THE TRANSITION OF CERAMICS FROM CRAFT TO SCIENCE-BASED INDUSTRY

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INTRODUCTION

The ceramic craft and ceramic industry have an image of conservative devotion to traditional ways that even today may bring into question the premise of the subject I'm here to discuss. We may ask: is it true that ceramics has become a science-based industry? I take my departure from a visit some twenty years ago to a Japanese national treasure potter who used traditional raw materials, traditional forming methods and an archaic hill climbing kiln to produce wonderful objects of classic Japanese design. During my visit I was surprised to see unobtrusive thermocouple instrumentation for his wood-fired kiln as well as a modern electric kiln used for glaze tests. From my observations and from archaeological studies of prehistoric ceramic change[1], I believe that the best craftspeople have always taken up and used whatever tools science and technology were able to provide for improved performance of their craft. The ceramic industry has always been as science-based as circumstances would permit.

Understanding and application of scientific data and principles has become central to the practice of ceramic engineering. Ceramics provides a wonderful field within which to think about technical innovation. The first ceramics were made some 25,000 years ago as ritual objects. By 7000 BC there was extensive manufacture of architectural plaster, an important innovation in which the very nature of a material was transformed by the application of fire. By 6500 BC or so, at the time permanent settlements and an agricultural economic base were becoming established, widespread manufacture of pottery was common and has remained so ever since. By about 6000 BC, essentially all the techniques of incised decoration, slip coatings, modeling and molding, raw material purification and other clay working technologies had been developed with the exception of the potter's wheel which came into use with the growth of urban centers about 3500 BC[2] .

The development of western science is much more recent than the development of ceramics. Inseminated by Greek philosophers puzzling about the nature of the world, nurtured by Islamic development of experimental observations of an astronomical and an alchemical nature, modern science took root and began to grow in the fertile culture of Renaissance Italy. The Italian Renaissance that created the culture appropriate for nurturing the development of science took root in the thirteenth and fourteenth century economy. Venice, Genoa and other Italian cities controlled the trade and redistribution of commodities in the Mediterranean and had widespread outposts and merchant colonies. At the same time there was a transfer of power from the feudal countryside to the urban commune. Government and economic policies increasingly created middle class commercial success. Merchants were involved in international finance with bank branches in France, Burgundy and England. Commerce, marketing and specialized manufacture developed extensively. There was a booming cloth industry in Florence. Milan had more than 100 workshops producing armor. There was ship building in Genoa and Venice. An efflorescence of arts, crafts and science began in this period of social transformation[3] .

By the end of the fifteenth century when science was in its infancy there was a glorious production of outstanding ceramics. Luca Della Robbia[4] developed tin glazed ceramic sculptures (Fig. 1). Wonderful maiolica tile was being produced (Figure 2) and magnificent maiolica pottery produced in the early sixteenth century (Fig. 3). It is not surprising that one of the earliest publications that can be properly described as ceramic science was the 1557 work of Cipriano Piccolpasso, Three Books of the Potters Art[5] .

Perhaps we should pause here and precise what we shall mean by "science" which is most simply defined as organized knowledge. In our view, science has three different faces: science is discovery and description; science is explanation; science is a way of thinking. In its first mode science is a search for structure, for discovery and description of ways of finding or organizing a rational arrangement of individual components of knowledge, a structure of things and groups of things; structure of processes and groups

[1]. SCHIFFER, MICHAEL B., *Technological Perspectives on Behavioral Change*, University of Arizona Press, Tucson (1992).
[2]. KINGERY, W.D., and Vandiver, P.B., *Ceramic Masterpieces*, Free Press, New York (1986).
[3]. GOLDTHWAITE, RICHARD A., "The Empire of Things: Consumer Demand in Renaissance Italy", pp. 153-175 in *Patronage, Art and Society in Renaissance Italy*, F.W. Kent and P. Simons, ed., Oxford, Clarendon Press, (1987).
[4]. KINGERY, W.D., AND ARONSON, M., "The Glazes of Luca Della Robbia." *Faenza. 42* (3), 221-224, (1990).
[5]. PICCOLPASSO, CIPRIANO, *Three Books of the Potter's Art*, 1558, Translated and introduced by Ronald Vitbone and Allen Caiger-Smith, Scholar Press, London, (1980).

of processes. Science is also a search for operational principles[6] explaining how things and processes work. An operational principle explains how the parts of a device or structure or process fit together and work together to achieve a given result. Finally, science is an organized way of thinking that requires defining questions about things and processes and operational principles in such a way that one can formulate conjectures or hypotheses that are subject to testing by experiment or experience.

Fig. 1. *Luca Della Robbia developed tin oxide opacified glazes for sculptural ceramics in Florence during the latter 15th Century.*

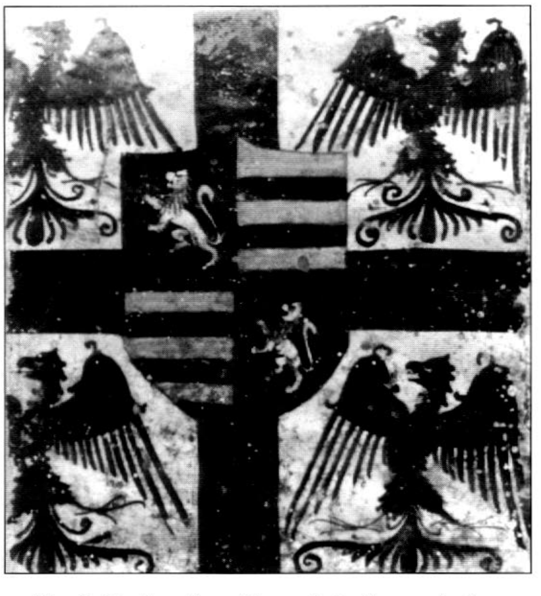

Fig. 2. *Custom floor tile made in Pesaro during 1492-1494, Poorly milled colors and many grains of sand indicate rather casual manufacture. (Victoria and Albert Museum, Department of Ceramics; reproduced by permission of the Trustees of the Victoria and Albert Museum).*

Fig. 3. *Perseus and Andromeda plate made in 1524 by Nicola da urbino for Isabella d'Este. (Courtesy of the Boston Museum of Art).*

[6]. POLANYI, MICHAEL, *Personal Knowledge*. University of Chicago Press, Chicago (1960).

CERAMICS UNDER SCIENTIFIC SCRUTINY

At the beginnings of the sixteenth century and the beginnings of science, natural philosophers were assembling and organizing data in such a way that a rational structure could be developed for a variety of things and processes. The craft of ceramic manufacture had achieved, after 8000 years, a substantial level of sophistication. With the new social emphasis on material culture the craft of ceramics began to be probed and dissected (as did mining, metallurgy, and glass-making). Made things as well as natural things, devised processes as well as natural processes, came under scientific scrutiny. The first evidence of this is Piccolpasso's 1557 book, *The Three Books of the Potter's Art,* in which he described the materials used and processes employed, opening the ceramic craft to the light of outside observation.

A significant event in European ceramics was the development of Medici porcelain in 1575[7]. Grand Duke Francesco I de Medici, son of Cosimo I, became regent of Tuscany in 1564. He was quiet and withdrawn, often melancholy and frequently retreated to a laboratory where he carried out experiments with alchemy and melting natural crystals. He initiated a program that required ten years of effort according to Andrea Gussoni, the Venetian ambassador to Florence. It was finally successful in making something equivalent to "Indian porcelain" (Fig. 4). We don't know details of the development program but it seems sure that this is an early example of a scientific way of thinking involving conjectures and experiment in the search for a successful process. In the event, firing of this product in available kilns was a very chancy operation and manufacture ceased in 1587 following the death of Grand Duke Francesco.

We have less information about the successful subsequent development of French softpaste porcelain at St. Cloud about 1695 but there is no evidence of scientific procedures.

This same situation with ceramics being the subject of scientific investigation occurred most of the time in most places during most of the eighteenth century. When samples of the raw materials used to manufacture Chinese porcelain were sent home to France by Père d'Entrecolle in 1712 and in 1722 they were given to R.A.F. Reaumur, a leading chemist, for analysis. He concluded that one of the constituents, *kaoling*, was refractory and infusible while the other, *petuntse,* was fusible; that a mixture of the two was critical. When a porcelain factory at Vincennes was taken over by the crown to become the Royal Manufactory and transferred to Sèvres in 1745 another chemist, Jean Hellot, director of the French Royal Academy, was put in charge of determining and recording the secrets of porcelain manufacture[7]. Hellot subsequently became the first technical director of the Manufacture Royal de Céramique de Sèvres. Pierre Joseph Macquer published *Elements de Chymie Théorétique* in 1749 which includes chemical descriptions of pottery and porcelain as did his *Dictionaire de Chymie* of 1766. Indeed, traces of the same role of science as a describer of ceramic materials and processes appear in Alexander Brongniart's treatise *Traité des Artes Céramique* published in 1844. In the description of many products and processes very different one from another, Brongniart attempted to "classify them in a rational manner"[8].

Francis Bacon, the seventeenth century apologist for the new science, proposed in

[7]. Kingery, W.D, and Smith D. "The Development of European Soft-Paste (Frit) Porcelain"; pp. 273-92 in *Ceramics and Civilization I: Ancient Technology to Modern Science.* Edited by W. D. Kingery. The American Ceramic Society, Columbus, OH (1985).
[8]. Brongniart, Alex, *Traité des Arts Céramiques,* second ed., Paris, 1854 (Pg. xiv, Volume I).

his *Novum Organon* (1620) that the essence of the inductive method was the collection of facts by experiment and observation. The emphasis of natural philosophy was to be observation rather than abstract argumentation as indicated in the motto of the Royal Society of London, *Nullus in verba*. This was the early relationship of science to ceramics - the collection and organization of facts about the structures and processes of the ceramic crafts; and this approach continued on through to the middle of the nineteenth century and beyond. This attitude that the gathering of facts and experimentation is the basis for process development and control came to permeate the practitioners of ceramics as evidenced by the appointment of a series of chemists as directors of the Manufacture Royal de Céramique at Sèvres.

Fig. 4. *Medici porcelain bottle dated 1581 and bearing the royal arms of Phillip II of Spain. (Courtesy of the Musee de Ceramiue, Sevres, France).*

EUROPEAN PORCELAIN

Oriental porcelain was imported to Europe from the twelfth century onward and there were substantial quantities coming into Egypt, Syria and Turkey by the fourteenth and fifteenth centuries. Beginning in the sixteenth century, the Portuguese and then the

English and the Dutch brought massive amounts of hard white translucent porcelain to Europe which led to a variety of more or less successful efforts to duplicate this material.

Success in this effort resulted from a purposeful program established at Meissen in 1705 by Count Erinfeld Walther von Tschirnhaus for Augustus the Strong, Monarch of Saxony and Poland. The political model of Louis XIV as to the divine rights of kings, the centralization of government, central control of economic and financial activities, the encouragement and support of commerce and industry, exploitation of natural resources and new manufactures was the model being followed in Saxony. Mercantile objectives and a positive balance of trade were particularly important since Saxony was mostly an area of raw material production with but little manufacture. Porcelain science was specially interesting since Augustus the Strong was an obsessive collector of Oriental porcelain, substantially depleting the national treasury with his purchases.

A critical participant in this endeavor was Count von Tschirnhaus, who had studied mathematics and physics at Leiden. During 1674-1680 he went on an extended scientific tour of Europe carrying out numerous experiments on materials behavior using high temperatures achieved by focusing sunlight in a solar furnace, research sufficiently well known and appreciated that he was made a member of the French Royal Academy. Dr. Martin Lister described seeing a burning glass more than 3 feet in diameter in Paris in 1698 similar to ones used by Tschirnhaus (Fig. 5). von Tschirnhaus carried out studies of Saxon mineral resources in collaboration with mining superintendent Pabst von Ohain which resulted in establishment of three glass houses together with the grinding and polishing equipment necessary to produce burning lenses. With these he achieved higher temperatures than had previously been attained and carried out experiments aimed at porcelain development. He wrote to his mathematical friend Liebnitz in 1694 that he had "no more than a little piece of artificial porcelain". He reported to the French Academy of Science in 1699 on researches establishing that pure sand and lime are separately infusible, but can be melted in a solar furnace when combined together. The lowest melting temperature of a lime-sand mixture is 1436° C, so the burning-glass furnace must have achieved at least this temperature. In order to understand production methods better von Tschirnhaus visited ceramic factories at St. Cloud and Delft in 1701.

The principal researcher, Johann Friedrich Bóttger had been assistant to a well-known apothecary in Berlin where he claimed to have transformed mercury into gold. In 1707 Paul Wildenstein, a Freiberg miner working in the laboratory recalled[10].

> .....Herr von Tzschirnhaussen, too, was giving instructions, and they began to research. Among other things, specimens of red procelain were made, as well as white. Köhler and I had to stand nearly every day by the large burning-glass to test the minerals. There, I ruined my eyes, so that I now can perceive very little at a distance.

On January 24, 1710, Augustus announced to the world the foundation of European porcelain manufacture and samples were exhibited at the Leipzig Easter Fair that year.

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[9]. KINGERY, W.D., "The Development of European Porcelain"; pp. 153-180 in *Ceramics and Civilization III: High-Technology Ceramics Past, Present and Future.* Edited by W.D. Kingery, The American Ceamic Society, Inc. westerville, OH, (1986).

[10]. GODER, WILLI, KLAUS HOFFMAN, INGELORE MENZHAUSEN, EBERMAN NEUBERT, WERNER PFUHL, FREDERICH RIRCHEL, WOLFGANG SCHULLE, ROFT SONNEMANN, EBERHARD W¨CHTLER, HANNES WALTER, OTFRIED WAGENBRETH, BÖTTGER: *Die Erfindung des Europaischen Porzellans,* W. Kolhammer, Stuttgard, 1982; French translation, *Meissen, La Decourerte de La porcelaine Europeenne* en Saxe, Pygmalion, Gerard Watelet, Paris, (1984).

Fig. 5. "Burning glass" solar furnace of the type used in Meissen porcelain research.

Père D'Entrecolles wrote letters in 1712 and 1722 about Chinese methods of production and samples of Chinese raw materials. The famous chemist René de Réaumur analyzed these and found that "kaoling" was infusible while "petuntse" fused readily. He concluded that Chinese porcelain consisted of a mixture of an infusible earth with a fusible constituent, a scientific explanation demonstrated after the same considerations were actually producing ware. Réaumur became interested in porcelain and invented a way of taking ordinary glass objects, packing them in a powder of calcimined gypsum and quartz, which maintained the shape of the ware when it was fired in an ordinary pottery kiln. The glass crystallized to a form that has been referred to as Reaumur porcelain, a "fibrous glass".

In 1746 the porcelain factory at the Vincennes was taken over by the crown to become a Royal manufactory and transferred to Sèvres. A chemist, Jean Hellot, director of the French Royal Academy was put in charge of determining the nature and recording the secrets of porcelain manufacture. He went on to become the first technical director of the Manufacture Royale de Céramique de Sèvres. The most popular European chemistry text in the eighteenth century was written by Pierre Joseph Macquer in 1749, widely used and translated into English. Macquer became the second technical director of the Manufacture Royale de Céramique de

Sèvres and it was he who developed the manufacture of hard porcelain. Another well known chemist Jean D'Arcet was technical director at Sèvres from 1782 to 1793. He carried out numerous experiments on high temperature chemistry and investigated enamel colors for porcelain. In Germany it was much the same situation. Frederick the Great brought Euler, the Swiss mathematician to Berlin to revive the Royal Prussian Academy of Sciences. Frederick was also instrumental in encouraging the chemist Johann Heidrich Pott to carry out lengthy high temperature experiments at the Berlin Porcelain Works. In 1762 at the end of the Seven Years War, Frederick occupied Dresden and brought back models, molds and workers to establish the Royal Porcelain Factory in Berlin. Andreas Seigfried Margraf, a well-known chemist and director of the Berlin Academy since 1754 was a consultant there as was his successor and leading chemist of his day, Martin Heinrich Klaproth.

In England the leading ceramic innovator was Josiah Wedgwood, who was a member of the Royal Academy, a close friend of the chemist John Priestly as well as James Watt, Matthew Boulton, Erasmus Darwin and others. Wedgwood carried out extensive experiments in developing a reproducible although highly nonlinear pyrometer for high temperature measurements. His instrument became a standard by the end of the century. Wedgwood was sufficiently interested in chemistry that he manufactured a line of mortars and chemical vessels made from a hard stoneware. Another chemist, Fougeroux de Boudanoy reported to the Royal Academy in 1776 a comprehensive view of the science of porcelain making which was confirmed by quite modern materials science model experiments using fusible borax as a constituent for a low temperature porcelain. By the end of the century the soft paste porcelain of France was replaced by hard paste, the material of choice for the continent. In England in addition to traditionally whitewares, bone china was being manufactured, establishing the principle classes of whiteware production which are still made to this day. At the beginning of the century, whiteware manufacture was seen as a source of challenging problems for chemists. In a very real sense by the end of the eighteenth century ceramics was viewed with an entirely different mind set as a *product* of chemical science.

HERMANN AUGUST SEGER

The general principles of classical inorganic chemistry mostly came out of experiments with gases over two decades or so following Lavoisier's law of the conservation of matter (1790). Their development in a form capable of explaining the operational principles of ceramic systems required most of the following century. In the meantime, analytical techniques were well developed and hundreds of process descriptions and chemical analyses of ceramic materials and products were widely available through texts such as Porter, Brongniart, and Salvatet, a tradition followed by Alfred B. Searle's translation of Emil Boury's "*Treatise on Ceramic Industries*" in 1901.

Until the latter part of the nineteenth century (with a notable exception in Josiah Wedgwood) science related to ceramic manufacture was restricted to royal porcelain manufactories, to top of the line high value added wares. In 1760 Wedgwood attempted to form an organization of the Staffordshire potters who would jointly support research activities of common interest. This proposal came to naught in disputations about cost sharing. It was more than 100 years until a new social organization for supporting ceramic research came into being in Germany as part of a widespread state-industry-university partnership. German universities had a strong tradition of research and an equally strong tradition of training Ph.D.'s for positions in industry. To this synergistic relationship between university and industry, the unification of Germany under Bismarck's Prussian leadership added an expansionist nationalist fervor that affected all fields of endeavor. There was state support of rapid industrial growth. University programs were promoted to produce the scientists and engineers needed for industry. The growth of chemical manufacturing and chemistry in the universities was particularly notable . In addition to producing students, there was active faculty participation in new technical enterprises which was both expected and encouraged. In 1869, Albrecht Konstantin Türrschmiedt established a laboratory associated with the "German Potter and Brickmaker Newspaper" which was joined by Hermann August Seger, trained in chemistry. Industrial scientific research was mostly published in the bulletin of the Deutsch Society for Fabrication of Bricks, Clayware, Lime and Cement. In his first publication, rather than chemical analysis, Segar emphasized the necessity of studying the physical properties of clay, its structure, plasticity, water absorption, drying and burning, shrinkage. Friedrich Hoffmann had a position as state architect and it was largely because of his invention of the continuous multi-chamber kiln and the introduction of machinery for production of bricks and terra cotta on a large scale that Seger became manager of his laboratory and editor of the German Clay and Brickmaking Newsletter and the Bulletin of the German Society for the Fabrication of Bricks, Clayware, Lime and Cement. One of his early success' was an investigation of the chemistry of oxidizing and reducing fires on brick clays containing lime and sulfates. These studies are still applicable to tile bodies. Seger not only studied the chemistry but also developed methods of gas analysis suitable for industry and visited manufacturing plants to advise on firing bricks in continuous kilns at the request of Hoffmann. In the laboratory his associate Dr. Aron carried out a long series of fundamental studies of plasticity, shrinkage and other properties of clay bodies including the influence of particle form and non-plastic ingredients.

In a note on the chemical constitution of clays[11] Seger comments on the contradiction between scientific chemical analyses and practical observations and illustrates it with experiments made at Sèvres and reported by Brongniart on efforts to produce hard Chinese porcelain. The constituents were mixed in the proper chemical proportions but a white enamel was produced instead of porcelain. This led Seger to propose a method of *rational analysis* in which clay is looked upon as a mixture of quartz grain, unweathered mineral fragments, mostly feldspar, and the weathered product, clay substance, which is for the most part a silicate of alumina containing water. Porcelain bodies are mostly composed of quartz, feldspar and kaolin. From the alkali content, the feldspar content can be determined. From the residual alumina content kaolin can be determined, leaving quartz as the residual SiO_2. The mindset of transforming chemical analyses into rational mineralogical compositions is still employed by ceramic engineers. It was Seger who introduced the idea of equivalent formulae for glazes and bodies. In this nomenclature the alkali and alkaline earth content (RO), the intermediate neutral content (R_20_3) and the siliceous content ($R0_2$) of a glaze are compared on the basis of one equivalent of

[11]. SEGER, H.A., *Collected Writing*, American Ceramic Society and Chem. Publ. Co., 1902 (Vol. I, Page 47).

RO. This rearrangement of the raw analysis into functional equivalents provided a means of comparing compositions of immediate use to ceramic engineers and is still common practice. Seger developed a series of compositions of increasing infusability formed into the shape of pyrometric cones which could be placed in the kiln and their melting behavior observed. These Seger cones which measure a combination of time and temperature are still widely employed in the ceramic industry.

The publications committee of the American Ceramic Society (Edward C. Stover, Herbert A. Wheeler, Stanley G. Bert, Edward Wharton Jr.) who arranged for the translation of Seger's collected writing edited by Albert Bleininger reflected the contemporary and historical view that "Dr. Seger was the pioneer who first blazed the way, along which all must travel... who hope to convert it [ceramics] from an empirical handicraft into a systematic and scientific industry"[12].

EARLY TWENTIETH CENTURY SOCIAL AND SCIENCE CONSTRUCTS (PRIOR TO WWII)

Ceramic education at the university level including chemistry and physics began at the University of Berlin in 1870, in England with classes at the University of Manchester in 1884, in France in 1893 at the Manufacture National de Sèvres and in the United States in 1894 at Ohio State University. The program at Ohio State was initiated by Edward Orton, Jr. with the support of the Ohio Brick and Drain Tile Association and the National Brick Manufactures Association who pressured the legislature to require that such a program be initiated. This important role of industry was also apparent in Germany, England and France. In the United States there were five university programs in ceramic engineering established by 1906 and another nine by 1930, very small potatoes in the overall educational establishment. Universally the faculty of these institutions encouraged their students to regard the ceramic industry as a systematic and science-based industry. Following the lead in Germany, the American Ceramic Society was organized in 1898 and the English Ceramic Society in 1900. Twenty of the twenty-two organizers of the American Ceramic Society were from industry. Industry dominated the ceramic engineering profession and the focus of ceramic research was entirely on practical manufacture. In a randomly selected year, 1923, every one of the papers published in the Journal of the American Ceramic Society was directly related to industry problems. At the same time, without exception, the industry and its engineers were hopeful for the development of a fully systematic science-based industry.

The historian Thomas P. Hughes "American Genesis"[13] described 1870-1970 as the "era of technological enthusiasm" in the United States. New inventions with regard to telegraphic and telephonic communications, with regard to electric illumination systems, the applications of electrical power and the development of transportation systems were changing the world. In this era of visionary new technology, ceramic materials came to be "enabling" contributors. There was the development of telegraph line insulators as early as 1850 and soapstone electrical

[12]. SEGER, H.A., *loe cit*, page vi.
[13]. HUGHES, THOMAS P., *American Genesis*.

insulators in late 1880's along with Edison's carbon microphone of 1878 and Edward G. Acheson's silicon carbide synthesis at Niagara Falls in 1895. Carl Auer von Welsbach commercially introduced the ninety-nine weight percent ThO_2-1 weight percent CeO_2 gas mantels that substantially increased the efficiency of gas illumination in 1890. Walther Nernst patented a ceramic filament for an electric light in 1899 and these were being manufactured by 1901. These high tech high value added ceramic materials were not considered part of the clay working "ceramic" industry for another fifty years but they served to galvanize scientists into studies of the new materials In many ways these high value added components took the place of prestigious hard porcelain in encouraging investment in scientific researches. When C.P. Steinmetz successfully proposed in 1900 that the General Electric Company set up a central research laboratory "entirely separate from the factory" the targets for initial work were mercury vapor lamps, Nernst-type lamps, new metal filaments and new materials for arc lamp electrodes. During this time the science of both natural and man-made materials advanced at an astounding rate. J. Willard Gibbs developed thermodynamics and the basis for the phase rule; Ostwald carried out studies of catalysis, chemical equilibrium and chemical kinetics; Boltsman related thermodynamic properties of a system to the atomic constituents. Maxwell developed a general relation for the transmission of electromagnetic radiation. Hertz experimentally demonstrated the transmission of electromagnetic waves and instigated development of wireless transmission. In 1895 Wilhelm Róntgen discovered the existence of completely unexpected x-rays. In the following year, Becquerel observed natural radiography. In 1897 J.J. Thompson determined that electrons had the nature of particles. In 1898 Rutherford identified alpha-rays and beta-rays, in 1900 Paul Vilar discovered gamma-rays and Max Planck proposed a theory for radiation quanta. In 1910 Rutherford proposed his model that the atom consisted of a central nucleus containing almost all of the mass surrounded by a swarm of electrons. During these years methods were developed for understanding the determination of internal structure of atoms and molecules, the key to material properties, along with continuing development of synthetic methods for particular structures. In 1912 Max von Laue discovered x-ray defraction by crystalline solids. By 1913 Bohr theorized the model of stationary electron levels in the atom and quantum theorists were beginning to provide a rationale for the unexpected stability of these states.

In parallel with this new extreme of exponentially increasing materials science there was a rapid growth in scientific instrumentation. Henry Sorby had observed the microstructure of polished and etched steels beginning in 1863. By the turn of the century this had become a centerpiece of metals research. In the 1930's invention of the electron microscope allowed higher magnifications and greater depth of focus. More rapid and effective methods of spectroscopic analysis were developed along with the wide spread availability of Le Chatelier's thermocouple and other instrumental methods for temperature measurement. Francis Aston invented the mass spectrograph in 1919. Following the 1912 discovery of x-ray defraction by crystals, W.H. Bragg and his son W.L. Bragg developed a diffraction equation and an x-ray spectrometer to determine crystal structures. In their 1915 book *X-rays and Crystal Structure* they reported nine types of structure in which the positions of atoms were determined. Their studies of single crystals were much extended by using a powdered sample in the Debye - Scherrer apparatus developed in 1916. Combining thermal and microscopic methods, phase equilibrium diagrams for metals were investigated beginning at the turn of the century and for silicate systems beginning in the 1920's. The development of materials science models and new experimental instrumentation reinforced one another to produce a virtual flood of new materials science.

The development of x-ray diffraction, chemical kinetics, phase equilibrium diagrams, colloid chemistry, the structure of clay minerals, plasticity and drying, the structure of non-crystalline glasses and glazes, the development of quantum theory, the behavior of electrons in metals, nuclear chemistry, all had some application to ceramic manufacture. Each was developed pretty much independent of one another and certainly independent of the ceramic industry. This new science was too overwhelming to be absorbed by a ceramic industry which was concurrently subjected to the great depression of the 1930's. Then the coming of World War II put a hiatus on the assimilation of new materials science.

THE LATER TWENTIETH CENTURY (POST WWII)

A decade or so after the end of World War II the century-long task of transforming ceramics from craft tradition to science-based industry was pretty well complete. More than half of an "ideal" ceramics engineering curricula consisted of basic science and engineering sciences[14]. Following the proposals included in Vannevar Bush's post-war science report, *Science - The Endless Frontier*, the National Science Foundation, the Department of Defense and the Atomic Energy Commission began provided large-scale funding for American science research. Engineering colleges soon joined their science siblings and based research programs and curricula on "engineering science". Perversely this led to changing roles, relationships and influences among the state, the universities and industry. Inevitably there was a decreased influence of the traditional industry over both university research and university curricula. These came to be dominated by high-tech high value added products.

A changed social structure and control of university ceramic research was based on the maturing of various strands of the science of materials. Separate research programs of electrons in solids (the physics community,) defects in solids (the physics and chemistry communities), molecular and crystal structure studies (chemistry, geology and biology), colloid chemistry and so forth, became overlapping. They were brought together within the rubric of materials science and engineering. Parallel to these developments there was an exponential expansion of scientific instrumentation of which the most important was probably the development and commercial availability of sophisticated electron microscopes and many different modes of instrumental analysis. In a recent book *Characterization of Materials*, John B. Wachtman[15] listed 147 acronyms for widely used instrumental techniques. In ceramic sciences, the new integration was spelled out in the texts of F.H. Norton (*Elements of Ceramics, 1953*), W.D. Kingery, (*Ceramic Fabrication Processes, 1958; Kinetics of High Temperature Processes, 1959; Introduction to Ceramics, 1960)*, and W.G. Laurence (*Ceramic Science for the Potter, 1972)*.

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[14]. READEY, DENNIS, "The Response of Ceramic Education to the Changing Role of Ceramics in Industry and Society. Pg. 343-378 in W.D. Kingery, Ed. *The Changing Roles of Ceramics in Society: 26,000 BP to the Present, Ceramics and Civilization V*, American Ceramic Society, (1990).

[15]. WACHTMAN, JOHN B., *Characterization of Materials*, published (1993).

These changed relationships have created problems for the traditional ceramic industry in relationship to the development of new science and new researches. In 1950, nearly all of the articles published in the Journal of the American Ceramic Society were industry related; by 1960 only a minority of articles were related to commercial product manufacture or use. The ceramic industry had lost most of its power to control the direction of university researches. As science continued its exponential growth, it has become further and further separated from the lower growth rates of brick, tile, whiteware and sanitary porcelain production (Fig. 6). As the sophistication of science and complexity of scientific instrumentation have increased, it has become increasingly difficult for small and middle sized firms in the ceramic industry to take advantage of the most recent results. Means need to be found for institutional arrangements that will bridge the gap. Models exist such as Wedgwood's 1760 proposed collaborative research proposal, like the collaboration of Crown, Manufacture and Scientific Academy in the eighteenth century, like the German nineteenth century program of industry-state-university partnership. Perhaps the Castellón Instituto de Tecnología Cerámica may be a model of what is possible.

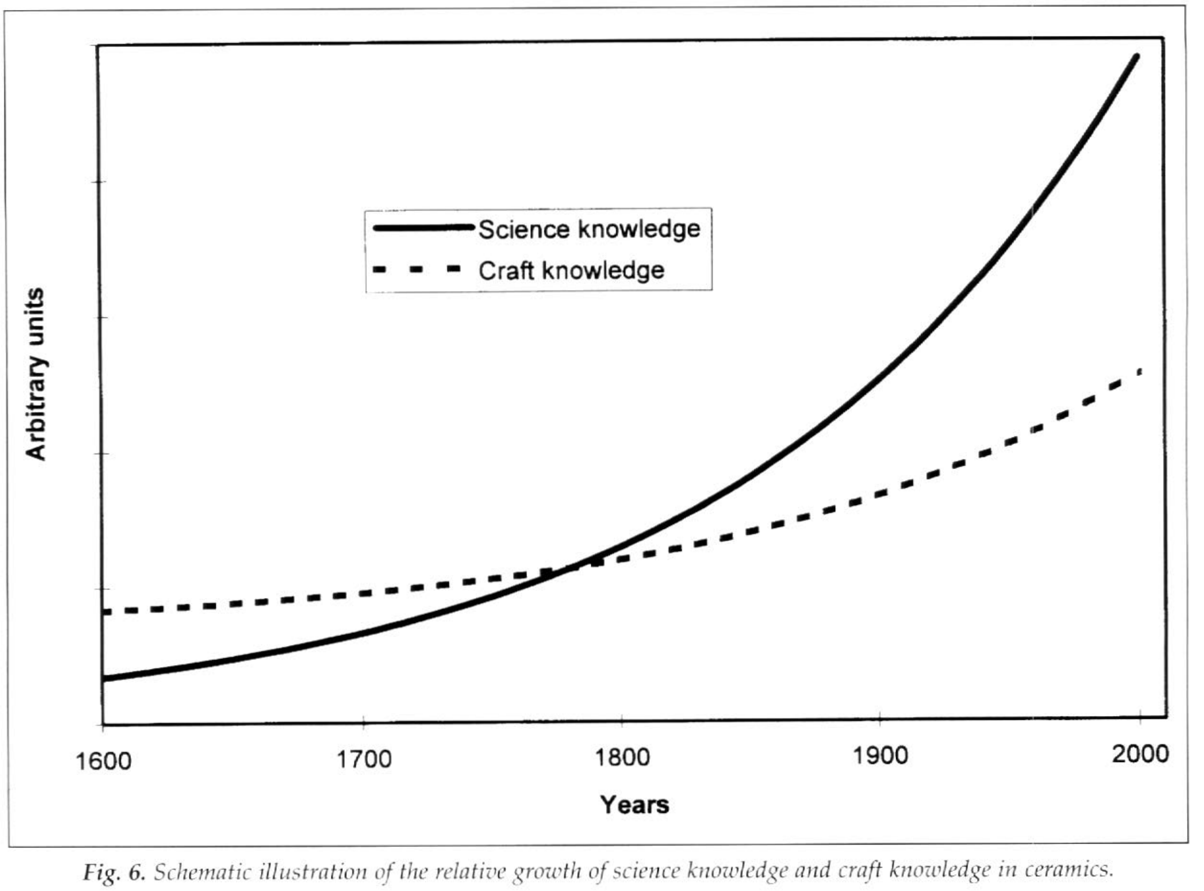

Fig. 6. Schematic illustration of the relative growth of science knowledge and craft knowledge in ceramics.

THE SCIENCE-TECHNOLOGY NEXUS

We have defined science as both the accumulation of organized facts and data (the structure of materials and of processes), and also as the development of predictive theory (the understanding of operational principles underlying material properties and processes) and finally as a method of inquiry (rigorous use of experimentation and observation as a way of testing hypotheses and conjectures). Science *per se* does not purposely develop new products, new processes, new applications for ceramic materials; that is the task of the engineer, craftsperson and industrialist who use scientific methods, scientific data and scientific explanations of operational principles as *tools* in the design and development of new products and processes. Clearly this relationship of science and technology is symbiotic. Many, perhaps most, of the advances of science depend on technology being used as a *tool* of science. In the era of late Renaissance science the telescope in the hands of Galileo was instrumental. The solar "burning glass" furnace in the hands of von Tschirnhaus was an essential tool in his studies of porcelain. X-ray diffraction and optical and electron microscopy have been essential tools in the scientific study of the internal structure of solids and the microstructure of ceramics.

With regard to the ceramic industry, the role of science has often been an indirect one in providing the basis for developing technologies such as temperature measurement not confined to the ceramic industry alone. Sebeck discovered thermoelectric phenomena in 1821. It was not until toward the end of the century that Le Chatelier applied this as a method of temperature measurement which provided new possibilities for control of ceramic drying and firing processes. Science used as a tool for technological development has led to the substantial, even revolutionary, developments of ceramic engineering and manufacturing over the past many years. Competitive pressures have led to the design and control of processes in which productivity and quality assurance have improved remarkably. Many of these advances have not been so much a consequence of university programs in Ceramic Engineering and Ceramic Science as from degree programs in Mechanical, Electrical and Chemical Engineering.

SUMMARY AND CONCLUSIONS

During the initial interactions of ceramics with modern science, ceramic crafts were primarily objects of study. The level of craft knowledge, accumulated experience and tacit learning was far greater than applicable science of the time. However, the exponential growth of science was much greater than the growth of craft knowledge induced through the *application* of scientific methods and rigorous use of experimentation. By the end of the eighteenth century, chemical analysis of compositions and control of the constitution of bodies, glazes and raw materials was an accepted part of industrial practice. Ceramics had changed its role from an object and instigator of chemical studies to a net user of chemical studies. Over the period of a century or so, the growth of scientific knowledge outran the level of craft knowledge by a substantial degree. Sometime during the first half of the twentieth century, ceramics had attained the role of a science-based technological industry. During the next half century science has continued an exponential growth rate far exceeding that of industrial knowledge. The challenge facing the ceramic industries has changed from developing science to being able to comprehend and apply it.

In this overall development the role of social constructs and cultural context can hardly be exaggerated. As might be expected, high value added products such as porcelain in the early eighteenth century and electronic ceramics in the middle twentieth century have been given the major portion of scientific attention and sophisticated technological development. Traditional clay-based ceramic industries must make special efforts to benefit from new science and new sophisticated science-based technologies. The challenge is to apply the wealth of scientific knowledge of structures, processes and operational principles as tools in solving specific problems facing the ceramic industry.