CHAPTER IV

RESULTS

Illustrative results of the experiments are divided into three categories: (1) information on volume and composition of gases from D-R materials, (2) results of phase transformation studies, and (3) data obtained from heat transfer measurements in hot slags.

A. Formation of Gas in DRI

Results of the experimental studies on formation of gas in DRI are presented under constant and variable temperature extractions. Sample examples are described.

1. Constant Temperature Extraction

The oxygen contents of DRI samples that react with hydrogen or carbon during hydrogen extraction tests are given in Tables 4-1 and 4-2. The size of the grains and the analyses of the materials reported by manufacturer are also specified.

The exhaust of the hydrogen extraction capsule contained H_2 , H_2^0 , CO and CO₂, while that of the helium extraction capsule contained He, CO, CO₂ and a small amount of water vapor that did not exceed 1.5 cubic centimeter of cold gas per gram of DRI. The reduction reactions that occur during final reduction of samples under hydrogen and helium are described in Chapter VI.

The composition of the gases produced during He extraction tests was determined as a function of the temperature of the capsule. The oxygen and carbon contents of the samples that reacted during a test were deduced from these data. Since the carbon contents of a number of samples exceed the balance of oxygen for complete reduction of DRI, the

-	Size	Pellet Type	- G	Α	В	C	D	Н
	mn	% Met	(94.3)	(93.6)	(89.9)	(93.9)	(89.4)	(93.0)
		%0			3.28	2.22	3.19	2.43
Extraction		S.D.			0.26	0.07	0.11	0.32
	ı¢	% C			2.23	1.57	2.08	1.40
		S.D.			0.17	0.08	0.08	0.34
		%0	2.01	2.17	3.24	2.14	3.05	
en	2 ^X	S.D.	0.32	0.22	0.29	0.03	0.12	
drpg		%C	1.06	1.18	2.44	1.50	2.04	
Hy		S.D.	0.22	0.10	0.21	0.06	0.08	
alysis	#	(% 0)		(2.23)	(3.45)	(2.11)	(3.61)	
		%C		1.67	2.21	1.93	2.22	
An		S.D.		0.05	0.04	0.04	0.02	

Table 4-1 Chemical Composition of HYL Pellets*

*Figures within parantheses are calculated from the data on chemical analysis of DRI based on the assumption that the pellets contain 5% Gangue.

[#]Reported by manufacturer.

¢ 16-18 mesh screens with openings of 1190-1000 microns.

 χ_{8-10} mesh screen with openings of 2.0 - 2.38mm.

Size	Pellet type	E	E (0.6 mm)	F	Lump Ore
m	% Met	94.6		91.7	92.0
	% 0	1.99	1.90	2.55	1.85
c	S.D.	0.05	1.12	0.17	0.10
	% C	1.38	1.38	0.93	1.07
xtra(S.D.	0.01	. 0.13	0.13	0.05
년 u a	% 0	1.87			
a Bort 2	S.D.	-			
Hyo	% C	1.35			
	S.D.	-			
# 0	% 0	1.48		2.14	2.17
lysi	% C	1.78		0.90	1.00
Ana	% Gangue	5.54		11.66	3.03

Table 4-2. Chemical Composition of MIDREX materials.

#Reported by manufacturer.

quantities obtained from extraction tests may be less than the total carbon content of the samples.

a. Period of Total Reduction

The time necessary for reduction reactions to approach an equilibrium state was about 10 hours and was chosen as the standard period for long term reduction of DRI samples.

In Figure 4-1, the rates of reduction of the 1 mm size samples of types B and E at 750°C are plotted against the reaction time. From this figure, % 0/% C ratio for the long-term (10 hours) extraction of type B pellets is 1.8. This ratio is 1.5 for type E. The volume fraction of CO_2 is therefore no more than 0.36 for type B and no more than 0.13 for type E pellets, at 750°C. A plot is made of the total volume of the gases evolved (CO, CO_2 , H_2O) from these samples as a function of the extraction time in Figure 4-2.

b. Long-Term Helium Extraction

Results of the 10-hour reduction of type B pellets under a helium atmosphere and at various temperatures are shown in Table 4-3. The percentages of oxygen and carbon that have undergone reaction are given in this table. The results show that above 700°C, CO is the major component of the exhaust while CO_2 and H_2O partial volumes decrease as temperature rises. These results are explained in terms of the equilibria of the reactions in Chapter VI. Similar data for various DRI samples with different chemical compositions are given in Tables 4-4 to 4-8. The total oxygen and carbon contents of the samples shown in parentheses are selected from the data of Tables 4-1 and 4-2.



Fig. 4-1

Percentage of Reacting Oxygen and Carbon of Types B and E Pellets vs. Period of Helium Extraction. Temp. of Furnace, 750°C. Particle Size, 1 mm.



Fig. 4-2 Total Volume of Released Gas During Helium Extraction of Types B and E Pellets. Temp. of Furnace, 750°C. Particle Size, 1 mm.

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	(%0	= 3.26, %	C = 2.21).				
	-				V(C	m ³ /g)	
T(°C)	Size (mm)	<u>%0</u>	%C	<u>co/co</u> 2	н ₂ 0	^{CO} 2	CO
505	2	0.08	0.00	0.0	0.2	1.2	.0.0
583	2	0.67	0.29	0.5	0.4	3.6	1.8
673	2	1.38	0.70	1.2	0.3	6.0	7.1
727	1 .	1.65	0.90	1.7	1.3	3.1	15.6
746	1	2.06	1.13	1.8	0.3	7.5	13.6
768	2	2.00	1.17	2.8	0.3	5.8	16.1
840	2	2.22	1.44	6.1	0.3	3.8	23.2
891	1	2.75	1.78	5.8	0.4	4.9	28.3
935	2	2.48	1.65	6.9	0.0	3.9	27.0
985	2	3.12	2.07	6.7	0.1	5.1	33.5

Table 4-3 Results of the Extraction for Type B Pellets

* The chemical compositions are selected from the data of Table 4-1.

The total volumes of gas are plotted against the temperature of the capsule in Figures 4-3 and 4-4. The effects of the size of the samples on these volumes are also shown. As is seen, the results of the 2 mm size samples do not differ appreciably from those of the 1 mm ones. However, the spread of the data obtained from the extraction of the 3 mm size samples is substantially wider than that of the others. This difference is probably due to the lack of homogeneity in chemical composition of the 3 mm crushed materials.

To prove that the total volume of the evolved gas is basically controlled by the chemical composition of the charge, 30% totally reduced type D pellets were mixed with 70% non-reduced ones to prepare a new sample (designated H in Table 4-1) with the same composition as that of type C. The results of hydrogen extraction for this sample (H) is given in Table 4-1. As is seen, the oxygen content of sample H is about 10% more than that of type C pellets.

The data obtained from helium extraction of sample H are illustrated in Table 4-5 and Figure 4-3. These data show that the total volume of the extracted gas and the content of oxygen removed from the sample are also about 10 percent higher than that of type C. This result indicates that the total volume of the evolved gas is nearly proportional to the oxygen content of DRI materials, if there is sufficient carbon available to react with the oxygen.

The results of helium extraction tests (Figures 4-3 and 4-4 show that the evolution of gas from DRI starts around 500°C, continues proportional with temperature and slows down as the temperature exceeds



Fig. 4-3 Total Volume of Gases Evolved During He Extraction of D-R Materials.



Fig. 4-4 Total Volume of Gases Evolved During He Extraction of D-R Materials.

					V (cm^3/g	
T(°C)	Size (mm)	<u>%0</u>	%C	co/co ₂	H ₂ O	<u> </u>	CO
420	2	0.00	0.00	0.0	0.1	0.2	0.0
543	1	0.35	0.11	0.0	0.5	2.5	0.0
553	2	0.40	0.15	0.2	0.2	2.5	0.4
608	3	0.88	0.40	0.5	0.0	4.9	2.6
673	2	1.45	0.73	1.1	0.2	6.4	7.3
695	1	1.64	0.83	1.3	0.9	6.7	8.8
737	3	2.64	1.53	2.2	0.0	9.1	19.6
774	1	1.95	1.19	3.7	0.2	4.7	17.5
803	2	2.02	1.28	4.5	0.1	4.3	19.5
903	2	2.53	1.67	6.3	0.0	4.3	26.9
908	1	2.62	1.71	6.0	0.1	4.6	27.4
940	3	2.55	1.57	4.8	1.4	5.0	24.3
978	1	2.96	1.95	6.2	0.0	5.1	31.4
997	1	2.77	1.79	6.2	0.8	4.7	28.7
1028	2	2.89	1.94	7.8	0.2	4.1	32.0

Table 4-4 Results of the Extraction for Type D pellets (%0 = .3.12, %C = 2.22).

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T(°C)	Size (mm)	<u>%0</u>	%C	co/co ₂	V(cm H ₂ O	$\frac{3}{2}$
565	1	0.24	0.05	0.0	0.8	1.7 0.0
615	1	0.51	0.14	0.0	0.9	3.6 0.0
651	1	0.47	0.23	0.9	0.0	2.3 2.0
662*	1	0.67	0.30	0.9	0.9	2.9 2.7
674	1	0.72	0.35	1.3	0.7	2.9 3.6
676	1	0.70	0.35	1.7	0.8	2.5 4.1
746	1	0.88	0.53	3.3	0.1	2.3 7.7
746*	l	1.08	0.70	3.0	1.0	2.0 10.1
747	2	0.94	0.60	5.1	0.1	1.8 9.4
853	1	1.52	0.96	6.7	1.1	2.3 15.5
890*	1	1.70	1.08	4.5	0.2	3.4 16.7
937	1	1.56	1.07	9.7	0.0	2.2 17.8
971	1	1.65	1.12	8.5	0.0	2.4 18.7

Table 4-5 Results of He Extraction for Type C Pellets

(%0 = 2.18, %C = 1.93).

* Results of He Extraction of Type H Pellets.

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Table	e 4-0 Results (n ne Exclact	1011 101	Type G t	errers	•	
<u> </u>	(7	<u>%0 = 2.01, %C</u>	= 1.06)	•		•	
T(°C)	Size (mm)	<u>%0</u>	%C	co/co ₂	<u><u>v</u>(<u>H</u>20</u>	<u>cm³/g</u>)
487	2	0.09	0.04	0.0	0.0	0.9	0.0
683	2	0.99	0.58	2.1	0.0	3.5	7.4
849	2	1.27	0.77	4.2	0.6	2.8	11.7
970	2	1.72	1.13	6.1	0.0	3.1	17.9
997	2	1.46	0.96	6.5	0.1	2.4	15.6

Table 4-6	Results of	He	Extra	ction	for	Туре	G	Pellets
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-	- -	•		<u>.</u>	V ((cm ³ /g)	
T(°C)	Size (mm)	%0	%C	co/co ₂	^H 2 ^O	^{C0} 2	CO
558	0.6	0.22	0.07	0.0	0.3	1.3	0.1
691	0.6	0.53	0.31	2.6	0.0	1.8	4.6
718	1	0.81	0.49	3.6	0.2	2.0	7.1
823	0.6	1.04	0.69	6.7	0.0	1.8	11.2
854	1	1.23	0.80	7.6	0.6	1.7	13.2
882	1	1.31	0.90	9.9	0.0	1.7	15.2
933	0.6	1.54	1.03	10.0	0.5	1.8	17.5
982	1	1.34	0.94	13.4	0.0	1.4	16.1
996	0.6	1.55	1.07	11.7	0.1	1.6	18.4

Table 4-7Results of He Extraction for Type E Pellets(%0 = 1.92, %C = 1.78).

					V(c	-	
T(°C)	Size (mm)	%0	%C	co/co ₂	^H 2 ^O	^{CO} 2	CO
559	1	0.29	0.12	0.3	0.1	1.8	0.5
692	1	0.65	0.36	2.2	0.2	2.1	4.6
808	1	1.04	0.66	5.2	0.1	2.0	10.4
917	1	1.49	0.95	5.0	0.0	3.0	15.1
923	1	1.53	0.97	4.7	0.0	3.2	15.0
993	1	1.63	0.94	5.0	0.0	5.5	12.1

Table 4-8. Results of He Extraction for Lump Ores (%0 = 1.85, %C = 1.00).

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900°C. At about 1200°C, the reactions become almost complete and the gas evolution stops. It is also shown that the total volume of gas decreases as the oxygen content of a sample falls off.

2. Variable Temperature extraction

To study the nature of the DRI melting process, we need to know the quantity and composition of the gases that evolve during heating of prereduced materials. Such information can be utilized to determine the changes of properties of materials and to develop a mathematical model for predicting the behavior of the melting system. The rates of evolution and composition of gases are determined by extracting DRI in a bomb and are used to evaluate the total volume of the gases evolved from DRI.

a. Gas Evolution History

The rate of evolution of gas during the bomb extraction of DRI was measured and plotted against the temperature of the center of the charge. This rate was integrated to obtain the total volume of the released gas. The effects of size, composition and the rate of rise of temperature of DRI on the rate and volume of the gases evolved were determined.

The measured temperature of the charge usually fluctuated around the predetermined temperature profile. The results of the bomb extractions were corrected for the actual rate of change of temperature of the sample by multiplying the measured gas rate with a correction factor. The method of derivation of this factor and a sample example of the procedure used to analyze the results of the bomb extractions are described in Appendix C.



Fig. 4-5 Gas Evolution from Type B Pellets. Temp. Rate, 250°C/min. Particle Size, 1 mm.



Fig. 4-6 Gas Evolution from Midrex Lump Ore. Temp. Rate, 250°C/min. Particle Size, 1 mm.

Plots are made of the rate of evolution of gas from type B pellets and lump ore materials in Figures 4-5 and 4-6. As is seen, the evolution of gas starts at about 600°C, reaches a maximum at about 700°C, decreases to a minimum at about 800°C, rises to a peak at around 1000°C, and falls off above that. A similar pattern has been obtained during the bomb extraction of DRI samples of various compositions (see Figures 4-11 to 4-13).

The shorter peak in gas evolution curve corresponds with the reduction of magnetite to wustite during which a gas mixture of about 50 percent CO will be produced. The carbide constituent of DRI also starts into solution around the same temperature (see IV.B). The larger peak is associated with the final reduction of wustite to pure iron. Above 1400°C, the rate of evolution of gas tends to zero. A detailed description of gas evolution from DRI is given in Chapter VI.

The total volume of gas was obtained by calculating the area under the gas evolution rate diagrams of DRI samples:

$$V_{t} = \int_{0}^{t} \dot{V} dt \qquad (4.1)$$

where ∇_t is the total volume of the gas evolved from DRI until time t and $\dot{\nabla}$ is the rate of evolution of gas at that time. The Trapezoidal Integration method was used for calculation of the area under the curve.

A plot is made of the total volume of the gases evolved versus temperature for type B pellets and lump ore materials in Figure 4-7. The helium extraction curves for these materials are reproduced in the same diagram. It is seen that the volumes of the gases evolved during



Fig. 4-7 Gas Evolution from Type B Pellets (1,3) and Midrex Lump Ore (2,4). Particle Size, 1 mm.

bomb extraction of the samples are less than those evolved during helium extraction.

Effects of chemical composition, size and the rate of rise of temperature on evolution of gas from DRI are described in subsequent sections.

1. Effect of DRI Composition

The total volumes of gases evolved during bomb extraction of DRI samples of different chemical compositions are plotted in Figures 4-8 and 4-9. The data points for curves which are reproduced are not shown. As is seen, the volumes are higher for DRI samples of higher oxygen contents. The carbon contents of the samples are almost sufficient for total reduction. The effect of the percentage of carbon can therefore be assumed insignificant.

In Figure 4-10, a plot is made of the total volumes of the gases evolved per gram of DRI materials and the balanced content of carbon that is necessary for release of these volumes against percent of metallization of DRI at different extraction temperatures. From this plot, it can be seen that the volume of the gases evolved is almost proportional to the oxygen content of DRI.

A comparison is made of the rate at which gases are evolved from D-R materials of type C with that of type H in Figure 4-11. It is seen that the 10 percent difference in oxygen content of the samples proportionately affects the rates of gas evolution. Because of the deficiency of carbon for total reduction of type H, however, the total volume of gases evolved from type H is less than that of type C at high temperatures.



Fig. 4-8 Gas Evolution from DRI. Grain Size, 1 mm. Temp. Rate, 250°C/min.



Fig. 4-9 Gas Evolution from DRI. Grain Size, 1 mm. Temp. Rate, 250°C/min.

Fig. 4-10 Gas Evolution as a Function of Chemical Composition of D-R Materials. Temp. Rate, 250°C/min.

Fig. 4-11 Comparison of Gas Evolution from Type C and Partially Reduced Type H Pellets. Temp. Rate, 250°C/min. Particle Size, 1 mm.

Fig. 4-12 Rate of Gas Evolution from Type D Pellets. Temp. Rate, 250°C/min. Particle Size, 1 and 2 mm.

Fig. 4-13 Rate of Gas Evolution from Type E Pellets. Temp. Rate, 250°C/min. Particle Size, 1 and 2 mm.

Fig. 4-14 Comparison of Gas Evolution During Bomb Extraction of D-R Materials of 1 and 2 mm Size.

2. Effect of Particle Size

Experimental results show that the effect of particle size on evolution of gas from DRI is not substantial. Comparisons are made of the rate of evolution of gas from D-R materials of 1 and 2 mm size in Figures 4-12, 4-13 and 6-2. The total volumes of the gases evolved are also compared in Figure 4-14. As is seen in these figures, the evolution of gas is slightly higher from samples of 1 mm grain size. The difference may be due to the difference in chemical composition of 1 and 2 mm crushed pellets.

It is seen from Figures 4-12, 4-13 and 6-2 that above about 1000°C the rate of evolution of gas from DRI shifts slightly to the higher temperatures as the particle size increases. This effect may be because of the variation of the thermal conductivity of DRI with grain size. A further explanation is given in Chapter VI.

3. Effect of Heating Rate

The effect of the rate of rise of temperature of DRI on evolution of gas from D-R materials is illustrated in Figures 4-15 and 4-16 where temperature rates ranging from 50 to 1000°C/min are employed. As is seen, the volume of the gases evolved is slightly influenced by the rate of rise of temperature of DRI. As this rate becomes greater, the total volume of the gases evolved increases below 1000°C but decreases above that temperature.

Comparisons are also made of the rate of evolution of gas from DRI materials heated under various temperature rates in Figures 4-17 and 4-18. It is seen that the rate of evolution of gas increases as the

Fig. 4-15 Effect of Heating Rate on Gas Evolution from Type B Pellets. Particle Size, 1 and 2 mm.

Fig. 4-16 Effect of Heating Rate on Gas Evolution from Type G Pellets. Particle Size, 2 mm.

Fig. 4-17 Comparison of Gas Evolution from Type B Pellets at Different Heating Rates. Particle Size, 1 and 2 mm.

Fig. 4-18 Comparison of Gas Evolution from Type E Pellets at Different Heating Rates. Particle Size, 1 mm.

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heating rate increases. For 1000°C/min, the evolution of gas occurs even at very low temperatures, but the smaller peak of the rate curves is eliminated.

b. Composition of Gas

The composition of gases evolved during bomb extraction of D-R materials was determined by analyzing the outlet gases from the bombs. These gases were principally CO with an undetectable $(\pm 0.1 \text{ cm}^3/\text{g}) \text{ H}_2^0$ content. The results are given in Table 4-9.

B. DRI Extraction Path

The temperatures at which DRI materials underwent a phase transformation were determined by differential thermal analysis of DRI. The rate of change of temperature during thermal analysis of DRI was about 10°C/min. Due to the higher thermal conductivity of DRI, the temperature of the sample was greater than that of the reference (powdered alumina). The difference was plotted against the temperature of the sample. Because of variation of the chemical composition of DRI, the transformation temperatures obtained during heating of DRI samples were not the same as those measured during cooling.

The results of bomb extractions were utilized to determine the changes of chemical composition of DRI materials when heated. The carbon and oxygen contents of the samples were determined by subtracting the quantities that underwent reduction reactions from the initial values.

The changes of oxygen and carbon content of different D-R samples as their temperature is increased are traced on binary iron-oxygen and

lable	4-9 Composit	ion of Gases	s Evolved Iro	m DRI.
Temp. Range, °C	<u>T, °C/min</u>	Pellet Type	Particle size, mm	%co ₂
25-1285	250	В	1	6.36
25-1282	150	D	2	6.01
25-1315	250	D	1	6.19
25-1323	250	D	2	5.98
1207-1299	250	F	1	2.67
943-1358	250	G	2	7.86
25 - 1219	250	Е	l	2.09
25 - 1268	250	E	1	1.78

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Fig. 4-19 Equilibrium Iron-Oxygen Binary System and Change of Oxygen Content of 1: Type D, 2: Type E and 3: Lump Ore Materials when Heated in Extraction Bomb. Temp. Rate, 250°C/min.

iron-carbon phase diagrams shown in Figures 4-19 and 4-20. As is seen from the latter, at the eutectoid temperature, Ta, a portion of the carbon content of DRI dissolves into the iron, resulting in the formation of an austenitic solid solution:

$$\operatorname{Fe}_{3}C_{(s)} = 3 \operatorname{Fe}_{(\gamma)} + \underline{C}_{(\chi)} \qquad \Delta H = -2200 \text{ cal/mole}$$

This transformation is exothermic and results in a change in the temperature difference between the reference and DRI. Above Ta, the percentage of austenite increases according to the lever rule. At b, the sample is entirely composed of austenite grains if equilibrium prevails. Above T_b , the oxidation of carbon continues and the percentage of the free iron increases. Above T_c , the FCC austenitic iron either transforms to BCC delta-iron or begins to melt into a high-carbon liquid iron phase. It can be seen that the melting temperature of DRI decreases if the percentage of carbon remaining in the sample increases.

A comparison is made of the transformation temperatures determined from the equilibrium diagram (Figure 4-20) and those measured by differential thermal analysis of D-R samples in Table 4-10. It is seen that the results are fairly consistent. The chemical composition and temperature associated with the phase changes of DRI materials are utilized to calculate the heat capacity and thermal conductivity of D-R particles when heated in steelmaking slags in Chapter V and Appendices E and F.

Fig. 4-20 Equilibrium Fe-Fe₃C System and Change of Carbon Content of 1: Type D, 2: Type E and 3: Lump Ore Materials when Heated in Extraction Bomb. Temp. Rate, 250°C/min.

Trans.	<u> </u>							
Temps.	<u>—</u>	HYL	MIDRE	X	0	re		
<u>(°C)</u>	DTA	<u> </u>	DTA	Eq.	DTA	Eq.		
a	720	727	729	727	723	727		
Ъ	960	957	-	943	777	787		
с	-	1494	1449	1457	1403	1398		
d	-	1500	1488	1500	-	-		
e	-	1526	1516	1510	1524	1535		

Table 4-10Transformation Temperatures of Type D, Type E- and Lump Ore Materials Determined by DTA and
from Heating Paths Shown in Fig. 4-20.

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C. Slag-Particle Heat Exchange

Typical results of heat transfer studies are given in this section. Detailed descriptions of the experimental data are given in Chapter VI.

1. Neutral Particle

The measured temperature of 3 cm diameter stationary nickel spheres immersed in hot liquid slags A and B is plotted in Figures 4-21 and 4-22. The effect of evolution of gas from the sphere into the slag on the rise of temperature of the particle is also shown. The rate of evolution of gas at the temperature of the bulk liquid slag and at atmospheric pressure ranges from 0 to $12 \ l/min$. It is seen that the effect of gas evolution on the rise of temperature at the center of the spheres is very small below a center temperature of about 700°C. Above 700°C, however, the rate of heating of the sphere increases with the gas evolution.

Comparisons are also made of the rise of the center temperature of 3 cm sintered iron spheres submerged into liquid slag B for different rates of evolution of gas in Figure 4-23. As is seen, the change of the heating rate of the sintered particles due to gas evolution is similar to that of the nickel spheres.

Growth of the shell of slag that solidifies on the surface of the immersed particles affects the rate of heating of the particle. The slag shell functions as a barrier, slowing the transport of heat to the surface of the sphere. The solidification and melting of this shell is influenced dramatically by the evolution of gas, as illustrated in Figure 4-24. Variation in the thickness of the shell (shown by vertical

Fig. 4-21 Effect of Gas Evolution on Rise of Temp. of 3 cm Dia. Ni Sphere Heated in Slag A. Slag Temp., 1250°C. Curve for 0 flow rate displaced 80 sec. to right.

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Fig. 4-23 Effect of Forced Bubbling on Rise of Temp. of 3 cm Dia. Sintered Iron Spheres Heated in Slag B. Slag Temp. 1250°C. Curves for 200 and 2000 cm³/min. displaced 40 and 20 sec to right.

Fig. 4-24 Effect of Gas Evoluion on Thickness of Slag Shell Frozen on 3 cm Ni Sphere Heated in Slag A. Slag Temp., 1250°C.

arrows) is greater when evolution of gas is introduced.

The thickness of the shell of slag also depends on the temperature of the bulk slag, the temperature of the sphere before immersion and the thermo-physical properties of the slag and the particle. Effects of the temperature of the bulk liquid slag and the rate of evolution of gas on the thickness of the solid shell of slag when the measured temperature of the sphere is 600°C are illustrated in Figure 4-25. The effect of the changes of properties of materials on the growth of the shell and the heating of the particles are discussed in Chapter VI.

2. DRI Pellet

The rise in temperature of the center of various DRI pellets when immersed in a hot bath of liquid slag is illustrated in Figures 4-26 and 4-27. The specifications of the pellets and the conditions of the liquid slag are summarized in Table 4-11. The first letter of the symbols used to designate the pellets indicate the type of commercial material utilized (cf. Tables 4-1 and 4-2).

Because of variation of the properties of pellets when they are reduced, the effects of various parameters on the rate of heating of the pellets in slag should be considered in an analysis of the results. Such effects are discussed in Chapter VII. From the data given in Figures 4-26 and 4-27, it can be seen that, below about 700°C, the rate of rise of temperature at the center of a reduced pellet without gas evolution is greater than that of a nonreduced pellet with gas evolution. Above that temperature, the nonreduced pellet is heated more rapidly. The central temperature is, however, greater when the pellet is totally

g. 4-25 Effects of Gas Evolution and Slag Temp. on Thickness of Slag Shell Frozen on 3 cm Ni Sphere. Temp. at Center of Particle, 600°C.

TIME,SEC

Fig. 4-26 Measured Temp. of Center of HYL Pellets (Type D) Heated in Slag A (cf. Table 4-11).

		НҮ L				MIDREX			
<u>Pellet</u>	D1	D2	D3	D4	<u>E1</u>	E2	E3		
							-		
Diameter, cm	1.62	1.62	1.61	1.62	1.43	1.43	1.43		
Weight, g	5.14	4.86	5.05	5.63	3.65	3.58	3.52		
Dia. of Thermo- couple well, cm	0.3	0.3	0.3	0.3	0.3	0.3	0.3		
Slag temp., °C	1235	1235	1275	1235	1235	1235	1235		
Gas evolution	yes	* nil	yes	$\mathtt{nil}^{\#}$	yes	yes^{χ}	nil [#]		

* Reduced by heating in slag.

 $^{\text{\#}}$ Totally reduced by H_2 .

^XAlthough the pellet was previously reduced by heating in slag, there was a considerable amount of gas being evolved during this experiment. The pellet had perhaps oxidized when cooled in the air after the first test.

Fig. 4-27 Measured Temp. of Center of Midrex Pellets (Type E) Heated in Slag A (cf. Table 4-11).

Fig. 4-28 Porosity of Solid Shell of Slag.

metallized.

3. Nature of Slag Shell

The thermal properties of the slag shell vary with various parameters such as porosity, diameter of the pores, direction of solidification, microscopic structure and the temperature of the shell. The porosity of the shell is influenced by gas evolution, as shown in Figure 4-28. The diameter of the pores varies from 10 micron to 2 mm. The distribution of pores of various sizes becomes less uniform as the rate of gas evolution increases. As is seen from the figure, the porosity of the shell of slag which forms on the surface of a DRI pellet is greater than that which solidifies on the surface of a nickel particle. The difference is due to the larger surface area of DRI pellets which is influenced by gas evolution as compared to that of nickel spheres. Variations of the thermal conductivity of the slag due to the change of the porosity of the shell are described in Appendix D.

The microscopic structure of the slag shell consists of three regions, as shown in Figure 4-29. Region 1 represents a sufficiently fast rate of cooling that has resulted in the formation of an amorphous structure. Region II indicates a slower rate of cooling that has allowed the growth of a coarse lamellar structure. Region III represents the solid-liquid interface (mushy zone) that has been chilled to tiny dendrites when the specimen has been withdrawn from the slag bath. Observation of the polished sections of solid slag shells under the microscope indicates that this region is usually sheared off. However, it cannot be determined from these observations whether shear occurs

Fig. 4-29 Microstructure of Crust of Solid Slag B Frozen on 3 cm Día. Ni Sphere.

when the particle is immersed or when it is withdrawn.

As is discussed in Chapter VI, the best fit of data has been • obtained with a 100 percent shear of the mushy interface due to the free or forced convection of liquid slag around the particle. The effects • of the microstructure and the direction of solidification on the thermal properties of the slag shell are described in reference 58. The effects of shear of the solid-liquid interface on heating of the particles are also discussed in reference 59.