

# HEATING AND MELTING OF D-R PELLETS IN HOT SLAG

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## ABSTRACT

The results of studies of the rates at which D-R pellets are heated and melted in liquid ferrous silicate slags are presented. The influences of the temperature of the slag, size and density of the pellets, and motion of the slag are presented and discussed. The experimental work reported includes the results of measurements of the amount and composition of gases evolved as pellets are heated. A simple mathematical model of the melting of single particles in a bath of hot slag is employed to determine the time required to melt spherical D-R pellets in a typical electric furnace slag.

## INTRODUCTION

Optimization of the design of the 3-phase arc electric furnace for melting direct-reduced iron (DRI) materials requires a quantitative understanding of the factors that control the rate at which particles or pellets of DRI are melted in, and pass through, the hot liquid slag. The properties which determine the heat transfer characteristics of slags have been under study in our laboratory<sup>1,2,3</sup>. Based on these studies, on recent measurements of the heating of D-R pellets in slags, and on the evolution of gases from pellets as they are heated, the rates of heating of DRI materials in electric furnace operations have been estimated.

The thermal diffusivity,  $\alpha$ , of a variety of compositions of metallurgical slags has been measured and found to be in the range of 0.003 to 0.010 cm<sup>2</sup>/sec. The results for several slags are shown in Fig. 1 and 2. Corresponding values of the thermal conductivities of these slags are numerically nearly the same, i.e., 0.004 to 0.010 cal/cm.sec.°C (1 to 2.5 BTU/ft.hr.°F) because the product of heat capacity times density of these slags is approximately

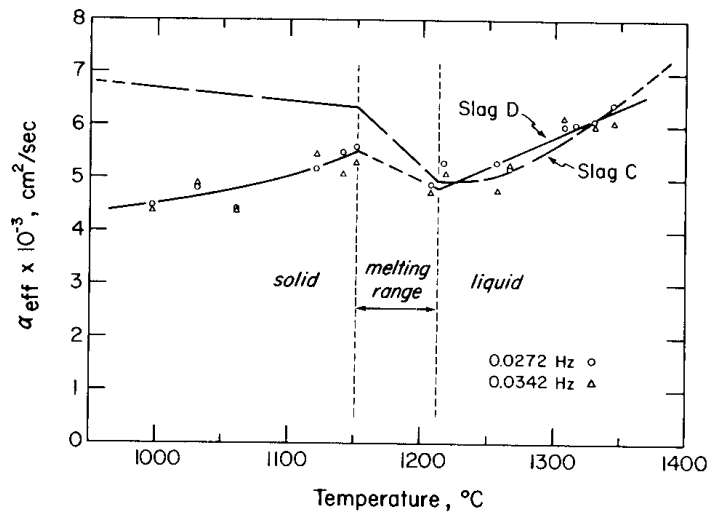


Fig. 1. Measured thermal diffusivities of slags<sup>2</sup>.  
Slag C: 60.6% FeO, 1.4% Fe<sub>2</sub>O<sub>3</sub>, 38.1% SiO<sub>2</sub>.  
Slag D: 55.1% FeO, 1.2% Fe<sub>2</sub>O<sub>3</sub>, 34.6% SiO<sub>2</sub>, 9.1% CaO.

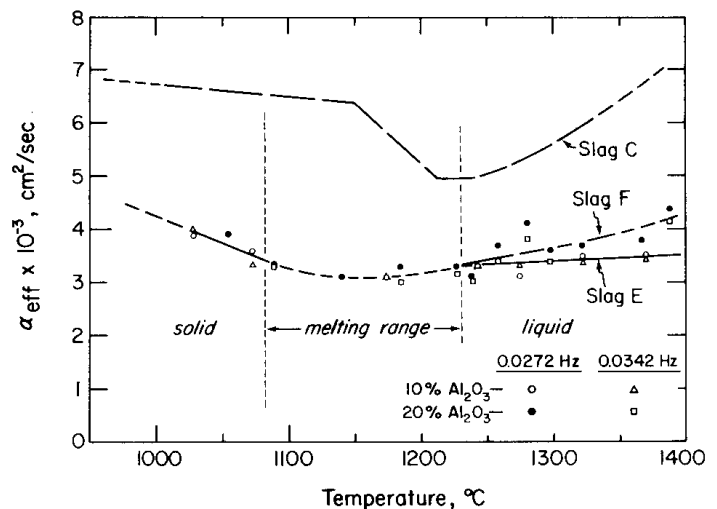


Fig. 2. Measured thermal diffusivities of slags<sup>2</sup>.  
Slag C: 60.6% FeO, 1.4% Fe<sub>2</sub>O<sub>3</sub>, 38.1% SiO<sub>2</sub>.  
Slag E: 55.1% FeO, 1.2% Fe<sub>2</sub>O<sub>3</sub>, 34.7% SiO<sub>2</sub>, 9.0% Al<sub>2</sub>O<sub>3</sub>.  
Slag F: 50.1% FeO, 1.1% Fe<sub>2</sub>O<sub>3</sub>, 31.5% SiO<sub>2</sub>, 17.3% Al<sub>2</sub>O<sub>3</sub>.

1 cal/cm<sup>3</sup>.°C. The measurements for a number of slags in the liquid state indicate that values of  $\alpha$  (and  $k$ ) do not change materially with composition as long as the FeO content is in excess of 10%, so that the slag is essentially opaque to the transmission of electromagnetic radiation with wavelengths of 0.5 to 10 microns<sup>1</sup>. It is to be noted that the thermal conductivity of slags in the solid state do not differ materially from that of the liquid state for the purposes of the research reported here.

A cold, solid metal object that is submerged in a bath of liquid slag will have a shell of solid slag formed on it immediately<sup>2,3</sup>. This slag will remelt gradually, but while it is present, it acts as the principal barrier to the transfer of heat from the body of liquid slag that is stirred by gas bubbling or other sources of agitation. The heat released because of solidification of the slag is relatively small; however, this heat is utilized in heating the metal and must be considered in analysis of the process<sup>2</sup>. Examples of measurements of the thickness of the solid slag shell on a nickel sphere are shown

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in Fig. 3. Gas injected into the slag through small pores in the sphere agitates the slag and results in the slag shell being thinner than when there is no agitation.

The slag shell may contain a number of pores as a result of gas bubbles being present in the slag as it freezes. The presence of these pores alters the thermal conductivity of the slag. The effective thermal conductivity,  $k_{eff}$ , of the shell can be estimated by the relationship:

$$k_{eff} = k_I(1-\psi) \cdot k_p$$

where  $k_I$  is the thermal conductivity of the slag from all effects,  $k_p$  is the thermal conductivity of the pore which must include both conductive and radiative effects. The fractional volumetric porosity of the shell is  $\psi$ .

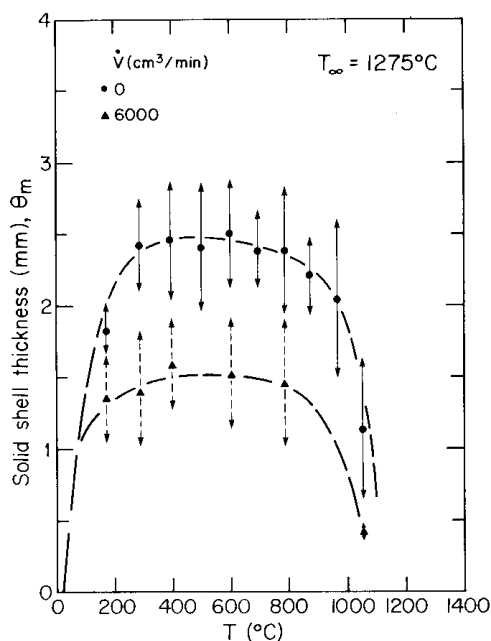


Fig. 3. Effect of gas evolved (NTP) from holes in metal sphere on thickness of solid shell of slag formed on sphere immersed in liquid slag (Slag II, 60.5% FeO, 1.4% Fe<sub>3</sub>O<sub>4</sub>, and 38.1% SiO<sub>2</sub>).

Measurements have shown that the behavior of a liquid slag as a medium for heat transfer can be described in terms of correlations of dimensionless numbers that apply to many liquids, e.g., the Nusselt number ( $N_{Nu} = hd/k_{eff}$ ) as a function of the Reynolds number ( $N_{Re} = vd/\nu$ ) and the Prandtl number ( $N_{Pr} = \nu/\alpha_{eff}$ ), where  $h$  is the heat transfer coefficient,  $d$  is a characteristic dimension,  $k_{eff}$  is the effective thermal conductivity of the liquid,  $v$  is the characteristic velocity,  $\nu$  is the kinematic viscosity and  $\alpha_{eff}$  is the effective diffusivity of the liquid. Thus, by knowing the flow regime for the liquid and the appropriate properties of the liquid, it is possible to predict the heat transfer coefficient for the liquid slag in contact with the solid shell of the slag, or with the surface of the metal particle if the slag shell has been melted.

It is to be recognized that the thickness of the solid shell is determined by the rate at which heat is transferred into the metal particle and the various factors that determine the rate at

which heat is supplied from the bulk of the slag<sup>2,3</sup>; i.e., the density, diameter and thermal conductivity of the D-R material or metal and the motion of the slag relative to the sphere, the bulk temperature and the liquidus and solidus temperatures, density, thermal conductivity and specific heat of the slag.

A number of measurements have been made of the rate at which spherical metal objects are heated when they are immersed in slags of various compositions. Because the heating process is influenced strongly by the motion of the slag, as is reflected in the fact that the Nusselt number is a function of the Reynolds and Prandtl numbers, the experiments were conducted by spinning a sphere in the slag and the temperature at the center of the slag was measured continuously<sup>2,3</sup>. The rate of heating of a sphere in slags of various compositions are shown in Fig. 4. An analysis of the heating process showed that the increased rate of heating resulted principally from the effects of small addition of agents, i.e., CaO and Al<sub>2</sub>O<sub>3</sub>, in lowering the liquidus and solidus temperature of a slag<sup>3</sup>.

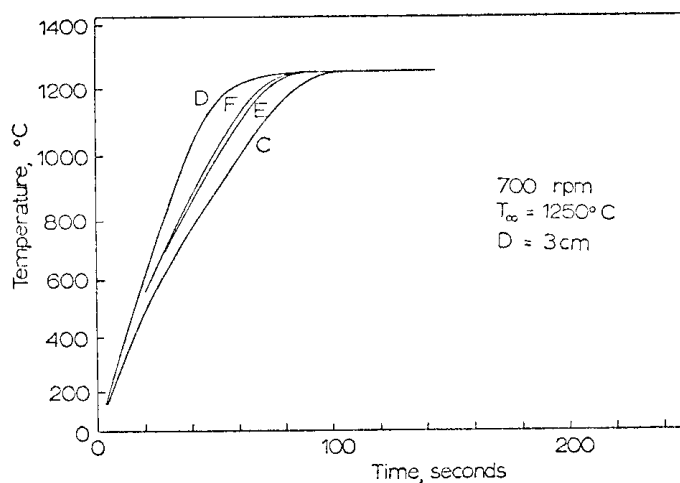


Fig. 4. Temperatures at the center of nickel spheres heated in slags C, D, E, and F. See Fig. 1 and 2 for slag compositions. Slag D is Slag C with 10% CaO added. Slags E and F are Slag C with 10% and 20% Al<sub>2</sub>O<sub>3</sub> added, respectively.

In the work reported here, measurements have been made of the thickness of the solid shell that may form on a cold metal sphere that has been immersed in a hot liquid slag, on the volumes and compositions of gases that are evolved from D-R iron particles as they are heated, and a mathematical model has been developed based on the currently reported results and earlier experimental work to estimate the influence of various factors on the residence time of D-R material when added to a hot slag. The important factors are the density and size of D-R particles, slag density, solidus and actual temperature of the slag, factors which determine the heat transfer coefficient of the liquid slag, and factors which determine the total amount of heat necessary to bring the particle to its melting point.

#### EXPERIMENTAL

The thickness of a shell of solid slag that forms on a sphere of metal in a hot liquid slag has been

measured by immersing cold nickel spheres in the slag and withdrawing them at selected times. Two examples of the results are shown in Fig. 3. The temperature at the center of each sphere was measured by a Pt-Pt/Rh thermocouple. The composition and properties of the slag employed and the properties of nickel from which the metal spheres (9 mm radius) were made are given in Tables I and II. The effect of evolution of gas from D-R iron materials was simulated by forcing nitrogen at a pressure of a few Torr through three small (0.5 mm diameter) ports in the lower portion of the sphere. Measurements were made with stationary spheres with and without simulated evolution of gas. The gas was supplied through a steel tube (12 mm O.D., 4 mm I.D.) that supported the sphere in the slag. The design of the sphere is shown in Fig. 5.

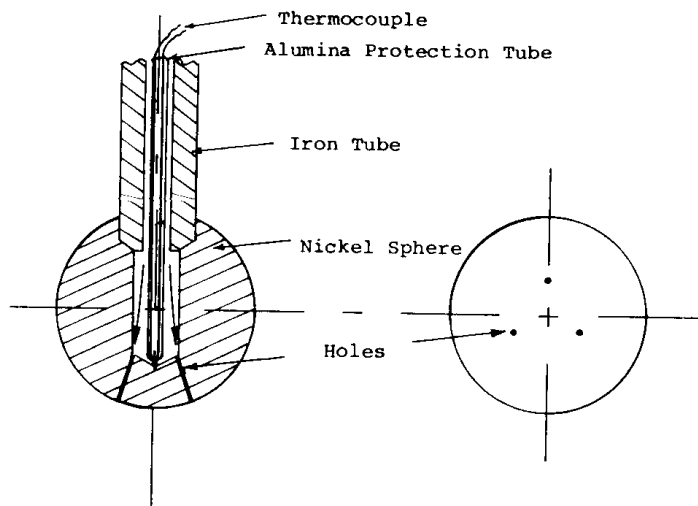


Fig. 5. Nickel sphere with thermocouple and gas parts.

The thickness of the slag layer was determined by immersing a sphere until the temperature at the center reached a desired value, and then the sphere was withdrawn. The slag shell was cracked off and its thickness at many places was measured with calipers. A cold sphere was employed for each measurement. Each vertical line in Fig. 3 shows the range of thickness of the shell obtained at a given center-line temperature. The mean thickness obtained for the shell at a central temperature of 600°C for a series of gas flow rates and bulk temperatures of the slag are shown in Fig. 6.

The bubbling of the gas from the sphere leads to a thinner slag shell on the average. There also was a slight grooving and local thinning of the shell on a line from the gas port to the top surface of the sphere.

The effects of gas evolution on the heating of stationary nickel spheres immersed in liquid slag are shown in Fig. 7. It is to be seen that there was little effect of gas evolution on the heating rate up to a center temperature of about 600°C. Above that temperature, the sphere heated more rapidly with higher rates of evolution of the gas. It is to be noted that the gas employed was argon, so it was chemically unreactive.

It appears that the apparently similar rates of heating up to approximately 600°C arises because the temperature near the center cannot respond in a short time to the higher heat transfer coefficient resulting from more active agitation of the slag

Table I. Compositions and Physical Properties of Slags

	Slag I	Slag II
Composition, wt%:		
FeO .....	40.5	60.5
Fe <sub>2</sub> O <sub>3</sub> .....	5	1.4
SiO <sub>2</sub> .....	40.5	38.1
CaO .....	7	--
Al <sub>2</sub> O <sub>3</sub> .....	5	--
MgO .....	1	--
S .....	1	--
Melting range <sup>3</sup> , °C .....	1125-1220	1140-1215
Density <sup>3</sup> , ρ, g/cm <sup>3</sup> .....	sol 3.8	3.7
	liq 3.5	3.6
Specific heat <sup>3</sup> , c <sub>s</sub> , cal/g·°C .....	sol 0.25	0.25
	liq 0.28	0.28
Thermal conductivity, k, cal/cm·sec·°C .....	sol 0.0043	0.0059
	liq 0.0046	0.0052
Heat of fusion <sup>3</sup> , h <sub>f</sub> , cal/g .....	102	80.7
Effective thermal diffusivity <sup>3</sup> , α, cm <sup>2</sup> /sec .....	sol 0.0045	0.0064
	liq 0.0047	0.0052
Viscosity <sup>4</sup> , η, poise .....	2.0	2.0
Kinematic viscosity, ν, cm <sup>2</sup> /sec .....	0.57	0.59

Table II. Physical Properties of Iron and Nickel

	Iron	Nickel
Specific heat <sup>4</sup> , c <sub>p</sub> , cal/g·°C, at temperature <sup>p</sup> , °C of:		
105 .....	0.115	0.113
340 .....	0.137	0.140
545 .....	0.170	0.127
740 .....	0.238	0.133
920 .....	0.153	0.139
1010 .....	0.153	0.142
Density <sup>4</sup> , ρ <sub>m</sub> , g/cm <sup>3</sup> .....	7.9	8.9
Thermal conductivity <sup>5</sup> , k, cal/cm·sec·°C .....	0.1746	0.2153

caused by the increased gas flow. The effect becomes noticeable only after some time, and when the temperature at the center rises above approximately 600°C. The overall more rapid rise in temperature probably results because the shell of solid slag is thinner, the shell melts away sooner, and the heat transfer coefficient in the liquid slag is increased because of agitation of the slag locally by the evolution of gas. As will be seen in the next section, the total volume of gas evolved from pellets 12 to 15 mm in diameter is in the range of 1,000 cm<sup>3</sup>/g (at temperature) for metallization in the range of 87-88 percent metallization to less than 700 cm<sup>3</sup>/g for metallization in the range of 92 percent. It is assumed that these pellets have "balanced" concentrations of carbon.

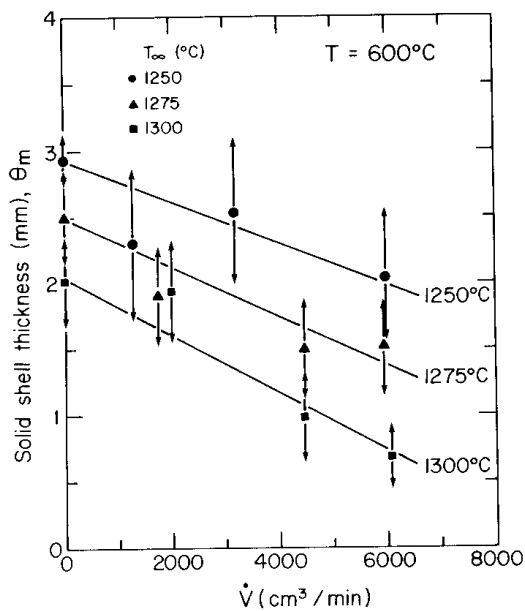


Fig. 6. Effects of bulk-temperature of slag and gas flow rate on mean thickness of solid slag shell formed on nickel spheres when center temperature of sphere was 600°C.  $T_\infty$  = temperature of bulk slag; 9-mm-radius nickel spheres. Slag composition, see Slag I, Table I.

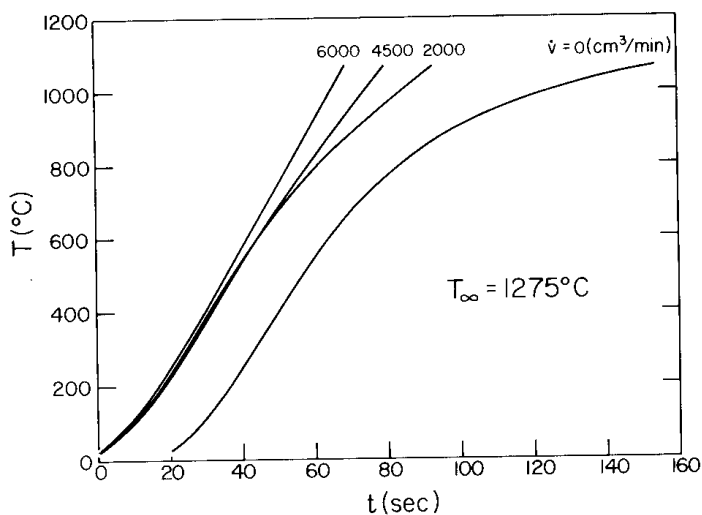


Fig. 7. Effect of gas evolution on heating of nickel spheres immersed in liquid slag. Spheres and slag employed are the same as for Fig. 3 and 5. Zero flow-rate curve is displaced 20 sec to the right.

#### Gases from D-R Iron

The volume, volumetric rate of evolution, and the composition of the gas evolved from D-R materials were measured by heating particles of the materials in a steel bomb. The bomb assembly and induction heating element are shown in Fig. 8. Initial experiments showed that with some of the commercially produced D-R products, there was a wide variation in the total volume of gas evolved from particle to particle. An average result was desired for each type of material, so the practice was followed of crushing the D-R pellets or lump ore and selecting two sizes of particles for study, 1 mm and 2 mm. For each group of pellets prepared

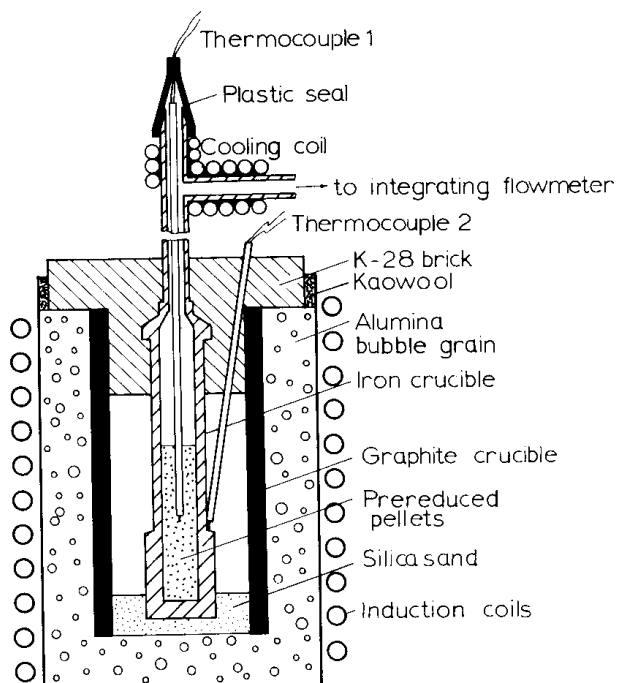


Fig. 8. Bomb assembly for determining gases evolved when heating D-R materials.

in this way, the results from run to run were quite consistent. Also, as will be shown later, the results for the two sizes chosen for study were also quite consistent. The volume of gases evolved by holding a sample of D-R material at constant temperature was determined in the apparatus shown in Fig. 9. This apparatus was also employed to determine the oxygen content of the material by hydrogen extraction.

The total volume of gas evolved when a given type of D-R iron was heated in the bomb apparently was controlled by the temperature of the material and its composition, i.e., %C and %O, but not by the rate of heating. Heating rates from 50 to 1000°C/min. were employed in the bomb extraction measurements; the results for 250°C/min. were typical and are shown for three types of materials in Fig. 10. The oxygen content of each type of material was obtained by hydrogen extraction employing the apparatus shown in Fig. 9. Essentially all of the gas to be evolved came off by the time that the material in the bomb reached 1200°C. The rate of evolution of gas as the temperature was raised was obtained by differentiating the plot of volume evolved versus time. The result for HyL pellets with approximately 89% metallization is shown in Fig. 11. The form of this type of curve was similar for all D-R materials studied. However, the peak at approximately 1000°C is smaller for materials containing less oxygen (higher degree of metallization). It is to be noted that it is

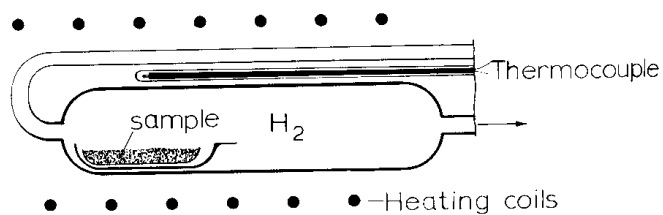


Fig. 9. Capsule and furnace for determining gases evolved with isothermal treatment of D-R materials.

necessary for the D-R material to have sufficient carbon to react with the oxygen to form CO and CO<sub>2</sub>, and the volume of gas is less if there is not a "balanced" carbon level relative to the oxygen content. Differential thermal analysis showed that the peak at approximately 700°C is associated with the eutectoid reaction in the iron-carbon system.

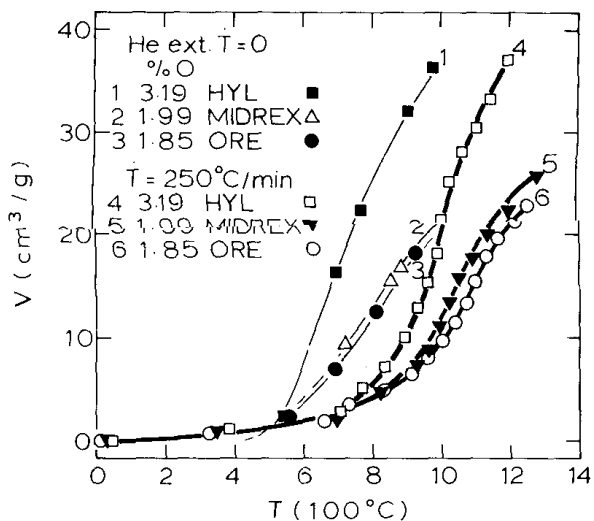


Fig. 10. Typical results of volume of gas evolved when D-R materials are heated. Curves 1, 2 and 3 are volumes obtained when materials were held at constant temperature for 10 hours. Curves 4, 5 and 6 were obtained when materials were heated at a rate of 250°C/min.

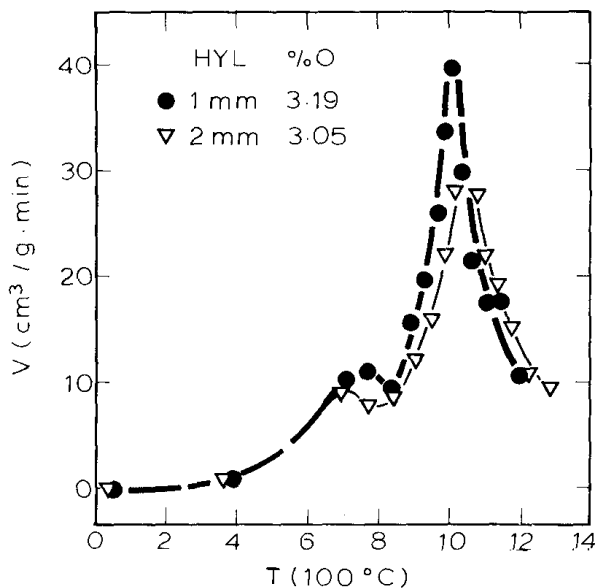


Fig. 11. Rate of evolution of gas from HyL pellet material heated in bomb at 250°C/min. Data the same as for line 4 in Fig. 10.

The oxygen content of each D-R material studied was determined by hydrogen extraction in which the evolved H<sub>2</sub>O and CO<sub>2</sub> were collected, and the loss in weight of the sample was measured. A materials balance on the system permitted the oxygen and carbon contents to be determined. In some cases with somewhat reactive material, the oxygen content was slightly higher than that reported by the manufacturer, possibly because of oxidation of the sample during shipping, storage and handling. To

minimize the pick-up of oxygen, all samples were stored in sealed containers.

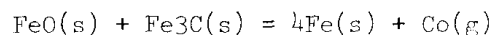
The carbon and oxygen contents of some of the D-R materials studied and the compositions of the gases evolved during the bomb heating tests are shown in Table III. The concentration of CO<sub>2</sub> in the gas from the HyL material was considerably higher than was obtained from the other materials. This probably results from the higher concentrations of oxygen (lower degree of metallization) in the HyL product. The amounts and compositions of gases evolved from the two sizes of particles from crushed samples of a material were similar and appeared to be within the variability of the results on repeated tests on a given sample.

#### Melting Times of D-R Materials

The information that has been described in the previous sections are essential to determining the rate at which a D-R particle is heated when it is immersed in a hot slag. However, the nature of motion of the slag relative to the particles in the slag also has a strong influence on the heating process as it establishes the rate at which heat is transferred from the bulk slag to the particle. The experiments with the spinning sphere show that the behavior of slags in this regard can be treated by the same dimensionless correlations that are employed with other liquids. Thus, to complete the analysis, it is necessary to obtain from the nature of boiling of the slag due to evolution of CO gas, the principal agent for stirring of the slag in an electric furnace, to the Nusselt number for the slag in the region around a pellet.

Of the many analyses that have been discussed in the literature, the work of Brian and Hales<sup>6</sup> provides a basis for relating the energy from gases expanding and rising in the slag with the Nusselt number. Using their correlation, the Prandtl number ( $N_{Nu} = \mu/\rho\alpha$ ) for a ferrous-silicate slag of approximately 150, and the typical range of carbon removal as CO gas to cause boiling of the slag in electric furnace operations, it is possible to estimate the heat transfer coefficient for a solid particle of D-R material immersed in a boiling slag. The range of values is approximately 0.0001 to 0.002 cal/cm<sup>2</sup>·sec·°C (0.7 to 15 BTU/ft<sup>2</sup>·hr·°F) for conditions of a very low agitation of the slag to a modest boil, and 0.002 to 0.15 cal/cm<sup>2</sup>·sec·°C (15 to 1100 BTU/ft<sup>2</sup>·hr·°F) for boiling conditions ranging from modest to very vigorous.

The time required to melt a single spherical D-R pellet that is immersed in hot liquid slag was calculated from the data given here by use of a finite-difference computer model of that heat-transfer process as was described earlier<sup>2</sup>. The important parameters employed in the calculations for spherical D-R materials are shown in Table IV. It was assumed in this set of calculations that the slag was typical of electric arc furnace operations whose bulk temperature was 1600°C with a liquidus temperature of 1530°C. Calculations were made for materials having various percentages of metallization and with a balance between the oxygen and carbon contents. The carbon was assumed to be present as Fe<sub>3</sub>C so that the reactions to form the carbonaceous gases were



and

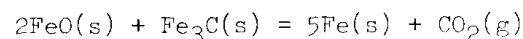


Table III. Composition of Gas Evolved from D-R Materials in Bomb Evolution Tests

Type of Material	Composition		Gas Evolved		
	%O*	%C <sup>†</sup>	%CO <sub>2</sub>	H <sub>2</sub> O	CO
Hyl Pellets					
D .....	3.19	2.22	6.0-6.2	nil	Bal
B .....	3.28	2.21	6.4	nil	Bal
Midrex Pellets .....	1.99	1.78	2.1-1.8	nil	Bal
Midrex Lump Ore .....	1.85	1.07	-	-	-

\*Hydrogen extraction, 1 mm particles  
<sup>†</sup>Reported by manufacturer

in the appropriate ratio to provide a gas containing 6 percent CO<sub>2</sub> with the balance CO.

The thermal balance in the model accounted for the heats of the reactions, the heats of fusion of all constituents, and the enthalpy increments of all constituents from room temperature to 1530°C, the assumed melting point of the iron. The model also included the formation and melting of the solid shell of the slag on the pellet. The Nusselt number in each calculation was based on the diameter of the pellet plus the added thickness of the slag shell. A vigorously boiling slag giving a heat transfer coefficient in the range of 0.01 cal/cm<sup>2</sup>.sec.°C (74 BTU/ft<sup>2</sup>.hr.°F) was assumed. An example of the calculation of temperatures in the pellet and slag shell for a 10 mm diameter pellet with a density when charged of 2.5 g/cm<sup>3</sup> is shown in Fig. 12. The calculation shows that approximately 35 seconds are required to melt the pellet for this system.

The effects of density, diameter, and percent metallization of pellets on the time required to completely melt spherical pellets were evaluated with the computer model. The results are shown in Fig. 13. Again a slag with a liquidus temperature of 1530°C and bulk temperature of 1600°C was em-

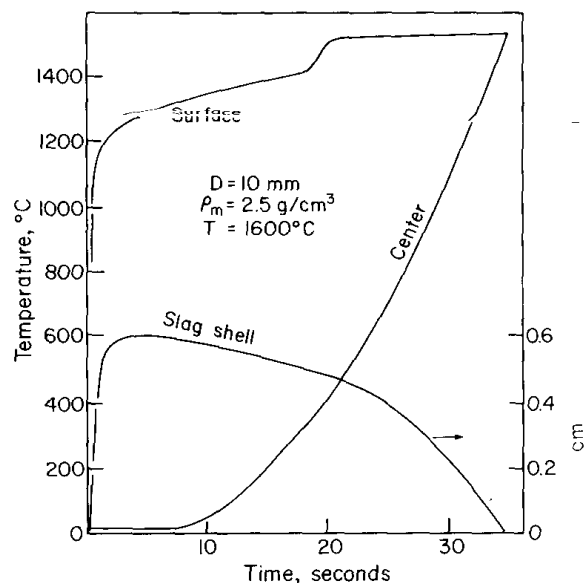


Fig. 12. Calculation of temperatures at surface and center and thickness of solid shell of slag of spherical, 10-mm-diam D-R pellet in hot (1600°C) liquid slag. Conditions of system are given in Table IV. 90% metallization.

Table IV. Properties of Slag and D-R Pellets Employed in Calculating Melting Times for Electric Furnace Operations

<u>Slag</u>	
Depth, L, cm .....	30
Density, $\rho_2$ , g/cm <sup>3</sup> .....	2.9
Thermal diffusivity, $\alpha$ , cm <sup>2</sup> /sec .....	0.004
Specific heat, $c_s$ , cal/g.°C ..	0.28
Melting point, °C .....	1530
Bulk temperature, °C .....	1600
Heat transfer coefficient, h, cal/cm <sup>2</sup> .sec.°C .....	0.01
<u>D-R Pellets</u>	
Density, $\rho_p$ , g/cm <sup>3</sup> .....	2 to 6
Radius, $r_p$ , cm .....	5, 10, 20 mm
Melting point, °C (liquidus) ..	1530
Heat of fusion, H, cal/g .....	60
Metallization, % .....	80, 90

ployed. In making the analysis, it was assumed that pellets with densities of less than 3 g/cm<sup>3</sup> remained suspended in the slag because of agitation of the slag and buoyancy effects of bubbles being evolved from the pellets. However, the larger pellets with higher densities were assumed to fall through the slag to the slag-metal interface where the rate of transfer of heat to the pellet was much larger, providing the temperature of the metal bath was maintained well above the melting point of the D-R material, i.e., 1530°C. This effect is also shown in Fig. 13. The higher density 5 mm diameter pellets were assumed to remain in the slag because their melting times were so short that they would melt completely before falling to the slag-metal interface.

#### Discussion

The calculated results (Fig. 13) show that the melting times of D-R pellets immersed in a vigorous-

ly boiling hot slag are influenced strongly by the size of the pellet. Increasing the density of the material apparently does not have a large effect until values in the range of  $3 \text{ g/cm}^3$  are reached. Then the larger sized pellets with diameters of greater than approximately 8 mm and initial densities of greater than that of the boiling slag ( $\rho > 3 \text{ g/cm}^3$ ) will tend to pass relatively rapidly to the slag-metal interface where melting can be completed rapidly, providing that the metal bath is sufficiently hot to complete the melting of the pellet. The descent to the slag-metal interface is speeded by sintering and fusion of the metal which increases rapidly the density of the particle.

body of liquid slag. The results probably apply for relatively high rates of feed of D-R materials to a furnace as long as the rate of input of heat to the slag is sufficient to maintain the bulk temperature 50 to  $75^\circ\text{C}$  above liquidus temperature of the D-R iron as melting proceeds, and about the same interval above the liquidus temperature of the slag. Experiments with the heating of elongated metal objects and of pairs or triplets of pellets in slag show that the heating time for a cluster of spherical pellets is much longer than that of a single pellet. For example, four 10 mm diameter pellets in a close-packed tetrahedral array can be expected to require a longer heating time than a single 20 mm diameter pellet which has the same total mass as do the four. With the small pellets, the rate of heating is governed essentially by the area of contact between the pellet and the slag so that the time of heating is approximately proportional to the diameter, and to the density of the pellet. With larger pellets, the transport of heat within the pellet also becomes important and the heating time goes up faster than the radius; with increased density, the range of proportionality of time of melting to particle diameter is extended.

An important aspect of continuous melting of D-R materials by continuous feeding of particles into the electric furnace is the actual mass of material "held up" in the slag, because the greater the amount with a given stirring action and heat input, the more likely two particles may come into contact, stick together and require a longer time to melt. If this occurs frequently, the ability to process materials through the slag is reduced. At a fixed steady-state mass feed rate, the amount of material "held up" in the slag is proportional to the melting time. For example, from Fig. 13, it is estimated that a feed of 10 mm pellets having a density of  $2.8 \text{ g/cm}^3$  will result in a hold up of approximately 0.63 times the feed rate. However, a feed of 20 mm pellets with a density of  $2.8 \text{ g/cm}^3$  will result in a hold up of approximately 1.78 times the feed rate. Although the hold up in the second case is almost three times that of the first, the actual number of the smaller particles being present in the slag at steady state would be 2.8 times as many as of the larger ones for the same feed rate. This ratio results from the fact that each larger particle has 8 times the mass of a smaller one.

There is a great deal more to be done in modeling the melting of D-R pellets in electric furnaces. For example, the effects of the formation of "islands", or aggregates, of cold pellets on the melting rate should be evaluated, particularly as to what happens to such islands when they float under the electrodes so that the arc will strike on them. A second important issue is how a foaming slag arising from evolution of gas from particles in the slag affects the overall transfer of heat from the arcs via the slag and metal bath to melt D-R iron materials when they are fed continuously to the furnace.

#### Summary

Recent results on the rate at which D-R pellets will melt when submerged in hot liquid slags have been summarized. Results on the compositions and amounts of gases evolved from several types of D-R iron materials indicate that although the

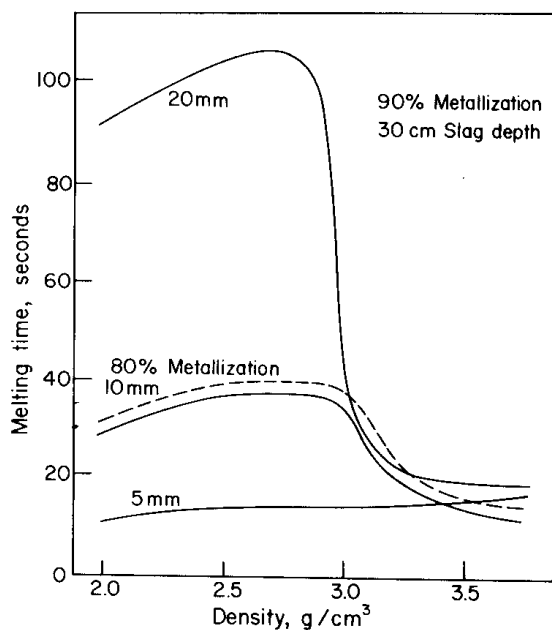


Fig. 13. Calculated times for melting of individual spherical D-R iron pellets that are immersed in a vigorously boiling, hot ( $1600^\circ\text{C}$ ) electric furnace slag. Conditions of system are given in Table IV. 90% and 80% metallization.

It is often argued that it is most advantageous when employing continuous feeding D-R iron material to an electric furnace to have material of the highest density possible, e.g., 7 to  $7.2 \text{ g/cm}^3$ . This would be true only if furnace operations were such that the bath was supplied heat at a rate rapid enough to keep the temperature of the bath above the melting point of the D-R material. That may be difficult to do, even with an actively boiling system. In such a system, the slag will be hot and must act as an agent for transfer of heat to the bath. Actual operating experience and the calculations described here suggest that the melting of less dense pellets that remain in the slag can be very rapid<sup>7</sup>. The investigation that is described here has not as yet reached the level of sophistication where it would be possible to decide on the optimal conditions of the physical and chemical characteristics of the D-R materials, of the character of the slag, and of furnace operating conditions for melting of D-R materials. The analysis required is complex and the work is progressing.

The experiments and analyses presented here related to the melting of individual particles in a

rate of evolution of gases from the materials is strongly dependent on the rate of heating, the total volume of gas evolved is not influenced by the rate of heating, but apparently is governed principally by the oxygen and carbon contents of materials. The gas evolved is principally CO with 2 to 6 volume percent CO<sub>2</sub>.

A computer simulation of the melting of single particles immersed in a hot liquid slag has been developed based on the experimental studies. The model reproduces mathematically the essential characteristics of the melting process which were elucidated from the experimental results, and permits determination of the time required to melt a particle of given diameter and density in a particular hot liquid slag. The parameters that describe the intensity of mixing of the slag, the bulk temperature of the slag, and the solidus temperature of the slag are important components of the model.

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#### REFERENCES

1. Fine, H. A., Engh, T., and Elliott, J. F., Met. Trans. B, vol. 7B, June 1976, pp. 277-285.
2. Elliott, J. F. and Nauman, J. D., Proc., Int. Symp. on Slags, Metals and Gases, Electrochem. Soc., Toronto, Canada, May 1975, pp. 238-250.
3. Nauman, J., Foo, G., and Elliott, J. F., Proc. Int. Symp. on Copper Extraction and Refining, TMS-AIME, Las Vegas, Nev., Feb. 1976.
4. Elliott, J. F., Gleiser, M. and Ramakrishna, V., Thermochemistry for Steelmaking, vol. II, Addison-Wesley Press, Inc., No. Reading, Mass., 1963.
5. Eckert, E. R. G. and Drake, R. M., Jr., Analysis and Heat and Mass Transfer, McGraw-Hill Book Co., New York, 1972.
6. Brian, P. L. T., Hales, H. B., and Sherwood, T. K., A.I.Ch.E. Jnl., vol. 15, no. 5, 1969, pp. 727-32.
7. Elliott, J. F. and Wright, J. K., Proceedings, 33rd Electric Furnace Conference, ISS-AIME, vol. 33, Dec. 1975.