

Nitrogen as Substitute to Nickel While Preparing Stainless Steel in Mini Steel Plants Using Electric Arc/Induction Furnaces

R. C. GUPTA

Department of Metallurgical Engineering, Institute of Technology,
Banaras Hindu University, Varanasi-221005

Abstract

Nickel is a major alloying element in stainless steel which is added to stabilise the austenite but it is now being substituted by nitrogen in view of increasing cost of nickel. Nitrogen in the melt could be added as master alloy in electric arc and air induction furnaces. It can also be added in the melt by exposing it to nitrogen gas atmosphere. The total nitrogen absorbed in the melt will depend upon mass transfer laws. In order to have gas/metal interaction, various melt conditions could be used in mini steel plants e.g., stirred melt exposure to gas in induction (vacuum type) furnace, gas bubbling through the melt in ladle or AOD converter and ionised gas exposure by plasma arc to the melt. The nitrogen addition method, using different melting techniques, is briefly described in this paper.

Introduction

The solubility of nitrogen^{1,4} in pure iron is 0.045 wt% (Fig. 1) in liquid state but it is very low in solid iron (ferrite). The dissolution (reaction 1) of diatomic nitrogen gas in liquid iron follows the Sievert's Law (eqn. 2).



$$\% \text{N}_2 = K_N \sqrt{P_{\text{N}_2}} \quad (2)$$

where K_N is equilibrium constant for reaction (1)
and P_{N_2} is partial pressure of nitrogen gas.

The solubility of nitrogen in stainless steel is affected by the type of alloying addition^{1,3} and its quantity as shown in fig.2. The molybdenum, manganese, tantalum, chromium, niobium and vanadium are found to enhance the nitrogen solubility whereas the

addition of nickel, cobalt, silicon and carbon decrease the solubility of nitrogen in the steel. The aluminium has been found to promote nitrogen solubility reported by Wade & Pehlke⁵, Evans & Pehlke⁶, and Machawa et al⁷, whereas Pehlke and Elliot² reported opposite effect. The surface active elements such as sulphur and oxygen present the melt retard the nitrogen absorption³ as shown in figs. 3 & 4.

The mechanism of nitrogen transfer from gas to metal has been discussed in detail by Lee & Rao⁸, Battle et al⁹ and Rao et al¹⁰. The rate of gaseous nitrogen absorption in metal is reportedly governed by diffusion laws as given below:

$$R = dc/dt = K_1 (A/V) (C_e - C) \quad \dots \quad (3)$$

$$R = dc/dt = K_{2rv} (A/V) (C_e^2 - C^2) \quad \dots \quad (4)$$

$$R = dc/dt = K_{2r} (A/V) (C_e^2 - C^2) \quad \dots \quad (5)$$

where,

A	=	exposed surface area, cm ²
C _e	=	equilibrium melt concentration, mole/cc,
C	=	melt concentration at time t, mole/cc,
K ₁	=	first order rate constant, cm/sec
K _{2rv}	=	second order rate constant for reaction 2[N] → N ₂ (gas) as defined by equation (4) cm ⁴ /mole/sec
K _{2r}	=	second order rate constant for reaction 2[N] → N ₂ (gas) as defined by equation (5) cm ⁴ /mole/sec
R	=	absorption rate, mole/cc/sec,
V	=	melt volume, cc.

The rate of gas absorption in the melt has been found to be affected by gas pressure and melt composition. In actual practice nitrogen could be introduced into the melt by two methods:

- 1st Method : Addition of nitrogen rich master alloys,
2nd Method : Gas/metal interaction techniques.

In the first method the total nitrogen in steel would depend upon mass balance of the charge and product material whereas in the second method the gas dissolution in liquid melt would depend upon various factors such as melt composition and temperature, gaseous pressure over the melt and gas/metal exposure time. These

techniques are described in the following lines.

Melting Practice Utilising Nitrogen Rich Master Alloys

The nitrogen rich master alloys given in table I could be added in the liquid melt to get steel containing desired nitrogen. The melting practice basically consist of two steps i.e., preparation of low carbon melt followed by addition of master alloys in the desired quantity. The meltings in this manner could be practiced in either direct arc furnace or in air induction melting units.

Melting in Direct Arc Furnaces

The direct arc furnaces are most commonly used in foundries and mini steel plants, thus it could be utilised easily to prepare nitrogen bearing stainless steel. Nijhawan et al¹¹ made several heats in 3 ton basic direct arc furnace to produce nitrogen steel. The procedure adopted by them was very similar to the conventional melting practice which consist of following three steps:

- a) The Oxidising Stage - In this stage the primary aim is to lower down carbon to such a level as to compensate pickup in latter stages. The oxidation of carbon could be achieved by oxygen blowing or by ore addition. The former being preferred on account of the relatively shorter time requirement and generation of high temperature in the melt.
- b) The Reducing Stage - The oxygen saturated melt is deoxidised in order to take a substantial portion of chromium from the slag back to the steel, in case the starting material is straight stainless steel scrap. This deoxidation is also needed to reduce subsequent losses of alloying elements which would occur if effective deoxidation has not been accomplished earlier. Ferro-silicon is used normally for deoxidation in case of these nickel free stainless steel, as aluminium may combine with nitrogen to form nitrides.
- c) The Finishing Stage - After removing the first slag, a fresh finishing slag of lime and flourspar is prepared and necessary alloy additions are then made. While melting Cr - Mn - N stainless steel, ferroalloys containing nitrogen i.e., nitrided electrolytic manganese, nitrided ferromanganese or nitrogen bearing ferro-chromium are added after the requisite preheat-

ing period. These alloy additions are thoroughly stirred in the bath for its homogenisation. In certain cases, the nitrogen bearing alloys may be added even during the reducing stage. Having made the additions of the alloying elements and measurement of the melt temperature, which should be 1500 to 1550°C, the melt is ready for tapping. It is advisable to take a sample from the bath and quench it for immediate magnetic testing which should clearly show the total non magnetic property. The melt is then poured into ladle and a slag cover is maintained over it while pouring is being done.

Nijhawan et al¹¹ reported that almost all nitrogen in the melt was recovered, but 7% loss of manganese was noticed. The charge should be calculated in advance for the desired nitrogen content in the melt.

Melting in Air Induction Furnace

While melting in induction furnace generally no refining of metal is practiced and hence job of nitrogen addition becomes relatively simple. For melting purposes, generally low carbon scrap or ferritic stainless steel is chosen and charged into the furnace and power is switched on. Once the charge starts softening, low carbon ferro-chromium is gradually added in desired quantity. A part of the low carbon ferro-chromium is often replaced by nitrogen containing ferro-chromium to raise the nitrogen input of the charge. The balance of the charge consisting of either nitrided electrolytic manganese or Fe-Cr-Mn-N master alloy is slowly added to the molten bath which is kept at a low temperature. During such an addition period care should be taken to see that the bath is not suddenly cooled down by abrupt addition of large quantity of material. This precaution is important to avoid the formation of a bridge on the top of the melt which may at times be difficult to break. After completion of melting, ferro-silicon is added to the bath and melt temperature is adjusted between 1500 to 1550°C. The melt is now poured into preheated ladle and then into the ingot moulds which are properly dressed before hand. These moulds are immediately capped after completion of pouring to get defect free castings.

Techniques Involving Gas & Liquid Metal Interaction

As pointed out earlier that the nitrogen gas is soluble in the liquid melt depending upon the melt condition and hence different melting systems could be used to alter gas/metal exposure conditions

(fig. 5) as listed below:

- i. Gas exposure to the static melt - Resistance Furnace Melting
- ii. Gas exposure to the stirred melt - Induction (air/vacuum) Melting
- iii. Gas bubbling through the melt - Ladle Technique and AOD unit
- iv. Ionised gas exposure to the melt - Nitrogen Plasma Arc Melting.

These techniques have been briefly discussed in following sections.

Melting in Resistance Furnace under Nitrogen Atmosphere

Steel melting on a laboratory scale can be done in resistance furnace where high temperature (1600°C) is obtained by passing electrical current through platinum or molybdenum wire. At constant melting temperature no convective current are developed in the melt and hence the gas exposed over the melt can dissolve through diffusion process. The concentration of the nitrogen in the melt can be expressed by :

$$(C_t - C_o)/(C_e - C_o) = A e^{I(x/L)/(2\sqrt{Dt})} \quad (6)$$

- C_e = equilibrium nitrogen concentration
 C_o = nitrogen concentration in the melt before gas exposure
 C_t = nitrogen concentration in the melt at a time t
 x = distance from gas/metal interface
 L = total depth of the melt
 A = x-sectional area of the gas/metal interface
 D = diffusivity of nitrogen in the melt
 t = time of gas/metal exposure

The above expression (eqn. 6) indicates that very long exposure time in hours would be needed to achieve equilibrium concentration.

Gallardo et al¹² studied the nitrogen dissolution in duplex stainless steel (22 Cr, 5 Ni, 3 Mo, .16 N) by melting in a platinum furnace. The melt (12 gm) was held in 1 cm dia alumina crucible giving melt height 2.5 cm. It was exposed to nitrogen gas at one atmospheric pressure for 1, 5 and 10 hours. The nitrogen concentration at various depth levels are shown in fig. 6 given by Gallardo et al.

Thus, it can be observed that if only diffusion process is allowed for nitrogen transport then very long gas/metal exposure time would be needed which may not be a practical method of melting. Moreover, the resistance furnace cannot be used for large scale melting due to various technical and economical reasons.

Melting in Induction Furnace under Nitrogen Atmosphere

In induction melting process the mass transfer of nitrogen to the melt is enhanced due to convective current generated in the melt because of electric current flowing in induction coil. Machline¹³ developed streamline flow model for melting in induction furnace where the mass transfer is hastened by convective current due to induction stirring. The mass transfer coefficient derived by Machline is expressed as:

$$K_1 = \sqrt{8 D V / \pi r h^2} \quad \dots \quad (7)$$

where, D = diffusivity of nitrogen in the steel
 V = velocity of the melt under induction stirring
 r = radius of the crucible
 h = melt depth

Fruehan & Martonik¹⁴ showed that in Fe-Cr and Fe-Cr-Ni melts, the dissolution rate is of the first order with respect to nitrogen concentration and is independent of chromium and nickel content for melts containing low (<0.003%) sulphur, hence, while calculating nitrogen in the melt, its diffusivity in stainless steel can be taken as $1.1 \times 10^{-4} \text{ cm}^2/\text{sec}$, which is accepted value for liquid iron at 1600°C .

In any given furnace for melting stainless steel by mass transfer coefficient $[K_1 = \sqrt{(8 D V / \pi r h^2)}]$ is constant (say = Y).

The equation (3) could be written as :

$$dc/dt = Y(C_e - C) \quad \dots \quad (8)$$

which on integration within limit of initial (C_o) and final (C_t) melt nitrogen concentration at gas exposure time zero (t_o) to time (t) during dissolution, gives equation :

$$(C_e - C_o)/(C_e - C_t) = e^{Yt} = Z \text{ (say)} \quad \dots \quad (9)$$

$$\text{or } C_t = (Z C_e - C_e + C_o)/Z \quad \dots \quad (10)$$

This equation (10) is useful in calculating the nitrogen concentration of the melt at given exposure time or vice-versa provided the surface active elements are below 0.003 wt%. As we discussed earlier, the presence of oxygen in the melt would retard the absorption rate¹⁴. Swisher and Turkdogan¹⁵ have studied the tensoactive effect of oxygen and have given the tensoactive factor " θ ",

$$\theta = (\% \text{ Oxygen in melt}) / (.014 - \% \text{ Oxygen in melt}) \quad \dots (11)$$

Hence, for melts containing oxygen, the mass transfer coefficient should be corrected by multiplying with $(1 - \theta)$,

$$\text{i.e.,} \quad K' = K(1 - \theta) = Y' \text{ (say)}$$

$$\text{hence,} \quad Z' = e^{Y't}$$

$$\text{or} \quad C_t = (z' C_e - C_e + C_0) / Z' \quad \dots (12)$$

Melting in Vacuum Induction Furnace

Gupta & Beech¹⁶ studies the rate of nitrogen absorption by melt containing 19 Cr and 7 Ni with very low oxygen and sulphur. The melting procedure, given by them, consists of first charging the crucible with nearly two third iron, all chromium and nickel to be melted. The remaining one third iron is held in secondary charging bucket. The minor alloying elements are held in rotary charging system provided in mot of the vacuum induction furnaces. After charging the furnace, the chamber is evacuated to 2×10^{-2} mm Hg. The power is turned on and raised to 30 KW for 10 kg melting. As the melting starts the argon gas is admitted in the chamber upto 10 cm Hg pressure. After melting initial charge, the remaining iron held in the bucket is charged and melted. The total melt time is about 50 min. The power is now reduced to 10 KW and the chamber is evacuated to facilitate deoxidation of homogenised melt via carbon boil for 15 min at 2×10^{-2} mm Hg pressure. The minor alloying additions required could be made at this stage. After ensuring melt composition, its temperature is adjusted at $1530 \pm 10^\circ\text{C}$ by controlling power. Now the nitrogen gas is admitted in the chamber at predetermined pressure and held for fixed time. The melt temperature is again noted few seconds before pouring the melt into the mould. The calculated and observed values of nitrogen content for different exposure time for 19 Cr - 7 Ni steel is shown in fig. 7, indicating a very good agreement.

Melting in Air Induction Furnace

The authors¹⁷ reported their experience of adding nitrogen in 1.5 Kg laboratory air induction furnace where first the metal was melted in the crucible and then nitrogen cloud was provided on the top of the melt (fig. 5b) for 22 min. The melting schedule and the rate of nitrogen absorption in the melt (16.2 Cr - 3.53 Ni - .1 C) is shown in fig. 8. It can be noticed that after 22 min gas/metal exposure time only 0.0453 wt.% nitrogen in the melt was obtained against equilibrium value of 0.2128 wt%. This large variation between calculated and observed values could be due to high oxygen (0.073 wt%) content in the melt which could not be avoided during melting in air.

Vacuum Vs. Air Induction Melting

Utilising the convective stirring offered by induction furnace, melting can be done either in vacuum or air induction furnace in principle. However, the vacuum induction furnace offers better melting conditions than air induction furnace. The closed chamber around crucible helps to carry out melting first in an inert atmosphere to avoid metal oxidation. Once the charge is molten then the dissolved oxygen could be easily removed by maintaining a negative pressure over the melt for some time before switching over to nitrogen positive pressure required for its dissolution. The system offers, means to carry out melting in a very clean and controlled manner as evident by study reported by Gupta & Beech¹⁶. While melting in air induction furnace under nitrogen gas cover, it is difficult to have oxygen free melt. The rate of nitrogen transfer to the metal will be severely affected by the presence of surface active element like oxygen even if sulphur levels are kept low by careful selection of raw materials. The fig. 9 shows the good agreement of calculated and observed nitrogen in the melt containing low (< 0.004 wt%) oxygen reported by Gupta & Beech¹⁶ while melting in vacuum furnace compared with experience of air melting practice reported by authors¹⁷. In air melting high (0.073 wt%) oxygen content resulted in wide difference between calculated (without applying correction for oxygen in melt) and experimental value.

Gas Bubbling through the Melt

Most of the mini-steel plants and foundries practice metal degassing by passing inert gas such as argon through porous plug provided at the bottom of the hot metal ladle. The same arrangement could be utilised for nitrogen addition into the melt by switching over

to nitrogen gas instead of argon. The gas bubble rising through hot metal would get dissolved into the metal depending upon the total contact time and surface area. Fruehan et al¹⁸ have given the expression for mass transfer coefficient under this condition developed by Calderbank.

$$K_1 = 1.28 \sqrt{[(D V')/d_B]} \quad (13)$$

where, D = Diffusivity of nitrogen in melt
 V' = Velocity of bubble
 d_B = Bubble diameter

The total bubble gas area (A) per unit time in contact with metal is given by :

$$A = n_B \cdot A_B = (V_N \cdot \text{tr} \cdot A_B)/V_B \quad (14)$$

where, n_B = Number of bubbles per sec
 A_B = Area of a single bubble
 V_N = Gas flow rate
 V_B = Volume of a single bubble
 h = height of the bath
 tr = retention time of the bubble in the bath

Substituting the values of K_1 and A in equation (3), the rate of nitrogen absorption could be written as :

$$dc/dt = [(1.28 \sqrt{D V'/d_B}) (6 V_N h/d_B h/d_B V') (p/M)](C_e - C) \quad (15)$$

where, p = density of steel
 M = mass of the steel

For a given set of condition the expression under big bracket is constant (say W). Integrating this equation in a manner similar to induction melting case between limits of initial (to) nitrogen concentration(C_o) to nitrogen concentration (Ct) at a time t sec.

$$(C_e - C)/(C_e - Ct) = e^{Wt} = S \text{ (say)} \quad (16)$$

$$\text{or } Ct = (S C_e - C_e + C_o)/S \quad (17)$$

Nitrogen Bubbling in Hot Metal Held in Ladle

Fruehan et al¹⁸ conducted experiments by bubbling nitrogen gas in 18 - 8 stainless steel melt (4200 gm) held in a tube (34 mm dia) giving a melt depth (h) of about 58.7 cm. The nitrogen gas was passed at the rate of 1 lit/min and 2.5 lit/min giving bubble melt surface area (A) as 42 sq. cm and 104 sq.cm respectively. The bubble dia as 6 cm and its velocity (22.5 cm/sec) was estimated. The nitrogen diffusivity in melt was taken as $1.1 \times 10^{-4} \text{ cm}^2 \text{ per sec}$ and density (ρ) of stainless steel as 7.9 gm/cc. The calculated values and experimentally observed values of nitrogen in the melt is shown in fig. 10. While calculating nitrogen absorption the major uncertainty arises from the estimation of bubble size. The smaller the bubble, the greater the total bubble surface area and mass transfer coefficient. The bubble velocity could be obtained from model of gas stirred in ladle developed by Sahai & Guthrie¹⁹.

The rate of nitrogen pickup in 200 metric tons of steel containing 0.005 and 0.03 wt% sulphur using 0.0046 m³/sec and 0.0092 m³/sec nitrogen gas flow rate through metal at 1600°C and bubble dia 6 cm is shown in fig. 11, which reveals that low sulphur and high flow rate increases the nitrogen absorption. The effect of smaller bubble size (3 cm) is shown in fig. 12 which given higher nitrogen absorption rate.

Injection of Nitrogen Gas in AOD Converter

In AOD process for stainless steel making, the nitrogen gas can be easily used with oxygen in place of argon. The nitrogen while bubbling through liquid melt will get dissolved in a manner similar to ladle gassing technique. The rate of nitrogenization of 75 metric ton, 18 - 8 stainless steel melt containing 0.03 and 0.008 wt% sulphur using 0.85 m³/sec nitrogen is shown in fig. 13. The rate in the case of high sulphur alloys is governed by mixed control and the calculation indicated an initial rate of about 0.01 % Nitrogen/min. The rate decreases with time and the predicated pickup is 0.08% Nitrogen in 10 min. If nitrogenization is carried out after desulphurisation, the rate will be some what higher as indicated for 0.008% S alloy. In this case the rate constant is higher, and the rate is primarily controlled by liquid phase mass transfer.

Melting Under Nitrogen Plasam Arc

Plasma arc is an attractive method of electrical heating with low

acoustic emission²⁰. When gases e.g., argon, nitrogen, hydrogen are passed through electric arc, it gets ionised at high plasma arc temperature ($\sim 10000^\circ\text{K}$). Sinha & Gupta²¹ have studied (fig. 14) the melt nitrogenation when exposed to nitrogen plasma and have also given the possible reasons for high rate constant values of nitrogen absorption ($0.8 - 2.5 \times 10^{-2} \text{ ms}^{-1}$) under plasma arc in their recent paper²². This absorption rate constant values under plasma arc are nearly four orders of magnitude higher (fig. 15) compared with unconvected gas/metal reaction in resistance melting. The effect of various operational parameters on nitrogen absorption are given in ref. 21. The mechanical and structural properties of alloys thus made were examined and found comparable²³ with properties of alloys obtained by other methods of melting.

Conclusions

The addition of nitrogen in the stainless steel could be made by various methods. The choice by operator will depend upon the availability of a specific facility within the plant, scale of melting operation, amount of nitrogen required in the alloy and accuracy limit for nitrogen content in the steel.

References

1. R.G. Ward, *An Introduction to the Physical Chemistry of Iron and Steel Making*, Edward Arnold Publisher, London (1962), 1752p.
2. R.D. Pehlke and J.F. Elliott, *Trans. AIME*, vol. 218, (1960) 1088p.
3. A.R. Perrin, M. Wolosiuk and A. Mclean, *Trans ISS*, vol. 14, No. 6 (1987) 45p.
4. L.S. Darken and R.W. Gurry, *Physical Chemistry of Metals*, McGraw Hill Book Co., New York (1953) 372p.
5. H. Wada and R.D. Pehlke, *Met. Trans. B*, vol. 9B 91978) 441p.
6. D.B. Evans and R.D. Pehlke, *Trans. AIME* vol. 230 (1964) 1651p.
7. S. Mackawa & Y. Nakagawa, *Jl. Iron & Steel Inst. Japan*, vol. 45, (1959) 255p.

8. H.G. Lee & Y.K. Rao, Ironmaking & Steelmakin, vol. 12, No. 5 (1985), 221p.
9. T.P. Battle & R.D. Pehlke, Ironmaking & Steelmaking, vol. 13, No. 4 (1986) 176p.
10. Y.K. Rao & H.G. Lee, Ironmaking & Steelmaking, vol. 12, No. 5 (1985) 205p.
11. B.R. Nijhawan, P.K. Gupta, S.S. Bhatnagar, B.K. Guha & S.S. Dhanjal, Jl. Iron & Steel Inst., vol. 205, No. 3 (1967) 292p.
12. S.V. Gallardo, D.N. Hawkings and J. Beech, Dept. Metallurgy, Sheffield University, UK, (1986) personal communication.
13. E.S. Machline, Trans. AIME, vol. 218 (1960)314p.
14. R.J. Fruehan and L.J. Martonik, Met. Trans. B. vol. 12B 91981) 379p.
15. J.H. Swisher & E.T. Turkdogan, Trans. AIME, vol. 239, No. 5 (1967) 602p.
16. R.C. Gupta and J. beech, Trans IIM, vol. 42, (1989) 571p.
17. O.P. Sinha and R.C. Gupta, Proceedings of Conf. on Processing of Material - Critical Issue, IISc., Bangalore, July 1989.
18. R.j. Fruehan, B. Lally and P.C. Glaws, Trans. ISI Japan, vol. 14, No. 4 (1987) 31p.
19. Y. Sahai and R.I.L Guthrie, Met. Trans. B. vol. 13B (1982)193p.
20. O.P. Sinha and R.C. Gupta, ISIJ Inst., vol. 33, No. 8 (1993) 903p.
21. O.P. Sinha and R.C. Gupta, ISIJ Inst., vol. 33, No. 5 (1993) 567p.
22. O.P. Sinha and R.C. Gupta, ISIJ Inst., vol. 34, No. 3 (1994) 295p.
23. O.P. Sinha, A.K. Singh, C. Ramchndra and R.C. Gupta, Met. Trans. A, vol. 23A, No. 12, (1992), 3317-3324p.



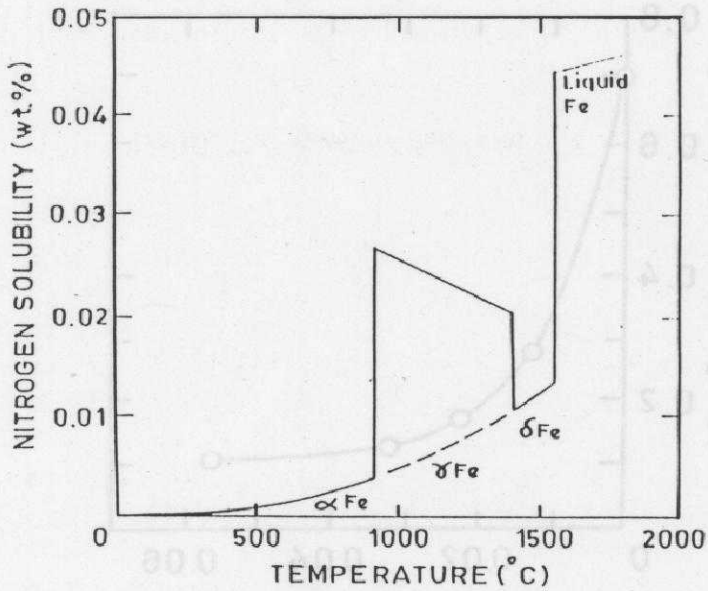


FIG. 1 SOLUBILITY OF NITROGEN IN PURE IRON UNDER NITROGEN AT ONE ATMOSPHERE (REF 1-4)

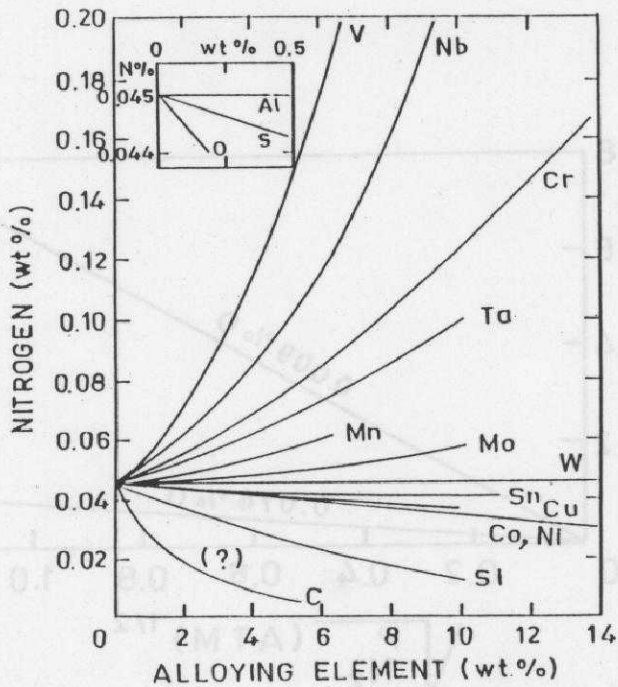


FIG. 2 EFFECT OF ALLOYING ELEMENTS ON THE SOLUBILITY OF NITROGEN AT ONE ATM. PRESSURE IN LIQUID BINARY IRON ALLOYS AT 1600 °C (REF 1-3)

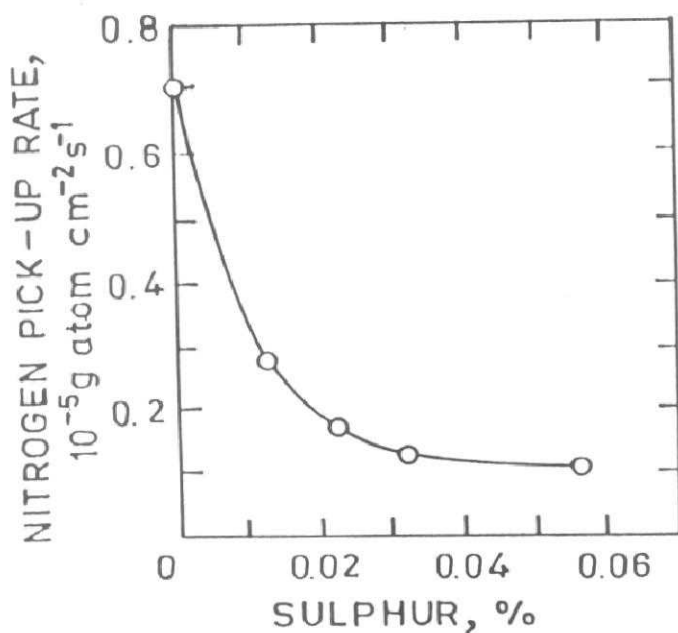


FIG. 3 EFFECT OF SULPHUR ON THE RATE OF NITROGEN PICKUP BY FALLING DROPLETS AT 1600 °C (REF 3)

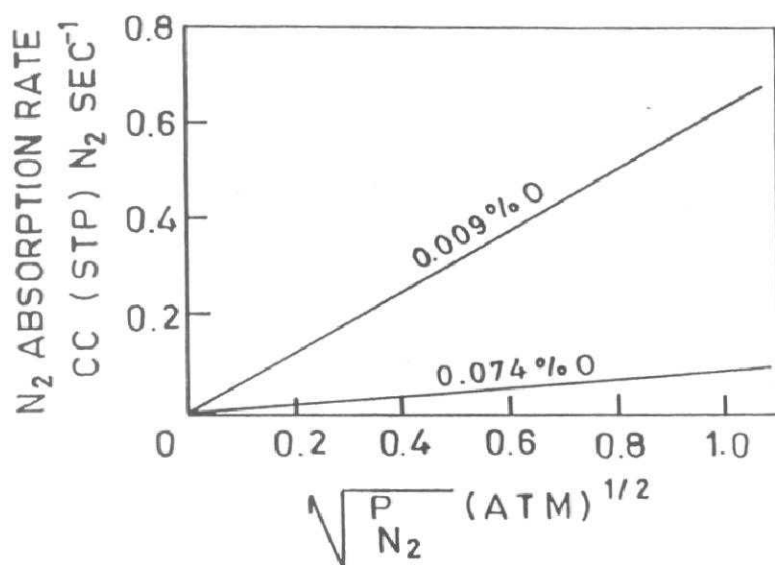


FIG. 4 EFFECT OF OXYGEN ON THE ABSORPTION OF NITROGEN BY LIQUID IRON AT 1600 °C (REF 3)

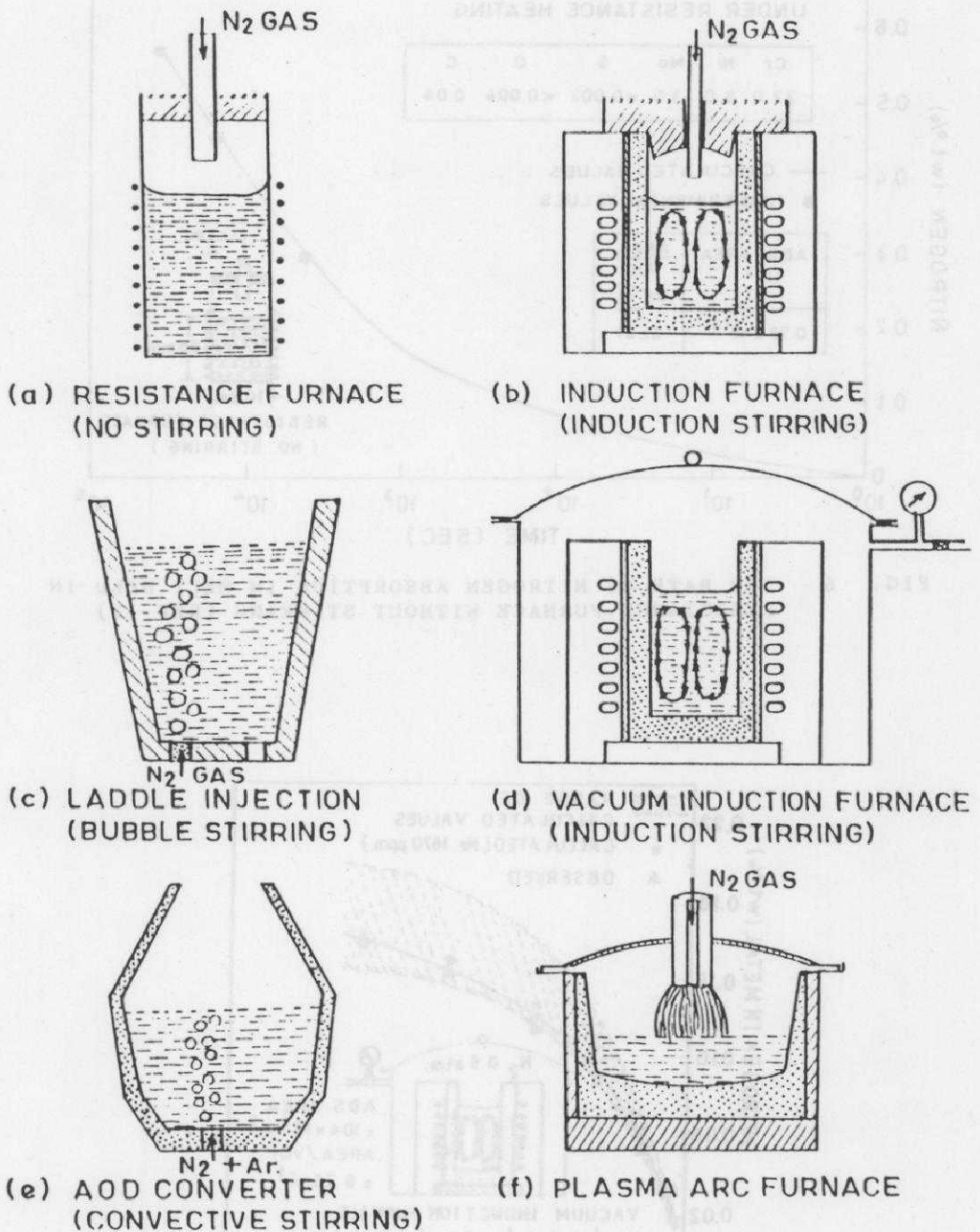


FIG. 5 MELTING UNITS FOR NITROGEN ADDITION WHILE MELTING STAINLESS STEEL

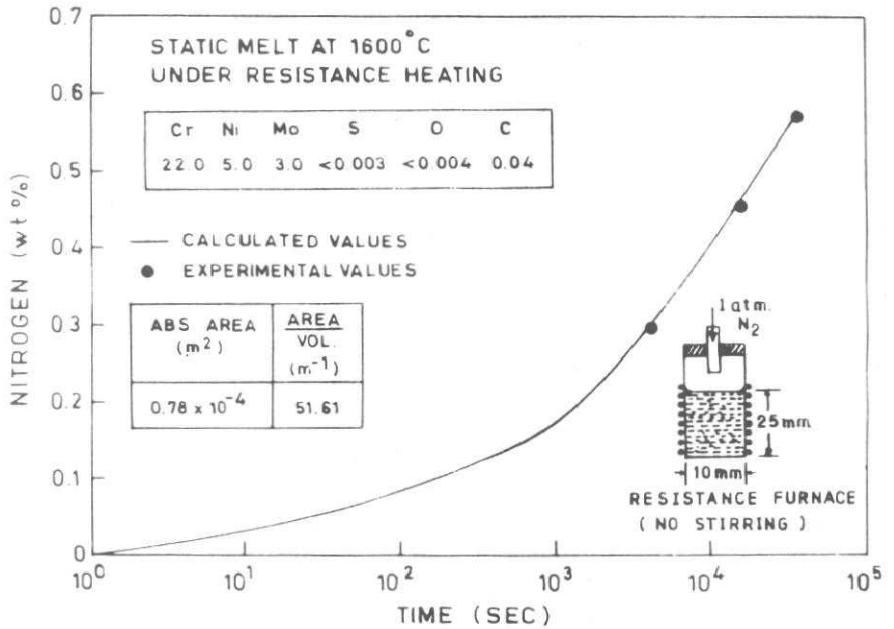


FIG. 6 THE RATE OF NITROGEN ABSORPTION IN MELT HELD IN RESISTANCE FURNACE WITHOUT STIRRING (REF 12)

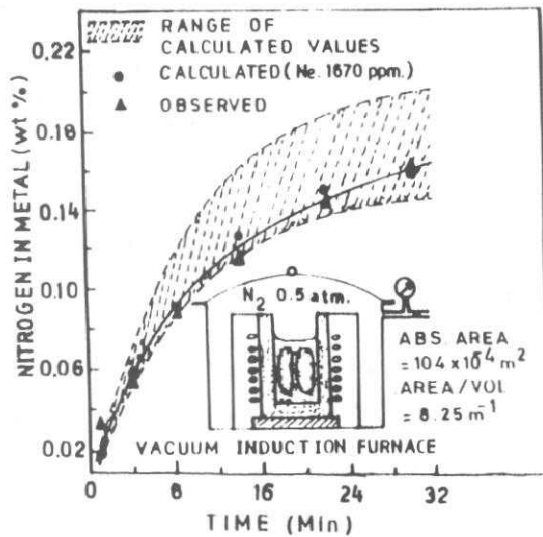


FIG. 7 THE RATE OF NITROGEN DISSOLUTION IN MELT DURING INDUCTION MELTING WITH CONTROLLED NITROGEN PRESSURE (REF 16)

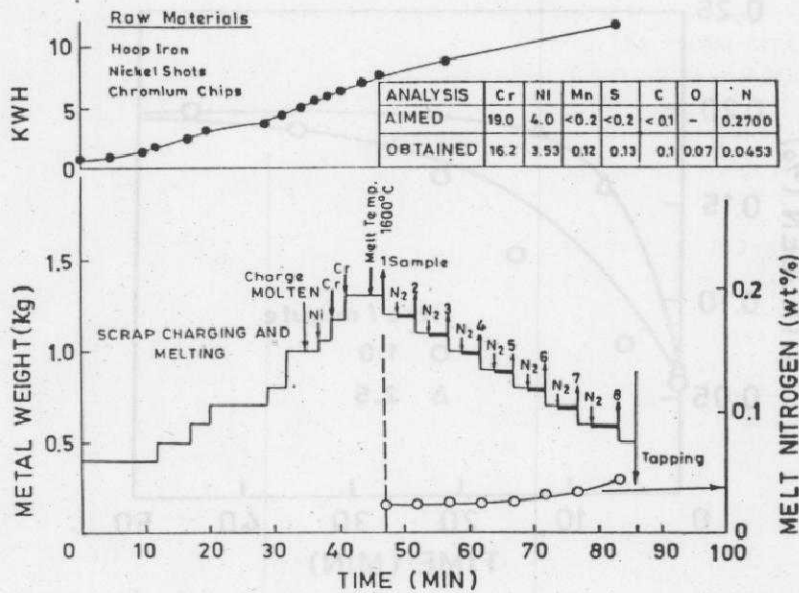


FIG. 8 MELTING SCHEDULE UNDER AIR INDUCTION FURNACE & RATE OF NITROGEN ABSORPTION (REF. 17)

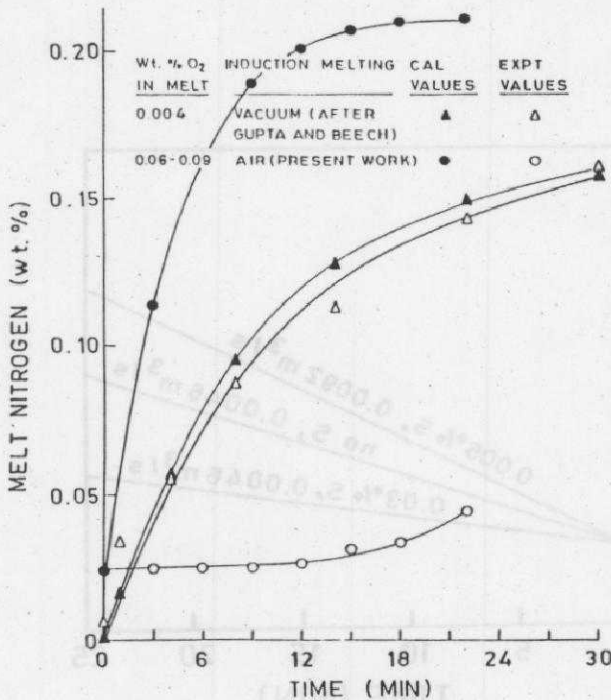


FIG. 9 DISSOLUTION OF NITROGEN IN MELT IN VACUUM & AIR INDUCTION MELTING SYSTEM OFFERING LOW (0.004 WT%) & HIGH (0.073 WT%) OXYGEN IN THE MELT (REF 17)

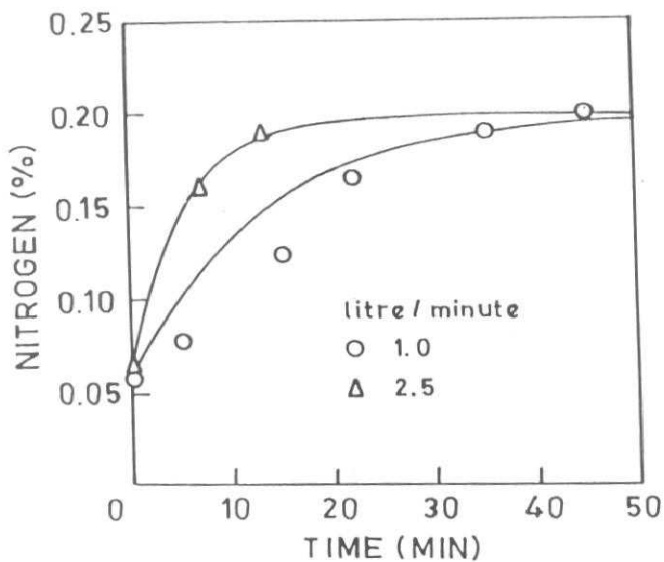


FIG. 10 COMPARISON OF THE CALCULATED RATE OF NITROGENATION FOR NITROGEN BUBBLED THROUGH 18-8 STAINLESS STEEL AT 1600 °C (REF 18)

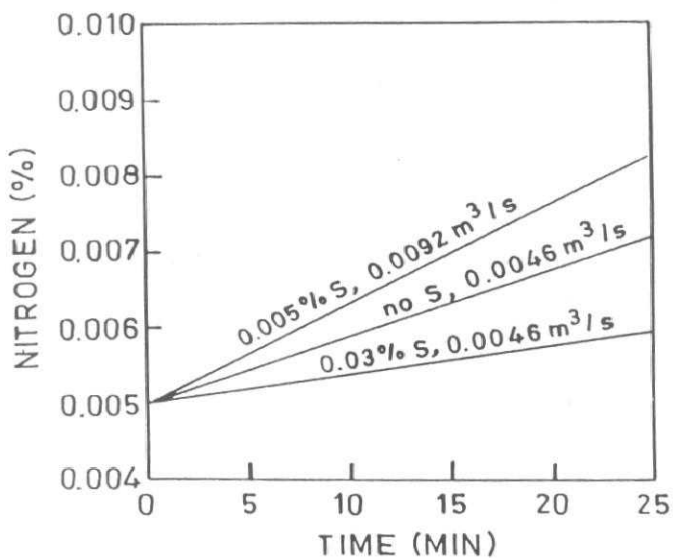


FIG. 11 RATE OF NITROGEN PICKUP IN 200 TON STEEL CONTAINING 0.005 & 0.03 % SULPHUR USING 0.0046 & 0.0092 cu.m/s (BUBBLE DIA 6 cm) OF NITROGEN AT 1600 °C (REF 18)

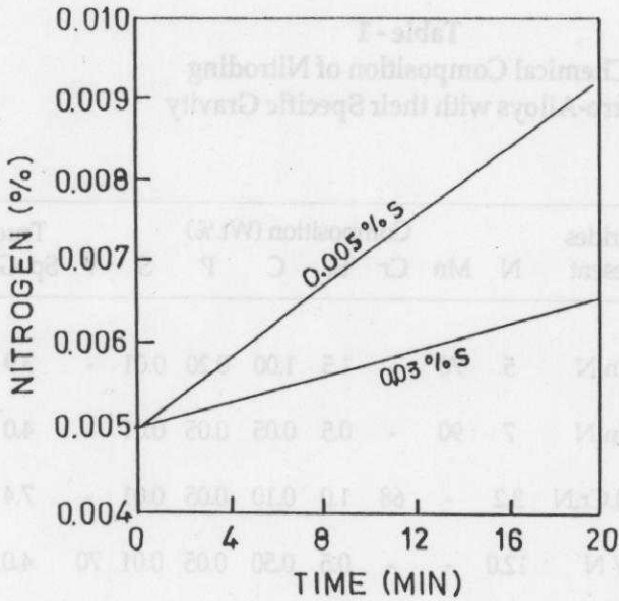


FIG. 12 RATE OF NITROGEN PICKUP IN 200 TON STEEL CONTAINING 0.005 & 0.03 % SULPHUR USING 0.0046 cu.m./s (BUBBLE DIA 3 cm) OF NITROGEN AT 1600 °C (REF 18)

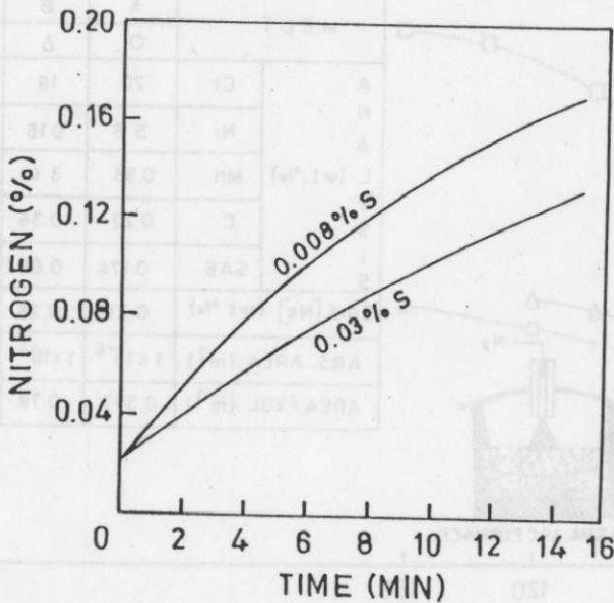


FIG. 13 RATE OF NITROGEN PICKUP IN 75 TON STAINLESS STEEL CONTAINING 0.008 & 0.03 % SULPHUR USING 0.85 cu.m./s OF NITROGEN AT 1600 °C IN AOD PROCESS (REF 18)

Table - 1
Chemical Composition of Nitriding
Ferro-Alloys with their Specific Gravity

Nitrided Ferroalloys	Nitrides present	Composition (Wt.%)								True Sp.Gr.
		N	Mn	Cr	Si	C	P	S	V	
Fe-Mn-N	Mn ₄ N	5	78	-	1.5	1.00	0.20	0.01	-	3.9
(Mn)N	Mn ₄ N	7	90	-	0.5	0.05	0.05	0.01	-	4.0
Fe-Cr-N	CrN.Cr ₂ N	3.2	-	68	1.0	0.10	0.05	0.01	-	7.4
Fe-V-N	VN	12.0	-	-	0.5	0.50	0.05	0.01	70	4.0
Fe-Si-N	Si ₃ N ₄	30.0	-	-	50.0	0.30	0.01	0.02	-	3.5

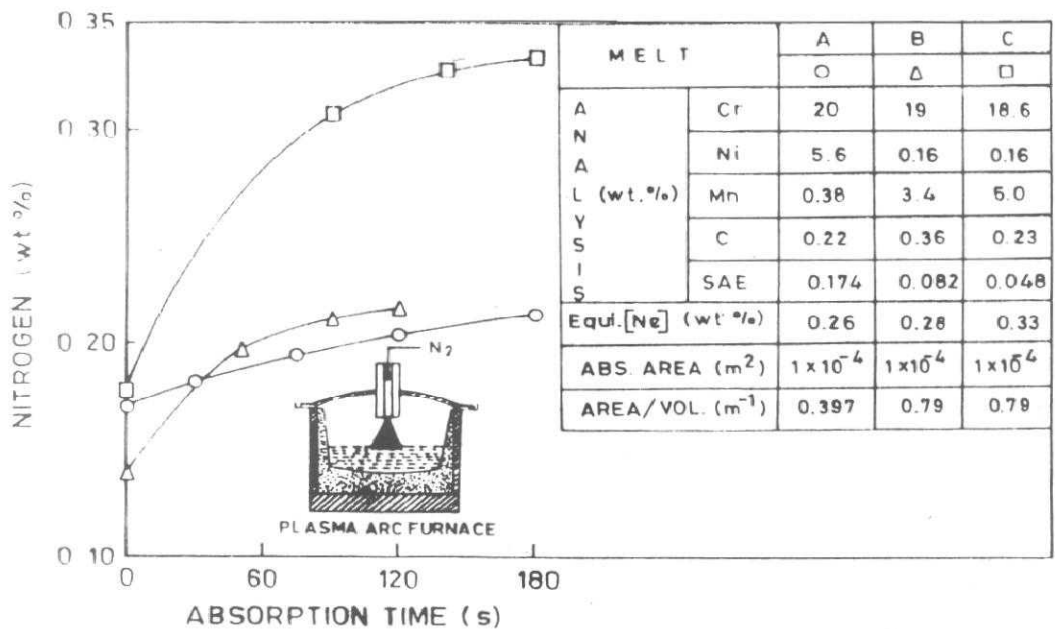


FIG. 14 NITROGEN PICKUP BY LIQUID MELT EXPOSED TO NITROGEN PLASMA (REF 22)

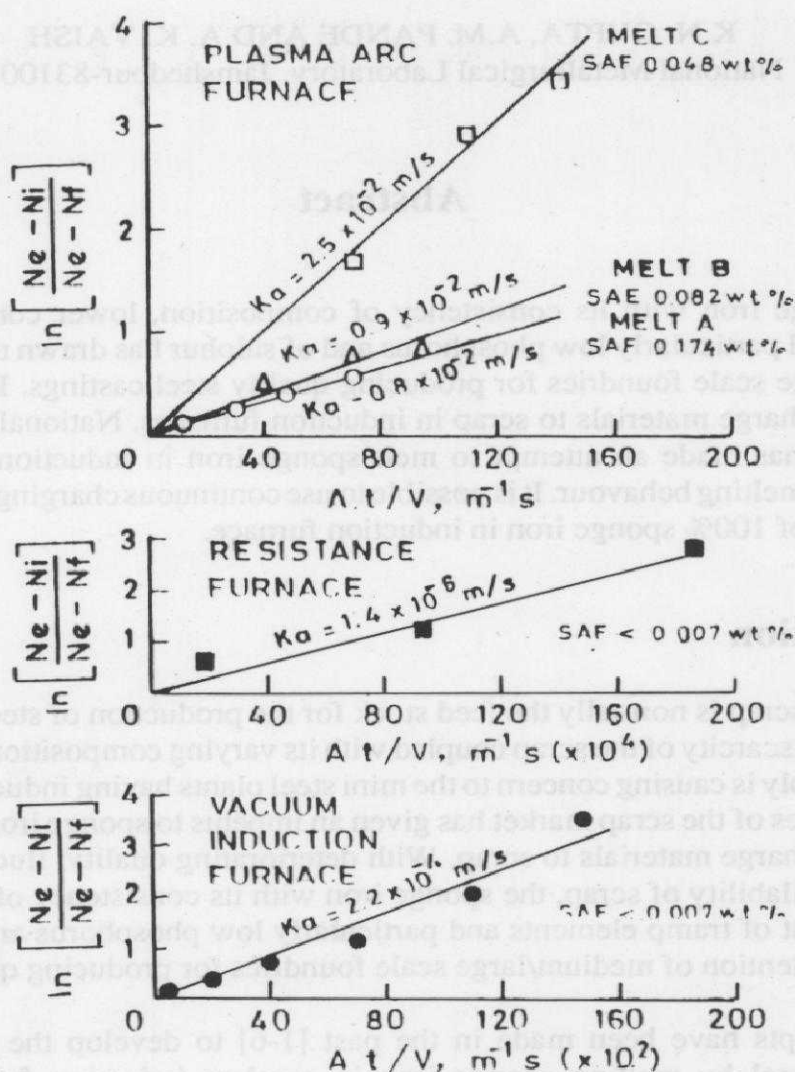


FIG. 15 NITROGEN PICKUP BY LIQUID MELT UNDER VARIOUS MELTING CONDITIONS (REF. 22)