2001 Brimacombe Memorial Lecture

Ingenuity and Innovation—The Hallmarks of Brimacombe's Pioneering Contributions to Process Engineering

I.V. SAMARASEKERA

Keith Brimacombe is remembered as one of the innovative giants in materials process engineering in the twentieth century. His impact stretches across diverse areas ranging from gas injection and flash smelting in nonferrous pyrometallurgy, on the one hand, to the continuous casting of steel, microstructural engineering, and rotary kilns on the other. Among his formidable research accomplishments, his contribution to steel processing stands out. It was an area which challenged him and from which he gained enormous intellectual satisfaction. In this article, Dr. Brimacombe's remarkable contributions to steel research are reviewed to reveal his ingenuity and innovation, which were hallmarks of his efforts. These qualities had a profound impact, not only on the quality of his research discoveries, but also on the people he mentored, the discipline of materials process engineering he fostered, and on institutions spanning universities, industry, professional societies, and government. How did he accomplish so much in such a short time? What can we learn from his example? We learn that it is not time, but creativity and dedication to the goal, that matters. We learn while Dr. Brimacombe possessed remarkable creative genius, it can be taught and fostered in individuals in our universities, in industry, and in society. We learn that breaking down barriers between artificial disciplinary boundaries, between institutions, and, most importantly, between people is critical in fostering ingenuity and innovation. We learn that enhancing communication through discourse and debate, recognizing and rewarding excellence, and creating the right culture in an organization is paramount. Above all, we learn that people are our most valuable resource. The importance of these lessons for universities, industry, and professional societies, at this time of immense technological and social transformation, will be explored in this article. Brimacombe's legacy and inspiring career are a beacon for us all as we manage change and steward this planet we call home.

Dr. Indira V. Samarasekera is Vice President Research at the University of British Columbia and incumbent of the Dofasco Chair in Advanced Steel Processing. She has been a Professor in the Department of Metals and Materials Engineering and the Centre for Metallurgical Process Engineering at the University of British Columbia since 1980. Dr. Samarasekera completed her undergraduate education in Sri Lanka, her birthplace, and obtained a Bachelor of Science Honours degree in Mechanical Engineering from the University of Ceylon in 1974. She spent the following year as a Mechanical Engineer at the Refinery of the Ceylon Petroleum Corporation and then proceeded to the United States as a Hays-Fulbright Scholar, obtaining a Master's degree in Mechanical Engineering from the University of California in 1976. In 1977, she immigrated to Canada and became a

candidate for the Postdoctoral degree under the supervision of Professor J. Keith Brimacombe, O.C., and obtained her doctorate in 1980.

Dr. Samarasekera's expertise in heat transfer and stress analysis has led her to research a number of processes with a major emphasis on the continuous casting and hot rolling of steel and the growth of single crystals for electronic devices. Collaborative research programs have been set up with Canadian companies and the research has focused on the development of mathematical models with a concerted effort to validate and apply the analyses to operating processes. To facilitate knowledge transfer to industry, Dr. Samarasekera has participated in short courses on the continuous casting of steel at companies in North and South America, Europe, Asia, and South Africa. In recognition of her research, Dr. Samarasekera has received with co-workers the Robert W. Hunt, the John Chipman, and the Charles H. Herty Best Paper awards from the ISS-AIME, the Williams and the Ablett Prizes from the Materials Society in Great Britain, and the Extraction and Processing Technology Award of the TMS. She has also been awarded the Killam Prize and the McDowell Medal by the University of British Columbia for research excellence. In 1991, she was awarded an E.W.R. Steacie Fellowship by the Natural Sciences and Research Council of Canada. She was recipient of the 1997 B.C. Science Council Award for New Frontiers in Research. Dr. Samarasekera is a Fellow of the Royal Society of Canada and also of the Canadian Academy of Engineering.

As a member of several technical societies, including TMS-CIMM, TMS-AIME, and the ISS-AIME, she has participated actively in numerous committees fostering continuing education and membership development and has assisted in organizing international symposia at conferences. In 1995, she served as President for TMS-CIM. Dr. Samarasekera is a member of the National Research Council of Canada.

I. OPENING REMARKS

OF all the honors bestowed on me in the past and or any that I may receive in the future, the distinction of being the first Brimacombe Memorial Lecturer will remain unsurpassed. I am deeply grateful to the Iron and Steel Society and to my peers who nominated me for this momentous task, and I thank you all. I am mindful of the task before me—for not only must I paint a portrait of J. Keith Brimacombe's life and career, but I must also distill his wisdom and timeless beliefs for posterity, a daunting challenge. For that is what he would have wanted: to reach beyond his time and touch the minds and lives of generations that live in another age and to inspire professionals to continue the work to which he devoted his life.

II. THE MAN BEHIND THE DREAM

"A child may ask, 'What is the world's story about?' And a grown man or woman may wonder, 'What way will the world go? How does it end and, while we're at it, what's the story all about?' I believe there is one story in the world, and only one, that has frightened and inspired us . . . Humans are caught—in their lives, in their thoughts, in their avarice and cruelty, and in their kindness and generosity—in a net of good and evil. I think this is the only story we have and that it occurs on all levels of feeling and intelligence. Virtue and vice were warp and woof of our first consciousness, and they will be the fabric of our last, and this despite any changes we may impose on field and river and mountain, on economy and manners. There is no other story. A man, after he has brushed off the dust and chips of his life, will have left only the hard clean questions: 'Was it good or evil? Have I done well—or ill?' And in out time when a man dies—if he has had wealth and influence and power and all the vestments that arouse envy, after the living take stock of the dead man's property and his eminence and his works and monuments—the question is still there: Was his life good or evil?" (John Steinbeck, *East of Eden*)

These words by the great American writer and Nobel Laureate John Steinbeck were among Keith Brimacombe's favorite sentiments and captured his view of life's story. J. Keith Brimacombe's life, by any measure, was a life of great good. Professor Brimacombe's passion for simple but enduring truths can be traced back to his roots in the prairies of Canada. Dr. Brimacombe was born on December 7, 1943 in Windsor, Nova Scotia, where his father was stationed as a flight instructor during the Second World War. At the age of 6 weeks, he returned to Rosalind, Alberta, where he was raised in a small farming community, a childhood he recalled with much joy—"the best place for a boy to grow up," he always said. He loved the small town environment where he could follow his curiosity. He spoke of the early mornings, which he loved throughout his life, to which he awoke to the sound of the first meadowlark. He treasured the times he spent as a boy working with his grandfather in the garden or Sunday afternoons at his grandparents' home, where the family would gather after church for fun and fellowship. Keith Brimacombe was the second son of Geoff and Jean Brimacombe and one of seven children. They provided him a warm and caring home, one in which education and learning were valued, both of his parents being teachers. He remarked later that this was a good beginning and it was the most important. He wanted to provide the same home in a different time and different place for his two daughters, Kathryn and Jane.

> *This surely is the essence of nurture of people involving as it does our family, our school, our church, our community, our province and our country, Canada. There is a fragility in this web of nurturing influences; but the supporting strand is the family, never perfect, which exists to create an atmosphere of love, security, encouragement and a strong sense of values. All that matters.*

J. Keith Brimacombe: "The Nature and Nurture of Research," NSERC Awards Ceremony, Canada Gold Medal for Science and Engineering, June 1997

Through the Canadian Air Force R.O.T.C. program, Keith Brimacombe enrolled at the University of British Columbia (UBC) in the Faculty of Applied Science. He completed a degree in Metallurgical Engineering with honors in 1966 (Figure 1) and received both an Athlone and a Commonwealth Fellowship. On the advice of Professor Samis, he traveled to London, to study under the supervision of Professor Denys Richardson, a renowned thermochemist at the Royal School of Mines at the Imperial College of Science and Technology. He met and married Margaret Rutter and returned to UBC in 1970 to begin a remarkable academic career, driven by the dream of establishing the best process engineering center.

Keith was an eclectic individual with exquisite tastes. He loved good food, wine, and music and enjoyed travel immensely. His first experience away from Canada, as a graduate student at the Imperial College of Science and

Fig. 1—J. Keith Brimacombe with parents Geoff and Jean at graduation from the University of British Columbia in 1966.

Technology, had a profound impact on Keith. In his words, "It was London, with its rich history, beautiful parks, and outstanding theatre, which cast a spell on the boy from the prairies." He subsequently traveled the world, sharing his knowledge with people on every continent. His capacity to enjoy the beauty of his surroundings was a reflection of his deep sensitivity. From a sunset on Lake Saima in Finland, to the majesty of Dubrovnik in the former Yugoslavia, to the wilds and wonder of Kruegar Park in South Africa, to the pastoral beauty of County Kerry in Ireland, Keith relished each with childlike wonder, which enhanced the experience for those who were with him. A talented photographer, he captured the beauty he beheld with his mind's eye on film. My own appreciation of the world was enriched because I had the good fortune to travel with Keith often. However, I never quite learned from Keith how to relish Sashimi or the many Japanese delicacies, which he did with such gusto! Keith loved life and communicated this love of life to everyone around him. He was blessed with a mischievous sense of humor and a rare ability to tell stories. He had countless warm humorous stories for every occasion and took great joy in entertaining you over a meal, a drink, or during a lecture. After Keith passed away, I visited his 80-year-old mother and asked her what qualities made him stand out when he was a boy. She said that he loved to make others feel important. He was generous in spirit and deed, and a man of kindness and warmth. In the years that I knew him, these qualities certainly characterized all his relationships and made him many friends. In spite of all of his accomplishments and international renown, he never lost his ability to laugh at himself or recognize his own foibles. Humor and humility, Keith Brimacombe valued both, and taught us the power of these attributes in human affairs.

> *We only live one life. For each of us, our lives are a uniquely precious gift—our one chance to make a difference in the world by what we have done.*

J. Keith Brimacombe, ISS President 1995: "President's Page—Making a Difference"[1]

III. INNOVATION AT WORK

Scholars engaged in studies of creativity have concluded that there are some distinct differences between truly innovative thinkers and the merely excellent. Most scientists and engineers engaged in the search for new knowledge tackle challenging problems that are well defined within the existing framework of their disciplines. Advances made over time, although excellent, do not transform the discipline. Gardner[2] analyzed the life's work of seven creative individuals of the twentieth century, including Einstein and Freud, and concluded that these individuals transcended the work of their predecessors and created new conceptual frameworks. In the case of Einstein, it was the theory of relativity and, in the case of Freud, it was the psychoanalytic theory. Both individuals invented new schools of thought, which radically altered their respective fields. Thus, true innovation is marked by a fundamental shift in the framework for inquiry.

If one examines the state of process metallurgy in the late 1960s, it was certainly in it's infancy. Many outstanding contributions had been made in the first half of the twentieth century to extractive metallurgy by great men of the ilk of Chipman, Darken, Ellingham, Richardson, and Elliott, in the areas of physical chemistry and the thermodynamics of metallurgical systems. However, little had been done in terms of process dynamics and the application of transport phenomena to characterize operating processes. Richardson had launched the Percy Group at Imperial College to begin to address this and sowed the first seeds. The late 1960s and the early 1970s were a time of enormous opportunity, because computers emerged as a powerful tool. This period bears remarkable similarity to the 1990s, when the Internet burst onto the global landscape. Upon returning from his doctorate studies at the Imperial College of Science and Technology in 1970, Keith Brimacombe seized the opportunity of the day, which was the application of mathematical modeling for the analysis of a range of metallurgical processes. He developed an interest in continuous casting, injection phenomena, and the rotary kiln as a result of the summers he spent at Noranda and Stelco following his return to Canada. This time in industry exposed him to unique opportunities for process development, which profoundly influenced the research he undertook over the next 27 years.

In the area of continuous casting, he joined a small band of pioneers, namely, Hills,[3] Mizikar,[4] and Szekely and Stanek[5] who were also harnessing this powerful tool to advance the understanding of the continuous casting process.

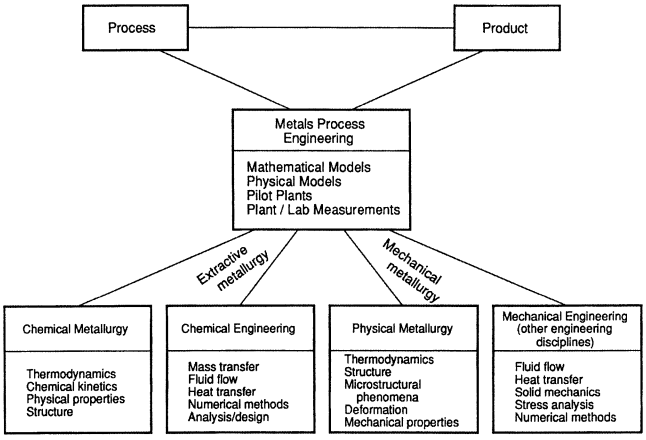


Fig. 2—The elements of metals process engineering and its relation to the process-product linkage.[6]

It was Brimacombe, however, who led the way in establishing a new framework, shown in Figure 2: namely, the process engineering methodology based on quantitative tools, which included mathematical models coupled with laboratory and industrial measurements.[6] He went further than anyone of his time to improve metallurgical processes, through the application of this new framework. Thus, by Gardner's definition,[2] Brimacombe was a true innovator, due to the creation of a new framework of inquiry.

Another hallmark of highly creative researchers is their innate curiosity and prolific output. One of the greatest minds of our time was Leonardo Da Vinci, who was endowed with a childlike curiosity, which he carried with him throughout his life. He was also extraordinarily prolific, and his contributions from art to architecture are legendary. The *Mona Lisa* and the *Last Supper* are regarded as two of the greatest paintings of all time. Da Vinci was also an inventor and military engineer. These characteristics of curiosity and inquiry characterize great researchers and outstanding research. Brimacombe's research certainly stood out in this regard. He was enchanted with knowledge and the pursuit of truth. Keith Brimacombe's research ideas were always bold and ambitious. He did not believe in incremental research, nor did he simply extend the ideas of others. He asked new questions and developed research methodologies that few others had undertaken. He and his students made ingenious and difficult measurements on operating processes under production conditions. He complemented these efforts with elegant laboratory measurements and mathematical models to make major strides in understanding, frequently radically altering previous conceptions of the phenomena under investigation. It was Brimacombe's innate curiosity and immense creativity that enabled him to ask the right questions in every endeavor he undertook. But he went further. Never satisfied with publishing the results in the best scientific journals, he explored ways of applying the knowledge in operation. It was his remarkable intellect, leadership, dedication, and enviable personal charm that enabled him to successfully translate complex research results into practical application for the benefit of industry and society.

As educators, we have an obligation to nurture these qualities in our young students. Without creativity or leadership, major strides simply cannot be made. We must not relinquish the process of engaging students and researchers in inquiry to electronic interaction *via* Web-based learning. While the latter is an enormously powerful tool, it must complement dialogue, debate, and discussion. Research, by definition, is a process, in which the "why?" is often more important than the "how to." Increasingly, as research programs become more targeted and milestone oriented, we run the risk of quenching the wellspring of innovation. Thus, discovery research must be allowed to flourish alongside targeted inquiry if we are to foster true innovation. These lessons become clear if we examine some of Brimacombe's major accomplishments, in the areas of continuous casting, rotary kilns, injection phenomena, microstructural engineering, and flash smelting.

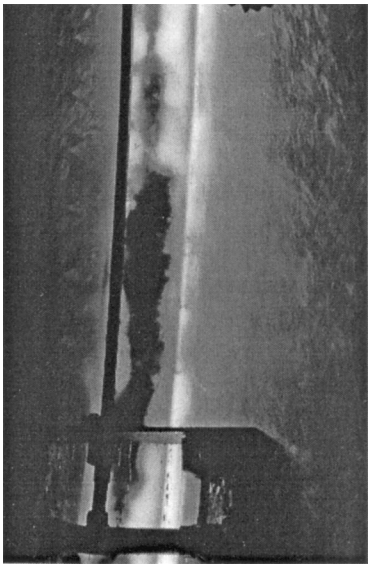


Fig. 3—Photograph of a continuously cast steel billet in the spray chamber showing dark, overcooled regions emanating from the mold.

IV. CONTINUOUS CASTING OF STEEL

Continuous casting, a relatively new process, had been commercialized in the mid-1960s and was transforming the steel industry in terms of productivity and quality. But there was little fundamental understanding of the process. The research Brimacombe conducted with a number of students and colleagues placed him at the forefront of the field at a very early age.

A. *Mathematical Modeling of Continuous Casting*

In the continuous casting process, liquid steel is poured into a water-cooled bottomless copper mold, from which it is withdrawn continuously. The production of semifinished steel sections by this process has been a steelmaker's dream since the mid-1880s and can be traced back to the pioneering efforts of Atha.[7] However, almost six decades of development work, involving numerous process innovations, had to be accomplished on pilot casters before the process was finally commercialized. Halliday's discovery in 1954 of the role of the negative strip in preventing sticking was a major breakthrough and led to successful commercialization.[7] However, the quality of continuously cast sections was a serious issue in the 1970s, when Brimacombe began to probe the process (Figure 3).

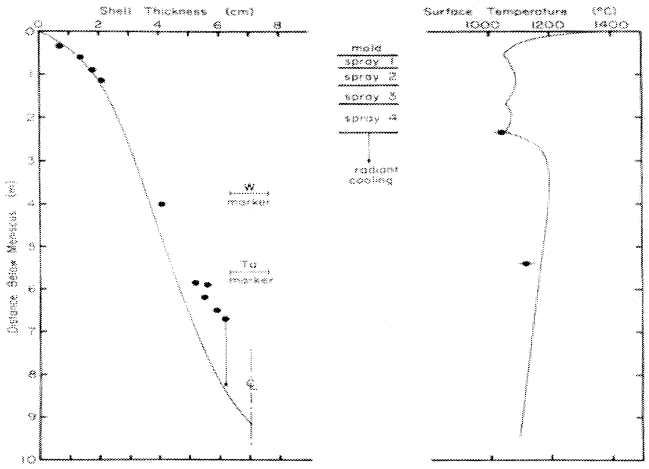
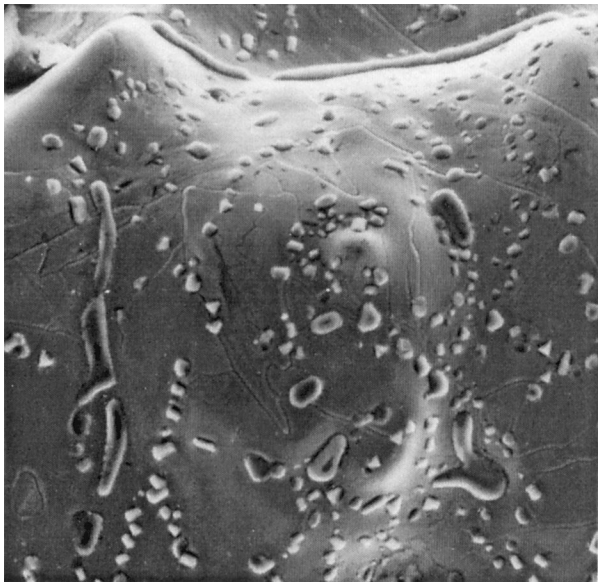


Fig. 4—Comparison of model-predicted shell thickness and surface temperature with values measured from a 14-cm billet.

What was the shell thickness of the strand at the bottom of the mold? What was the surface-temperature profile of the semisolid section in the mold and the sprays? What was liquid-pool depth? How did process variables such as casting speed affect these parameters? All were questions vitally important to the design and operation of the continuous casting process. Brimacombe and Weinberg, in their early articles,[8,9] compared shell-thickness profiles and pool depths obtained from autoradiographs of six tests conducted on a Weybridge mold with the results of models developed by Hills[3] and Mizikar.[4] In a subsequent article, which was clearly a landmark contribution to the field, Brimacombe[10] offered more conclusive proof of the power of the models to predict the shell growth, pool depth, and surface temperature, as shown in Figure 4. He also applied the models to evaluate the influence of design parameters, such as casting speed and mold length, on critical process variables such as shell growth and pool depth, pioneering a new approach to machine design.

Clearly, this body of work served as the foundation for quantitative analysis of the continuous casting process. It established the tradition of utilizing a quantitative approach in conjunction with good industrial measurements as process engineering tools and placed subsequent process developments on a more scientific footing. Mathematical modeling of the continuous casting process is now a widespread activity.

(*a*)



(*b*)

Fig. 5—(*a*) Scanning electron micrograph looking into an open halfway crack. (*b*) Interior surface of halfway crack.

B. *Crack Formation*

One of the critical challenges in continuous casting is the production of crack-free sections. When continuous casting was first commercialized, cracks, both surface and internal, were a prevalent problem, and trial-and-error approaches were adopted to minimize or eliminate crack formation. In an early study, Van Drunen *et al.*,[11] in a study aimed at understanding the mechanism of half-crack formation in continuously cast steel billets, discovered the following.

(1) The cracks were open, as shown in Figure 5. They also reported that the interior surface of the crack was smooth and undulating, as shown in Figure 5. The crack surface showed no evidence of fracture, leading the investigators to conclude that the cracks were a result of a hot tearing process.
(2) They concluded, based on work published by Hall[12] and Adams,[13] that these cracks were occurring close to the solidus, where the ductility of steel approached values near zero.
(3) A tensile strain was being generated close to the solidification front, which, in combination with the poor mechanical properties of steel, led to cracking. Thus, the distance of the tip of the crack from the surface of the cast section was a measure of the shell thickness at crack initiation.

Figure 6 superimposes the data for halfway cracking for

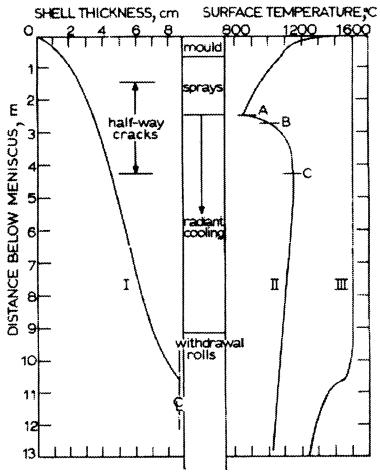


Fig. 6—Model calculated profiles of liquid pool (I), surface temperature (II), centerline temperature (III), for a 17.2-cm billet cast at 2.2 cm/s. The location of halfway cracks is also shown.

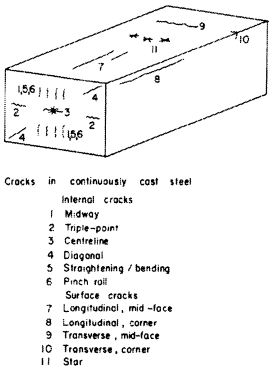


Fig. 7—Schematic drawing of strand cast section showing different types of cracks.

the caster under investigation, on a graph of model predictions of shell growth and surface temperature.[11] Clearly, halfway cracking was shown to be associated with significant reheating of the surface of the billet. The surface reheating was linked to improper spray design, which was rectified to result in an elimination of halfway cracking.

This was a critical breakthrough in the analysis of cracking of continuously cast steel sections, as shown in Figure 7.[14] In the case of billet casting, it has since been established that all cracks, with the exception of craze cracking and, on occasion, transverse corner cracks, are hot tears. In the case of a majority of the cracks, it has been possible to pinpoint the location of crack formation in the machine and to establish whether the tensile strains giving rise to the cracking are mechanical or thermal. It has also been possible to identify design and/or operating conditions responsible for the thermal strain. This philosophy has led to a diagnosis for the occurrence of halfway cracks, longitudinal corner cracks, transverse depressions, and transverse cracks—both midface and corner cracks, off-corner internal cracks, pinch-roll cracks, diagonal cracks, and centerline cracks in billets. Clearly, a single discovery of how halfway cracks form in billets paved the way for the development of a framework for the diagnosis and elimination of defects in continuously cast steel billets.

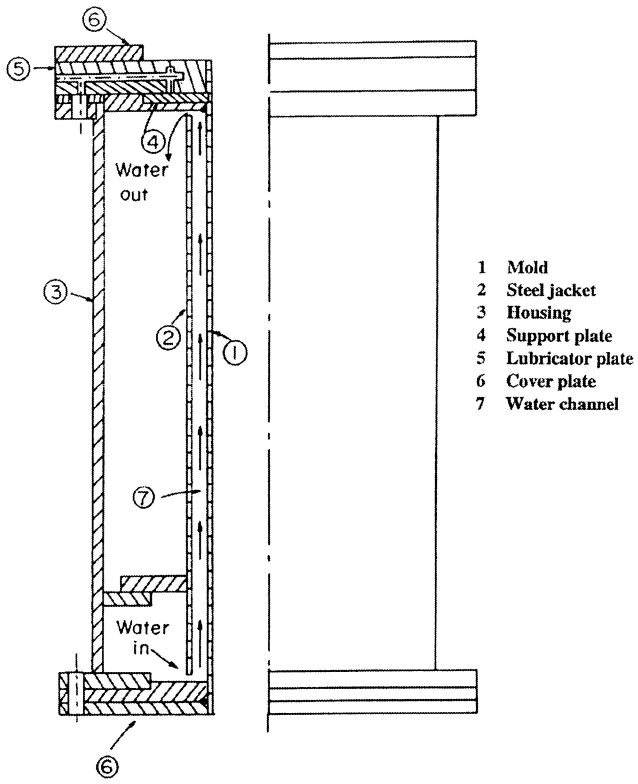


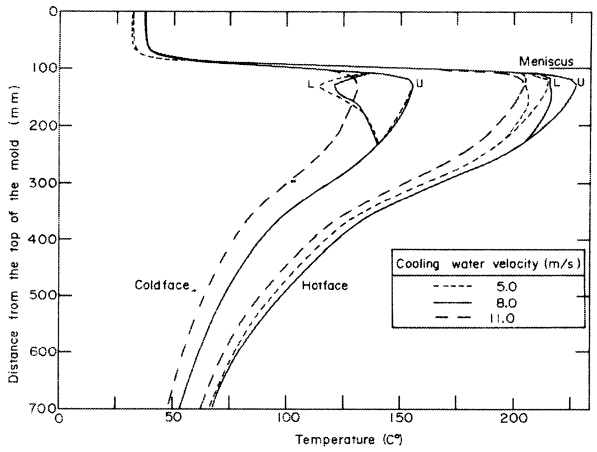
Fig. 8—Schematic drawing of billet mold assembly.

C. *Continuous Casting of Steel Billets*

My own foray into research on the continuous casting of steel began in 1977. The objective of the work was to answer a relatively simple question—do billet molds distort? The question arose as a result of a presentation Dr. Brimacombe had made on continuous casting at a steel company. He postulated that because the air gap controls heat transfer, the mold cooling water should have no effect on mold heat transfer. Over a drink, at the end of the day, an operator indicated to Dr. Brimacombe that there was a flaw in the theory, because the operator had observed that he could indeed alter the mold heat transfer by altering the mold water flow. Dr. Brimacombe's response was that this could only occur if the billet mold tube was distorting. At the time, there were no studies reporting the distortion of mold tubes, and no measurements had ever been conducted to assess whether this was the case.

This was the genesis of the work on the thermomechanical behavior of billet mold tubes. Figure 8 is a sectional view of a continuous casting billet mold assembly, showing the water-cooled copper tube. Of particular significance is that the millet mold is unsupported over most of its length and is held in place by split plates which fit into slots at the top of the tube, as shown in the figure. Studies on the behavior of the billet mold have revealed the following important features.

(1) The billet mold tube has a nonuniform temperature distribution during operation, with maximum temperatures close to the meniscus, where the heat transfer is highest, as shown in Figure 9(a). The heat flux decreases with distance below the meniscus because of the increasing



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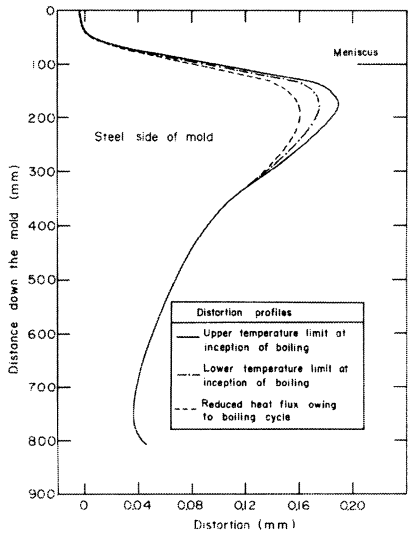


(*b*)

Fig. 9—(*a*) Model predicted axial hot and cold-face profiles of billet mold tube. (*b*) Model predicted axial thermal distortion profiles.

width of the air gap between the solidifying shell and the mold wall.[15,16]

(2) The mold tube acquires a distorted shape because of outward expansion of the mold wall due to the thermal field. The maximum bulge occurs 50 to 100 mm below the meniscus, as shown in Figure 9(b), because of two-dimensional heat flow in the meniscus region. This results in the mold acquiring a thermally generated negative taper of ~2.0 pct/m above the point of maximum bulging and ~0.6 pct/m below it.[17]

(3) Perhaps the most significant consequence of the thermal distortion of billet mold tubes was the resultant interaction with the solidifying shell at the meniscus. This interaction is exacerbated when the mold acquires a negative taper at the meniscus. It was postulated that oscillation marks form during the negative strip, as a result of the mechanical interaction between the mold and the newly forming shell, schematically shown in Figure 10.[18]

(4) The influence of the negative-strip time and mold cooling-water velocity on the oscillation-mark depth supported the proposed mechanism. Interestingly, for the

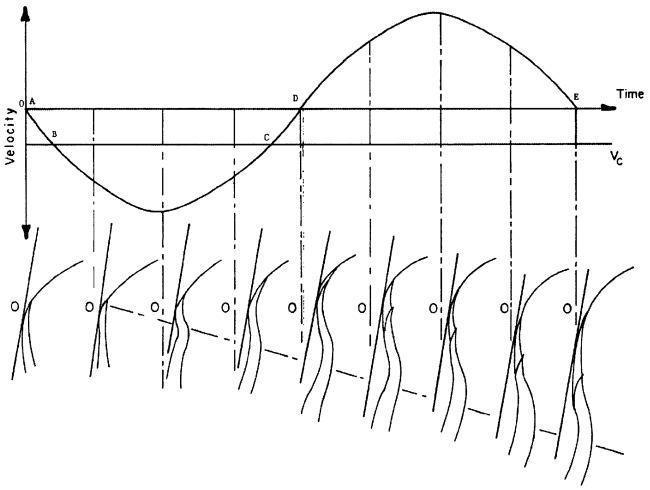


Fig. 10—Mechanism of oscillation-mark formation in billets with oil lubrication.

better part of two decades following commercialization, most billet molds had zero taper, or a single taper of 0.6 pct/m, which was less than the thermally generated negative taper of 2.0 pct/m. Nonuniform oscillation-mark depths resulted in nonuniform heat transfer and shell growth, resulting in quality problems such as off-squareness and off-corner internal cracks.[18–21]

(5) A subsequent study provided overwhelming evidence of this effect, by linking the meniscus heat flux to the design taper at the meniscus. Mold heat-transfer measurements, conducted on an operating mold and instrumented with thermocouples and load cells, revealed that mold heat transfer at the meniscus is a strong function of design taper at the meniscus, for tapers below ~2.5 pct/m, which is less than the thermally generated negative taper, as shown in Figure 11(a).[22]

(6) The increase in mold-wall temperature, with a low-design taper, causes the lubricating oil to boil off, as shown in Figure 11(b), resulting in sticking. There is a higher incidence of bleeds and laps with a low-meniscus taper, particularly for grades with a long freezing range, as shown in Figure 12.[23,24]

Two pivotal discoveries—the relationship between oscillation-mark depth and mold water velocity, mold taper, and mold heat flux—finally uncovered the role of mold shape on mold behaviour and billet quality.

D. *Process Transients*

An unconquered frontier is process transients. Many billet casters operate with optimum design and operating conditions, and yet defects occur intermittently. These defects are often due to uncontrolled process transients. Of these, the most significant in an open-stream pouring operation is metal-level turbulence. Oscillator malfunction is another.[25]

(1) McLean and co-workers have demonstrated the importance of tundish design on stream condition and air entrainment. Ropey streams entrain a significant amount of air and give rise to excessive turbulence in the mold (as shown in Figure 13) and, consequently, metal-level fluctuations.[26]

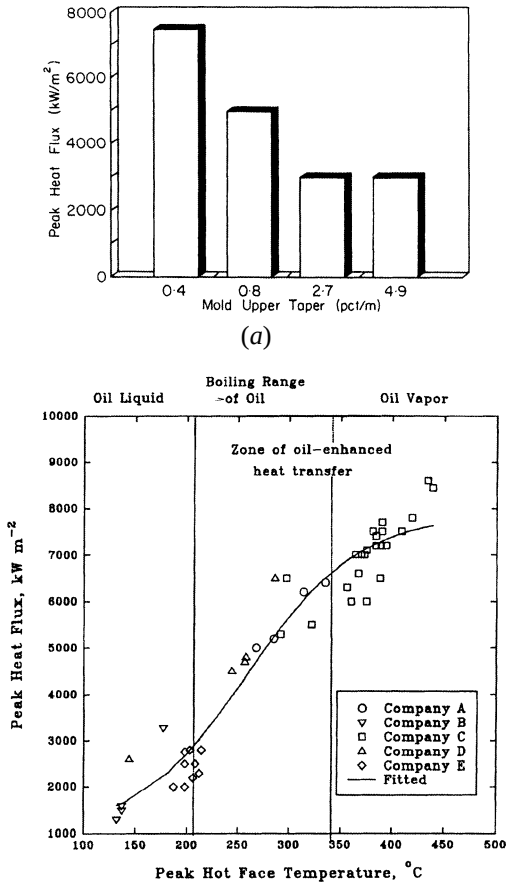


Fig. 11—(*a*) Measured mold peak heat fluxes for different meniscus tapers. (*b*) The influence of peak mold heat flux at the meniscus on lubricating oil behavior.

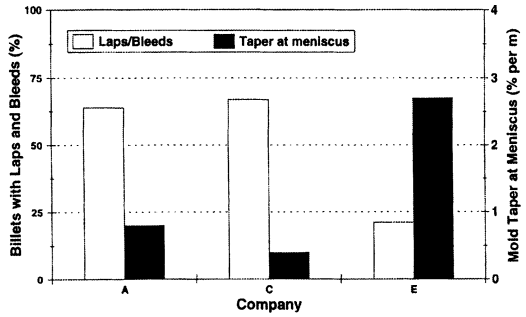


Fig. 12—The influence of mold meniscus taper on laps and bleeds.

(2) Recent work has shown that metal-level turbulence can cause transverse depressions and cracks, off-squareness, bleeds, and laps. The significant reduction in off-squareness associated with billets cast with mold-powder lubrication is a direct result of the use of a submerged entry nozzle, which transfers molten steel from the tundish to the mold, eliminating air entrainment and its consequences.[27,28]

(3) The current practice of controlling the metal level, through a radioactive sensor which adjusts speed accordingly, is inherently unsuitable in maintaining a steady state. A more appropriate flow-control system consists of a stopper rod, coupled with good tundish design. It is important to minimize local variations in meniscus position resulting from turbulence; it is also important that the system does not respond to these local changes by continuously adjusting the casting speed, thereby exacerbating the transients.

Detection of process transients is an important first step in controlling or minimizing their impact. The "Intelligent Mold" described by Brimacombe in the 1993 Howe Memorial lecture[29] envisages a mold instrumented with sensors, capable of detecting process upsets, and equipped with an expert system which can prescribe corrective measures online.

> *The tools on the shop floor, which make or break a company, will increasingly demand knowledgeable operators. Processes will be made smart. . .The message is clear. The use of knowledge by knowledgeable people will underpin the steel industry through the next millennium. Simply stated the steel industry must work smartly.*
>
> **J. Keith Brimacombe, ISS President 1995**

E. *Mold and Spray Design and Operation*

The consequence of this series of discoveries, made over a period of nearly three decades, on mold and spray design have been profound. In the case of spray design for continuous casting of steel billets, the principle is simple: minimize reheating below the mold, in the sprays, or below the sprays.[30] This is accomplished by prescribing a desirable surface-temperature profile through the spray chamber, as shown in Figure 14.[30] This allows spray heat-transfer coefficients and corresponding water-flux profiles in the spray chamber to be determined, as shown in Figure 14. Details of the spray-nozzle configuration, type, and spacing, which give rise to optimum cooling, are also shown in Figure 14. This design philosophy has been shown to eliminate halfway cracking in billets, the most serious spray-related defect. Interestingly, it was found that in direct-chill casting of Zinc Jumbos, shown in Figure 15, reheating was responsible for a serious cracking problem, as shown in Figure 16.[31] The strong parallels between the two problems and the common solution emphasize the importance of transferring knowledge between industries that rarely read each other's literature.

Profound shifts in mold design and operation have also emerged from the results of this body of work. In a recent article, which surveys mold design and operating conditions at North American minimills, optimum conditions recommended as a result of the research are being widely adopted. These are summarized in Table I and are aimed at controlling the thermomechanical behavior of the mold tube.[32] The reasons for the choice of specific values for each parameter have been described in an earlier publication. Thus, the link between discovery, new knowledge, and process improvements is clear.

F. *Meniscus Phenomena in the Continuous Casting of Steel Slabs*

Brimacombe and co-workers also contributed significantly to the understanding of meniscus phenomena in the

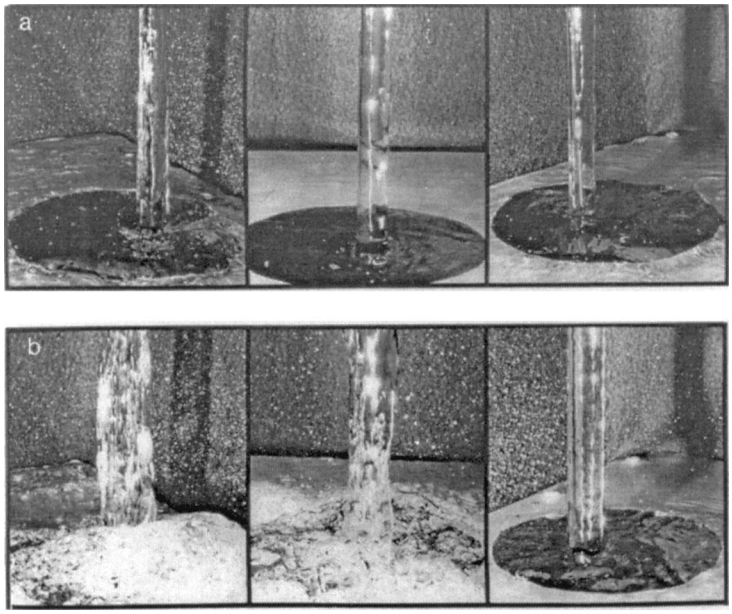


Fig. 13—(*a*) and (*b*) Photographs of meniscus turbulence with smooth and rough tundish streams.

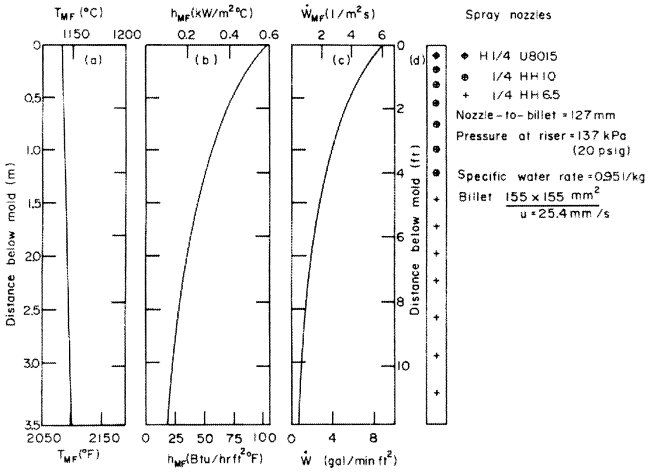


Fig. 14—Design of the spray chamber of a billet casting machine.[30]

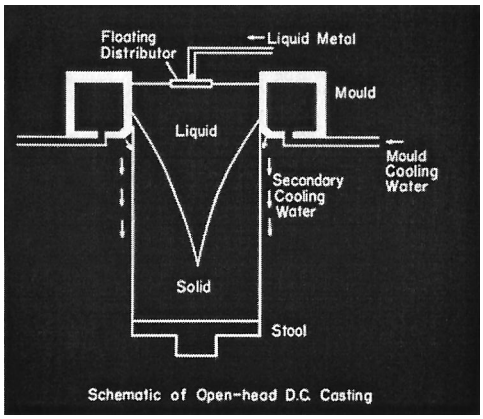


Fig. 15—Direct chill casting process.

continuous casting of steel slabs.[33,34,35] They were the first to postulate a mechanism for longitudinal midface cracking in slabs, which has since been confirmed by numerous other investigators. The highlights of these studies are as follows.

(1) They demonstrated that longitudinal midface cracks in continuously cast slabs can form close to the meniscus (Figure 17(a)) or close to the input-stream impingement.[33]
(2) They showed that these cracks form as a result tensile strains generated by rapid cooling of the shell, which concentrate in local regions of high temperature resulting from nonuniform heat extraction, as shown in Figure 17(b).
(3) The influence of the impinging metal stream, mold-powder practice, metal-level control, steel composition, end-plate taper, submold support, and spray practice on longitudinal midface cracks was clarified based on this mechanism.[33]

The study of the formation of oscillation marks in continuously cast steel slabs, conducted by Takeuchi and Brimacombe, was another landmark investigation.[34,35] They performed metallographic studies of slab samples and developed a mathematical model of heat flow, lubrication, and meniscus shape in the meniscus region of the mold. They concluded that, depending on local convection, partial solidification of the meniscus could occur, resulting in a thin rigid skin. A mathematical model of heat transfer and fluid flow in the flux channel revealed that, owing to the shape of the flux channel, a positive pressure is generated in the flux channel when the mold moves down in a negative strip, as shown schematically in Figure 18. The reverse occurs during a positive strip. They postulated that the following events resulted in oscillation-mark formation and the associated features on the slab surface.[34,35]

(1) Cyclic pressure changes result in a push-pull action on the newly solidified shell and deformation of the shell, causing an oscillation mark.

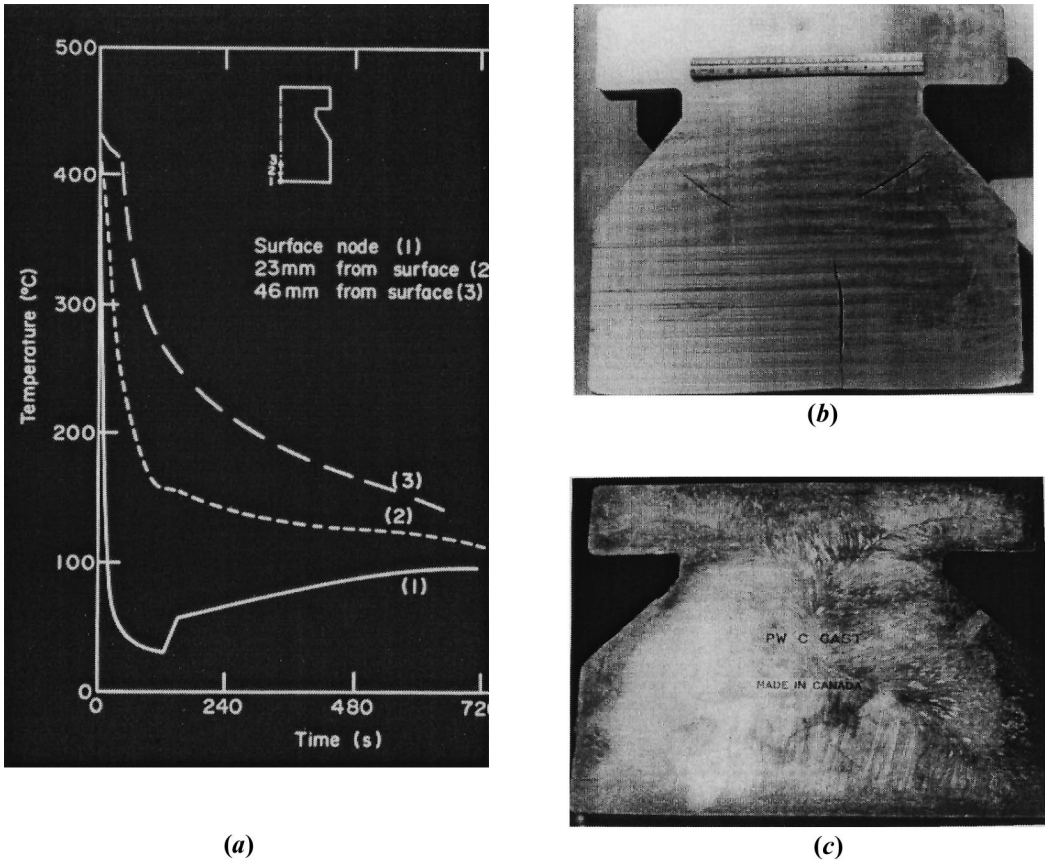


Fig. 16—(*a*) Model predictions showing surface reheating of jumbo, (*b*) cracking of jumbo due to surface reheating in sprays, and (*c*) crack free jumbo when reheating was corrected.[31]

Table I. Optimum Mold Design and Operating Conditions

Copper grade	DHP, silver-bearing Cu, Cr-Zr
Taper	double or multiple
Minimum wall thickness (mm)	13 for smaller billets[9] (*i.e.*, 100 to 150 mm sq.) 20 for larger billets (*i.e.*, 200-mm sq.)
Inside corner radius (mm)	3 to 4
Meniscus level (mm)	100 to 150
Water velocity (m/s)	>10 to 11
Mould tube support	four sides near top or top/bottom
Negative-strip time (s)	0.12 to 0.15
Mould lead (mm)	3 to 4
Water quality, *e.g.*, total hardness	<5 ppm, no deposits on mold tubes
Cooling water channel width (mm)	3 to 5
Measure internal mold dimensions	yes

(2) If the skin is rigid, overflow can occur at the commencement of the positive strip, causing a subsurface hook to form; if the skin is semirigid, it moves with the meniscus, overflow does not occur, and there is no hook.
(3) The influence of the negative-strip time on oscillation-mark depth and other features observed in slab samples were explained on the basis of the proposed mechanism.

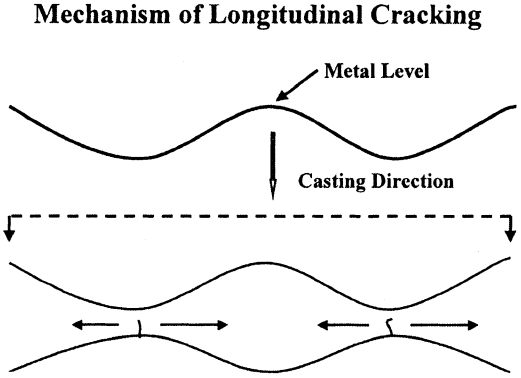
This study was an important step in the understanding of the phenomena occurring in the liquid-flux channel at the meniscus.

A subsequent study, conducted by Mahapatra *et al.* at Stelco's Lake Erie Works (Hamilton, Ontario) slab caster, using an instrumented mold, demonstrated the importance of the slag rim on oscillation-mark formation.[36,37] This study confirmed the importance of mold hot-face temperature at the meniscus on the thickness of the slag rim. It demonstrated that differences in mold hot-face temperature between the broad faces of the slab mold, resulting from differences in thickness of the copper plates, led to dissimilar heat transfer between the two broad faces. It was proposed that these differences in heat transfer were linked to the slag-rim thickness on each face (as shown in Figure 19) and, consequently, to the depth of the oscillation marks. The slag-rim thickness arguably alters the shape of the flux channel and the formation of oscillation marks, confirming earlier work by Emi *et al.*, as shown in Figure 20.[38]

G. *The Future of Continuous Casting*

Clearly, in all of these studies on continuous casting, mathematical models have been ingeniously combined with evaluation of steel samples and industrial and laboratory measurements to reveal the inner workings of this process and to enable significant improvements to steel quality to be made. We have now entered an invigorating period of

(*a*)



(*b*)

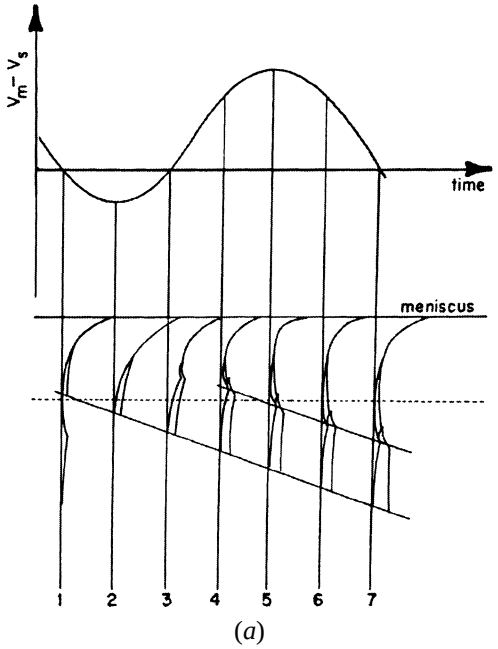
Fig. 17—(*a*) Oberhoffer's etch of section normal to longitudinal crack from rephosphorized slab, heat 12. Magnification 4.5 times.[33] (*b*) Mechanisms of longitudinal cracking.

innovation in continuous casting of steel. Thin-slab casting has been extensively commercialized and is competing with conventional continuous casting in the production of high-strength steels. Bessemer's dream of strip casting is almost a commercial reality, as BHP, Nucor, and IHI team up to commercialize the world's first strip-casting operation, Castrip,* for plain-carbon steels in 2001. These revolutionary developments in continuous casting have been well served by the foundation of knowledge and process developments which Brimacombe so ably advanced.

*CASTRIP is a trademark of BHP, Australia.

V. MICROSTRUCTURAL ENGINEERING

Brimacombe was struck by the fact that the undergraduate physical metallurgy courses were largely qualitative in nature. He also found that the application of this knowledge to industrial processes, such as heat treatment and hot rolling, was of an empirical nature. He then asked the obvious question: Why shouldn't one develop mathematical models based on physical laws, such as heat transfer and deformation of solids, to these industrial processes? To build such a program, Brimacombe coined the phrase "microstructural engineering" and, with the support of the Stelco/NSERC Chair, he and co-workers initiated projects on reheat furnaces, hot rolling, controlled cooling, heat treatment, and continuous



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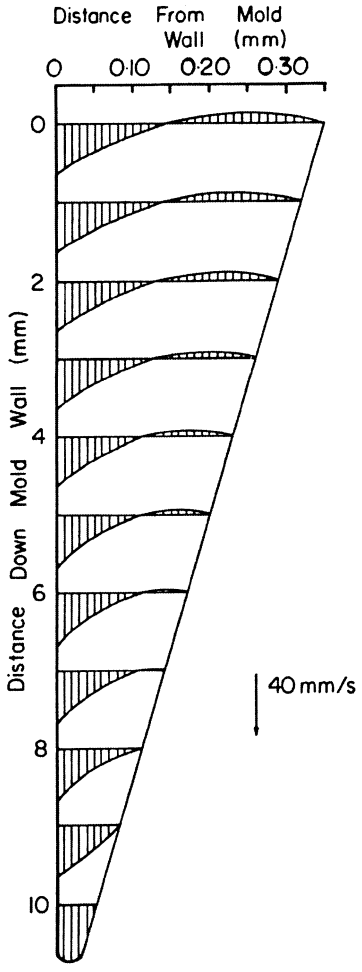


(*b*)

Fig. 18—(*a*) Schematic representation of the formation of an oscillation mark with subsurface hooks. (*b*) Schematic representation of the formation of an oscillation mark with subsurface hooks.

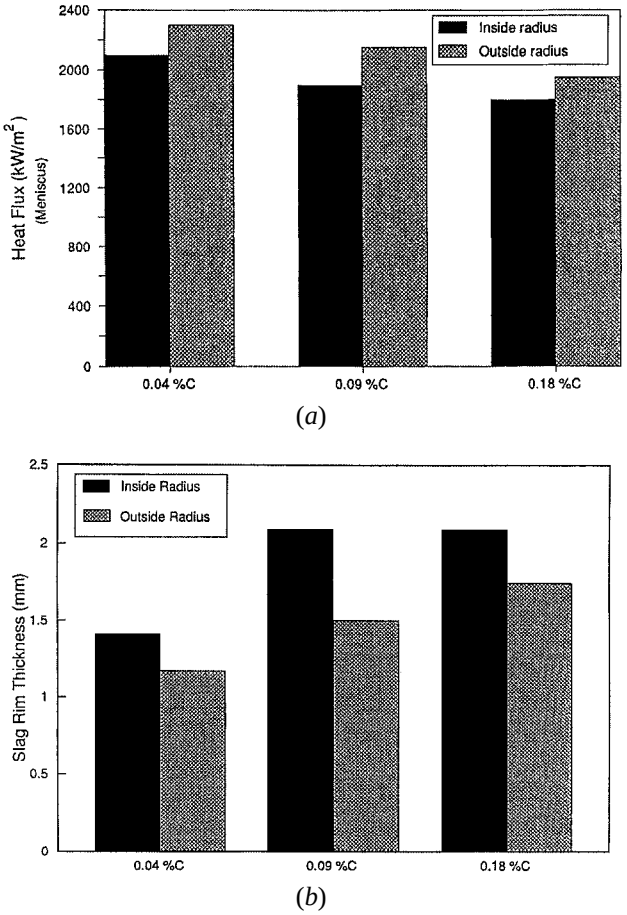


Fig. 19—(*a*) Differences in meniscus heat flux between inside and outside radius due to differences in copper plate thickness and (*b*) corresponding differences in slag rim thickness.[37]

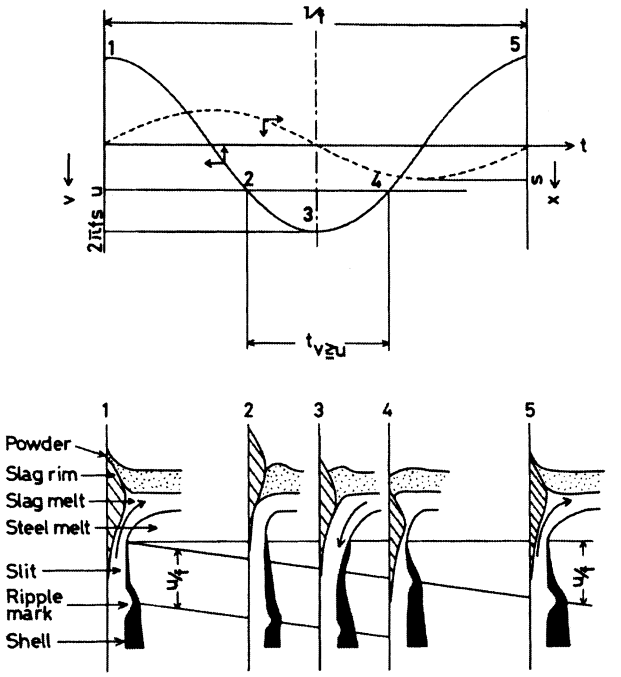


Fig. 20—Schematic diagram showing the role of the slag rim during oscillation-mark formation.[38]

cooling. For each process, mathematical models were developed to predict the thermal, deformation, and microstructural evolution of steel as a function of steel composition and processing parameters. Yet again, Brimacombe had conceived a new framework for the study of downstream steel processing operations with a view to predicting final properties. As an example of the work, a brief synopsis of the first study, the controlled cooling of a steel rod, is described.

The Stelmor Process for the controlled cooling of a steel rod had been developed by Stelco and Morgan over three decades ago to replace lead baths for controlled cooling of a wire rod. It is estimated that there are over 150 Stelmor lines globally. The process consists of blowing air through a cooling bed, on which the steel rod from the last rolling stand is placed in loops and moved at a fixed speed. In developing a model of this process, it was discovered that the characteristics of the austenite-to-ferrite and austenite-to-pearlite transformation had simply not been characterized with adequate precision for use in mathematical models, especially as a function of steel composition and temperature. This led to an extensive program for the characterization of the phase-transformation kinetics for steel and development of appropriate equations to quantify the measurements. Figure 21 shows the model predictions of thermal history and fraction transformed at two locations in the rod, for a variety of steel grades.[39] The ultimate test of the model was its capability of predicting the final mechanical properties of a controlled-cooled steel rod under industrial conditions, shown in Figure 22.[40,41,42] A true testament to the power of Brimacombe's vision, that knowledge can be applied on the shop floor.

Brimacombe was also determined to extend this work for other metals, and a successful study on the hot rolling of aluminum was completed with the support of Alcan International. The extension of this approach to predict the texture and mechanical properties of hot-rolled aluminum illustrates the universality of these concepts.

VI. ROTARY KILNS

The rotary kiln attracted Brimacombe's interest as a result of an early study in collaboration with Stelco on the Stelco Lurgi/Republic National (SL/RN) direct reduction process. A 5.5-m-long pilot kiln, shown in Figure 23, was installed at UBC and provided the basis for outstanding experimental and modeling work for nearly two decades. The pilot kiln was equipped with an array of thermocouples to measure the temperature distribution in the refractory, free-board gas, and solids bed, as shown in Figure 23, and sampling ports were placed along the length of the kiln to determine the extent of chemical reaction. Key findings that resulted from the kiln research transformed our understanding of this century-old reactor, known for its flexibility in handling a variety of solids and fuels.[43–51]

(1) Bed-behavior diagrams were developed to characterize the complete range of solids motion, slipping, slumping, rolling, cascading, cataracting, and centrifuging as a function of operating conditions.
(2) The mechanism of segregation of fines was clarified, leading to the development of wedge-shaped mixers to reduce the inconsistency of product quality and minimize dust losses and accretion formation.

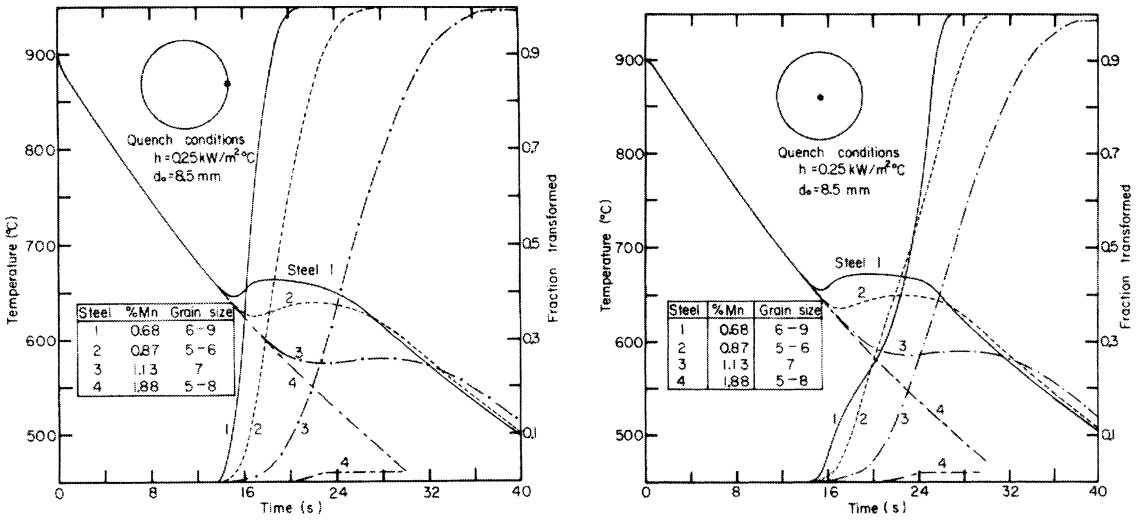
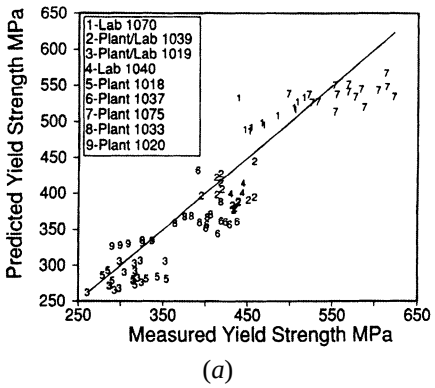
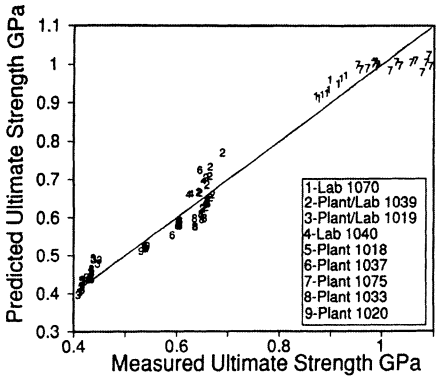


Fig. 21—Effect of pct Mn of steel on the local temperature and fraction austenite transformed at the surface and center of an 8.5-mm-diameter rod under quench conditions.



(*a*)



(*b*)

Fig. 22—Comparison of model predicted and measured strengths, (*a*) yield and (*b*) ultimate, for control cooled steel rod.

(3) Mathematical modeling of the rotary kiln revealed that, in the absence of an endothermic reaction, the rotary kiln is a relatively poor gas-solids heat exchanger. Thus, the use of preheaters (to transfer heat from the waste gases to the solids before they are charged to the kiln) for processing operations such as calcinations and direct reduction was scientifically rationalized.

The power of the process engineering approach in generating new understanding of an old reactor was unquestionably demonstrated.

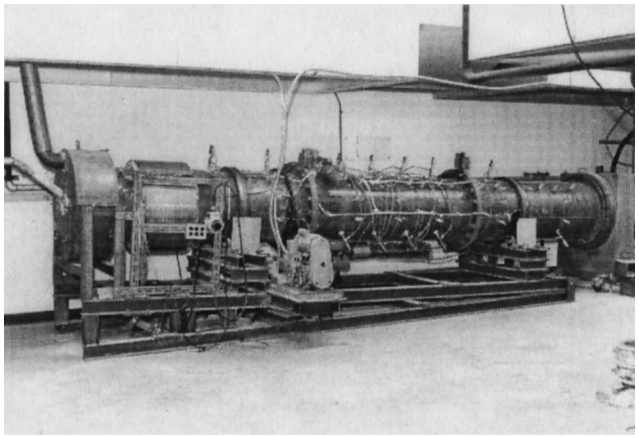


Fig. 23—Instrumented pilot kiln at the University of British Columbia.

VII. INJECTION PHENOMENA

Brimacombe's interest in injection phenomena can be traced back to his Ph.D. thesis, under the supervision of Richardson. His thesis was entitled "Mass Transfer and Interfacial Phenomena Involving Bubble-Agitated Interfaces."[52] With the aid of a Schlieren system, he discovered the effects of interfacial turbulence on the transport of indium from a mercury amalgam into the aqueous ferric nitrate solution in contact with it. Spontaneous movement of the interface due to interfacial tension gradients were the cause of these observations, widely known as the Marangoni effect. This effect was first demonstrated by Lord Thomson in 1855,[53] in which he introduced a small quantity of alcohol into a glass containing water, causing rapid movement of the surface outward from where the alcohol was introduced—"tears of strong wine." On many occasions Brimacombe would demonstrate this effect at his favorite restaurant, Bishop's in Vancouver! While chemical engineers had been studying these phenomena in aqueous organic systems, little had been hitherto conducted in metallurgical systems.

Mackey and Campos[54] recently reviewed Brimacombe's

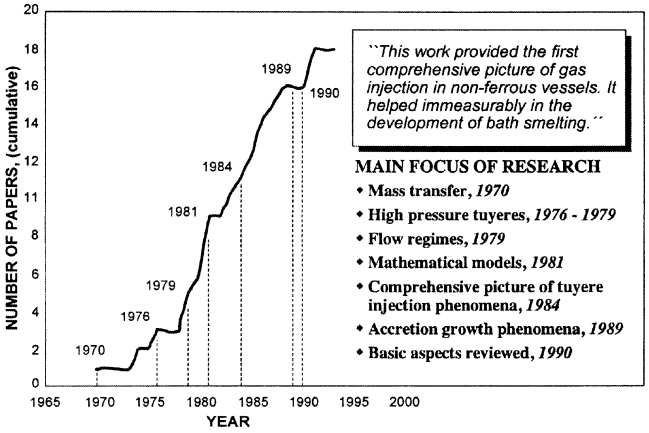


Fig. 24—Brimacombe's contributions to bath smelting science.[54]

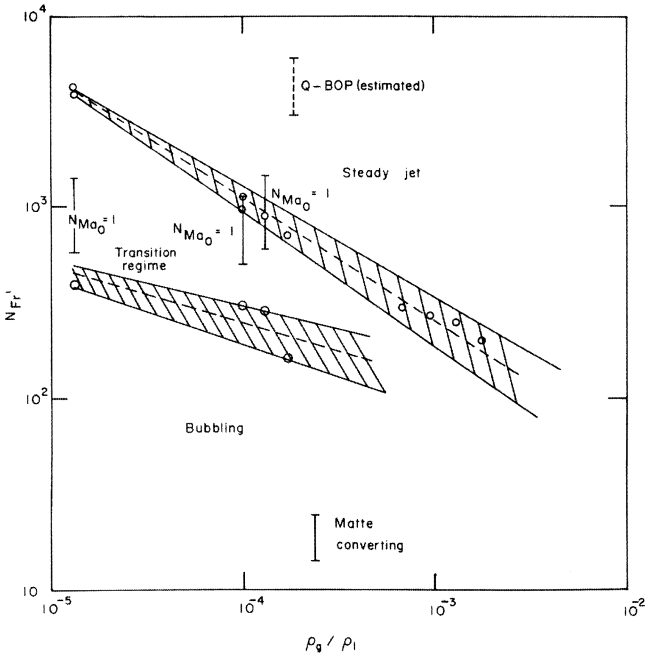


Fig. 25—Jet behavior diagram showing injection regimes as a function of modified Froude number and gas/liquid density ratio.

contributions to bath smelting and provided a detailed overview (Figure 24).

Brimacombe was clearly intrigued by the potential of interfacial phenomena in metallurgical systems and the role of injection in operating processes. The seminal work by Hoefele and Brimacombe,[55] shown in Figure 25, laid the foundation for understanding bubbling and jetting regimes in metallurgical processes, as a function of gas-to-liquid density and the ratio of gas inertial force to the buoyancy force. Jetting is defined as the continuous discharge of the gas from a tuyere. To test the concepts developed in the laboratory, Hoefele extended his work to a nickel converter at the INCO Thomson smelter. Here, he demonstrated that at low injection pressures, the gas discharges discontinuously in the form of bubbles, so that liquid contacts and freezes against the tuyeres between successive bubbles. Increasing the backpressure from 100 to 550 KPa resulted in jetting and a steady uninterrupted flow of gas-jetting, as shown in Figure 26. The concept was later patented with the help of Canadian Liquid Air and subsequently tested in industrial operations at the Asarco Tacoma Smelter, the Noranda Horne Smelter, and the INCO Copper Cliff Smelter.[56] The research also demonstrated that high-pressure gas injection minimized tuyere blockage due to accretion formation (associated with discontinuous gas flow in the bubbling regime) and refractory wear around the tuyeres due to the elimination of punching. Several industrial and laboratory studies followed from this early work, which were creative and gave enormous insight into these complex processes:

(1) dynamics of bubble formation and growth at tuyeres,[57]
(2) accretion growth,[58,59]
(3) bath slopping and splashing,[60] and
(4) heat transfer and losses in Peirce–Smith converters.[61]

> *There is nothing quite like going to the process, asking it important questions, and learning how to interpret the answers one receives in reply. . . . . for example, by injecting a process engineer bodily into a Pierce–Smith converter through a tuyere . . .*
>
> **J. Keith Brimacombe: Extractive Metallurgy Lecture, 1989[6]**

Extension of this work to zinc fuming was equally rewarding.[62,63,64] In this process, coal particulates are injected with air into a lead blast-furnace slag containing zinc, as shown in Figure 27. The coal was partitioned between the bath and the air bubbles. The coal, which is entrained in the air bubbles, provides heat for the operation, and the coal entrained in the slag serves as a reductant, releasing the zinc as a fume (Figure 27). With the aid of an elegant mathematical model and measurements on an industrial fuming operation at Cominco, they showed that, at the standard operating conditions, there was a relatively low level of entrainment of coal in the bath and, consequently, low process efficiency. With the aid of high-pressure injection, they improved the rate of coal entrainment in the bath and significantly increased the rates of slag reduction. This is a marvelous demonstration of how knowledge gained in one process, namely, the Peirce–Smith converter, was successfully translated to improve another process, namely, zinc fuming.

VIII. FLASH SMELTING

Not content to limiting himself to bath smelting processes, Brimacombe launched into the extremely complex phenomena of flash smelting, a process originally developed by INCO in the 1940s. In this process, finely ground sulfide concentrates are injected *via* a burner in a jet of oxygen into a furnace, where they undergo combustion and melt. With the support of the Natural Science and Engineering Research Council of Canada, INCO, Noranda, Cominco, and Hatch Associates, a highly instrumented pilot plant and a series of smaller furnaces were constructed to understand the principles of smelting of concentrates in a flash furnace. One cannot do justice to the technical intricacies of these studies, but highlights of the accomplishments are listed to illustrate their impact.

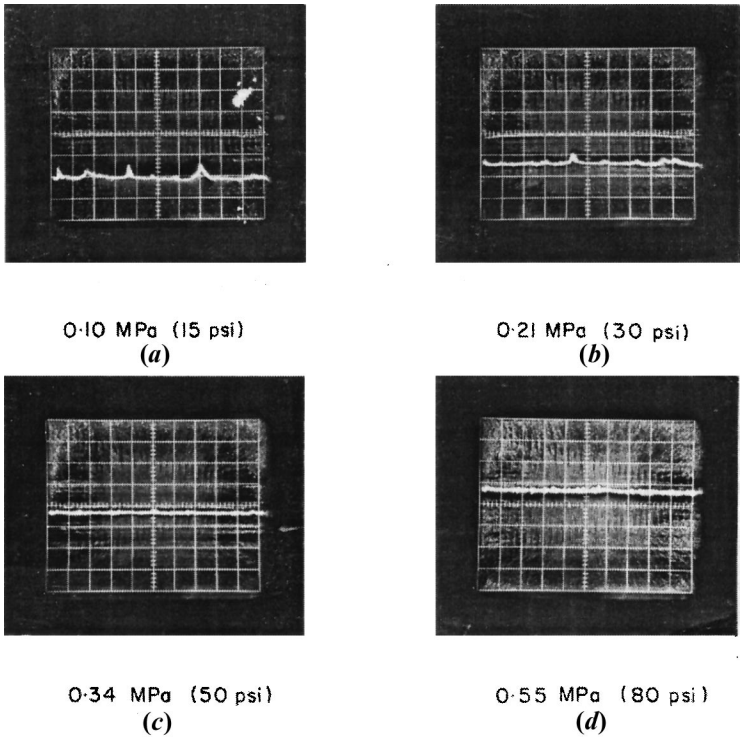


Fig. 26—(*a*) through (*d*) Pressure traces measured during high-pressure injection of air into no. 3 nickel converter. Vertical scale: 155 kPa/div. (22.2 psi/div.). Horizontal scale: 50 ms/div.

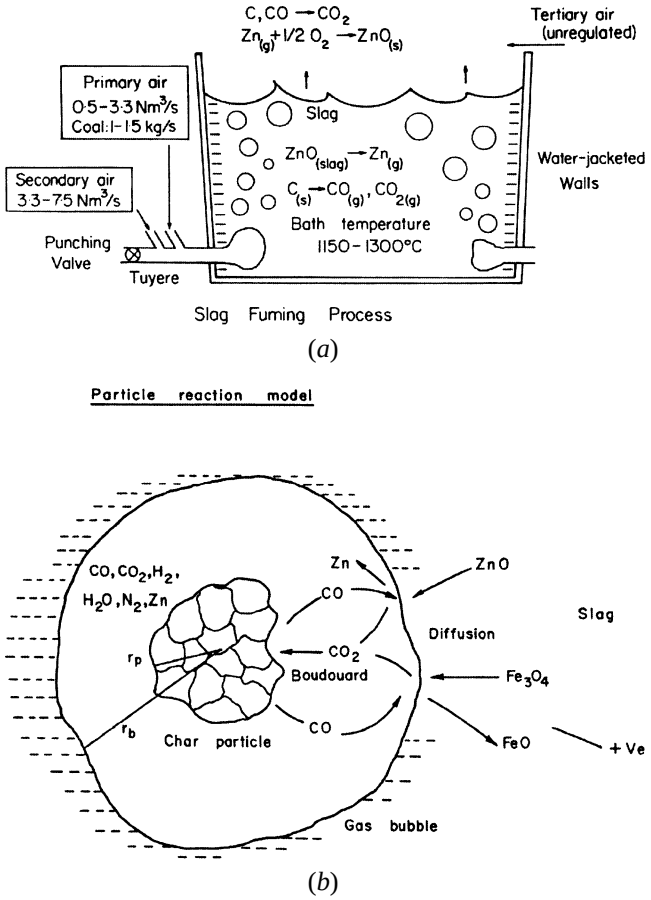


Fig. 27—(*a*) Schematic diagram of fuming furnace cross section showing construction and reactions. (*b*) Slag-char particle reaction system.

(1) A major study was conducted to understand the flash smelting of chalcocite concentrates through the development of a mathematical model. The model accounted for some critical aspects of the phenomena, including two-phase particle gas flow; radiative and convective heat transfer between the gas, particle, and walls; and particle reaction kinetics. The model was validated by comparison with the pilot-plant data from UBC's flash smelter, as well as with industrial data.[65]
(2) The study has shown that the conditions of combustion, oxygen content, particle size, and burner design, have a dramatic effect of dusting during combustion. Figure 28 illustrates the results.
(3) To complete the process model studies, a laminar-flow reactor was employed to study single-sulfide-particle combustion characteristics through high-speed photographic measurements, shown in Figure 29. This work led to determination of the kinetics of the reaction under various atmospheres and heat-transfer conditions. The results were used to formulate a mechanistic model for use in the overall process model.[66]

A powerful combination of experimental reactors, pilot-plant measurements, and full-scale industrial measurements were combined with a mathematical model of the process to reveal the inner workings of yet another reactor.

IX. CASTING OF INGOTS

Two studies that have an unusual symmetry but remarkably different origins, are the works conducted under Brimacombe's supervision by Thomas *et al.*[67,68] and Cockcroft *et al.*[69,70] Thomas set out to study the problem

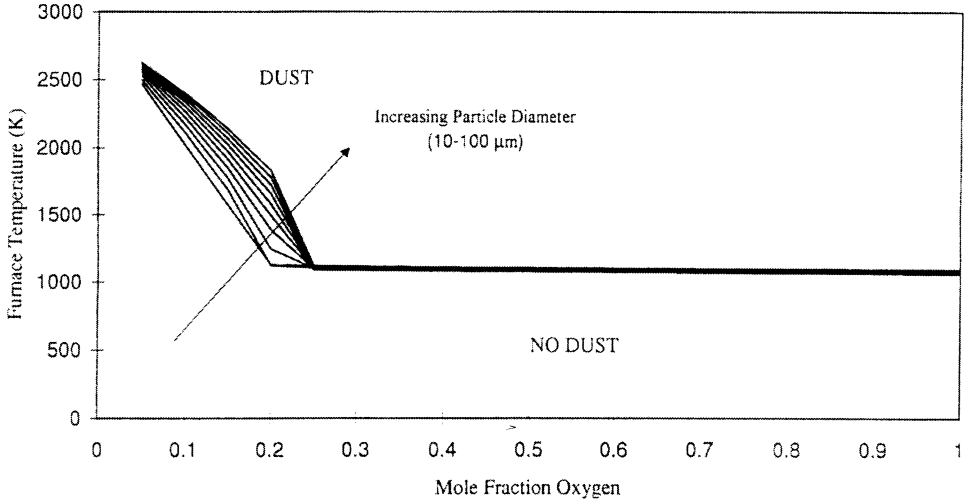


Fig. 28—Predicted dusting behavior diagram for MK concentrate combustion, as a function of particle size, temperature, and reactor gas composition ($f_{Cu} = 0$).[65]

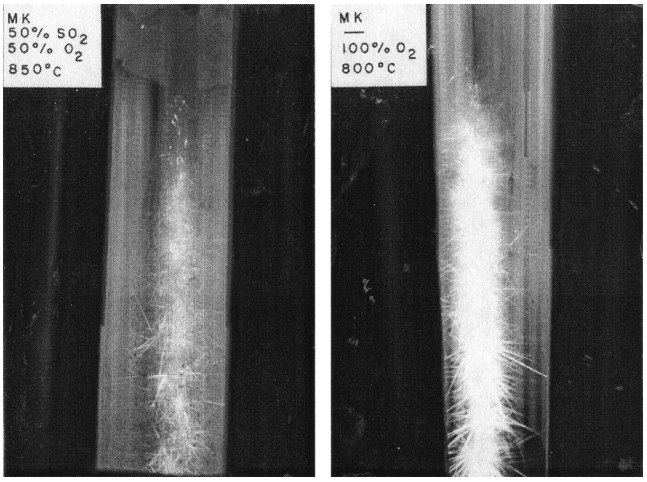


Fig. 29—Combustion photographs of MK concentrate particles in laminar flow reactor.[66]

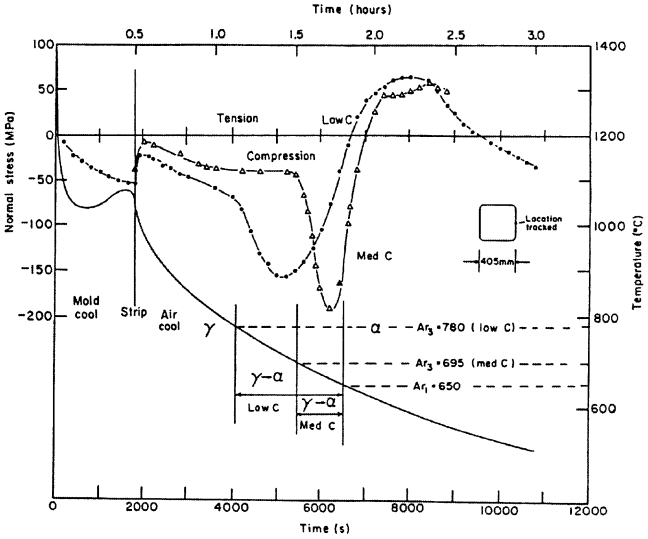
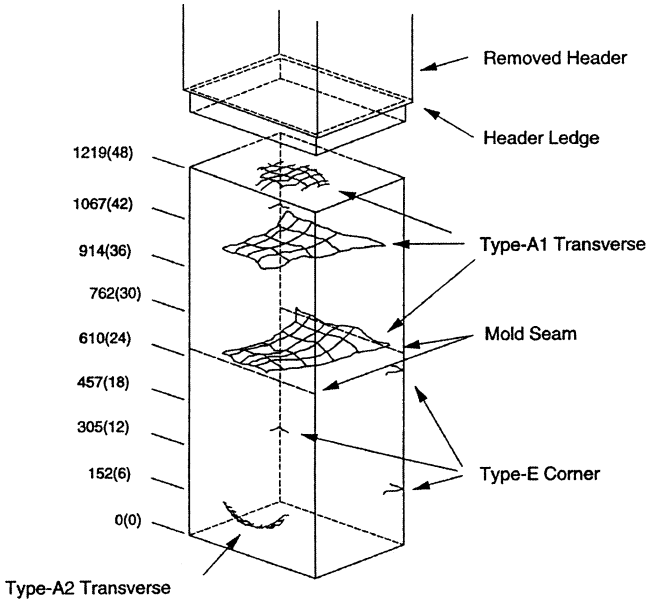


Fig. 30—Effect of carbon content of the steel on the thermal and stress histories of a 405 × 405 mm ingot during processing at the midface surface location.[68]

of panel cracking in large steel ingots, a defect that had plagued the industry for years, while Cockcroft's challenge was to solve a cracking problem in fused-cast large aluminum, zirconia, silica (AZS) refractory blocks. In the case of midface panel cracking in steel ingots, a mathematical thermal-stress analysis revealed that the movement of the two-phase region through the ingot and the associated expansion results in a high tensile stress at the surface, as shown in Figure 30, which is responsible for cracking. A proposed solution is to prevent the surface temperature of the ingot from dropping below the phase-transformation temperature by reheating it immediately upon removal from the mold. Interestingly, the cracking shown in Figure 31 in the fused-cast refractory blocks is associated with a tetragonal-to-monoclinic phase transformation which occurs in the zirconia component. Modifications to the molding procedure, based on a thermoelastic-stress model, led to the elimination of the type A transverse cracks.

There is much at stake here. If we do not take up the challenge and build strong teaching and research programs in materials process engineering, just who is going to engineer the processes to make materials (including metals!) products with the desired properties, price, and reliability in service? Who is going to run the growing materials industry and to manage technological change needed to sustain it? Are we going to leave this field, which impacts directly on our competitiveness of our industry to the chemical, mechanical and industrial engineers?

J. Keith Brimacombe: Extractive Metallurgy Lecture, 1989[6]



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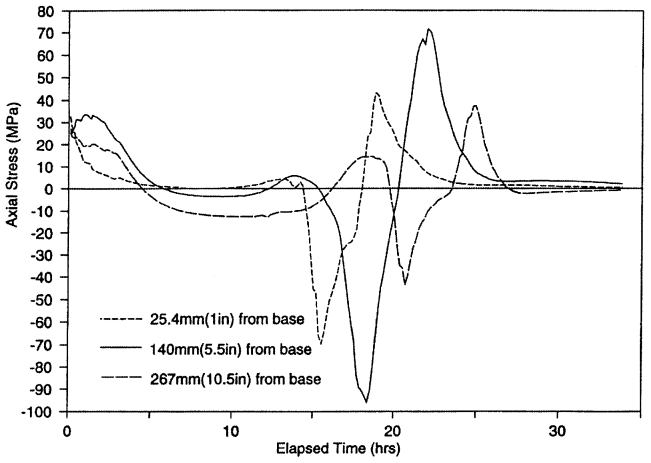

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Fig. 31—(*a*) Schematic illustration of the results of the autopsy performed on the instrumented "voidless," AZS refractory (units are millimeters (inches)).[70] (*b*) Axial stress (σ_z) predicted by the model at the center of the major face at varying distances from the base.[70]

X. INVIGORATING MENTORSHIP

As we embark on our journey through the twenty-first century, fundamental shifts have occurred in the world. We are in the midst of revolutionary economic and social change driven by knowledge and innovation, whose impact will far exceed that of the industrial revolution. Increasingly, nations everywhere are realizing the need to invest in the education of their citizens and in knowledge creation to spur innovation. Thus, people and knowledge are surpassing the traditional concepts of labor and natural resources as the vehicles for wealth creation. We as a profession have an obligation to mentor and enrich the development of the next generation of engineers and scientists who will sustain our industries.

Keith Brimacombe was a mentor par excellence. Brimacombe's influence on students is now legendary. He was a strong advocate of the importance of research in the education of young engineers and of its impact on their intellectual development. Over a 27-year period, 65 graduate students, including 31 doctoral candidates, and 25 researchers from Canada and countries around the world have benefited from his vision, imagination, intuition, and, above all, uncompromising commitment to excellence in research. Of equal significance is that Dr. Brimacombe has chosen to work closely with industry, not by following, but by providing leadership and focusing attention on areas that are both intellectually challenging and of long-term benefit to the economy. He has taken an interdisciplinary approach, with imagination and creativity. He has developed mathematical models of a process coupled with careful measurements in both the laboratory and in industry, often at a distance of 3500 km or more from the university. Thus, students have learned first-hand that industrial processes are complex and that ingenuity and intellectual rigor are required to unravel their mysteries. This course provides fertile ground for the education of graduate students, many of whom are now leaders in academia or industry. Professor Brimacombe was also a firm mentor and made it clear that he was intolerant of mediocrity. I remember research meetings with him, first as a student, then as a fledgling professor, and subsequently as a colleague. He had this amazing ability to look at seemingly disparate data you had brought and gently offer ideas that would reveal some insight; then, with consummate skill, draw the same ideas from you and leave you with the feeling that they were somehow your own. Through his creativity and that of the student, who was a true partner in the process, a profound discovery would occur that would transform our understanding of the process. Brimacombe would remark that there was nothing more satisfying than watching the raw creativity of a student flower and blossom. He was passionate about the need to think deeply and write clearly. In later years, with the advent of the revolution in computer technology, he grew frustrated as students spent more time typing and playing with the latest software, and surfing the Internet, instead of thinking. He wrote beautifully and was passionate about the quality of his students' writing. He would say, "When you write, you reveal how you think—muddled or clear." Every document, thesis, journal or conference article would go through several drafts and was returned covered in red ink. In later years we would call this process "Rembrandting." It was this passion for perfection and excellence that earned him and his students 20 best-article awards. Brimacombe's mentorship was a success not only because of his relentless pursuit of excellence, but because of his love of people. When students first arrived, he welcomed them with characteristic kindness and warmth, quickly dispensing with all the formalities and titles. He expended every effort to ensure that his students and their families were comfortable, and in the early days, helped them find dwellings and procure furniture. He invited students to his home and took a genuine interest in their lives, setting the tone for lifetime friendships. True mentorship and high performance are based on establishing strong human relationships. Organizations would do well if they embraced this philosophy.

(1) **Strong Interpersonal Relationships**—To successfully mentor a young researcher, one has to establish a trusting and supportive interpersonal relationship. In this age, where it is all too easy to communicate by e-mail and other impersonal means, face-to-face meetings have

taken on renewed importance. The human species has established language and personal communication over many millennia. The power to transform and inspire others through direct human contact is unmistakable. Mentorship takes time and effort and cannot be accomplished electronically! Organizations must recognize the need to provide young engineers with opportunities to network and develop relationships across a broad spectrum.

(2) **Excellence and Innovative Thinking**—A commitment to excellence is paramount. Young engineers must be inspired to pursue excellence in every endeavor. There is a great tendency to rely on past experience and apply techniques that have worked before in finding solutions for new problems. Teaching young students and engineers to think innovatively, not reproductively, is critical. Learning to rethink, as opposed to drawing from how one has been taught to solve a problem, is a critical skill. Of particular importance is the concept of redefining the framework of investigation, as described earlier.

(3) **Novel Combinations**—The ability to combine ideas from seemingly unrelated sources, connecting events and observations to create a big picture, is a distinguishing quality of true genius. Students should be encouraged to read widely and expand their horizons beyond narrow disciplinary boundaries to develop this skill. Broadening their experience base, to include academia, industry, and international travel, is a necessary foundation for enhancing one's ability to think creatively. Equally important is the concept of life-long learning and expanding one's knowledge base.

(4) **Encourage Discovery**—Increasingly, there is an emphasis on targeted research with predetermined outcomes. However, some of the greatest discoveries came as a result of individuals with insight finding what they were not looking for. Alexander Fleming's discovery of a mold growing on a culture of deadly bacteria was not what he was looking for, but paved the way for the development of penicillin.

(5) **Stimulate Collaboration**—Creating synergies by interacting across disciplinary boundaries has rich rewards. Many of the challenging problems we face today cannot be solved by an individual, or by a single disciplinary group. Students must be taught to work in teams and to interact across disciplinary boundaries.

Nurturing is at the core of professional development as well. In the progression from school to university to a professional career, young talent can be aided, shaped, or impeded. The challenges continue in the workplace, where learning does not stop and one is expected to contribute to society. At each stage, if fortunate, the young professional is influenced by mentors who help show the way. They are nurturers of a profession, passing the torch from one generation to the next.

J. Keith Brimacombe: TMS Presidential Perspectives, 1993

XI. INGENUITY AND ENTREPRENEURSHIP

We stand at the threshold of a new global age: an age in which interdependence transcends national boundaries, information is exchanged instantly, concern for our planet and the environment is international, and the global economy and innovation are interlinked. Ingenuity and entrepreneurship are of fundamental importance to compete in what is now being called a global economy. Ingenuity is defined as being clever at inventing and organizing, while entrepreneurship is defined as undertaking a commercial enterprise with the chance of profit or loss. Schumpeter, a radical twentieth-century economist, challenged classical economics and introduced the critical role that innovation and entrepreneurship plays in economic progress with his view of "creative destruction." He claimed that industrial cycles are 50 to 60 years long, as shown in Figure 32. According to his theory, each upswing, created by ingenuity and entrepreneurship, disrupted the previous order and stimulated investment and expansion of the economy. We clearly have entered the new industrial wave associated with digital networks, software, and new media. If I were to predict the next wave, it would be the biotechnology revolution associated with deciphering the human genome and other life forms! The challenge to our industry and to universities is to capitalize on each technological wave. Brimacombe exemplified ingenuity and entrepreneurship throughout his career, and there are lessons to be gleaned from his example for both the university and industry.

A. *Technology Transfer*

In the late 1960s, technology transfer from universities to industry happened by diffusion of knowledge from the published literature. Very few academics considered it appropriate to undertake such activity aggressively. Brimacombe, however, was driven by the desire to see the fruits of his research implemented in industry. Not satisfied that publications in peer-reviewed journals were an effective means of reaching out to the shop floor, where knowledge implementation creates wealth, he has worked tirelessly at the university-industry interface to make knowledge transfer to industry a reality.

Even if knowledge has been boiled down to principles and rules of thumb, it is of little value to a materials production company, if it is not applied where it matters most—on the shop floor where day in, day out, products are made.

J. Keith Brimacombe: 1996 Campbell Memorial Lecture[71]

A gifted speaker, he was renowned for his ability to translate complex research results to changes that are required to the process for improved quality and/or productivity. He presented, with colleagues, over 50 courses on continuous casting of steel in the United States of America, Canada, Brazil, Argentina, Venezuela, Mexico, Trinidad, United Kingdom, Norway, Sweden, Finland, Denmark, India, Italy, New Zealand, and South Africa. He also launched a successful course on continuous casting in Vancouver, which continues today and attracts over 100 participants from steel companies, suppliers, and users around the world.

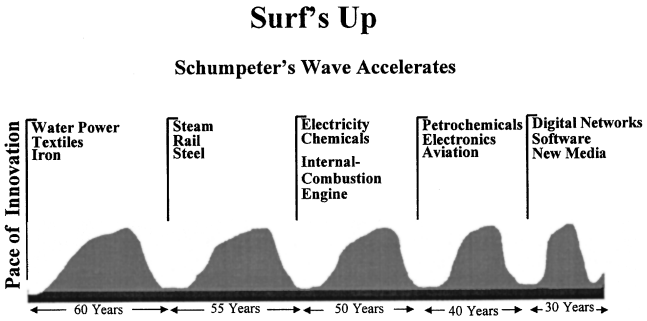


Fig. 32—Schumpeter's view of economic progress as creative destruction cycles.

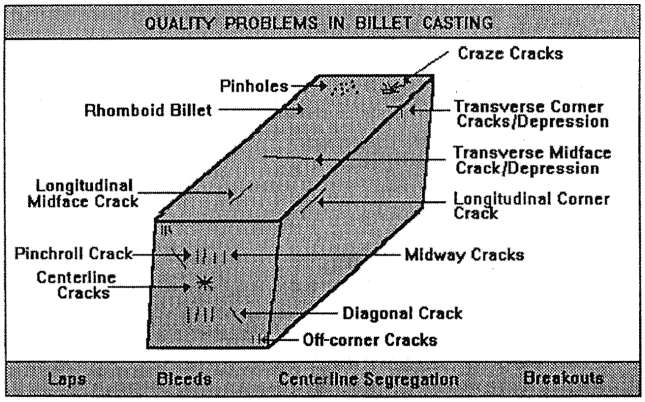
With the rapid technological changes occurring today, it is imperative that employees are knowledgeable and have the necessary skills to do the job. Life-long learning and continuing education is not a luxury, but a necessity to remain competitive. With the advent of new media and the possibility of distance education, progressive industries are upgrading in-house training centers and exposing their employees to courses ranging from business, management, and information technology to technical topics. Among the technical societies, the Iron and Steel Society has led the way in successfully offering courses on a range of topics. In addition, others such as Cramb, Fruehan, Wolf, Irons, and Guthrie have complemented Brimacombe's efforts in offering courses to industry.

The revolution in computer technology has advanced the transfer of knowledge. Since the early 1980s, before the advent of MICROSOFT WINDOWS* technology, Brimacombe drove the development of user-friendly mathematical models as a means of transferring research results to industry. Clearly, his vision has become a reality with the personal-computer revolution. Brimacombe was also instrumental in developing "smart" systems for the transfer of knowledge. A knowledge base, developed over two decades through in-plant trials, mathematical models, and billet-quality evaluation, served as the basis for an expert system: CRACX.[72] The system focused on surface and internal cracks and includes quality problems such as off-squareness, off-corner internal cracks, longitudinal corner cracks, midway cracks, centerline cracks, transverse cracks, transverse depressions, and bleeds and laps, as shown in Figure 33. Data provided by casting personnel served as input to the system, and uncertainties in the input data are handled through the application of fuzzy logic. The CRACX system also incorporates a computer model, which predicts shell growth, and the thermal history of the billet for a given set of operating conditions, as shown in Figure 33. The system has been purchased by over 25 companies worldwide. These kinds of systems serve not only as a diagnostic tool, but also as a great training tool for young engineers.

*MICROSOFT and WINDOWS are trademarks of Microsoft Corporation, Redmond, WA.

B. *Process and Product Innovation*

The expert system is a powerful tool, providing ready access to knowledge developed by experts over the years.



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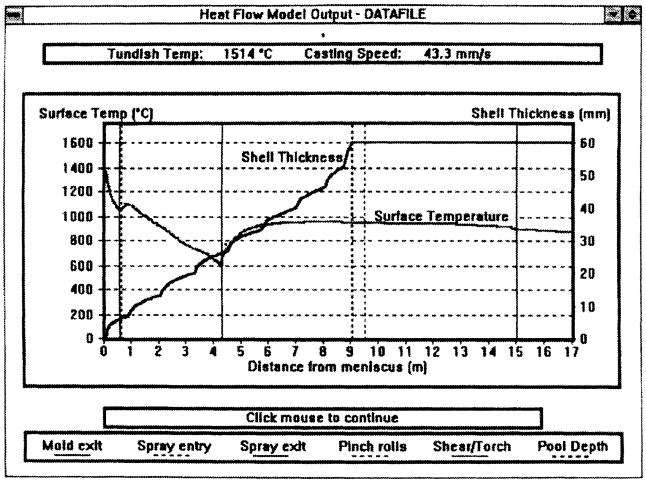

(*b*)

Fig. 33—(*a*) Depiction of billet quality problems in the CRAC-X expert system.[72] (*b*) Axial profiles of midface temperature and shell thickness predictions in CRAC-X.

However, it does not empower the process and cannot respond to process upsets which occur in real situations. Brimacombe in his 1993 Howe Memorial Lecture[29] advocated the development of an "intelligent mold," as shown in Figure 34. The mold can sense events, with thermocouples as "eyes" and load cells as "touch" and a modified version of the current expert system as a "brain." Many companies have been developing systems for detecting process upsets, and the breakout detection system, in use for some time, is the most rudimentary of such "intelligent systems." However, a new era is being ushered in. As the price of microcomputers continues to plunge, they will become plentiful as scrap paper. It is predicted that this will usher in an era of computing in which computers will be connected to one another. The Massachusetts Institute of Technology (MIT) media laboratory is working on a concept of "personal area networks." in which people will be wearing computers, such as in shoes, and information will be exchanged with a handshake! For the steel industry, the opportunities will be enormous, both for people, processes, and products. While the use of microprocessors for process control has a long history, the use of microprocessors in products is a new concept and one that needs to be embraced. Operators and other steel plant personnel will be equipped with wearable computers to transfer important information as these technologies evolve.

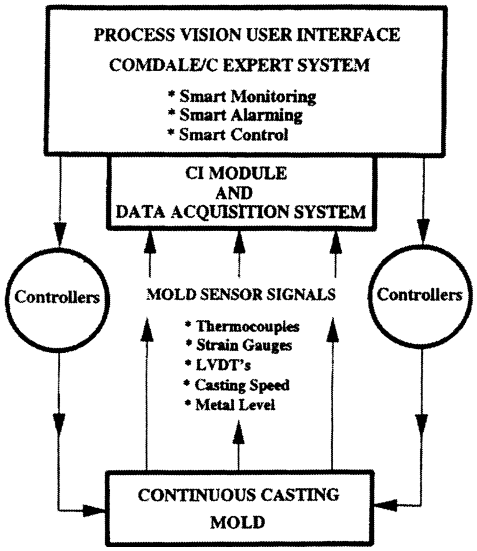

Fig. 34—Intelligent mold concept.

Laboratory Measurements with Advanced High Resolution Visual Systems and Computer-Aided Analysis

Smart Sensors for Continuous In-Plant Measurement and Analysis

Mathematical Models Coupled to Expert Systems for Analysis

Fig. 35—Process innovation framework.

The industry has been traditionally slower at developing and adopting "smart technologies," partly because of the searing temperatures and high levels of electrical noise in the steel processing environment. For the industry to survive economically and technologically, it is necessary for research to be focused on "smart" technologies. These include the use of sensors and microprocessors in strategic locations to detect the "health" of the process and the product. A new process-innovation framework will also evolve, as illustrated in Figure 35.

C. *Disruptive Technologies*

These developments say little about the role of new processes, which are at the heart of real transformation. Fortunately, the steel industry has entered an unprecedented era of change: a period that Harvard Business School Professor Christensen calls a period of "disruptive innovation." In this period, leading companies with the best management structures can fail if they do no recognize the role of disruptive technologies. In fact, Christensen[73] claims that many leading firms failed because they listened to their customers and invested in technologies that provided their customers with improved products, along the lines they had been providing them. By investing capital in opportunities that provided the best return on investment, they lost their leadership

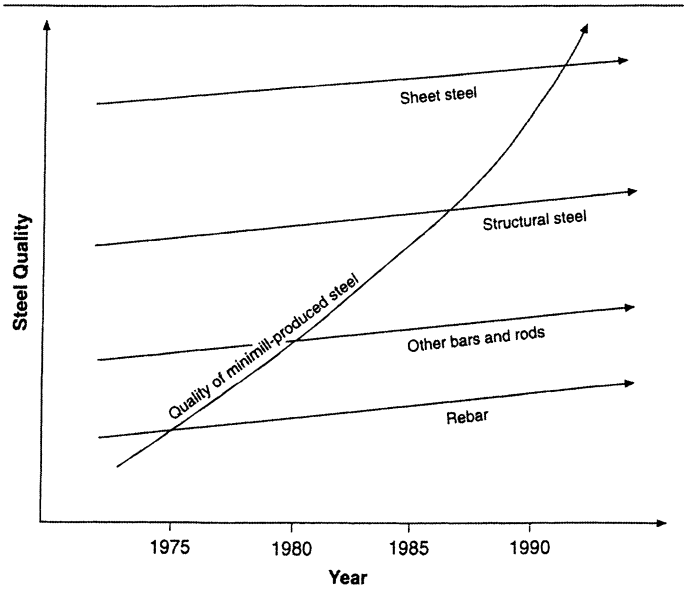

Fig. 36—The progress of disruptive minimill steel technology.

position, because they ignored new technologies with lower-performance products and lower margins, which eventually captured a greater share of their market or created new markets. The story of steel since the early 1980s demonstrates Christensen's claim and is illustrated in Figure 36. Minimill steel production is a "disruptive technology." Emerging in the 1960s, it captured the rebar market and by 1980 held 90 pct of this market. The integrated steel mills were relinquishing their lowest-margin products and investing in high-quality rolled sheet, where premium prices provided a good return on investment. However, the minimills continued their march toward higher quality and productivity and, by the mid 1980s, captured the entire market for long products, which included bars, rods, and structural shapes such as angles. This is indeed a powerful example of disruptive technology at work. The next wave began in 1987, when Schloemann Siemag AG introduced thin-slab casting. A revolutionary concept with evolutionary equipment, it only required a radical change to the continuous casting mold, but all else remained the same. With it, however, came a significant reduction in capital cost. Instead of the $2 billion required to build an integrated steel plant, a minimill could enter the flat-rolled business with an investment at that time of $250 million. The integrated steel companies did not seize this opportunity, since it could not provide the premium quality that their high-end customers needed, and continued their investment in conventional continuous casting technology. Nucor's success was their ability to ride this new wave of "disruptive technology." Having learned the lessons of the 1980s, many integrated steel companies have invested in thin-slab plants and are shifting production of the lower-quality, lower-margin products to these facilities. The inexorable march toward higher-quality flat-rolled products *via* thin-slab casting continues, and it will be interesting to witness the conclusion of this story.

A new chapter in this story is about to begin. In March of 2000, Nucor, BHP, and IHI of Japan initiated a collaborative venture that will lead to the commercialization of a direct strip-casting process for low-carbon and stainless steel in

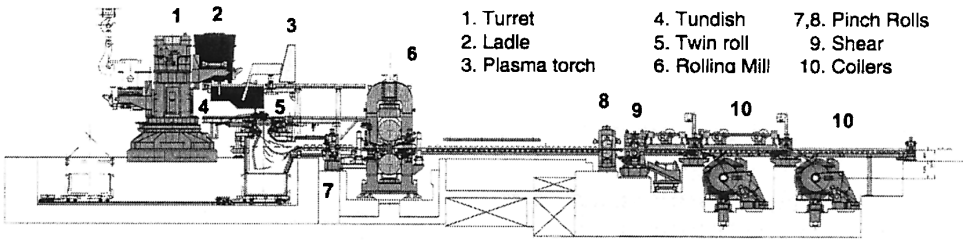

Fig. 37—General arrangement of the Port Kembla development plant.

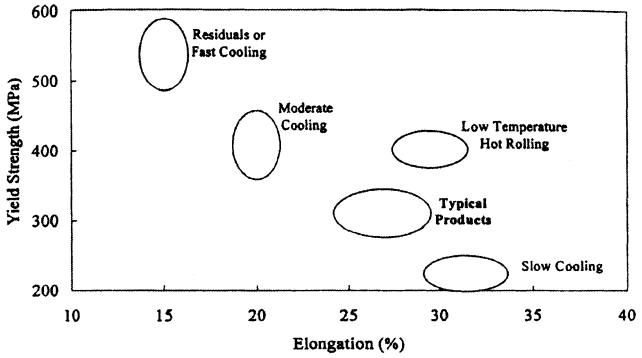

Fig. 38—Product opportunities in strip casting from a single low-carbon steel chemistry.

2001, making it the first such facility in the world for plain-carbon steel. Unlike the thin-slab casting process, the twin-roll process bears little resemblance to conventional continuous casting for slabs and is based on Bessemer's dream of casting steel through a twin-roll mold. That dream is becoming a reality following the pilot-plant work conducted at BHP under the title Project M, which resulted in a full-scale demonstration plant in 1995, shown in Figure 37. Mahapatra, a former student at UBC, has been at the very heart of this development.[74] The new process, the CASTRIP mill, will be 60-m long from caster to coiler, compared to a 300- to 400-m-long thin-slab casting plant and a 500- to 800-m-long conventional operation. It is estimated to utilize 50 pct less energy, eliminates the rough and cold rolling operations, and requires only a minimal amount of hot rolling. It is expected that strips ranging in thickness from 0.7 to 2.1 mm and 1000- to 2000-mm wide will be produced by this process at speeds of 150 m/min. Capital costs will be significantly lower than thin-slab casting—another disruptive technology. This process is revolutionary not only in design, but also in product capability. The significantly higher cooling rates during solidification result in a greater tolerance for residuals due to reduced microsegregation. Since the solidification process is so fundamentally different, there are also opportunities for control of the ferritic microstructure through control of cooling rates. It is predicted that a greater range of properties can be produced by controlling solidification, cooling during the austenite-to-ferrite transformation, and in-line rolling, as shown in Figure 38, with a single low-carbon steel chemistry. This is revolutionary indeed, not only from a processing standpoint but also from a product point of view.

There are other innovations that address the high surface-quality requirements for stringent applications. A national project in Japan has been underway for some time to control initial solidification in the mold by reducing the contact between the solidifying shell and the mold through the application of electromagnetic pressure, as shown in Figure 39. Pilot tests have demonstrated that it is possible to cast smooth surfaces, without oscillation marks, with low withdrawal resistance through the application of low-frequency magnetic fields in pulses.[75] Other novel developments include the casting of clad steels, through the appropriate use of electromagnetic fields in the mold, to create an outer shell of steel of one composition, with an inner core of another composition, as shown. These technologies promise to revolutionize conventional casting technologies, while we adopt radically new technologies such as twin-roll strip casting. There has never been a more exciting time in the history of continuous casting and steelmaking.

XII. INSPIRED LEADERSHIP

The steel industry requires visionary leadership and talented people to harness the winds of progress in this time of great change. We are also witnessing the early signs of a demographic shift, reflected in shortages of skilled people, as the baby boom generation approaches retirement. New leaders and managers are needed at the very time when the competition from young and emerging industries such as information technology, biotechnology, and e-business is attracting the best young graduates. There is also competition within universities for bright young minds from emerging areas such as genomics, e-commerce, microelectronics, and quantum structures. Universities are reallocating resources to support burgeoning new fields. Thus, there are challenges ahead for the materials engineering discipline and the metals industries in the areas of education, research, and professional leadership.

A. *Education*

Although Brimacombe returned to UBC in 1970, at a time so different from the one in which we find ourselves today, there are strong parallels. The Internet is transforming our lives in every area, much like the computer did in the 1970s and 1980s. We have to look at harnessing this new resource to our benefit and not to our detriment. If we look back at Brimacombe's contribution, it was apparent that he understood how to harness the advent of computational technology to the benefit of materials engineering education. In the early 1970s, metallurgy programs were strongly science oriented and weak in engineering. There were no design courses, and many of the subjects were highly qualitative and focused on physics, chemistry, thermodynamics, materials science,

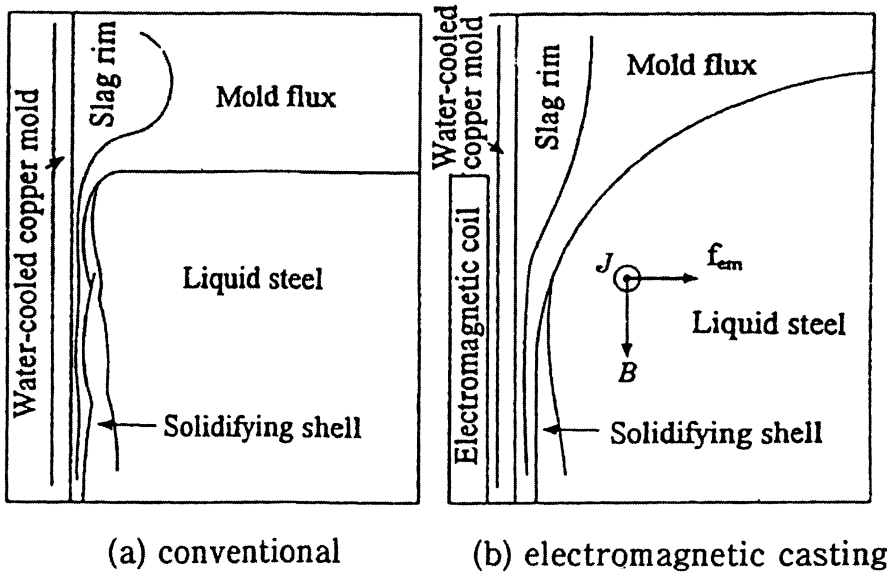

Fig. 39—(*a*) and (*b*) Principles of electromagnetic casting of steel.

and mathematics. It was also a time when significant computational capability was becoming available. He had a clear vision of what needed to be done and set out to do it.

> *What has caused us at universities to lose sight of the realities of materials processing and properties? Perhaps the answer lies in the smoldering embers of metallurgy. Although metals—iron, copper, bronze and steel—profoundly shaped the course of civilization over millennia, we have been incapable of defining the engineering discipline that underpins them. We have been caught up in atoms and structures and free energies while losing sight of heat losses and evaporation and dust formation.*

J. Keith Brimacombe

He introduced courses on heat, mass, and momentum transfer into the undergraduate metallurgical engineering curriculum and developed unique courses on mathematical modeling of metallurgical processes. Brimacombe also introduced the concept of design, which had always been in the domain of chemical and mechanical engineers. He insisted that students should acquaint themselves with real-life problems and interacted with industry to gather material that could be utilized in his teaching. He single-handedly transformed the curriculum in metallurgical engineering at UBC from a largely science base to one with sound engineering. He accompanied students on field trips and encouraged them to apply their knowledge to understand and solve industrial problems. His legacy are the men and women who obtained their undergraduate degrees from UBC at that time, now employed as engineers and managers in our industries in Canada and around the world.

Clearly, the Internet is transforming our lives and is having an enormous impact on education. Internet course delivery is no longer a dream but a reality. There are enormous opportunities to transform our course offerings from lecture-based to discussion-based learning, with course material being offered on the Web. However, there are several fundamental questions that have yet to be answered. Will this new mode of instruction with reduced classroom lecture hours be as effective? Meadowcroft, in a recent lecture at the Brimacombe Memorial Symposium, October 2001, examined the future of materials engineering education in light of these new developments. Some of the benefits are clear. Professors will be able to spend less time transferring information to students, which can be handled effectively by Web courses; instead, there will be more time for discussion and problem solving. The best lecturers worldwide in a given field can be enlisted to produce the best set of basic courses in a given discipline, exposing students to great minds from around the world. Students will be able to take the Web portion of the course at any time, and as many times as desired, facilitating distance education and allowing individuals to combine employment with education more readily. Finally, there is a cost to all of this. New technologies and change come at a price. Perhaps the greatest risk lies in the potential change in the extent of human contact. Not simply between student and teacher, but among students. Today, young people benefit enormously from a campus setting and the opportunities to socialize and network, which are so vital to their development as citizens and professionals in a given field. If many more hours are spent interacting with a screen and less are spent in a classroom with others, it will change the nature of the learning experience. Students will probably have a reduced opportunity to interact with others outside their field. Universities will have to pay special attention to this element of an individual's undergraduate education and incorporate it in the new learning environment. Experiential learning is not about simply acquiring facts, but about engaging with others in the quest for expanding one's mind. We will need stellar leadership and wisdom to guide us through this period.

B. *Research—The Search for New Knowledge*

Lester C. Thurow, former dean of MIT's Sloan School of Management, has stressed that in this new century there will

be greater dependence on knowledge than in any other time in our history. He writes "In the twenty-first century, brainpower and imagination, invention and organization of new technologies are key strategic ingredients." He goes on to say that "Today, knowledge and skills now stand alone as the only source of comparative advantage." Thus, every industry will need access to an advancing knowledge base for their competitiveness. For the steel industry, the competition comes not only from companies within the steel family but from other materials, such as aluminum, plastics, and composite materials. Thus, the investment in research and development is critical—both at universities and in industry. In research-intensive universities, students, both undergraduate and graduate, benefit from the research culture. Research is the medium by which young people are taught to think critically, make new discoveries, and translate these discoveries into innovations that benefit industry. In industry, without research there is inadequate potential to develop new products or processes, diminished receptor capacity for evaluating new technologies, and weakened problem-solving skills.

The research models have significantly changed over time. Brimacombe believed passionately that the greatest breakthroughs would result from interdisciplinary efforts—an idea which was not yet fashionable in academia. How right he was, a concept that is crucial for our time. Universities and industry would do well to facilitate such interaction, by breaking down the barriers that exist to building such research groups. Brimacombe also recognized the need to work closely with industry. The Stelco Chair, awarded to him early in his career in 1980, helped build steel research at UBC for the better part of a decade. As a result of Brimacombe's vision and inspiration, the Natural Sciences and Engineering Research Council (NSERC) of Canada, a federal granting agency, began providing matching funds for industrial contributions, which led to the birth of the industrial/NSERC Chairs in many fields, of which the Stelco/NSERC Chair was the first. Dofasco is now leading the way with research Chairs at UBC and at McMaster University, strengthening research capacity in steel processing and products in Canada.

Individual investigator-driven research has given way to multi-investigator research teams, consortia, and networks. These models, although more difficult to manage, are a strong base from which to tackle major initiatives. The American Iron and Steel Institute's Advanced Control Program, with support from the Department of Energy, led to the establishment of a large project on Microstructural Engineering in Hot Strip Mills at UBC under Brimacombe's leadership. Over 5 years, the research group developed a user-friendly model for the prediction of the microstructural evolution and mechanical properties of steel during hot rolling for eight steel grades. There are other examples of dynamic consortia. The steel research center at Carnegie Mellon University, supported by over 20 steel companies, has provided the steel industry with highly skilled graduates and an impressive body of knowledge on liquid-steel processing.

Despite these successes, the number of universities in North America undertaking steel research is low. This is an area of concern for the future. Highly skilled people will be the principle asset in the future, and so industry must ensure that there are strong programs in steel research in many centers. National networks in steel research should be developed and expanded to encompass international players to build critical mass in key areas of need. These networks should include researchers with skills not only in traditional areas of metallurgy but also in robotics, process control, management, e-business, and the environmental sciences. If steel is to be the material of choice for a wide range of societal applications, it must be also the material with knowledge and value. Research and development is critical to staying this course.

> *The financial vitality of any steel company begins on the shop floor, where products are made amidst noise, heat and intense activity. Therefore, this is where knowledgeable people need to be, armed with the tools necessary to do their job. There is a pressing need that many of these people be university graduates who have knowledge of the forces at work. . . .*
>
> **J. Keith Brimacombe, ISS President 1995**

C. *Leadership and Professional Societies*

Professional societies have a critical role to play in nurturing the next generation of professionals who will lead our industries. Briamcombe believed passionately in this role and was the only professional to have been President of Metallurgical Society of CIM, in Canada (1985), TMS in the United States of America in 1993, and the ISS in 1995. At the time of his passing, he was President-elect of AIME. He captured the essence of the role of the ISS in the following remarks during his Presidency.

> *The Iron and Steel Society exists solely to support the person engaged in working in the iron and steel industry. It begins with the attraction of fine young minds to the industry through the ISS Foundation. It continues with ongoing education* via *short courses and publications, such as our conference proceedings and other technical books. The ISS supports members through the provision of forums, at which the professional can share ideas and interact with others on the world stage of steel. It continues with opportunities to lead the industry through the ISS Divisions and committees that serve the world steel community.*
>
> **J. Keith Brimacombe, ISS President 1995**

In an era when time is measured in dollars instead of days, professional societies, universities, and industry face challenges. Organizations are increasingly reluctant to foster participation in society activities, or to encourage their employees to present articles or provide time for networking. These challenges must be turned into opportunities, if we are to remain vibrant.

(1) **Support Students**—Continued support of students, in the form of scholarships, but equally importantly, to participate in conferences and field trips, is paramount

if we are to attract them to careers in the steel industry. The return is incalculable.

(2) **Mentor Young Professionals**—Professional societies should create programs to mentor young professionals. In addition to expanding their technical knowledge, young professionals need opportunities to develop leadership skills. Time has now become the scarcest resource in organizations, and young professionals do not necessarily receive the mentoring needed for their professional development. An organization or an industry that invests in their young professional is minding their future.

(3) **Participation in Society Activities**—Universities and industry must encourage and support participation in professional society activities. This could include participation in short courses as a lecturer or attendee, committee activities, or presentations at conferences. The leadership, networking, and communication skills that one acquires are invaluable.

(4) **Quality Programming**—Professional societies must strive to develop the best possible programs, be they conferences or courses or opportunities for networking, to fulfill their mission.

(5) **International Networks**—Globalization is a fact of life and steel is an international industry. Professional societies must strengthen their international ties by partnering, networking, or simply collaborating to provide greater opportunities for their members.

It has been a privilege to write and deliver this lecture in honor of J. Keith Brimacombe, (Figure 40), a rare human being. He was one of the warmest and most caring of individuals. He was a born leader with enviable charm and charisma. Never content with the status quo, he thought deeply about needed change and altered the discipline irrevocably through his creativity. He transformed professional societies, sculpting the finest of stepping stones for those to follow. Brimacombe challenged and inspired many around the world by the power of his ideas. For his pioneering efforts, he received 28 major national and international awards and 20 best-article awards. In 1989 he was made an Officer of the Order of Canada, the nation's highest honor reserved for citizens whose extraordinary achievements have led to a better Canada. I was fortunate to have spent 20 years of my life's journey in his company.

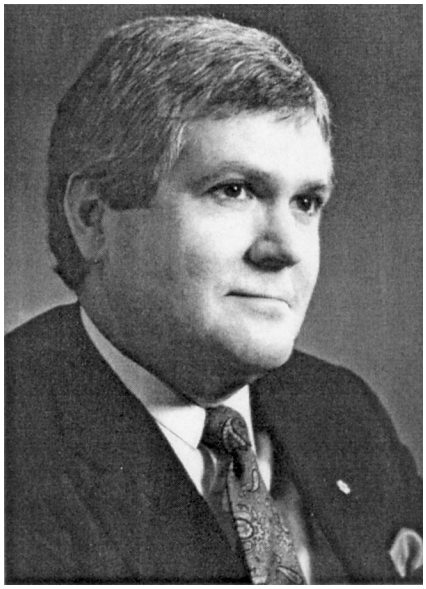

Fig. 40—Photograph of J. Keith Brimacombe 1989.

Lo! The leader in these glorious wars
Now to glorious burial slowly borne,
Follow'd by the brave of other lands,
He, on whom from both her open hands
Lavish Honour shower'd all her stars,
And affluent Fortune emptied all her horn.
Yea, let all good things await
Him who cares not to be great
But as he saves or serves the state.
Not once or twice in our rough island-story
The path of duty was the way to glory.

(Alfred Lord Tennyson (1809–1892),
Ode on the Death of Duke of Wellington)

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