded, through Project Hawkeye, with modifications to existing radar equipment that made the exposed part of the *Schnorkel* detectable. The move-countermove continued as the Germans, through Project Chimney Sweeper, developed an antiradar covering, called *Sumpf* (swamp), that could be placed on *Schnorkel*.

Sumpf was an early version of the technology that more recently (along with other antiradar measures) is used to make the stealth bomber almost invisible to radar. It was well known that a reflecting surface could be made into an absorbing surface by coating it with a quarter-wave layer, that is, a partly transparent layer whose thickness is one-quarter the wavelength of the light or other electromagnetic radiation passing through it. By placing several layers on a surface, one could render it invisible to radar operating at several wavelengths. What Schwan was asked to do was measure the electrical properties of different materials that might be useful as coatings. For this work, involving microwaves of wavelength as short as 10 centimeters, Schwan was provided with two of the most advanced German magnetrons (built by Siemens).

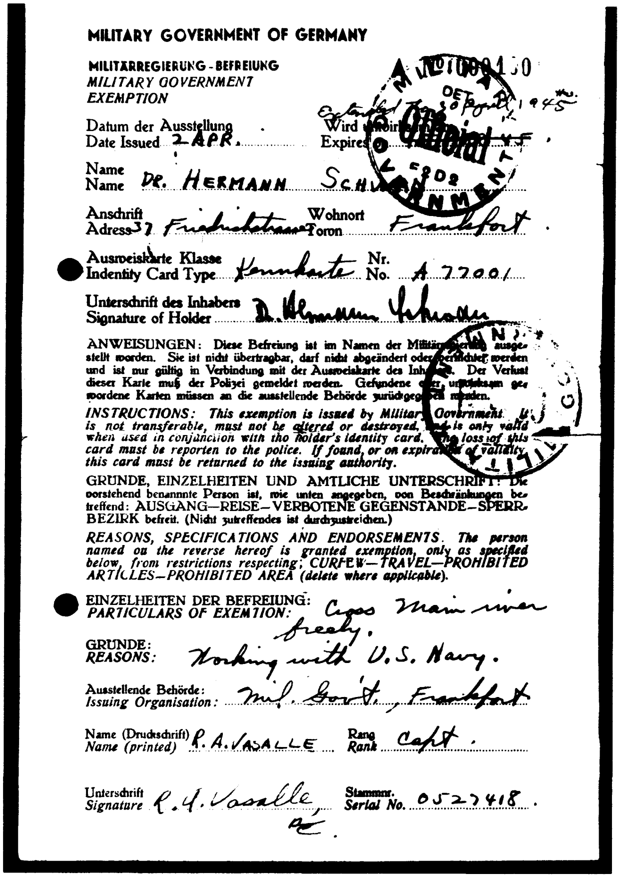
Reluctant to contribute to the war effort, Schwan sought ways to delay taking the data that would be useful to Project Chimney Sweeper. The Allied bombing provided one excuse. The Institute was, in fact, heavily damaged in a series of raids in March 1944. (These raids were so destructive that a large proportion of all buildings in Frankfurt were rendered uninhabitable.) "Necessary" improvements to instrumentation provided another excuse. Finally, however, he had to report the data, but he did make one attempt to leak to the Allies the frequencies at which *Sumpf* was effective. (Schwan was so worried that this attempt would be discovered by the German authorities that he purchased a handgun with the intent to shoot himself when the Gestapo came banging on the door.)[22] The Germans did effectively employ *Sumpf* in late 1944, but too late to have much effect of the course of events.

In February 1945 US and British forces moved into Germany, and in March General Patton's army approached Frankfurt. Most of the Institute staff had long since moved to facilities more centrally located. About half a dozen people remained at the Institute in Frankfurt, and they asked Schwan to represent them, partly because he spoke English. On 15 March there were reports of approaching US forces, and at 9 P.M. the residents of Frankfurt received the order to evacuate the city. Schwan elected instead to move to the Institute—he suspected that the Americans would arrive there first—and he crossed from the north side of the river, where he lived, to the south side, where the Institute was located, at about 11 P.M. Just a few hours later all of the city's bridges over the Main were blown up by the Germans.

Because Patton's army bypassed the city, it was about 20 March when Frankfurt was finally occupied. Schwan represented the people at the Institute, and he cooperated fully with the US military. Indeed, he was one of the first Germans to receive a pass to cross the temporary bridge constructed across the river (Figure 3). (On the north side of the river was not only his apartment but also the military government of the city, where Schwan went to ask for coal and other supplies for the Institute.)

It was at this point that Schwan became involved in one of the largest transfers of scientific and technical know-how in history. This was the transfer, in the years 1945 through 1948, from Germany to the United States, the Soviet Union, Britain, and France of German scientific and technical information, equipment, and experts.[23]

In August 1944 a British-US collaboration, called the Combined Intelligence Objectives Subcommittee (CIOS), was established to identify and exploit German documents, matériel, and persons that might contribute to shortening the war.[24] CIOS, whose mission was soon extended to include the gathering of information of scientific and industrial value, sent hundreds of investigators to examine sites and interrogate scientists and technicians in liberated Europe and in Germany and Austria. Beginning in May 1945, much of the US effort to gather scientific and technical information in Europe was carried out by the Field Information Agency, Technical (FIAT) of the Office of Military Government for Germany.[25] FIAT undertook an ambitious program to microfilm documents and to publish reviews of the information available.[26]



MILITARY GOVERNMENT OF GERMANY

MILITÄRREGIERUNG - BEFREIUNG
MILITARY GOVERNMENT
EXEMPTION

Datum der Ausstellung
Date Issued 2 APR.

Wird ungültig
Expires

Extended to 30 April 1945

Name
Name DR. HERMANN SCHWAN

Anschrift
Adress 37 Friedrichstrasse

Wohnort
Town Frankfort

Ausweiskarte Klasse
Indentity Card Type Kennkarte

Nr.
No. A 72001

Unterschrift des Inhabers
Signature of Holder Dr. Hermann Schwan

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GRÜNDE, EINZELHEITEN UND AMTLICHE UNTERSCHRIFT: Die vorstehend benannte Person ist, wie unten angegeben, von Beschränkungen betreffend: AUSGANG—REISE—VERBOTENE GEGENSTÄNDE—SPERRBEZIRK befreit. (Nicht zutreffendes ist durchzustreichen.)

REASONS, SPECIFICATIONS AND ENDORSEMENTS. The person named on the reverse hereof is granted exemption, only as specified below, from restrictions respecting; CURFEW—TRAVEL—PROHIBITED ARTICLES—PROHIBITED AREA (delete where applicable).

EINZELHEITEN DER BEFREIUNG:
PARTICULARS OF EXEMTION: Cross Main river freely.

GRÜNDE:
REASONS: Working with U.S. Navy.

Ausstellende Behörde:
Issuing Organisation: Mil. Gov't, Frankfort

Name (Druckschrift)
Name (printed) R. A. VASALLE

Rang
Rank Capt.

Unterschrift
Signature R. A. Vasalle

Stammnr.
Serial No. 0527418

Figure 3. Just ten days after Patton's forces moved into Frankfurt, Schwan received this pass from the US authorities to cross the Main over the hastily constructed temporary bridge.

For more than two years, from the first days of the US occupation, investigators visited the Institute for the Physical Foundations of Medicine and asked Schwan and others about the work there. Of foremost interest was the Institute's relatively minor involvement in the German atomic pile project; the Institute was to have studied the effects of intense radiation. A powerful electron accelerator (a type of cascade generator consisting of three transformers on top of each other) had been designed to accelerate a 10 or 100 milliamp current to three million volts to produce an intense x-ray beam. The accelerator was never completed. The tower that was to house it was destroyed in a small-scale bombing raid (which suggests to Schwan that it was targeted). The transformers were placed in a cave in what became the Soviet Zone of Germany and were later taken to the Soviet Union.

Schwan was questioned about the antiradar covering and his other work at the Institute. He told the first investigators that many of his instruments had been transported about a hundred miles northeast of Frankfurt. Though the site was then just behind the line of Allied advance, Schwan went with two US soldiers in a jeep to locate his equipment. The soldiers recovered his high-frequency equipment, including a variable-frequency generator and two special magnetrons used to drive coaxial lines, but allowed him to keep only his 1-gigahertz equipment. Other investigators who came to the Institute microfilmed a large number of documents and asked for reports. Schwan was asked to write up his own research results, and he contributed six FIAT reports, all published in 1947 and 1948.[27]

Since Rajewsky had been a Nazi Party member, he could not serve as Director of the Institute (see dialogue below), and soon after V-E Day he asked Schwan to be acting director. Schwan, who had already proved his theoretical and experimental abilities, soon showed that he possessed adminstrative abilities as well.[28] In addition to attending to the many needs of the Institute, he was able, within weeks of war's end, to get some of his equipment to work and gather data on the conductivity and dielectric constant of blood in the range 100 to 1000 megahertz.[29]

SCHWAN: *. . . The next comment pertains to loyalty and disloyalty in general. How far should you go with your responsibilities in this regard? Well, I chose to try to transmit information to the outside. I didn't tell you about another experience I had which had a negative effect on me. After the war, Rajewsky approached me and asked me to sign a statement that he was always anti-Nazi, in spite of the fact that he had been a member of the Nazi Party. He wanted me to attest that he saved a number of Jews from persecution, hiding some of them in his house.*

NEBEKER: *Were those statements true?*

SCHWAN: *I didn't know. I was initially weak enough to sign the statement. I had considerable qualms about signing it. A couple of days later I came back to him and said, "Herr Professor, I've written another statement in which I stated that although you knew I was an anti-Nazi, you gave me a job." I believe that was the case indeed. I said, "I shouldn't have signed the other statement. I don't know anything about your hiding Jewish people and so on." He gave me back the original certificate and accepted the weaker, second statement. But I know he considered me disloyal. . . . In retrospect today, I don't know if I would take those two actions again. I'm convinced that nine out of ten people—if not 99 out of 100 people—wouldn't act as I had acted on similar occasions. It's*

> *very, very demanding, of course. While Rajewsky frequently recommended me for all sorts of things like the Rajewsky Prize and other things, he nevertheless felt that I couldn't be trusted. His wife told me later that he admired me, but that he felt that I was not trustworthy. So much about loyalty and one's responsibilities to mankind and one's society.*[30]

In 1946 Schwan was awarded his *Habilitation*, which is a degree beyond the Ph.D. that in Germany qualifies one to teach at a university. His thesis, entitled "The determination of the dielectric properties of semiconductors, especially biological substances in the decimeter wave range," dealt largely with the techniques of measurement and drew on Schwan's improvements in instrumentation for Project Chimney Sweeper. (Some of the materials he investigated for that project were similar to biological materials in that they were highly conductive and with large dielectric constants.) One of the FIAT reports mentioned above was, in fact, this *Habilitationsschrift*.

One of the US investigators was a Navy lieutenant by the name of David Goldman. He had received one of the first Ph.D.s in biophysics in the United States (from Kenneth S. Cole at Columbia University), and had already contributed to the field by analyzing ion conductance across a membrane by means of what is today called Goldman theory.[31] Goldman visited the Institute several times and talked at length with Schwan about his work on the electromagnetic properties of biological materials. It may have been Goldman's initiative that led to Schwan's emigration to the United States.

In addition to equipment and information, US authorities—like Soviet, British, and French authorities—sought German and Austrian scientists and engineers. Project Overcast, which from the summer of 1945 to the summer of 1946 brought to the United States some 160 specialists in rockets and jet aircraft, evolved into a broader program, called Project Paperclip, to attract civilian as well as military experts.[32] In Schwan's words:

> One day a lieutenant came to me and said, "Here is a contract. Think it over. I won't put any pressure on you. I'll come back after a week, and you can tell me if you'd like to accept it or not." The contract specified that I would be transported for half a year to the United States and back. Quarters in the United States and aboard ship would be that of a junior officer. I would be on leave from the university. My salary would continue to be paid in Germany at double the rate. In the United States I would get free lodging and free food in the officers' canteen, and a per diem of six dollars a day. That was almost too good to believe, and so I accepted.[33]

Schwan was eager to learn about work done in the United States and elsewhere: "Germany had been isolated scientifically since the Nazis came to power. Here I had a chance to catch up in knowledge again, and hopefully do some good work."[34] He was assigned to the Aeromedical Equipment Laboratory at the Navy base in Philadelphia, and he arrived in early September 1947. One of his first tasks was to study the noise spectrum of jet engines (from ultrasonic through audible to very low frequency vibrations) and to determine the bioeffects of such vibrations (for which purpose he obtained appropriate sonic equipment). An immediate application of this work was to design "ear defenders" to protect human hearing against engine noise.

A Research Program in the United States

Schwan expected to work only six months in the United States and to work only on assigned projects. It therefore surprised him when, shortly after arriving at the Aeromedical Equipment Laboratory, he was invited to submit a proposal for research he would like to do. He proposed an ambitious, long-term investigation of the electrical properties of biological materials, using state-of-the-art instrumentation to extend the investigation to frequencies higher and lower than those studied earlier. The Navy approved his proposal, and in 1948 Schwan began the research program that was to occupy him for most of the next four decades.

This was a new, fundamental approach to biophysics. Almost all previous work had been directed toward particular questions raised by physicians or biologists, such as what is the electrical behavior of a neuron or what are the effects of x-rays. Schwan proposed focusing on the biological materials themselves, determining the full range of their physical properties, including how energy in various forms interacts with the biological materials. The resulting understanding of the electrical properties of membranes, cells, and tissues could later, he believed, serve as a basis for solving problems encountered in research, diagnosis, and treatment. As Schwan put it, "What a physicist does, if he becomes interested in some material, is to measure its properties without any question about how he can apply the information. As he measures the properties, he asks himself, "Why are the properties as observed?" To this he adds the question, "How does energy interact with the material?" If he knows why the properties are as observed, he can explain how energies interact with it. Finally, out of this comes intelligently undertaken application."[35]

What made Schwan's proposal especially attractive was his mastery of the principles of the instrumentation that promised to yield new knowledge. One of his first accomplishments was building a bridge circuit for the accurate determination of impedance of highly lossy substances at low frequency.[36] (See Figure 4.) The reactance of most biological materials, such as intact tissues or cell suspensions, was impossible to measure at low frequencies with existing instruments because it is much smaller than the resistance. One needed to build an instrument of high resolution and—the greatest challenge—to calibrate the small reactances of that instrument in the frequency range of interest. Schwan located a manufacturer (Leeds and Northrup) willing to build a variable conductance box to his specifications, and he designed a procedure for achieving the high-precision calibration over the entire range of the bridge circuit.

The building, calibrating, and testing of the instrument took more than a year, but its use quickly yielded important results. Schwan began using it to measure the capacitance of muscle tissue in the frequency range 10 hertz to 100 kilohertz. The measurements at higher frequencies confirmed some earlier results, while those at lower frequencies, which no one earlier had succeeded in taking, revealed an unexpected capacitative dispersion (that is, a step-like change in capacitance).[37] Schwan was able to account for this capacitative dispersion as the result of a hitherto unsuspected mechanism of dielectric relaxation in muscle tissue.

Figure 4. This photograph, from about 1955, shows Schwan with an impedance bridge.

In his investigation of the electrical properties of biological materials, Schwan focused on two fundamental properties, conductivity and permittivity. (Conductivity is defined to be the ratio of induced current to applied field and equals the reciprocal of the resistance per unit volume; permittivity is related in a simple way both to capacitance and to the dielectric constant, which is the ratio of the strength of an electric field in vacuum to that in the material for the same distribution of charge.) A knowledge of these two properties allows one to calculate many other properties of the material. By Mie theory, for example, one could calculate how electromagnetic energy is in part scattered by and in part propagated through a living organism. Schwan had begun this work in Frankfurt; now vastly superior instruments were available.

The first step in Schwan's program was the accurate determination of the electric properties of biological materials. Before the war, researchers had measured the dielectric constant of biological materials for frequencies from 1000 hertz to 10 megahertz. Schwan, in a study of muscle tissue, extended the range from a few hertz to 1 gigahertz—almost nine decades as compared with the four decades achieved earlier.[38] (Additional data, communicated to Schwan by Julia F. Herrick and others at the Mayo Clinic, extended the range to 8.5 gigahertz.) Measurement at the low frequencies required the high-resolution bridge mentioned above. Measurement at the high frequencies was based on controlled propagation of electromagnetic waves and used transmission line and waveguide components. The resulting graph (Figure 5) shows that the dielectric constant changes in distinct stages, called dispersions, which were labeled α, β, and γ.

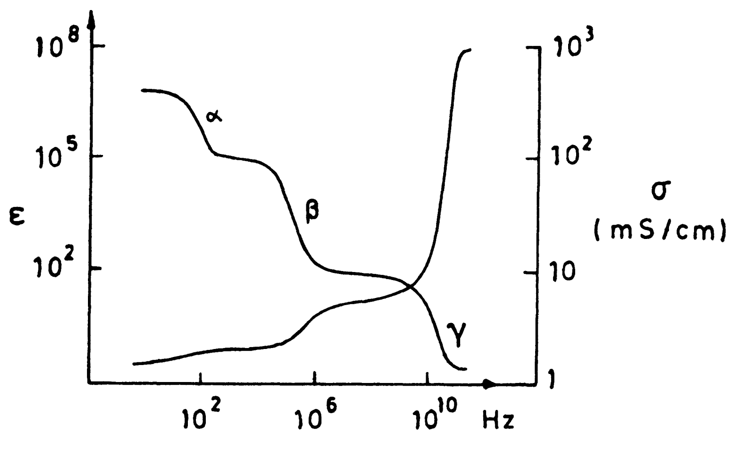

Figure 5. This graph of the dielectric constant of muscle tissue as a function of frequency shows the three dispersions, labeled α, β, and γ.

The second step of Schwan's program was to explain the measurements in terms of the atomic, molecular, and macromolecular structures of the material, that is, to give biophysical explanations of the properties. Two pioneering biophysicists, Kenneth Cole and Hugo Fricke, had earlier discovered and explained the β dispersion as resulting from electrical charging of cell membranes. Schwan identified the γ dispersion as that of water and found that the α dispersion was the result of a variety of processes, including the slow charging of intracellular membranes and the polarization of the counter-ion cloud that surrounds the surface of charged membranes.[39] He used a variety of methods to elucidate these mechanisms, especially bulk measurements on different preparations of tissues, cells, and cell components.

The decision to investigate the electrical properties of cell suspensions and tissues at low frequencies was in part motivated by the work of Fricke and Cole at higher frequencies. Both had postulated that the cell membrane properties displayed "constant phase angle" behavior similar to that observed at the interface between a metal electrode and electrolyte. It is characterized by a frequency dependence of both resistance and capacitance such that the electrical phase angle of the interface does not change with frequency. But I thought that the behavior at higher frequencies could be explained by different postulates. Variability in cell size and shape and its interior components could simulate observed deviations from single time constant behavior. Such behavior is predicted by an equivalent circuit which puts the membrane capacitance in series with internal and extracellular fluid conductivities. Such single time constant behavior could be anticipated only for uniform cell size and spherical shape and no internal content of organelles and proteins. I also knew that red cell suspensions approximate the single time constant behavior much better than tissues since they better fulfill at least some of the necessary assumptions. It became apparent to me that extension to lower frequencies would more clearly show if membranes display the constant phase angle law or not. However, it also became clear that this would require equipment of high resolution, able to detect with accuracy the small capacitive current component which reflects the membrane capacity. Conductance determinations alone would be inconclusive since the low frequency conductance is dominated by the strong contribution of the extracellular fluids. The question how the membrane behaves electrically was to emerge as a major topic of biophysical interest. To answer the question raised by the constant phase angle model was therefore important. Today, this constant phase angle concept is no longer used, and the conductive properties of the membrane are linked to its channels as first formulated by the famous Hodgkin-Huxley model.[40]

In thus relating electrical properties to biological structure, Schwan was contributing to a research tradition going back to the nineteenth century. An outstanding example was work done about 1910 by the German physiologist R. Höber, who showed by measurements of conductivity of red blood cells at different frequencies that such a cell consisted of an electrically conducting interior surrounded by a membrane of high resistance.[41] At that time the physical structure of a living cell was largely unknown, and Höber's argument was hotly contested but soon confirmed by other sorts of investigation.

It happened that Höber had left Germany in 1936—his wife was Jewish—and in 1948 was a research professor at the University of Pennsylvania, situated not more than a few miles from the Aeromedical Equipment Laboratory. He knew of Schwan's 1948 paper, and when he learned that Schwan was in town he invited him to give a seminar for the Philadelphia Physiological Society and the Department of Physiology of the University of Pennsylvania's medical school. This led first to Schwan's serving as consultant to several departments at the School of Medicine and then, in 1950, to Schwan's appointment as assistant professor in the Department of Physical Medicine.

Schwan welcomed the move to the university for several reasons. A number of people there were interested in the sort of work he was doing. Besides Höber, there was the cardiologist Calvin Kay, who was working to improve electrocardiographic techniques, and there was an electromedical laboratory at the Moore School of Electrical Engineering.[42] Schwan also valued an academic setting, with the opportunity to teach and to direct the research of graduate students.

Because the Navy permitted him to take the equipment he had assembled and built at the Aeromedical Equipment Laboratory, Schwan quickly established a laboratory at the university. It was not long before he had two Ph.D. students: Ed Carstensen, who was interested in the acoustic properties of biological materials, and Kam Li, who worked on microwave properties. In 1952 Schwan was named associate professor in the School of Medicine and was also appointed head of the Electromedical Group (renamed the Electromedical Division in 1954) at the University of Pennsylvania's Moore School of Electrical Engineering.

Schwan was familiar with studies of ultrasound from his days at the Frankfurt Institute, especially the work of Justus Lehmann. He believed that the acoustic properties of biological materials could be profitably investigated with an approach similar to the one he was already taking to investigate electromagnetic properties: investigation of frequency dependence and the step-by-step identification of which tissue and cellular components are responsible for which phenomena. Moreover, there were striking similarities in the mathematical descriptions and some similarities in the required instrumentation. Thus he was happy to add bioacoustics to his research program to accommodate the graduate student Ed Carstensen, who came to the University of Pennsylvania with prior training and a strong interest in bioacoustics.

Schwan and Carstensen studied the acoustic properties of blood and discovered the mechanism of ultrasonic absorption. They found that, unlike the absorption of electromagnetic waves of low and radio frequencies, where the cell membranes are of paramount importance, ultrasonic absorption occurs mainly by the proteins within the cells. Some years later Schwan collaborated with another graduate student, Helmuth Pauly, on acoustic properties of tissues. The caliber of this work is indicated by the selection of four of Schwan's papers for inclusion in the *Benchmark Papers in Acoustics* volume on ultrasonic biophysics.[43]

The third step of Schwan's research program—after measuring physical properties and learning what structures and mechanisms account for them—was to use this understanding in applications. As Schwan put it, "Don't just observe properties. You must understand what's going on, and then you gain predictive power."[44] Schwan and his coworkers were involved in many areas of application. Most significant were his contributions to evaluating health hazards of electric fields, and this is dealt with at some length below. Also very significant were extensive studies of the linear and nonlinear properties of bioelectrodes.

Many of the instruments used in biomedical research and in medical diagnosis include bioelectrodes, as do devices (such as cardiac defibrillators and pacemakers) used in medical treatment. Hence, understanding electrode behavior, especially electrode artifacts and electrode polarization (resulting from the electric potential generated at the interface of the electrode and the tissue), is of widespread practical importance. Schwan and his collaborators studied electrode behavior over a wide frequency range and modeled the observed frequency dependence, and they discovered at what current levels nonlinear effects become important. Going beyond understanding the phenomena, they developed techniques for eliminating, minimizing, or compensating for the effects of electrode polarization. This work has been widely cited, and in 1992 the *Annals of Biomedical Engineering* published a special issue on electrodes in honor of Schwan.[45]

In 1948, through friends made at the International House of the University of Pennsylvania, he became acquainted with Anne Marie Del Borello. They were married the following summer, and the family grew over the next twelve years with the arrival of four daughters and one son. In 1952 Schwan became a naturalized citizen of the United States.

Through the 1950s and the following three decades, Schwan's research program flourished. Schwan and his coworkers continued work in the areas described above. They gathered more data on the electrical properties of tissues, cells, and cellular organelles. They elucidated the mechanisms responsible for certain properties, notably counter-ion relaxation (caused by the movement of ions along a cell or particle surface) and protein bound water relaxation (according to which water molecules at the surface of protein molecules have a behavior intermediate between frozen and liquid water).[46]

In 1957 Schwan published a 62-page review article entitled "Electrical properties of tissue and cell suspensions."[47] This article provided for the first time a comprehensive account of the field and soon became frequently and widely cited. Another extremely influential publication appeared in 1962, in which Schwan and coworkers showed that the α dispersion (mentioned above) occurred in nonbiological colloidal systems.[48]

Schwan conducted extensive investigations on the propagation of electromagnetic energy into tissues and into the human organism as a whole. He and coworkers determined reflection and absorption coefficients and how energy passed through complex tissue arrangements. They built a novel unechoic facility for these measurements and made use of mannequins filled with fluids simulating tissues.[49] In other work, Schwan, H. N. Kritikos, and K. R. Foster studied in detail temperature increases in different tissues (including the possibility that microwaves might generate localized "hot spots") and the effects on the human thermoregulatory system.[50] Some of this work involved lengthy calculations, and Schwan made much use of computers. It was by calculation that Schwan and coworkers discovered a resonance effect in the absorption of microwaves; they later confirmed the effect experimentally.[51]

In almost every area of his work, Schwan contributed also to the practical application of the knowledge or techniques. Besides study of the health effects of microwaves (discussed below) and the already mentioned work on bioelectrodes, there was important work on diathermy (the generation of heat in tissues for medical purposes), on impedance plethysmography (which allows determination of blood volume changes in tissues and hence is used to diagnose venous occlusions), and on electrophoresis (a research and diagnostic technique based on the different mobilities of suspended particles in electric fields). Schwan's work on suspensions of red blood cells led to his development with R. H. Okada of a hematocrit (which electronically measures the number of cells in a blood sample), that was successfully built and marketed.

Schwan and coworkers pursued applications of their investigations in bioacoustics, just as they did in their study of ultrasonic diathermy, where they compared its effectiveness to that of radio-frequency and microwave diathermy. One of the most important applications of bioacoustics to date, echocardiography (a procedure for recording cardiac structure and function using ultrasound), was developed at Schwan's laboratory. In 1957 John Reid, who had already gained recognition for his pioneering work on ultrasonic visualization with John J. Wild in Minneapolis, entered the Ph.D. program at the University of Pennsylvania. Schwan secured NIH support for and supervised Reid's research, which was carried out in cooperation with cardiologists Calvin Kay and Claude Joyner of the Penn Department of Medicine.

Establishing Biomedical Engineering as a Discipline

As mentioned at the beginning of this article, biophysical research long predates World War II. But work was concentrated in two areas—electrophysiology (especially the study of excitability and contractibility and the study of electrical conductance of blood and tissues) and biological effects of ionizing radiation. There were few biophysical institutions. The Kaiser Wilhelm Institute at Frankfurt, the Johnson Foundation for Medical Physics at the University of Pennsylvania, and the Biophysics Department of the Cleveland Clinic have already been mentioned. There were a few others, including the laboratory established by Hugo Fricke at Cold Spring Harbor on Long Island, Kenneth Cole's biophysical laboratory at Columbia University, and the Siemens research laboratory at Erlangen headed by J. Paetzold. It may be that the first biophysical societies were two established during the war: the one formed by Rajewsky discussed above, and one organized in Holland at about the same time by H. C. Burger, head of a medical physics laboratory in Utrecht.[52]

During and after the war, biophysics and biomedical engineering grew rapidly, both in numbers of researchers and in range of studies. It is noteworthy that both Schrödinger's *What is Life?* (which showed how physics could elucidate biology) and the first of Otto Glasser's texts on medical physics appeared during World War II.[53] In the postwar decades there slowly emerged, in a complicated and sometimes contentious way, an institutional and organizational base for this work. From the mid-1950s on, Schwan gave a substantial portion of his time to building that base.

Schwan's great organizational achievement was the establishment of biomedical engineering at the University of Pennsylvania. Starting from a single assistant professorship (the financial support for which vanished after two years), Schwan gradually built a biomedical engineering research and teaching program that by the time of his retirement in 1983 comprised 12 primary faculty positions, an undergraduate program with about 150 enrolled, and a graduate program with about 60 enrolled.

Essential to this achievement was Schwan's success in obtaining outside funding. In 1952 he won support from the Office of Naval Research, which continued until 1978. Also in 1952 the National Institutes of Health (NIH) and the Air Force approved grant requests. Schwan's NIH grant, under the title "Electrical and Acoustic Properties of Biological Materials," was approved and extended for a total of 25 years. The Air Force support continued until 1964.[54]

In 1960 Schwan won university approval of an independent Ph.D. program in biomedical engineering and shortly thereafter received a substantial training grant from NIH. This grant, which continued for 20 years, made it possible to attract excellent graduate students and was vital to the establishment of the Biomedical Electronic Engineering Department. Schwan was chairman until 1973, which was the year the department changed its name to the Bioengineering Department and added an undergraduate program. The University increased its support of biomedical engineering as the program grew.

This department seems to have been the first department in biomedical engineering at any university, and it served as a model for programs elsewhere. Before 1970, Ph.D. programs had begun at a few other schools, including Purdue University and the University of Washington.[55] In the late 1950s Schwan met often with James Dow and others at Drexel University, also in Philadelphia. They established a master's program in biomedical engineering, which was primarily directed toward medical doctors, while the Penn doctoral program attracted mainly engineers.[56]

Schwan also played a major role in the establishment of professional organizations. Here the situation was, and remains, especially complicated, mainly because biophysics and biomedical engineering encompass a great variety of work carried out by people with very different backgrounds.

Not long after the war, the American Institute of Electrical Engineers (AIEE) formed a Committee on Electrical Techniques in Medicine and Biology, which organized its first annual conference in 1948. In 1952 the Institute of Radio Engineers (IRE) formed a Professional Group on Medical Electronics.[57] In 1953 the AIEE Committee, the IRE Professional Group, and representatives of the Instrument Society of America formed a Joint Committee for Engineering in Medicine and Biology (JCEMB). The mission of JCEMB was to organize annual conferences, and these have continued to the present.

Beginning in the early 1950s Schwan was a member of both the AIEE Committee and the IRE Professional Group, and also served on JCEMB. In 1959 and again in 1965 the annual conference was held in Philadelphia, and he acted both times as conference chair. Over the years attendance at the conferences has increased from less than a hundred in the early 1950s to nearly 2000 in the late 1980s. In January 1963 AIEE and IRE merged to form the Institute of Electrical and Electronics Engineers (IEEE). The members of the AIEE and IRE technical committees for biomedical engineering were in fact a contributing force to the merger, as almost all of them favored it and had been collaborating with their counterparts in the other society for years. Schwan was instrumental in melding the two committees into the IEEE Group on Engineering in Biology and Medicine (later the IEEE Engineering in Medicine and Biology Society).

In the mid-1950s Schwan and others considered how a biophysical society might be established. Some favored affiliation, either with the American Institute of Physics or the Federation of Biological Societies, while others thought an independent society preferable. The latter view prevailed, and in 1956 a committee, consisting of K. S. Cole, E. Pollard, Otto Schmitt, and Samuel Talbot, set to work to determine the organizational structure of what was to be called the Biophysical Society. R. Stacy was selected as conference chair and Schwan as publicity chair for the first annual conference. Schwan wrote, "I mailed more than 1000 letters, asking early recipients to let me know about others interested in a biophysical society. The response was overwhelmingly favorable."[58] Seven hundred attended the first conference, held in Columbus, Ohio, in 1957 (see Figure 6). Schwan had done so well at publicity that he was asked to continue that work, which he did for the next four years. The society grew, but assumed a biological orientation as biochemists and physiologists entered in large numbers.

The National Institutes of Health played a large role in establishing the new field.[59] Its support of the research and training at the University of Pennsylvania has already been mentioned. Schwan in large measure repaid this debt by serving for many years as member, and sometimes chairman, of various NIH study sections and councils.

NATIONAL BIOPHYSICS CONFERENCE

A steering committee of some fifty scientists, representing various aspects of biophysical research in this country, has organized a national biophysics conference to take place in Columbus, Ohio, from March 4 - 6, 1957. The conference will encompass studies which employ the approach of physics in biological measurement and theory, at levels of organization from molecules and cells to complex systems and psychophysics.

The program is expected to include twelve invited papers related to different biophysical fields and a large number of contributed papers. Scientists with biophysical interests may write to Dr. Herman P. Schwan for further details and information on presenting contributed papers.

Samuel A. Talbot, Chairman
Program Committee
Department of Medicine
Johns Hopkins Hospital
Baltimore 5, Maryland

Herman P. Schwan, Chairman
Publicity Committee
School of Medicine
University of Pennsylvania
Philadelphia 4, Pennsylvania

Figure 6. The 1956 announcement of the March 1957 meeting that led to the founding of the Biophysical Society.

[In the first years at the University of Pennsylvania] people didn't understand what I was doing. Cole and Fricke, yes. I met Cole and Fricke. But most of the physiologists didn't even understand Cole. I remember very well when I came to the University of Pennsylvania, that the physiologists often said to me, "Herman, you seem to understand that work of Cole. Can you explain it to us? We have no idea if that's important or not." I tried my best, of course, to do so. The physiologists and early biophysicists just were not trained enough to understand the relevance of this work. It took quite some time. I think an interest in such biophysical investigation started to develop very slowly. Interest increased after two British physiologists, [A. L. Hodgkin and A. F.] Huxley, [received] the Nobel Prize for their work on the electric properties of nerve axons. Then interest in that sort of work grew fairly fast. Cole told me that he brought my work to the attention of G. Falk and P. Fatt. My first presentation was in 1950 at the American Physiological Society meeting in Columbus, Ohio. Then I tried to publish it in physiological journals. There was no biophysical journal at that time. I was turned down twice, by two journals. I was very discouraged. And then I submitted to a German journal where it was published in '55—five years later than Columbus meeting. By '56 I did have a reputation in the field, and I was asked to write a review article on electric properties of biological materials. I wrote a long review article which was published in '57, where I reported for the first time in English about all that sort of work. There was only that German publication before and the abstract, which doesn't say much. This review article was a great success. I think it has been quoted in the Citation Index almost a thousand times. It's still being quoted since it was the first really comprehensive treatment of electrical properties of biological materials.[60]

The interdisciplinary nature of biomedical engineering made it difficult to find or to establish an organizational home for its practitioners. In the mid-1960s Schwan worked hard to bring about a change of IEEE membership rules, so that M.D.s and Ph.D.s in the biological sciences (who were not engineers) could be full members of the IEEE Group on Engineering in Biology and Medicine. What Schwan proposed was that technical groups become semiautonomous societies able to establish their own membership requirements. When this was not approved by the IEEE Board of Directors (though the designation 'group' was soon changed to 'society'), Schwan worked with three others—Jack Brown, John Jacobs, and Larry Stark—to found the Biomedical Engineering Society in 1968.[61] Schwan and others hoped that this society would bring together those trained in engineering and those trained in biology and medicine. The society, however, soon became dominated by physiologists, disappointing Schwan and never having much adverse effect on membership in the IEEE Group on Engineering in Biology and Medicine.

Schwan has been active in several other societies. He helped establish the International Federation of Medical Electronics in 1957 and was a founding member of the Bioelectromagnetics Society, which was formed in the mid-1970s. He was a member of the International

Institute of Medical Electronics and Biological Engineering and served two years on its advisory board in the late 1960s.

After his 1947 move to the United States, Schwan maintained close ties with German researchers mainly through frequent trips to Germany. In 1962 he was a visiting professor at the University of Frankfurt, and in 1986/87 at the University of Würzburg. In 1962 he received the lifetime appointment of foreign scientific member of the Max Planck Institute for Biophysics.

Although Germany was a world leader in biophysics before World War II, in the postwar period biophysics and, especially, biomedical engineering developed much more rapidly in the United States. Schwan attributes this principally to three factors: (1) the existence of many private as well as public universities fosters independent ventures, (2) the separation between undergraduate and graduate education at American universities makes it easier for a graduate program to be highly selective and to adopt an interdisciplinary position (most biomedical engineering programs, Schwan points out, began as research laboratories that added a doctoral program, and in some cases later an undergraduate program), and (3) there are many sources of outside funding, notably the National Institutes of Health.[62] There are, of course, many other reasons for American leadership in biophysics and biomedical engineering, one of which is the emigration to the United States of scientists trained in Germany, such as Max Delbrück, R. Höber, Justus Lehmann, Schwan, and Georg von Békésy.

Safety Standards for Microwaves

During World War II some servicemen expressed concern that the microwave radiation produced by radar transmitters might cause health problems. Studies at the Naval Research Laboratory and other military laboratories failed to reveal any adverse effects. In the immediate postwar years, as microwave oscillators of greater and greater power became available, more people expressed concern. In 1953 the US Navy convened a meeting on microwave health hazards. The attendees—including Kenneth Cole, David Goldman, James Hardy, and Schwan—arrived at 100 mW/cm^2 as the dividing line between safe and hazardous exposure. Because there was no evidence that harmful effects occurred except through heating, the principal consideration was whether the human body could readily dissipate the heat generated by the microwaves. After the meeting, Schwan recalculated what heat the body would absorb and how much could readily be dissipated. He decided that 100 mW/cm^2 might not be safe and proposed instead a standard of 10 mW/cm^2.[63] (Schwan thought that setting a standard that was anything but a power of 10 would give an improper impression of accurate knowledge of what the dividing line ought to be.)[64] The Navy quickly adopted Schwan's proposal.

In 1955 Julia Herrick of the Mayo Clinic organized what may have been the first scientific conference on microwave bioeffects.[65] Among the fourteen papers presented was one by Schwan and Kam Li that argued for a 10 mW/cm^2 standard.[66] This paper was published the following year, as was another by the same authors entitled "Hazards due to total body irradiation by radar."[67] Over the following decades the number of articles specifically on the health hazards of electromagnetic radiation steadily increased, and Schwan has been a prolific contributor to this literature.[68]

In 1959 the American Standards Association, now the American National Standards Institute (ANSI), agreed to establish a committee, which would be jointly sponsored by AIEE and the Navy's Bureau of Ships, for the purpose of setting a health standard for microwave exposure.[69] Schwan was selected as chairman of the committee, which was designated C95, and at its first meeting in February 1960 he set up six subcommittees, designated C95.I through C95.VI, each investigating a particular issue. Things moved extremely slowly, mainly because most committee members seemed to be too busy to give much time to the effort, but also because many committee members were unwilling to make recommendations on the basis of available evidence. Schwan repeatedly emphasized that the committee's task was not to undertake research, but to decide on the basis of what was already known.

Particularly dilatory was Subcommittee IV, charged with setting a safety level for human exposure to microwaves. After two years, during which time the subcommittee accomplished almost nothing, Schwan reconstituted C95.IV and assumed the chairmanship himself. The evidence available to the subcommittee included (1) physiological knowledge about metabolic rates and tolerances to heat, (2) work on mode of propagation of electromagnetic radiation in biological materials and on dosimetry of energies absorbed, (3) diathermy experience (which involved microwave radiation at levels far above suggested standards), and (4) the literature specifically on the possible health hazards of microwaves.[70] C95.IV recommended the standard of 10 mW/cm^2, and this was approved by the whole committee in November 1966 as ANSI Standard C95.1-1966.

This standard aroused some dissension within the committee and some controversy outside. There seemed to be, at that time, more concern that the standard was too strict than that it was too lax.[71] Some critics contended that Schwan had had too much influence in the setting of the standard. Because of this criticism (and also because he found himself doing too much committee work, especially for IEEE and NIH), Schwan decided in 1965 to resign the chairmanship of C95. Thus, the periodic review and modification of the standard (required by ANSI rules) would be done entirely by others. Schwan felt vindicated when the first review, completed in 1974, simply confirmed the earlier standard.[72]

In 1977 a widespread and intense public interest in possible hazards of microwave radiation appeared rather suddenly. Defective television sets and leaking microwave ovens had attracted considerable attention beginning in the late 1960s, and in February 1976 the State Department made public much of its information about the microwave bombardment of the US Embassy in Moscow. (In much of the period from the early 1950s into the 1970s, the Soviets directed low-intensity microwave radiation at the Embassy building.) Probably most important in arousing public interest were the efforts of the science writer Paul Brodeur.[73] He expanded two articles that appeared in *New Yorker* (December 1976) into a book, published in 1977 and entitled *The Zapping of America: Microwaves, Their Deadly Risk, and the Cover-Up*.[74]

Schwan was drawn into the public debate. He had already given many hours of testimony before governmental bodies: the Senate Committee on Commerce in 1967 and 1968, the Congressional Committee on Science and Astronautics in 1973, and the New York State Public Service Commission from 1976 to 1978.[75] Schwan had always argued that additional research was called for, especially to determine if there were genetic or cumulative effects of microwave radiation.[76] Accordingly, he thought that safety standards would gradually change to reflect increased understanding of the effects of microwaves. Yet Schwan repeatedly found himself in the position of defending the 10 mW/cm^2 standard against those who believed the limit should be set much lower.

Some critics have charged that Schwan was unaware of Soviet research indicating "weak effects" of microwaves. In fact, Schwan met on many occasions with the leading Russian researcher Z. V. Gordon and discussed her work in detail. Other critics have claimed that Schwan was considering only thermal effects of microwaves. This too is mistaken. A principal point of contention at the Frankfurt Institute in the late 1930s was the reality of nonthermal effects.[77] Some argued, erroneously as it turned out, that the pearl chain effect, which was undoubtedly a nonthermal effect, occurred at weak fields. There were other reports of nonthermal effects that were unfounded. As a result of this experience and his understanding of the relevant biophysics, Schwan was thereafter quite skeptical of alleged nonthermal effects at weak fields.[78]

Schwan readily acknowledges the difficulties of setting safety standards for electromagnetic radiation and for electric and magnetic fields: The range of possible effects is large, deciding how to measure exposure is problematic (biological effect may be highly dependent upon what biological structures are exposed, upon frequency, upon whether the fields are intermittent, or upon how the fields are modulated), epidemiological evidence is usually ambiguous, and cumulative and long-term effects are especially difficult to determine. These questions are very much open, and the amount of research aimed at answering them has continued to increase (costing today about $25 million annually).[79]

A Diverse Career

Throughout his career, research has been the center of Schwan's activities. He has published more than 250 papers in journals of engineering, medicine, biology, and physics. In recognition of his research contributions, he has received numerous awards, including the Boris Rajewsky Prize for Biophysics, the Humboldt Prize of the Humboldt Foundation, and the W. J. Morlock Award of the IEEE. He was the first recipient of the d'Arsonval Medal of the Bioelectromagnetics Society. In 1982 the journal *Bioelec-tromagnetics* published a festschrift in his honor, and in 1986 the National Council on Radiation Protection and Measurements selected him as the Tenth Lauriston S. Taylor Lecturer. He has been named Member of the National Academy of Engineering, Foreign Scientific Member of the Max Planck Society, and Honorary Member of the German Biophysical Society. In 1983 he received the IEEE Edison Medal "for a career of creative endeavor by which engineering, physics, biology, and medicine have been amalgamated into a coherent field of electromagnetic bioengineering."

[Vladimir Zworykin] became very much interested in telemetry. . . . In the RCA laboratories he developed the technique of a pill that serves as a monitor. A person would swallow it, and it would go down through the esophagus and stomach and so on. You then could observe all sorts of very useful information, including pH and temperature. The "pill" could send them out to the receivers while travelling through the body.

. . . When Zworykin was vice president of RCA, he was the prime mover in the development of the first American electron microscope.

. . . We met fairly frequently. We had quite a discussion about certain regulations and the constitution of the International Federation [of Medical Electronics], which were adopted in due time. There was always the problem of proper representation of countries. I was primarily responsible for the International Federation adopting what I called the Logarithmic Rule. Not every country has the same vote. I suggested a logarithmic rule. Small countries, say up to 10 members, had one vote. Countries with up to ten times more members had two votes, and countries with ten times more, three votes. That worked out satisfactorily.

. . . His mind was always active with regard to all sorts of things. . . . For example, he thought of a little pocket calculator that you can carry with you, which has your total medical information on it. He envisioned a phone hook-up, sort of like a modem-like hook-up, where whenever you have a symptom, you could get properly hooked up to a specialist . . . they listen to your heartbeat and other relevant things.[80]

As the preceding account makes clear, Schwan has had many other activities. As a teacher he helped establish graduate and undergraduate programs in biomedical engineering, introduced many new courses, and supervised about twenty Ph.D. theses and about ten Master's theses (see Figure 7). According to Schwan, about half of his Ph.D. students became head of bioengineering departments or programs that they helped establish.[81] He received the American Society of Engineering Education Award in 1983, and in 1986 the University of Pennsylvania presented him with an honorary doctorate. He has been a peripatetic lecturer, giving almost 400 conference presentations and invited lectures in the period since the early 1950s. And he has served his profession in other ways: as advisor to government (to NIH and NSF, to the Department of Health, Education, and Welfare, to the Navy and the Army, to the Veterans Administration), as consultant to industry (to Bell Laboratories, General Electric, and many other companies), as organizer of conferences and conference sessions, and as journal editor and reviewer.

In recent years Schwan has written extensively on the history of biomedical engineering: on the gradual expansion of research topics and on the development of particular research lines,[82] on the evolution of health standards for radio frequency and microwave radiation,[83] and especially on institutional history.[84]

Figure 7. This 1990 photo shows Schwan with eleven of his former students. Those pictured are, from upper left to lower right, Dov Jaron, Richard Beard, Willis Tompkins, Dennis Silage, Lee L. Huntsman, Robert E. Yantorno, John Li, John M. Reid, Banu Onaral, Schwan, Zenka Delalic, and Maryam Moussavi. Among Schwan's other former students are Edwin L. Carstensen, Clifford Ferris, and David B. Geselowitz.

Schwan has himself lived through most of the history of his discipline. In late 1937, when he began work at the Kaiser Wilhelm Institute for the Physical Foundations of Medicine, there were probably only a few dozen people doing what today would be called biophysics or biomedical engineering, and most of the research concerned electrophysiology or the effects of ionizing radiation. Today there are tens of thousands of biophysicists and biomedical engineers, and their research spans an enormous range. There are a dozen or so professional organizations for these scientists and engineers, and several dozen universities have programs leading to advanced degrees in biophysics and biomedical engineering.

Herman Schwan contributed to this growth in several ways. He pioneered new research areas: dielectric properties of biological materials—from molecules to whole organisms—at high and low frequencies, the propagation of electromagnetic energy in biological materials, and the ultrasonic properties of biological materials. He achieved both accurate measurement of properties and explanation of many of the observed values. Furthermore, he applied the resulting biophysical understanding to practical problems: understanding electrode effects, developing new diagnostic and therapeutic instruments, and helping to set microwave safety standards. And he helped build the institutional basis—both at the University of Pennsylvania and in several thriving professional organizations—for the new discipline.

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[1] L. A. Geddes, "Clinical engineering and the background of interdisciplinary engineering," *Medical Instrumentation*, vol. 9, 1975, pp. 239–249.

[2] Kenneth S. Cole, *Membranes, Ions and Impulses: A Chapter of Classical Biophysics* (Berkeley: University of California Press), pp. 1, 67–68.

[3] W. E. Röntgen, *Eine neue Art von Strahlen* (Würzburg, 1895); H. S. Gasser and J. A. Erlanger, "A study of the action currents of nerve with the cathode ray oscillograph"; *American Journal of Physiology*, vol. 62, 1922, pp. 496–524; E. D. Adrian and D. W. Bronk, "The discharge of impulses in motor nerve fibres. Part I. Impulses in single fibres of the phrenic nerve," *Journal of Physiology*, vol. 66, 1928, pp. 81–101; L. Marton, "Electron microscopy of biological objects," *Nature*, vol. 133, 1934, p. 911.

[4] An overview is provided by L. A. Geddes in "The beginnings of electromedicine," *IEEE Engineering in Medicine and Biology Magazine*, December 1984, pp. 8–23.

[5] Margaret Rowbottom and Charles Susskind, *Electricity and Medicine: History of their Interaction* (San Francisco: San Francisco Press, 1984), p. 246.

[6] H. P. Schwan, "Early history of bioelectromagnetics," *Bioelectromagnetics Journal*, vol. 13, 1992, pp. 453–467.

[7] H. P. Schwan, "Entwicklung der Biophysik und das Frankfurter Institut für Biophysik," draft manuscript of an article to appear in the proceedings of a conference held at Schlema, Germany, September 1991.

[8] The information about Herman Schwan contained in this article comes mainly from the following sources: (1) an extensive oral-history interview of Schwan conducted by the author 26 June and 1 July 1992 (from which an edited transcript has been prepared); (2) personal communications, both by mail and telephone, with Schwan; (3) Schwan's published writings; (4) other published writings; and (5) the Project Paperclip file on Schwan in the National Archives. (The transcript of the extensive interview, letters from Schwan, a full list of Schwan's publications, and copies of many documents from the Project Paperclip file on Schwan are available at the IEEE Center for the History of Electrical Engineering.)

[9] Wilhelm Schwan, *Elementare Geometrie* (Leipzig: Akademische Verlagsgesellschaft, 1929); Gerhard Hessenberg, *Grundlager der Geometrie*, edited by Wilhelm Schwan (Berlin: Walter de Gruyter, 1930).

[10] The political impotence of intellectuals was a striking feature of German society from the late nineteenth century through World War II and became especially marked in the Third Reich (see Chapter 20 of Richard Grunberger's *A Social History of the Third Reich* (New York: Penguin Books, 1974).

[11] Interview 1992, p. 8.

[12] Interview 1992, p. 13.

[13] Interview 1992, p. 15.

[14] Interview 1992, pp. 17–18.

[15] Interview 1992, pp. 16–17.

[16] Interview 1992, p. 18.

[17] H. Schaefer and H. P. Schwan, "The question of selective heating of small particles in the ultrashortwave condensor fields," *Annalen der Physik*, vol. 43, 1943, pp. 99–135.

[18] In September 1991 a conference was held at the same site to celebrate the fiftieth anniversary of the German biophysical society. Schwan was the only attendee who had also been at the 1941 meeting. His paper, "Entwicklung der Biophysik und das Frankfurter Institut für Biophysik" (cited above), will appear in the conference proceedings. The 1941 meeting is also briefly discussed in Schwan's "Early history of bioelectromagnetics."

[19] Schwan, "Entwicklung . . . ," pp. 5–6.

[20] Quoted on p. 723 of Henry E. Guerlac's *Radar in World War II* (Tomash Publishers and American Institute of Physics, 1987).

[21] Guerlac, *Radar in World War II*, pp. 727–729.

[22] Deposition made by Hermann Muth 8 July 1947 and deposition made by Hans Holzamer 9 July 1947, both in the Project Paperclip personal file on Schwan; and Interview 1992, pp. 42–43.

[23] John Gimbel, *Science, Technology, and Reparations: Exploitation and Plunder in Postwar Germany* (Stanford CA: Stanford University Press, 1990); and John Gimbel, "Project Paperclip: German scientists, American policy, and the Cold War," *Diplomatic History*, vol. 14, 1990, pp. 343–365.

[24] Gimbel, *Science, Technology, and Reparations*, pp. 3–6.

[25] Ibid., p. 29.

[26] Ibid., pp. 60–74.

[27] Two reports appeared in 1947, as FIAT Report 1097 and FIAT Report

1099. The other four reports appeared the following year in *FIAT Review of German Science, Biophysics II.*

[28] Deposition made by Boris Rajewsky 8 July 1947, in the Project Paperclip personal file on Schwan.

[29] B. Rajewsky and H. Schwan, "The dielectric constant and conductivity of blood at ultrahigh frequencies," *Naturwissenschaften*, vol. 35, 1948, p. 315.

[30] Interview 1992, pp. 106–107.

[31] D. E. Goldman, "Potential, impedance, and rectification in membranes," *Journal of General Physiology*, vol. 27, 1943, pp. 37–60. See also Cole, *Membranes, Ions and Impulses*, pp. 196–197, and 267–268.

[32] Gimbel, *Science, Technology, and Reparations*, pp. 37–59, and Gimbel, "Project Paperclip. . . . "

[33] Interview 1992, pp. 55–56, slightly edited.

[34] Ibid.

[35] Interview 1992, p. 128.

[36] H. P. Schwan and K. Sittel, "Wheatstone bridge for admittance determinations of highly conducting materials at low frequencies," *Transactions of the AIEE (Comm. and Elec.)*, May 1953, pp. 114–122.

[37] The discovery was presented first in abstract form in *American Journal of Physiology*, vol. 163, 1950, p. 748, then in detail in "Electrical properties of muscle tissue at low frequencies," *Zeitschrift für Naturforschung*, vol. 9b, 1954, p. 245. See also Cole, *Membranes, Ions and Impulses*, p. 46.

[38] Schwan, "Electrical properties of tissue and cell suspensions," *Advances in Biological and Medical Physics*, vol. 5, 1957, pp. 147–208.

[39] For a summary of this work, see Schwan, "Electrical properties of cells: principles, some recent results, and some unresolved problems," in W. S. Adelman and D. Goldman, eds., *The Biophysical Approach to Excitable Systems* (New York: Plenum Press, 1981), pp. 3–24; and Schwan, *Biological Effects of Non-ionizing Radiations: Cellular Properties and Interactions*, Lauriston S. Taylor Lectures in Radiation Protection and Measurements, Lecture No. 10 (National Council on Radiation Protection and Measurements, Bethesda MD, 1987).

[40] Interview 1992, Schwan's footnote to p. 112.

[41] Cole, *Membranes, Ions and Impulses*, pp. 6–7.

[42] Schwan, "Biomedical engineering at the University of Pennsylvania," *IEEE Engineering in Medicine and Biology Magazine*, vol. 10, no. 3, 1991, pp. 47–49.

[43] "Determination of the acoustic properties of blood and its components" (with E. L. Carstensen and K. Li), "Absorption of sound arising from the presence of intact cells in blood" (with E. L. Carstensen), "Acoustic properties of hemoglobin solutions" (with E. L. Carstensen), and "Mechanism of absorption of ultrasound in liver tissue" (with H. Pauly), all reprinted in *Ultrasonic Biophysics*, edited by Floyd Dunn and William D. O'Brien, Jr. (Stroudsburg PA: Dowden, Hutchinson & Ross, 1976), vol. 7 of the *Benchmark Papers in Acoustics* book series.

[44] Interview 1992, p. 133.

[45] *Annals of Biomedical Engineering*, vol. 20, no. 3, 1992. Schwan's attention

to electrode properties stimulated a number of other researchers, including L. A. Geddes, to contribute to this area.

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[47] *Advances in Biological and Medical Physics*, vol. 5, 1957, pp. 147–209.

[48] H. P. Schwan, G. Schwarz, J. Maczuk, and H. Pauly, "On the low-frequency dielectric dispersion of colloidal particles in electrolyte solution," *Journal of Physical Chemistry*, vol. 66, 1962, pp. 2626–2635.

[49] A. Anne, O. M. Salati, and H. P. Schwan, "Relative microwave absorption cross sections of biological significance," *Biological Effects of Microwave Radiation*, vol. 1, 1961, pp. 153–176.

[50] H. N. Kritikos, K. R. Foster, and H. P. Schwan, "Temperature profiles in spheres due to electromagnetic heating," *Journal of Microwave Power*, vol. 16, 1981, pp. 327–344; and W. I. Way, H. Kritikos, and H. P. Schwan, "Thermoregulatory physiologic responses in the human body exposed to microwave radiation," *Bioelectromagnetics*, vol. 2, 1981, pp. 341–356.

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[52] Schwan, "Organizational development of biomedical engineering," *IEEE Engineering in Medicine and Biology Magazine*, vol. 10, no. 3, 1991, pp. 25–29, 33.

[53] Erwin Schrödinger, *What is Life? The Physical Aspect of the Living Cell* (Cambridge UK: Cambridge University Press, 1944); Otto Glasser, *Medical Physics* (Chicago, 1944).

[54] Schwan, "Biomedical engineering at the University of Pennsylvania."

[55] L. A. Geddes, *A Century of Progress: The History of Electical Engineering at Purdue (1888–1988)* (West Lafayette IN: School of Electrical Engineering, Purdue University, 1988), pp. 97–102, 165–203; Arthur W. Guy, "The Bioelectromagnetics Research Laboratory, University of Washington: reflections on twenty-five years of research," *Bioelectromagnetics*, vol. 9, 1988, pp. 113–128, and L. L. Huntsman, "Biomedical engineering at the University of Washington," *IEEE Engineering in Medicine and Biology Magazine*, vol. 10, no. 3, 1991, pp. 42–43.

[56] Schwan, "Biomedical engineering at the University of Pennsylvania," and H. H. Sun, "Biomedical engineering at Drexel University," *IEEE Engineering in Medicine and Biology Magazine*, vol. 10, no. 3, 1991, pp. 44–46.

[57] L. H. Montgomery, "The origin of the professional group on medical electronics," *Proceedings of the IRE*, vol. 47, 1959, pp. 1993–1999.

[58] Schwan, "Organizational development. . . ."

[59] See J. H. U. Brown's "personal view of biomedical engineering," *IEEE Engineering in Medicine and Biology Magazine*, vol. 10, no. 3, 1991, pp. 34–37, 46.

[60] Interview 1992, pp. 114–115.

[61] Interview 1992, p. 158, and Brown, "A personal view of biomedical engineering."

[62] Schwan, "Entwicklung . . . " and Interview 1992, pp. 199–200.

[63] Nicholas H. Steneck et al., "The origins of U.S. safety standards for microwave radiation," *Science*, vol. 208, 1980, pp. 1230–1237, and Schwan, "Early history of bioelectromagnetics."

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[69] Steneck et al., "The origins of U.S. safety standards . . . " and Nicholas H. Steneck, *The Microwave Debate* (Cambridge MA: MIT Press, 1984), pp. 55–60.

[70] Interview 1992, pp. 85–86.

[71] Steneck, *The Microwave Debate*, pp. 61–62.

[72] Telephone interview of Schwan, 30 October 1992.

[73] Steneck, *The Microwave Debate*, pp. 189–195.

[74] Paul Brodeur, "A reporter at large: microwaves-I and -II," *New Yorker*, 13 and 27 December 1976, and Paul Brodeur, *The Zapping of America* (New York: Norton, 1977).

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[76] See the quotations of Schwan on page 125 of Steneck's *The Microwave*

Debate.

[77] Schwan, "Entwicklung. . . ."

[78] Telephone interview of Schwan, 30 October 1992.

[79] *EPRI Journal*, March 1992, pp. 5–13.

[80] Interview 1992, pp. 98–102.

[81] Interview 1992, p. 205.

[82] "Biomedical engineering and basic research: historical perspectives," *Medical Progress through Technology*, vol. 7, 1980, pp. 63–67; "Physical properties of biological matter: some history, principles, and applications," *Bioelectromagnetics*, vol. 3, 1982, pp. 3–8; "Ultrasound and electromagnetic radiation in hyperthermia—a historical perspective," *British Journal of Cancer*, vol. 45, suppl. V, 1982, pp. 84–92; "Historical review, state of the art, open problems," in A. Chiabrera, C. Nicolini, and H. P. Schwan, eds., *Interactions between Electromagnetic Fields and Cells* (New York: Plenum Press), pp. 1–18; "Early history of bioelectromagnetics."

[83] "Microwave bioeffects research: historical perspectives on productive approaches," *Journal of Microwave Power*, vol. 14, 1979, pp. 1–5; "History of the genesis and development of the study of effects of low energy electromagnetic fields," in *Advances in Biological Effects and Dosimetry of Low Energy Electromagnetic Fields* (New York: Plenum Press, 1983); "Microwaves and thermoregulation: historical introduction," in *Microwaves and Thermoregulation* (New York: Academic Press, 1983); "Science and standards. RF-hazards and standards: an historical perspective," *Journal of Microwave Power*, vol. 19, 1984, pp. 225–231.

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