The Science and Technology of Steelmaking – Measurements, Models and Manufacturing

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> ***The exchange of knowledge between researchers, users and the resource community is required to transform a fundamental scientific concept into a reliable operating system.***

In our efforts to characterize and improve the performance of an existing steelmaking process, or in our quest to generate useful knowledge as a basis to develop new manufacturing routes, measurements and models should be considered as two interdependent requirements. Without measurements, our models are incomplete and unsatisfactory. Without models, we fail to realize, or perhaps even comprehend, the potential significance of our measurements. Sometimes in our enthusiasm, we construct sophisticated, elegant models and forget the reality of the actual manufacturing process. In this computer age, we need to remember the importance of observations and accurate measurements. In addition, as engineers and applied scientists, we have an obligation and a responsibility to facilitate the transfer of new knowledge into the realm of operating practice. During this process of generation, evaluation and communication of new knowledge, knowledge exchange is perhaps the most difficult step. In this context, the preeminent aim of collaborative activities between our educational institutions, industrial organizations, government funding agencies and professional societies, is to ensure the availability of high quality people who not only understand the fundamental aspects and practical implications of their discipline, but also are fully equipped with the essential skills of communication that will enable them to participate throughout their career in this most challenging and satisfying activity, the science and technology of steelmaking.

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INTRODUCTION

"*A never-ending challenge to the competitiveness of the steel industry is the application of knowledge on the shop floor where, finally, productivity and quality are realized.*"
1993 Howe Memorial Lecture, The Iron and Steel Society of AIME[1]

During the past century, the steel industry has been transformed by major technological changes. Coupled with the implementation of innovative production systems, there have been increasing demands for improved steel quality. These demands have been met by advances in our knowledge and understanding of the chemical, physical and thermal interactions between steel, gas, slag and refractory phases, which occur within individual reaction vessels and also during transfer operations between the primary furnace and the casting mold. In a typical steel plant, the reactors include converters or arc furnaces, ladle furnaces, vacuum vessels, tundishes and casting molds. In recent years, transfer operations between one reactor and the next must be controlled precisely. Otherwise, these transfer steps become destroyers of quality.

As we move into the next century, there is an increasing need for new process control strategies to achieve consistent quality products with maximum yield, optimum cost and minimum impact on the environment. Successful new strategies are most likely to evolve from a knowledge-based foundation of measurements, models and a solid understanding of the fundamental aspects of the manufacturing process (Figure 1).

At an International Conference in Tokyo on Computer-Assisted Materials Design and Process Simulation, in a paper entitled "Computer Simulation of Solidification and Casting Processes," J. Keith Brimacombe and his co-authors emphasized the importance of "balancing the application of sophisticated computer models with painstaking measurements." While acknowledging that "the computer has transformed the ability to analyze casting and solidification processes quantitatively with mathematical models," they went on to state "without careful companion measurements, both in the laboratory and in-plant, to characterize thermophysical properties and complicated boundary conditions, as well as to validate the mathematical models, the power of the computer is severely blunted."[2] Although these comments were made with respect to casting processes, they are equally valid within the general context of this article.

In the following sections, examples are provided of some laboratory data and plant studies, together with process models and innovative technologies that have been developed for monitoring and control of specific aspects of the steelmaking operation. These technological considerations are discussed within the philosophical context of several themes, which are in many ways a reflection of some of the ideas and concepts expressed so eloquently by Brimacombe in memorial lectures to professional societies, in keynote presentations at international conferences and in commentaries published during his years as president of The Minerals, Metals and Materials Society, and later, ISS. They are but a few threads drawn from the multicolored tapestry that was the fabric of Keith's career.

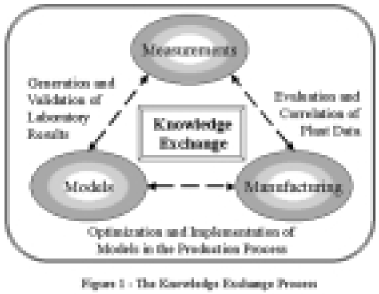

Figure 1 *The knowledge exchange process.*

OXYGEN CONTROL IN MOLTEN STEEL

"When you can measure what you are speaking about and express it in numbers, you know something about it. When you cannot measure it, your knowledge is meager and unsatisfactory."
Lord Kelvin

In discussions of steel quality, interactions between oxygen and elements such as carbon, manganese, chromium, silicon, aluminum and calcium are particularly interesting. The same is true with respect to reactions involving the elements sulfur, phosphorus, hydrogen and nitrogen. Control of oxygen potential throughout steelmaking operations is essential. Without oxygen control, controlling the behavior of the other elements is impossible. In this context, control of the composition, properties and performance of steelmaking slags and refractories is also a mandatory requirement for producing quality steel.

A major thrust in current steelmaking technology is the production of steel with lower residual concentrations of oxygen and sulfur. These elements have a profound influence on the quality of the final steel product because of their effect on inclusion formation. Since these reaction products have a direct bearing on the properties of steel in service, considerable attention has been directed toward developing a thorough understanding of the factors that influence their formation and properties, as well as methods for minimizing their presence in solid steel. Factors that influence their formation include: interactions within the molten steel itself, interactions between molten steel and air during transfer operations from one vessel to another, interactions between steel and molten slag, and finally, interactions between steel and refractory materials.

In steelmaking processes, molten steel is inevitably brought into direct contact with air. Little et al. have shown that large inclusions are primarily due to reoxidation of the metal during transfer operations.[3] An exposed metal meniscus in the ladle or tundish, and a molten stream or turbulence of the metal in the mold cavity, provide ample opportunity for liquid steel to react with air, which is an unlimited supplier of oxygen.[4] In addition, these conditions can also contribute to the absorption of nitrogen, as well as hydrogen, particularly when the humidity content of the atmosphere is high.

Reactions between molten steel and the surrounding atmosphere have been investigated using levitation melting and a falling droplet technique (Figure 2).[5,6] The solutes oxygen and sulfur and the interrelationships that exist between these solutes and the elements nitrogen and hydrogen have been studied. When present in molten steel, oxygen and sulfur behave as surface-active elements. Experiments have shown that both oxygen and sulfur drastically decrease the nitrogen absorption rate (Figures 3 and 4). The same behavior has been observed with respect to hydrogen absorption. On the other hand, in the case of oxygen absorption, the rate is not affected by the sulfur content of the steel, but rather by diffusion in the gas phase (Figure 5). Thus, if steel is produced

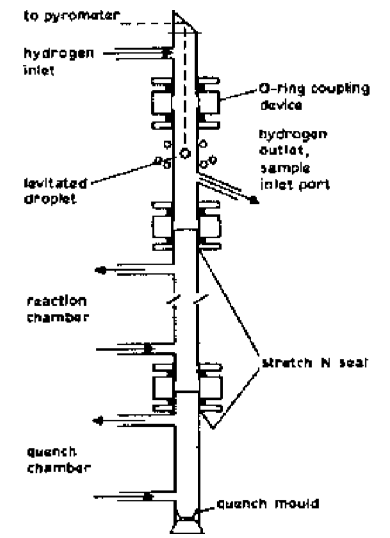

Figure 2 *Levitation melting and falling droplet facility for the investigation of reactions between molten steel and gas atmospheres.*[5, 6]

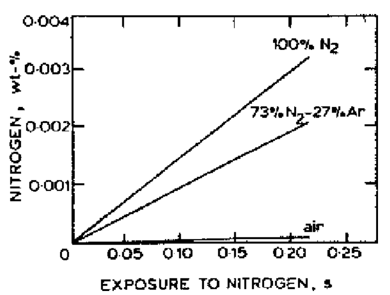

Figure 3 *Absorption of nitrogen by steel droplets after falling for various times through different gas atmospheres.*[5]

with very low oxygen and sulfur contents, then molten steel is more susceptible to hydrogen and nitrogen absorption. For example, during ladle desulfurization treatments, nitrogen absorption may be about 15 ppm when the final sulfur level is 90 ppm. However, when the final sulfur level is 20 ppm, nitrogen absorption may be as high as 50 ppm.[7] This implies that while problems associated with the presence of sulfides may be avoided by producing low sulfur steels, new problems may be introduced due to high nitrogen contents and possibly even high

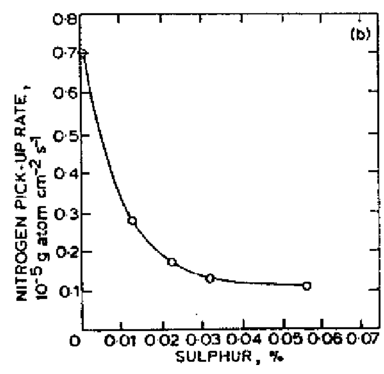

Figure 4 *Decreased in nitrogen absorption rate by steel droplets with an increase in sulfur content.*[5]

hydrogen contents. For this reason, there are advantages to producing steel with final sulfur concentrations that are at the higher end of the sulfur specification rather than at the lower end. In this way, nitrogen and hydrogen absorption can be minimized. By the same logic, delaying the addition of deoxidizers and/or desulfurizing treatments will also decrease opportunities for nitrogen and hydrogen absorption.

BEHAVIOR AND CHARACTERIZATION OF STEELMAKING SLAGS

"*We must see what we can learn from each other. The power of knowledge stems not just from its depth, but also from its breadth.*"
Presidential Perspective: The Power of Knowledge[8]

To a large extent, oxygen control in steelmaking is affected by the composition and properties of the slag phase. Without oxygen control, the behavior of the other elements cannot be managed. Steelmaking slag systems involve at least eight important components: CaO, MgO, MnO, FeO, SiO_2, Al_2O_3, P_2O_5, CaF_2, and often a number of others such as Na_2O, TiO_2 and Cr_2O_3. One of the greatest obstacles to the application

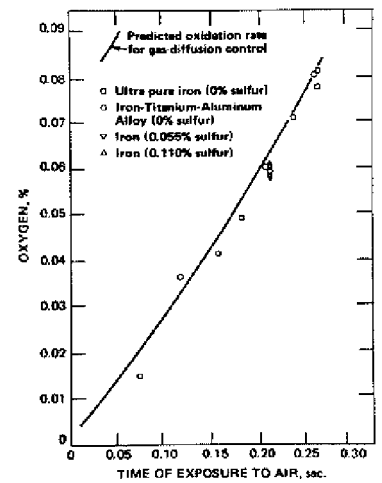

Figure 5 *Absorption of oxygen by steel droplets containing different amounts of sulfur, aluminum (0.1 percent) and titanium (0.1 percent) after falling for various times through air.*[6]

of physical chemistry principles to the elucidation of slag-metal and slag-gas reactions is a lack of knowledge about activities of the reacting species. Since iron oxide in slag participates in numerous reactions between metal, slag and gas phases, and important steelmaking reactions such as desulfurization and dephosphorization are related to the ferrous oxide activity, evaluation of the activity of this component is particularly important.

In addition, molten slag can contribute to reoxidation of the steel. For example, consider the reoxidation of aluminum by ferrous oxide in molten slags:

$$2\,Al(\text{in Fe}) + 3\,FeO(\text{in slag}) = Al_2O_3(s) + 3\,Fe \quad .....(1)$$

Equation (1) will proceed to the right-hand side with an increase in FeO activity. Hence, it is required to lower the FeO activity in molten slag especially in secondary refining vessels. For this purpose, aluminum or calcium carbide is spread over the slag. Currently, control strategies for such practices are based on samples taken from the molten slag during ladle treatment.

Based on practical experience, plant operators pay particular attention to the concentrations of "total" Fe plus MnO, (%T.Fe) + (%MnO). Manganese oxide can also reoxidize aluminum although (%MnO) < (%T.Fe). For example, Hara et al. have reported this effect where, as shown in Figure 6, the total oxygen concentration in steel after RH degassing increased with an increase in (%FeO) + (%MnO) in the slag phase.[9] However, chemical analysis for FeO and MnO in slags requires at least 20 minutes, while ladle treatment is generally completed within 15 to 20 minutes. Hence, a knowledge of (%T.Fe) + (%MnO) based on chemical analysis cannot really assist plant operators to control the molten slag of a particular heat during actual production.

In view of the industrial significance of ferrous oxide activity, numerous experimental determinations have been conducted by many laboratories during the past five decades. Nevertheless, our knowledge of the activity of FeO in multicomponent industrial slags is still far from satisfactory. The conventional experimental technique for determining ferrous oxide activity consists of equilibrating molten slags with liquid iron. Chemical analysis for oxygen made on samples taken from liquid iron yields values of ferrous oxide activities. Alternatively, molten slags contained in an iron crucible are brought into equilibrium under a stream of CO-CO_2 or H_2-H_2O. These techniques however, require a relatively complex experimental setup and long duration.

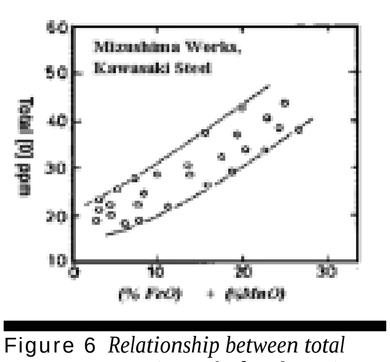

Figure 6 *Relationship between total oxygen contents in steel after degassing and slag chemistry.*[9]

Rapid Determination of Ferrous Oxide Activities

Ogura et al. have developed a "shop floor" activity determinator for ferrous oxide based on the principles of zirconia sensors.[10] This equipment uses samples taken from the slag phase. However, knowledge of sample weight is not required, and activity measurements can be completed within five minutes. This electrochemical technique based on magnesia-stabilized zirconia permits rapid determination of ferrous oxide activity within homogeneous and heterogeneous slag systems.[11] Using this technique, FeO activity has been measured for many different slag systems by Iwase et al.[12, 13]

This research led to the manufacture of an analytical instrument to determine FeO activities.[10, 14] A diagram of the automatic activity determinator is shown in Figure 7. To operate this system, a solid state sensor (F) is attached to the elevator mechanism (E), and an iron crucible (K) is placed on the steel pedestal (O). The electrical contact to the outer electrode of the zirconia cell is made via this pedestal. Pure silver (M) is premelted within the iron crucible. A sample of slag (L), 1 to 3 g, is placed in the iron crucible. The iron crucible is moved upward via an elevator mechanism (P) into a transparent silica reaction tube (H). The furnace is subsequently heated to a temperature of 1,750 degrees Kelvin under a stream of argon within 2.5 minutes according to a computer program. The electrochemical cell is lowered until it contacts

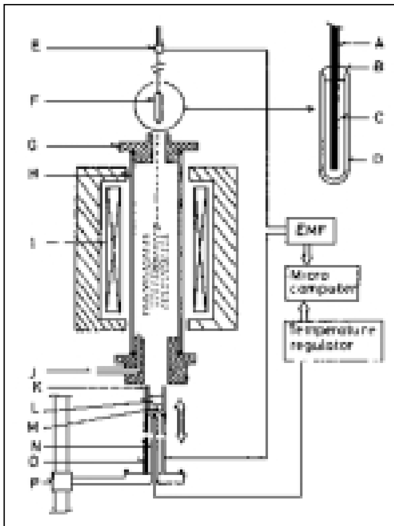

Figure 7 *Illustration of automatic activity determinator: (a) Mo rod; (b) zirconia cement; (c) Mo + MoO_2 reference electrode; (d) reference electrode; (e) elevator mechanism; (f) zirconia cell; (g) water-cooled brass flange; (h) transparent silica tube; (i) tungsten filament; (j) Ar inlet; (k) iron crucible; (l) slag sample; (m) silver; (n) Pt-PtRh 13 thermocouple; (o) stainless steel pedestal; and (p) elevator mechanism.*[11]

both the molten silver and the slag. Open-circuit cell voltages generated are monitored on the LCD of the microcomputer. The cell potential is then converted to the FeO activity and displayed on the LCD. In this way, a single activity measurement is completed within five minutes. This determinator, which is now used by several steel companies in different parts of the world, has permitted new control strategies to be developed for the behavior of phosphorus and sulfur in liquid iron and for reducing steelmaking slag volume.

Applications of the Activity Determinator for Optimization of Steelmaking Operations

An example of the industrial application of the activity determinator by Hamm et al.[15] relates to control of the desulfurization reaction, which can be expressed as:

$$(CaO) + [S] + Fe = (CaS) + (FeO) \quad .....(2)$$

Equation (2) implies that if the activity of CaO (i.e., the basicity of the slag) is kept constant, a logarithmic plot of the sulfur partition ratio against FeO activity should be a straight line with a slope of –1. The relationship obtained by Hamm et al. is shown in Figure 8. Although the slope is different from the theoretical value, there is a good correlation between the two parameters, indicating that the sulfur partition ratio can be monitored, and therefore controlled, through FeO activity measurements.

Figure 9 shows the relationship between a_{FeO}, which was determined by the activity determinator and (%T.Fe) + (%MnO) obtained by chemical analysis for industrial slags taken from different ladle steelmaking operations. As shown in this figure, the empirical parameter, (%T.Fe) + (%MnO), is proportional to the FeO activities. However, FeO activities of slags from one melt shop are different from those at another even though the empirical parameter, (%T.Fe) + (MnO), is the same.

From a thermochemical point-of-view, this behavior is quite understandable if differences in slag basicity are accounted for. In other words, we can state that the empirical parameter is not an appropriate model for close control of FeO activity. Oh-nuki et al. have reported that improved slag reduction, together with increased steel cleanliness, was achieved at the ladle furnace with the aid of measurements obtained by the FeO activity determinator.[16]

Manganese control during steelmaking is governed by the equilibrium reaction:

$$[Mn] + (FeO) = (MnO) + Fe \quad .....(3)$$

Where (i) and [i] indicate component (i) in slag and molten steel, respectively. The partition ratio is expressed as:

$$\log\{(\%Mn) / [\%Mn]\} = \log\ a_{FeO} + (\text{constant}) \quad .....(4)$$

Where, (%Mn) and [%Mn] are the weight-percent concentrations of manganese in the slag and metal phases. According to Equation (4), a logarithmic plot between (%Mn)/[%Mn] and the a_{FeO} should yield a straight line with a slope of unity. Hamm et al. have shown such a relationship based on actual data from practical steelmaking operations (Figure 10).[15] These authors also reported that a_{FeO} measurements can be used to calculate alloying efficiency with a higher degree of precision, thus resulting in significant cost reduction and more accurate heat chemistries.

Characterizing Slag Behavior

In discussing the refining capacities of slags, the ratio of basic oxides to acidic oxides expressed in weight percent, or sometimes as a molar ratio, is traditionally used as a measure of slag basicity. However, the simple (CaO/SiO_2) ratio ignores the effects of other oxides. The ratio ($CaO + MgO$)/($Al_2O_3 + SiO_2$) implies that lime and magnesia behave as equivalent basic oxides and that alumina and silica have the same degree of acidity, neither of which is the case. To some degree, this can be offset by using empirical coefficients although the modified ratios are somewhat restricted in their applicability to specific applications.

Optical basicity provides a good foundation for a better understanding of the behavior of molten slags than the conventional basicity ratios. The concept of optical basicity was developed by glass scientists Duffy and Ingram[17] and introduced to the metallurgical community by Duffy, Ingram and Sommerville in the late 1970s.[18] This approach has proved to be a valuable tool for designing slags or fluxes that will have the required characteristics with respect to behavior of, for example, sulfur, phosphorus, hydrogen, magnesia and alkali oxides.[19-25] The

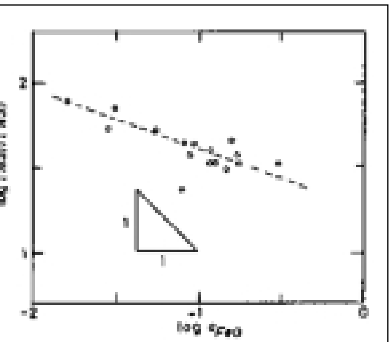

Figure 8 *Relationship between sulfur partition ratio and FeO activity.*[15]

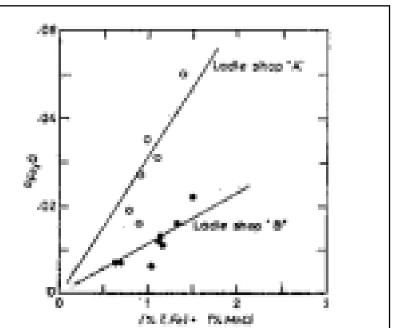

Figure 9 *Relationship between FeO activity determined by the activity sensor and (%T.Fe) + (%MnO).*[15]

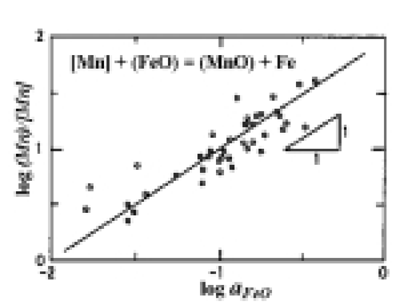

Figure 10 *Plant data showing the relationship between manganese partition ratio and FeO activity.*[15]

relationships between sulfide capacity, water vapor capacity and optical basicity are illustrated in Figure 11.[26] In the case of slag compositions for ladle desulfurizing treatments, a highly basic slag is generally used. While such slags have a high capacity for absorbing sulfur, they also have a strong ability to transfer hydrogen from moisture-containing atmospheres into molten steel at a faster rate than would be the case with a more acidic slag. This has important implications with respect to ladle slags, as well as the selection of tundish fluxes and continuous casting mold powders. The optical basicity of molten slag can be calculated using the following relationships:

$$\Lambda = \sum_{i=1}^{n} \Lambda_i N_i$$

$$N_i = \frac{X_i n_{Oi}}{\sum_{i=1}^{n} X_i n_{Oi}}$$

Where:

- Λ = Optical basicity of the slag
- Λ_i = Optical basicity value of component "i"
- N_i = Compositional fraction
- X_i = Mole fraction of component "i" in the slag
- n_{Oi} = Number of oxygen atoms in component "i"

PREVENTION/DETECTION OF DETRIMENTAL VARIATIONS DURING STEEL PROCESSING

"The very pliancy of the steelmaking processes demands increased watchfulness to prevent and detect unsought variation."
Henry Marion Howe[27]

As previously mentioned, the steelmaking system can be described in terms of a series of metallurgical reactors linked by a number of transfer steps. Within this system, the furnace and ladle are batch reactors, while the tundish and molds are continuous reactors. This difference has important implications with respect to the influence of transfer operations on steel quality. In the quest for steel quality, we must not only prevent detrimental variations during processing, but also develop sensor technologies that will permit us to continuously monitor and detect, at an early stage, the occurrence of any detrimental variations due to perturbations or imperfections within the processing system. There is good evidence from plant observations that quality achieved within one reactor can be lost during transfer to the next. In addition, short, intermittent variations during the transfer process can have relatively long-time, adverse effects on behavior within the next reactor. These adverse effects relate to changes in chemistry, temperature and fluid flow, the formation of inclusions and ultimately, their location and distribution within the cast product. They can also affect surface quality, segregation and crack formation. Improvements in our understanding of the importance of these phenomena have led to developments in processing technologies, which are having a pronounced effect on steel quality. Several examples of these aspects of steel processing are described in the following sections.

Optimization of the Electric Arc Furnace Process

In the latter half of the 1990s, researchers at the University of Toronto participated in a collaborative research effort between Goodfellow Technologies Inc., of Mississauga, Ontario, Canada and Co-Steel Lasco of Whitby, Ontario, Canada. The group examined the potential for replacing electrical energy with chemical energy through post combustion in an electric arc furnace.[28] By monitoring the chemical composition of the gases leaving the furnace and integrating the results within the control system for the furnace (Figure 12), the operating conditions can be adjusted to take greater advantage of the chemical energy available within the furnace, which otherwise would be lost.[29] Up to 30 percent of the total energy input can be lost in the exit gases, and much of this is in the form of unused chemical energy due to incomplete combustion within the furnace. Expert Furnace System Optimization Process (EFSOP) is also a useful tool for evaluating the design and operational aspects of the furnace fume system, which, in turn, has beneficial implications with respect to safety and environmental regulations.[30]

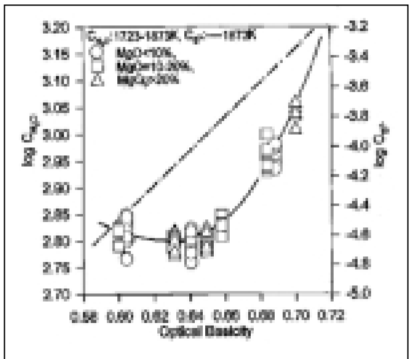

Figure 11 *Relationships between sulfide capacity (broken line), water vapor capacity (solid line) and optical basicity.*[26]

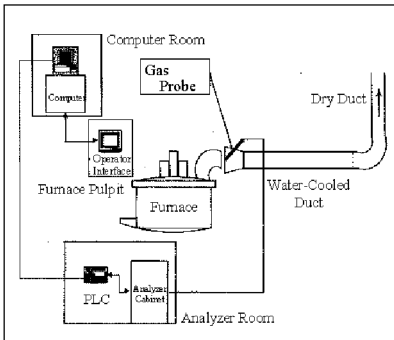

Figure 12 *Diagram of the gas monitoring system and instrumentaion facilities for dynamic control of the electric arc furnace operation.*

While other systems are available for analyzing exit gases, particularly in the case of integrated steel plants using oxygen converters, this system has several unique features in terms of the combination of hardware and software used for the dynamic control of an electric arc furnace operation.

After an extensive development program, the new technology has been implemented in regular production. Substantial energy savings of more than $1 million/year and productivity improvements of more than 5 percent have been achieved.[31] The main advantages of this new processing technology can be summarized as follows: reduced energy costs, increased productivity, optimized furnace practice, improved operational safety and environmental control strategies.

Presently, EFSOP installations are in regular production operation within the United States, Canada, Mexico and the U.K. This is an auspicious start for this new technology and augers well for the future.

Furnace to Ladle Transfer

During furnace tapping, an uncontrolled and variable amount of air is entrained by the tapping steam and carried into the ladle. This air entrainment has a direct bearing on fluid flow patterns in the ladle, which in turn, determine whether an alloy additive dissolves in the steel or is carried up to the surface to be lost by oxidation due to contact with the atmosphere. For this reason, the timing, location and method of deoxidizer and other alloy additions all influence alloy recovery and final steel quality. As previously mentioned, in addition to reoxidation, steel can pick up nitrogen and hydrogen from a humid atmosphere during this transfer operation.

Improvements in furnace tapping operations to minimize slag carryover into the ladle and to promote the formation of a more compact tapping stream include the use of slidegate valves and bottom tapping systems. With more compact streams, protecting the steel from contamination with air, by gas shrouding the stream with a protective atmosphere should be easier.

When elements with a high affinity for oxygen and sulfur, such as calcium or rare earth elements, are added to the ladle, the effectiveness of the added element is strongly influenced by the quantity and composition of the slag carried over from the furnace. This furnace slag can constitute a major source of oxygen that then transfers to the steel during ladle processing. This transfer of oxygen from slag to metal is enhanced during any gas stirring operation that brings fresh metal into contact with the slag. In addition, as the steel is poured from the ladle, the interaction that occurs between the descending slag layer and the refractory ladle walls can produce a reaction product or glaze, which serves as a reservoir for oxygen and perhaps sulfur. These elements can then transfer into the next batch of steel during ladle processing and can adversely affect steel quality. If there is substantial carryover of slag from the furnace, the iron oxide and manganese oxide content, which is likely to be high, then a reducing agent, may be added to minimize the use of expensive deoxidizing agent or loss of alloying elements that may be added to the steel. If phosphorus oxide is present in the slag carried over from the steelmaking vessel, then during slag reduction or steel deoxidation, phosphorus may revert to the steel from the slag phase. Again, this is a destroyer of quality.

Continuous Monitoring of Ladle Metallurgy Operations

In recent years, acoustic technology and vibration analysis to monitor and control steelmaking processes have found increasing application. The sound emitted during certain metallurgical operations reflects the corresponding operating conditions. Thus, the acoustic response may be used to monitor and control the process. Accelerometers have been used to detect vibrations generated by gas-solid interactions within the blast furnace, in torpedo cars during hot metal treatment, within steelmaking converters during decarburization and slag foaming, and in ladles, tundishes and submerged nozzles during steel processing. These applications have been reviewed in more detail elsewhere.[32]

Studies conducted within the Hungarian steel industry have shown that with the aid of a remote microphone, the desulfurization rate of hot metal or molten steel during injection of appropriate reagents can be measured by the change in sound caused by the generation of bubbles.[33] We can also continuously monitor the desulfurization process by measuring, with an accelerometer, the vibrations caused by gas injection. This technology could also be used as an online detection system to continuously monitor changes in the concentration of dissolved oxygen during processing of molten steel. An investigation of factors such as temperature and surface tension, which influence the sound emitted by bubbles when gas is injected into a liquid, has been conducted by Zhang.[34] For more than three decades, the term “ladle metallurgy” has been used to signify a number of processes, which include: steel reheating, deoxidation, alloying, desulfurization and modification of inclusions and various techniques for promoting thermal and chemical uniformity within the steel by injecting argon or nitrogen through porous refractory units located within the base of the ladle or through submerged lances. The application of vibration monitoring to control argon stirring during ladle processing has been described by Kemeny,[35] and by Minion et al.[36]

During treatment of steel in a ladle arc furnace, minimizing the refractory attack caused by arc flare is important. This is

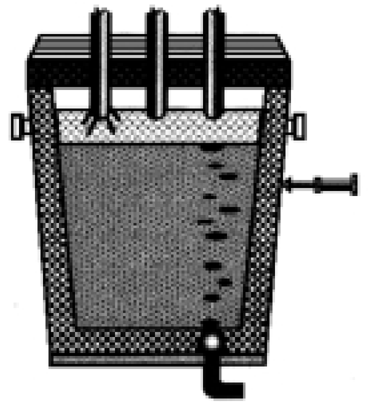

Figure 13 *Vibration monitoring of gas rinsing and arc flare during ladle-furnace processing.*

achieved by ensuring that sufficient slag is present with appropriate foaming characteristics to enclose the arc discharge. A unique technology has been developed by Kemeny et al. to control this process by monitoring the vibrations generated not only by the rising gas bubbles, but also by the arc flare (Figure 13).

The gas bubbling process is often highly variable and frequently excessive. This can lead to slag entrainment, steel reoxidation and accelerated refractory attack. These two separate processes – gas bubbling and arc flare – create pressure waves that can be independently monitored by measuring the vibrations on the outside steel shell of the ladle. Separate characteristic frequency ranges can be identified, which relate to the rising gas bubbles and the arc flare. If there is insufficient slag present, this will be indicated by a high reading on the arc flare indicator. As synthetic flux is added to the ladle, the arc flare value will progressively decrease until an acceptable level of flux addition is achieved. Using this nonintrusive, continuous monitoring technology to independently control both the bubbling and arc heating processes, the following benefits have been achieved: consistent stirring practice, predictable alloy recovery, less aluminum fade, predictable desulfurization, clean steel with low total oxygen content, less nozzle clogging, less arc flare and slag overheating, improved refractory performance and reduced argon consumption.

Several techniques have been used to detect slag carryover. These include electromagnetic devices, weight measurements and vibration sensors. Because of the significant difference in density between metal and slag, there is a change in momentum transfer to a submerged refractory nozzle when slag is entrained by the stream. This change in momentum is reflected in a change in vibrational movement of the nozzle and also the tundish.[37-39] By continuously sensing these vibrational signals with accelerometers, monitoring the transfer operation and detecting the onset of slag carryover is possible. In some instances, detecting the onset of vortex formation before slag has left the ladle or tundish may be possible. This would permit the operator to implement corrective measures before slag carryover actually occurs.

Ladle to Tundish Transfer

Recognizing that the tundish, like the ladle, is a metallurgical reactor involving interactions between molten steel, slag and refractory phases, as well as the atmosphere, is important. It is now accepted that the tundish is not only a distributing vessel, but also a continuous reactor. This is particularly significant because the tundish links together the ladle that is a batch reactor with the casting molds, which are themselves continuous reactors. A major challenge for the steelmaker is to ensure that the tundish is in fact a continuous refiner and not a continuous contaminator. In this context, tundish slags play an important role. There are three requirements for a good tundish flux:

- Thermal insulation of the molten steel
- Protection of the steel from reaction with the atmosphere
- Absorption of nonmetallic inclusions from the molten steel

Thermal insulation is best obtained with a solid powder layer. On the other hand, prevention of reoxidation, nitrogen and hydrogen absorption from the atmosphere by the molten steel, as well as absorption of nonmetallic inclusions from the steel, are all best achieved by the presence of a liquid layer. Viscosity of the tundish flux is also important for producing clean steel. If viscosity is too high, this will limit the ability of the flux to absorb inclusions. If viscosity is too low, then flux may be drawn down into the mold, particularly during ladle transfer operations, when conditions are unstable. Tundish slags can now be designed using the concept of optical basicity to obtain a flux that has the required characteristics in terms of chemical properties, as well as viscosity, to ensure the tundish will function as a refining vessel and not a contaminator.[24]

Methods of preventing reoxidation during metal transfer between ladle and tundish and tundish and mold by extended refractory nozzles and/or gas-shrouding devices are now well-established practices. However, significant contamination can still occur during ladle-change operations, when exposure of steel to air for even a few seconds can lead to the casting of inferior steel over the next several minutes. An increase in the nitrogen content of the steel by a few ppm is a valid indicator that reoxidation has occurred. Since the rate of oxygen dissolution is about 200 or 300 times faster than that of nitrogen,[6] analysis of samples for total oxygen can yield values of several hundred ppm. This represents massive reoxidation and the generation of very large inclusions. Much of this reoxidation material will separate in the tundish and collect in the tundish flux. In so doing, iron oxide and manganese oxide contents of the tundish flux may be markedly increased.

The influence of thermal effects on liquid steel flow in tundishes during a ladle change operation and during steady state conditions have been reported by Lowry and Sahai based on results from an elegant one-third scale water modeling study, together with in-plant tracer measurements, on a six-strand bloom caster.[40] From residence time distribution diagrams pertaining to the actual steel casting tundish, we can conclude that steel flow following a ladle change is radically different from that under almost isothermal, steady state conditions during the latter half of a ladle pour. During a ladle change, the new steel entering the tundish is at a higher temperature than the steel already present in the tundish. The new, higher temperature steel actually reaches the nozzles at the end of the tundish before it reaches the nozzles closest to the incoming ladle stream. This behavior is the reverse of that observed under steady state conditions. Steady state flow is reestablished when the new steel displaces the previous steel. This requires almost 2.5 times the mean residence time for the tundish. This time period could amount to 25 percent or more of the ladle casting time depending on tundish capacity and casting rate. This is a significant portion of the casting time during which the metal flow is in a reverse mode. These effects will influence factors such as alloy additions, inclusion flotation and inter-grade mixing and should be included in any consideration and analysis of tundish design for improvement in steel quality.

During the casting operation, ladle slag can be drawn by vortex formation into the tundish as the metal level in the ladle decreases. Again, this is an example in which slag that is a refining agent in one vessel becomes a contaminating agent in the next. Some of this entrained slag may enter the tundish flux and consequently alter its behavior, while other portions may be carried over into the mold and end up adversely affecting the performance of the mold flux or generating defects in the final product. From flotation considerations, there may also be a higher content of inclusions in the last portion of steel to leave the ladle. In a typical ladle change operation, total oxygen content in the tundish can change quite drastically, both at the entrance to the tundish close to the incoming ladle stream and at the exit above the mold. In addition, the weight of metal in a tundish under stable operating conditions may drop by about half during the ladle change operation. In turn, this can adversely affect the quality of the steel entering the casting molds. While the ladle change may require approximately two minutes, the effect on the quality of the steel leaving the tundish could extend for more than 15 minutes.[41]

Tundish to Mold Transfer

During the past decade, studies by Brimacombe et al. have generated increasing awareness of the critical importance of "meniscus control" because of the direct correlation that has been established between fluid flow behavior at the meniscus and surface quality of the cast products.[42] When the metal delivery system involves the use of submerged-entry nozzles (SEN), the behavior of fluid flow in the mold, as well as at the meniscus, is extremely important. The design of the nozzle, as well as the depth of submergence, directly influences fluid flow within the casting mold, behavior at the meniscus, vortex formation and distribution and location of inclusions in the final product.

To minimize nozzle blockage and enhance the flotation of nonmetallic inclusions, argon gas is sometimes injected into the SEN. This can have a pronounced effect on fluid flow behavior. If argon injection is excessive, mold slag can be drawn into the molten steel and end up as defects in the product. Even in the absence of argon injection, if the submerged entry nozzle has not been properly fired and is porous, or if cracks are present in the nozzle wall caused by damage during handling, or if cracks form during use, air can be drawn into the nozzle. The oxygen from this will cause reoxidation, while the nitrogen will behave essentially like argon and cause considerable disturbance of the mold powder at the meniscus. In addition, if the formation of reoxidation material is excessive, the composition of the mold flux can change, and this can adversely affect subsequent performance.

The behavior of synthetic slags in the casting mold is a critical parameter for the production of quality steel. This is the last slag with which the molten steel has contact before solidification. All of the previous work that has been conducted in the furnace, ladle and tundish to generate quality steel can be destroyed in the casting mold. For this reason, the mold can be considered the "heart" of quality, and the mold slag must be designed to perform a range of functions, which is considerably greater than that required of any of the previous slags in the furnace, ladle or tundish. These functions include prevention of reoxidation, provision of thermal insulation, availability as a flux to dissolve impurities, performance as a lubricant and possession of good heat transfer characteristics to enhance solidification. The interaction of the mold flux with refractory nozzles, and the behavior with respect to the absorption of hydrogen from the atmosphere and subsequent pickup of hydrogen by the steel, are also important considerations when designing the most appropriate composition of the flux for a particular application.

In the case of small billets, reoxidation of mold streams by direct contact with air, will result in the formation of oxide slag within the mold. If this oxide material is drawn into the solidifying steel, it can produce large centerline defects. If it is entrapped as a solid crust between the solidifying steel shell and the mold wall, then large surface slag defects can be generated. While open streams can be protected by gas shrouding systems, differences in stream character between strands, or even instability at different times on the same strand, can adversely affect meniscus behavior, fluid flow patterns, surface quality, pinholes and the location of inclusions in the final product.

With multistrand billet casting and a central ladle stream, smooth streams are usually found at the ends of the tundish. Such streams entrain very little air and the steel meniscus is quiescent with a slow motion from the outside of the mold toward the stream. In this case, mold scum will float on the surface but could be driven deep within the steel pool by the incoming tundish stream. Rough streams, such as those issuing from tundish nozzles located nearest to the ladle stream, have not only a higher surface to volume ratio than a smooth stream, but will also entrain more air, causing increased turbulence in the mold and excessive splashing at the meniscus (Figure 14). Within a turbulent mold pool, new steel is continuously brought to the surface, where further contact with the air can occur. Turbulent pools provide little opportunity for proper separation of reoxidation products. These oxides, in the form of mold scum, are thrown to the outside of the mold, where they can be entrapped in the freezing interface at the surface of the billet and give rise to surface slag defects.

In addition to differences in stream characteristics between one strand and another, a major concern with respect to steel quality is the variability in character of a specific stream during the casting operation caused by fluid flow changes within the tundish. From experiments conducted with various tundish nozzle designs, it has been found that steel streams of consistent quality could be obtained with regular nozzles possessing a logarithmic-type entry modified to include eight deep slots or castellations in the upper rim. With these castellated nozzles the appearance of the tundish streams remained unchanged by conditions in the tundish.(4)

Based on recent advances in the understanding of electromagnetic force fields and their effects on liquid metal flow, together with parallel developments in induction power systems, Beitelman and co-workers have successfully pioneered a new system for steel flow control in the mold during billet casting. The technology is applicable for open stream pouring between the tundish and mold and also in cases where submerged entry nozzles are used to protect the steel from reoxidation.[43]

This novel in-mold electromagnetic stirring system (M-EMS), incorporates two sets of stirring coils with independent control of each of the electromagnetic fields (Figure 15). The stirring coil in the lower region of the mold (M-EMS) provides the main stirring action while the coil in the meniscus region has a more localized effect and is termed the auxiliary coil-stirring modifier (AC-SM). Depending on the

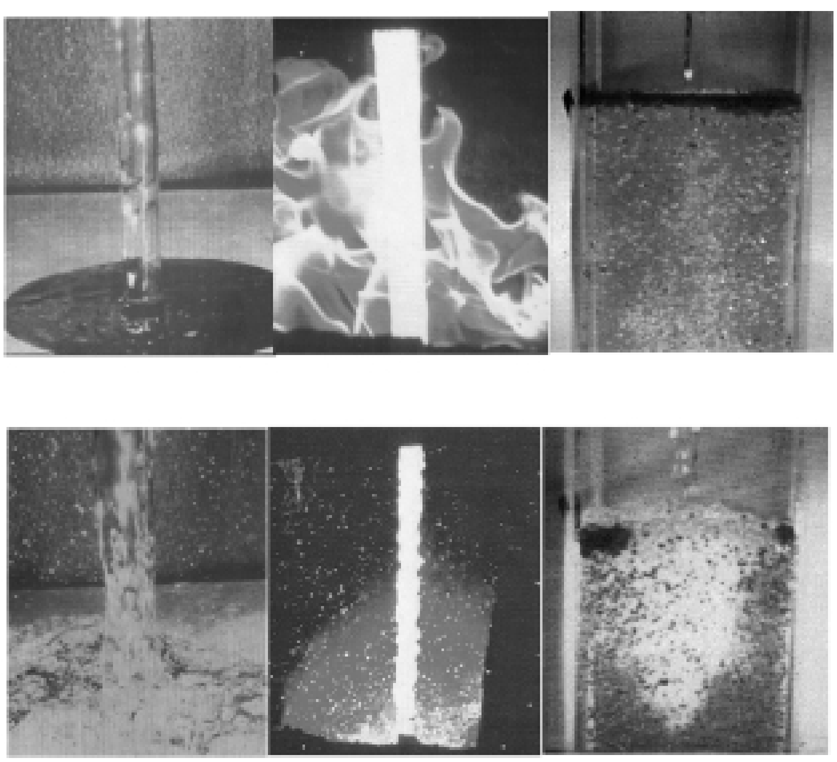

Figure 14 *Smooth tundish streams with little air entrainment, quiescent conditions at the meniscus, no splashing and deep penetration in the mold pool compared with rough tundish streams, massive air entrainment, turbulent conditions at the meniscus, considerable splashing, droplet formation and shallow penetration within the mold pool.*

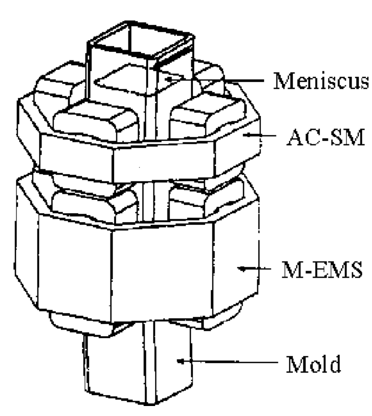

Figure 15 *Dual-coil electromagnetic stirring system for billet casting.[44]*

casting requirements, the stirring intensity at the meniscus can be enhanced, diminished or essentially eliminated by adjusting the current input to the AC-SM and controlling the direction of the magnetic field relative to that of the M-EMS.[44] Since solidification of the steel skin begins at the meniscus, excessive motion at the meniscus will produce ripple marks on the solidified billet surface, which serve as "finger prints" or "witness marks" reflecting conditions at the meniscus at the time solidification was initiated.

Chaotic movement at the meniscus will produce billets with rough irregular wave marks that are frequently associated with surface cracks and in the case of submerged pouring practice, accelerated wear of the SEN, mold powder entrapment and surface defects. On the other hand, a calm meniscus will produce a smoother surface on the solidified steel billet and reduced refractory wear of the nozzle.

Since this system provides independent control of liquid steel flow at the meniscus and within the lower region of the mold, electromagnetic stirring conditions can be optimized to achieve maximum benefits in each of these locations for both open stream and submerged pouring practices.

Operating experience at Ispat Sidbec in Canada, as well as several other plants, has confirmed that the dual-coil system has major beneficial implications with respect to the quality of continuously cast steel, as well as productivity.[44]

This innovative casting technology promotes good surface quality, reduces the incidence of pinholes, decreases segregation of elements such as carbon, sulfur and phosphorus and diminishes crack formation and center line defects. In addition, by preventing overstirring at the meniscus, mold powder entrapment, surface defects and accelerated wear of the SEN can be avoided.[45]

INNOVATIVE DEVELOPMENTS THROUGH SYNERGISTIC PARTNERSHIPS

"*There must be builders of bridges between the creators of knowledge and the creators of wealth.*"
1996 Campbell Memorial Lecture ASM International[42]

On our technological journey through the 21st century, we will cross a number of bridges that will span our knowledge gaps, bringing a new understanding of existing processes and permit the development of new processing routes, new diagnostic systems, new products and new partnerships between people.

In this context of collaborative interactions, basic studies should be performed by the research community in close cooperation with the user community and the resource community, the provider of equipment and materials (Figure 16).

We must recognize and acknowledge that these three communities represent quite distinct cultures, with very different objectives, and collaboration is not always an easy task. Nevertheless, when effective communication is established between the members of this triumvirate, there is a powerful driving force for the synergistic development of innovative technologies.

We cannot overemphasize that considerable research, together with inplant evaluation, is required to transform a fundamental scientific concept into a reliable operating system.

In this collaborative process, the exchange of knowledge between the different communities is perhaps the most difficult step since it not only requires a willingness to share knowledge, but also an ability and a willingness to receive knowledge.

In the knowledge exchange process, the receptor capacity of individuals is frequently the rate-limiting step.

To promote and encourage the exchange of knowledge and experience between the laboratory and the workplace and facilitate development and use of new products and processes, well-trained people will always constitute the critical link (Figure 17).

In the end, the preeminent aim of collaborative activities between our educational institutions, industrial organizations, government funding agencies and professional societies, must be to ensure the availability of high quality people.

ROLE OF THE PROFESSIONAL SOCIETY

"*We must also continue to build bridges with other societies with common goals, all for the benefit of our members, our industries, and the global village. Breaking down the walls between solitudes is never easy but it is the only way.*"
A Letter to the Membership[46]

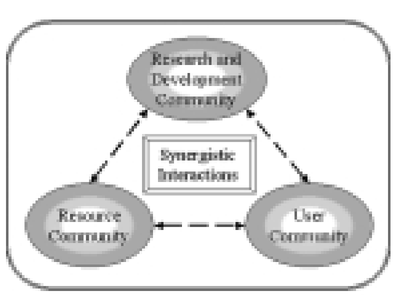

Figure 16 *Triumvirate for collaborative partnerships.*

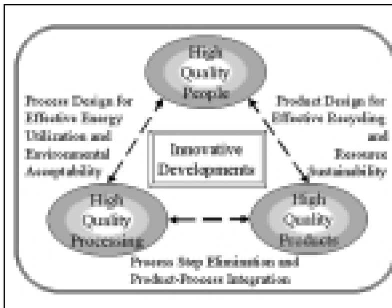

Figure 17 *High quality people and innovative developments.*

For many years, the ISS has played a pivotal role in the organization of international meetings. The promotion of this kind of interaction is perhaps one of the most worthwhile endeavors with which a professional society can be involved. It is certainly an activity that was strongly endorsed and encouraged by Brimacombe. Throughout his career, and particularly during his tenure as president of three professional societies, Brimacombe emphasized the importance of good relationships and communication between different professional groups within North America, as well as those located in countries overseas. In the spirit of technical exchange, he played a major role in organizing joint conferences, international symposia and intensive courses designed specifically for industrial personnel (Figure 18). A measure of the success he achieved in these endeavors may be deduced from the many honors and distinctions he received from professional institutions throughout the world.

In addition to his scientific accomplishments, and they were many, Brimacombe had a tremendous interest in and concern for educational issues as confirmed by his presidency of the TMS Foundation, his presidency of the Canadian Foundation for Innovation and his encouragement of the formation of joint student chapters. During almost three decades at UBC, Keith greatly influenced the training of numerous young engineers, as well as visiting researchers from universities and industrial organizations, many of whom now occupy prominent positions within academia and industry around the globe. In the final analysis, perhaps our greatest challenge is to ensure the availability of men and women with a sound understanding of the fundamental aspects and practical implications of their discipline and who are fully equipped with the behavioral attributes and communicative skills that will enable them to apply their knowledge with wisdom and integrity throughout their professional careers within this most challenging and satisfying field of activity, the science and technology of steelmaking.

JAMES KEITH BRIMACOMBE – BRIDGE BUILDER PAR EXCELLENCE

"*Passing the torch to the next generation of materials professionals begins with lighting the candle of dreams and all that is possible in our talented young people.*"
Presidential Perspective; Passing the Torch[47]

Throughout his career, Brimacombe was a great builder of bridges:

- ♦ Bridges of education to enhance knowledge exchange
- ♦ Bridges of innovation to transform industrial operations
- ♦ Bridges of friendship to facilitate communication between different cultures

Regardless of whether we work in industry, government or academia, all of us have the great privilege of participating in this bridge-building process. Therefore, let us build with vision, enthusiasm, integrity and wisdom.

In this way, the torch will be passed on from this generation to the next, and together we can ensure that the shining flame of Brimacombe's scientific and philosophical legacy will brighten the road that leads to knowledge, enlighten the pathway called wisdom and set ablaze the imagination and minds of the young engineers and teachers of tomorrow on their journey through the 21st century. By these endeavors, we will honor and commemorate the highest standards of achievement and professionalism so well exemplified by Brimacombe throughout his distinguished career. I&SM

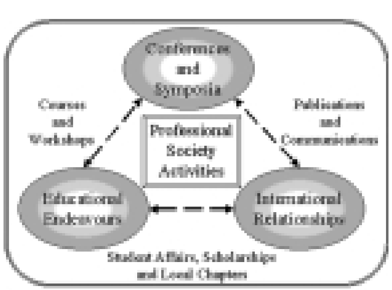

Figure 18 *Activities of the professional society.*

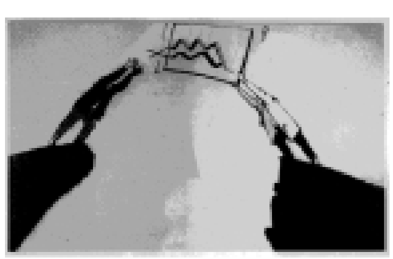

Figure 19 *Bridging the gap.*

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