CANADA

DEPARTMENT OF MINES AND TECHNICAL SURVEYS, OTTAWA

MINES BRANCH RESEARCH REPORT

R 47

PRICE 25 CENTS

# VACUUM DEGASSING OF STEEL
## PART I:
## LITERATURE SURVEY, AND PRELIMINARY WORK

by

D. E. PARSONS AND W. A. MORGAN

PHYSICAL METALLURGY DIVISION

MAY 25, 1959

Mines Branch Research Report R 47

# VACUUM DEGASSING OF STEEL. PART I: LITERATURE SURVEY, AND PRELIMINARY WORK*

by

D. E. Parsons** and W. A. Morgan***

===

## ABSTRACT

This report discusses methods and equipment used for vacuum degassing and vacuum casting of steel on an industrial scale in the U.S.A., Germany, and the U.S.S.R. The production of degassed alloy and carbon steel ingots up to 350 tons in the U.S.A. and Germany is reviewed.

German, Russian and American ladle-degassing techniques are compared. The deoxidation of open hearth or basic bessemer rimming steels, for use in the production of killed steel rails, silicon transformer sheet and forging ingots, is discussed. A summary of published test results includes gas contents and mechanical properties of vacuum degassed steel.

An experimental 500-lb vacuum stream degassing unit, in service for about 6 months at the Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, is described and some preliminary results of the effect of vacuum casting on gas content and tensile ductility of carbon and chromium-molybdenum-vanadium steels are presented.

A list of references concerning vacuum casting and vacuum degassing of steel is appended.

---

*A summary of this report was presented at the Annual Meeting of the Canadian Institute of Mining and Metallurgy, Montreal, Quebec, on April 14, 1959, by permission of the Director, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada.

**Senior Scientific Officer and ***Head, Ferrous Metals Section; Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada.

Direction des mines, Rapport de recherche R 47

# DÉGAZAGE SOUS VIDE DE L'ACIER. PARTIE I: RELEVÉ DES OUVRAGES PUBLIÉS ET TRAVAUX PRÉLIMINAIRES*

par

MM. D. E. Parsons** et W. A. Morgan***

---

## RÉSUMÉ

Dans ce rapport, il est question des procédés et des appareils de dégazage et de moulage sous vide de l'acier, employes à l'échelle industrielle aux États-Unis, en Allemagne et en URSS. On passe en revue la production des lingots en acier allié et en acier au carbone, dégazés, pesant jusqu'à 350 tonnes, aux États-Unis et en Allemagne.

Le rapport établit la comparaison entre les techniques allemande, russe et américaine de dégazage de la poche de coulée. On y traite de la désoxydation des aciers sur sole ou des aciers basiques effervescents Bessemer, destinés à la production des rails en acier calmé, de la tôle d'acier pour transformateurs au silicium, et des lingots de forgeage. Dans un sommaire des résultats publiés des essais, on donne entre autres les teneurs en gaz et les propriétés mécaniques de l'acier dégazé sous vide.

Les auteurs décrivent un appareil d'essai de dégazage par jet sous vide, pesant 500 liv., en usage depuis environ 6 mois à la Division de la métallurgie, Direction des mines, ministère des Mines et des Relevés techniques, à Ottawa. On fournit certains résultats préliminaires de l'effet du moulage sous vide sur la teneur en gaz et la ductilité d'aciers au carbone et au chrome-molybdène-vanadium.

L'appendice énumère des ouvrages de référence traitant du moulage et du dégazage sous vide de l'acier.

---

*Avec la permission du chef de la Direction des mines, ministère des Mines et des Relevés techniques, à Ottawa (Canada), on a donné lecture d'un sommaire de ce rapport à la réunion annuelle de l'Institut canadien des Mines et de la Métallurgie, a Montréal (Québec), le 14 avril 1959.

**Agent scientifique senior et ***chef de la Section des métaux ferreux, Division de la métallurgie physique, Direction des mines, ministère des Mines et des Relevés techniques, Ottawa (Canada).

CONTENTS

## LIST OF FIGURES

# LIST OF TABLES

## INTRODUCTION

This report will present a brief review of the literature pertaining to vacuum casting and vacuum degassing techniques in current use in the U.S.A., Germany, the U.K. and the U.S.S.R. for the elimination of flaking and hydrogen embrittlement of steel. Degassing is widely used for the production of steel forging ingots, and is used to some extent in the production of heavy section castings.

Further applications of vacuum degassing in Russia and Germany, for the conversion of open hearth and basic bessemer grades of carbon steel into transformer sheet or killed rail steel, are discussed.

A description is also given of the vacuum stream degassing unit which is in use at the Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa. This equipment has been operational for about six months and, while tests are incomplete, some preliminary results on 500-lb steel melts will be mentioned.

## TYPES OF DEGASSING EQUIPMENT AND METHODS OF DEGASSING

Four methods of vacuum degassing which are in large-scale industrial use are illustrated schematically in Figure 1.

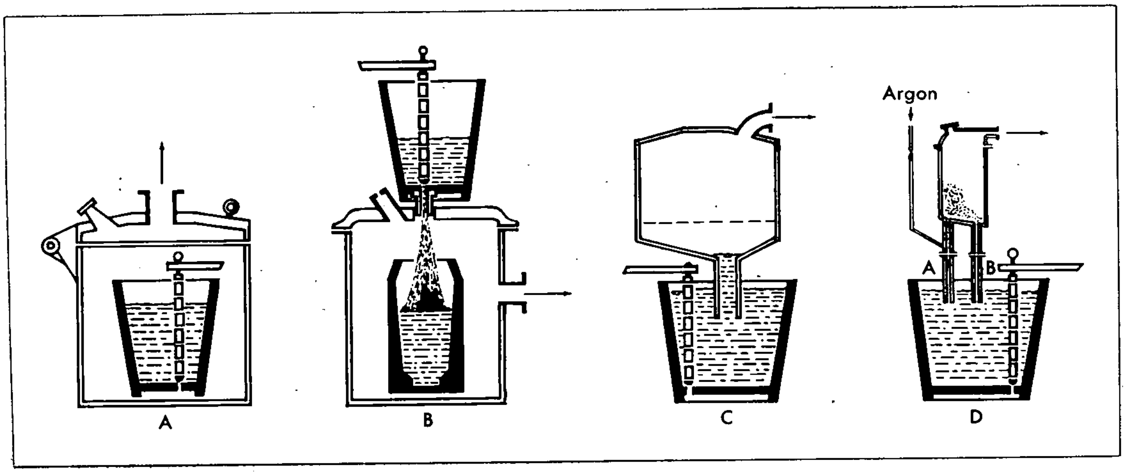
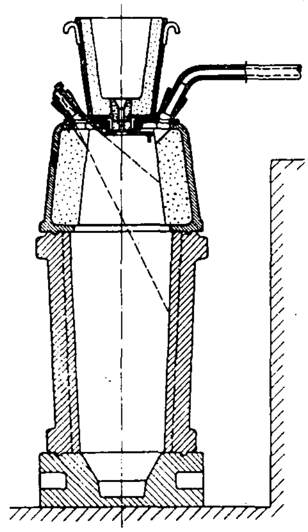



Figure 1. - Four vacuum degassing techniques.[1]

Method A - Ladle degassing.
Method B - Vacuum stream degassing.
Method C - Pipette degassing by lifting.
Method D - Continuous degassing by the syphon method.

Other variations of these four basic methods have been used on a laboratory scale. For example, early work in Russia was done by use of a collecting hood placed directly over the ingot mould. Since this time an industrial application has developed where 150 tons of steel in the ladle is sealed directly on top of the mould hot top assembly and a system analogous to method B is used without a separate vacuum chamber. This technique is illustrated in Figure 2.



Equipment for pouring large ingots (Lenin Works in Pilsen).

Figure 2. - Russian degassing method with ladle sealed directly to the mould.(2)(3)

-

A subsequent variation of method A, Figure I, used in Germany and Russia, left a sealed port, through which metal could be poured, at the top centre of the lid and moved the pumping port to the middle of the side section. This modified vacuum tank for ladle degassing is illustrated in Figure 3.

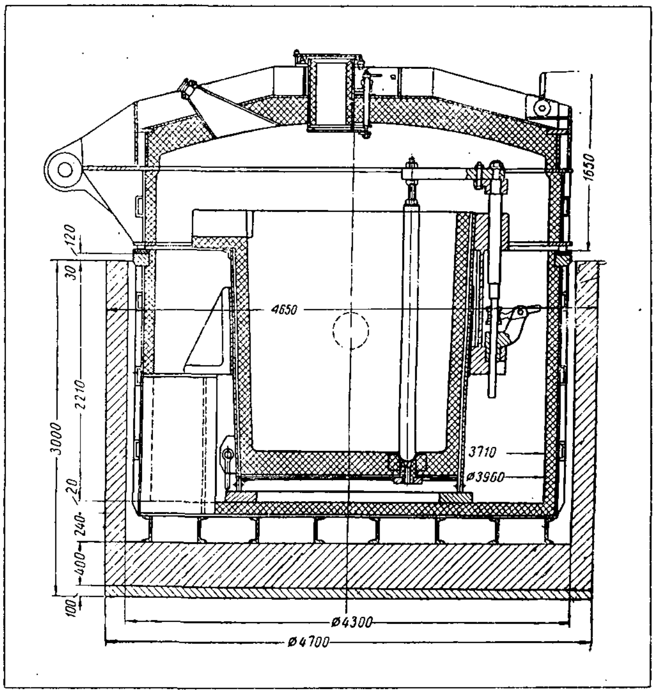



Figure 3. - Ladle degassing tank with hinged lid and vacuum port in the centre of the lid.[4]

-

(1) Ladle Degassing - Method A, Figure 1.

The ladle degassing method A, in Figure 1, illustrates a technique for vacuum degassing of metals which, in one form or another, has been used since 1893. The method was revived by the Germans and Russians in 1940 and 1945, and a recent modification of this method is being used in the U.S.A., by A. Finkl and Sons Co.,[5] for the production of forging ingots and heavy section castings. In Russia, ladle degassing is used for the production of large tonnages of transformer sheet, for rail production, for alloy constructional steels, and for the production of forgings. The transformer steel application[(6)(7)] may be classed as a vacuum refining technique dependent on slag reactions, whereas rail, alloy steel and degassed forgings involve deoxidation and degassing in the more familiar sense.

Thermodynamically, the solubility of hydrogen in molten steel is pressure-dependent, according to the Sievert relation $H = K\sqrt{pH_2}$. The efficiency of hydrogen removal, however, is controlled by kinetics, and all the successful methods seek to improve degassing rates.

Ladle degassing in the traditional manner provides a relatively small contact area for exposure of molten steel to the vacuum, and unless the bath is very shallow, encounters difficulty from the ferrostatic pressure of the metal. In fact, if the bath depth is 60 in., the metal at this depth is subjected to 1 atmosphere pressure despite exposure of surface metal to high vacuum.

For effective ladle degassing, stirring is necessary. This is usually accomplished, in steels which have not been aluminum killed, by displacement of the carbon-oxygen equilibrium at reduced pressure. The resultant evolution of CO agitates the metal, exposing new metal by vacuum. When the steel is returned to atmospheric pressure for solidification, effective deoxidation of the metal by carbon has been accomplished without retention of deoxidation product in the steel.

This technique is used in Germany and Russia for treatment of unkilled basic bessemer steel, from the 0.1% carbon level for the production of transformer sheet, and from higher carbon levels (0.5%) for the production of killed and degassed rail steel.

In the application of degassing to transformer steels, the slag is allowed to remain on the metal and act as an oxygen reservoir. Application of vacuum, at pressures of 30 to 35 mm, results in a boil which reduces the oxygen and carbon contents to about 0.004% and 0.030% respectively. Sulphur reduction from 0.007% to about 0.003% occurs when the carbon monoxide evolution mixes the metal and the basic slag.

Historically, Russian development work started in 1940, when tests were carried out using either a 16-ton ladle sealed in a vacuum pot (Method A, Figure 1), or a gas-collecting hood placed over a 4-ton ingot mould. The test apparatus used for collecting gas above the ingot mould is illustrated in Figure 4.

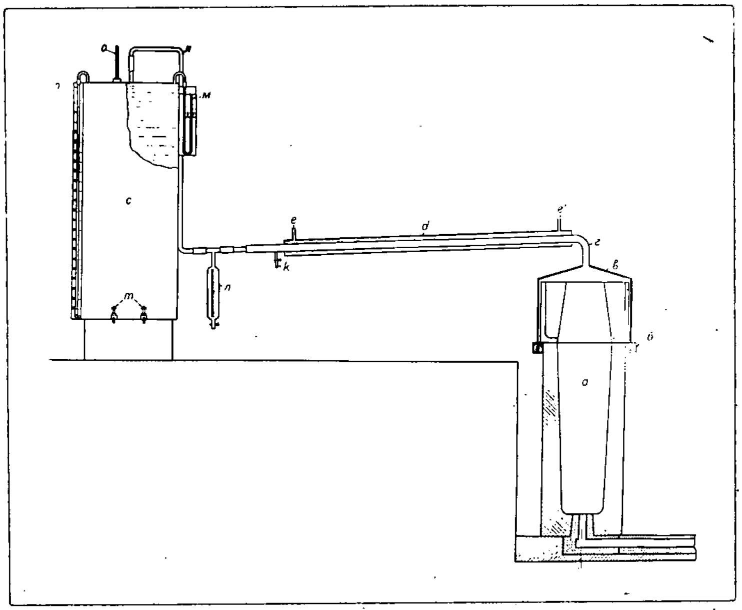


Figure 4. - Gas-collecting hood placed above the mould.

-

Tests were carried out at the Yenakievsky metallurgical plant where bessemer steel was vacuum treated in a 16-ton ladle or in a 4-ton ingot mould. Three melts of rail steel and seven melts of other steel were treated in the ladle, and seven melts of rimming steel were treated in the ingot mould. Vacuums of 70 to 100 mm Hg were the lowest which could be controlled. Treatment time in the ladle was 12 to 14 min; in the ingot mould, 25 to 30 min. After vacuum treatment the steel was teemed in air.

The rimmed steel then acted like killed steel and solidified with shrinkage. The ingots were rolled to billets 1/2 in.x 3/4 in.

x 6 in. Analyses showed that the oxygen contents of converter steels were reduced to about 1/4 to 1/10 their original values, in some instances to 0.004%. The nitrogen content of bessemer steel was also reduced by 30% to 50%. No gas bubbles were observed and no sulphur segregation of the rimming type was observed. The distribution of carbon, sulphur, phosphorus, nitrogen and oxygen in the ingot was very uniform. Thus, killed quality rolled bar stock was obtained from bessemer rimming grade steel.

At the Dneiprospetsstal plant, vacuum chambers resembling the one illustrated in Figure 3, with provision of a seal so that molten metal may be transferred from a ladle outside the tank into another ladle held inside the tank, are used for treating 25-ton arc furnace melts.

Usually, a ladle filled with steel is placed in the chamber and kept there for 10 min at 30 to 35 mm Hg.

The output of this plant is mainly used for transformer sheet. Vacuum treatment is intended to reduce watt losses and to increase plasticity. All other things being equal, the improvement of electrical properties of the transformer steel is due to reduction in its content of impurities such as carbon, sulphur and oxygen. Elimination of these elements is facilitated by high liquid metal temperatures, but casting of overheated metal results in unsound ingots unless vacuum degassing is used. It has been reported that after degassing these steels can be continuously cast.

Before degassing was commenced the average carbon contents were of the order of 0.04 - 0.09%, and not less than 0.007% sulphur was present. After vacuum treatment almost all the steel produced contains less than 0.03% carbon and 0.003 - 0.005% sulphur. The oxygen content is reduced by 1/2 to 2/3 of its original value.

Figures 5 and 6 illustrate frequency curves for final carbon and sulphur contents. Figures 7 and 8 illustrate the magnetic induction and hysteresis loops, respectively, for vacuum induction melted steel. (Data similar to those shown in Figures 7 and 8 are not available for ladle degassed metal.)

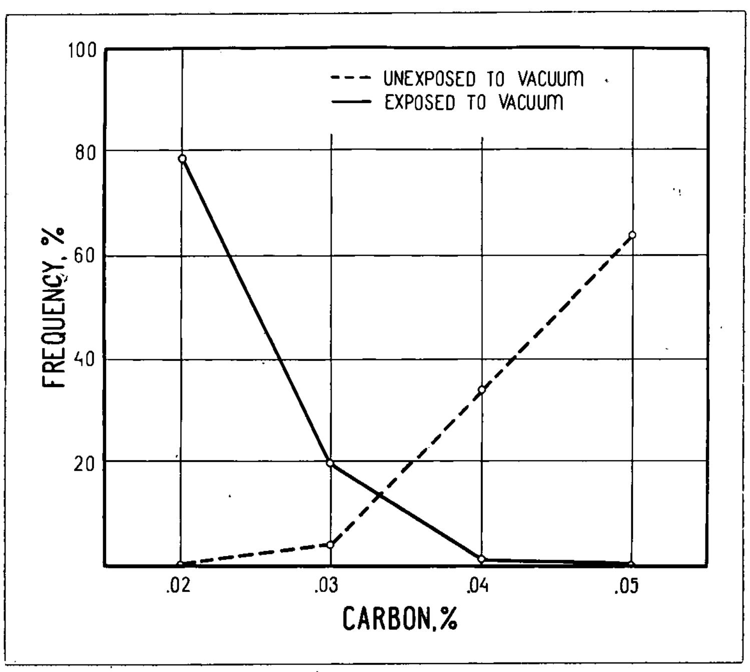



Figure 5. - Carbon content of transformer steel (ladle degassed steel).(6)

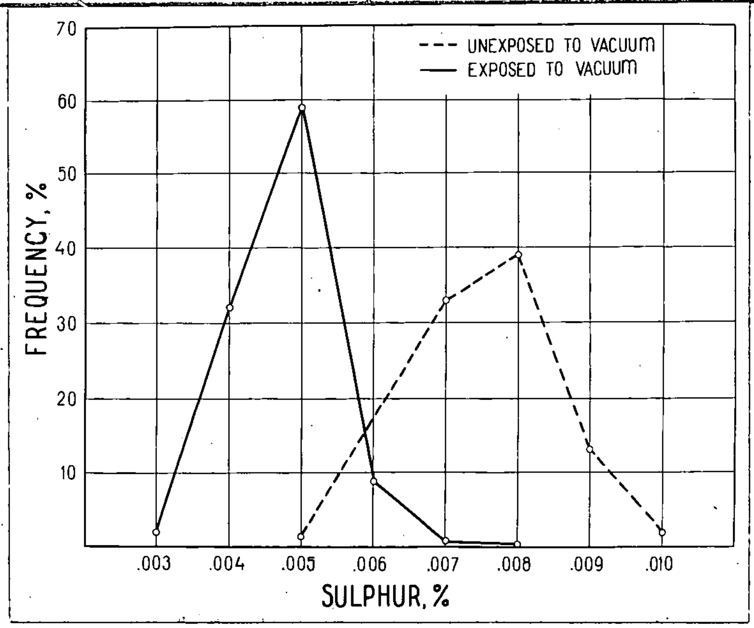



Figure 6. - Sulphur content of transformer steel (ladle degassed steel).(6)

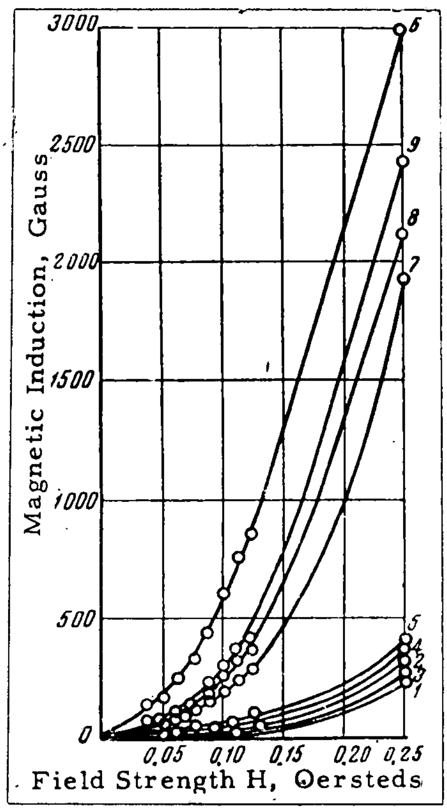



Figure 7. - Reduction in coercive force obtained in vacuum induction melted transformer steel vs. air melted transformer steel.(6) Melts 1-5 are vacuum melted, melts 6-9 are air melted, 4% silicon-iron alloys.

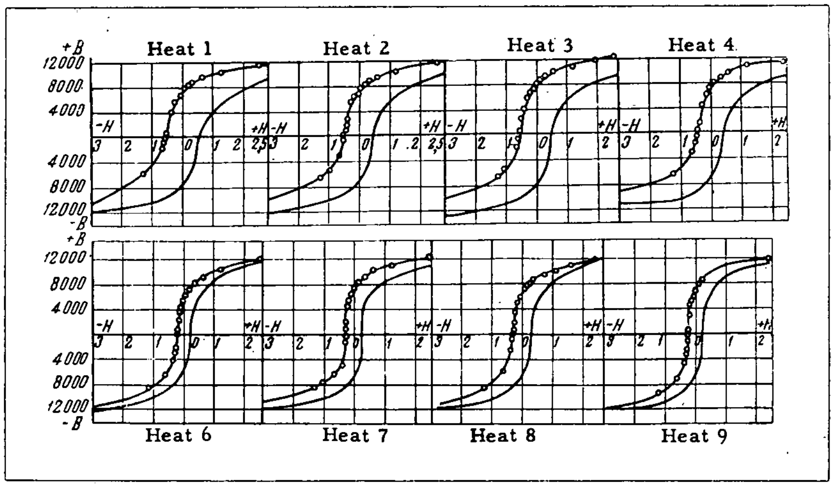



Figure 8. - Hysteresis loops, air melted silicon transformer steel vs. vacuum induction melted transformer steel. Melts 1-4 are air melted, melts 6-9 are vacuum induction melted, 4% silicon-iron alloys.(6)

The reduction in carbon, sulphur and oxygen contents of transformer steel contributes to considerable improvement of steel plasticity and makes possible cold rolling of the steel with higher content of silicon. Watt losses were decreased by 20 - 25%.

While the low carbon, sulphur and oxygen contents in 4% silicon transformer steel can also be attained by appropriate heat treatment of sheets made of this steel, it is easier and cheaper to treat steel with lower contents of the impurities mentioned, and the use of vacuum allows considerable reduction in melting time.

At this plant, also, the tendency of chromium-nickel construction steel to form flakes and hair line cracks was controlled by vacuum removal of hydrogen. The same degassing chambers were used as for the transformer steels.

Before treatment, out of 50 heats, 35 had hair line cracks, After treatment, out of 41 heats, only 13 had hair line cracks and the extent of the latter cracks was reduced, so that wastage of alloy construction steels was almost completely eliminated.

Good results were obtained in vacuum treatment of chromium stainless steels. Bonus effects were additional purification from sulphur, and more complete chromium recovery, from resultant mixing of the slag and metal.

At the Dzerzhinsky plant the change in hydrogen content of basic bessemer steel before and after ladle treatment was studied. Here, when producing rail steel from pig iron, the blast is stopped at a high carbon content, and the metal is deoxidized and cast into moulds. The pressure is reduced to 2 to 10 mm Hg in 4 or 5 min. The total ladle exposure of 18 tons of metal does not exceed 15 min. After treatment the steel is air cast in moulds and used for rail production. Data reported for 15 melts treated at pressures of 2 to 11 mm Hg (average 6 mm) gave average hydrogens of 4.2 ppm before and 2 ppm afterwards. Oxygen contents (average) were reduced from 0.0049% to 0.0019%. These results are shown in Table 1.

TABLE 1

Gas Content of Rail Steel

| | Before | After |
|---|---|---|
| Hydrogen range | 1.9/6.8 ppm | 0.6/3.7 ppm (15 melts) |
| Oxygen range | 0.0030/0.0071% | 0.0009/0.0015% (11 melts) |

Figure 9 shows gas reductions for degassed bessemer steel.

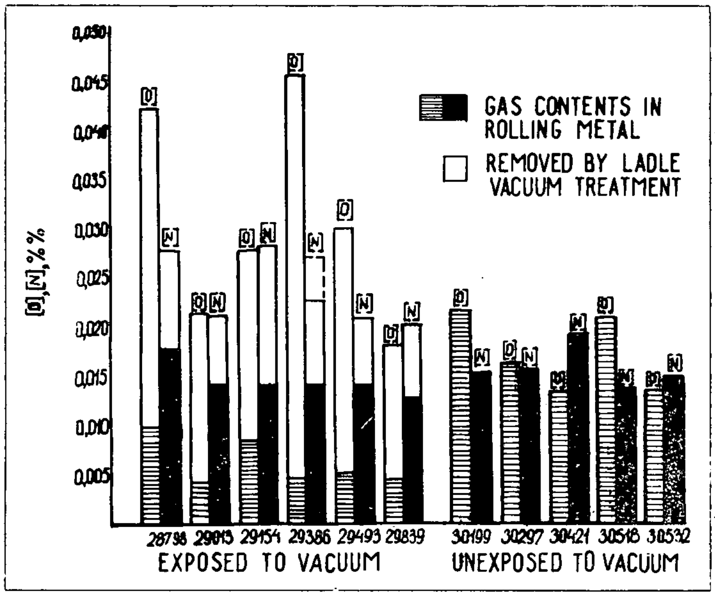



Figure 9. - Oxygen and nitrogen contents of basic bessemer steel.(6)

At the Pilsen Lenin Works, tests were carried out in 1955 which led to erection of a vacuum casting plant where the ladle was sealed directly to the mould as illustrated in Figure 2. This equipment was used for the production of ingots up to 120 tons. Provision was also made for vacuum ladle treatment of 55-ton batches of alloy steel, intended for castings, by sealing the ladle with a gas-tight lid. The pumping capacity was 1000 cfm at 1 mm or 600 cfm at 8 microns. Comparison of vacuum vs. air cast metal was facilitated by use of a ladle having two pouring nozzles. Hydrogen reductions of about 50% were reported. Steel, treated, was produced in a 55-ton acid open hearth furnace by the silicon reduction process from liquid steel taken from 55-ton basic openhearth furnaces. The steel was cast into 5-ton ingots. This work demonstrated the necessity for returning the ingot mould to atmospheric pressure for solidification, subsequent to vacuum treatment, to obtain the benefits of carbon deoxidation. Vacuum treatment at 35 mm does not eliminate flaking but is stated to reduce the incidence of flaking.

One difficulty, fundamental to ladle degassing, is the loss of temperature. The minimum temperature depends on the casting or ingot section and on the fluidity required. In extreme cases of temperature drop, slag and inclusions are unable to float out of the steel and some form of energy input is necessary.

One recent and successful variation of ladle degassing is employed by A. Finkl and Sons Co., Chicago, Illinois, where the intention is to reduce hydrogen to levels at which flaking and embrittlement will not occur in forging ingots or in heavy section castings. Final hydrogen contents in modified AISI 4350 of 2.5 ppm, reduced from an initial level of 5 to 6 ppm, are obtained. The slag must be removed, and use of deoxidizers is restricted to vanadium, i.e. no aluminum can be added. It has also been necessary to increase the boiling action resulting from displacement of the carbon-oxygen equilibrium, by lance injection of helium gas into the 70-ton melt held under 1 mm vacuum. The result is a 50 in. boil in killed electric furnace steel which is effective in removing hydrogen. The relatively high carbon content and low oxygen level of the steel, and the absence of the slag action in providing an oxygen reservoir, probably explain the necessity for injection of inert gas to obtain turbulence.

The necessity for removing slag demonstrates that, while basic slag is useful and necessary for sulphur removal or for maintenance of a strong carbon monoxide boil, effective hydrogen removal is rendered more difficult by the presence of slag.

(2) <u>Vacuum Stream Droplet Degassing - Method B, Figure 1.</u>

In this technique, metal is held in, or poured into, a ladle sealed on top of the vacuum tank. When the stopper is opened the metal melts through an aluminum rupture disc and is spray cast into an ingot mould or ladle held inside the vacuum tank. In vacuum the metal stream breaks into droplets which subdivide as they fall, thereby exposing a large surface area of metal to vacuum. In the absence of air, oxidation of the droplets does not occur. The extent to which the metal sprays depends on the pressure. At operating vacuums between 300 and 1200 microns, the spray angle measured to the vertical axis is between 30° and 45°. (Total spray cones of 60° to 90° are obtained.)[8]

The stream droplet method was originally developed by Bochumer Verein A. G.[9][10] in Germany and was reported in the technical literature in 1954. Ingots of up to 150 tons were being cast in a tank 14-1/2 ft. in diameter by 29 ft. in height. Operating vacuums of 5-20 mm were reported at this time. The pumping system consisted of 8 mechanical and 1 booster pumps providing a free air displacement of 3000 cfm. In addition to spray casting of large forging ingots, the system was used to degas metal by spray casting into a second ladle held inside the tank. This ladle was later removed from the tank and the metal was used for castings. With precautions and attention to the density of the nozzle stream after degassing, it was possible to degas and air cast without affecting the low gas content obtained by spray degassing.

The hydrogen reduction obtained at Bochumer Verein on ingots of 8 to 150 tons is shown in Figure 10.

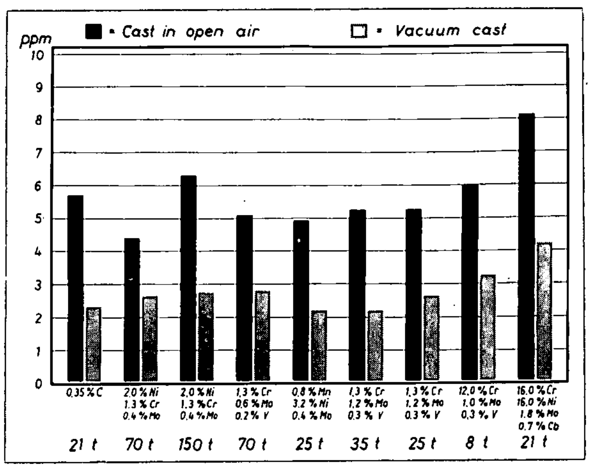



Figure 10. - Hydrogen reduction obtained on vacuum spray cast ingots(10)

The hydrogen reduction obtained at Bochumer Verein on vacuum spray cast metal collected inside the tank in a ladle and air poured into castings is shown in Figure 11.

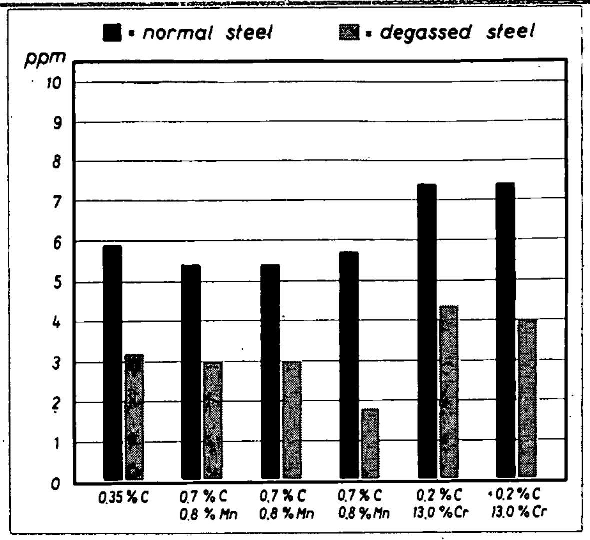



Figure 11. - Hydrogen reduction by vacuum spray degassing for castings.(10)

Hydrogen contents were reduced by about 50%, from initial contents of 4-8 ppm to final contents of 2-4 ppm.

The reduction of oxygen and nitrogen contents obtained at Bochumer Verein is shown in Figure 12. Oxygen contents were reduced to less than half their original value, except when the steel had been fully killed with aluminum before degassing. In steels which were fully aluminum killed, no reduction of oxygen content was obtained. Reductions of about 10% to 30% in nitrogen content were obtained in the absence of large quantities of aluminum.

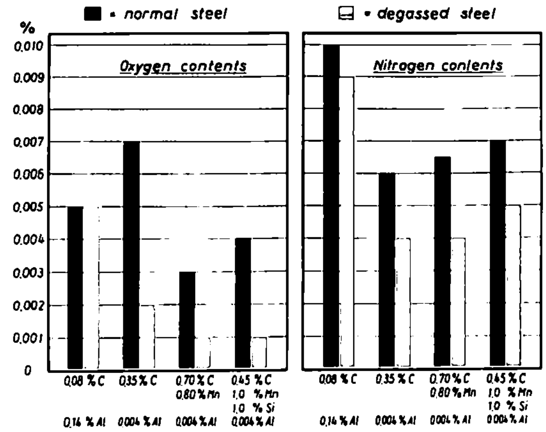



Figure 12. - Effect of degassing on the oxygen and nitrogen contents of steel ingots.(10) Note that when the steel is fully killed with aluminum, no decrease of oxygen occurs during spray degassing.

This method of degassing eliminated flaking, and the segregation of hydrogen to the centre of forgings was eliminated or strongly reduced, depending on composition. The results showed a significant reduction in the relative amounts of $SiO_2$ and $Al_2O_3$, and an almost complete elimination of MnO, in these tests.

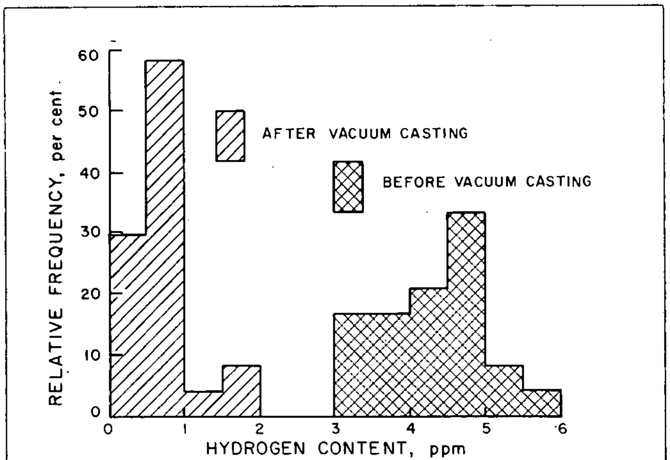
Comparison of air melted vs. vacuum cast steels showed marked improvement in tensile ductility as measured by percent elongation and percent reduction of area after vacuum casting.

Between 1952 and 1955, approximately 25,000 tons of vacuum cast ingots have been used and approximately 1900 tons of castings have been made from vacuum-treated steel. The forging ingot output have been used to produce generator shafts, turbine rotor forgings, back-up rolls, rolls, dies, and rails.

Since 1957, use of vacuum stream degassing techniques for the production of forging ingots has increased, until at this time there are at least three large installations in the U.S.A.: the Bethlehem Steel Company, the U.S. Steel Company (Duquesne Works), and Erie Forge and Steel. Four stream degassing units are reported to be in operation in Russia. In Canada the only installation is the 500-lb laboratory unit in use at the Mines Branch, Department of Mines and Technical Surveys, Ottawa. Pumping, for all the installations in the U.S.A., is accomplished by use of four-stage steam ejector systems having capacities of the order of 100,000 cfm measured with standard air at 1 mm or 0.5 mm. The pumps are connected to tanks of about 17 ft. diameter and 30 ft. in height. The overall height of the steam ejector pumps is of the order of 80 ft.

With this equipment, ingots up to 250 tons and, in at least one instance, carbon steel ingots up to 350 tons, have been cast in the pressure range 100 microns to 1200 microns. Final hydrogen contents of 0.8 to 1.2 ppm are consistently obtained heat-to-heat and surface-to-centre in these large ingots. Test forgings (16 in. x 16 in. x 28 in.) of degassed steel did not show flaking, even when air cooled and quenched directly from the austenite range. Records of many casts show that flaking and loss of tensile ductility at the centre of heavy sections have been eliminated as forging problems.

Typical hydrogen reductions reported by U.S. Steel Company[11] are shown in Figure 13.




FREQUENCY DISTRIBUTION OF HYDROGEN CONTENT IN STEEL.

Figure 13. - Frequency distribution of hydrogen content in steel.[11]

The hydrogen content of 24 heats ranged from 3.3 to 5.8 ppm before vacuum casting with an average of 4.3 ppm, and from 0.3 to 2.0 ppm after vacuum casting. (The average is less than the 1.5 ppm aim.)

Table 2 gives the U.S. Steel hydrogen, oxygen and nitrogen contents of heats before and after vacuum casting.

TABLE 2. - Gas Content of Vacuum Cast Steel
(from Orehoski and Hornak[11])

| Gas | Before or After Vacuum Casting | Number of Heats | Gas Content, ppm Range | Gas Content, ppm Average | Reduction |
|---|---|---|---|---|---|
| | Before | 24 | 3.3-5.8 | 4.3 | |
| Hydrogen | After | 24 | 0.3-2.0 | 0.8 | 81% |
| | Before | 7 | 20-70 | 36.5 | |
| Oxygen | After | 7 | 10-60 | 26.5 | 27% |
| | Before | 9 | 30-200 | 80.0 | |
| Nitrogen | After | 9 | 30-190 | 75.0 | 6% |

For all heats and compositions, average hydrogen reductions of about 63% are reported by Bethlehem Steel Company,[12] and since steels used for rotor forgings are not generally aluminum killed, a reduction of the order of 30% in oxygen content occurs. Very little reduction of nitrogen occurs.

The steam ejector stream degassing installation at Erie Forge and Steel Company is shown in Figures 14 and 15.

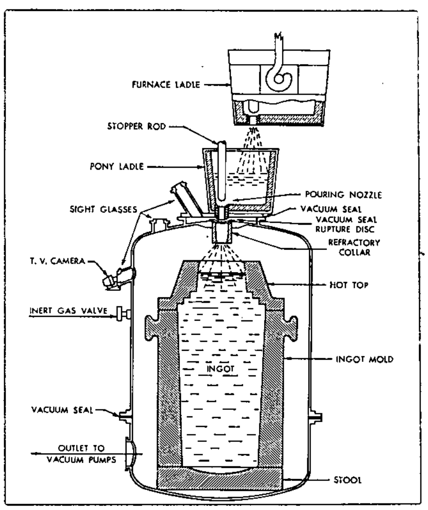



Figure 14. - Erie Forge and Steel Company spray degassing unit.

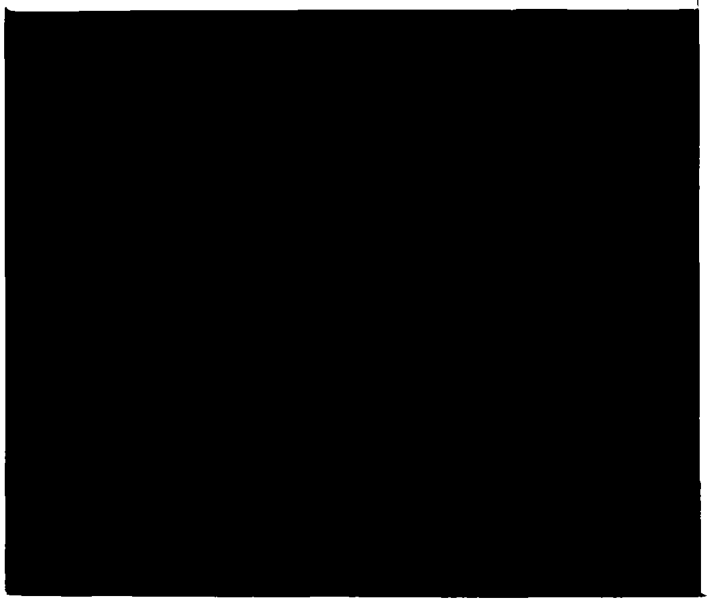
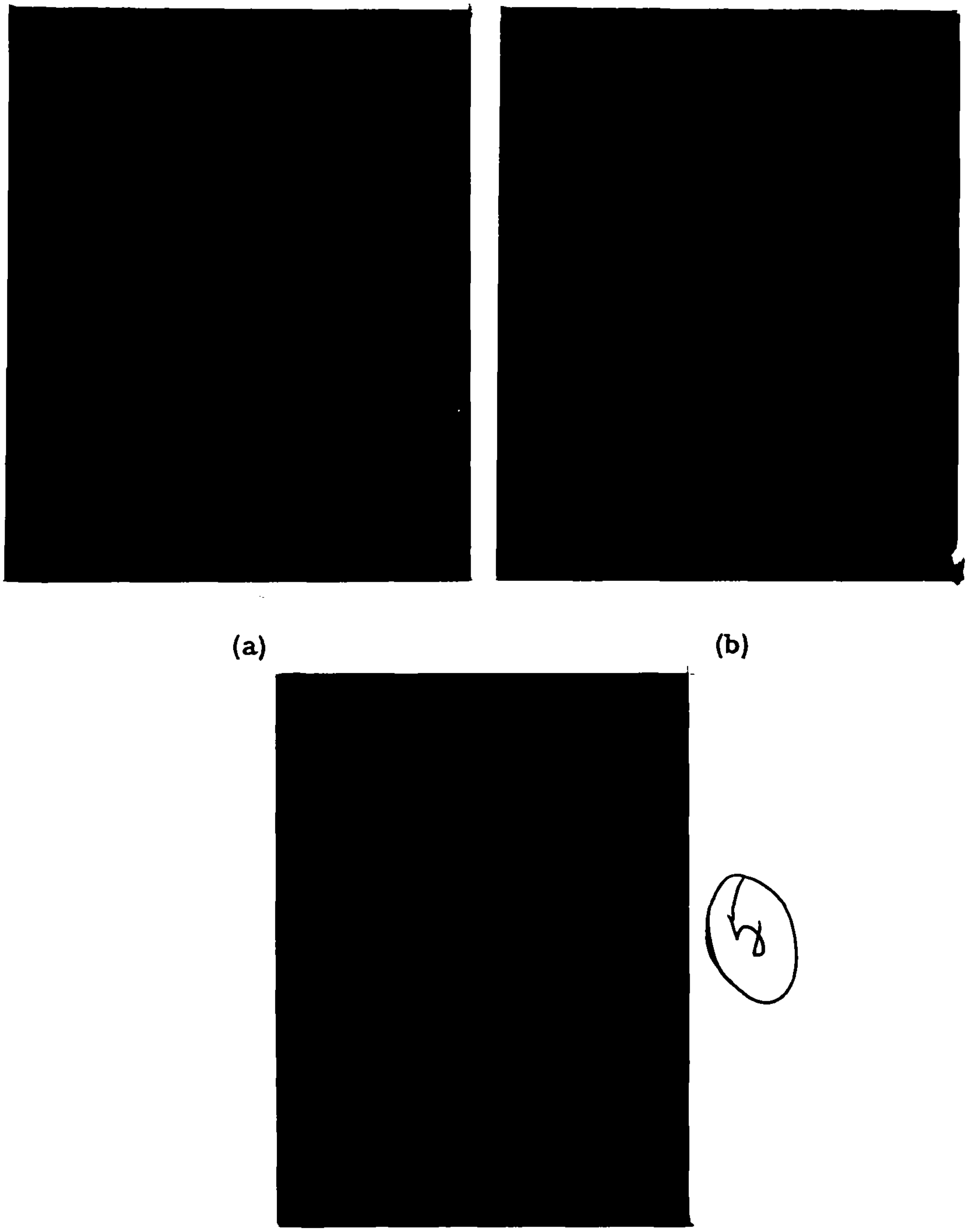


Figure 15. - Vacuum stream degassing unit for casting 250-ton ingots at vacuums of 300-750 microns. (Erie Forge and Steel Company)

Views of the U.S. Steel, Bethlehem, and Bochumer Verein installations are shown in Figure 16.



(a) (b)

(c)

Figure 16 (a-c). - Vacuum stream degassing installations.

(a) - U.S. Steel
(b) - Bethlehem
(c) - Bochumer Verein

Data reported by Bethlehem Steel Company, giving the hydrogen contents in the air and vacuum cast conditions, and a comparison of hydrogen segregation in air and vacuum cast ingots, are shown in Figure 17. Segregation data for hydrogen in U.S. Steel forging ingots are also shown.[11][12]

(a)

(b)

(f)

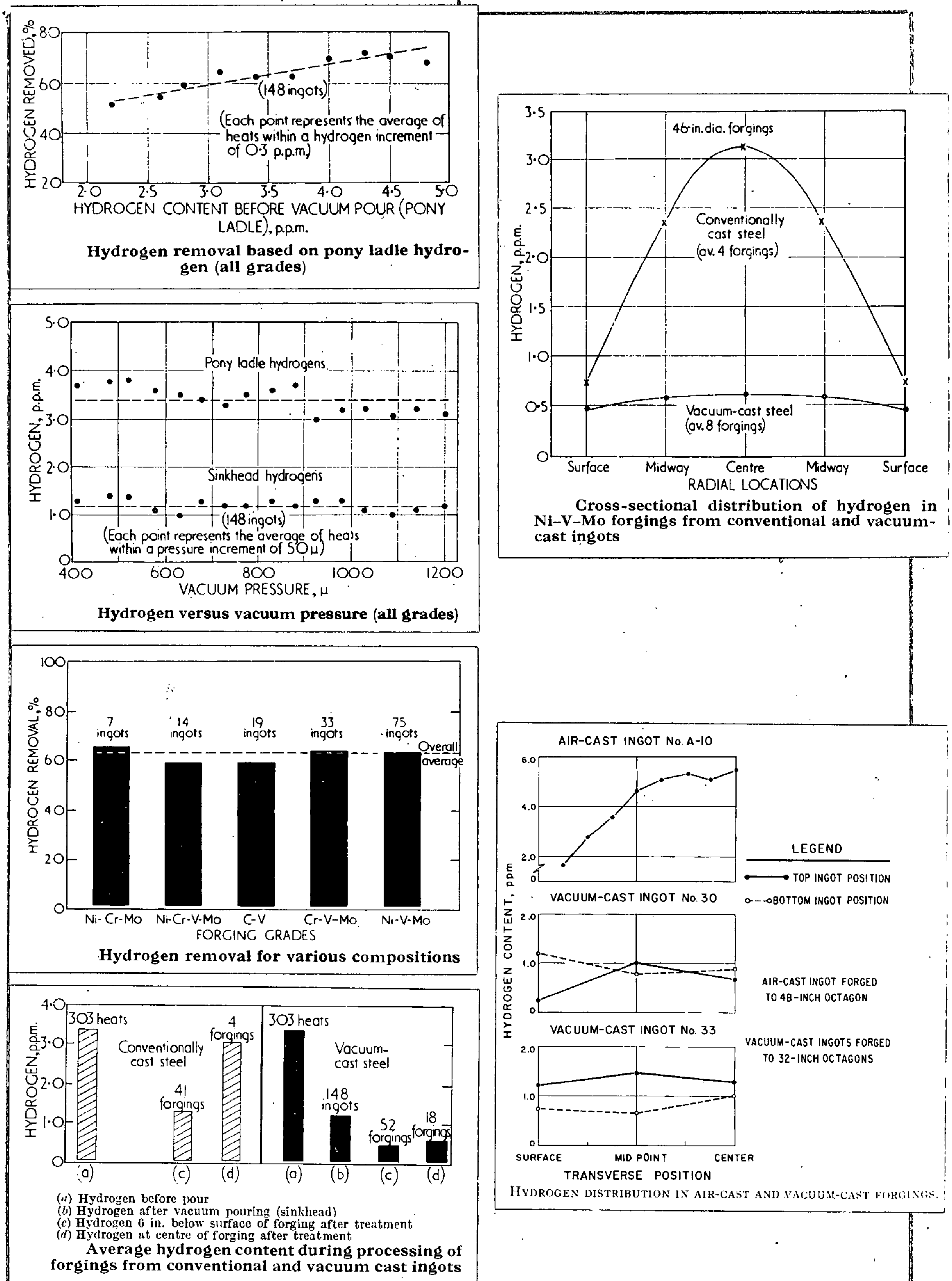
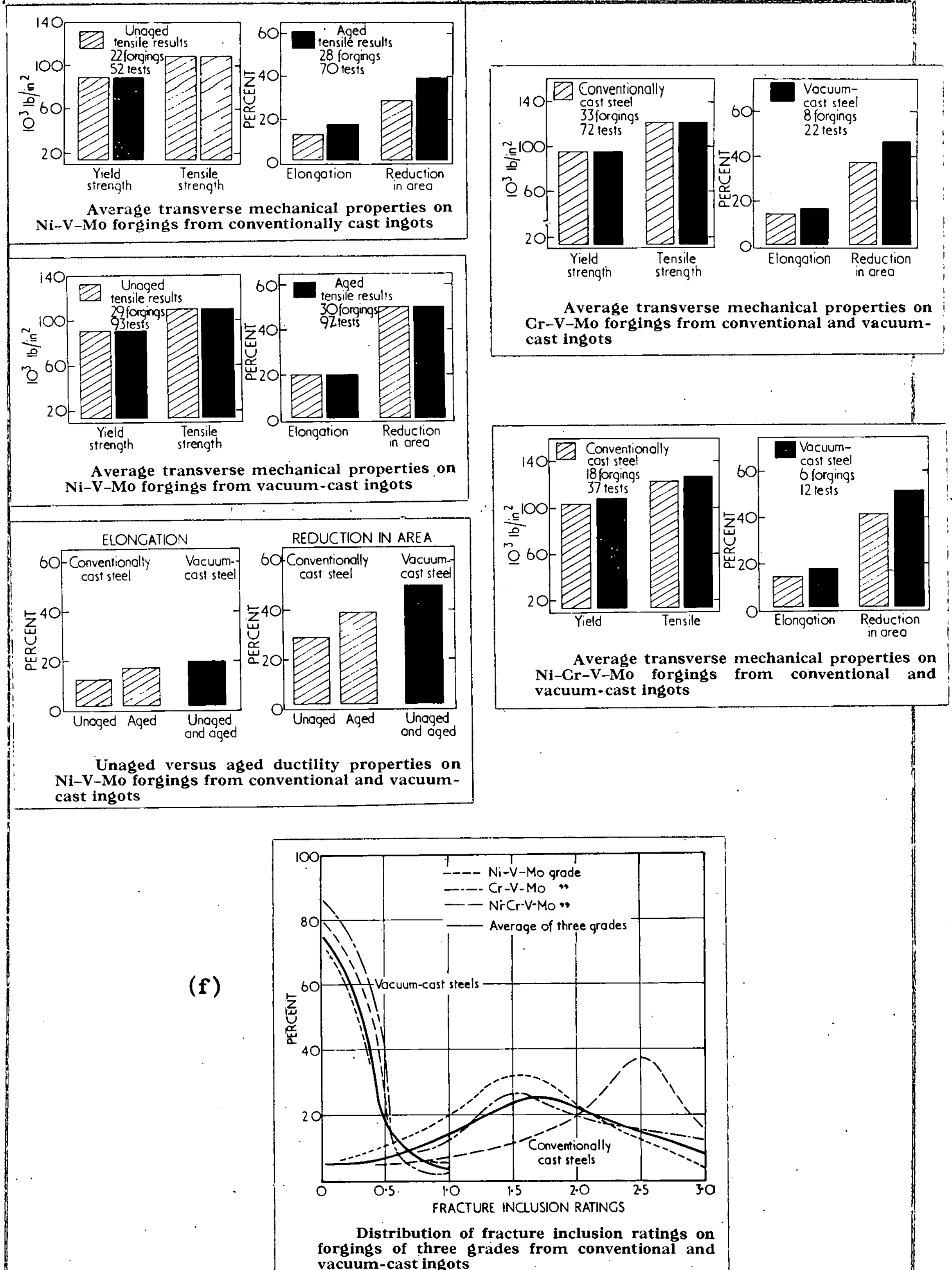



Figure 17. - Hydrogen data for stream degassed ingots.[11][12]

The improved tensile ductility resulting from vacuum treatment, and a chart illustrating the reduction in size and number of silicate inclusions, are shown in Figure 18. The tensile ductilities of aged and unaged vacuum cast steel are the same but are higher than the values obtained in air cast steel even after a dehydrogenizing (aging) treatment at 500°F.[12]

top




(a) Average transverse mechanical properties on Ni-V-Mo forgings from conventionally cast ingots

(b) Average transverse mechanical properties on Cr-V-Mo forgings from conventional and vacuum-cast ingots

(c) Average transverse mechanical properties on Ni-V-Mo forgings from vacuum-cast ingots

(d) Average transverse mechanical properties on Ni-Cr-V-Mo forgings from conventional and vacuum-cast ingots

(e) Unaged versus aged ductility properties on Ni-V-Mo forgings from conventional and vacuum-cast ingots

(f) Distribution of fracture inclusion ratings on forgings of three grades from conventional and vacuum-cast ingots

Figure 18. - Mechanical test results and cleanliness data, Bethlehem Steel Company.[12]

In general, according to Bethlehem data, vacuum spray casting does not affect Charpy impact values or transition temperatures. The U.S. Steel Company results showed an improvement in Charpy impact strength, and in transition temperatures, which might have resulted either from degassing or from process changes which accompanied use of the degassing process.

The U.S. Steel Company reports that surface defects can result if the spray washes the sides of the ingot moulds. Others report that this has little effect on ingot surface, since oxidation of the metal droplets does not occur in the vacuum.

Analysis of the fumes given off shows that $Mn_3O_4$ is the principal constituent. Despite this, the quantity of manganese lost as fume does not have any significant effect on ingot composition. Analysis of evolved gases by U.S. Steel indicates maximum hydrogen and carbon monoxide contents of about 68% and 38% respectively. Typical Bethlehem Steel Company analyses for hydrogen and carbon monoxide were 31% and 29% respectively.

The presence of hydrogen, carbon monoxide and finely dispersed dust necessitates breaking vacuum with nitrogen or argon. As soon as the hydrogen and carbon monoxide contents reach safe levels, air is allowed to enter and the ingot solidifies at atmospheric pressure. Other precautions must be taken when steam ejector pumps are used, to avoid any possibility of steam back-streaming into the tank in the event of a steam plant failure.

The reported benefits of vacuum stream degassing may be summarized as follows:

(1) Reduces the hydrogen content in most steels to less than 1 ppm, although the amount of hydrogen retained depends on the grades of steel; this assumes pouring pressures of less than 1 mm Hg.

(2) Reduces the sensitivity to thermal flaking.

(3) Improves the tensile ductility and the transverse properties of large forgings.

(4) Does not affect the ingot structure or the alloy segregation characteristics of large ingots.

(5) Deoxidizes some steels, the amount of oxygen removed being related to the composition of the steel.

(6) Improves cleanliness. Reduction in the size and quantity of silicate inclusions was reported by Bethlehem Steel Company (Stoll) and by Bochumer Verein A.G. (Tix).

(7) Higher tensile ductility is reflected in improved forgeability and in fewer rejects for centre looseness after ultrasonic testing.

(8) Comparison of McQuaid-Ehn grain size showed no difference between vacuum cast and conventionally cast steels.

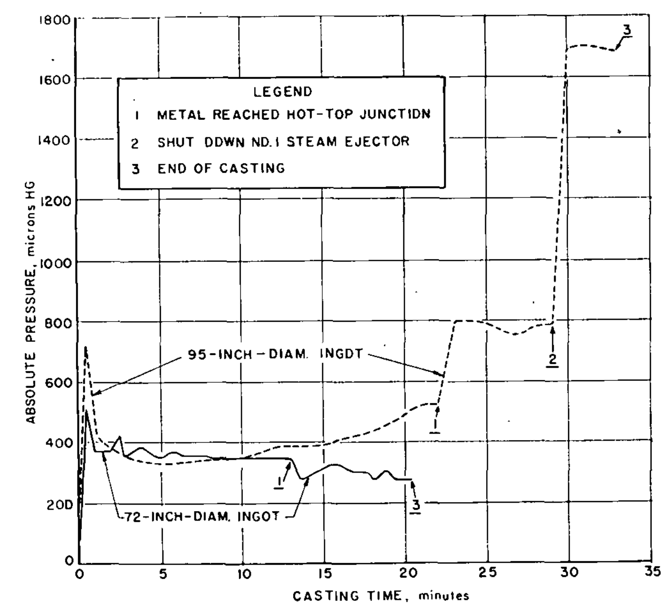
Operating pressure graphs for ingots stream degassed by

top

U.S. Steel Company and by Bethlehem Steel Company are shown in Figure 19.[11][12]

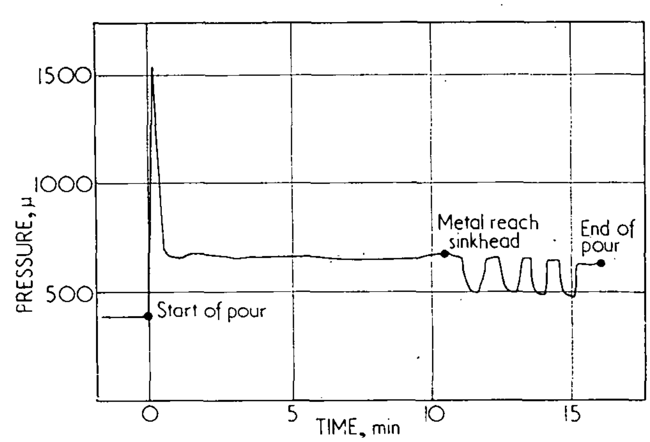
Data concerning relative humidity, blank-off pressure and operating pressure are shown in Figure 20.[11][12]

(a)




VARIATION IN PRESSURE DURING VACUUM CASTING.

(b)



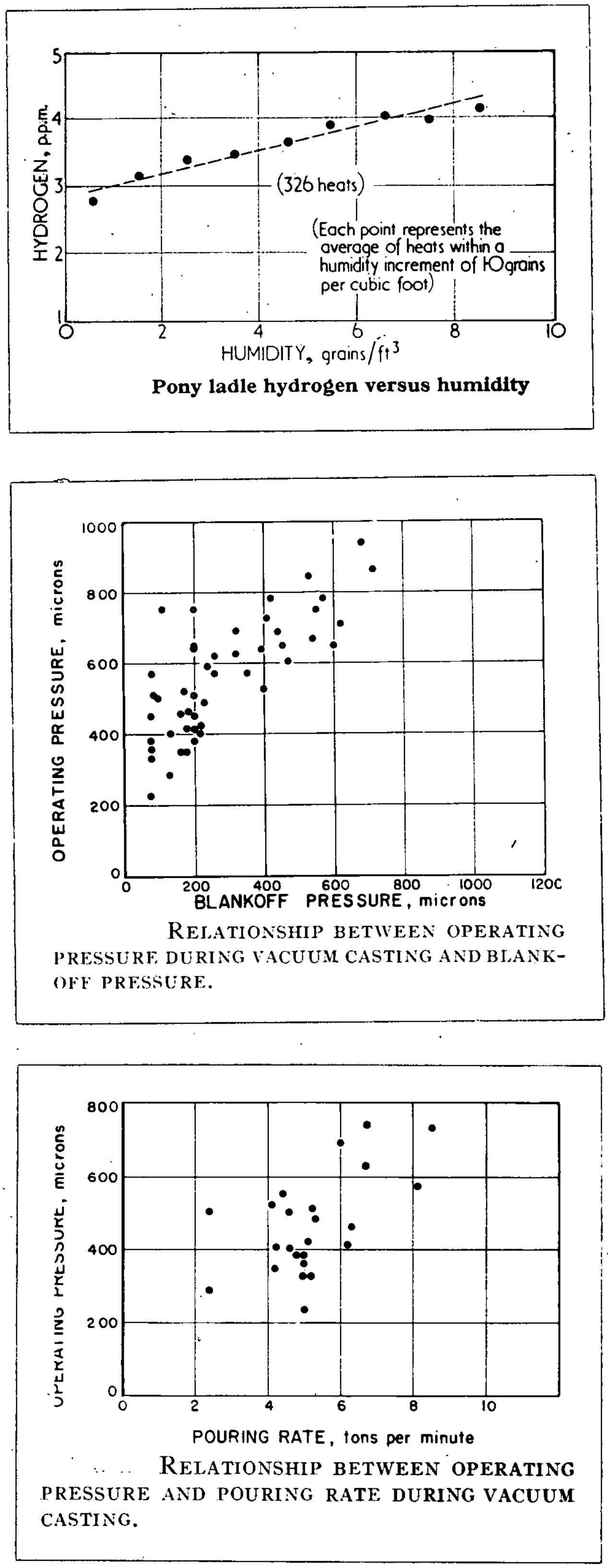

**Typical pressure curve during pour of ingot in 250-ton vacuum-degassing unit**

Figure 19. - Pressure curves for vacuum-cast ingots.

(a)

(b)

(c)




(a) Pony ladle hydrogen versus humidity

(b) RELATIONSHIP BETWEEN OPERATING PRESSURE DURING VACUUM CASTING AND BLANK-OFF PRESSURE.

(c) RELATIONSHIP BETWEEN OPERATING PRESSURE AND POURING RATE DURING VACUUM CASTING.

Figure 20. - Operating data on hydrogen vs. relative humidity and relationship between operating pressure, blank-off pressure, and pouring rate.(11)(12)

(3) Pipette, Lifting Method of Degassing - Method C, Figure 1.

This method is illustrated schematically in Figure 1 C, and three installations of this type at Dortmund-Horder Huttenunion A.G. will be described. The original work was carried out with a vacuum tank pump assembly that was mounted on a platform and was raised or lowered above the ladle by a crane. The apparatus is illustrated in Figure 21.[13]

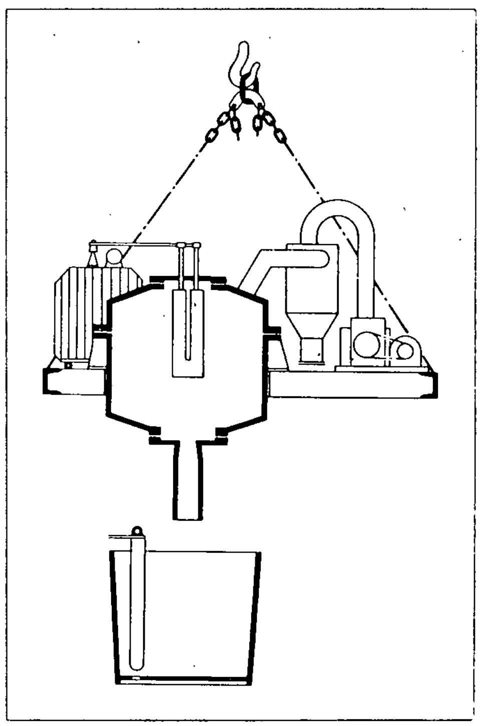


Figure 21. - Experimental pipette apparatus. This apparatus was raised and lowered about 60 cm (24 in.) for each increment of metal.[13]

-

This unit was used to treat 3300 tons of open hearth steel, each ladle holding 88-110 tons of steel, which was degassed by raising and lowering the vacuum tank, thereby allowing 4.4-ton batches of steel to be sucked up and exposed to vacuum. After treatment the tank was raised (see Figure 22), the metal was returned to the bottom of the ladle, and a fresh increment was treated. Treatment time for 88-110 tons of steel was about 30 minutes; the individual portions (4.4 tons) each required 30 seconds for treatment, and about 25 cycles were required per ladle. The treatment reduced the oxygen and hydrogen contents of the steel to about one-third of their initial values.

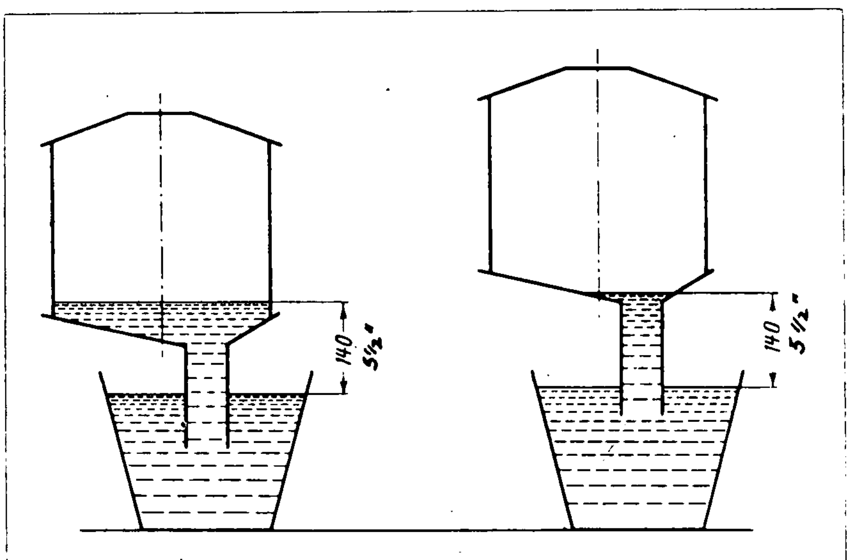



Figure 22. - Method of exposing 4.4-ton increments of steel to vacuum.[13]

After the experimental installation had shown that a large-scale treatment of steel under reduced pressure is possible and economic, one industrial plant for the treatment of open hearth steel, illustrated in Figure 23, and one plant for the treatment of basic converter steel, were erected.

(a)

(b)

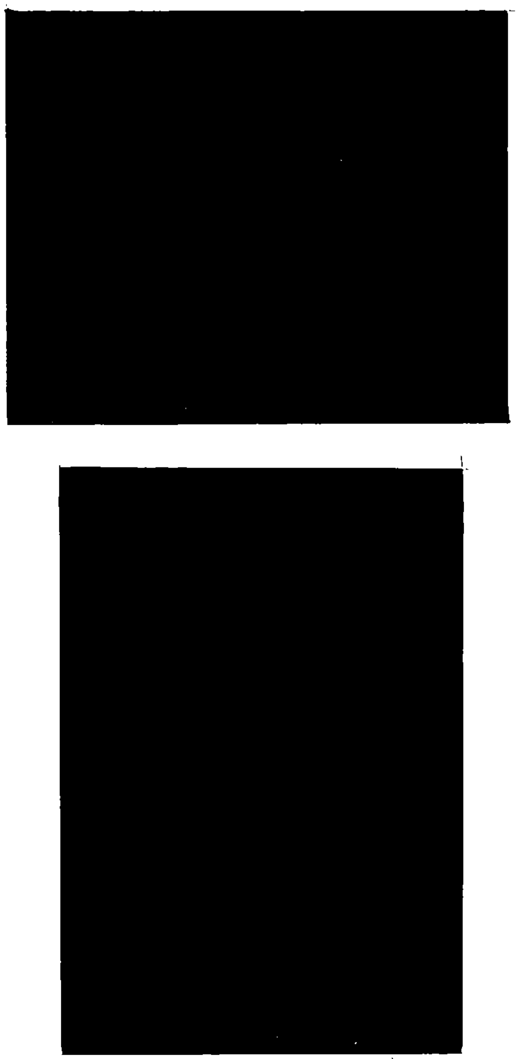


Figure 23. - Dortmund-Horder apparatus.[13] This figure shows top and bottom views of the Dortmund-Horder open hearth installation.

The Dortmund-Horder vacuum treatment of steel depends on the following:

(1) Displacement of the carbon-oxygen equilibrium by continuous removal of a gaseous product.

(2) Removal of elements the solubility of which depends on the pressure; for example, hydrogen and nitrogen dissolved in iron. The product of the concentration of carbon, multiplied by the concentration of oxygen in the molten metal, is directly proportional to the partial pressure of carbon monoxide in the gas phase, indicating that even at 10 mm Hg it should be possible to obtain 0.01% carbon and 0.003% oxygen in the metal.

Since the dissolved gases are dissolved in the atomic state in iron, the solubilities of nitrogen and hydrogen are proportional to the square root of their partial pressures, i.e., their solubility is much less affected by pressure than is the carbon-oxygen equilibrium. Without stirring, nitrogen and hydrogen are only eliminated at the surface of the bath and the rate is limited by diffusion from the deeper parts of the bath towards the surface. Hydrogen, however, does diffuse faster than nitrogen; but elimination of both is speeded by the evolution of carbon monoxide, which assists diffusion.

For rapid degassing, use of strong deoxidizers must be avoided, at least until after the CO flushing action has been operative. Also, before any vacuum treatment, the slag in contact with the bath must be removed so far as possible.

If slag removal is not possible to the desired extent, the residual slag must be rendered less reactive; e.g., by making it more viscous with burned lime or dolomite.

The experimental apparatus, illustrated in Figure 21, contained a 420 kva transformer, three rotating piston pumps with a capacity of 720 cfm, and a Roots blower with a capacity of 900 cfm. Heat was supplied by use of a carbon resistance heater inside the degassing vessel. Tests were carried out, using glycerine and water (at the same viscosity as steel), which showed that with slow lifting the return metal did not mix with other metal in the ladle but that with fast lifting mixing did occur. Hence, by flow control the degassing process could be regulated. Alloy additions could be made through a vacuum lock when required, followed by up and down cycling of the unit to provide good mixing. The quantity of gas sucked out per 88-ton heat was 1060 cft (10 1/2 cft/ton). Most of the steel treated was 0.22-0.35% carbon steel with lower-than-average phosphorus and sulphur. The off-gas composition by volume was 80% CO, 15% $H_2$, 5% $N_2$, and 1% $CO_2$.

Very little nitrogen was removed. However, removal of nitrogen is not so important when the oxygen content is especially low, since in this case additions of small amounts of nitride formers, Al and Ti, are not lost and can eliminate the deleterious action of nitrogen on aging of steel without formation of harmful $Al_2O_3$ or

$TiO_2$ inclusions.

Vacuum treatment at 1-10 mm Hg of 4.4 tons takes 1 minute and results in considerable frothing. The degassing vessel must therefore be about 6 1/2 feet high to contain the froth.

Agents for the elimination of oxygen and nitrogen, and alloying elements which have a higher affinity for oxygen than iron, are only added after degassing. The process ensures satisfactory mixing.

Sufficient oxygen is removed from the steel by degassing so that it can be cast without rimming action even in the absence of a deoxidant. Final oxygen contents of 0.003 - 0.006% were about 1/3 of the initial values. Vacuum treatment reduced the hydrogen from an average of 7.2 to less than 2.2 ppm; in some cases, as low as 1.2 ppm was obtained. The vacuum vessel must be heated.

Most of the steel produced in the experimental plant was cast into large ingots which were press-forged into crankshafts. In ordinary open hearth steel, deoxidation products and flakes were sometimes formed, but, despite ultrasonic indications at the cogged down stage, it was reported that ingot discontinuities welded up more easily, during hot working of vacuum treated steel, to give clear ultrasonic patterns.

Segregation is lower in vacuum treated than in untreated steel, giving uniform sulphur prints and an absence of fine cracks near segregates and non-metallics after deep etching. The whole of the 150-ton test lot of 0.22%, 0.35%, 0.45% and 0.53% carbon steels was rolled to billets and was then die-forged into difficult shapes without a single reject for flaws or remachining. Occasional bubbles immediately beneath the surface did not lead to reject die-forged parts as they do with untreated open hearth steel. Also, even on heavily forged fly wheels the flash showed no cracks, even at the outermost edge.

The success of this experimental plant led to construction of an open hearth degassing plant having a mechanical pump capacity at 5 mm Hg of 3600 cfm. A 400-kw carbon resistance heater was used. Treatment time for 88 tons is 30 minutes.

A plant was also built in the basic bessemer section which raises and lowers the ladle beneath the vacuum tank to provide 10-minute treatment periods. The pumps for the bessemer plant consist of a Roots blower and water ring pump with a capacity of 9000 cfm. Indirect arc heating supplies up to 3000 kw to the vessel. In the absence of oxygen, the degassing vessel roof can be built of carbon bricks. A 30-ton melt can be heated 30°C (55°F) during the 10-minute treatment. Alloying elements can also be melted into the steel in the vacuum chamber. Carbon has to be added to the steel, since the carbon content of basic converter steel is insufficient to allow removal of oxygen through displacement of the CO equilibrium at the usual bessemer steel carbon level.

Effect of vacuum treatment on steel works operation at Dortmund-Horder carbon steel mill:(13)

Pipette degassing introduces considerable simplification into steel works operation. It is no longer necessary to allow the carbon elimination reaction to die down slowly in heats for which there are special quality specifications. In arc furnace remelting, boiling for degassing of steel or for the easier separation of inclusions is superfluous. The reducing period in the arc furnace can be eliminated if the sulphur content permits.* For carbon steel it is claimed that additions and alloying elements no longer need to be precalcined to protect the steel from intake of hydrogen. The heated degassing vessel is regarded as an arc furnace with high output and refining capability. In refining by top-blowing of oxygen, the use of highly concentrated oxygen is no longer necessary. The oxygen concentration can be based on economic considerations without regard for the nitrogen content.

Fields of application of vacuum steel produced by Dortmund-Horder:

The special feature of this vacuum treated steel is its high degree of purity. This is of special importance in view of the continuous increase in demand for uniformity and freedom from defects of steel supplied to the rolling mills and other processing stages, consequent upon increasing automation.

Deep-drawing sheet and strip which must have surface quality, e.g. for galvanizing, deserve special mention.

*The usual refractory and heating precautions are rigorously maintained by manufacturers of large alloy steel forging ingots.

Vacuum treatment eliminates surface defects resulting from deoxidation products. Since oxygen is removed from the steel with the aid of carbon, considerably less aluminum is required to combine with nitrogen.

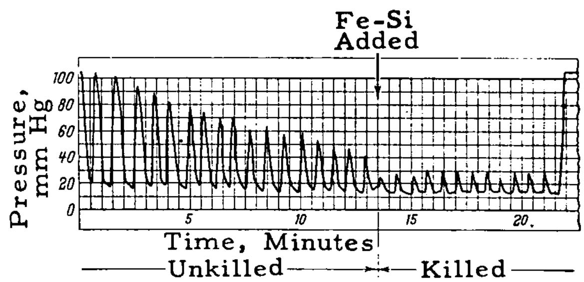
Since reaction with oxygen no longer interferes with the effect of trace elements in vacuum-treated steel, these elements become of enhanced importance for improving the quality of steel. This applies especially to nitride formers.

Another noteworthy feature is the observation, previously made on heavy forgings, that vacuum-treated steel machines more easily than untreated steel.

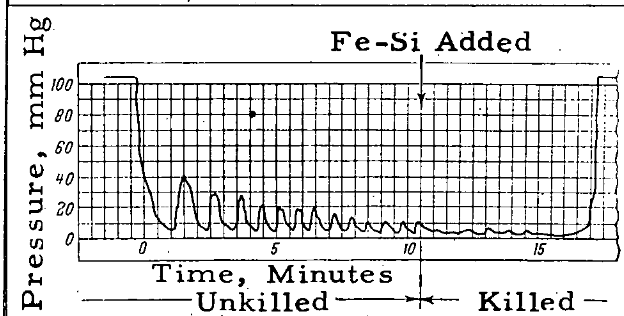
A new field opened up by vacuum treatment is the production of plain and alloyed steels with very low carbon and oxygen contents. The small amount of grain boundary or intergranular substance in vacuum-treated steel means that these steels will be much less subject to intergranular corrosion, and they are especially suitable for surface treatment through metal diffusion, particularly by chromizing.

The process can also be used for the treatment of cast iron or non-ferrous metals.

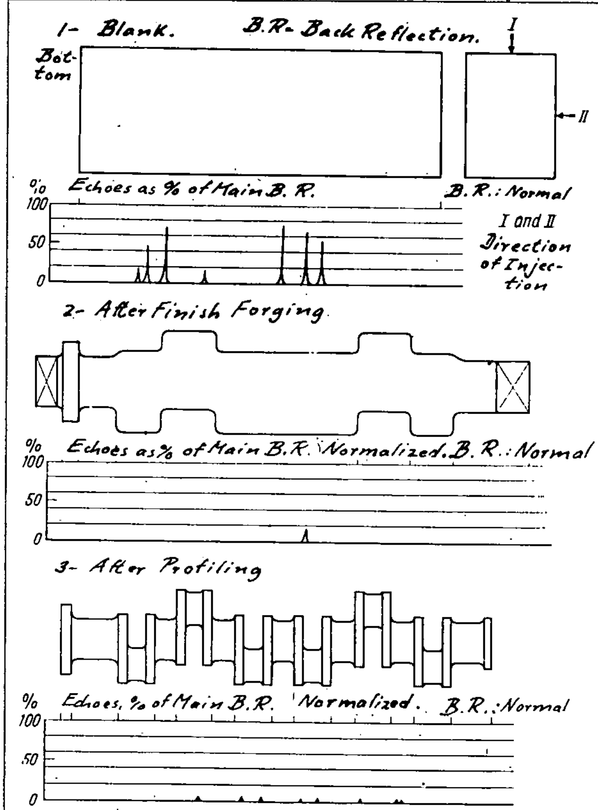
Figure 24 illustrates the pressure records for heats of open hearth steel in the experimental and open hearth plants, and also shows typical ultrasonic patterns taken during the production of crankshafts from degassed steel.




Variation of pressure during vacuum treatment of an 80-ton (88 net ton) open-hearth heat (experimental plant).




Variation of pressure during treatment of a 40-ton heat in the open-hearth installation.




Variation of ultrasound pattern during forging operation.

Figure 24. - Dortmund-Horder pressure data, and results of ultrasonic tests. (13)

(4) Vacuum Pipette Degassing - Method D, Figure 1.

Heraeus-Ruhrstahl has devised the most recent ladle vacuum degassing technique, shown in Figure 1-D. In this method a vacuum tank, operating at 1-2 mm Hg, is placed above the ladle containing molten steel. Two legs dip into the molten steel. An inert gas (argon) is introduced into one leg, reducing the density of the steel, which then sprays upward inside the vacuum tank and is degassed. The denser metal returns to the ladle via the other leg and, because of its higher specific weight, collects at the bottom of the ladle. Meanwhile, other metal sucked up from the upper portion of the ladle is continuously cycled through the vacuum chamber. Temperature drop is small and an induction heater on the return leg can be used to compensate for heat losses. An example of this type of unit, at Henrichshutte of Ruhrstahl A. G., is illustrated in Figure 25.[14]

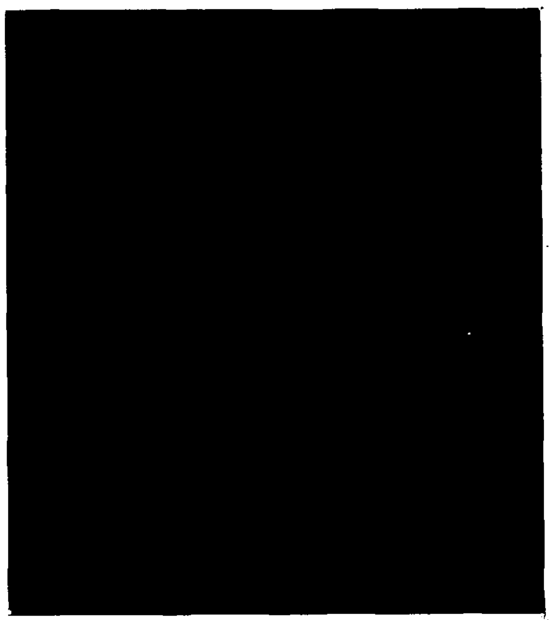
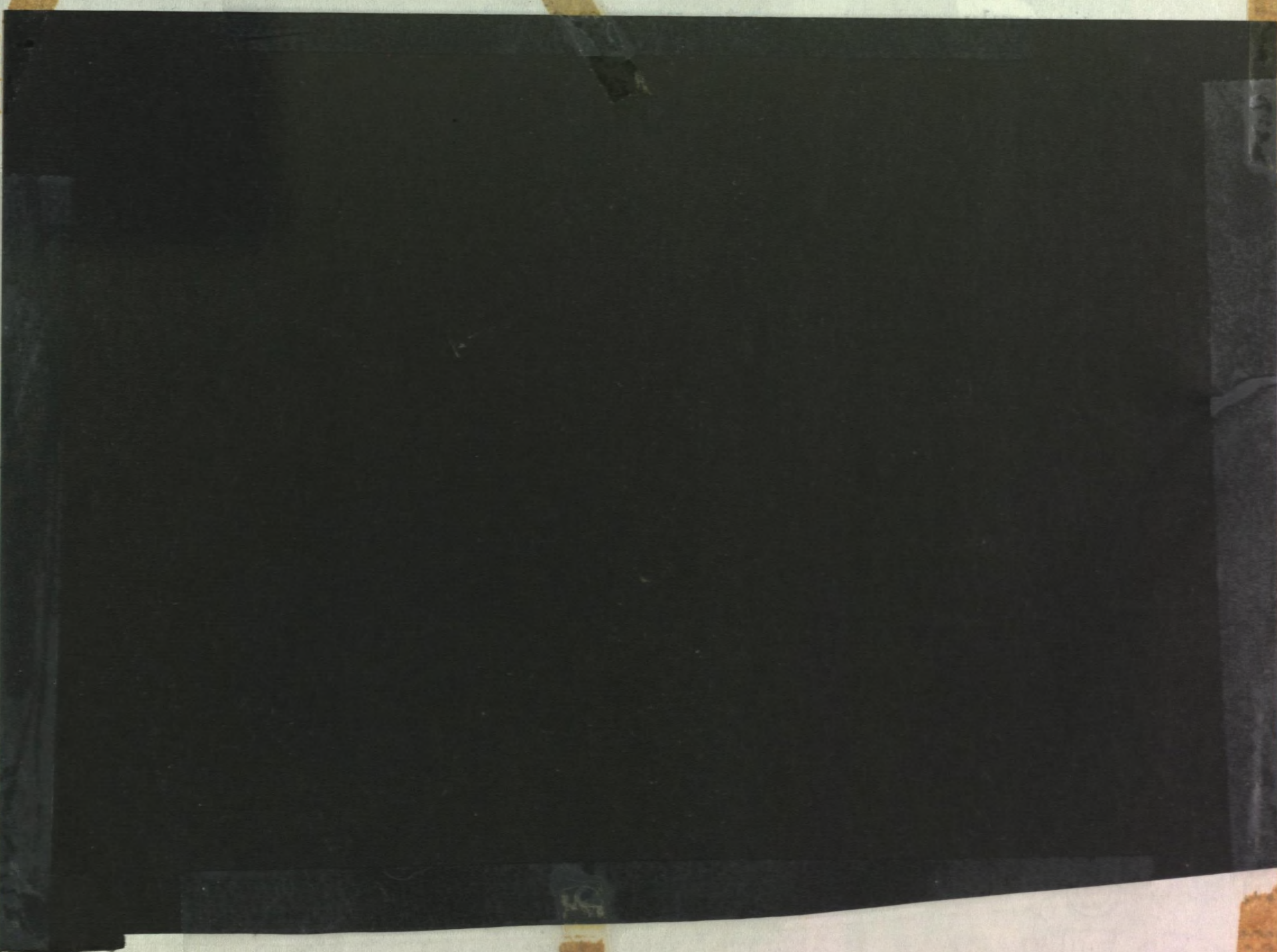


Figure 25. - Vacuum degassing at Henrichshutte, Ruhrstahl A. G.[1][14]

8



top

By this continuous process, 100 tons of steel can be vacuum degassed in the relatively short time of about 15 minutes.

The plant's present production program is concentrated in large forgings, with castings up to 200 tons and medium plates also occupying an important position. Forgings from ingots weighing up to 180 metric tons are in the form of crankshafts, turbine shafts, rotors, back-up rolls for steel rolling mills, wheels, axles, and many other products.

With such a program of heavy forgings, the problem of flaking resulting from contamination by hydrogen and other gases has been of primary concern to the firm and has resulted in a research program largely oriented toward vacuum degassing.

The vacuum-flow steel degassing technique developed at Henrichshütte has now been in commercial operation for over 6 months with apparent success, although operating figures have not yet been released by the firm. Capital costs are quite low.

The apparatus is reportedly capable of bringing the hydrogen, nitrogen and oxygen contents of all types of steel to as low levels as are obtained in vacuum casting techniques. The operation is carried out in normal steel ladles of capacities between 60 and 80 metric tons.

The method is adaptable to all types of carbon steel, rimming and killed, as well as most alloy steels. At Ruhrstahl, it is used both on open hearth and electric furnace steels. In all

top

cases a special effort is made to remove furnace slag, because of its high oxygen content, but with some alloy steels a special slag is made to cover the steel in the ladle during the degassing operation, thereby preventing excessive oxidation.

The degassing operation in the 60 to 80 ton ladles requires from 12 to 15 minutes.

A vacuum of 1-2 mm Hg is maintained in the vacuum container. A cyclone dust catcher is inverted between the container and the vacuum pumps.

Vacuum pumps consist of an initial series of 3 Roots pumps in parallel, with a pumping capacity of 16, 800 cfm. This is followed by a second series of two Roots pumps in parallel with a capacity of 3600 cfm, and one further Roots pump of 600 cfm capacity. The final pump is a water ring pump with an eccentric paddle-wheel type rotor. It has a capacity of 450 cfm and exhausts gases through a pipe into the atmosphere. Continuous gas analysis samples are taken for Orsat analysis.

## MINES BRANCH EXPERIMENTAL STREAM DEGASSING UNIT

This unit has been in operation at the Physical Metallurgy Division laboratories since April, 1958. The pumps and degassing tank are a model 438 stream degassing apparatus built by F. J. Stokes Company. The unit is intended for vacuum treatment of 500-lb steel heats which are melted in a 250 kva, 200 lb/hr direct arc furnace.

The vacuum installation is illustrated in Figure 26.

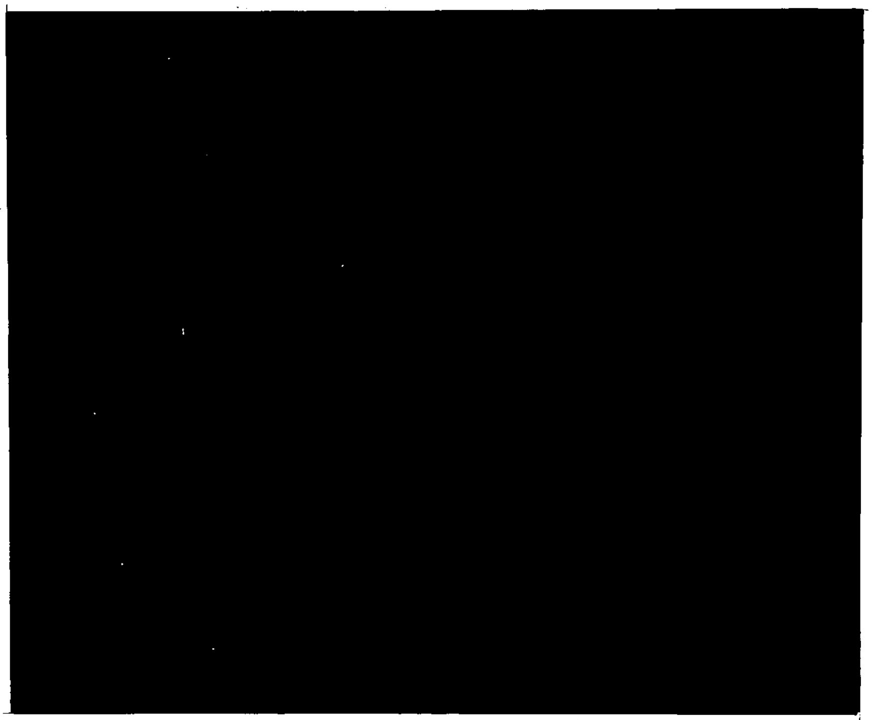


Figure 26. - Experimental vacuum stream degassing unit.

The rotary pump and mechanical blower are visible at the left of Figure 26, with a pneumatic main line vacuum valve shown at the centre of the picture. At the right of centre, the filter is visible, connected to the tank. The tank and ladle are shown at the extreme right of the picture.

In Figure 27, the stream degassing unit is shown during the casting of a 500-lb ingot. A walkway and safety splash plates are shown in position.

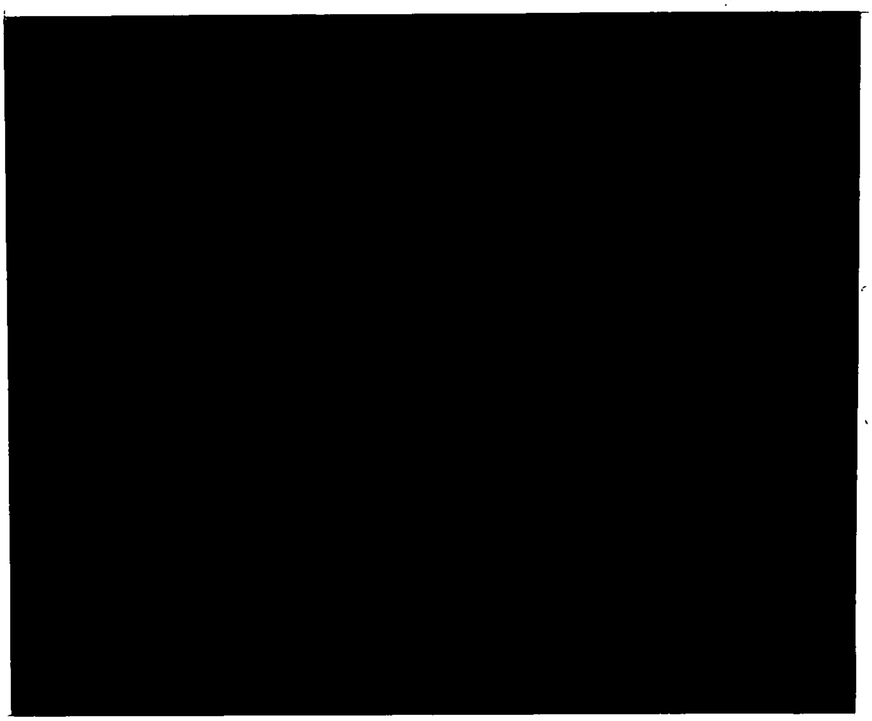


Figure 27. - Vacuum casting a 500-lb ingot at the Mines Branch.

10

The vacuum tank is situated about 20 ft from the direct arc furnace and is serviced by two travelling 3-ton cranes and by a 1 1/2 ton jib crane. The ladle shown at the top of the tank is a 1000-lb commercial bottom-pour type, modified for use with the degassing unit. In tests up to this time, the metal has been tapped into this ladle which was then placed in position above the tank for vacuum pouring. The integrated pump speed of this unit from atmosphere to 1 mm is 500 cfm, and with a system volume of 76 cft, pump down of the system without refractory lining is accomplished in 1.2 minutes. Inleak rate of the empty tank was 30 microns/hour measured at 10 microns. The large "hogging capacity" is necessary when ladle degassing tests are carried out. In this instance, with 500 pounds of molten steel the ladle must be sealed in the tank; pump down, degassing, and air pouring must be accomplished in 10 minutes. However, in all other circumstances time is available for routine pouring of ingot moulds or sand castings held inside the tank. Blank-off pressures of the tank, of the order of 35 microns, are obtained before the ladle is sealed on top of the tank. Inleak rates of the order of 4 microns/minute, measured at 50 microns, are obtained prior to spray pouring. Initial vacuums of 500-600 microns are obtained after the ladle and steel are sealed above the tank. Operating pressures during the actual pour increase to between 3 and 10 mm, depending on pouring rate (nozzle size) and on refractory practice. With nozzle openings varying between 1 1/2 inches and 1/2 inch, and pouring rates of 1/4 ton per minute, final sinkhead hydrogen contents of 1.1 to 1.9 ppm are obtained. It is expected that, for killed steel, attention to ladle refractories, nozzle and stopper seals should enable lower operating pressures to be maintained during ingot pouring.

Spray angles of at least 60° are obtained during spray casting of ingots and castings.

## Detailed Description of Equipment

### General

The unit is specifically designed to degas nominal charges of 500 lb of steel. Absolute operational level of vacuum is intended to be at least 500 microns; however, this vacuum depends on alloy composition, deoxidation, refractory and mould techniques, and upon the drying measures taken prior to degassing.

The unit consists of a single degassing chamber with special rupture disc and ladle support seal, integral with its head; a vacuum pumping manifold, complete with filter and high vacuum valve; and a Stokes model 170-5 mechanical booster blower pump, together with controls and instrumentation.

Depending on the available ladle and mould configurations used, the equipment can be operated for larger heats if so desired.

### Degassing Chamber

The degassing chamber is a 2-piece carbon steel tank having an outside diameter of 48 inches. This tank, oriented with its long axis vertical, has flanged and dished heads on either end, with the main seal flange being located 5 ft 9 inches above the floor level. The lower dished portion of the tank is filled with rammed magnesia and a single course of firebrick is used at the floor line to prevent any possible damage to the tank caused by an inadvertent run-out or by excessive reaction. About 15 inches free fall is provided above the hot top, at present, but by removal of stools or use of a squat ingot mould this drop distance can be increased considerably. Because of the 60° spray which occurs when metal enters the vacuum, it is necessary to use a refractory funnel above the ingot mould hot top.

The base section of the degassing tank contains a 10-inch-diameter vacuum pumping nozzle; two 4-inch-diameter vacuum reserve ports equipped with a 4-wire, high vacuum instrumentation lead-through; a 1-inch-diameter vacuum instrumentation connection; and a machine-grooved "O" - ring seal flange.

The cover section contains a machined flange to mate with the "O" - ring surface; a completely water-jacketed head for the protection of the seals; and a 1-inch-diameter, intermediate ladle volume, by-pass line, with a remotely operated valve. A removable 8-inch-diameter rupture disc assembly, an intermediate ladle support with a flanged and machined "O" - ring groove, and a $5\frac{1}{4}$-inch-diameter sheltered sight glass are also included in the cover assembly.

Vacuum Manifold and Filter

Connected directly to the 10-inch-diameter vacuum nozzle by means of a 2-ft-long spool piece (so as to remove valve and pumping unit from the critical molten metal area), is a cylindrical filter chamber, fabricated of mild steel, 24 inches in diameter and having an approximate height of 30 inches. This filter chamber is equipped with an "O"- ring seal and removable flange cover, to afford opportunities for cleaning. A single full height and width, stainless steel, screen baffle is located in the maximum cross-section position of this chamber, to prevent the carry-over of damaging metallic particles. No attempt is made to filter out the smaller dust-size particles, since such a filter would result in a prohibitive loss of pumping efficiency.

Extending from the filter chamber is a 3-inch-diameter, manually operated, vacuum break valve, located on the pump side to permit any air-blasting to be in the reverse direction of the filter. Argon is also fed in this aperture when required. Located on the pump side of the filter is a 10-inch-diameter nozzle, extending to and including a 10-inch-diameter, pneumatically operated, high vacuum gate valve which effects isolation of the chamber from the vacuum pump and allows determination of the inleak rate.

Vacuum Pump

The unit is evacuated with one standard Stokes 170 - 5 mechanical blower pump, rated at 1400 cfm. The speed curve for this pump is illustrated in Figure 28, to show the very large "hogging" ability of this unit.

The pump consists of a complete blower unit capable of 1480 cfm free air displacement at 3100 rpm. Its discharge is equipped with a large-diameter poppet valve. The blower unit is driven by a special, high-slip, constant torque, variable-speed drive motor rated at 550 v, 60 ~ 3 $\phi$. This special Stokes motor is capable of sustaining power outputs of up to 60 hp (corresponding to 20 mm vacuum) for a maximum period of 7 minutes without overheating. The normal motor rating is 15 hp. It is completely equipped with internal protection devices and thermoguards. By use of this special motor, providing outstandingly high pumping capacity, it is possible to obtain an average integrated pumping speed from atmosphere to 1 mm of 500 cfm.

This is accomplished by pumping directly through the blower and exhausting through the poppet relief valve from 760 mm down to 525 mm at speeds much in excess of the capacity of the rotary, oil-sealed mechanical vacuum pump (130 cfm). At the 525 mm point, the poppet valve automatically closes because of the pressure balance within the interstage manifold. This feature completely eliminates any vacuum by-pass manifolding, its valving and controls, together with the necessity of valving sequencing and maintenance, and results in a direct connected vacuum manifold of short-run and high efficiency.

Considering the operation of the blower pump: As soon as

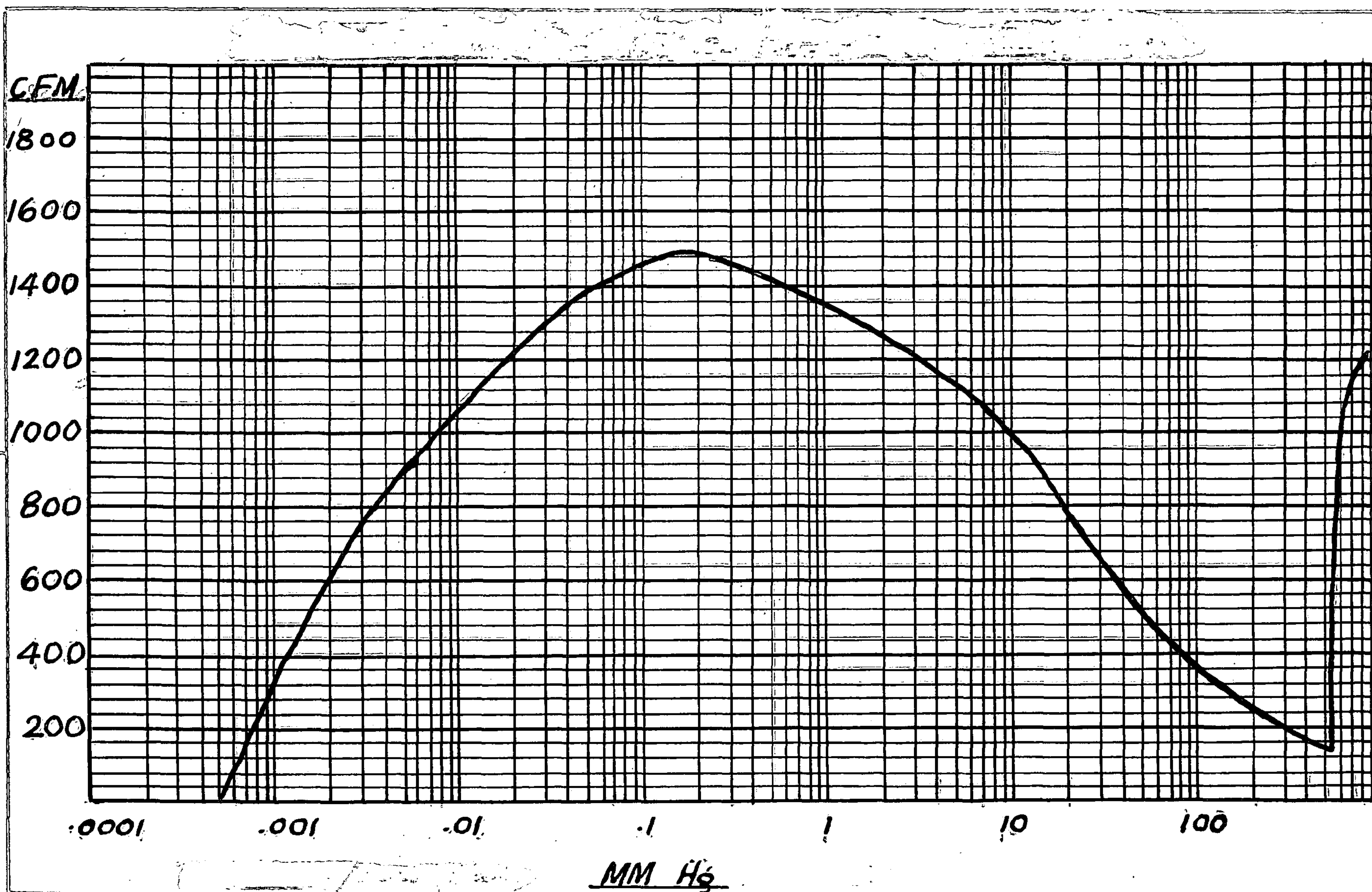



Figure 128. Pumping speed, Mines Branch degassing unit.

the degassing chamber load is thrown on it, the blower pump, which has previously been idling at full speed, slows down to the order of 700 rpm, at which speed maximum torque is developed. As the compression effort in the blower pump is reduced per cubic foot of gas handled, the constant torque motor speeds up, handling a larger amount of gas. This relationship continues constantly throughout the pump down cycle, with the poppet valve closing at 525 mm, after which the power input of the backing pump also becomes effective. The constant torque, variable speed power output characteristic of the motor continues, with the output of the motor decreasing to the order of 15 hp at 20 mm. The speed of the blower continues to rise until the peak speed is reached somewhat below 1 mm. Finally, the speed output of the unit becomes limited below 100 microns, because of the flow characteristics of the raw rarefied gas being handled. (Note that the unit has this very high pumping speed, not only in the several hundred mm area, when pressure release is obtained by means of the poppet valve, but also in the 10 mm to 100 mm vacuum range, wherein the high power input of the special motor can be utilized. One of the unique advantages of this unit is its stepless performance which requires no control sequencing or attention.)

The backing pump on this unit is a standard Stokes model 212 G microvac pump rated at 130 cfm, free air displacement. This pump is driven by a 5-hp polyphase motor and is equipped with an oil injection, gas-ballasting feature.

Two Stokes thermopile gauges, calibrated against alphatron and McLeod gauges and having ranges 100 to 20,000 microns and 1 to 1000 microns respectively, were used for pressure readings.

## RESULTS

Preliminary test results have been obtained on twenty melts where metal, prepared in a 250 kva, 200 lb/hr direct-arc furnace by double-slag basic practice, was degassed by the stream droplet method at pressures of 4 to 10 mm.

Comparison of the hydrogen, oxygen and nitrogen contents of melts before and after degassing and of air cast versus vacuum cast melts was made.

Four other melts were treated by ladle degassing the metal, held in the ladle, inside the vacuum chamber.

Six groups of melts are discussed, as follows:

(1) Carbon steel slab castings (moulds held inside the vacuum tank).

(2) Carbon steel - 500-lb ingots.

(3) Cr-Mo-V - 500-lb ingots, "MM" composition.

(4) Cr-Mo-V - 500-lb ingots, "MU" composition.

(5) Cr-Mo-V - 500-lb ingots, modified "MU" composition. ("MUX")

(6) Ladle degassed, carbon steel, slab castings (moulds poured in air).

(1) Carbon Steel Slab Castings

For these tests, carbon steel was spray cast into the vacuum tank through an 18-inch-diameter funnel, which guided the degassed metal into the riser of a dry-sand, slab mould casting having the dimensions shown in Figure 29. Previous work[15] had shown that this casting was susceptible to loss of tensile ductility at the centre of heavy sections when melting and casting were carried out in air to obtain normal hydrogen levels of 3 to 4 ppm.

Hydrogen samples taken from the risers of castings prepared by air casting gave average initial hydrogen contents of 3.6 ppm; and, after vacuum casting, average final hydrogen contents of 1.5 ppm were obtained for a reduction of about 60% in hydrogen content. Reductions in oxygen content from about 90 ppm to about 40 ppm were obtained on two preliminary tests. Some reduction of nitrogen content was usually obtained in these carbon steel slab castings. Possibly the oxygen and nitrogen reductions resulted from the rolling action (CO evolution) which took place in the mould after vacuum stream degassing.

Sections through the castings were examined, in the air cast and in the vacuum cast slabs, by radiography and deep etching, and this examination indicated some improvement in soundness and cleanliness at the centre of the vacuum cast samples.

The tensile ductility, measured at the centre of the slab casting, is considerably better than that of air cast samples unless the latter are subjected to dehydrogenizing heat treatment.

Comparative results of gas analyses made on air cast and on vacuum cast carbon steel slabs are shown in Figure 31 for individual melts. Averaged results are shown, item (1), in Figure 33.

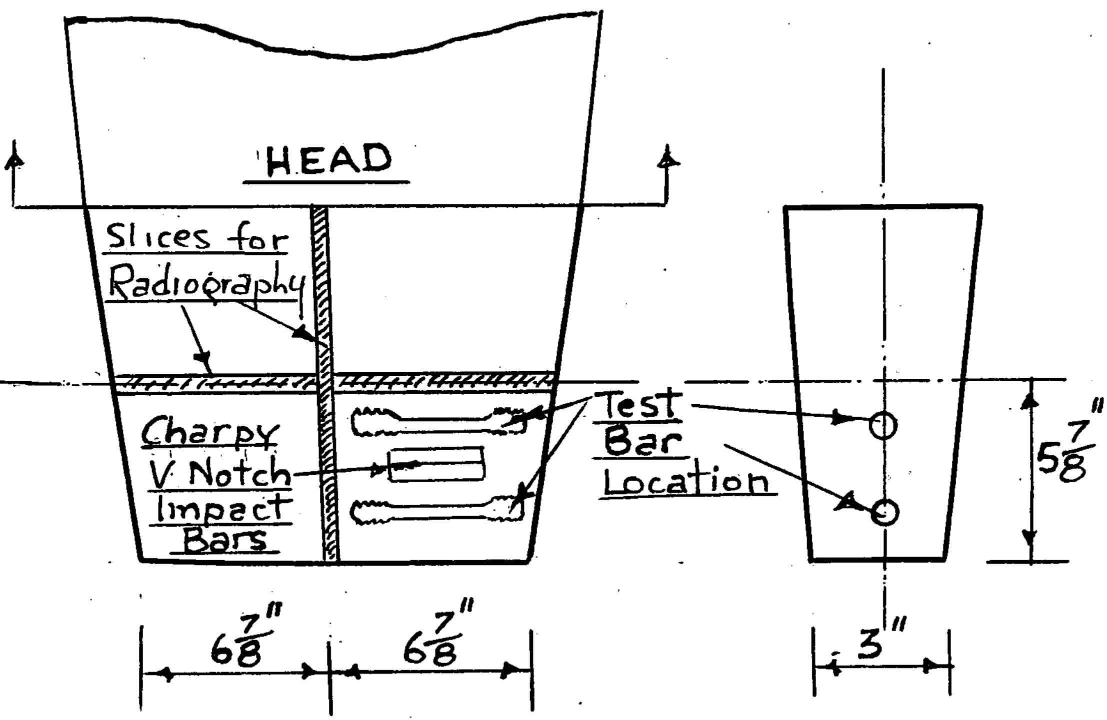



Figure 29. - Dry-sand slab casting.

## (2)(3)(4)(5) Vacuum Stream Degassed 500-lb Ingots

Carbon steel ingots of approximate AISI 1030 composition (2), and three Cr-Mo-V forging compositions (3)(4)(5), were spray cast in the vacuum tank, through the collecting funnel, and into a 500-lb ingot mould. Hydrogen samples were taken during melting and immediately before vacuum casting. Hydrogen samples after vacuum degassing were obtained from the sinkhead. All hydrogen samples were taken by the pin tube and liquid nitrogen method.

The 500-lb ingot and distribution of material are shown in Figure 30. Blocks B, C and D from each ingot were forged to 2 1/2" x 2 1/2" section and were then rolled to give bar sections of 1 1/2" x 2 1/4" for testing. The forging axis coincided with the mid-radius position of the ingot.

For AISI 1030 carbon steel ingots, average initial hydrogen contents of 3.5 ppm were reduced to 1.8 ppm (average) by vacuum stream casting at 4 to 10 mm Hg. Similar hydrogen reductions of the order of 50% were also obtained for the Cr-Mo-V 500-lb forging ingots. The comparative gas results for individual air and vacuum cast ingots are shown in Figures 31 and 32. Averaged gas results are shown in Figure 33 for the carbon steel (2) and for the three compositions Cr-Mo-V (3)(4)(5).

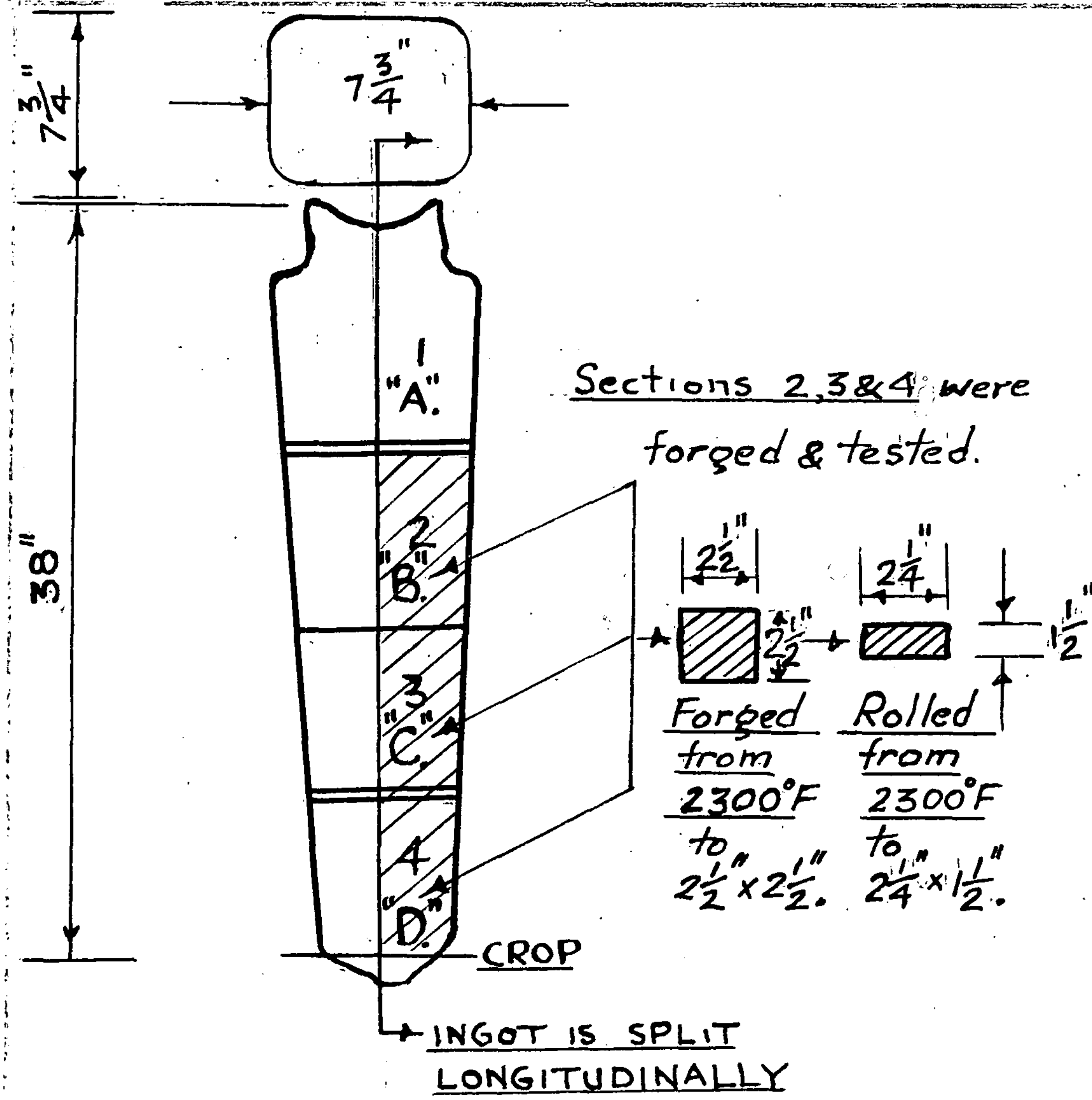



Figure 30. - 500-lb ingot used for vacuum tests.

The chemical composition of the test melts is shown in Table 3. One melt in each of the groups 1 to 4 was cast in air in the conventional manner to provide an air cast standard. In addition, in some melts of each group, 50 pounds of metal was air cast into test coupons prior to vacuum casting the 500-lb ingot.

The record of hydrogen analyses made throughout melting, and the final hydrogen contents, together with the operating pressure, are shown in Table 4.

Some available oxygen and nitrogen determinations made on air cast and vacuum cast test melts are shown in Table 5.

The results of tensile and Charpy V notch impact tests on carbon steel melts, groups 1 and 2, are shown in Tables 6 and 7.

The gas contents of all the melts are shown in Figures 31 to 33, inclusive. Averaged gas results are shown in the lower half of Figure 33.

# TABLE 3

Chemical Composition of Mines Branch Melts

| Code Number | Melt Number | Percent C | Mn | Si | S | P | Cr | Mo | V | Casting Medium | Product |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | | | | | | | | | | | |
| Carbon Steel | 1120 | .28 | .64 | .46 | .020 | .011 | | | | Air | Casting |
| Slab Castings | 1144 | .28 | .74 | .36 | .019 | .018 | | | | Vacuum | Casting |
| (mould in | 1152 | .27 | .70 | .35 | .020 | .020 | | | | Vacuum | Casting |
| tank) | 1183 | .39 | .80 | .60 | .020 | .019 | | | | Air and Vacuum | Casting |
| (2) | | | | | | | | | | | |
| Carbon | 1172 | .27 | .75 | .37 | .023 | .019 | | | | Air | Ingot |
| Steel | 1126 | .32 | .81 | .44 | .015 | .013 | | | | Vacuum | Ingot |
| Ingots, | 1170 | .26 | .77 | .32 | .030 | .026 | | | | Vacuum | Ingot |
| 500 lb | 1198 | .25 | .88 | .09 | .022 | .022 | | | | Air and Vacuum | Ingot |
| (3) | | | | | | | | | | | |
| Cr-Mo-V | 1179 | .28 | .85 | .50 | .018 | .011 | 1.83 | .75 | .51 | Air | Ingot |
| 500-lb | 1137 | .27 | .86 | .20 | .012 | .014 | 1.38 | .58 | .34 | Vacuum | Ingot |
| Ingots | 1174 | .31 | .90 | .93 | .023 | .019 | 1.81 | .58 | .47 | Vacuum | Ingot |
| ("MM") | 1187 | .28 | .98 | .56 | .019 | .032 | 1.71 | .73 | .42 | Air and Vacuum | Ingot |
| (4) | | | | | | | | | | | |
| Cr-Mo-V | 1182 | .25 | 1.07 | .29 | .017 | .011 | .71 | 1.32 | 1.10 | Air | Ingot |
| 500-lb | 1157 | .24 | .98 | .17 | .013 | .013 | .86 | .70 | .93 | Vacuum | Ingot |
| Ingots | 1162 | .32 | 1.05 | .21 | — | — | 1.37 | 1.30 | .90 | Vacuum | Ingot |
| ("MU") | 1190 | .26 | 1.05 | .27 | .029 | .007 | 1.23 | 1.22 | 1.03 | Air and Vacuum | Ingot |
| (5) | | | | | | | | | | | |
| Cr-Mo-V | 1146 | .30 | 1.10 | .28 | .015 | .018 | .94 | 1.17 | .33 | Vacuum | Ingot |
| 500-lb | 1156 | .19 | .85 | .02 | .090 | .012 | 1.22 | 1.24 | .98 | Air (Ingot) | 100 lb |
| Ingots | 1167 | .37 | 1.21 | .13 | .016 | .009 | 1.23 | 1.17 | .98 | Air | Ingot |
| ("MUX") | 1180 | .31 | 1.00 | .42 | .018 | .011 | 1.05 | 1.12 | 1.14 | Core Oil and Vacuum | Ingot |
| (6) | | | | | | | | | | | |
| Carbon Steel | 1099 | .42 | .83 | .60 | .015 | .018 | | | | Ladle Vacuum | Casting |
| Slab Castings | 1103 | .27 | .63 | .36 | .018 | .024 | | | | Ladle Vacuum | Casting |
| (ladle degassed, | 1109 | .24 | .76 | .42 | .021 | .023 | | | | Ladle Vacuum | Casting |
| mould poured in air) | 1112 | .33 | .81 | .52 | .024 | .026 | | | | Ladle Vacuum | Casting |

TABLE 4

Hydrogen Contents

(1) Carbon Steel Slab Castings

| Melt No. | Hydrogen Content, ppm x $10^{-4}$ | | | | | Lowest Pressure | Highest Pressure | Average Pressure |
|---|---|---|---|---|---|---|---|---|
| | End of boil | Tap | Ladle | Riser | | | | |
| 1120 | .00025 | .00035 | .00037 | .00043 | Air | 760 mm | 760 mm | 760 mm |
| 1144 | .00026 | .00033 | .00037 | .00014 | Vac | 1.7 mm | 7 mm | 5 mm |
| 1152 | .00018 | -- | .00019 | -- | Vac | 1.4 mm | 10+ mm | 7 mm |
| 1183 | .00032 | .00034 | .00031 | .00019 | Vac | 700 microns | 9 mm | 7 mm |
| + 1201 | .00018 | .00022 | .00033 | .00012 | Vac | 2.2 mm | 10 mm | 7 mm |
| (2) Carbon Steel 500-lb Ingots | | | | | | | | |
| 1172 | -- | .00047 | .00034 | -- | Air | 760 mm | 760 mm | 760 mm |
| 1126 | -- | .00032 | .00038 | -- | Vac | N.D. | N.D. | N.D. |
| 1170 | .00021 | .00031 | .00035 | .00020 | Vac | 4 mm | 8.5 mm | 6 mm |
| 1198 | .00018 | .00027 | .00034 | .00016 | Vac | 700 microns | 6 mm | 5 mm |
| (3) Cr-Mo-V "MM" Composition 500-lb Ingots | | | | | | | | |
| *1179 | -- | .00063 | .00140 | .00091 | Air | 760 mm | 760 mm | 760 mm |
| 1137 | .00049 | .00059 | .00059 | -- | Vac | 3.8 mm | 15 mm | 12 mm |
| **1174 | .00045 | .00063 | .00120 | -- | Vac | 1.3 mm | 12 mm | 10 mm |
| 1187 | .00030 | .00034 | -- | .00019 | Vac | 700 microns | 8 mm | 6 mm |
| (4) Cr-Mo-V "MU" Composition 500-lb Ingots | | | | | | | | |
| 1182 | .00036 | .00037 | .00040 | .00044 | Air | 760 mm | 760 mm | 760 mm |
| 1157 | .00031 | .00028 | .00031 | .00013 | Vac | 1.25 mm | 15 mm | 5 mm |
| 1162 | .0003 | -- | -- | -- | Vac | 1.6 mm | 15 mm | 6 mm |
| 1190 | .00034 | .00042 | .00034 | .00024 | Vac | 1.35 mm | 8 mm | 7 mm |
| (5) Modified "MU" Composition 500-lb Ingots ("MUX") | | | | | | | | |
| 1146 | .00024 | .00032 | .00035 | .00011 | Vac | 1.75 mm | -- | -- |
| 1156 | -- | -- | -- | -- | Air | 760 mm | 760 mm | 760 mm |
| 1167 | .00031 | .00036 | .00030 | .00036 | Air | 760 mm | 760 mm | 760 mm |
| ***1180 | .00038 | .00049 | .00054 | .00061 | Oilfumes | 600 microns | 100+ mm | 100+ mm |
| (6) Ladle Degassed Carbon Steel Slab Castings | | | | | | | | |
| | End of boil | Ladle before | Ladle after | Riser | | | | |
| 1099 | .00026 | .00029 | -- | .00019 | Vac | -- | -- | 5 mm |
| 1103 | .00021 | .00036 | .00015 | .00018 | Vac | 5 mm | 4 mm | 3 mm |
| 1109 | .00023 | .00034 | .00020 | -- | Vac | 4 mm | -- | 8 mm |
| 1112 | .00050 | .00040 | .00017 | .00041 | Vac | 4 mm | -- | -- |

+ Only gas result available; therefore melt No. 1201 is only included in Table 4.

* Excessive holding time (10 minutes) before tapping.

** Last heat on thin shell. Slow melt.

*** Core sand funnel - soot and oil fumes.

TABLE 5

Vacuum Fusion and Kjeldahl Gas Contents (%)

| (Melt) No. | | Pressure (Av.) During Casting | Kjeldahl Nitrogen, Wt. % | Vacuum Fusion, Nitrogen, Wt% | Vacuum Fusion, Oxygen, Wt. % |
|---|---|---|---|---|---|
| Std. | 1120 | 760 mm | .011 | .009 | .009 |
| | 1144 | 5 mm | | .006 | .004 |
| | 1152 | 7 mm | .007 | | |
| | 1183 | 7 mm | .010 | .006/.006# | .010/.004# |
| *KB | 1201 | 760 mm | | | |
| | 1201 | 7 mm | | | |
| Std. | 1172 | 760 mm | | .008 | .006 |
| | 1126 | -- | .006 | | |
| | 1170 | 6 mm | | .005 | .006 |
| *KB | 1198 | 760 mm | | | |
| | 1198 | | | | |
| *Std. | 1179 | 760 mm | .006 | .006 | .005 |
| | 1137 | 12 mm | | | |
| | 1174 | 10 mm | .007 | | |
| *KB | 1187 | 760 mm | | .006 | .007 |
| | 1187 | 6 mm | | .005 | .004 |
| Std | 1182 | 760 mm | .006 | .010 | .008 |
| | 1157 | 5 mm | .007 | | |
| | 1162 | 6 mm | .008 | | |
| *KB | 1190 | 760 mm | | .006 | .010 |
| | 1190 | 7 mm | | .006 | .004 |
| | 1146 | -- | .004 | | |
| | 1156 | 760 mm | | | |
| | 1167 | 760 mm | | | |
| * | 1180 | 100+ mm | .009 | | |
| | 1099 | | .014 | | |
| | 1103 | | .009 | | |
| | 1109 | | .008 | | |
| | 1112 | | .007 | | |

* Core oil in sand.
KB - Air cast 50-lb test coupon.

#Note: The .006/.006 refers to composition before and after degassing, respectively. Similarly, .010/.004.

## TABLE 6

**(a)** Tensile and Impact Properties of Carbon Steel Slabs (1) *

| Tensile Bar Code No. | Casting Medium | U.T.S., psi | Yield Point, psi | % Elong 4D | % RA |
|---|---|---|---|---|---|
| 1120 A - 4 | Air | 73,400 | 48,200 | 21.0 | 25.1 |
| 1120 B - 4 | Air | 70,600 | 45,800 | 14.0 | 22.9 |
| 1144 A - 4 | Vac | 74,300 | 47,900 | 33.0 | 44.9 |
| 1144 B - 4 | Vac | 74,100 | 46,900 | 34.0 | 50.8 |
| 1152 A - 4 | Vac | 80,000 | 48,300 | 27.0 | 40.8 |
| 1152 B - 4 | Vac | 79,300 | 49,600 | 27.0 | 40.8 |

Normalized - 1650°F. Drawn - 2 hr 1250°F.

* Centre of three-inch section.

**(b)** Room Temperature Charpy V Notch Impact Strength (ft-lb)

| Bar No. | 1120 (Air) | 1144 (Vac) | 1152 (Vac) |
|---|---|---|---|
| 1 | 30 | 42 | 33 |
| 2 | 29 | 40 | 31 |
| 3 | 26 | 40 | 33 |
| 4 | 36 | 44 | 32 |
| 5 | 29 | 31 | 33 |

TABLE 7

(a) Tensile and Impact Properties of Carbon Steel 500-lb Ingots (2) *

| Tensile Bar Code No. | Casting Medium | U.T.S., psi | Yield Point, psi | % Elong 4D | % RA |
|---|---|---|---|---|---|
| 1172-1 - 4 | Air | 79,800 | 50,500 | 33.5 | 61.8 |
| 1172-2 - 4 | Air | 79,300 | 51,200 | 35.5 | 63.0 |
| 1172-3 - 4 | Air | 79,900 | 50,900 | 34.0 | 62.1 |
| 1126-1 - 4 | Vac | 78,000 | 48,900 | 36.0 | 61.8 |
| 1126-2 - 4 | Vac | 78,200 | 49,800 | 36.0 | 61.8 |
| 1126-3 - 4 | Vac | 77,900 | 48,700 | 36.0 | 61.8 |
| 1170-1 - 4 | Vac | 74,900 | 49,400 | 36.0 | 65.2 |
| 1170-2 - 4 | Vac | 73,800 | 49,600 | 36.0 | 65.8 |
| 1170-3 - 4 | Vac | 74,400 | 50,400 | 36.0 | 66.1 |

* Forged, rolled, normalized 1650°F; drawn 2 hr 1250°F.

(b) Room Temperature Charpy V Notch Impact Strength (ft-lb)

| Bar No. | 1172 (Air) | 1126 (Vac) | 1170 (Vac) |
|---|---|---|---|
| 1 | 47 | 53 | 84 |
| 2 | 49 | 50 | 78 |
| 3 | 47 | 54 | 92 |
| 4 | 47 | 54 | 100 |
| 5 | 45 | 46 | 64 |

SUMMARY OF PRELIMINARY RESULTS

The preliminary results of vacuum stream degassing tests at the Mines Branch show hydrogen reductions to 1.5-1.9 ppm average, from 3.6-3.4 ppm initial content (60% to 45% reduction).

Oxygen and nitrogen reductions from 90 ppm and 80 ppm to 40 ppm and 70 ppm, for reductions of 55% and 12% respectively, were obtained on the carbon steel slab tests.

Oxygen and nitrogen reductions from 60 ppm and 75 ppm to 40 ppm and 60 ppm, for reductions of 33% and 20% respectively, were obtained for the carbon steel ingots.

In the Cr-Mo-V composition "MM", there was a slight reduction in oxygen content but no reduction in nitrogen. However, in the Cr-Mo-V composition "MU" a significant decrease in oxygen and a slight reduction in nitrogen content were obtained. Additional tests will be required to confirm the oxygen and nitrogen results on Cr-Mo-V steels. Possibly, reduction of oxygen and nitrogen content can be increased by operating at lower pressures, by deoxidizing only with ferrosilicon before vacuum casting, and by holding the ingot under vacuum for 30-45 sec before restoring atmospheric pressure for solidification.

Tensile tests obtained on normalized and drawn test bars cut from the centre section of the carbon steel slab castings, air cast versus vacuum cast, showed a definite improvement in tensile ductility to a level only obtained in air-cast bars after a dehydrogenizing heat treatment.

At this time there are not sufficient tests available to make any definite conclusion about the tensile properties and impact strength of the other groups of steels.

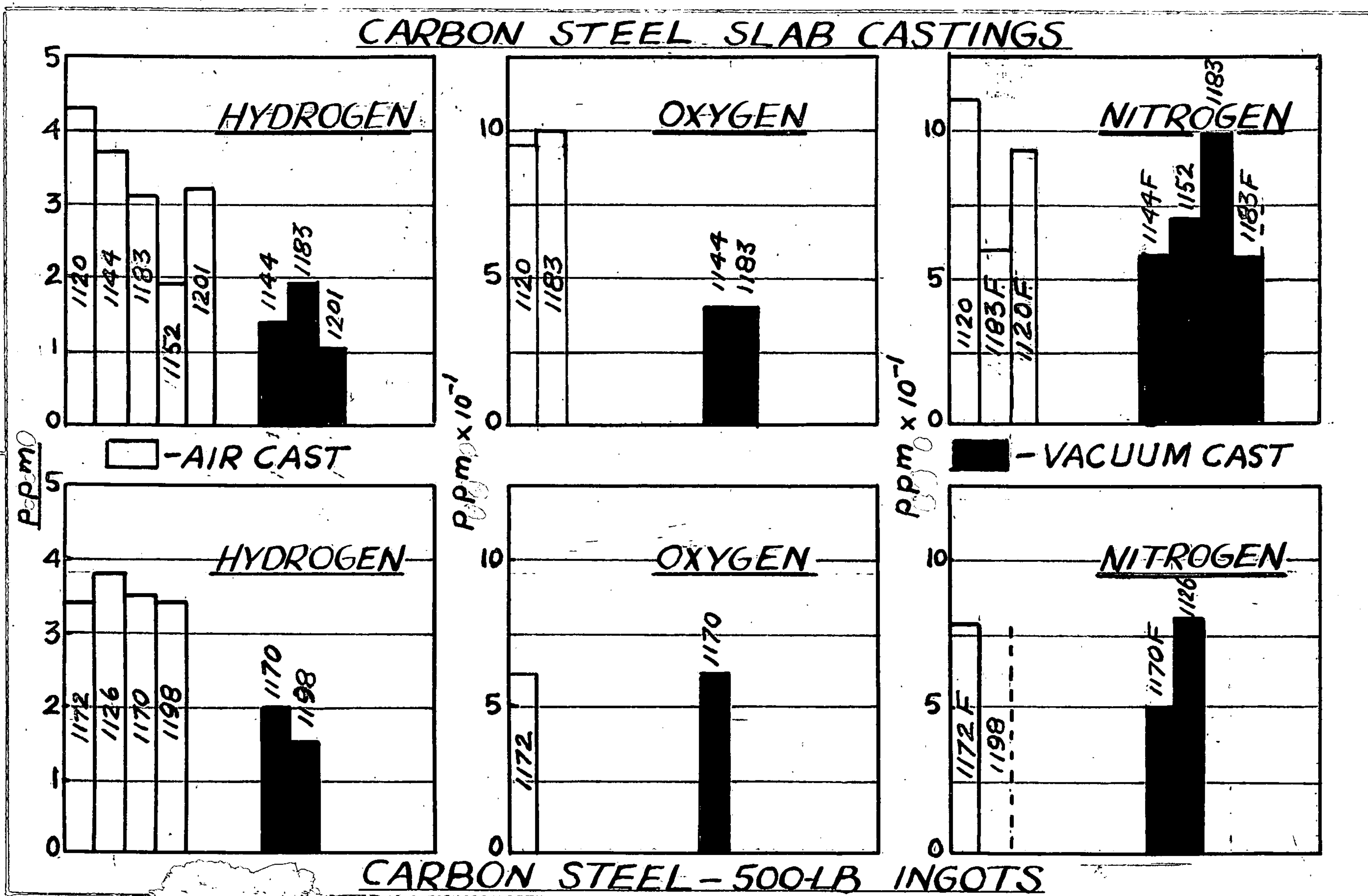



Figure 31. - Hydrogen, oxygen and nitrogen contents of carbon steel slab castings and carbon steel 500-lb ingots (air cast vs. vacuum cast). The melt numbers are shown on the bar graphs. The suffix "F" after the melt number denotes a vacuum fusion nitrogen analysis.

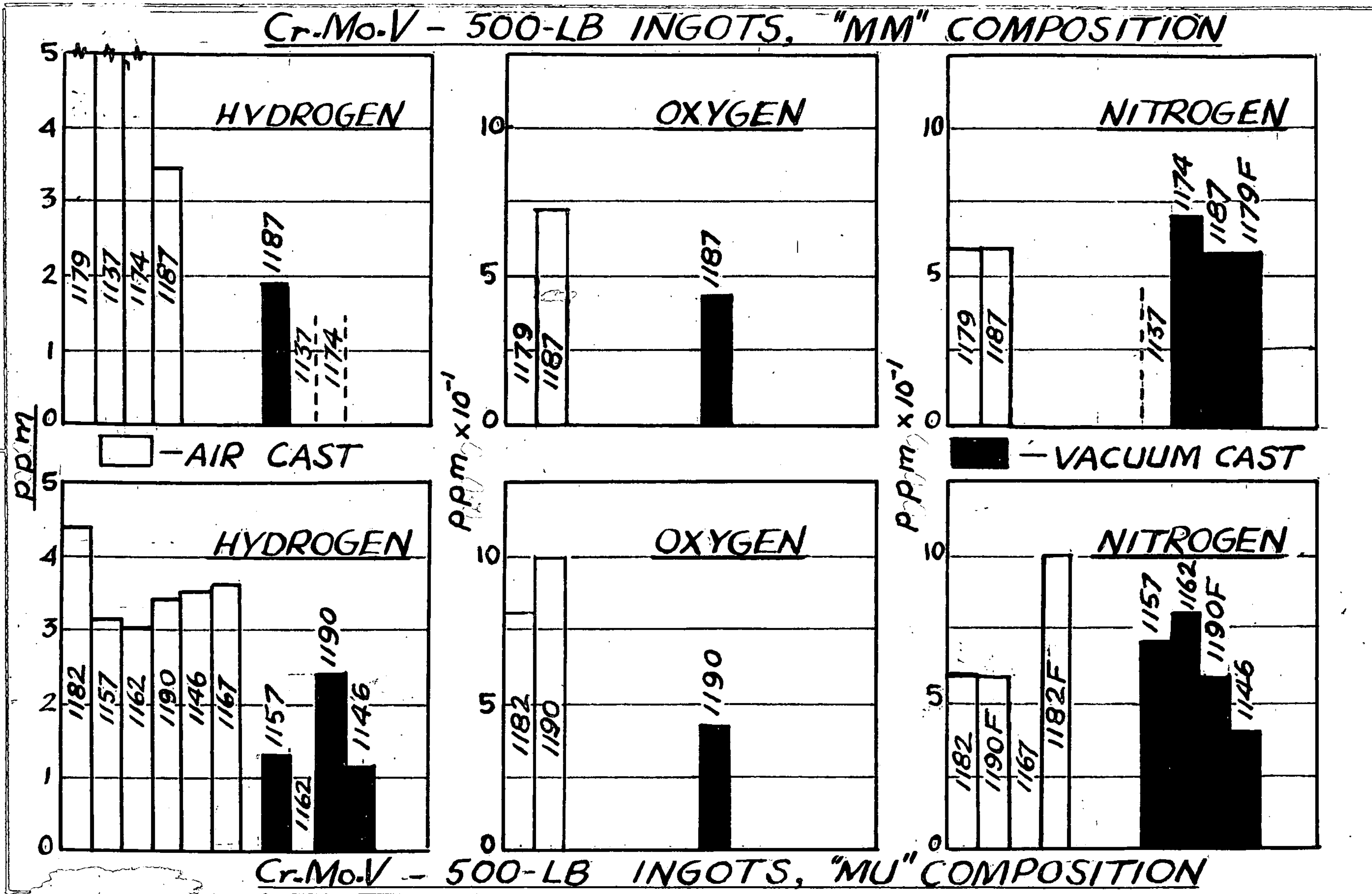







Figure 32. - Hydrogen, oxygen and nitrogen contents of Cr-Mo-V 500-lb ingots, "MM" and "MU" compositions (air cast vs. vacuum cast).

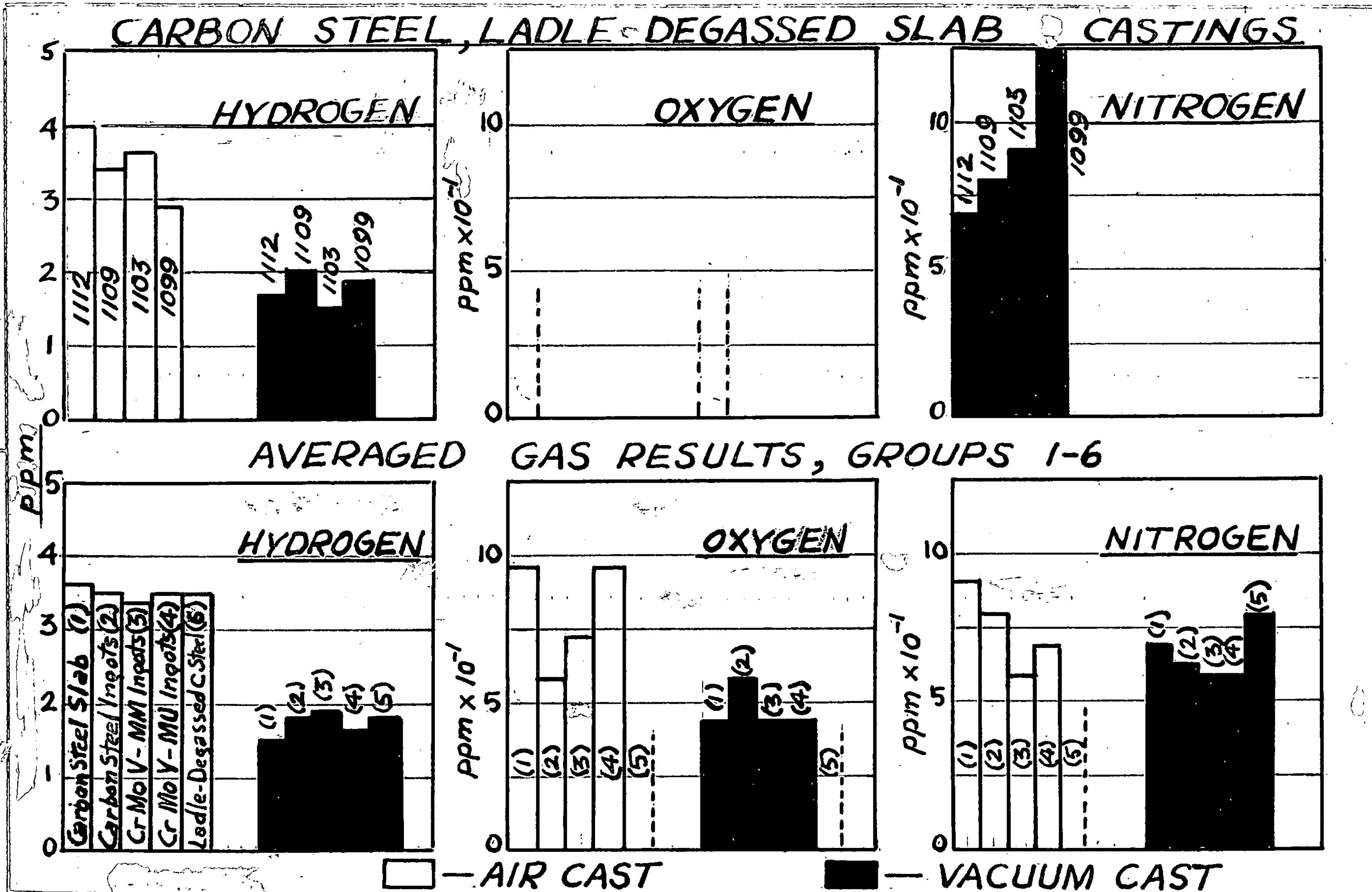



Figure 33. Hydrogen, oxygen and nitrogen contents of carbon steel ladle degassed slab castings; averaged gas results, groups 1-6, (air cast vs. vacuum cast).

## GENERAL DISCUSSION AND SUMMARY

Published results indicate that vacuum spray casting has found widespread acceptance in the U.S.A., Germany and Russia as a routine step in the production of large forging ingots. The effectiveness of this method of vacuum degassing has been proven by the U.S. Steel Company, the Bethlehem Steel Company, Bochumer Verein, and others, where flaking has been eliminated as a production problem in forgings of carbon and alloy steel of up to 350 tons size, 130-in. diameter ingots. These large forgings formerly required extended and expensive dehydrogenizing and slow cooling cycles, but reduction of the hydrogen content to the order of 1 ppm, and elimination of hydrogen segregation at the centre of heavy-section castings and forgings, now allow the choice of the heat treatment cycle to be based on normal alloy homogenizing and grain refining considerations. In some instances it has been possible to eliminate the slow cooling and dehydrogenizing cycles which were formerly used.

Among the other benefits obtained by vacuum casting are the following: reduction by about 30% of the oxygen content of steels which are not fully aluminum killed, and reduction by 10 to 15% of the nitrogen content. Reduction of total gas content, and use of vacuum casting refractory techniques, can result in improved steel cleanliness. The absence of hydrogen segregation in the central areas of large forgings, and the low average hydrogen level, both allow rapid cooling without hazard of flaking. Improved tensile ductility, especially in the transverse direction, compared with aged or unaged air-cast steel, is consistently obtained in sections which are too large for economical dehydrogenizing heat treatment. In large forgings the tensile ductility of vacuum cast steel is unchanged by aging and is higher than that of air cast steel in the aged (dehydrogenized) condition.

Other benefits are reported, such as improved forgeability and machinability.

As a result of European work, vacuum ladle degassing has been proven economical and practical for upgrading basic bessemer and open hearth steels and for improving steel cleanliness and deoxidation. Control over ingot solidification by this method has been of assistance in continuous casting. The results of Russian work indicate some reduction in watt losses and some improvement of the electrical properties of electrical sheet steel which depend on low impurity levels. Improved plasticity after vacuum degassing facilitates the rolling of silicon transformer sheet.

German work at Bochum has proved the utility of vacuum stream degassing for large forging ingots and for the production of critically stressed heavy section castings. Other German work, at Dortmund, has demonstrated, in plain carbon steels, the practicability of the use of vacuum degassing as a method of controlling rejects due to hair line cracks, as a control over cleanliness, and as a method of improving tensile ductility, forgeability and machinability.

While little information is yet available about the most recent

German degassing method (Ruhrstahl A.G.), it would appear to be an efficient ladle degassing method, and the operating pressure of 100 microns should produce the usual improvements due to vacuum treatment. In general, ladle treatment would appear to be accomplished at lower capital cost than other methods, and this fact may encourage the use of vacuum degassing.

The economics of the various processes are not reported in detail but a considerable amount of operating data is available and the choice of any particular method would require detailed cost analysis.

Vacuum stream degassing, even with its relatively large capital expenditure, seems to have been most widely accepted by large companies in the U.S.A., while, with the exception of Bochumer Verein, ladle degassing recently seems to have been used more extensively in Europe and Russia.

The only installation known in the United Kingdom is a 15-ton experimental degassing unit used for test work by a forging manufacturer, Wm. Beardmores Limited. Also, there is reported to be a special vacuum technique under development by Efco Edwards, in which induction-melted metal is held, for part of its melting period, under vacuum, followed by air casting.

Practical benefits of vacuum degassing can be summarized as follows:

(a) Effective reduction of hydrogen content, the final content being dependent on operating vacuum and steel composition.

(b) Reduction or elimination of hydrogen segregation at the centre of large forgings and castings.

(c) Choice of heat treatment can be based on homogenizing and grain refining, rather than on dehydrogenizing requirements.

(d) Improved cleanliness can be obtained.

(e) The tensile ductility of vacuum cast steel (stream degassed at 0.2 - 1.2 mm) is the same in the aged or unaged condition, and is higher than that of air-cast steel even in the aged condition.

(f) Under some conditions, improved electrical properties can be obtained by reduction of the carbon, sulphur and oxygen levels of steel.

(g) Improved machinability, forgeability and hot workability have been reported for degassed steel.

(h) Savings have been reported in the production of low-alloy constructional steel, by reduction or elimination of rejects due to hair line cracking.

(i) Under some conditions, centre looseness is claimed to be more easily eliminated in vacuum degassed than in air cast steel.

(j) Vacuum treatment can assist in control of the ingot solidification pattern to assist continuous casting operation.

(k) Improved plasticity facilitates cold reduction of silicon transformer sheet.

## REFERENCES


1. A. M. Aksoy, Vacuum Metallurgy in Europe. Metal Progress, February 1959, pp. 87-89.

2. Z. Eminger and F. Kinsky, Results of Vacuum Casting of Steel, Part I. Hutnicke Listy, Vol. 11, 1956, No. 6, pp. 345-355. Brutcher Translation No. 3861.

3. Z. Eminger et al., Importance of Vacuum Casting of Steel to Industrial Practice--2. Hutnicke Listy, Vol. 12, 1957, No. 8, pp. 755-768. Brutcher Translation No. 4139.

4. G. A. Garnyk and A. M. Samarin, Vacuum Metallurgy of Steel - Deoxidation and Desulphurization in Vacuum. Izvestiya Akademii Neuk SSSR, Otd. Tekhn. Nauk, May 1957, No. 5, pp. 77-84. Brutcher Translation No. 4054.

5. C. Finkl, Discussion at Session on Vacuum Degassing of Steel. Electric Furnace Conference, AIME, Dec. 3-5, 1958.

6. A. M. Samarin, Influence of Liquid Steel Treatment in Vacuum on the Composition and Properties of Some Steels. Lecture, New York University, August 1957.

7. G. A. Garnyk and A. M. Samarin, Vacuum Melting of Transformer Steel. Stal, No. 6, 1956, pp. 514-518.

8. K. C. Taylor, F. J. Stokes Co.; Vacuum Stream Degassing. Paper to Regional Meeting, Committee on Vacuum Techniques, Boston, Mass., Nov. 10, 1957.

9. A. Tix, Production Application of Degassing Steel in Vacuum, Especially for Big Forging Ingots. Stahl und Eisen, Jan. 26, 1956, 76, pp. 61-68. (Elec. Furn. Proc. AIME, 1955, 13, 70-84.)

10. A. Tix, Research Director, Bochumer Verein A.G.; Steels Degassed During Pouring of Large Forging Ingots. Metal Progress, June 1956, pp. 81-87.

11. M. A. Orehoski and J. N. Hornak, Applied Research Laboratory, U. S. Steel Company; Effect of Vacuum Stream Degassing on Properties of Forging Steels. Electric Furnace Conference, AIME, Dec. 3-5, 1958.

12. J. H. Stoll, Chief Metallurgist, Bethlehem Steel Company; Vacuum Pouring of Ingots for Heavy Forgings. Proc. AISI, May 21, 1958; Journal of the Iron and Steel Institute, Jan. 1959, pp. 67-80.

## REFERENCES (concluded)

13. F. Harders, Director; The Vacuum-Lifter Process of the Dortmund-Horder Huttenunion, A. G. Journal of the Iron and Steel Institute, Nov. 1958, pp. 306-311.

14. F. Weston Starratt, Vacuum-Flow Steel Degassing. Journal of Metals, AIME, July 1958, p. 465.

15. D. K. Faurschou, Mines Branch tests, 1957-1958, unpublished. Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada.

=====