The Linde Argon-Oxygen Process for Stainless Steel; A Case Study of Major Innovation in a Basic Industry

W. A. KRIVSKY

The Lecture traces the development of the Linde Argon-Oxygen Process from its conception in 1955 to its full scale and widespread utilization in the specialty steel industry on a world-wide basis at the present time. The basic invention was derived from first principles of physical chemistry known to all third year college chemistry students. Its long saga of development over a fifteen-year period required a great deal more; namely, a corporation with tremendous resources and, more importantly, almost boundless faith to continue in spite of some devastating reversals, a small company with great vision and engineering ingenuity to evolve a nontraditional process for the manufacture of stainless steel which many larger companies had despaired of, and a marketing effort which was able to do the almost impossible which was to convince a basic industry such as steel of the merits of a revolutionary new process significantly different in method of operation and capital requirements without being a part of that industry itself and without means of proving the process in-house. The development of the Linde Argon-Oxygen Process is a massive tribute to American industry, the dedication of many of its members, and the tremendous ability of different industries to work together in a major development. The Lecture attempts, as any good case history should, to generalize from this specific case the lessons to be learned by industry, by individual engineers and scientists, by government, and the academic community in major process innovation in a basic industry. Such an increased understanding leading to improved implementation of new knowledge into major industry is critically important if the United States is to improve its standing in international markets. Since the Linde Argon-Oxygen Process is an all-American development, its study should lead us to fuller understanding of both the unique advantages our system provides for such innovation and means by which we may accelerate such badly-needed developments in the future.

DR. WILLIAM A. KRIVSKY is president, Crucible Specialty Metals Div., Colt Industries, Syracuse, N. Y.

Dr. Krivsky, who holds his doctorate (1954) in process metallurgy from MIT, joined Union Carbide Corp. that year and as research metallurgist and later manager of metals research invented the Argon-Oxygen Process for stainless steel which forms the subject matter of the EMD Lecture. He holds the basic patent on the process assigned to the Union Carbide Corp. After 1959 he was associated with Brush Beryllium Co. as vice president and general manager; Continental Copper and Steel Industries as administrative vice president; and General Cable Corp. as group vice president.

Dr. Krivsky has served on several technical committees of AIME and is a past chairman of the Extractive Metallurgy Division. He has also served as a director of TMS and is currently an AIME director. In 1959 he was recipient of the Extractive Metallurgy Division's Gold Medal, jointly with Dr. R. Schuhmann, for their contribution on the thermodynamics of copper smelting. In 1965 he edited the book *High Temperature Refractory Metals* based upon an international symposium which he organized and chaired for the AIME.

The 1973 Extractive Metallurgy Division Lecture was delivered on Feb. 28 at the 102nd TMS-AIME Annual Meeting in Chicago.

A great deal has been written and spoken about the effectiveness of basic industries in the United States in applying advanced technology to large scale metallurgical processes. Arguments have been put forth about the amount and type of fundamental research that should be done, the methodology of translating basic research in economical new processes, the role of the Federal government in this endeavor, the educational process which results in individuals who can accomplish this objective, and the various forms of organizational alignments within corporations that stimulate and make effective such effort. In spite of many differing views on these subjects, general agreement exists on the fundamental principle which gives such great importance to the subject; namely, the corporation, the industry, or the nation which makes most effective use of technology will be the most competitive, the most prosperous, and will thereby be capable of supporting the highest standard of living for its members.

In reaching general conclusions on such a complex and vital issue, it has been useful in many fields to examine, in detail, many case histories of specific instances. We have available to us in the steelmaking industry the recent example of the Linde A-O_2 Decarburization Process. Let us examine its origin, its development, and its commercialization and determine what general lessons it teaches which will permit us to more effectively exploit our knowledge and technology in the future.

THE LINDE AOD PROCESS TODAY

First of all, let us discuss the process itself. A charge containing essentially all of the important alloying elements of the stainless steel composition to be produced in their entirety is melted down in an electric arc furnace. Fig. 1 shows such a heat being poured from a furnace after slag-off. The molten steel is then transferred by ladle to a separate refining vessel which is similar to a Bessemer converter with two or more tuyeres in the bottom, Fig. 2. Oxygen is blown through the molten bath admixed with varying amounts of argon, with the ratio of argon to oxygen increasing with time during the blow and finishing with pure argon in many cases, Fig. 3. Very small final additions of alloying elements and deoxidizing elements are made to the melt, Fig. 4, and the finished steel is tapped directly from the vessel, Fig. 5.

This new duplex process replaces conventional stainless steelmaking which used only a single melting and refining vessel; namely, the electric furnace. The significant changes in practice brought about may be seen by the comparison of the older conventional practice and the AOD Process shown in Table I. In the conventional practice the charge melted down in the electric furnace in the production of a typical 18 pct Cr-8 pct Ni grade could only contain about 4 pct Cr. If the extra low carbon (ELC) product was sought, even less chromium could be included in the charge. With the new practice all the chromium required in the final product (~18 pct) is charged into the furnace. In the conventional practice, the molten furnace charge was lanced with pure oxygen to the end point of 3300°F and a carbon content of 0.02 pct. During this step approximately one-half of the original chromium charged (4 pct) was oxidized into the slag, leaving the metal with about a
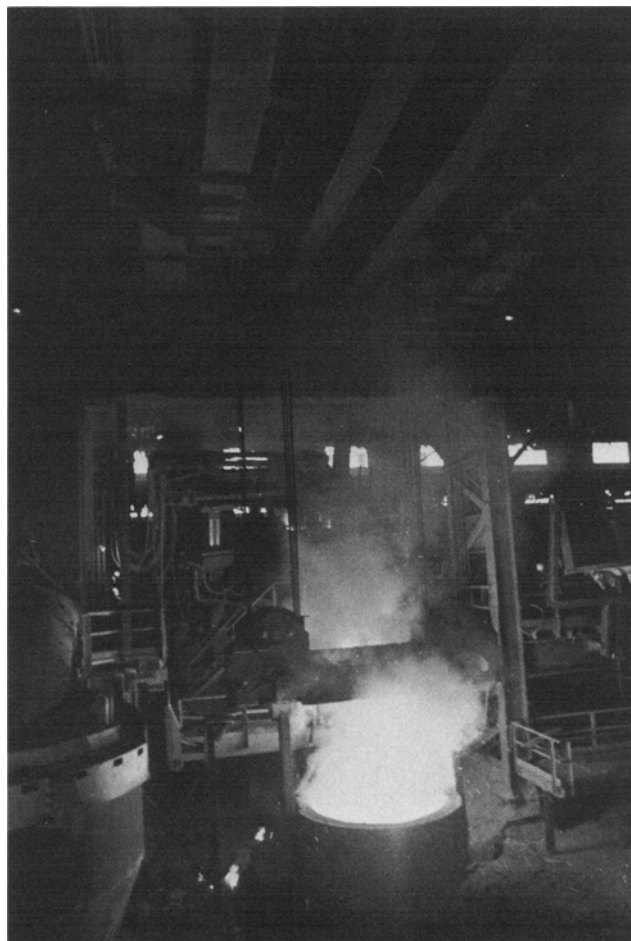

Fig. 1—Tapping an electric furnace after melting of charge only.

2 pct Cr content. In the Linde AOD Process, blowing the heat with varying A-O_2 mixtures in a separate vessel is done to an end point of 3100°F and 0.03 pct C. It should be noted that the temperature is about 200°F lower than at the conventional practice end point. During this step the chromium content in the bath is about 16.5 pct Cr. In the conventional practice following blowing, reducing agent in the form of FeSi or FeCrSi was added to the slag to reduce about one-half of the chromium in the slag back into the bath (1 pct). This was followed by a very large addition of low carbon ferrochrome (15 to 17 pct) to the bath to reach final composition. In the Linde AOD Process, FeSi or FeCrSi is added to the slag to recover about one-half of the oxidized chromium (0.75 pct). Generally no additions of low carbon ferrochromium are necessary and it should be evident at this point that a major economic advantage of the process is in the substitution of low cost high carbon ferrochrome in the charge for the relatively high cost low carbon ferrochrome in the heat finishing. Graphically, the progress of the chromium and carbon during the two different practices is shown in Fig. 6 for the production of 304L stainless steel. It can be seen from this figure that there is roughly one order of magnitude difference in the Cr-C relationship when blown with A-O_2 mixtures rather than with pure oxygen. This is the real crux of the invention and the successful application of high temperature physical chemistry to steelmaking innovation.
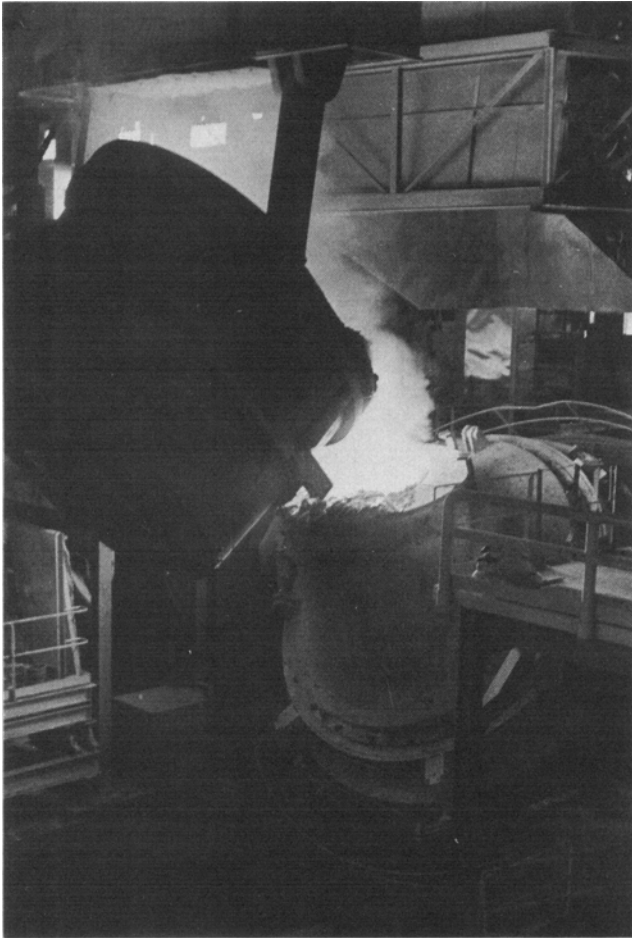
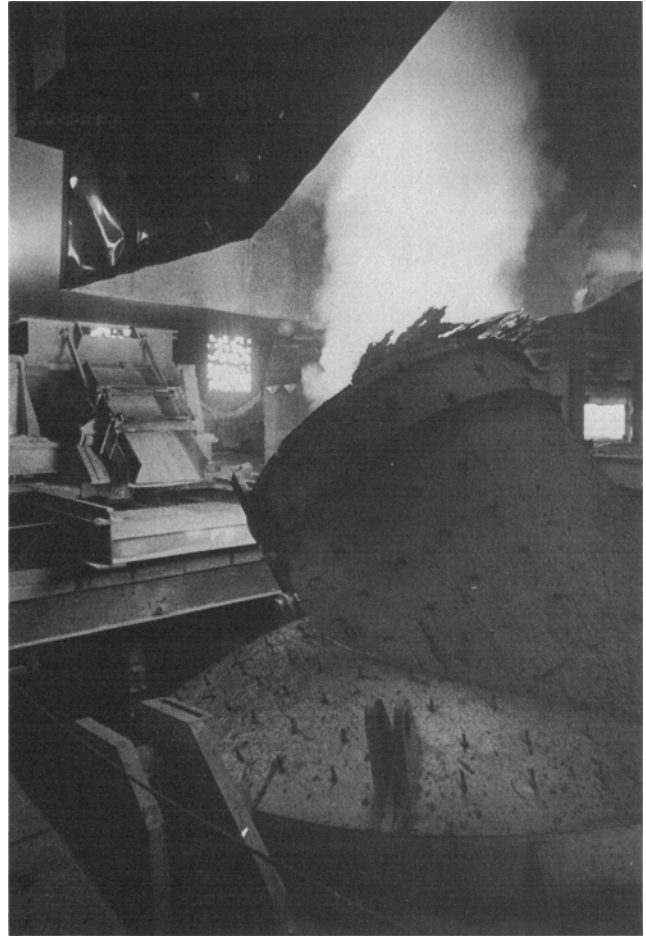Fig. 2—Transferring hot metal to separate refining vessel.

Fig. 3—Argon-oxygen decarburization in refining vessel.

ORIGIN OF THE PROCESS

How did it all begin? What was the origin of the invention and how was it developed into the commercial practice we have today?

It all started in 1954 at the Metals Research Laboratories of the Union Carbide Corporation in Niagara Falls, New York, in quite an innocent manner and without specifically attempting to develop a new steelmaking process. Just prior to that time, Richardson in England had published a thermodynamic study of the relationship of chromium to carbon in stainless steel refining in which he had classically equilibrated carbon monoxide-carbon dioxide gas mixtures with Fe-Cr-C melts. His results were somewhat different than those of Hilty and Crafts published earlier. The experimental method of Hilty and Crafts was substantially different from that of Richardson in that they had blown small induction furnace heats of Fe-Cr-C with oxygen, attempting to establish equilibrium values for chromium and carbon by approaching such values from both high and low carbon contents. The present author set out to resolve the difference in the two studies by extending the range of Cr-C relationship studied following the general experimental method of Hilty and Crafts. The initial work was done in a 100-pound induction furnace; and it became rapidly evident that, in attempting to establish equilibrium Cr-C relationships, it was essentially impossible to achieve the isothermal conditions necessary because of the highly exothermic nature of the Cr-O

reaction. Some tentative attempts were made to control the exothermicity of the reaction by diluting the oxygen with argon in the small furnace, and it was immediately noted that for any given chromium level and temperature, the carbon level was approximately an order of magnitude lower than those predicted by the earlier work of either Richardson or Hilty and Crafts!

At this point a review of the basic physical chemistry of the system revealed what was taking place and began to lead us in the proper direction for the inven-

Table I. Stainless Steelmaking Conventional vs Argon-Oxygen

| Conventional	A-O$_2$
1.) Melt charge in electric furnace a) 4 pct Cr charge normal; less Cr charged for ELC grades	Melt charge in electric furnace a) 18 pct Cr charged even for ELC grades b) deslag melted charge transfer charge; to AOD vessel
2.) Lance with oxygen; end point 3300°F 2 pct Cr 0.02 pct C	Blow with oxygen-argon mixture; end point 3100°F 17 pct Cr 0.03 pct C
3.) Recover $\frac{1}{2}$ of Cr (1 pct) in slag with FeCrSi or FeSi add'n.	Recover 0.75 pct Cr from slag. Pure argon injection
4.) Add 15 to 17 pct Cr as low carbon FeCr to final specification	No low carbon FeCr addition necessary
Final Composition: Cr-18.5 pct C-0.02 pct	Final Compositon: Cr-18.5 pct C-0.01 pct
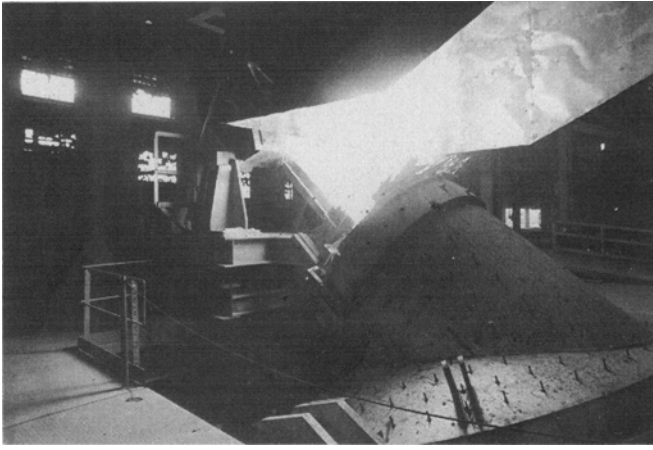
Fig. 4—Adding final additions to refining vessel after blowing.

tion of the Linde AOD Process. Table II summarizes the basic physical chemistry of the Linde AOD Process and brings us to a full understanding of the differences between conventional practice and the new process. It is clear from this Table that in conventional steelmaking the pressure of carbon monoxide is 1 atm, since all the oxygen blown into the bath is converted to essentially carbon monoxide as it exits the system and therefore, for a given temperature, the equilibrium carbon content will be proportional to the three-fourths power of the chromium content. In the Linde AOD Process the carbon content will be a function of *both* the three-fourths power of the chromium level *and* the resulting partial pressure of carbon monoxide *after* dilution with argon which passes through the bath unchanged. Table III illustrates the effect of the ratio of argon to oxygen in the input gas stream on the carbon content reduction relative to conventional practice. The resulting carbon monoxide pressure, which controls the carbon content, is derived from the consideration that while a mol of argon goes through the bath unchanged, a corresponding mol of oxygen results in the formation of 2 moles of carbon monoxide. These theoretical considerations are now borne out in practice literally hundreds of times daily around the world. It should not be overlooked at this point that the Process has an alternative method of utilization; namely, that the same Cr-C relationship can be achieved at significantly lower temperatures than in conventional practice.

Further work in the laboratory was then continued to fully verify what had been found initially and, for the first time, consciously directed to the possible development of a new steelmaking practice. There were several economic factors that gave impetus to the commercial exploitation of these laboratory findings at the time. It had been known for some time that the decarburization of expensive, nickel-base alloys could be enhanced by the use of a vacuum. Extending such a practice to stainless steel was considered totally impractical because of the low cost of the product and its scale of manufacture. The effect of the present process was to develop a crude vacuum without the usual equipment; it was affectionately labeled "a poor man's vacuum." Simultaneously there was a growing market demand for the extra low carbon (ELC) grades of stainless steels, but the production costs
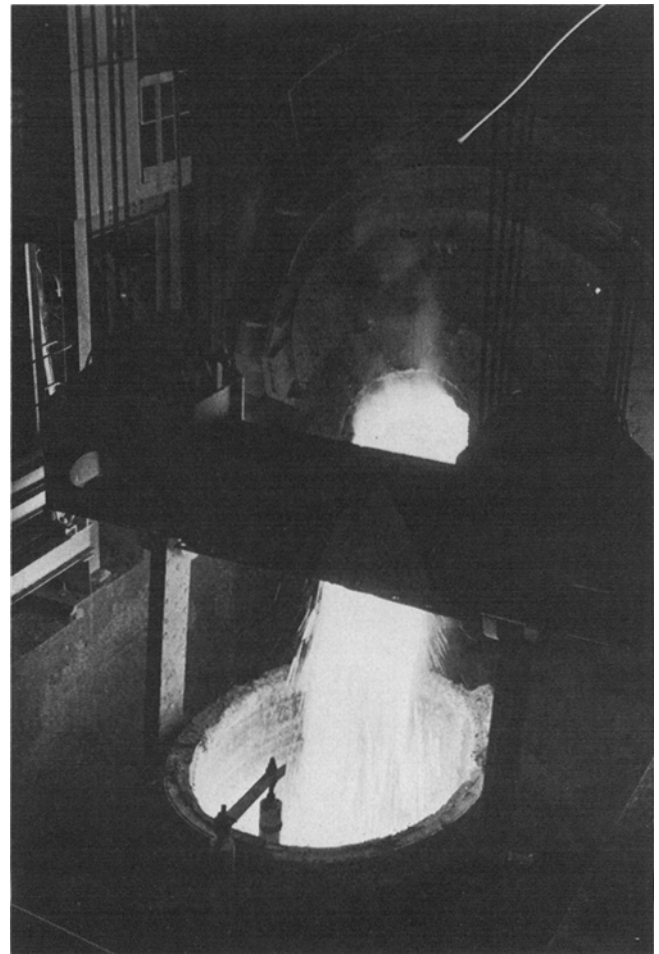

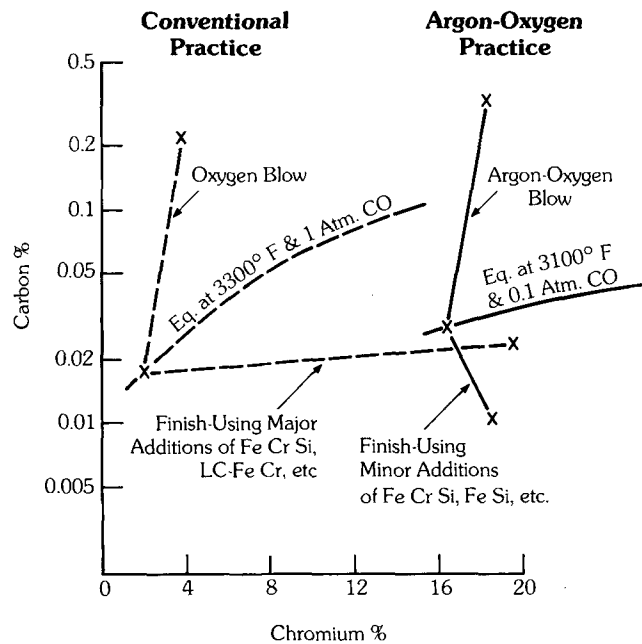Fig. 5—Tapping finished steel from refining vessel.

Fig. 6—Conventional vs Argon-oxygen practice for 302 L.

were nearly prohibitive because of the effect of the high finishing temperatures on refractory life as well as the poor reproducibility of the conventional process. The argon dilution principle appeared to afford

Table II. Chemistry of Argon-Oxygen Stainless Steelmaking

$$Cr_3O_4(s) + 4\underline{C} \rightleftharpoons 3\underline{Cr} + 4CO\ (g)$$

$$K_1 = a^3_{Cr} \cdot P^4_{co}\ /a^4_{\underline{c}} \cdot a_{Cr_3O_4}$$

$$K_2 = (\%\ \underline{Cr})^3 P^4_{co}\ /(\%\ \underline{C})^4$$

Conventional steelmaking

$$\%\ \underline{C} = 1/K_3(\%\ \underline{Cr})^{3/4}$$

A-O_2 steelmaking

$$\%\ \underline{C} = 1/K_3(\%\ \underline{Cr})^{3/4} P_{co}$$

Table III.
Carbon Content as a Function of Argon-Oxygen Ratio vs Conventional Practice

Constant Chromium Level; Constant Temperature

A/O$_2$ Input	P$_{CO}$ Atm	Reduction in Carbon Level, pct
1	$\frac{2}{3}$	$33\frac{1}{3}$
2	$\frac{1}{2}$	50
4	$\frac{1}{3}$	$66\frac{2}{3}$
8	$\frac{1}{5}$	80
18	$\frac{1}{10}$	90

an ideal method for the manufacture of such grades. Another simultaneous development of the time was the rising use of the BOF process in the United States which was leading to significant increases in oxygen producing capacity which, for relatively minor additional capital investment, could produce vast quantities of argon at lower cost than previously. All these considerations led us to pursue the development of the Linde AOD Process. The original work to resolve the minor differences between the results of Richardson and those of Hilty and Crafts was never completed. Those differences had admirably served their purpose!

Scale up of the process was successfully accomplished from the 100-pound furnace to a one-ton arc furnace. Verification of the smaller scale heats was excellent and further work on scale-up proceeded with great confidence. It should be clearly understood that this initial work was being done following the conventional practice right in the electric arc furnace but merely substituting A-O_2 mixtures for the pure oxygen normally injected. Various troubles were experienced with splashing of the bath and refractory erosion even in the one-ton tests but, generally speaking, it was expected that such problems would be overcome with improved and multiple lances as heat size increased. The next step in development utilized the 3 ton and 5 ton furnaces of the Haynes Stellite Company, then yet a division of Union Carbide. Success was again demonstrated but a great deal of difficulty was experienced in making the lancing practice effective. Lances were experimentally coated with just about every known refractory, and single and multiheaded lances were attempted positioned above the bath. It was found that the argon, at least, had to be injected into the bath and was not effective when blown on the surface. Further, the results showed the importance of getting gas dispersal throughout the bath for if the beneficial dilution principle functioned only locally, the effect on the total bath was minimal.

FAILURE OF THE FIRST PRODUCTION ATTEMPTS

Union Carbide, not being a stainless steel producer, had gone about as far as it could go alone in the scale-up efforts. It obviously needed a partner with larger furnaces in order to bring the process to full commercial scale. A long search of all the stainless steel producers followed, with very discouraging results in general. For various reasons, nearly every company declined to participate in the further development until the Joslyn Stainless Steel Company was approached. Here, in spite of the fact that they were one of the smaller producers without the technical and financial reserves of some of their larger competitors, they nevertheless had the courage and foresight to proceed. In 1960 Union Carbide and Joslyn signed a joint development agreement.

The first tests conducted at Joslyn on a 15 ton scale turned out to be nearly absolute, dismal failures. Although a great deal of attention had been paid to the lance problem and various methods, including the use of three fireclay-sleeved lances positioned above the bath, were tried, no successful heats were produced. Very careful and detailed analysis of the results indicated that while local action of the argon dilution principle near the point of injection was effective, the net effect on the entire bath, after it had homogenized following the blow, was inconsequential. Large scale testing was regretfully abandoned but work was continued on a laboratory scale. This work again clearly indicated the feasibility of the process if the argon could be distributed throughout the entire bath. The process never failed to perform under such circumstances. Conversely, whenever the bath diameter was large relative to surface injection devices, no discernible benefit was achieved in the bath as a whole.

RECOVERY FROM FAILURE

Armed with this more clear understanding, Union Carbide and Joslyn made the historic decision to build a refining vessel apart from the electric arc furnace. This first such vessel was only $\frac{3}{4}$ ton in capacity and provided for the top blowing of oxygen and the bottom injection of argon through a tuyere. The results were dramatically favorable and supported all the laboratory scale work previously done.

However, the idea of applying the argon dilution principle directly in the electric furnace died very slowly. There was obvious reluctance to develop a process that would create another step in the manufacturing process and that would require an additional capital investment. What was not realized at this point in time, was that the separate refining vessel would *double* the steel output of a given furnace. Since its cost was only a small fraction of the cost of an additional electric furnace, it represented a very inexpensive means of increasing steelmaking capacity. Nevertheless, forty-five additional 15-ton heats were tried in the arc furnace, which, in spite of various configurations of lances, totally failed to give any beneficial results compared to the $\frac{3}{4}$ ton separate vessel.

As a result of these efforts, the two companies proceeded with the design of a 15-ton separate refining vessel. After much experimentation with top and bot-

tom injection of one or both gases, use of porous bottoms, and with various tuyere designs, there finally emerged in 1967 a simple multiple tuyere which combined both gases in the injection. Fig. 7 is a photograph of this early unit which on October 24, 1967 produced the first full heat of stainless steel ever completely refined, finished, and poured directly into molds utilizing the Linde AOD Process. This was a heat of type 304 ELC and its log of manufacture is shown in Table IV. Two additional heats were produced in this unit with equal success. The tide in the fortunes of development were simultaneously turning for an overseas company, also working with Linde, which reported similar success working in an 8-ton separate refining vessel. Noting the additional beneficial effect of the Linde AOD Process as a means to low-cost capital investment for additional steelmaking capacity as well as a lower operating cost practice, Joslyn made the decision to build a full commercial installation based on the argon dilution principle and separate melting and refining vessels. This unit was built early in 1968 and is shown in Fig. 8. It featured two tuyeres installed on the bottom back side of the vessel which emerged above the bath when the vessel was rotated for charging, sampling, holding or tapping. The vessel was 9 ft in diameter and $13\frac{1}{2}$ ft high. During 1968 some one hundred heats were made in this unit from which the following general conclusions were reached:

1) Process economies were established beyond any question.

2) The charge to the electric furnace could be made up of the lowest cost chromium and nickel units without any restriction on starting carbon or silicon levels.

3) Recovery of chromium was very high—approximately 97 pct as was total metallics.

4) Silicon usage to recover oxidized metals was reduced by 40 pct.

Following this campaign, Joslyn modified this first production vessel, Fig. 9, and converted its entire melt shop to 100 pct AOD Practice in July 1969. By December of that year they were able to report the results of 1300 heats to the Electric Furnace Conference. The design principles used in this Joslyn production unit are the basis of every AOD installation currently in use throughout the world, ranging in size from 5 to 100 ton. Table V summarizes the major economic advantages of the fully commercialized process. In addition to the already-discussed ability to utilize very large quantities of the lowest cost raw materials in the charge almost without limitation and with very high yields, thereby minimizing the use of expensive finishing additions, the process greatly increases the productivity of an electric furnace. One arc furnace plus an AOD vessel has the productivity of two arc furnaces operated conventionally. Since an AOD vessel is significantly less expensive capital-wise than a second arc furnace, the combination is the most economical method to increase capacity. Operating cost comparisons with conventional practice vary in detail from installation to installation but generally speaking it may be said that the cost of operating the refining vessel is more than offset by the savings in raw materials and the elimination of the refining and finishing steps from the electric arc furnace. Desulfurization is accomplished rapidly and effectively with a desulfurizing
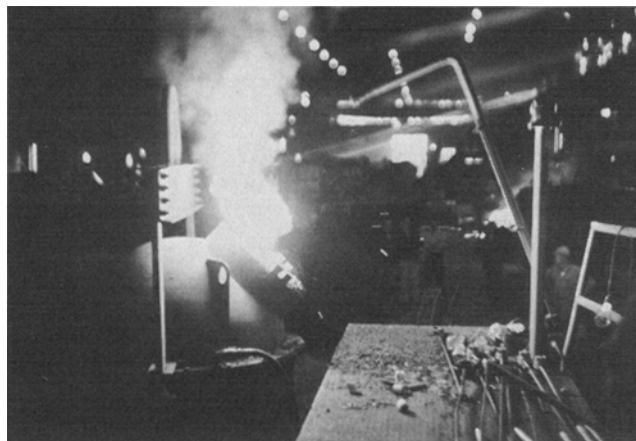

Fig. 7—First 15-ton refining vessel.

Table IV. Log of First Complete Stainless AOD Heat October 24, 1967

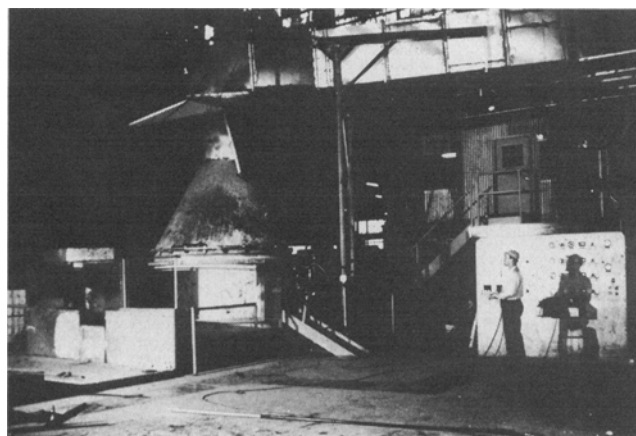| 304L	Time, min	Pct C	Pct Cr	ppm O$_2$	°F
B/4 tap	−4	0.290	18.08	600	3140
B/4 O$_2$	6	0.259	18.02	230	2990
step 1	28	0.084	16.99	560	3160
step 2	46	0.033	16.46	800	3130
argon	51	0.027	16.46	660	3100
addns.	58	0.021	17.60	390	2980
product	−	0.008	18.62	170	−

Fig. 8—Original Joslyn production unit.

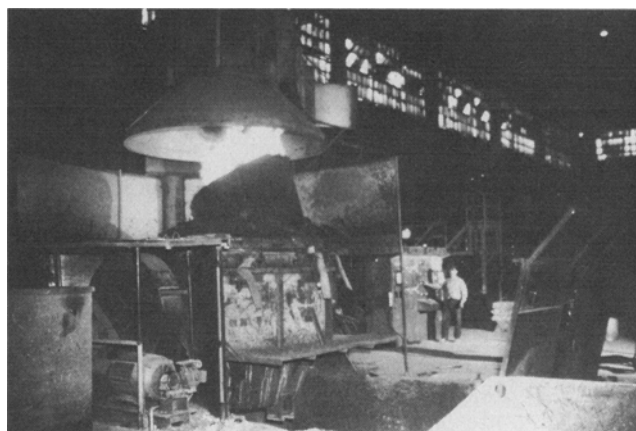
Fig. 9—Final Joslyn production unit.

Table V. Commercial Advantages of the AOD Process

1.) Lower Cost Materials

   -No practical limitations on starting carbon contents
   -Almost completely eliminates expensive low carbon chromium units
   -Readily adaptable to new materials

2.) Significantly increased yield of metallic elements

3.) Greater Productivity

   -One arc furnace plus AOD vessel equals two times arc furnace output
   -AOD vessel significantly less expensive than a second arc furnace

4.) Operating Costs

   -Savings of eliminating the refining and finishing stages from the arc furnace
   more than offset the operating cost of the AOD

5.) Desulfurization

   -7 to 10 min to slag off, add desulfurizing slag and stir

6.) Lead Residuals

   -Routine removal of lead to below 0.007 pct

7.) Quality

   -Cleaner, more reproducible, more easily machined steel

Table VI. AOD Installations in the U. S.

Company	Startup Date	Vessel Capacity Tons
Armco Steel Corp./Advanced Materials Div. Baltimore, Maryland	1/71	35
Baldwin-Lima-Hamilton Corp. Standard Steel Division Burnham, Pennsylvania	8/71	18
Babcock and Wilcox Beaver Falls, Pennsylvania	Mid. 1973	25
Cabot Corporation/Stellite Division Kokomo, Indiana	1/70	5
Carpenter Technology Corp. Reading, Pennsylvania	1/72	15
Colt Industries, Inc./Crucible Stainless Steel Div. Midland, Pennsylvania	3/72	100
Eastern Stainless Steel Co. A Division of EASCO Corp. Baltimore, Maryland	11/70	50
Electralloy Corporation Oil City, Pennsylvania	9/70	17
International Nickel Co., Inc. Huntington Alloy Products Div. Huntington, West Virginia	10/71	38
Jessop Steel Co. Washington, Pennsylvania	10/71	20
Jones and Laughlin Steel Corp. Stainless and Strip Division Detroit, Michigan	12/71	70
Joslyn Mfg. and Supply Co. Joslyn Stainless Steels Div. Fort Wayne, Indiana	4/68	17
United States Steel Corp./South Works South Chicago, Illinois	12/71	100

slag and argon agitation. Lead is routinely removed to below the 0.007 pct level. Quality of the steel produced is far more reproducible than in conventional practice, especially in the ELC grades and is substantially cleaner and more freely machining.

EXPLOITATION OF THE JOSLYN SUCCESS

It must be remembered that Union Carbide Corporation is not a stainless steel producer and the outstanding success at Joslyn needed to be repeated many more times before the project would be a commercial success for Union Carbide. Practically every major stainless steel producer in the world was contacted. With the cooperation of Joslyn, demonstrations were arranged for various companies at Fort Wayne. Savings calculations were made for every potential licensee under literally thousands of local conditions and process alternatives. Questions of further scale-up and product quality had to be answered. Prospects were enabled to take Joslyn-produced AOD ingots, finish them in their own mills, evaluate, and test market them. In certain cases Union Carbide even arranged to have the 15-ton test vessel at Joslyn shipped to various prospects so that they might actually carry out their own tests. In spite of local difficulties in accommodating the vessel, this program was highly developed and extremely successful in convincing prospects to obtain licenses to the process. The second licensee to the process in the United States was Electralloy in September of 1970; the first foreign licensee was Ilsa Viola in Italy in July of 1970. The final tributes to Linde and Union Carbide marketing efforts may be seen in Table VI and Table VII which respectively lists U. S. and foreign licensees. During 1973 Union Carbide expects 50 pct of the stainless

Table VII. Overseas AOD Installations

Company	Startup Date	Vessel Capacity Tons
Avesta Jernwerks AB/Axel Johnson and Co. Avesta, Sweden	6/73	60
Boschgotthardshutte Siegen, W. Germany	10/73	18
British Steel Corp./Panteg Works Pontypool, Wales, U. K.	11/71	60
British Steel Corp./Stocksbridge Works Stocksbridge, U. K.	7/72	15
FIAT, Sp. A. Torino, Italy	1/75	70
Ilssa Viola Pont St. Martin, Italy	7/70	22
IMI Alloy Steels Ltd. Somercotes, U. K.	3/71	8
Nippon Metal Industry Co. Kinuura, Japan	7/72	75
Nippon Metal Industry Co. Sagamihara, Japan	11/71	55
Olarra S. A. Bilbao, Spain	10/72 / 7/73	14 / 10
Rotherham Stainless and Nickel Alloys, Ltd. Rotherham, U. K.	11/71	8
Southern Cross Steel Middelburg, South Africa	9/72	25
Spartan Steel and Alloys Ltd. Birmingham, U. K.	10/71	8
Terni/Finisider Group Terni, Italy	8/72	60

steel produced in the U. S. will be by means of AOD and that additionally 625,000 ton will be produced overseas.

THE PURSUIT OF PATENT PROTECTION

Obviously, the marketing effort had to be based on a very strong patent structure and process know-how. The struggle for patent coverage was nearly as epical as was the process development history. The author originally filed patent applications on behalf of Union Carbide on June 27, 1956. There followed a ten-year campaign with the U. S. Patent Office which finally culminated on May 24, 1966 in the issuance of the basic patent after several interference and appeal procedures were successfully overcome. The tenacity of the Union Carbide's patent counsel was extreme but turned out to be highly rewarding since the basic patent has now ten more years to run, whereas had it been uncontested and issued quickly it could well be expiring in the next year or two, just about the time the process itself had been commercially fully substantiated. Further, an improvement patent was granted in 1962 which basically related to the sequencing of various gas mixtures for optimum results during the refining process.

LESSONS FROM THIS DEVELOPMENT

It is a great pleasure to able to recount the long and arduous saga of an ultimately overwhelming success story, especially when one has had a part in it. This, however, is not the main purpose; far more important at this point is what we can learn from this experience for our future mutual benefit. It is believed that there are many lessons to be learned here concerning technical innovation which affect many classes of individuals.

For the Individual Researcher

1) The lesson taught here is that of the extreme importance of looking for the unexpected or the unusual in any research work and the total acceptance of the research data. This may sound elementary but it is not always easy to do as a young, unknown researcher when faced with apparent contradictions with the published word of far more well-known and respected investigators. In this case, the markedly different results obtained in the very first argon tests from those of the early Hilty and Crafts and Richardson studies could have been ascribed to some mysterious and unknown experimental error and the total development could have been lost right at that point.

2) All unexpected results can be understood ultimately in terms of basic theory if a sufficient effort is made. This extremely important step is highly productive of inventions and must be thoroughly pursued. In this particular case, going back to fundamental physical chemistry led to a highly important new process which would have not been reached had not this step been completely executed.

3) Regardless of the scientific nature of research work, the researcher must strive to understand the practical and commercial environment of the system he is studying. In the present case it was not the orig-

inal intent of the work to invent a better process to produce stainless steel—as has already been said the work was primarily intended to rationalize disagreeing data between two separate investigations. Fortunately sufficient information had been learned about stainless steel melting problems and the impact of large scale oxygen plants to permit recognition of the potential importance of the process. Without this knowledge, the development of a commercial process could have been totally missed at a very early stage.

4) Abiding persistence and tenacity is absolutely required if one is going to evolve abstract research results into commercial development. There is a time during this period when the individual researcher, and only the individual researcher, has any idea at all of the commercial significance of that which has been discovered. He must be able to convince others for the necessary support and reject any discouragement until the work is complete.

For the Educators in the Metallurgical Profession

1) Traditionally, particularly in recent years, it is believed that an excellent job has been done in our metallurgical curricula of teaching fundamental principles of physics, chemistry, and mathematics and their applications to metallurgy. It is definitely believed that this type of training is the best suited to prepare a student for making a contribution to his profession.

2) It is believed that metallurgical education would benefit from greater depth in teaching of the engineering principles involved in metallurgical processing. This development nearly floundered on the design of the refining vessel; and had individuals had stronger backgrounds in heat and fluid flow associated with high temperature processes, it is believed that design solutions would have been reached more directly. This is in no way meant to mitigate the significant ingenuity that was demonstrated in the final design solution. It is only to say that teaching engineering technology applied to high temperature processes would be highly productive and has not been done in metallurgical education to the same extent as has been done in the case of physical chemistry.

3) In teaching principles and their application, the simultaneous teaching of so-called descriptive courses concerning the historical production of the various metals has necessarily been significantly reduced. Yet to make a contribution in the real world one must know and understand the current status; some means must be provided to familiarize the student with the current state of the art. It must be remembered that there is a time in the development sequence when only the individual researcher can know what he really has. Unless he can relate it readily to the real world, he will have an almost impossible task of convincing others as well as himself that he should persist. He cannot exist in a vacuum of knowledge concerning present practice.

4) A very similar comment may be made relative to process economics. The most difficult task for a young researcher is to convince himself of the ultimate economies of his new process vs existing prac-

tice. He must be taught to make process economic studies at least to be able to highlight major differences in cost. This important aspect of an engineering education requires considerable strangthening in most metallurgical curricula as they exist today. Courses taken in other departments simply do not sufficiently relate; they must be made specific to the metallurgical industry to be of maximum benefit.

For the Metallurgical Industry

1) Those of us in the metallurgical industry—be it ferrous or nonferrous—who are more or less responsible for technical innovation in order to stay competitive in world markets can learn much from Union Carbide's example. In this case, 15 years persistence on all fronts including technological, marketing, and legal areas was maintained. The faith and absolute conviction to invest millions of dollars without return for many years is absolutely necessary for significant innovation in a basic industry.

2) It is absolutely necessary to have top technical talent in several disciplines in order to develop the full conviction to persist or to change direction.

3) Discouragements enroute to a major development will be legion, but they must be viewed for what they really are; and effort cannot be discontinued just because a specific timetable, written in ignorance of later-developed facts, is violated. We, in business, tend to live by schedules and timetables. Too rigorous application of this discipline in the area of technical innovation can prematurely terminate potentially profitable inventions.

4) Industry needs to understand that there is far more scientific knowledge available today than has been brought to bear on the profit problem. To fully bring it to bear requires a complex harnessing of many different scientific and engineering disciplines together with knowledgeable and, to a degree, imaginative economic analysis. *The pay backs on technical innovation in basic industries are longer in maturing than generally expected but, compensatingly, are larger in magnitude than anticipated.* In the present case, while the lower raw material cost and the lower refractory costs were envisioned from the beginning, the decreased cost of installed capacity and the significant improvements in quality were late developments and were really not added to the benefits until the process was well along into its advanced engineering form.

For the Government

1) We hear a great deal currently about the desirability of breaking industry into smaller competing units. It should be clear from the present case that only a corporation with similar resources to Union Carbide could have proceeded for 15 years without compensation for its efforts. It should be also clear that without significant staffs in research, engineering, marketing, and patent development, a successful conclusion would not have been attained. Bigness, *per se,* is not bad.

2) It should be noted that the successful co-partner in this development was Joslyn Stainless Steel, one of the smallest producers in the United States. While superficially this might seem to enhance some of the arguments of the advocates for a larger number of smaller competitors, size, *per se,* had very little to do with it. What was significant was the courage and vision of the individuals involved and this type individual, however rare, can be found in any size organization.

3) What was uniquely American about this development, and what needs to be preserved and enhanced, is that one of the largest corporations in the world sought out and found in one of the smaller corporations the right partner for this particular development. This is free choice and true natural selection. No amount of outside legislated cooperation would have produced the same result because the natural selection process would have been violated. Cooperation on the scale demonstrated here can only be obtained from two partners freely convinced of a common goal that individually benefits each partner to a degree that justifies the expense and the risk. That freedom to search and select the most appropriate partner is one of the precious heritages of the American free enterprise system.

CONCLUSION

It has been both an honor and a pleasure to recount the development of the Linde AOD Process and to attempt to generalize from the teachings of this particular development, concepts which may accelerate other basic developments in the future. It is particularly interesting that this Extractive Metallurgy Division Lecture of 1973 bears on a subject of interest to the Iron and Steel Division. Possibly that fact, more than all others, testifies to the relevantness of the AIME where special interests stem from common basic knowledge and the resulting cross-fertilization of concepts is one of the great strengths of the Institute.