Appendix A

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Sample Calculation for the ${\rm H}_2$ Extraction

The weight changes obtained from the hydrogen extraction of a granular 2 mm size D-R sample of the type D pellets are given in Table A-1. The reduction reactions associated with these weight changes are basically of C/H_2 combustion type:

$$0 + C = CO \tag{A.1}$$

$$20 + C = C0_2$$
 (A.2)

$$0 + H_2 = H_2 0$$
 (A.3)

Table A-1. H₂ Extraction Data for Type D Pellets. Grain Size, 2 mm.

Weights	Initital	Final	Gain	
(Gram)				
Sample	4.1971	3.9752	-0.2219	
H ₂ 0 absorbent	64.9596	64.9804	0.0208	
correction	-	-	-0.0138	
total	-	-	0.0070	
CO ₂ absorbent	64.3738	64.3856	0.0118	
correction	-	-	0.0133	
total	-	-	0.0251	
co*	-	_	0.1906	

*Calculated from Equation (A.4).

The reacting contents of oxygen and carbon can be calculated from the given data as follows:

$$W_{\rm CO} = \Delta W_{\rm S} - W_{\rm CO_2} - W_{\rm O} \tag{A.4}$$

$$W_{O} = W_{H_{2}O}(\frac{M_{O}}{M_{H_{2}O}}) + W_{CO_{2}}(\frac{2M_{O}}{M_{CO_{2}}}) + W_{CO}(\frac{M_{O}}{M_{CO}})$$
(A.5)

$$W_{\rm C} = W_{\rm CO_2} \left(\frac{M_{\rm C}}{M_{\rm CO_2}}\right) + W_{\rm CO} \left(\frac{M_{\rm C}}{M_{\rm CO}}\right)$$
 (A.6)

$$%0 = 100\left(\frac{W_{O}}{W_{S}}\right) \tag{A.7}$$

$$%C = 100\left(\frac{W_{C}}{W_{S}}\right)$$
(A.8)

 W_i is the weight gain of the specie i, ΔW_S is the weight loss of the sample, w_0 is the weight of oxygen in the water vapor evolved, M_i is the molar weight of the specie i, and %i is the reacting content of i in the sample.

$$W_{CO} = 0.2219 - 0.0251 - 0.0070(\frac{16}{18}) = 0.1906$$
$$W_{O} = 0.0070(\frac{16}{18}) + 0.0251(\frac{32}{44}) + 0.1906(\frac{16}{28}) = 0.1334$$
$$W_{C} = 0.0251(\frac{12}{44}) + 0.1906(\frac{12}{28}) = 0.0885$$

Hence:

% 0 = 3.18 % C = 2.10

Appendix B

Volumetric Measurement of Evolved Gas

Volumetric flow rate of the gases evolved from DRI was measured by an integrating flowmeter similar to the one described by Naci Seving.⁹³ After the evolved gas passed through a mercury manometer, a dibutyl phthalate bubbler and a glass bulb held in a water tank, it entered the flowmeter. The temperature of the gas was kept constant at 25°C by controlling the temperature of the water in the tank. The pressure drop in the gas stream, measured by the mercury manometer, was less than 5 mm of mercury. A negative pressure of about 5 mm mercury was applied to the system by suction of the outlet of the flowmeter to facilitate the evolution of gas when a D-R pellet was heated in liquid slag.

The flowmeter translated the rate of flow of gas into a characteristic frequency (Figure B-1). The spread of data at flow rates greater than 200 cm^3/min is because of the abrupt pressure drop in the stream when the instrument was discharged of the trapped gas (see Ref. 93). At flow rates greater than 450 cm^3/min , the flowmeter became unstable and did not operate properly.

For simplicity, the rate of evolution of gas was expressed in terms of the characteristic frequency of the instrument as follows:

$$V = 19f + 1/9 f^{2.7}$$
 $f \le 8$ (B.1)
 $V = 33f - 81$ $f > 8$ (B.2)

(B.2)

where V is the gas rate in cm^3/min and f is the frequency in Cycles/min.





Appendix C

Data Analysis for Bomb Extraction

The gas flow rates obtained from bomb evolution experiments were corrected for the actual rate of change of temperature of DRI. For a small temperature change T, the rate of evolution of gas may be expressed as a linear function of the heating rate (Figure C-1):

$$\dot{V} = a\dot{T} + b$$
 (C.1)

where \dot{V} and T are the rates of evolution of gas and rise of temperature, a is the proportionality constant and b is the rate of flow of gas at zero temperature rate. Assuming b small, Equation (C.1) reduces to the following equation:

$$\dot{\mathbf{V}} = (\dot{\mathbf{V}}_{a}/\dot{\mathbf{T}}_{a}) \dot{\mathbf{T}}$$
(C.2)

in which \dot{V}_a is the measured flow rate and \dot{T}_a is the corresponding temperature rate.

A schematic plot is made of temperature fluctuations of a DRI sample in Figure C-2. The response of the flowmeter to the passage of the gases evolved is sketched in the same figure. The actual gas rate at time t = $(t_i + t_{i+1})/2$ is evaluated by substituting f into Equations (B.1) and (B.2):

$$f = 1/(t_{i+1} - t_i)$$
 (C.3)

$$\dot{V}_{a} = 19(t_{i+1} - t_{i})^{-1} + (t_{i+1} - t_{i})^{-2.7}/9 \quad t_{i+1} - t_{i}^{>} .25 \text{ min (C.4)}$$

$$\dot{V}_a = 33(t_{i+1}-t_i)^{-1} - 81$$
 $t_{i+1}-t_i < .25 \text{ min (C.5)}$

The temperature of the sample and its actual rate at time t can be





evaluated from the following equations:

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$$\overline{T} \simeq \frac{T_i + T_{i+1}}{2} \tag{C.6}$$

$$T_{a} = \frac{T_{i+1} - T_{i}}{t_{i+1} - t_{i}}$$
(C.7)

Substituting into Equation (C.2) results in the corrected rate of evolution of gas for temperature rate \dot{T} :

$$\dot{V} = \left[\frac{19(t_{i+1} - t_i)^{-1} + (t_{i+1} - t_i)^{-2.7/9}}{(T_{i+1} - T_i)/(T_{i+1} - T_i)}\right] \dot{T}$$

$$T_{i+1} - t_i \ge .25 \text{ min} \qquad (C.8)$$

$$V = \left[\frac{33(t_{i+1}-t_i)^{-1} - 81}{(T_{i+1}-T_i)/(t_{i+1}-t_i)}\right] T \quad t_{i+1}-t_i < .25 \text{ min}$$
 (C.9)

These expressions were used to calculate the corrected rate of flow of the gases evolved from DRI. This rate was corresponding to the time between two sequential cycles at t_i and t_{i+1} . It was plotted against the mean sample temperature \overline{T} .



Appendix D

Properties of Slag

The thermal expansivity of the liquid slags, defined by Equation (D.1), has been assumed equal to the thermal expansivity of similar ferrous-silicate slags given in reference 84.

$$\beta = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_{p} \tag{D.1}$$

In the above equation V is volume of slag and p is pressure of the system.

The thermal diffusivity, α , and the kinematic viscosity, ν , are defined by the following equations:

$$\alpha \equiv k/\rho C_{p}$$
(D.2)
$$\rho \equiv \mu/\rho$$
(D.3)

where k is thermal conductivity, ρ is density, C_p is specific heat and μ is viscosity of the slag. The dimensionless Prandtl number is defined as follows:

$$Pr = \nu/\alpha \tag{D.4}$$

The dimensionless Grashof number, Gr, for a liquid slag at temperature T_m can be determined from the following relationship:

$$Gr = \frac{g \beta (T_{\infty} - T_{s}) (R+\theta)^{3}}{v^{2}}$$
(D.5)

where g is gravitational acceleration, T_s is temperature of solid-liquid interface, R is radius of immersed particle and θ is thickness of solid shell of slag. The combination of Prandtl and Grashof groups is called the Rayleigh number:

 $Ra = Pr \quad . \quad Gr \tag{D.6}$

The heats of fusion of the slags are assumed equal to the weighted mean of the heats of fusion of the components.

The evolution of gas from DRI pellets into the slag results in a change in the density and porosity of the solid and liquid slag phases. The thermal conductivity of the porous substance, k, is equal to the geometric mean of the thermal conductivities of the pores, k_p , and of the substratum, k_s :⁷⁹

$$k = k_{p}^{1-\psi} \cdot k_{s}^{\psi}$$
(D.7)

where ψ is the porosity (volume fraction) of the substance. Ben-Amoz⁷⁹ derived the above formula by solving the heat conduction equation with space fluctuating properties and showed that the effective thermal conductivity and diffusivity of a multiphase material can similarly be predicted from a geometric mean formula. The predicted conductivities have been consistent with the results of Kon and Fortini,⁸³ and Woodside and Messmer⁹⁰ for oxides and metals of less than 50 percent porosity.

The thermal conductivity of the pores is equal to the sum of the radiation, k_r , and conduction, k_c , components:

$$k_{p} = k_{r} + k_{c} \tag{D.8}$$

For homogeneously distributed pores, the approximation suggested by $Marino^{80}$ and $Loeb^{81}$ may be used to calculate the radiative component of the thermal conductivity:

$$k_r = 3 \sigma d T^3$$
 (D.9)

in which σ is the Stephan-Boltzman constant and d is the diameter of the spherical pores. The conduction contribution may be evaluated from the information available on the thermal conductivity of air between 500 and 1500°K:⁸²

$$k_c = 3.04 \times 10^{-4} [1 - \exp(-7.65 \times 10^{-4} T)]$$
 (Cal/cm.sec.°K) (D.10)

The overall thermal conductivity of the pores can therefore be calculated from the following expression:

$$k_p = 4.08 \times 10^{-12} d$$
. $T^3 + 3.04 \times 10^{-4} [1 - exp(-7.65 \times 10^{-4}T)]$
(Cal/cm.sec.°K) (D.11)

Equations (D.7) and (D.11) were inserted in the model for calculation of the thermal conductivity of the slags. A summary of the thermo-physical properties of the slags employed in heat transfer studies is given in Table 5-1.

APPENDIX E

Thermal Properties of Specimen

The effective thermal conductivity of DRI pellets may be calculated from the geometric mean of the thermal conductivities of the constituents and the pores, as described in Appendix D:⁷⁹

$$k = k_{p}^{\psi_{p}} \cdot k_{Fe}^{\psi_{Fe}} \cdot k_{Fe0''}^{\psi''Fe0''} \cdot k_{Fe_{3}C}^{\psi_{Fe_{3}C}} \cdot k_{Al_{2}O_{3}}^{\psi_{Al_{2}O_{3}}} \cdot k_{SiO_{2}}^{\psi_{SiO_{2}}}$$
(E.1)

where $k_{\rm M}$ is the thermal conductivity of constituent M. The volume fraction of M denoted by $\psi_{\rm M}$ is assumed to be proportional to the weight fraction of M designated by W_M:

$$\psi_{\rm M} = W_{\rm M} (1 - \psi_{\rm p}) \tag{E.2}$$

For simplicity, the change of ψ_p when DRI pellets are heated is assumed negligible.

The heat of fusion of DRI materials, ΔH , may be estimated from the heats of fusion of the constituents. Since at the melting point the oxygen and carbon contents of the samples are negligible, ΔH can be calculated from the following equation:

$$\Delta H = W_{Fe} \Delta H_{Fe} + W_{Al_2O_3} \Delta H_{Al_2O_3} + W_{SiO_2} \Delta H_{SiO_2}$$
(E.3)

in which ΔH_M is the heat of fusion of the component M of DRI. The specific heat of DRI is calculated in Appendix F.

Typical quantities of the constants used for calculation of the rate of transfer of heat to the thermocouple bead embedded inside the specimens are given in Table E-1. These coefficients are derived from the following equations which include the terms for transfer of heat by radiation and conduction from the surface of the insertion well to the thermocouple bead and the change of the temperature of the bead with time: 58

$$\dot{q} = \chi A_1 F \sigma (T_{W,j}^4 - T_{b,j}^4) + y A_2 k (T_{W,j}^- - T_{b,j}^-) / \Delta r$$
(E.4)
$$T_{b,j+1} = T_{b,j} + \dot{Q} \Delta t / m C_p$$
(E.5)

where χA_1 is the area of the thermocouple well that radiates heat to the thermocouple bead or to the platinum foil used to protect the bead, $T_{W,j}$ is the temperature of the surface of the well, $T_{b,j}$ and $T_{b,j+1}$ are the present and future temperatures of the bead, y A_2 is the area of the bead or the platinum foil that contacts the particle, m is the mass of the thermocouple bead and the platinum foil if present, C_p is the heat capacity of platinum and F is calculated from the following equation:

$$F = 1/(1/\varepsilon_1 + 1/\varepsilon_1 - 1)$$
(E.6)

where ε_w and ε_b are the emissivities of the surfaces of the well and the platinum foil when used to protect the bead, respectively. For a small thermocouple bead enclosed in the well, the emissivity of the well is unity and F is equal to the emissivity of the bead. Equations (E.4) and (E.5) may be rewritten in the following form:

$$\dot{Q} = A(T_{w,j}^{4} - T_{b,j}^{4}) + B(T_{w,j}^{-} - T_{b,j}^{-})$$
 (E.7)

$$T_{b,j+1} = T_{b,j} + \dot{Q} \Delta t/D$$
 (E.8)

where the coefficients A, B and D are defined as follows:

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$$A \equiv \chi A_{1} F \sigma \qquad (E.9)$$

$$B \equiv yA_2 k \tag{E.10}$$

$$D \equiv m C$$
(E.11)

Table E-1Typical Constants Used for Temperature Calculations(See Equations E.9 to E.11).

	Nickel	Sphere	DRI P	ellet
Coefficient	Small	Large	E	D
A, 10 ¹⁴ Cal/sec. °K ⁴	2	6	1	1
B, 10 ⁴ Cal/sec. °K	3	1	6	6
D, Cal/°K	0.0030	0.0037	0.0016	0.0011

Appendix F

Overall Specific Heat of DRI

The contribution of various items explained in Section V.B.2 to the overall specific heat of sponge materials is evaluated at different temperature ranges determined from the equilibrium phase diagram (see Figure F-1). The results are summarized in Table 5-3.

1. Specific Heat of Materials

The specific heat of iron-bearing sponge pellets can be evaluated by summing up the specific heats of the components of the sponge. The principal components are: Iron, Oxygen, Carbon, Gangue, Sulphur and Phosphorous. The dominant portion of the gangue is generally the "acid gangue" (SiO₂ + Al₂O₃), while the sulphur and phosphorous contents of the sponge are negligible.

To calculate the specific heat of a D-R pellet, let us assume, for simplicity, that oxygen and carbon are inform of "FeO" and Fe₃C chemical compounds. The reaction between these compounds below the carbide decomposition temperature T_a (see Figure F-1) may be written as follows:

$$"FeO" + Fe_{2}C = 3.95 Fe + CO$$
 (F.1)

$$2"FeO" + Fe_3C = 4.9 Fe + CO_2$$
 (F.2)

For a gaseous product composed of 90% CO and 10% CO_2 , the stoichiometric quantities of reactants and products are as demonstrated in Eq. (F.3):

1.1 "FeO" + Fe₃C = 4.05 Fe + 0.9 CO + 0.1 CO₂ (F.3)
3.53 x
$$10^{-3}$$
g + 8.02 x 10^{-3} g = 1.01 x 10^{-2} g + 1 cm³

The weights of the components participating in these reactions can be subtracted from the initial values to obtain the chemical analysis of the pellet:

$$W_{Fe} = W_{i,Fe} - (-1.01 E-2)V$$
 (F.4)

$$W_{"FeO"} = W_{i,"FeO"} - (3.53 \text{ E}-3)V$$
 (F.5)

$$W_{Fe_3C} = W_{i, Fe_3C} - (8.02 E-3)V$$
 (F.6)

where $W_{i,M}$ and W_M are initial and present weights of component M, and V is the volume of the released gas, all per gram of DRI.

The specific heats of the species present in DRI are given in Table E-1. From the data given, the specific heats of D-R materials are computed for the specified temperature ranges, based on the assumption that the Neumann-Kopp rule is valid at elevated temperatures:

$$CM = W_{Fe} \cdot C_{Fe} + W_{"FeO"} \cdot C_{"FeO"} + W_{Fe_3C} \cdot C_{Fe_3C} + W_{A1_2O_3} \cdot C_{A1_2O_3} + W_{SiO_2} \cdot C_{SiO_2}$$
(F.7)

Material	Relationship (Cal.°K ⁻¹ .g ⁻¹)	Temp. Range (°K)
Fea	7.48 E-2 + 1.06 E-4 T	273 - 1033
Feg	1.61 E-1	1033-1181
Fey	3.29 E-2 + 8.34 E-5T	1181-1674
^{Fe} 0.95 ⁰	$1.69E-1 + 2.90E-5T - 9.70E2 T^{-2}$	298 - m.p.
Fe ₃ C) _a	0.109 + 1.11E-4T	273-463
FegC) _β	0.143 + 1.67E-5T	463-1500
A1203	0.25 + 4.17E-5T - 6.69E3T ⁻²	298 - 1800
SiO ₂)	1.87E-1 +1.36E-4T - 4.49E3T ⁻²	298-848
SiO ₂) _R	2.40E-1 + 3.23E-5T	848-2000

Table F-1. Specific Heat of Materials. 94

2. Enthalpy of Reactions

Equation (F.3) illustrates the final reduction of the sponge material below the carbide decomposition temperature Ta (see Figure F-1), where the total carbon content of the sample is in carbide form. A comparison of the free energy of the reduction reactions (F.3) and (F.8) is made in Table F-2.

$$1.1 "FeO"+C = 1.05Fe + 0.9C0 + 0.1C0_2$$
(F.8)

The results indicate that above T_a , the reduction of the sample according to the reaction (F.3) occurs more favorably.

The reduction reactions specified in Eqs. (F.3) and (F.8) are endothermic. The associated enthalpies may be converted into specific heat terms for the sponge material, as shown in Table F-2. Multiplying the heats of reduction of the sponge by a "Specific Gas Volume", G, (the total volume of the released gases per unit weight of the sample per unit temperature increment) results in the specific heat terms required. The specific gas volume is determined as a function of temperature, from the bomb extraction results:

$$G(T) = \frac{\partial V}{\partial T} \simeq V_{T+0.5} - V_{T-0.5}$$
 (F.9)

	Tabl	eF-2E	nthalpies and	l Free Energi	77 es of Reactions.	,94
Temp.	Entl (Cal	halpy . cm ⁻³)	Standard Fre (Cal. cm	ee Energy ⁻³)	C _R	
Range (°K)	(F.3)	(F.8)	F.3)	(F.8)	(Cal.k ⁻¹ .g ⁻¹)	
T < T a	1.29	-	-	-	1.29 G(T)	
$T_{a} \leq T \leq T_{a} + 8$	1.35	-	-0.02*	0.22*	1.35 G(T)	
T _a +8 <t<t<sub>b</t<t<sub>	1.47	-	-0.60 [≠]	-0.24 [≠]	1.47 G(T)	
$T \ge T_b$	-	1.35	_	-	1.35 G(T)	
Calculat	ed at 1	.000°K.	⁷ Calculated	at 1400°K.		

3. Heat of Phase Transformation

The formation of Austenitic iron phase in D-R sponge pellets at eutectoid temperature, T_a , is exothermic:

$$Fe_3C = 3Fe + C -1.23 (cal. g_{Fe_3C}^{-1})$$
 (F.10)

The contribution of the associated enthalpy to the specific heat of the sponge materials is determined as a function of the sponge composition.

The iron rich portion of the iron-iron carbide equilibrium diagram

is reconstructed in Figure F-1 (cf. Figure 4-20). The variation of the carbon content of a DRI pellet is also schematically shown as a function of temperature. The loci of the transformation temperatures are given in Table 4-10. The change in the amount of the structural constituent, Fe₃C, at the eutectoid temperature can be calculated from Eq. (F.13):

$$W_{i, Fe_3C} = (CA - 0.02)/6.66$$
 (F.11)

$$W_{Fe_3C} = (CA - 0.77)/5.92$$
 (F.12)

$$\Delta W_{\text{Fe}_{3}\text{C}} = 1.88 \times 10^{-2} \text{ CA} - 0.127 \tag{F.13}$$

in which CA is the carbon content of the sponge at temperature T.

Assuming the completion of the phase change be achieved within eight degrees above eutectoid point allows the transformation enthalpy to be divided into this range, in order to yield the specific heat of the sponge due to the phase change.

$$C_{\rm T} = 2.89 \times 10^{-3} CA - 1.95 \times 10^{-2}$$
 (F.14)

Above the eutectoid temperature, the austenitizing process continues until the chemical composition of the particle reaches the curve separating austenite and austenite-cementite phase region. It is assumed that the influence of the enthalpy change due to the completion of the austenitizing process on the specific heat of the sponge is negligible. The thermodynamic data available justify such an assumption.





Appendix G

Thickness of Thermal Boundary Layer

At steady state, the Nusselt number of the slag bath can be calculated from Equation (5.12). If T_{∞} is the temperature of bulk liquid slag and T_{i} is the temperature at the solid-liquid slag interface, the following equation can be written for transfer of heat into the surface of an immersed specimen:

$$-k\left(\frac{\partial T}{\partial r}\right)_{i}^{+} = h \left(T_{\infty} - T_{i}\right)$$
(G.1)

Substituting for partial derivative in terms of the thickness of the thermal boundary layer, $\delta_{\rm T}$, and from Equation (5.9) for h results in the following correlation:

$$\delta_{\rm T} = 2({\rm R} + \theta) / {\rm Nu} \tag{G.2}$$

From the data given in Table 5-4 the thickness of the thermal boundary layer can be calculated for various specimens. The ratio of $\delta_{\rm T}^{/\theta}$ is generally greater than three.

Appendix H

Conduction Heat Transfer

The conduction equation in spherical coordinates can be written as follows:

$$\frac{\partial T}{\partial t} = \alpha \left[\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right]$$
(H.1)

Substituting $\xi = r(T-T_{\infty})$ in Eq. (H.1) yields:

$$\frac{\partial \xi}{\partial t} = \alpha \frac{\partial^2 \xi}{\partial r^2} \tag{H.2}$$

where:

$$\xi = 0 \qquad \qquad t = 0 \qquad (H.3)$$

$$\xi = (R+\theta)(T_{i}-T_{\infty}) \qquad r = R + \theta \qquad (H.4)$$

Solving (H.2) for boundary conditions (H.3) and (H.4) yields:⁸⁵

$$T - T_{\infty} = (T_i - T_{\infty}) \frac{R + \theta}{r} \operatorname{erfc} \frac{r - R - \theta}{\sqrt{\pi \alpha t}}$$
 (H.5)

The rate of transfer of heat to the particle is calculated from the following expression:

$$\left(\frac{q}{A}\right)_{R+\theta^{+}} = -k \left(\frac{\partial T}{\partial r}\right)_{R+\theta^{+}} = -k \left(T_{i} - T_{\infty}\right) \left[\frac{1}{R+\theta} + \frac{1}{\sqrt{\pi\alpha t}}\right]$$
(H.6)

which leads to the coefficient of transfer of heat in the liquid slag:

$$h = k \left[\frac{1}{R+\theta} + \frac{1}{\sqrt{\pi \alpha t}}\right]$$
(H.7)

Substituting for h from Equation (5.33) the Nusselt number of the slag is obtained:

$$Nu = 2 + 2(R+\theta) / \sqrt{\pi \alpha t}$$
(H.8)

Appendix I

Porosity of Liquid Slag

Porosity of the liquid slag of around an immersed particle with local gas evolution was calculated from the information given in Table 3-5. The number of gas bubbles evolved from a gas port that cover the surface of the particle can be calculated from the following equation:

$$n = f \frac{\ell}{v}$$
 (I.1)

where f and v are frequency and velocity of gas bubbles and l is the length of coverage (Figure I-1). For a thickness of D_b , the porosity of the forced convection layer of around the particle can then be estimated from the following correlation:

$$P = N \frac{f\ell}{6v} \left(\frac{b}{b}\right)^2$$
(I.2)

where N is the number of active bubbling sites, D_b is the average diameter of the bubbles and D is the diameter of the particle.



Fig. I-1 Immersed Particle with Gas Evolution.

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Appendix J

Computer Program

A listing of the computer model transcribed in Fortran IV is provided in the following sections with brief commentary statements to clarify the procedures employed to compute the rate of heating and melting of submerged particles. Copies of the subprograms used to calculate properties of materials are also included. The definition of the terms used is given in the last section.

The model has been originally developed in reference 58 for melting an immersed inert sphere in slag. It is generalized for evolution of gas from particles, changes of properties of materials with temperature and time, and condition of liquid bath as related to the solidification and melting of slag and particle and to the heat transfer mechanisms that dominate the Nusselt quantity of the slag. Those properties which vary the most with temperature are supplied in form of table functions. The model is applicable to both inert spheres and DRI pellets heated in hot fluid media.

The approach is in general the same as that described in reference 58. Slight changes are however made to increase the accuracy of results. First, the temperatures and gas volumes of the space elements are initialized, the areas and volumes attributed to these elements are calculated and a small initial shell thickness is set. The calculations are then carried out on an iterative basis. The Nusslt number of the bath, the temperature and properties of the elements, the thickness of the frozen shell or the fraction of the particle that may melt are calculated at each iteration. 1. Main Program

C....INPUT DATA IDT, IDR, NU , K2, K3, K4, K5 REAL COMMON VG(20), GG(20), PS, TA, CA, TB, F1 , F2, F3 , F4, F5, W1, W2, W3 C.S.CKS ,CKL, DP,DB ,K2,K3,K4,K5 ,DDD,FF2 DIMENSION A(99),V(99),I(99),E(99), EV(99),TT(99),GV(99) AF=0200 IF(AF.EQ.0) GO TO 77 IF(AF-CJ)66,98,77 98 AF=017 READ(5,100)NO, NUT, NOS,N1,IDR,IDT,BB,TO,TMS,TMSP,CA,K3 ,S,R,D,K2, CCPL, CPS, U, XX, DL, TM, OD, ZT, CJ, DSS, RR, TR, CB, TA, TB, (VG(I), I=1, CN1), CKS, F, PS, (GG(I), I=1, N1), DS1, ACRM, GNU, AA, H, DDD, K4, K5, TTT IF (NO.EQ.0.)GO TO 201 FORMAT(415/ (8F10.4)) 100 WRITE(6,111)NO,NOT, NOS,N1,IDR,IDT,BB,TO,TMS,TMSP,CA,K3,S,R,D,K2, CCPL, CPS, U, XX, DL, TM, DD, ZT, CJ, DSS, RR, TR, CB, TA, TB, (VG(I), I=1, CN1), CKS, F, PS, (GG(I), I=1, N1), DS1 , ACRM, GNU, AA, H , DDD, K4, K5, TTT 111 FORMAT(415/5X, 'IDR', T15, 'IDT', T25, 'BB', T35, 'TO', T45, 'TMS', T55, 'TMS' CP*,T65,'CA*,T75,'K3*/8F10.4/5X,'S',T15,'R',T25,'D',T35,'K2',T45,'C CPL ', T55, 'CPS', T66, 'U', T75, 'XX'/8F10.4/5X, 'DL', T15, 'TM ', T25, 'DD', CT35, ' ZT', F45, 'CJ', T55, 'DSS', T65, 'RR', T75, 'TR'/8F10, 4/5X, 'CB' C, [15, 'TA', T25, 'TB', T35, 'VG(1)', T45, '2', T55, '3', T65, '4', T75, '5' C/8F10.4/5X,'6',T15,'7',T25,'8',T35,'9',T45,'10',T55,'11',T65,'12' C, T75, '13'/8F10, 4/5X, '14 15 16 CKS F. C... PS GG(1) ... 2'/8F13.4/5X,'3',9X,'4 5 6 C 7 8 ••••• 9 ••••• 10*/8F10.4/5X,*11*,9X,*12 14 15 16DS1 ... ACRM*/8F10.4/ C ... 13 C5X, GNU AΑ H 000 К4 K51 /8F10.4) READ(5,10) F1,F2,F3,F4,F5,TI,CKL,YYY,FF2 ,FNU,TMS,TMSP,NU,DP,FR,WT 66 C,R 1.) FORMAT(8F10.4) IF(F1)201,201,11 WRITE(6,12) F1, F2, F3, F4, F5, TI, CKL, YYY, FF2, FNU, TMS, TMSP, NU, DP, FR, WT 11 C . R 12

FORMAT(//// 5X, 'PELLET COMPOSITION : ', LJF10.4/ (12F10.4))

217.

```
C....CALCULATE CONSTANTS
     DR = (R - RR) / (NO - NOS)
     XX = DR
     DS=DS1*(1.-S)
     AF = AF + 1
     NOM=NO-1
     MM=NOS+1
     M = NOS - 1
C....VARIABLES
                                                                .
     KL=0
    LLL=0
     TEM=0.
     TGV=0
     J=0
     TIME1=0
     GR=0
     TGV1=0.
     Y=0.
     W1 = F1
     W2=F2
     W3=F3
C..... AND TEMPERATURES ,
C....AND CALCULATE AREA AND VOLUMES OF ELEMENTS
     DO 400 I=1,NO
     GV(I)=0.
     EV (I) = 0.
400
     DO 101 N=1,M
     T(N) = TMS
     E(N) = \Gamma MS
     A(N) = ((N - .5) * IDR + R) * * 2
     V(N)=.333*((N-.5)*IDR+R)**3 -.333*((N-1.5)*IDR+R)**3
101
     A(1) = A(1) * F
     DC 102 N=NOS,NUM
     T(N) = FO
                                                              1
     TT(N) = TO
     A(N) = ((N - NOS - .5) * DR + RR) * * 2
     V(N)=.333*((N-NOS-.5))*DR+RR)**3-.333*((N-NOS-1.5)*DR+RR)**3
102
     V(NOS+1) = ((RR+DR/2) **3 - RR**3)/3
```

```
T(NO) = TO
      TT(NO) = TO
      T(1) = T0
      A(NO) = (R - XX/2) \approx 2
      V(NO) = (R** 3-(R-XX-DR/2) **3)/3
C.....SET INITIAL SHELL THICKNESS
      BUND=R
      X = .10 \times IDR
      DM = X
      X N = X
                                                                     1
      TIME=0.
                                                                      1
C....CALCULATION OF HEAT TRANSFER COEFFICIENT
88
      ENU = GNU
      PNU=0.
      IF(TIME.LT.TTT) PNU=FNU*(1-TIME/TTT)
      IF (TIME.GT.0)ENU=2*BOND/(3.1416*
                                            CKL/ DL/CPL*TIME)**.5+2+PNU
      IF (ENU.LT. NU
                     ) ENU=NU
      HTRANS=ENU<sup>★</sup> CKL
                           /BOND/2.
      BCND = BOND + XN
      TIME = J * IDT
37
      IF(T(1)-TI)85,90,9)
      IF(T(1)) 90,90,84
35
90
      WRITE(6,73) TIME, T(1), T(NC), T(NOS)
     FCRMAT( CHANGED ,4F12.4)
13
      GO TO 200
84
     KL = KL + 1
      J=J+1
      THICK=BOND-R
     IF(TIME .LT.Y) GO TO 4
ó
     Y = Y + 1
     IF (TIME-TIME1) 16,16,17
15
C....CALCULATION OF VOLUME AND RATE OF EVOLUTION OF GAS
     TGV = 3.
17
     DO 300 I=MM,NO
     EV(I) = VVV(T(I))
     GV(I) = EV(I) *3 *V(I)/(R**3-RR**3)
     IGV = IGV+GV(I)
```

```
TT(I) = T(I)
3)0
     GR = (TGV - TGV1)/(TIME - TIME1)*60.
      TGV1 = TGV
      TIME1 = TIME
      THICKN = (THICK ) \times 100.
16
      WW1=W1*190.
      WW2 = W2 * 100
      WW3=W3*100.
      WRITE(6,70)TIME, THICKN , TGV, GR, (T(I), I=1, NO), (GV(I), I=MM, NO), FFM
     C, hW1, hW2, hW3, ENU
                                                                   1
19
      FORMAT(/(10F12.2))
      IF(T(NOS).GE.1373.AND.TI.LT.1773.) GC TO 200
C.....OALCULATION OF TEMPERATURE OF THERMOCOUPLE
C..... ELEMENTES
4
     HIN=AA*1E-14*(T(NOS+1)**4-T(NOS)**4)+BB*1E-4*(T(NOS+1) -T(NOS))
      E(NOS)=HIN*IDT/ DD+T(NOS)
      CALL FFF (CPM,T(NUS+1), CKM, CS)
      HOUT=A(NOS+1)*(T(NOS+2)-T(NOS+1))*CKM
                                                  /DR
     E(NOS+1)=T(NOS+1)+(HOUT -HIN)*IDT*3/((DR*.5+RR)**3-RR**3)/CPM/D
      NA = NOS + 2
      DO 51 N=NA,NOM
      HIN=A(N-1)*(T(N-1)-T(N))
     HOUT = A(N) * (T(N+1) - T(N))
     CALL FFF (CPM,T(N) , CKM , CS )
51
     E(N) = T(N) + CKM/D/CPM*IDT /V(N) / DR*(HIN+HOUT)
     CALL FFF (CPM, T(NO) , CKM , CS )
     HIN=-HOUT*CKM/DR
     HOUT=A(NO)*CS*(T(1)-T(NO))/XX
     CPC=CPM
     VV = (CPM*D*((R-XX)**3-(R-XX-DR/2)**3)+CPD*DSS*((R-XX/2)**3-(R-XX)
    S**3))/3
     E(NO) = (HIN+HOUT)
                                             ) *I DT/VV+T(NO)
     N=1
C....CALCULATION OF TEMPERATURE AT SURFACE OF
                                                             PARTICLE
     If (R+IDR-BEND)108,108,103
103
     HIN=-HOUT
     CALL FFF (CPU,T(1), CKM,CS)
     VU = (DS*CPS*((R+X/2) **3-R**3) + CPO *DSS*(R**3-(R-XX/2) **3))/3
```

```
220
```

```
IF (BOND-R) 1,2,3
1
      BOND=R
2
      XN=0.
      X=0.
      IF (T(1)-TM) 1007,1008,1008
1007 HOUT = R * * 2 * HTRANS * (TI - T(1))
      E(1) = (HIN+HOUT)*IDT/VU+T(1)
      IF (E(1)-TM) 203,203,1009
C....CALCULATION OF MELTED FRACTION OF PARTICLE
                                                                   ,
1009 QR= (E(1)-TM)*VU/IDT
      GO TO 1610
1008 QR=R**2*HTRANS*(TI-TM)+HIN
1010 FM = QR \times IDT \times 3 / (R \times 3 \times D \times ACRM)
      TFM=TFM+FM
      IF (TFM.LT.U.) E(1)=TM+QR*TFM/FM*IDT/VU
      IF (TFM.GE.0.) E(1)=TM
      IF (TFM-1.) 203,1005,1005
10/5 WRITE (6,1006) TIME, TEM
1006 FCRMAT(////1)X, 'TOTAL MELTING TIME = (,2F10,2)
      GO TO 200
C..... ALCULATION OF TEMPERATURE AT SURFACE OF
                                                                 PARTICLE
C.....WITH SLAG SHELL THICKNESS LESS THAN IDR
3
      A1 = (R+.5*X) **2
      HOUT=A1*F*(TMS - T(1))*CK(T(1))/X
                                                                        .
      E(1) = (HIN+HOUT) \times IDT/VU
                                   +T(1)
      IF(E(1)-E(NO))29,30,30
29
      E(1) = E(NO)
      XN = -IDT/H/DS*(CK(T(1))*(E(1)-TMS)/X + (TI-TMSP) *HTRANS)
30
      IF(TIME.LE. WI.AND.YYY.GT.0.) XN=XN*FR
      BA = BOND + XN - R
      L=BA/IDR
      X = IDR \approx (BA / IDR - L)
                                                                  4
      IF(DM - IDR/10.)9,8,8
7
      DM = IDR/10.
8
      IF(X-IDR/10)7,203,203
1
      X = IDR/10.
203
      IF(NOT - KL)2 -, 20, 99
```

```
221
```

1

```
C.....SUBSTITUTE FOR TEMPERATURES AND START A NEW ITERATION
99
      DO 705 K=1.NO
7.)5
     T(K) = E(K)
      GC TO 88
C.....CALCULATION OF TEMPERATURE AT SURFACE OF PARTICLE
C.....AND THROUGHOUT SOLID SLAG SHELL
108
      HIN=-HOUT
      HOUT=A(1)*(T(2)-T(1))* CK(T(1))/IDR
                                                                    1
      CALL FFF (CPU, T(1) , CKM , CS)
      VOL = (DS*CPS*((R+IDR/2)**3-R**3)+CPO*DSS*(R**3-(R-XX/2)**3))/3
      E(1) = (HIN+HOUT)*IDT/VOL + I(1)
109
      N = N + 1
      IF (R+(N )*IDR-BOND)115,115,110
110
      AX = (BOND - X/2) * (BOND - X/2)
                                                                     .
      VX=.333*(BOND-X/2)**3-.333*(BOND-IDR/2-X)**3
      HIN=A(N-1)*(T(N-1)-T(N))/IDR
      HOUT=AX*(TMS -T(N))/X
      E(N) = (HIN+HOUT) * CK(T(N))/DS/ CPS * IDT/VX+T(N)
      QQ = (E(N) + TMS)/2.
      XN = -IDT/H/DS * (CK(QQ) * (E(N) - TMS) / X + (TI - TMSP) * HTRANS)
      IF(TIME.LE. WT.AND.YYY.GT.O.) XN=XN*FR
      BA=BOND+XN-R
     L=BA/IDR
     X = IDR * (BA / IDR - L)
      IF(DM - IDR/10.)9.8.8
115
     IF(N-NOS+1)116,90,90
116
     A9 = (T(N+1) - T(N)) * A(N) - (T(N) - T(N-1)) * A(N-1)
     E(N) = CK(T(N))/DS/CPS/V(N) * IDT/ IDR*A9+ T(N)
     IF(E(N)-TMS )109,109,402
402
     E(N) = TMS
     GO TO 109
201
     STOP
     END
```

222

C.....VOLUME OF GAS EVOLVED AT TEMP. Q
FUNCTION VVV(Q)
COMMON VG(20), GG(20), PS, TA, CA, TB, F1 , F2, F3 , F4, F5, W1, W2, W3
C, S, CKS , CKL, DP, DB , K2, K3, K4, K5 , DDD, FF2
IF (F2.LE.0.OR.F3.LE.O) GO TO 1011
I=(Q-273.) / 100.
IF (I.GT.O.)VVV=(VG(I)+(VG(I+1)-VG(I))*((Q-273.)/100.-I))*F2/FF2
IF (I.EQ.O.) VVV= VG(1)*(Q-273.)/100.
RETURN
1011 VVV=0.
RETURN

END

223.

```
C.....SPECIFIC HEAT AND THERMAL CONDUCTIVITY OF DRI PELLET
      SUBROUTINE FFF (CPM,Q,CKM,CS)
      REAL K2,K3,K4,K5
      COMMON VG(20), GG(20), PS, TA, CA, TB, F1, F2, F3, F4, F5, W1, W2, W3
     C,S,CKS,CKL, DP,DB,K2,K3,K4,K5,DDD,FF2
      J=Q/100.-1.
      CHECK=CM(Q)
      \Box U = 3.04E - 4*(1 - E XP(-7.65E - 4*Q)) + 4.08E + 12*Q**3 *DDD
      CKM = 00**PS*GG(J)**(W1*(1-PS))*K2** (W2*(1-PS))*K3**(W3 *(1-PS))
     C * K 4 * * (F 4 * (1 - P S)) * K 5 * * (F 5 * (1 - P S))
      CS = CKM
      G = VVV(Q+.5) - VVV(Q-.5)
      IF(Q-TA)1001,1002,1002
1001 CPM = CHECK+1.29 \times G
      RETURN
1002 IF(Q-FA-8)1003,1003,1004
1003 CPM = CHECK+1.35%G+2.89E-3*CA-1.95E-2
      RETURN
1004 IF( Q.LT.TB) CPM=CHECK+1.47*G
      IF( Q.GE.TB ) CPM=CHECK+1.35*G
      RETURN
```

.

END

224.

1

```
C.....SPECIFIC HEAT OF MATERIALS USED IN CALCULATION
C....OF SPECIFIC HEAT OF DRI PELLET
      FUNCTION CM(Q)
      COMMON VG(20), GG(20), PS, TA, CA, TB, F1 , F2, F3 , F4, F5, W1, W2, W3
                                                                            1
     C, S, CKS, CKL, DP, DB, K2, K3, K4, K5, DDD, FF2
      W1 = F1 + 1.01E - 2 \times VV(0)
      W2 = F2 - 3.53E - 3 \times VV(Q)
      W3 = F3 - 8 \cdot 02E - 3 * VVV(Q)
      IF (Q.LE.1033) C1=7.48E-2+1.06E-4*0
      IF (Q.GT.1033.AND.Q.LE.1181) C1=.161
      IF (Q.GT.1181) C1= 3.29E-2 +8.34E-5*Q
      C2 = .169+2.9 E-5*0-9.7E2/0**2
      IF (Q.LE.463) C3=.109+1.11E-4*Q
      IF (Q.GT.463) C3=.143+1.67E-5*0
      C4 = .25 + 4 \cdot 17 = -5 \times Q - 6 \cdot 69 = 3/Q \times 2
      IF (Q.LE.848) C5=1.87E-1+1.36E-4*Q-4.49E3/Q**2
      IF (Q.GT.848) C5= 2.4 E-1+3.23E-5*0
      CM = W1 \times C1 + W2 \times C2 + W3 \times C3 + F4 \times C4 + F5 \times C5
      RETURN
      END
```

225

```
C.....CONDUCTIVITY OF SOLID SLAG SHELL

FUNCTION CK(Q)

COMMON VG(2G), GG(20), PS, TA, CA, TB, F1, F2, F3, F4, F5, W1, W2, W3

C, S, CKS, CKL, DP, DB, K2, K3, K4, K5, DDD, FF2

PC = 3.04E-4*(1-EXP(-7.65E-4*Q))+4.08E-12*Q**3 *DP

CK = CKS **(1-S)*PC**S

RETURN

END
```

```
C.....SPECIFIC HEAT AND THERMAL CUNDUCTIVITY OF NI PARTICL
SUBROUFINE FFF (CPA+0, CKM ,CS)
COMMON VG(20)+ GG(20)+P5+FA+CA+TB+F1 +F2+F3 +F4+F5+W1+W2+W3
C+5+CKS +CKL+SG+ OP+DH +K2+K3+K4+K5 +JUD
J=0/100+-1.
GO = 3.04F-4*(1+FxP(-/*obE-4*Q))+ 4.08E-12*Q**3 *DDD
CKM=00**P5*GG(J)**(1+D5)
CS = CKM
IF(0+LT+903)CPM=+13+B+01==0*Q-2+27E3/w**2
IF(Q+GE+903)CPM=+12+1.70==0*Q-3+80E3/w**2
RETURN
END
```

i i

1

7. Definition of Terms

A(N) = AREA BETWEEN NODES N AND N+1 AT DISTANCE IDR/2 = CONSTANT FOR HEAT TRANSFER TO THERMOCOUPLE ΔΔ ACRM =HEAT OF FUSION OF PARTICLE = TERMAL DIFUSIVITY OF LIQ. SLAG ALL DIFUSIVITY OF SOLID SLAG ALP = TERMAL = CONSTANT FOR HEAT TRANSFER TO THERMOCOUPLE 83 =THERMAL CONDUCTIVITY OF POROUS LIQ. SLAG Вĸ BOND = R + THICKNESS OF SHELL = SPECIFIC HEAT 0F IRON C 1 "FEO" С2 = SPECIFIC HEAT 0F = SPECIFIC OF FE3C 63 HEAT = SPECIFIC HEAT OF AL203 C4 C5 = SPECIFIC HEAT OF SID2 = CARBON CONTENT OF PARTICLE AT TEMP. TΔ C۵ OF PARTICLE AT CR = CARBON CONTENT TEMP. TB = CONSTANT FOR HEAT TRANSFER TO THERMOCOUPLE CC C < = THERMAL CONDUCTIVITY UF POROUS SOLID SHELL =THERMAL CONDUCTIVITY OF LIQ. SLAG CKL =THERMAL CONDUCTIVITY OF PARTICLE CKM =THERMAL CONDUCTIVITY OF SOLID SLAG C≺S См = SPECIFIC HEAT OF U-R MATERIAL =SPECIFIC HEAT OF LIQ. SLAG CPL =SPECIFIC HEAT OF PARTICLE Cov =SPECIFIC HEAT OF EXTERNAL ELEMENT OF PARTICLE CoD =SPECIFIC HEAT OF SOLID SHELL CPS CS =CONDUCTIVITYT OF EXTERNAL ELEMENT OF PARTICLE = DENSITY OF PARTICLE Ð = PORE DIAMETER IN LIQ. SLAG D3 = CONSTANT FOR HEAT TRANSFER TO THERMOCOUPLE DD = PORE DIAMETER IN PARTICLE DDD = DENSITY OF IIQ. SLAG DL = PORE DIAMETER IN SOLID SLAG D > ÐP =WIDTH OF AN ELEMENT IN PARTICLE = DENSITY OF POROUS SOLID SHELL DS SOLID SLAG = DENSITY OF D51 EXTERNAL ELEMENT OF PARTICLE 055 = DENSTTY OF E(N) = TEMP. AT NODE N FOR PRESENT TIME

EE = CONSTANT FOR HEAT TRANSFER TO THERMOCOUPLE EV(N) = GAS VOL. PER GRAM OF SPONGE ELEMENT N

CORRECTION FACTOR FOR PARTICLE-SLAG INTERFACE F Ξ INITIAL WT. FRACTIUN OF F) IRON IN D-R PELI ET Ξ INITIAL F2 WT. FRACTION OF "FEO" IN D-R PELLET Ξ F3 FRACTION OF FE3C IN D-R INITIAL WT. PELLET = F4 FRACTION OF AL203 IN D-R PELLET WEIGHT = FRACTIUN OF F'5 WEIGHT SI02 - IN D-R PELLET Ξ = NUSSELT NUMBER FNU G SPECIFIC GAS VOLUME Ξ THERMAL CONDUCTIVITY OF METAL AS A FUN. OF TEMP. GG Ξ RATE OF GAS EVOLUTION FROM PARTICLE G२ Ξ VOL. FRACTION OF GAS EVOLVED FROM ELEMENT I GV(I) ==HEAT OF FUSION OF SLAG н 0F HEAT FUSION OF IRON H1 = HFAT 05 FUSION OF IFE01 H2 Ξ 0-05 FUSION FE3C HEAT HZ Ξ 0-0F = HEAT FUSION 4L203 H4 OF FUSION OF SIO2 Н5 = HEAT HTRANS= HEAT TRANSFER COEFFICIENT IDR =WIDTH OF AN ELEMENT IN SLAG = LENGTH OF A TIME ELEMENT IDT THERMAL CONDUCTIVITY OF 'FEO' К2 = = THERMAL CONDUCTIVITY OF FE3C KЗ = THERMAL CONDUCTIVITY OF AL203 K4 THERMAL CUNDUCTIVITY OF SIO2 KS. = NO. OF TEMP. INTERVALS FOR GG AND VG N1 Ξ NO. OF NODES ND = = NO. OF NODES IN SLAG NDS NO. OF TIME STEPS ALLOWABLE NOT = THERMAL CONDUCTIVITY OF PARTICLE PORES 00 = TOTAL GAS VOL. EVOLVED FROM PELLET TGV = POROSITY OF PARTICLE PS = TEMPERATURE OF SPONGE Q. Ξ FLOW OF HEAT FOR MELTING PARTICLE QR = R RADIUS OF PARTICLE Ξ RR = RADIUS OF THERMOCOUPLE HOLE

T(N) = TEMP. AT NODE N FOR PAST TIME . TEMP. AT WHICH SOLID-SOLID TRANSFORMATION TΑ = STARTS TEMP. AT WHICH SULID-SOLID TRANSFORMATION ENDS TR = = VOL. FRACTION OF PARTICLE MELTED TEM = TEMP. OF BULK LIQ. SLAG ΤI TIME AFTER IMMESION OF PARTICLE TIME = TM = MELTING TEMP. OF PARTICLE TMS = SOLIDUS TEMP. OF SLAG TMSP = LIQUIDUS TEMP. OF SLAG = INITIAL TEMP. OF PARTICLE TO. Τマ MELTING RANGE OF SLAG = = VISCOSITY OF SLAG , POISE U $V(N) = VOL \cdot AT NODE N$ VOL. OF GAS EVOLVED FROM 1 GRAM OF SPONGE AT TEMP. T(I) VG(I)= HALF OF TOTAL VOL. OF EXTERNAL ELEMENT ON PARTICLE VOL AND Ξ ADJACENT ELEMENT IN SLAG VVV VOL. OF GAS EVOLVED FROM 1 GRAM OF Ξ DRI WT. FRACTION OF IRON IN D-R PELLET W1 = WT. FRACTION OF 'FEO' IN D-R PELLET W2 Ξ WR WT. FRACTION OF FE3C IN D-R PELLET = DIS. FROM FURTHEST ELEMENT TO THE MOVING BOUNDARY x = XV THICKNESS CHANGE IN ONE TIME STEP = THICKNESS OF EXTERNAL ELEMENT OF PARTICLE XХ = YYY = GAS BUBBLING CONTROLLER - 1 . BUBBLING - 0 . NO BUBBLING

S = POROSITY OF SLAG SHELL SS = POROSITY OF LIQ. SLAG