History of Ceramic Engineering by Someone Who Has Been There for About Half of It

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INTRODUCTION

Motivation and Scope

The reasons for choosing this topic are: the title is close to being true; a similar paper was written in 1988,[1] and a couple of others earlier,[2,3]; and it is of interest to examine the current status of ceramic engineering education some 20 years later. More directly, I have a vested interest in that I was the sixth, and last, ceramic engineering department chair at The Ohio State University where Edward Orton, Jr. founded ceramic engineering as a distinct engineering discipline in 1894 and was its first chair. The focus, comments, and evaluations are relative to the clearly identifiable BS ceramic engineering degree because that is the level program that started as a separate academic discipline and continues today. In addition, the status and viability of the relatively small number—and curricularly similar—BS ceramic engineering programs whose genealogy goes back to the beginning can be easily evaluated. In contrast, the much larger spectrum of diverse and significant graduate level ceramics research and education efforts—mainly in materials science and engineering programs—have many different origins, most unrelated to the founding of the discipline, and are not always easily identified as ceramics.

For the Colorado School of Mines, the interactions between ceramic engineering, and some of its notable persons, with Colorado is of particular interest. For example, there is Mount Orton in Rocky Mountain National Park that presumably was named after Edward Orton, Jr.,[4,5] and the interesting questions are why and how it was so named. As a result, contacts were made with the Board of Geographical Names and the USGS and some of the Orton archives were examined to see if these questions could be answered. Furthermore, if Orton had a Colorado Mountain named after him, what other contacts did he have in Colorado? Did he have any interaction with the predecessors of CoorsTek, for example.

In addition to the Orton-Colorado connection, several connections and coincidences in ceramics involving myself, ceramic engineering history, Colorado, and the Colorado School of Mines are presented. Some of these connections will be perceived to be stretching just a tad, but the intent is to stimulate interest in the Mines community. Dispersed in the paper will be a few scientific and technical points for similar reasons.

Finally, the history of ceramic engineering as a stand-alone academic discipline can serve as a model for the past and future—although differing in detail—of other small and specialized or boutique engineering disciplines, which are popular today.

Originally, my intention was to also present the evolution of lighting technology to demonstrate the role of high technology ceramics as "enabling" materials and their impact on ceramic engineering education. However, including historical discussions of "limelight," the Welsbach mantle, the Nernst lamp, high-pressure sodium vapor lamps, and fluorescent bulbs, proved to be just too much for this presentation: perhaps at some other time? However, the critical role that the development of translucent, high-density aluminum oxide, Al_2O_3, had on enabling the high-pressure sodium lamp, and its ubiquitous deployment, will be briefly sketched.

Iridium Flares

Figure 1. Iridium flare 7/23/2007, Bloomington, Ill., (D. W. Readey photo)

Figure 1 shows an Iridium Flare taken on July 23, 2007 from my current driveway in Bloomington, Illinois and it demonstrates one of the things that I do in my spare time these days—practice amateur astronomy—in addition to showing that occasionally, but rarely, the skies are clear in Illinois. The flare occurs when either the antennas or solar panels, Figure 2, [6]of an Iridium satellite is in the correct position to reflect sunlight to earth. The reflections can become quite bright—up to -8 magnitude—depending on where the satellite is relative to the observer when it is in the correct position to reflect. The times when these are visible—usually shortly before sunrise or shortly after sunset—for different locations are listed on several websites; e.g. http://www.Heavens-Above.com.[7]

Figure 1 is a 30-second time exposure and shows that the flare starts dim, brightens to a maximum, and then fads away. As such, the flare brightness fairly accurately represents the history of ceramic engineering as a discrete academic discipline—it had a clearly identifiable start in the United States in 1894, reached its maximum enrollment and number of programs between 1960 and 1980, and currently is fading with only a few programs left, which may also disappear.

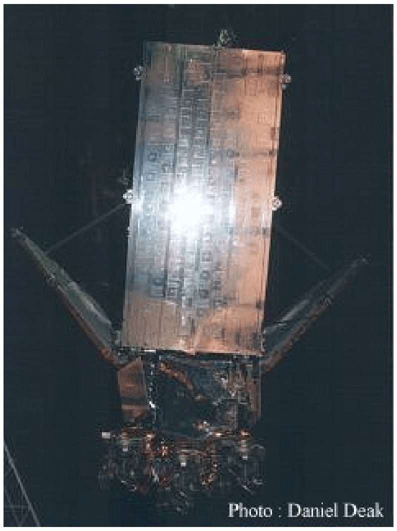


Photo : Daniel Deak

Figure 2. Iridium satellite. [6] (Daniel Deak photo)

Iridium satellites have other connections to ceramics and ceramic engineering education beyond providing interesting photographs. Certainly, there are several ceramic parts on each of these satellites either as capacitors, circuit boards, integrated circuit packages, and other components. These represent the "enabling" use of modern ceramics that is a recurring theme. But there is even a more personal and interesting ceramics connection. The Iridium satellite system consists of 66 active communication satellites that were intended for global coverage of cell phone communications. As originally planned, there were to be a total of 77 satellites, the atomic number of iridium, hence the name. Motorola was the prime mover and financial backer for the system and began planning the system in about 1990. The total cost was to be about $4 billion for the current 66 satellites and the system could not operate until completed in 1998. It went into bankruptcy in 1999 and was purchased for about 10 cents on the dollar by the current owners because it was not cost effective for most communications but it is acceptable for television networks, the U. S. Government, and others who currently use the services.[8]

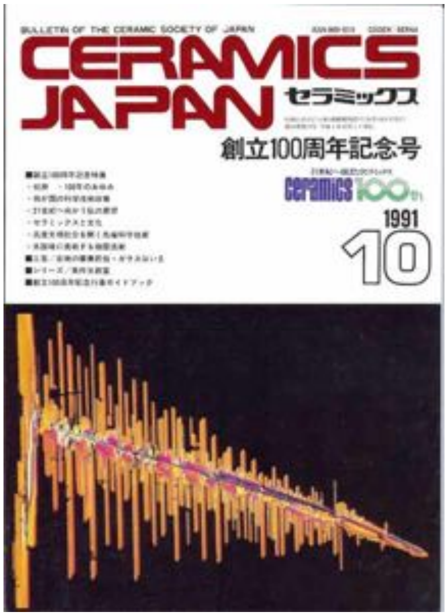


Figure 3. Cover of the *Bulletin of the Ceramic Society of Japan* on the 100th anniversary of the Society. (D. W. Readey photo)

I was president of the American Ceramic Society in 1991 when the Society went to Japan to celebrate the 100th anniversary of the Ceramic Society of Japan, Figure 3. Their president was Kazuo Inamori, founder and owner of Kyocera Corporation. Figure 4 was taken at the celebratory banquet of my wife, Suzann, with Dr. Inamori. The connection between Inamori and the Iridium satellites is that at the opening of the Kyocera Advanced Ceramics Technology Center in Vancouver Washington in September 1992, Figure 5, Dr. Inamori told my wife and me that he had been approached by Motorola to invest in the Iridium satellite program.[9] Apparently, Kyocera had a great deal of cash on hand at that time. He did indeed invest in the Iridium system and agreed to make the wireless telephone handsets for it.[10] The ceramic part encased in the polymer memento is a Si_3N_4 turbocharger rotor, Figure 6, which is typical of the ceramic automotive parts that were to be made at the Vancouver, Washington facility.

Figure 4. Suzann Readey and Kazuo Inamori at the Ceramic Society of Japan's 100th, Sept. 1991 anniversary banquet celebration. (D. W. Readey photo.)

Kazuo Inamori

Inamori is important to ceramic engineering education because he, and the corporation that he founded, have had a large impact on modern advanced ceramics, or “fine ceramics,” as they are called in Japan.[11] Furthermore, he has been a strong supporter of ceramic engineering education in the U.S. contributing seven chaired professorships. In a book written by David Halberstam, focusing on the US position in the post cold war world, Halberstam talks about the growth of Japan’s industry and cites Inamori as the embodiment of the Japanese drive for excellence and sense of responsibility, and gives the history of the foundation of the Kyocera Corporation.[12] Inamori was not accepted into a top college in Japan because of his family background but got a degree from a smaller university in 1955 and went to work for a ceramics company in Kyoto. Because of largely internal politics, Inamori left the company and borrowed \$10,000 from relatives and with a \$100,000 line of credit, founded Kyocera in 1959 at the age of 27—a highly unusual step for a young person in Japan. He had difficulty in selling his products in Japan because of the "old boy's network." So, in 1962, he came to the United States to buy patents to upgrade his business and look for new markets. After visiting various ceramics companies, he and everyone else realized that the quality his ceramics was superior to much that he had seen in this country. His success was largely due to his personal presence on the shop floor—ensuring that each step in the manufacturing process was precisely performed—and a strong desire for achieving perfection, rather than the highest profit, in his products. Interestingly, the then American Lava Corporation would not let him visit their plant during his 1962 visit.[12]

Figure 5. Ribbon cutting at opening of Kyocera automotive ceramics plant in Vancouver, WA, September 3, 1992. (Photo courtesy of Kyocera, Corp.)

Today, Kyocera is a \$13 billion company with about 18% in ceramic products, 34% in electronic devices and semiconductors, 20% in telecommunications equipment, 21% in information technology, and the rest in various areas including optical instruments and cameras.[13] In 1984, with his own funds, he started the Inamori Foundation which annually awards three Nobel-class Kyoto prizes in Advanced Technology, Basic Sciences, and Arts and Philosophy, which includes a stipend of ¥50 million (roughly \$500,000) each.[14] In addition, he funded Kyocera chairs in ceramic engineering at MIT, Case Western Reserve, and the University of Washington in the mid 1980's.[15] More recently, he has given Alfred University \$10 million for 4 endowed ceramic engineering chairs in the Inamori School of Engineering at Alfred.[16]

Figure 6. Souvenir from Kyocera plant opening with an imbedded silicon nitride—Si_3N_4—turbo charger rotor. (D. W. Readey photo)

American Lava

The American Lava Corporation has other interesting connections with ceramic engineering and Colorado beyond not letting Inamori in the front door. Moritz Thurnauer, the grandfather of Hans Thurnauer—a pioneer in advanced technical ceramics—started a ceramics factory in Germany during the 1800's that made acetylene (carbide) lamp burner tips from soapstone—block talc ($3MgO\cdot4SiO_2\cdot H_2O$)[17]—and Welsbach gas-light mantles.[18] In 1902, the Thurnhauer family established the Sunshine Lava Company to make talc burner tips in the United States in Chattanooga, Tennessee—to be near the talc deposits in North Carolina—and hired P. J. Kreusi, the son of one of

Edison's major assistants, John Kreusi, a master Swiss machinist [19,20,], as the company's first manager.[21,22] These ceramic lamp burner tips were not sold directly to the consumer but to a lamp manufacturer, which has been typically the case for high technology "enabling" ceramics in distinction to clay-based, commodity ceramics are sold. Block talc and block pyrophyllite ($Al_2O_3{\cdot}4SiO_2{\cdot}H_2O$)[23], because of their clay-like layer crystal structures and crystal habits, are soft and can be easily machined—with conventional metal-working tools—and fired at high temperatures to make insulating ceramics of very complex shapes. However, as with most ceramics, a significant amount of shrinkage occurs during firing that must be taken into account in the original pre-fired dimensions. Most of us who have worked with ceramics for more than a few years have had the opportunity to make a high temperature components from block talc or pyrophyllite.


Figure 7. Hans Thurnauer. (Photo courtesy of the Am. Ceramic Soc.)

During World War I, German assets were seized by the U. S. Government and after the war, Kreusi and his brother bought the plant which was then called American Lava.[22]

Hans Thurnauer (1908-2007), Figure 7, the grandson of American Lava's founder, came to the United States and received his MS in ceramic engineering as an exchange student at the University of Illinois in 1932. He went back to Germany to study for the PhD but subsequently returned to the US in 1935 because of the political environment in his home country and got a position at American Lava, through efforts of a faculty member at Illinois. At American Lava, he worked on electrical ceramics and ceramics for abrasion and wear applications, eventually becoming research director, vice president, and director until the company was taken over by 3M Corporation in 1953 when he became director of the inorganics section of the 3M research laboratory. He went back to Germany and received his PhD in 1958 and worked for 3M until 1964. He retired several times after that including once from CoorsTek where he was a consultant from 1966 until 1972.[18] In gratitude for the Illinois education and their efforts on his behalf, Thurnauer established the Hans Thurnauer Professorship in Materials Science and Engineering at the University of Illinois in 2003[24] and the first holder of this professorship is Professor Jennifer Lewis, Figure 8, who is currently director of the F. Seitz Materials Research Laboratory at Illinois[25] and whom we tried to hire into the Colorado Center for Advanced Ceramics at CSM in 1991 when she finished her ScD from MIT. General Electric bought American Lava from 3M in 1983 and it was later bought by Coors Ceramics, now CoorsTek. The plant was sold to Xion Technologies in 2002 and subsequently sold to Advanced Ceramic Technologies who continues to operate it and manufactures of variety of ceramic electronic components.[26,27]


Figure 8. Jennifer Lewis, Thurnauer Professor at the University of Illinois. (Photo courtesy of J. Lewis.)

WHAT ARE “CERAMICS?”

Ceramic Materials

Ceramics are some of the oldest known man-made objects. Figure 9 is the "Venus of Věstonice" a fired ceramic object some 26,000 years old found in the Czech Republic. One dictionary definition of ceramics[28] is:

Figure 9. "Venus of Věstonice," 26,000 year-old ceramic piece from the Czech Republic. (http://commons.wikimedia.org/wiki/Image:Vestonicka_venuse_v_NM.jpg, accessed 3/4/2008, Li-sung photo)

> "of or relating to the manufacture of any product made essentially a nonmetallic mineral(clay) by firing at a high temperature [Greek, *keramikos*, from *keramos*, potter's clay, pottery]"

"Traditional" ceramics are clay-based such as ”triaxial porcelain," typically high quality whiteware ceramics made from clay ($Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O$), feldspar ($K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$) and silica or "flint" (SiO_2). This is in distinction to "modern," "high-tech," "advanced," or "fine" (as used in Japan) ceramics that are made from processed or refined industrial chemicals such as: Al_2O_3, SiC, Si_3N_4, TiC, TiB_2, $Y_3Fe_5O_{12}$, ZnSe, and $Zr_{0.9}Y_{0.1}O_{1.95}$, etc.

Ceramic Engineering and Science

Figure 10 illustrates the continuum from fundamental science, through ceramic science, to ceramic engineering. Fundamental

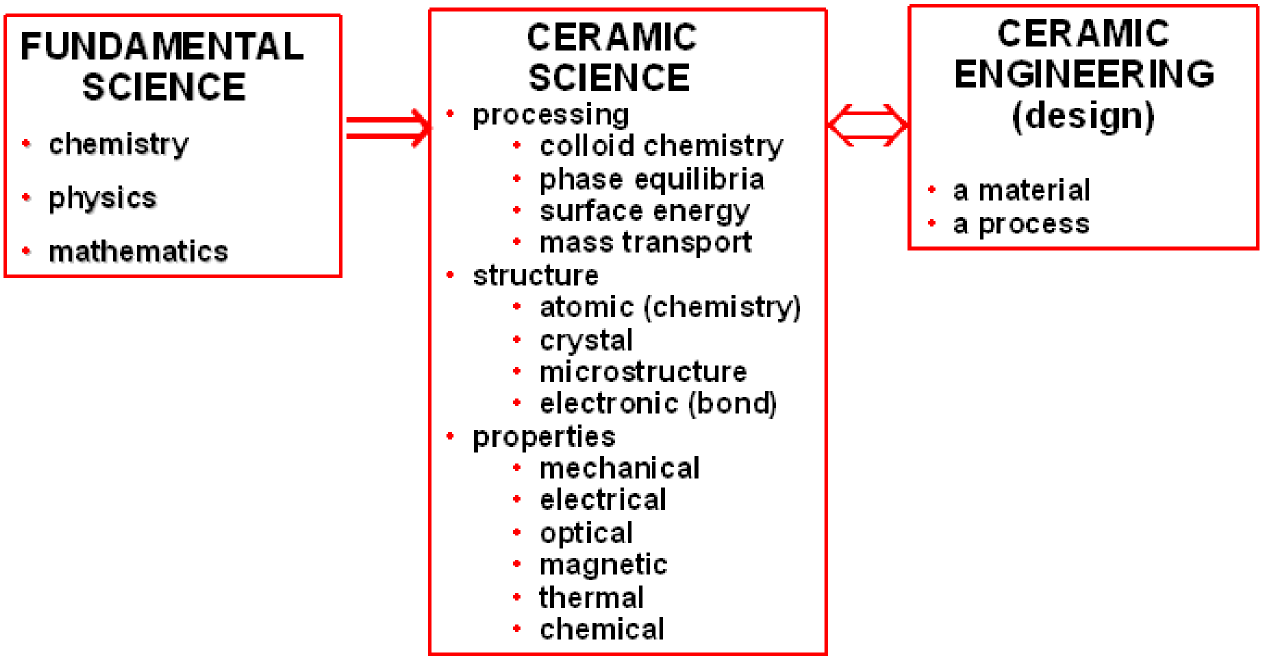


Figure 10. Continuum from fundamental science to ceramic science to ceramic engineering

science includes the principles of chemistry, physics, and mathematics. Ceramic science is concerned with how the principles of fundamental science relate to the processing, structure, and property relationships of ceramics. Like all branches of engineering, the focus of ceramic engineering is design. However, the ceramic engineer does not usually design a component, a machine, or a system. Rather he or she frequently designs a ***material*** having a specific set of properties and/or a ***process*** to fabricate the material. Ceramic engineering is ***not*** the application of a set of successful recipes passed down from one generation to the next! The ceramic engineering design function draws heavily on the principles of ceramic science often blurring the distinction between the two.

Figure 11 shows the relationships between the processing, structure, and properties of ceramic materials. This dictates the core of a modern ceramic engineering education. It was the realization of the influence of structure that transformed ceramic and other fields of materials engineering from what they were at the turn of the 20th century to their present state. For ceramics, the materials evolution from processing through structure to properties is a strongly vertically-integrated process.[4] If something goes wrong in the processing it will be reflected in the final properties. This is true for other materials such as metals. But metals can frequently be recovered if the desired properties are not achieved; they can be heat-treated again, or in the worst case, recovered as scrap and remelted, cast, deformed and heat treated. In contrast, most high technology ceramics begin as industrial powders with a sub-micron particle size that go through some forming and firing steps to produce a final dense ceramic part. If the properties of the final part are not those desired, the ceramic part ends up as "land fill" simply because the cost of regrinding the material to the initial fine particle size is prohibitively costly with the exception of a few extremely high value-added parts made from high-cost raw materials.

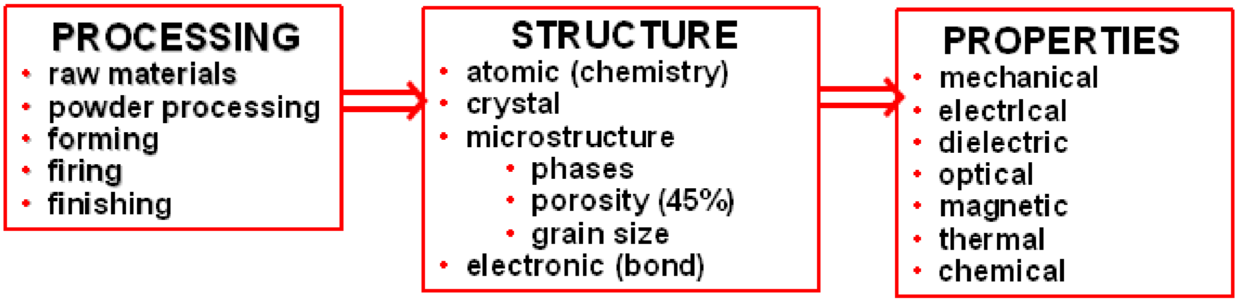


Figure 11. The vertically-integrated ceramic manufacturing from processing through structure to the final properties.

Processing—Structure—Properties

Figure 12 illustrates the steps in the processing of a modern high technology ceramic material; in this case, a polycrystalline, single phase, multi-component magnetic garnet material ($Y_{3-x-y}Gd_xDy_yFe_{5-a-b-c}Al_aMn_bIn_cO_{12}$—each constituent is added to adjust one or more of the suite of magnetic properties necessary for this application) used in phased array electronically-steered radar antennas such as those used in the Patriot missile system, Figure 13. First the multi-

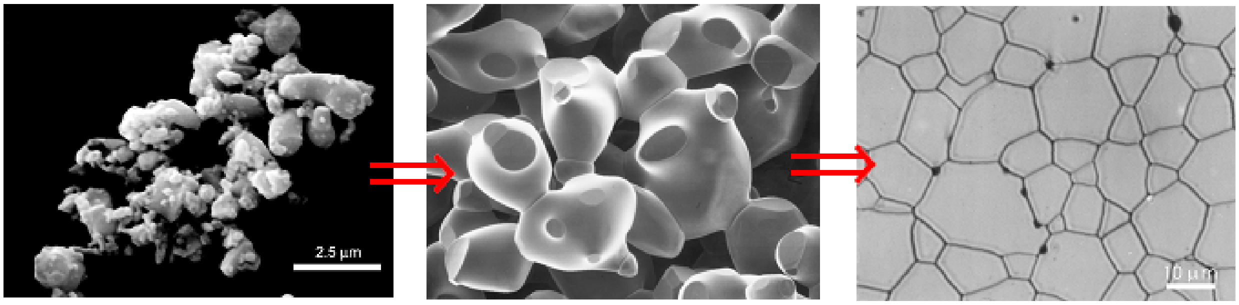


Figure 12. The changes in microstructure that takes place during solid state sintering at high temperatures of a high technology ceramic material: from a packed powder with about 45% by volume of pores (left); to the densifying powders at high temperatures where atoms and ions can move to reduce the surface area—pores—(middle); to the final polycrystalline microstructure with virtually no residual pores—black (right). (D. W. Readey photos.)

component powder is prepared (left photograph) by reacting the constituent oxides at high temperature to form the single phase material, which is then ground to a particle size appropriate for the forming and firing steps—about 1 µm or less so that each powder particle is a small single crystal. Ceramic powders when formed into some object—which can be done by any number of forming processes—pack like cannon balls and the formed part has about 45% porosity by volume. For most high technology ceramics, zero porosity is desired or at least left at a controlled amount. This is one of the major challenges in ceramics: being able to produce a given ceramic with little or zero porosity starting with something that is 45% porous. To accomplish this, high temperatures are necessary where the atoms or ions making up the ceramic are sufficiently mobile and can move to fill pores to eliminate the high surface area and surface energy associated with the porosity. Material flows by solid state atomic diffusion to fill the pores, middle photograph. If everything is done properly, the final part is a dense polycrystalline ceramic that has the correct crystallite (grain) size to give the desired properties, right photograph. In this microwave application, an average grain size of about 14 µm was necessary to give the magnetic hysteresis loop properties necessary for the application. Of course, for this application—a radar antenna—ceramics are required since they are both magnetic yet electrically insulating so that the microwave beam can pass through the antenna and be steered by changing the magnetization of the ceramic parts.

Figure 13. Phased-array radar for the Patriot missile system. (U.S. Defense Dept photo.)

Energy Intensity of Ceramics

Because ceramics are typically fired or densified at high temperatures, they are thought to be energy intensive materials. That is simply not true. For example, compare the energy intensities of aluminum oxide—Al_2O_3—and aluminum. To extract aluminum metal from aluminum oxide,

$$Al_2O_3(s) = 2\ Al(s) + 3/2\ O_2(g)$$

a free energy of almost 1600 kilojoules of energy per mole of Al_2O_3 is required.[29] On the other hand, the amount of energy to sinter that same aluminum oxide to a dense ceramic part is basically the heat energy lost on cooling the ceramic from the firing temperature, which is typically around 1700 ^oC. The heat capacity of Al_2O_3 is about 125 J/mole,[29] so the amount of heat required to heat one mole of alumina from room temperature to the firing temperature is:

$$\Delta H = C_p\Delta T = 125(2000\text{-}300) = 212.5 \text{ kJ/mole}$$

If the furnace were very energy efficient and perfectly insulated, then on cooling, all of this heat could be recovered to do some useful work and there would be essentially no energy lost. Even in the worst case of all this heat energy being lost, the necessary energy to fire the ceramic is only about one-eighth that required to extract the aluminum from the oxide. So intrinsically, ceramics are much less energy intensive than metals, for example, simply because the energy necessary to win the metal from the ore is typically much larger than the energy needed to fire ceramics. Practically, however, most ceramic furnaces are not very energy efficient and much more energy is actually used than required; but furnace efficiency will improve as the cost of energy increases.

Table 1
Traditional Ceramics

Classification	Products
heavy clay products	brick, roof tile, drain pipe
terra cotta	decorative heavy clay pieces
abrasives	grinding wheels, sandpaper, grain
cement	Portland cement manufacture
whiteware	china, decorative porcelains, sanitary ware, spark plugs, some electrical ceramics
enamels	porcelain enamel coatings
glass	window glass, flat glass, bottles, dishes
refractories	high temperature insulation, corrosion resistant ceramics

Traditional Ceramics

Traditional ceramics are essentially based on clays and similar raw materials taken from the earth without a great deal of preprocessing or purification before being made into ceramic parts, Table 1. It should be noted that each of these products are "simple" or end-items in themselves that could be sold as individual units to consumers.[4] Although, some, such as porcelain enamels, are not stand-alone but are an "enabling" part of a more complex system—e.g. water heater—more typical of the role that modern, high-technology ceramics play.

As mentioned above, high quality whiteware ceramics are made from clay ($Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O$), feldspar ($K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$) and silica or "flint" (SiO_2). Figure 14 shows the platy character of clay crystallites—a micron or so in lateral dimension and fractions of a micron or nanometers in the thickness of the plates. As a result, ceramists have been working with "nanomaterials" for literally thousands of years! The platy habit of clay crystals in the presence of water generates the "plasticity" of clays allowing them to be easily formed into complex shapes by a variety of forming techniques.

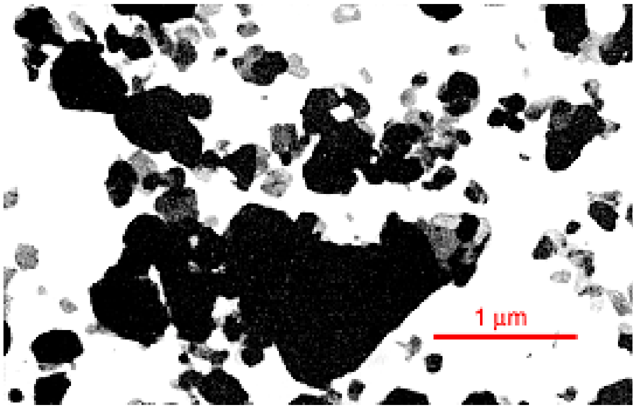


Figure 14. Electron micrograph of clay particles—crystals. (Courtesy of J. M. Huber Corporation.)

In contrast to most high technology ceramics, Figure 12, the fired microstructures of traditional clay-based ceramics are much more complex. Figure 15 shows the microstructure of a fired—typically in the neighborhood of 1300 °C—triaxial porcelain demonstrating this. The microstructure is very inhomogeneous and not in equilibrium; if it were, the only phases present would be uniform sized crystals of mullite ($3Al_2O_3 \cdot 2SiO_2$) in a silicate glass matrix that would have been a silicate liquid at the firing temperature. However, the relatively large SiO_2 crystals have only partially reacted (dissolved) with the glass—largely from the melted feldspar—and cracks have formed around the SiO_2 due to phase transformations that occur on cooling. Large mullite crystals have formed in the glass while fine mullite crystals exist where the clay particles were—the clay decomposes into mullite and SiO_2. In addition, there is present the ubiquitous residual porosity.

Microstructure and Ceramic Engineering

The relationship between microstructure—structure that can be seen in a microscope—and properties is now a well-established part of a ceramic engineering and ceramic engineering education. However, this has only occurred over the last fifty or so years. In contrast, the importance of microstructure-property relations for metals was recognized much earlier. The historical development of the microstructural investigation of metals has been comprehensively documented by C. S. Smith.[30] The importance of composition on strength dominated the development of metals, primarily iron and steels, during the late nineteenth century. Since iron and steel were important structural materials, strength was the most important property and remains so for most applications of metals. This ultimately led to the investigation of microstructure by Sorby[30] and its relation to

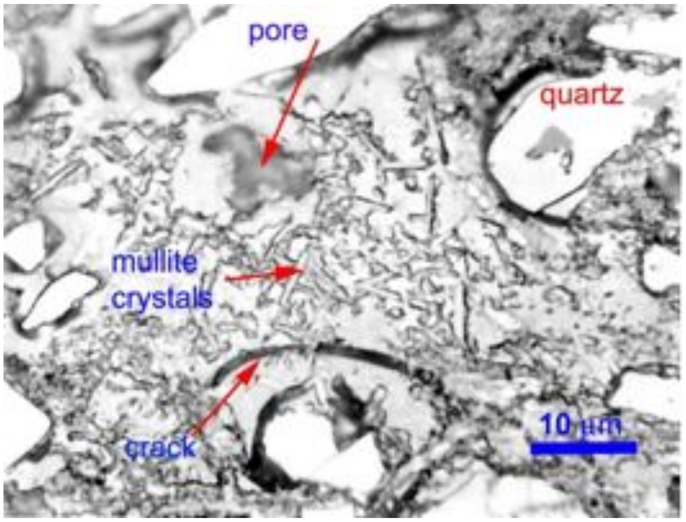


Figure 15. Triaxial porcelain showing the complexity of the multi-phase, non-equilibrium microstructure. (D. W. Readey photo)

composition and properties. Interestingly, Sorby first studied the microstructure of rocks in transmitted light using thin sections. When he studied metals, he again used thin, mounted samples but examined them in reflected light.

Mineralogists quickly adopted Sorby's thin section technique for rocks while the metallurgists adopted his techniques more slowly.[30] It is worth noting that the term "microstructure" originally had nothing to do with the scale of what was being observed in the microscope. Initially, Sorby called what he could see in the optical microscope "microscopical structures."[30] By 1900, the term had been shortened to "microstructure," was in common use by metallurgists,[31] and continued to be used in that way for over a hundred years. Today, with the advent of materials science, the use of the term "microstructure" has been co-opted and not only "microstructure" but also "nanostructure" and "mesostructure" are used to refer to the size of the features seen in microscopes. Nevertheless, microstructure evaluation was used much earlier and more extensively by the metallurgists than the early ceramists. The first microstructural evaluation techniques for ceramics were the thin sections used by the geologists.[32] However, the wide use of microstructure analysis of ceramics came long after a rather extensive understanding of the relations between composition, heat treatment, microstructure, and properties of steel had become available.[33]

Why did the use and correlation of microstructures with properties come much earlier for metals than ceramics? There are several possible reasons but probably the most important is that the mechanical strength of metals, particularly iron and steel, was the main property of interest. As is now well understood, most of the mechanical properties of metals could be correlated with their average microstructures. This is certainly not true for ceramics. The strength of ceramics is determined by the presence of random flaws, virtually impossible to detect by routine microstructure analysis; and a toughness parameter which *is* related to the average microstructure.[34]

There may have been an interest in improving the mechanical properties of ceramics, but there was little evidence that composition or processing influenced strength except that firing at a higher temperature helped. For load-bearing ceramics, bricks for example, the strength was usually adequate. Certainly, there were probably few spectacular examples of ceramic mechanical failures comparable to an iron bridge collapsing or boiler exploding that would have prompted more careful scrutiny of the strength of the ceramics. In contrast, the opacity and gloss of enamels depend on their average microstructures which explains why they were examined in the early literature.

Even if there had been attempts to correlate microstructure with mechanical properties, efforts would have met with little success because of the complex and fine-scale microstructures in clay-based ceramics. The optical microscope simply does not have the resolving power to be of much use but the much later wide availability of electron microscopes enabled full microstructure observation and evaluation of ceramics, both clay-based and otherwise.

As late as the middle 1950's, the main use of microscopy in ceramics was to identify the phases present and their distribution with little effort to correlate microstructure with properties.[35] In the early 1960's the role of microstructure of ceramics was still insufficiently appreciated that a paper entitled "Effects of Microstructure on the Properties of Ceramics"[36] could justifiably appear in the literature. Today, the correlation between processing, microstructure, and properties is central to ceramic engineering education. As a result, ceramic engineering and metallurgical engineering have much more in common today than they once did.

Engineering Education and Industry

There is no question that *industry* creates the demand for academic training in specific branches of engineering. Certainly, that was the case for ceramic engineering. Engineering disciplines are born and die as industrial demand waxes and wanes. An important recent example is the creation of computer science and engineering programs. In conflict with this is the periodically recurring academic theme that a degree should *not* be narrowly focused and oriented to the industrial job market. Engineering is usually the focus of such introspection particularly when the industrial demand for engineers is high. It should be kept in mind, however, that many universities were created specifically to provide educated people to aid industry and agriculture in a given state or locality. The Land Gant Universities, which play a significant role in engineering education, were founded to "...promote the liberal and practical education of the industrial classes in the several pursuits and professions of life."[37] It was the need for a scientific basis for the manufacture of ceramic products that lead to the beginning of formal ceramic engineering education.

EDWARD ORTON, JR. AND CERAMIC ENGINEERING

Birth of Ceramic Engineering

Edward Orton, Jr. was born into a family committed to education and the study of geology. He was the son of Dr. Edward Orton, who began training for the ministry and later switched to science. The senior Orton started his career in Ohio as principal of the preparatory school of Antioch College in Yellow Springs in 1863. Orton's father was virtually exiled from New York for his liberal religious views which were opposite to the more rigid contemporary views.[38] "He did not pretend to know the answer to the question of the ages-`Is there an immortal life?' He was too good and thorough a scientist to affirm a fact that he knew must forever remain in the realm of belief or hope."[39] He taught geology and later became a principal assistant to the State Geologist of Ohio. He was named president of Antioch College and in 1973 inducted as the first president of the newly formed Ohio State Agricultural and Mechanical College later to become The Ohio State University. He was also its professor of geology, mining, and metallurgy. After resigning the presidency of Ohio State in 1881, he became the State Geologist until his death in 1899.

Edward Orton, Jr., Figure 16, was trained as a mining engineer at Ohio State and received his degree in 1884. During his junior year he prepared a report on the clays of Ohio which was published in the reports of the Geological Survey of Ohio. His senior thesis was entitled "Plans and Specifications for a Fire-Brick Factory" Considering his later accomplishments, it is clear even at this early age that Orton was a born entrepreneur. While in college, he began the predecessor of what is today the Ohio State Marching Band, Figure 17.

Figure 16. Edward Orton, Jr., (1863-1932) in 1912. (The Ohio State University Photo Archives, Image Orton, Edward x3556.)

From 1884 to 1893 he held a number of positions as a chemist and superintendent of iron and coal mines, blast furnaces, and clay plants. In one of these positions, he became the first regular manufacturer of ferrosilicon in the United States. In 1890 he was superintendent of an unprofitable paving brick plant. He could find no technical literature in the English language on clay-working that was helpful in solving some of his production problems. Technical literature on ceramics like that on the metallurgy of iron, which he had used to solve production problems in that industry, was unavailable. In contrast, production problems in ceramics were solved by common sense and trial and error rather than by the application of the principles of chemistry and physics.

His next job was to prepare a report on the clay-working industries in Ohio. He traveled extensively and found a lack of technical data and literature on clay working, information he felt necessary to improve production of clay-based products. Therefore, he began working with the Ohio Brick and Drain Tile Association and the National Brick Manufacturers Association to get a bill passed in the state legislature establishing formal education in clay-working. He was successful, and without any help from inside the university, a bill was passed in April 1894. The statute required "The Board of Trustees of The Ohio State University to establish in said University a department of ceramics, equipped and designed for the technical education of clay-, cement-, and glass-workers."[40] Furthermore, the statute specified the curriculum, equipment necessary, annual budget, and salary for the department head. The Board of Trustees met on May 26, 1894, and directed Orton to organize the department and he became "Director of the Department of Ceramics" on July 1 and later in the year was named "Director of the Department of Clayworking and Ceramics." The first students began a two-year "short course" that fall and Orton's first courses were concerned with the chemistry of silicates. During the 1895-96 school year there were nine first-year and six second-year students, Figure 18.

The departmental laboratories were set up in the basement of the newly-completed Orton Hall, Figure 19. Orton Hall stands on the main oval of the Ohio State campus, today houses the department of geology, and was named after Edward Orton, Jr.'s father. In 1923, Orton Jr. funded the Edward Orton library in Orton Hall and there is a plaque in the entrance, Figure 20, memorializing the founding of ceramic engineering as a separate academic discipline. Shortly after the establishment of ceramic engineering at Ohio State, several other states began ceramic engineering degree programs (see

Figure 17. The Ohio State Marching Band performing script Ohio. (The Ohio State University Photo Archives script Ohio 1998.)

Figure 18. 1895-96 students in ceramic engineering at Ohio State with Orton. (Ohio State University Photo Archives, Image Ceramic Engineering 222.)

Figure 19. Orton Hall on the Main Oval of Ohio State's campus. (D. W. Readey photo.)

Table II) suggesting that if Orton had not started it, someone else would have.

Orton's Philosophy of Engineering Education

Some points made in 1900 Ohio State College of Engineering Bulletin are still relevant today and certainly reflect some of Orton's feelings about engineering education.[41]

> The First year of each of the four year courses leading to a degree is very similar. There are two reasons for this:
>
> First. All engineering education is based on the constant use of the fundamental sciences, Mathematics, Physics, Chemistry and Drawing. Consequently, it naturally happens that the various courses start from a common point, proceed side by side for a time, but specialize and subdivide more and more as they progress towards completion.

Figure 20. Memorial plaque in the lobby of Orton Hall commemorating the birthplace of ceramic engineering. (D. W. Readey photo.)

> Second. It is very commonly the case with young men entering college for a technical education, that their natural aptitude for one line of work or another has not been sufficiently developed to enable them to make a wise or final selection of their course in the university.

This philosophy of the beginning engineering education has not changed with the exception that it has become somewhat less chauvinistic. Concerning the "Course in Ceramics", the following comments are offered[41] which reveal Orton's philosophy of what the ceramic engineer of 1900 should know.

> The Ceramic Industries include, according to the classification here adopted, those industries in which the production and utilization of natural and artificial silicates is the end in view, viz., clayware, glass and cement. These three industries constitute a natural division of chemical technology, and though they are intimately connected with the field of the metallurgist on the one hand and with the manufacturing chemist on the other, still they have an individuality which necessitates their study and exploitation as a separate field of industrial science.
>
> The work which the ceramic engineer must be prepared to supervise is broad and varied. In the preparation of any product of uniform physical and chemical qualities from the crude rocks and minerals of the earth's surface, a knowledge of chemistry is the foremost essential ...In this course, therefore, chemistry forms an important part of the training, beginning with the first term and continuing through three years of purely chemical work, followed by a year of practice in the application of chemistry to ceramic operations."

Orton clearly recognized the similarities between metallurgy, chemistry, and ceramics yet he felt there were sufficient differences to justify a separate ceramic engineering program. The current academic philosophy is just the opposite with the inclusion of the various materials engineering disciplines—metals, ceramics, polymers, semiconductors, etc.—under the umbrella of "materials science and engineering." The early emphasis on chemistry is notable since its importance in ceramics was apparently rediscovered not too long ago.[42,43]

Orton, the Renaissance Man

Edward Orton, Jr., Figure 21—1926—accomplished a great deal during his life in addition to founding ceramic engineering.[40,44] He left the University when he joined the Army in 1917 and afterward, devoted his professional efforts to the American Ceramic Society, the cone business, and reserve officer activities.

Figure 21. Edward Orton, Jr. in 1926. (The Ohio State University Photo Archives, Image Orton, Edward, WWJ.)

1896	Started the pyrometric cone business, which is now the Edward Orton, Jr. Ceramic Foundation. Pyrometric cones, shown in Figure 22, are inexpensive time-temperature integrators made from clay-based materials indicating when a ceramic material of a given composition reaches its optimum fired condition.
1898	One of the organizers of the American Ceramic Society and served as its secretary until 1917.
1899-1906	State geologist of Ohio
1902-1908	Dean of engineering, Ohio State
1910-1916	Dean of engineering, Ohio State
1917-1919	U.S. Army, commission reserve Colonel
1922-1924	Commissioned Brigadier General, reserves, known from then on as "General Orton;" President Ohio Reserve Officers Association: President Columbus Chamber of Commerce; Dedicated Orton Library
1925-31	Vice-president, Ohio Archeological and Historical Society; Treasurer, Columbus Gallery of Fine Arts; President of the American Ceramic Society; Vice-President, Reserve Officers Association of the U.S.
1932	Died, Columbus Ohio

Figure 22. Pyrometric cones. (Photo courtesy of the Edward Orton, Jr. Ceramic Foundation.)

Orton and Colorado

Mount Orton

Since this presentation is made at the Colorado School of Mines, the relationship between Edward Orton, Jr. and Colorado merits some discussion. There is a Mount Orton in the Wild Basin area of Rocky Mountain National Park shown in Figure 23. Figure 24 is a view of Mount Orton from the Northwest. It is about two miles south of Long's Peak and is only 11,722 feet high. Nevertheless, the interesting questions are, "Is this mountain named after Edward Orton, Jr.?" and, if so, "How did it come to be named?" Since Orton seemed to work within the system and use the government to his advantage, it seems likely that Orton may

Figure 23. Location of Mount Orton in Rocky Mountain National Park. (taken from http://www.nps.gov/carto/PDF/ROMOmap1.pdf, accessed 12/15/2007, red inset around Mt. Orton added by D. Readey)

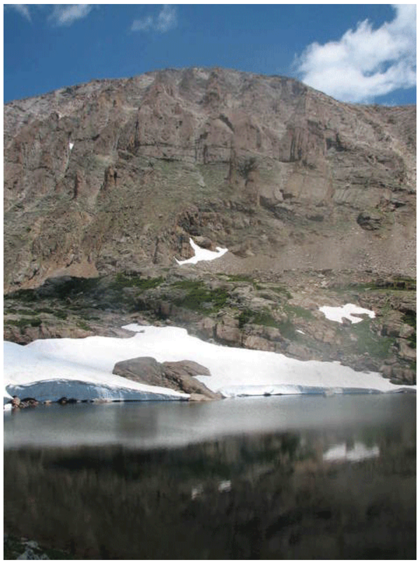


Figure 24. Mount Orton as viewed from the Northwest across Lion Lake. (http://i185.photobucket.com/albums/x300/hikemaster/Scott/7-10%20Snowbank%20Lake/July10012.jpg, accessed 2/13/2008)

have worked with either the state or the federal government to get the mountain named, probably after his father. However, this does not appear to be the case.

In his 1977 Orton Memorial Lecture at the American Ceramic Society annual meeting, Hans Thurnauer offers some insight into how Mount Orton got its name.[4] In the early 1900's Orton spent several summers in Rocky Mountain National Park conducting a survey of Mills Moraine in the Wild Basin and Long's Peak area. Why should the state geologist from Ohio be doing a survey in Colorado? Was he working for the U.S. Geological Survey? There is no evidence of this and no state or federal reports about this work exist.[45,46] In 1908, on one of these excursions he and some of his students were joined by Dean Babcock[47] who lived in Estes Park and was one of the first forest rangers in Rocky Mountain National Park.[48,49] According to Thurnauer and others,[4,5,47,50] Babcock saw to it that Mount Orton was listed on the Cooper-Babcock map of the area in 1911. And the name was officially approved by the Board of Geographical Names in 1911.[51] Apparently, this was not widely known until quite later when a painting of Mount Orton by Dean Babcock, commissioned by Orton, Figure 25 was presented to the Orton Library in Orton Hall in 1923.[52] Interestingly, there is a letter in the Orton archives[53] from T.C. Mendenhall (1841-1924) congratulating Orton on having the mountain named after him dated February 1, 1923 and pointing out that he, Mendenhall, was responsible for the establishment of the Board of Geographical Names while he was superintendent of the U. S. Coast and Geodetic Survey, and was chair of the Board until 1894. Mendenhall had been the first physics professor appointed at the predecessor to Ohio State in 1873 and the Mendenhall Glacier in Alaska is named after him.[54] The latter is relevant for a couple of reasons, the first being that Orton's primary reason for his Colorado survey was his interest in glaciology.

Although, no published reports exist on Orton's Colorado and Rocky Mountain activities, there is a typed 62-page manuscript for a 55-slide presentation to Sigma Xi at the Case School (presumably now the Case Western-Reserve University) on June 5 (either 1905 1908, not clear from the handwritten date) in the Orton archives at Ohio State,[55] which give a detailed presentation on the glaciological history of that region based on his observations and that sheds some light on his Colorado activities. In it he states,

Figure 25. Painting of Mount Orton by Dean Babcock that hangs in the Orton library in Orton Hall. (D. W. Readey photo.)

> The investigation which I am to present to you this evening ...is not a serious study, undertaken with the high purpose of making an addition to scientific knowledge. It is chosen from the field of my pleasure rather than my duties, and represents merely some observations made during a couple of short summer vacation trips, in a field outside the line of my own professional work—and with no other motive than the pure pleasure of doing it.

It appears that he was surveying the area simply as a hobby and to satisfy his own personal curiosity. Following a discussion of glaciers and the ice age, Orton says,

> What is the value of such investigations? The value of much of the knowledge of the world is chiefly confined to the pleasure which it gives. We are not able to earn our living any better because we know about such things, but we are able to enjoy our lives much better from such knowledge.

After a discussion about glacier motion, he says, "This ice flows like a stiff fluid. Incredible as it may seem, it literally flows...Whatever the method, the result is clear: it flows..."

<u>Other Colorado Connections</u>

Figure 26. The logo of the Herold Pottery. (courtesy of CoorsTek.)

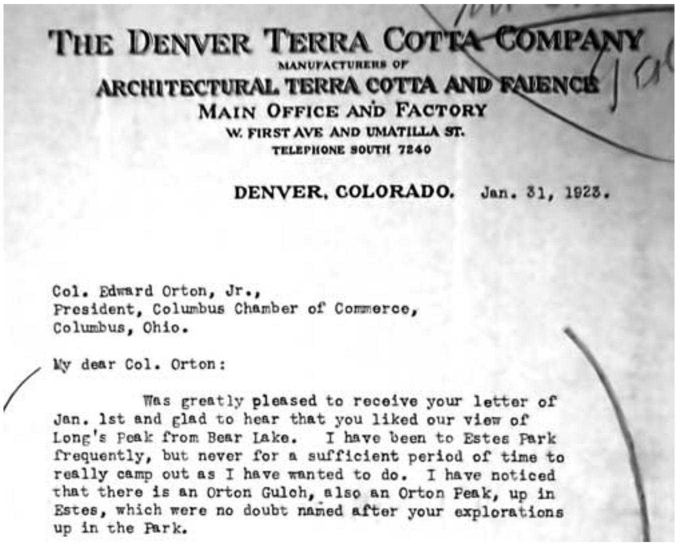
The predecessor of the Coors Ceramics Company, now CoorsTek, was the Herold China and Pottery Company, Figure 26, founded in 1910 by a German immigrant, John Herold.[56] The company made a heat-resistant porcelain and in 1914, Adolph Coors owned 70% of the company through investment, and John Herold resigned leaving Adolf to take control of the company. In 1915 during World War I, there was an embargo on German chemical and scientific porcelain and the federal government asked domestic potteries to satisfy the demand. Of the seventeen potteries that answered this call, only two were successful in producing chemical porcelains, the Herold Pottery and Champion Spark Plug Company and both supplied them until 1940 when the World War II demand for spark plugs caused Champion to focus on that business only. In 1920, Herold Pottery became the Coors Porcelain Company, Figure 27, and has evolved into CoorsTek, which is the largest U.S.-based high-technology ceramics manufacturer and still makes chemical laboratory porcelain ware that now only represents about 2% of its annual sales. If one looks carefully at the fine print of Figure 25, it is seen that Herman F. Coors is the manager of the pottery.

Figure 27. Logo of the Coors Porcelain Company circa 1920. (courtesy of CoorsTek.)

It is only natural to ask whether Edward Orton, Jr., with his interests in ceramics and Colorado had any contact with either the Herold Pottery or Coors Porcelain. There is no evidence in the Orton archives that he did. The reason for this may have been the fact that his visits to Colorado were in the early 1900's and predated the Herold Pottery. The only

Colorado correspondence found in the OSU Orton archives is a letter from the Denver Terra Cotta Company, Figure 28, essentially congratulating Orton on the naming of Mount Orton. [57] It is interesting to note that the Denver Terra Cotta company supplied much of the decorative clay pieces to many of the buildings in the Denver area, became part of the Northwestern Terra Cotta Company in 1926 [58] and closed in 1965.[59]

So the conclusion is that Orton was drawn to Colorado purely as a vacation location and, while he was there, he surveyed part of what is now Rocky Mountain National Park as a hobby and had a mountain named after him because of his interests!



THE DENVER TERRA COTTA COMPANY
MANUFACTURERS OF
ARCHITECTURAL TERRA COTTA AND FAIENCE
MAIN OFFICE AND FACTORY
W. FIRST AVE AND UMATILLA ST.
TELEPHONE SOUTH 7240

DENVER, COLORADO. Jan. 31, 1923.

Col. Edward Orton, Jr.,
President, Columbus Chamber of Commerce,
Columbus, Ohio.

My dear Col. Orton:

Was greatly pleased to receive your letter of Jan. 1st and glad to hear that you liked our view of Long's Peak from Bear Lake. I have been to Estes Park frequently, but never for a sufficient period of time to really camp out as I have wanted to do. I have noticed that there is an Orton Gulch, also an Orton Peak, up in Estes, which were no doubt named after your explorations up in the Park.

Figure 28. Letter to Orton from Denver Terra Cotta Company congratulating him on the naming of Mount Orton. (The Ohio State University Archives, Edward Orton, Jr. Papers [Record Group 40/39/7/25])

Growth of Ceramic Engineering Education

Ceramic Engineering in 1925

The thirtieth anniversary of ceramic engineering was celebrated in at a meeting of ceramic educators and industrialists on January 16 and 17, 1925 at Ohio State and sponsored by the Ohio Ceramic Industries Association. The meeting was summarized by several papers published in the *Bulletin of the American Ceramic Society*. The divisions of the American Ceramic Society at this time reflected the major clay-based ceramic industries and included: Art, Enamel, Glass, Refractories, White Wares, Terra Cotta, and Heavy Clay Products. A total of 493 graduates in ceramic engineering had gone into these industries up until this time and the enrollments at the various schools is shown in Table II.[60]

Ceramic Engineering in 1936

By 1936 the total ceramic engineering enrollment had risen modestly to about 587 with the addition of undergraduate programs at the University of Toronto(1925), the University of Missouri(1926), and the Virginia Polytechnic Institute(1928). In 1934, the Massachusetts Institute of Technology started the first all-graduate program in ceramics and 7 students were registered in 1936.[61] The total ceramic engineering enrollment was not significantly higher in 1936 than it was in 1925 because it had decreased considerably during the depression and in 1936 it was beginning to increase due to preparations for World War II.[62].

Table II
1925 Ceramic Engineering Enrollment

Institution	Year Founded	1925 Enrollment
The Ohio State University	1894	101
New York State School of Clay-Working and Ceramics (now Alfred)	1900	129
Rutgers	1902	30
University of Illinois	1905	89
Iowa State College	1906	35
University of Washington	1919	12
North Carolina State College	1923	8
Georgia School of Technology	1924	4
The Pennsylvania State College (now University)	1925	11
	Total	479

World War II

Just as the number of graduates began to increase, World War II caused another decline in ceramic enrollments. There was an unsuccessful attempt to have ceramic engineering declared essential to the war effort to defer ceramic engineers from entering military service. It has been suggested that part of the reason for the lack of success was that a good definition of ceramics did not exist.[63] Ceramics was perceived to include pottery, tile, and other products of little or no importance to national defense. Whether a good, concise, yet comprehensive definition of ceramics has ever existed is debatable. As McMahon pointed out,[64] "The first editorial of the *Clay-Worker* stated, `We intend to give our readers carefully prepared articles on the manufacture of bricks (all kinds), encaustic tiles, terra cotta, sewer pipe, pottery, etc.' It is the `etc.' that has bothered us ever since." Certainly, a major factor influencing the future of ceramic engineering is an inaccurate and incomplete perception of what ceramic engineering is all about.

A main part of the effort to get ceramic engineers deferred was a pamphlet published jointly by the Ohio Ceramic Industries Association and The Ohio State University in 1942 to show that ceramic engineering was essential to the war effort.[65] This document pointed out that there were about 4000 ceramic plants which could hire five or more ceramic engineers each. Since there had been only a total of 1500 ceramic engineers graduated by all the schools since the beginning of the degree, there was a clear shortage of talent. As a result, the demand for ceramic engineers was high and the average annual starting salary of $2500 was above the average for engineers. An article published in February 1942 indicated that all 1942 ceramic engineering graduates already had jobs.[66]

Post World War II

Immediately after the war, returning service men and women caused a rapid expansion in enrollment in ceramic engineering departments to about 900 in 1948.[67] The number of degrees granted increased as well: 1946-47, 98; 1947-48, 209; 1948-49, 244. Then the enrollments and the number of degrees granted began to decline again: 1950, 330; 1951, 260; 1952, 187; 153, 125(est.); 1954, 137(est.).[68]. It was also a time of change in the content of ceramic engineering education. There was a trend to teaching more "unit processes" or general principles rather than "super trade school" courses.[69,70] The curriculum in 1952 consisted of mathematics(11.6%), chemistry(13.9%), physics(6.9%), mechanics(5.6%), engineering drawing(3.3%), and ceramics(21.6%).[70] The importance of chemistry was still appreciated, "In the field of ceramics, chemistry plays a far more important role than in some other branches of engineering."[70]

In the mid to late 1950's, the similarities between materials was becoming realized and the inclusive concept of materials science and engineering and the beginning of "materials" degree programs began to impact ceramic engineering, as well as metallurgical engineering, education.[71] The incorporation of metals and ceramics—and to a lesser degree polymers, composites, and electronic materials—into a single degree program is, of course, the complete opposite to Orton's original motivation for a separate degree program. In fact, "A curriculum in ceramics cannot be superseded by one on material sciences per se...it is no substitute for courses dealing with ceramic science and technology."[4] This sentiment is echoed by many of our metallurgical engineering colleagues about their field.

Post 1950: The Inaccurate Perception of Ceramic Engineering

By 1960, because of the impact of the transistor and, with it, a better understanding of solid state physics, the space program, the cold war with new defense requirements, emphasis on new materials having unique properties that were "systems enabling" began to grow. Ceramics as a subfield of materials was perceived by some to be behind metallurgy in applying the principles of solid state physics to the design of new materials. A conference was held in 1962 to address this issue:[72]

> The traditional education of a ceramist has been largely directed toward production techniques of useful glass or clay-based products. So long as the demands upon these materials remained less than critical, specifications could be met by known technology. However, the needs of the future, as well as the present, can no longer be satisfied in this manner due to the critical performance demanded of materials for electronics, space exploration, and energy conversion uses, just to mention a few examples. A greater understanding of the relationships between structure and properties is inherent in any effort to improve the performance of ceramic materials. This in turn involves increased attention to those aspects of physics and chemistry (solid state physics, crystal chemistry, surface chemistry, etc.) that are presently applicable to the problems of ceramics and related ionic solids.

This is an overly critical comment and is partly due to the lack of familiarity—without much effort on the part of the critics to improve that familiarity—with what constituted a ceramic engineering education. Perhaps, this criticism might have been more accurately directed at the amount of federally-sponsored graduate research being done by the faculty in traditional ceramic engineering schools compared to their counterparts in metallurgical engineering. Evaluated data do not exist to support this, but personal observation , based on the three years spent in Washington at the AEC/ERDA/DOE—during its evolution to better solve US-dependence of foreign sources of energy (sic)—in the mid 1970's, was that the latter was indeed true. The number of proposals for research that were received from the traditional ceramics schools paled in comparison to the numbers from metallurgical engineering programs, many of which had by then morphed into materials science and engineering programs.

This lack of familiarity of high technology ceramics and what was being done in industrial and university research laboratories was and is surprisingly wide-spread. Even Thurnauer in his Orton Lecture in 1977 says that, "Even today, ferrite (magnetic oxides) production remains more of an art than a science."[4] Such a statement from someone working in high technology ceramics is very surprising since, even in the 1950's, ceramic engineers were working with the physicists and electrical engineers at companies such as Raytheon designing compositions, microstructures, and processes to make very complex and sophisticated magnetic oxides tailored to carefully specified sets of properties required in a number of applications including radar, Figure 12. In addition, such materials had been, and continue to be commercially-available from various manufacturers.[73]

Even more egregious are some very recent comments by a world-renowned materials scientist in a book about the origins of materials science:[74]

> A book edited by Levinson (1981)[75] treated grain boundary phenomena in electroceramics in depth, including the band theory required to explain the effects. It includes a splendid overview of such phenomena in general by W. D. Kingery...The book marks a major shift in concern by the community of ceramic researchers, away from topics like porcelain...Kingery had a major role in bringing this about.

By 1981, in reality, there had been a significant amount of research and education focused on the fundamental understanding on the processing, structure, and properties of ceramics that had been well-integrated into ceramic engineering practice and education decades earlier. How is it that a large part of even the materials community could be so unfamiliar with what had been going on for such a long time? It is indeed a puzzle but this lack of familiarity with modern ceramic engineering practice and education, even by colleagues in metals and materials, certainly is an important factor that has adversely affected ceramic engineering education. Furthermore, the failure to appreciate the contribution to materials science and engineering practice and education made by ceramic engineering demonstrates a prejudicially narrow view of what materials science and engineering is all about!

Since most of the applications of high technology ceramics are primarily as critical "enabling" parts of systems, much of the development—even the manufacture in some cases—of these materials was done by the user (systems) companies in their research laboratories. A notable exception to this has been CoorsTek—and its previous embodiments—which has been a "stand-alone" ceramics manufacturer who has worked with a very large number of customers developing and manufacturing sophisticated, high technology ceramics to user's specifications,

Figure 29. These research laboratories at large companies hire PhDs—examples of Raytheon high technology ceramics circa 1975 are shown in Figure 30—and most of these did not come from the traditional ceramics programs that did not have strong graduate research programs but rather from schools such as MIT that had only a graduate program in ceramics for many years; albeit the MIT program was strongly clay-based for many years.[76]

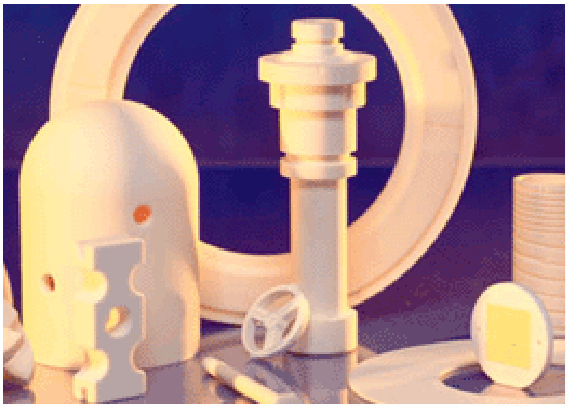


Figure 29. Some high technology ceramics. (Photo courtesy of CoorsTek.)

As a result, since advanced degree students were not available from the traditional ceramics schools, it was perceived that their undergraduate education was still focused on clay-based ceramics and was not keeping up with high technology ceramic materials. This too is certainly a misperception. Nevertheless, the reality is that ceramic engineering graduates, particularly the BS level, were never looked upon by the materials user community as a source for materials engineers, to the detriment of both U.S. industry and ceramic engineering education. This perception and the increase in the number and size of materials science and engineering programs have together had a significant impact on ceramic engineering education.

Figure 30. Optical, magnetic, and dielectric ceramics circa 1975. (Courtesy of the Raytheon Company)

How I Got Involved

During sophomore year in metallurgical engineering, a colleague and I went to Professor George Kuczynski (1921-1990), Figure 31—we had heard that he consulted for Argonne National Laboratory—and asked him if he could help us get a summer position at Argonne. This was back in the early days of summer internships (1957) when they were far less competitive. He was able to get my colleague into a metallurgy group and me in the ceramics group. As it turns out, Kuczynski consulted for the ceramics group and I ended working on his project, the sintering of aluminum oxide. The next three summers were spent in that group at Argonne where an interest in the broad range of

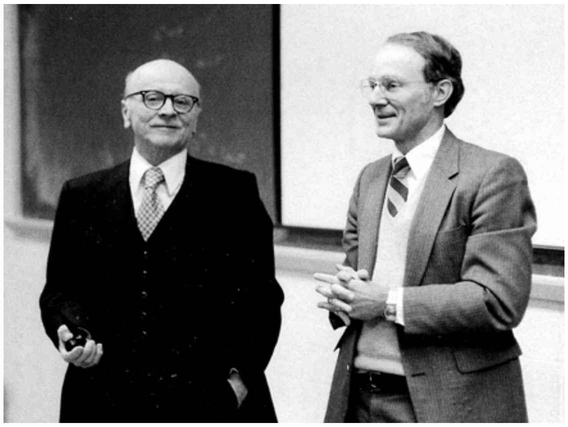


Figure 31. Professor G. C. Kuczynski giving a lecture at Ohio State in 1983. (M. J. Readey photo.)

materials and properties encompassed by ceramics emerged.

When it came time to consider graduate school—sometime in the senior year—which hadn't been given a great deal planning since an active duty ROTC obligation was looming after the B.S. in metallurgical engineering, applications to Illinois in metallurgical engineering and MIT in ceramics were both accepted. So Professor Kuczynski was asked for his advice, which was: "Readey, go to MIT, study ceramics with that young man Kingery! Ceramics are materials of the future!"

Figure 32. Attendees at the high temperature kinetics conference in 1957 organized by the then 29-year old W. D. Kingery, 2nd from right, bottom row—along with a young George Kuczynski, 3rd from left, front row, a young Bob Coble, 1st on right, bottom row. [Courtesy of the MIT Press. Photo by J. D. Plunkett, from W. D. Kingery, ed., *Kinetics of High-Temperature Processes,* (MIT Press, Cambridge), 1959. http://mitpress.mit.edu/9780262611916/]

4/1/1999

Figure 33. W. D. Kingery presenting the Coors Ceramics Lecture at CSM in 1999. (D. W. Readey photo.)

And I am still waiting!!

However, his first observation was indeed correct, Professor William David Kingery (1928-2002), Figure 32 was a young man of about 31 at the time, was publishing his third book, and had won almost every

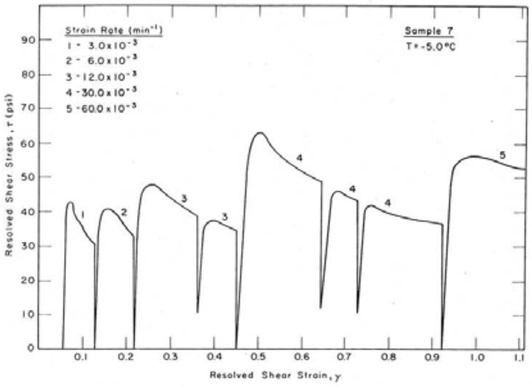


Figure 34. Stress-strain curve with increasing strain rates showing the plasticity of single crystal ice. (D. W. Readey)

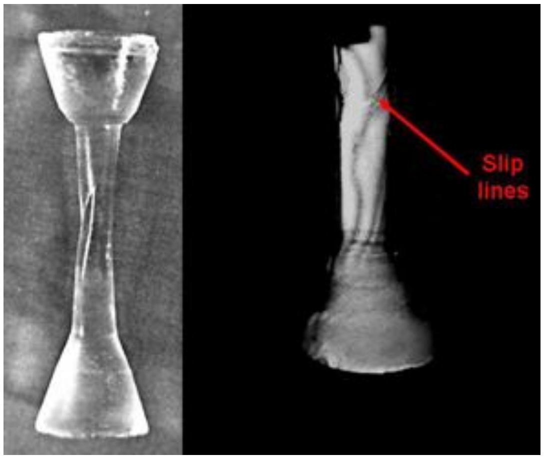


Figure 35. Plastically-deformed single crystals of ice. (D. W. Readey)

technical award from the American Ceramic Society. Kingery is considered by many to be "the father of modern ceramics"[77], Figure 33 and his text is still considered to the major reference on ceramics.[78]

After a couple of abortive research attempts, the plastic deformation of ice ended up being the successful Sc.D. thesis topic. At the time, Kingery had a large contract with the Air Force to study the mechanical properties of ice and snow. This was 1959, during the cold war, and the Air Force wanted to use Artic ice sheets as emergency landing fields for B 47s flying across the North Pole. As Kingery pointed out, with a background in both metallurgy and ceramics both are useful working with ice since, "You can consider ice (H_2O) to be either a hydride (metal) or oxide (ceramic)." As it turns out, ice is quite ductile at normal temperatures above about -30 ^{o}C since it is above 90% of its melting point, Figures 34 and 35. It is, of course, this plastic deformation at the base of a glacier that causes it to flow, in response to Orton's concerns about the flow of ice. This was "*materials* science and engineering" before most people thought much about the terminology.

Another interesting coincidence, Kingery had obtained several samples of polycrystalline natural ice of fairly large crystallite size from the Mendenhall glacier in Alaska that he wanted to compare with the deformation of laboratory-prepared ice. Unfortunately, the crystal size was not sufficiently large to extract a single crystal for part of the thesis study. The coincidence with Orton, glaciology, plastic deformation of ice, T. C. Mendenhall, and the Mendenhall glacier (see above) is only now fully appreciated. The army obligation—after several sets of orders to active duty and rescissions during graduate school—was served at Harry Diamond Laboratories in Washington, D.C. working on thin film transistors of cadmium sulfide but not until after a little apprehension caused by the Cuban Missile Crisis in October 1962 while taking the basic officer's course at Aberdeen Proving Grounds in Maryland.

Ceramic Engineering Today[1]

Events Affecting Ceramic Engineering Education

Over the last 300 years, there have been many scientific, technological, and educational events that have affected ceramic engineering and ceramic engineering education and led it to where it is today. Table II lists some of these events. Of course, any such list will not be inclusive and will reflect a certain degree of personal bias as does this list. Unfortunately, time and space do not permit a detailed discussion of each of these, and only a few will be mentioned for different reasons. First, the discovery of European porcelain is a fascinating story since it represents some of the first almost scientifically-based attempts to make ceramics that replicated those being imported to Europe from China.[79,80,81,82] In addition, it represents one of the first government-funded, high temperature, secret research projects, in ceramics that—in another first—used solar energy and

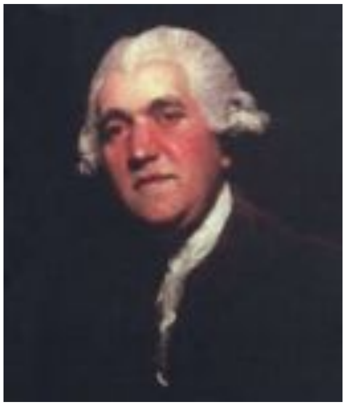


Figure 36. Josiah Wedgewood (http://en.wikipedia.org/wiki/Image:JosiahWedgewood.jpeg, accessed 2/25/2008)

Table II

Important Events in Science, Technology, and Education Impacting Ceramic Engineering

1707	European porcelain Tschirnhaus, Boettger	1930	Graduate ceramics program—MIT F. H. Norton
1760	New compositions, production methods Josiah Wedgewood	1931	Electron microscope Ernst Ruska
1850	Microstructures of rocks and metals Henry C. Sorby	1941	Double layer theory Deryaguin, Landau, Verwey, Overbeek
1870	The spark plug J. J. Lenoir	1942	Ferrites—magnetic oxides J. L. Snoek
1870	Ceramics education—Europe August Hermann Seger	1943	$BaTiO_3$—high dielectric constants Wainer, Wul, Goodman
1877	The phase rule Josiah Willard Gibbs	1947	Transistor—solid state physics Bardeen, Brittain, Schockly
1880	Welsbach mantle Carl Auer von Welsbach	1950	Fracture mechanics—flaw dependence G. R. Irwin
1894	Ceramic engineering education—U.S. Edward Orton, Jr.	1954	UO_2 as a nuclear fuel material GE and others
1898	American Ceramic Society Edward Orton, Jr. and others	1959	Materials Science programs Morris Fine, Northwestern
1897	Nernst lamp Walther Hermann Nernst	1959	High pressure sodium lamp Robert L. Coble
1912	X-ray diffraction Friedrich, Knipping, Laue	1970's	High strength ceramics DARPA
1920	Theory of fracture A. A. Griffith	1986	High-T_C superconductors Karl Müller, Johannes Bendorz

lenses to achieve the high temperatures—1400 ^{o}C—necessary to fuse the ingredients.[81]

Alyssa Wedgewood was a junior at CSM in the last class that I taught at CSM before retiring in 2006. Out of curiosity, I asked her whether she was related to Josiah Wedgewood., Figure 36. I expected that the odds of an affirmative reply were pretty small. Quite surprisingly, she said that her family descended from Josiah Wedgewood's brother! It is indeed a small world to have a descendent from the family of a person who had a major influence on the science and production of modern ceramics in my last class at Mines!

Both Thurnauer[4] and Kingery[83] feel that the Welsbach mantle really represented the beginning of high technology ceramics. At one time, I did not agree, [1] but since have changed my mind. The Welsbach mantle consists of woven fabric or string soaked with a solution of thorium and cerium sulfates that is heated to high temperature to form a porous sintered ceramic of about 99% ThO_2.[83] In the high temperatures generated by a gas flame, the mantle is considerably more luminescent in the visible part of the spectrum than the gas flame by itself making the hot, luminous ceramic ideal for lighting applications. The early success of the Nernst lamp, based on the luminescence given off by yttrium oxide-doped zirconium oxide heated to high temperatures by its own ionic conductivity—the same material and principle that are used in the electrolyte of the solid oxide fuel cell (SOFC)—is also a fascinating story, and the patent for which made Nernst a very wealthy professor.[83]

Figure 37. High pressure sodium vapor lamps. (D. W. Readey photo.)

Another important ceramic contribution to lighting technology—and an outstanding example of the system "enabling" qualities of many high technology ceramics—was the development of transparent aluminum oxide that made the high pressure sodium vapor lamp possible, Figure 37. Figure 38 shows a sodium vapor bulb with its glass outer shell and inner dense Al_2O_3 tube that carries the arc and the sodium vapor. Sodium vapor lamps are ubiquitous for outdoor lighting purposes because they are far more electrically efficient in terms of light output per watt of electrical input—about a factor of five to eight.[84] This development has saved many, many billions of dollars in outdoor lighting costs to say nothing of increased night-time security on the streets of cities and towns all over the world. The key breakthrough that enabled the high efficiency lamp was the invention of a composition and process to make low porosity,

Figure 38. High pressure sodium vapor lamps. (D. W. Readey photo.)

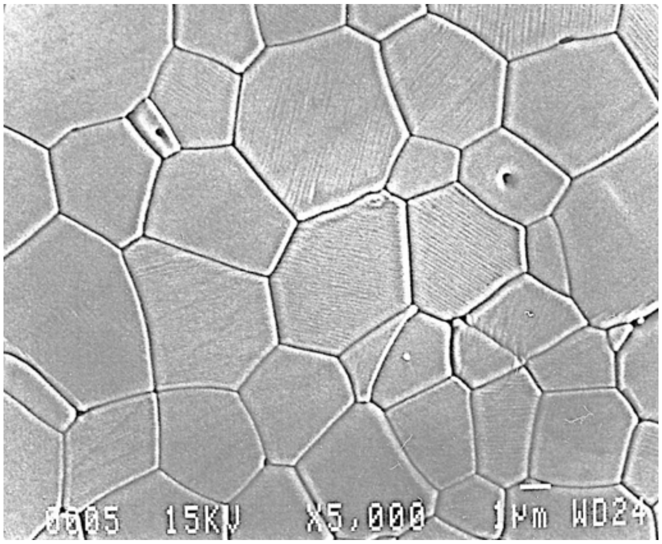


Figure 39. Dense translucent Al_2O_3 used in sodium vapor lamps. (S. Larpkiattaworn and D. W. Readey photo.)

Figure 40. Robert L. Coble, 1928-1991. ("Robert L. Coble's Contribution to the High-Pressure Sodium Arc Lamp," (http://home.frognet.net/~ejcov/coble.html, accessed 2/1/2008)

translucent aluminum oxide by carefully controlled sintering conditions, Figure 39.[85] This was accomplished by Robert L. Coble (1928-1991), Figures 32 and 40, while investigating the fundamentals of the sintering process at the General Electric Research Center in the late 1950's.[86]

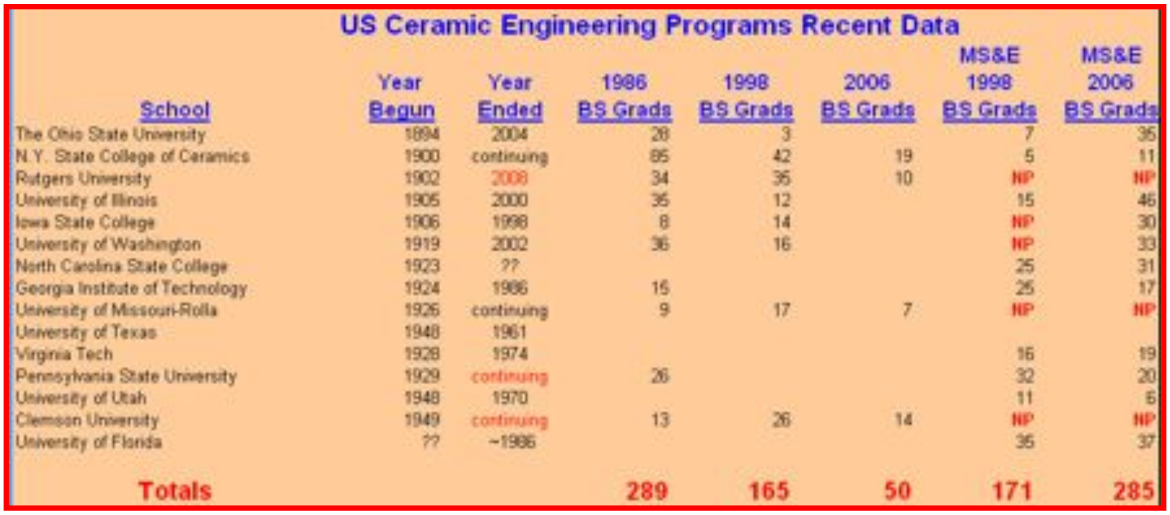
The Changed Industry

Today, the clay-based traditional ceramic industries which include whitewares, structural clay products, and porcelain enamels hire very few technically-trained ceramists above the two year technical school level. These are mature industries and are not expanding in the United States and much of their manufacturing is being done outside the U.S. The refractories industry has been faced with difficult financial times because of the decline in the basic metals industries in this country and, it too, has largely moved off shore. At the same time, the glass container industry is experiencing severe competition from substitute materials such as aluminum and polymers.

As a result, the major industries that hire ceramic engineers today are typically user industries who want to make ceramics based on synthetic raw materials for electronic and other high technology applications.[87,88] Currently, about 65% of the B.S. graduates enter industry directly and 35% enter graduate school.[89] Of those assuming industrial positions, about 40% enter the electronics industry, 15% glass, 20% engineered—high technology—ceramics, 15% refractories, and 10% all of the other.[61] Clearly, the industrial market for ceramic engineers has changed radically from what it was for the first fifty years of the field.

Ceramic Engineering Education Today

Table III



US Ceramic Engineering Programs Recent Data

School	Year Begun	Year Ended	1986 BS Grads	1998 BS Grads	2006 BS Grads	MS&E 1998 BS Grads	MS&E 2006 BS Grads
The Ohio State University	1894	2004	28	3		7	35
N.Y. State College of Ceramics	1900	continuing	85	42	19	5	11
Rutgers University	1902	2008	34	35	10	NP	NP
University of Illinois	1905	2000	35	12		15	46
Iowa State College	1906	1998	8	14		NP	30
University of Washington	1919	2002	36	16		NP	33
North Carolina State College	1923	??				25	31
Georgia Institute of Technology	1924	1986	15			25	17
University of Missouri-Rolla	1926	continuing	9	17	7	NP	NP
University of Texas	1948	1961					
Virginia Tech	1928	1974				16	19
Pennsylvania State University	1929	continuing	26			32	20
University of Utah	1948	1970				11	6
Clemson University	1949	continuing	13	26	14	NP	NP
University of Florida	??	~1986				35	37
Totals			**289**	**165**	**50**	**171**	**285**

Table III gives recent data on ceramic engineering B.S. undergraduate programs.[90,91] There are only 4 continuing ceramic engineering programs with the additional caveats that the Penn State program is a separately ABET(Accreditation Board for Engineering and

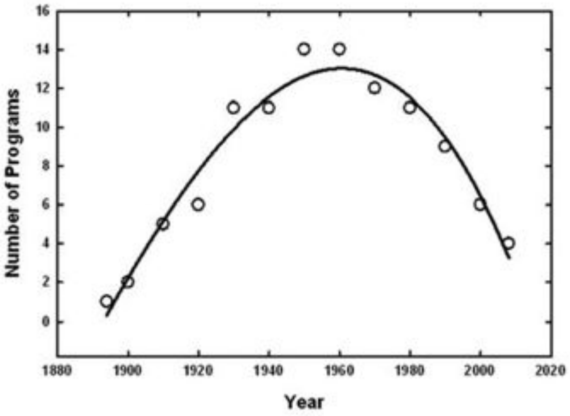


Figure 41. Number of ceramic engineering programs versus time.

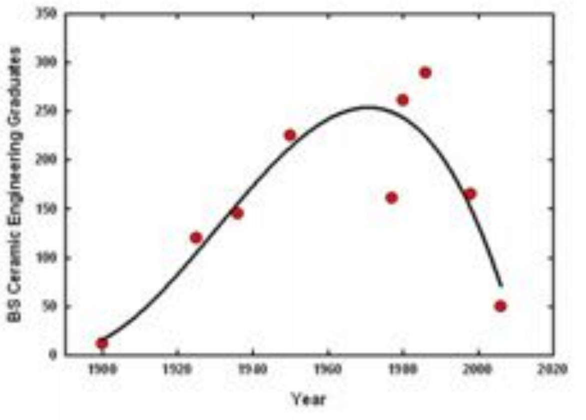


Figure 42. Number of ceramic engineering graduates versus time.

Technology)-accredited option in materials science and the name of the program at Clemson is "Ceramic and Materials Engineering." Most of the ceramic engineering programs have been subsumed into materials engineering programs. In some cases, such as Ohio State, parallel degree programs in ceramic engineering, metallurgical engineering, and materials science and engineering (MS&E) were all offered as separate ABET-accredited programs. However, over time, the majority of the students migrated to the materials degree program, which eventually led to the discontinuance of the ceramics and metallurgy programs for lack of students. Nationally, there were only 50 ceramic engineering graduates in 2006 compared with 74,186 total B.S. engineering graduates and a total of 909 materials graduates in all materials disciplines.[92] In 2006, there were a total of 65 MS&E programs compared with 9 metallurgical engineering and the 4 ceramic engineering programs. Clearly, materials science and engineering is replacing ceramic and metallurgical engineering programs. Apparently, those industries that hire the B.S. degree graduates prefer the materials degree over the other two.

Figure 41 shows the number of ceramic engineering programs over the years reaching a maximum of 14 in about 1950 and declining ever since the initiation of MS&E programs. Figure 42 plots similar data for the number of B.S. ceramic engineering graduates peaking in about 1990. This peak probably represents the excitement generated by the interest in high temperature structural ceramics generated by the Defense Advanced Research Projects Agency (DARPA) program and further energized by the discovery of high temperature ceramic superconductors.[93,94,95]

The Future of Ceramic Engineering Education

It needs to be emphasized once again that the focus of this paper is the B.S. undergraduate program in ceramic engineering and not ceramic materials themselves and ceramics research in MS&E graduate programs, industry, and the national laboratories. Ceramics research is extremely healthy, broad, and well-supported but frequently may not be separately identified under the broad aegis of MS&E and ceramic materials will always be important as enabling materials.

Nevertheless, the number of ceramic engineering programs and the number of B.S. graduates from these programs are both rapidly declining and the degree may disappear in the not very distant future. Is this a desirable result? Recall that it is industry that determines the need for the various engineering degrees and it was industry needs that prompted Orton to begin ceramic engineering. He felt that manufacturing ceramics was sufficiently different from that of chemicals and metals that it warranted a separate degree program. And he was correct!

The early ceramic engineering programs were focused on processing of the clay-based materials and it is in the processing where materials differ. The relationships between the structure and properties are similar for all types of materials but the relationships between the processing and structure are very different. The main differences between separate polymer, ceramic, and metallurgical, etc. engineering degree programs are in processing. In an MS&E program, the processing is less focused and the number of courses in processing specific to the different materials is severely limited by the 4-year degree constraint. As a result, the MS&E B.S. graduate has a much poorer background in processing of any material compared to a colleague who gets her degree in one of the materials specific disciplines, such as ceramic engineering. The dichotomy is that most B.S. degree graduates of any materials degree program end up running or developing an industrial manufacturing process for some type of material. Yet industry seems to prefer the graduate with an MS&E degree with less processing understanding than her colleague with a specific materials degree. Strange!

The cycle seems to have come full circle—from the industrial need for a specific degree 100 years ago to a desire for a more general degree today. In all fairness, as discussed above, the materials field is itself not large compared to other academic engineering disciplines such as mechanical, electrical, civil, or chemical engineering. So combining specific materials programs into a single materials degree gives these programs relatively more influence in their academic institutions and generates some economy of scale that provides better financial justification for maintaining such programs within a college or university. Do such considerations outweigh the loss of the materials-specific education? Universities and industry apparently think so!

Given the current status of ceramic engineering education in the U.S., there are several questions that beg answers. Will ceramic engineering disappear as a separate B.S. degree program? Was it simply a "boutique" or very specialized degree for which there was only a need when the clay-based U.S. ceramic industry was strong and had a need for such special training? Does the history of ceramic engineering portend the cycle of any specialized degree program—one that satisfies certain industrial needs until those needs change? Would ceramic engineering have come into existence without Edward Orton, Jr.?

High technology ceramics existed when ceramic engineering education began but were neither widely recognized as part of the field nor widely incorporated into the undergraduate degree programs until much later. Unfortunately, this led to a widespread and misinformed impression that the degree remained focused solely on clay-based materials and probably accelerated the inclusion of high technology ceramics into MS&E programs to the detriment of ceramic engineering. What if Orton's perspective had been broader and that his ceramics vision included high technology ceramics such as the Welsbach mantle, Nernst lamp, and copper oxide rectifiers as well as the clay-based materials? Could someone have had such a broad experience and vision in 1894 to be so inclusive? Probably not! Could someone else have seen the broader scope of ceramic engineering and ceramic materials and incorporated them into the ceramic engineering degree? They did, but not until about 50 years later. But by then it was undoubtedly too late given the inception, growth, and incorporation of ceramics under the umbrella of materials science and engineering.

> Orton concludes his 1908 Sigma Xi lecture with,[55]
>
> Sunset found me on a home bound train, rapidly whirling away to the south beyond Denver. As we rounded a favorable bend in the road, I turned for a last look, and low in the north a streamer of cloud floated lazily aside, and I beheld Longs Peak, 75 miles away, its summit rose-tipped with the setting sun. In a moment the color purpled, faded and was gone. Night had blotted the vision from my eyes, but death alone will blot it from my memory.

I suspect that Orton might have similar thoughts about the current state of ceramic engineering education.

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