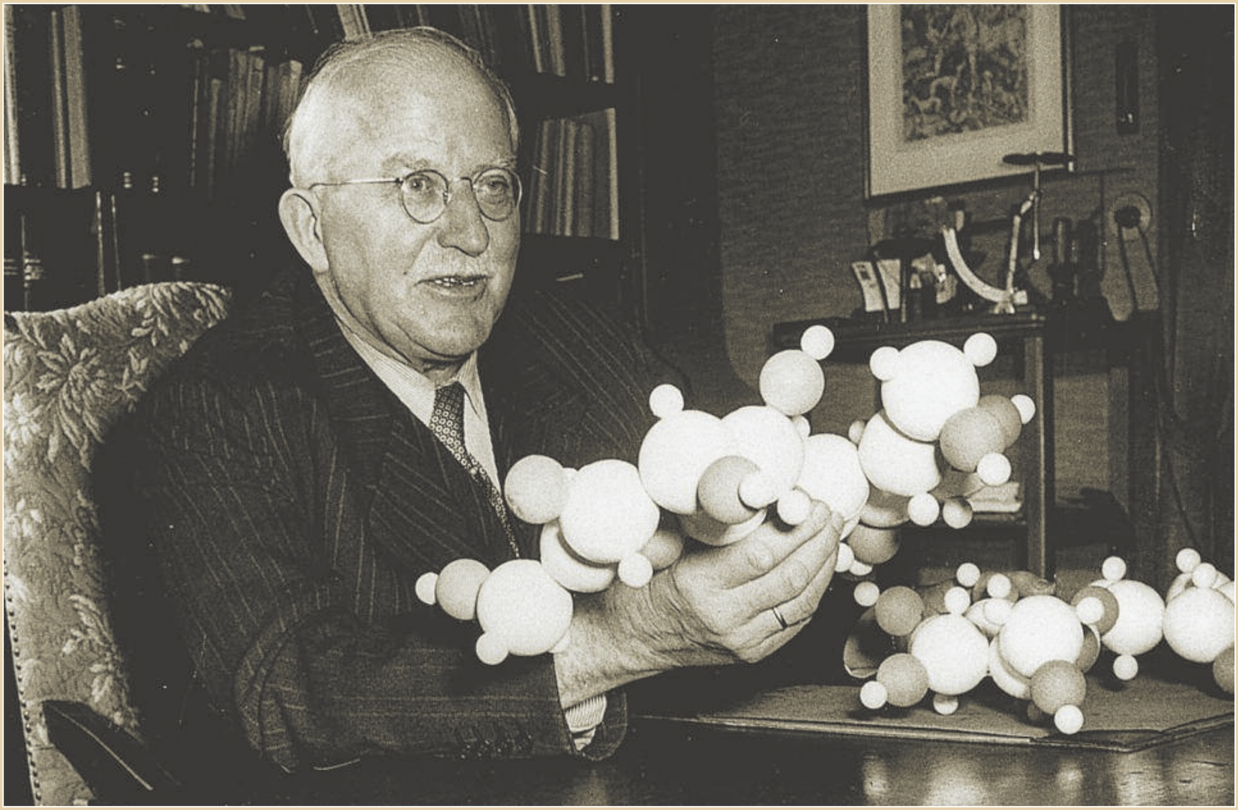
AN INTERNATIONAL HISTORIC
CHEMICAL LANDMARK

THE FOUNDATION OF POLYMER SCIENCE BY HERMANN STAUDINGER (1881-1965)

FREIBURG, BADEN-WÜRTTEMBERG
APRIL 19, 1999



AMERICAN CHEMICAL SOCIETY

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Hermann Staudinger House, the home of the Institute for Macromolecular Chemistry.

This booklet commemorates the designation of the foundation of polymer science by Hermann Staudinger as an International Historic Chemical Landmark. The designation was jointly conferred by the American Chemical Society and the Gesellschaft Deutscher Chemiker, learned societies whose aims are to promote the interests of chemists and chemistry and to serve the public interest. A plaque marking the designation was presented to the Institute for Macromolecular Chemistry in Freiburg-im-Breisgau, Germany, on April 19, 1999, for installation at Hermann Staudinger House. The inscription reads:

> This building is named after Hermann Staudinger, who, between 1926 and 1956, carried out his pathbreaking research on macromolecular chemistry in Freiburg. His theories on the polymer structures of fibers and plastics and his later research on biological macromolecules formed the basis for countless modern developments in the fields of materials science and biosciences and supported the rapid growth of the plastics industry. For his work in the field of polymers, Staudinger was awarded the Nobel Prize for chemistry in 1953.

The pioneering research of Hermann Staudinger, first at the Eigenössische Technische Hochschule (ETH) in Zurich, then at the Albert Ludwigs University in Freiburg, has led to the development of polymer science as a modern multidisciplinary field. In 1926, Staudinger became director of the chemistry department at Freiburg. He established the Institute for Macromolecular Chemistry within that department in January 1940. This institute was the first in Europe devoted exclusively to polymer science. On Nov. 27, 1944, near the end of the Second World War, Staudinger's laboratory was destroyed by Allied bombing. In the years after the war, he concentrated on the rebuilding of the chemistry department and his institute. Staudinger retired from the chemistry department in 1951 and was succeeded by Arthur Lüttringhaus. The Institute for Macromolecular Chemistry was transferred from the university to the state of Baden-Württemberg, on a temporary basis, with Staudinger remaining as director. He resigned in 1956. Elfriede Husemann succeeded Staudinger as director, and the Institute for Macromolecular Chemistry became an independent university institute. In 1962, she was appointed to the newly established chair of macromolecular chemistry and the institute was moved into a new building, now called "Hermann Staudinger Haus," located in Stefan-Meier-Strasse.

On the Cover:

Hermann Staudinger, 1953.

Acknowledgments:

The American Chemical Society gratefully acknowledges the assistance of those who helped us to prepare this booklet, including: Rolf Mülhaupt, Albert Ludwigs University of Freiburg; Helmet Ringsdorf, University of Mainz; Ulrike Fell, Gesellschaft Deutscher Chemiker; and Peter J. T. Morris, Science Museum, London, the NHCLP liason. It was produced by the Office of Communications, American Chemical Society. Design: Dalhman/Middour Design. ¨

Photos courtesy of Helmet Ringsdorf, Claus Priesner, and the Albert Ludwigs University of Freiburg.

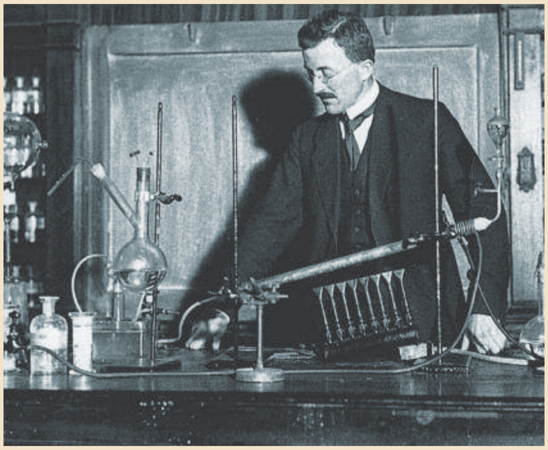
HERMANN STAUDINGER (1881-1965): FATHER OF MACROMOLECULAR CHEMISTRY

In 1920, Hermann Staudinger, then professor of organic chemistry at ETH in Zurich, created a stir in the international chemical community when he postulated that materials such as natural rubber have very high molecular weight. In a paper entitled "Über Polymerisation," Staudinger presented several reactions that form high molecular weight molecules by linking together a large number of small molecules. During this reaction, which he called "polymerization," individual repeating units are joined together by covalent bonds. This new concept, referred to as "macromolecules" by Staudinger in 1922, covered both synthetic and natural polymers and was the key to a wide range of modern polymeric materials and innovative applications. Today, the molecular architectures of synthetic polymers and biopolymers are tailored with high precision to meet the demands of modern technology. The products of polymer chemistry are diverse, from food packaging, textile fibers, auto parts, and toys, to membranes for water desalination, carriers used in controlled drug release, and biopolymers for tissue engineering.

Hermann Staudinger, probably in Zurich. Photo courtesy of Claus Priesner.

Staudinger's concept, however, represented a strong challenge to his contemporaries. The scientific community was very reluctant to admit the existence of extremely large compounds with molecular weights exceeding 5000. Instead, micelle-type aggregates, as observed for soap molecules, were considered to account for the unusual properties of such materials. Moreover, some scientists were convinced that the size of a molecule could never exceed the size of the unit cell, as measured by X-ray crystallography.

Staudinger, following the scientific tradition of classical organic chemistry, presented sound experimental evidence to support the existence of high molecular weight polymers. He selected natural rubber as the model system because Carl Harries and Rudolf Pummerer had suggested independently that natural rubber consisted of aggregated small cyclic polyisoprene units via "partial valencies" associated with the double bonds. Such aggregates should have been destroyed when the double bonds were removed by hydrogenation. Staudinger's hydrogenation experiments showed that hydrogenated rubber was very similar to normal unsaturated rubber.



Hermann Staudinger early in his career.

During the late 1920s, Staudinger provided additional evidence based on viscometry to confirm that molecular weights remained unchanged during chemical modification of polymers. Despite the impressive experimental evidence, Staudinger continued to encounter very strong opposition for nearly two decades from leading organic chemists. For instance, Heinrich Wieland, 1927 Nobel laureate in chemistry, wrote to Staudinger, "Dear colleague, drop the idea of large molecules; organic molecules with a molecular weight higher than 5000 do not exist. Purify your products, such as rubber, then they will crystallize and prove to be low molecular compounds!" In his autobiography, Staudinger commented: "My colleagues were very skeptical about this change, and those who knew my publications in the field of low molecular chemistry asked me why I was neglecting this interesting field and instead was working on a very unpleasant field and poorly defined compounds, like rubber and synthetic polymers. At that time the chemistry of these compounds often was designated, in view of their properties, as Schmierenchemie ('grease chemistry')."

Staudinger never ceased to promote his concepts of polymer sciences, despite his colleagues' mistrust of many of his methods and results. In lively discussions, he eloquently defended his ideas against all attacks using his ingenuity, persistence, and pronounced enthusiasm. By the end of the 1920s and during the 1930s, Staudinger's macromolecular concept found increasing acceptance by other chemists. Although some of his opponents still maintained their objections, his concept was already being applied in industrial processes. At long last, on Dec. 10, 1953, Staudinger received his reward for the concept of macromolecules and his prolonged effort to establish the science of large molecules when he was awarded the Nobel Prize for chemistry.

His Life—His Career

Hermann Staudinger was born in Worms on the Rhine on March 23, 1881. Because he loved plants and flowers, he studied botany under Georg Klebs at the University of Halle after graduating from high school in 1899. His father suggested that he take some chemistry courses to get a better understanding of botany. Following this paternal advice, Hermann studied chemistry at the Universities of Halle, Darmstadt, and Munich. Chemistry became his main interest, and in 1903 at the age of 22, he took his Ph.D. under Daniel Vorländer in Halle.


Hermann Staudinger receiving the Nobel Prize for chemistry from King Gustav Adolf of Sweden.

He continued his research in organic chemistry in the laboratory of Johannes Thiele at the University of Strasbourg. During his investigations of carboxylic acid compounds, he discovered the highly reactive ketenes. In 1907, immediately after completing his postdoctoral work on the ketenes, Staudinger, at the age of 26, was appointed full professor at the Technical University of Karlsruhe, succeeding Roland Scholl. In Karlsruhe, he met eminent chemists such as Carl Engler and Fritz Haber, the later founder of high-pressure chemistry. At that time, Staudinger's research focused on ketene chemistry, reactions of oxalyl chloride, aliphatic diazo compounds, and preparation of butadiene and isoprene.

In 1912, Richard Willstätter, a world leader in organic chemistry, was appointed director of the newly founded Kaiser Wilhelm Institute for Chemistry in Berlin-Dahlem. ETH in Zürich offered his vacated chair in chemistry to Staudinger who had just published his first book, *Die Ketene*. At ETH, Staudinger continued his research on organic synthesis. In addition, he started to investigate physiologically active natural compounds. With Leopold Ruzicka (who would win the Nobel Prize for chemistry in 1939), Staudinger identified the structure of natural pyrethrins and developed synthetic routes to these important natural insecticides. During World War I, Staudinger also conducted research into ersatz compounds, substitutes for natural products that were in short supply during the war. In addition to the successful development of synthetic pepper, Staudinger and Thadaeus Reichstein carried out the difficult analysis of natural coffee aroma. Eventually, they came up with a credible ersatz aroma (furfuryl mercaptan with traces of methyl mercaptan), which was converted into an industrial process.

During this period, Staudinger was a typical practitioner of mainstream organic chemistry, which was already a highly sophisticated and respected science, led by chemists such as Adolf von Baeyer, Emil Fischer, and Richard Willstätter. By 1914, organic chemists had prepared more than 100,000 synthetic compounds used for various applications, including dyes and pharmaceuticals. Although not yet 40, Staudinger was considered a leading organic chemist. During the 1920s, Staudinger decided to leave the safe and prestigious haven of classical organic chemistry to embark on the stormy high seas of polymer science. Staudinger's pioneering spirit drove him to break away from the typical thinking of traditional organic chemists and to advance new and revolutionary ideas.

In 1926, he was appointed to a chair at Albert Ludwigs University in Freiburg, where he dedicated all his efforts to establishing and expanding the frontiers of polymer science. His research topics included natural rubber, cellulose, and synthetic polymers such as polyoxymethylene, polystyrene, and polyethylene oxide, which Staudinger consid-


Hermann Staudinger (center) with colleagues in 1935.

ered to be model systems for the much more complex biopolymers. As well as making synthetic polymers, Staudinger tried to determine the molecular weights of polymers by using end-group analysis, by measuring the viscosity of polymer solutions, and by using electron microscopy analysis.

Hermann Staudinger always maintained a close relationship with industry to obtain funds for his research and to act as a technical consultant for firms interested in plastics and rubber. For many years, the "Förderverein" (association of supporters) of the Institute for Macromolecular Chemistry linked the research managers of the various companies who sponsored polymer research in Freiburg. Staudinger's internal group seminar, which started in 1950, attracted both academic and industrial chemists, and it soon became the largest German annual polymer meeting with more than 700 participants during the 1990s.

Hermann Staudinger's Life and Achievements

March 23, 1881—Born in Worms, son of Franz Staudinger and Auguste Wenck

1899—Graduated from high school in Worms, later studied chemistry in Halle, Darmstadt, and Munich

1903—Prepared Ph.D. thesis under Daniel Vorländer in Halle

1907—Completed postdoctoral work under J. Thiele in Strasbourg, discovered ketenes

1912—Became associate professor of organic chemistry at the Technical University of Karlsruhe

1912—Became professor of organic chemistry at ETH in Zurich

1920—Proposed that rubber, plastics, and many biomolecules are in fact high molecular weight compounds (which he called "macromolecules" in 1922)

1926—Became professor of organic chemistry and director of the chemistry laboratory at Albert Ludwigs University in Freiburg

1928—Married Magda Woit

1940—Founded the Institute for Macromolecular Chemistry at the chemistry department, the first European research institute devoted exclusively to polymer research

1947—Started the journal *Makromolekulare Chemie*

1951—Retired as professor of organic chemistry, succeeded by Arthur Lüttringhaus

1951—Became director of the Institute for Macromolecular Chemistry, which was separated from the university and became the Government Research Laboratory of the state of Baden-Württemberg.

1953—Awarded the Nobel Prize for chemistry

1956—Resigned as director, succeeded by Elfriede Husemann. The institute again became part of the university's chemistry department.

1962—Elfriede Husemann was appointed full professor of macromolecular chemistry of the newly established chair at the University of Freiburg; the Institute for Macromolecular Chemistry obtained a new building in Stefan-Meier Str. 31.

Sept. 8, 1965—Staudinger died in Freiburg.

Staudinger's wife, Magda Staudinger, a plant physiologist, also made important contributions to macromolecular research. She carried out morphological studies on macromolecular compounds using visible, ultraviolet, and electron microscopy. Later in her career, she also introduced phase contrast microscopy into macromolecular chemistry. Photo courtesy of Claus Priesner.

Staudinger's research was published in more than 800 publications amounting to more than 10,000 printed pages. He summarized his research in his autobiography, *Arbeitserinnerungen (From Organic Chemistry to Macromolecules)* published in 1970. His collected works, entitled *Das Wissenschaftliche Werk von Hermann Staudinger (The Scientific Contributions of Hermann Staudinger)*, were edited by Magda Staudinger and published between 1969 and 1976.

For many years, Staudinger's textbook, entitled *Die hochmolekularen organischen Verbindungen Kautschuk und Cellulose (The High Molecular Weight Organic Compounds Rubber and Cellulose)*, published in 1932 by Springer in Berlin, was the "bible" of many academic and industrial scientists. In 1947, Staudinger inaugurated the new journal *Makromolekulare Chemie* with Wepf & Co., publishers in Basel. For more than 50 years, this journal has provided an excellent forum for scientific exchanges and has promoted the expansion of polymer science.

Political Concern

Staudinger also was concerned with moral and political issues outside the scope of academic chemistry. During World War I, he publicly criticized chemical warfare and opposed his old friend Fritz Haber, who had developed poison gas to support the German war effort. In 1917, Staudinger published a paper, based on a calculation of the industrial balance between the warring powers, in which he stated that the war was lost to Germany and should be stopped immediately, as any further bloodshed was senseless. His courageous statements were in direct opposition to the nationalist spirit of that period.

Staudinger's quest for peace meant that his patriotism was called into question many times. In fact, in 1934, during the Nazi period, the dean of Freiburg University, the famous German philosopher Martin Heidegger, initiated dismissal procedures against Staudinger. Although Staudinger was interrogated by the Gestapo and had to resign, his removal was postponed, and finally withdrawn, when he agreed to stop questioning Nazi authority in public. Even so, all of his requests to travel abroad to attend conferences were rejected after 1937.

Industrial Significance of Polymer Science

During the late 19th century, cellulose derivatives were developed as artificial substitutes for silk and ivory. However, the real breakthrough in industrial production occurred in 1908, when Leo Hendrik Baekeland developed phenolic resins as the first true synthetic polymer, which became known as Bakelite. Since then, there has been a very fruitful cross-fertilization between technical progress and advances in polymer sciences. The production of polymers increased from 15 million tons in 1965 to more than 150 million tons in 1996, including 100 million tons of thermoplastics, 18 million tons of synthetic fibers, 22 million tons of thermosets, and 10 million tons of elastomers. More than 1 million tons of thermoplastics such as polyethylene, polypropylene, and polyvinyl chloride (PVC) are produced every year.

Hermann Staudinger (1881-1965).

No other materials can match the versatility of polymeric materials. Because of their molecular architectures, they can variously be stiff, soft, or elastic, permeable or impermeable, and transparent or opaque. Moreover, polymers are relatively inexpensive and can be readily processed by injection molding, blow molding, extrusion, spinning, casting, or compression molding. Because of their versatility, synthetic polymers have myriad applications. Some are very familiar: appliances, packaging, telephones, auto parts, and fabrics. Others are less visible, including circuit boards, composites for space ships, and medical uses such as absorbable sutures and implant materials.

Many polymeric materials can be readily recycled by remolding recycled polymer pellets or by heating the polymer to recover the feedstock. For example, commodity polyolefins, such as polypropylene, are cracked at temperatures above 400 °C to form synthetic oil and gas, which can replace natural oil and gas in refineries and energy production. Moreover, light polymeric materials can save weight in automotive construction, thus reducing fuel consumption and exhaust emission. As thermal insulators, polymer foams help to conserve energy. The petroleum used to make polymers, which is 4% of all consumption, saves more than 10% of all the petroleum used because of the improved insulation and weight-reduction in automotive construction made possible by these polymers. Polymeric materials are prime examples of environmentally friendly materials that help protect fossil resources for future generations.

Macromolecules: A Bridge Between Material Sciences and Life Sciences

The development of polymer sciences stimulated the production of new materials with a wide variety of applications in high technology. As early as 1926, Staudinger emphasized the significance of macromolecules for biochemistry and biology. His intention, supported by his wife, Magda, was to create a new research discipline of macromolecular bioscience or, as we would call it today, macromolecular life science. He concluded his Nobel Prize acceptance speech by describing his vision: "In the light of new insights in macromolecular chemistry, the miracle of life shows an exceptional multitude and perfection of architectures characteristic of living matter." Nature uses a very small number of monomers, such as amino acids and saccharides, to produce a large variety of biopolymers with specific functions in cell structures, transport, catalysis, and replication. Today, innovations in life sciences, especially biotechnology, will continue to stimulate the creation of new synthetic biopolymers, with unprecedented control of molecular architectures and biological activities.

At the beginning of the 21st century, polymer science is ready to meet the challenges of tomorrow's technologies.

FURTHER READING

Key Publications

H. Staudinger; *From Organic Chemistry to Macromolecules: A Scientific Autobiography on my Original Papers*; Wiley-Interscience: New York, London, Sydney, and Toronto, 1970 (translation of Arbeitserinnerungen, Dr. Alfred Hüthig Verlag: Heidelberg, 1961).

H. Staudinger; *Die Ketene*; Enke Verlag: Stuttgart, 1912.

H. Staudinger; *Anleitung zur organischen qualitativen Analyse*; Springer Verlag: Berlin, 1. Auflage 1923 und 6. Auflage 1955.

H. Staudinger; *Die hochmolekularen organischen Verbindungen Kautschuk und Cellulose*; Springer Verlag: Berlin, 1932, Nachdruck, 1961.

H. Staudinger; *Organische Kolloidchemie*; Vieweg Verlag: Braunschweig, 1940.

H. Staudinger; *Makromolekulare Chemie und Biologie*; Verlag Wepf & Co.: Basel, 1947.

H. Staudinger; Über Polymerisation. *Ber. Dtsch. Chem.* Ges. **1920**, *53*, 1073.

H. Staudinger und J. Fritschi; Über die Konstitution des Kautschuks, 6. Mitteilung über Isopren und Kautschuk. *Ber. Dtsch. Chem. Ges.* **1924**, *57*, 1203.

M. Staudinger; *Das Wissenschaftliche Werk von Hermann Staudinger*; Verlag Hüthig & Wepf: Basel, 1969–1976.

Works About Hermann Staudinger

Hans Batzer and Helmut Ringsdorf; Staudinger, Hermann. In *Badische Biographien*, Neue Folge, 1987, vol. 2.

Yasu Furukawa; *Inventing Polymer Science: Staudinger, Carothers and the Emergence of Macromolecular Chemistry*; University of Pennsylvania Press: Philadelphia, 1998.

Laylin K. James; Hermann Staudinger. In *Nobel Laureates in Chemistry, 1901–1992*; ACS and CHF: Washington, DC, 1993, 359–367.

H. F. Mark; Hermann Staudinger zum Gedenken. *Die Naturwissenschaften* **1966**, *53*(4), 93–95.

Peter J. T. Morris; Hermann Staudinger. In *Polymer Pioneers*; Center for the History of Chemistry: Philadelphia, 1986.

Robert Olby; Hermann Staudinger. In *Dictionary of Science Biography*, vol. XIII; Charles Scribner's Sons: New York, 1976.

C. Priesner; Hermann Staudinger und die makromolekulare Chemie in Freiburg. *Chemie in unserer Zeit* **1987**, *21*(5), 151–160.

C. Priesner; *H. Staudinger, H. Mark und K. H. Meyer: Thesen zur Grösse und Struktur der Makromoleküle*; Verlag Chemie, Weinheim: Deerfield Beach, FL, and Basel, 1980.

Willem Quarles; Hermann Staudinger: Thirty Years of Macromolecules. *Journal of Chemical Education*, **1951**, *28*, 120–122.

M. Staudinger; Hermann Staudinger—Der Mensch und der Forscher. In *Makromolekulare Chemie: Das Werk Hermann Staudinger in seiner heutigen Bedeutung*; Ernst Jostkleigrewe, ed.; Verlag Schnell & Steiner: Munich and Zurich, 1987, 9–29.

V. E. Yarsley; Hermann Staudinger, His Life and Work; *Chemistry and Industry* **1967**, *18*, 250–271.

V. E. Yarsley; Hermann Staudinger. In *Pioneers of Polymers*; The Plastics and Rubber Institute: London, 1981.

Staudinger's Political Activities

Yasu Furukawa; Staudinger, Polymers and Political Struggles. *Chemical Heritage* **1993–1994**, *10*, 46.

Bernd Martin; *Martin Heidegger und das Dritte Reich*; Wissenschaftliche Buchgesellschaft: Darmstadt, 1986.

H. Sachse; Hermann Staudinger zu Technik und Politik. *Nachr. Chem. Tech. Lab.* **1984**, *32*(11), 974.

H. Staudinger; Technik und Krieg. In *Die Friedenswarte. Blätter für zwischenstaatliche Organisation* **1917**, *19*, 196 and Revue de la Croix Rouge **1919**, 508–515.

H. Staudinger; *Vom Aufstand der Technischen Sklaven;* Charmier: Essen-Frieburg, 1947.

THE HISTORIC CHEMICAL LANDMARKS PROGRAM

The Historic Chemical Landmarks Program recognizes our scientific and technical heritage and encourages the preservation of historically important achievements and artifacts in chemistry, chemical engineering, and the chemical process industries. It helps to remind chemists, historians, students, and teachers of how chemical discoveries are made and developed, and how they are utilized for the benefit of people.

An historic chemical landmark represents a distinctive step in the evolution of chemical science and technology. Designations of sites and artifacts note events or developments of clear historical importance to chemists and chemical engineers. Collections mark the contributions of a number of objects with special significance to the historical development of chemistry and chemical engineering.

The American Chemical Society started a National Historic Chemical Landmarks Program in 1992. It has been extended internationally as part of the 1999 International Chemistry Celebration. The Gesellschaft Deutscher Chemiker has joined the American Chemical Society in designating the Foundation of Polymer Chemistry an Historic Chemical Landmark, the third to be designated under the international arm of this program.

For further information about the Historic Chemical Landmarks Program, contact:

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