Appendix A
Sample Calculation for the $H_{2}$ 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 $\mathrm{C} / \mathrm{H}_{2}$ combustion type:

$$
\begin{gather*}
0+\mathrm{C}=\mathrm{CO}  \tag{A.1}\\
20+\mathrm{C}=\mathrm{CO}_{2}  \tag{A.2}\\
0+\mathrm{H}_{2}=\mathrm{H}_{2} \mathrm{O} \tag{A.3}
\end{gather*}
$$

Table A-1. $\mathrm{H}_{2}$ Extraction Data for Type D Pellets.
Grain Size, 2 mm.

| Weights <br> (Gram) | Initital | Final | Gain |
| :---: | :---: | :---: | :---: |
| Sample | 4.1971 | 3.9752 | -0.2219 |
| $\mathrm{H}_{2} \mathrm{O}$ absorbent | 64.9596 | 64.9804 | 0.0208 |
| correction | - | - | -0.0138 |
| total | - | - | 0.0070 |
| $\mathrm{CO}_{2}$ absorbent | 64.3738 | 64.3856 | 0.0118 |
| correction | - | - | 0.0133 |
| total | - | - | 0.0251 |
| CO* | - | - | 0.1906 |

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

$$
\begin{align*}
& \mathrm{W}_{\mathrm{CO}}=\Delta \mathrm{W}_{\mathrm{S}}-\mathrm{W}_{\mathrm{CO}_{2}}-\mathrm{W}_{\mathrm{O}}  \tag{A.4}\\
& \mathrm{~W}_{\mathrm{O}}=\mathrm{W}_{\mathrm{H}_{2} \mathrm{O}}\left(\frac{\mathrm{M}_{0}}{\mathrm{M}_{\mathrm{H}_{2} \mathrm{O}}}\right)+\mathrm{W}_{\mathrm{CO}_{2}}\left(\frac{2 \mathrm{M}_{\mathrm{O}}}{\mathrm{M}_{\mathrm{CO}}}\right)+\mathrm{W}_{\mathrm{CO}}\left(\frac{\mathrm{M}_{0}}{\mathrm{M}_{\mathrm{CO}}}\right)  \tag{A.5}\\
& \mathrm{W}_{\mathrm{C}}=\mathrm{W}_{\mathrm{CO}}\left(\frac{\left(\frac{\mathrm{M}_{\mathrm{C}}}{\mathrm{M}_{\mathrm{CO}}}\right)+\mathrm{W}_{\mathrm{CO}}\left(\frac{\mathrm{M}_{\mathrm{C}}}{\mathrm{M}_{\mathrm{CO}}}\right)}{\%} \begin{array}{l}
\%=100\left(\frac{\mathrm{~W}_{0}}{\mathrm{~W}_{\mathrm{S}}}\right) \\
\% \mathrm{C}=100\left(\frac{\mathrm{~W}_{\mathrm{C}}}{\mathrm{~W}_{\mathrm{S}}}\right)
\end{array}\right. \tag{A.6}
\end{align*}
$$

$W_{i}$ is the weight gain of the specie $i, \Delta W_{S}$ 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.

$$
\begin{aligned}
& W_{C O}=0.2219-0.0251-0.0070\left(\frac{16}{18}\right)=0.1906 \\
& W_{0}=0.0070\left(\frac{16}{18}\right)+0.0251\left(\frac{32}{44}\right)+0.1906\left(\frac{16}{28}\right)=0.1334 \\
& W_{C}=0.0251\left(\frac{12}{44}\right)+0.1906\left(\frac{12}{28}\right)=0.0885
\end{aligned}
$$

Hence:

$$
\begin{aligned}
& \% ~ D=3.18 \\
& \% C=2.10
\end{aligned}
$$

## 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 $25^{\circ} \mathrm{C}$ 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 $200 \mathrm{~cm}^{3} / \mathrm{min}$ 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 $450 \mathrm{~cm}^{3} / \mathrm{min}$, 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:

$$
\begin{array}{ll}
\dot{V}=19 f+1 / 9 f^{2.7} & f \leq 8 \\
\dot{V}=33 f-81 & f \geq 8 \tag{B.2}
\end{array}
$$

where $\dot{V}$ is the gas rate in $\mathrm{cm}^{3} / \mathrm{min}$ and $f$ is the frequency in Cycles/min.


Fig. B-1 A Calibration Curve for Flowneter.

## Apperidix 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 $C-1$ ):

$$
\begin{equation*}
\dot{\mathrm{V}}=a \dot{T}+b \tag{C.1}
\end{equation*}
$$

where $\dot{V}$ and $\dot{T}$ 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:

$$
\begin{equation*}
\dot{\mathrm{V}}=\left(\dot{\mathrm{V}}_{\mathrm{a}} / \dot{\mathrm{T}}_{\mathrm{a}}\right) \dot{\mathrm{T}} \tag{C.2}
\end{equation*}
$$

in which $\dot{\mathrm{V}}_{\mathrm{a}}$ is the measured flow rate and $\dot{\mathrm{T}}_{\mathrm{a}}$ 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 $t=\left(t_{i}+t_{i+1}\right) / 2$ is evaluated by substituting $f$ into Equations (B.1) and (B.2):

$$
\begin{align*}
& f=1 /\left(t_{i+1}-t_{i}\right)  \tag{C.3}\\
& \dot{v}_{a}=19\left(t_{i+1}-t_{i}\right)^{-1}+\left(t_{i+1}-t_{i}\right)^{-2.7} / 9  \tag{C.4}\\
& t_{i+1}-t_{i} \geq .25 \mathrm{~min}  \tag{C.5}\\
& \dot{v}_{a}=33\left(t_{i+1}-t_{i}\right)^{-1}-81
\end{align*} t_{i+1}-t_{i}<.25 \mathrm{~min}
$$

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


Fig. C-I Temp. Profile for a Schematic Gas Evolution Pattern.
evaluated from the following equations:

$$
\begin{align*}
& \bar{T} \simeq \frac{T_{i}+T_{i+1}}{2}  \tag{C.6}\\
& \bar{T}_{a}=\frac{T_{i+1}-T_{i}}{t_{i+1}-t_{i}} \tag{C.7}
\end{align*}
$$

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

$$
\begin{align*}
& \dot{V}=\left[\frac{19\left(t_{i+1}-t_{i}\right)^{-1}+\left(t_{i+1}-t_{i}\right)^{-2.7} / 9}{\left(T_{i+1}-T_{i}\right) /\left(T_{i+1}-T_{i}\right)}\right] \dot{T} \\
& T_{i+1}-t_{i} \geq .25 \mathrm{~min}  \tag{C.8}\\
& \dot{V}=\left[\frac{33\left(t_{i+1}-t_{i}\right)^{-1}-81}{\left(T_{i+1}-T_{i}\right) /\left(t_{i+1}-t_{i}\right)}\right] \dot{T} \quad t_{i+1}-t_{i}<.25 \mathrm{~min} \tag{C.9}
\end{align*}
$$

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 $\overline{\mathrm{T}}$.


Fig. C-2 Temp. Fluctuations of Bomb Sample (curve a) and Response of Flowmeter to Flow of Gases Evolved (curve b).

## 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.

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

In the above equation $V$ is volume of slag and $p$ is pressure of the system.
The thermal diffusivity, $\alpha$, and the kinematic viscosity, $\nu$, are defined by the following equations:

$$
\begin{align*}
\alpha & \equiv k / \rho C_{p}  \tag{D.2}\\
v & \equiv \mu / \rho \tag{D.3}
\end{align*}
$$

where $k$ is thermal conductivity, $\rho$ is density, $C_{p}$ is specific heat and $\mu$ is viscosity of the slag. The dimensionless Prandtl number is defined as follows:

$$
\begin{equation*}
\operatorname{Pr}=\nu / \alpha \tag{D.4}
\end{equation*}
$$

The dimensionless Grashof number, Gr, for a liquid slag at temperature $\mathrm{T}_{\infty}$ can be determined from the following relationship:

$$
\begin{equation*}
G r=\frac{g \beta\left(T_{\infty}-T_{s}\right)(R+\theta)^{3}}{v^{2}} \tag{D.5}
\end{equation*}
$$

where $g$ is gravitational acceleration, $T_{s}$ is temperature of solid-liquid interface, $R$ is radius of immersed particle and $\theta$ is thickness of solid shell of slag. The combination of Prandtl and Grashof groups is called
the Rayleigh number:

$$
\begin{equation*}
\operatorname{Ra}=\operatorname{Pr} \cdot G r \tag{D.6}
\end{equation*}
$$

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, $k_{s}:^{79}$

$$
\begin{equation*}
k=k_{p}^{I-\psi} \cdot k_{s}^{\psi} \tag{D.7}
\end{equation*}
$$

where $\psi$ is the porosity (volume fraction) of the substance. Ben-Amoz 79 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 Messmer ${ }^{90}$ 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:

$$
\begin{equation*}
k_{p}=k_{r}+k_{c} \tag{D.8}
\end{equation*}
$$

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:

$$
\begin{equation*}
k_{r}=3 \sigma \mathrm{~d}^{3} \tag{D.9}
\end{equation*}
$$

in which $\sigma$ 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 $1500^{\circ} \mathrm{K}:{ }^{82}$

$$
k_{c}=3.04 \times 10^{-4}\left[1-\exp \left(-7.65 \times 10^{-4} \mathrm{~T}\right)\right] \quad\left(\mathrm{Cal} / \mathrm{cm} \cdot \mathrm{sec} \cdot{ }^{\circ} \mathrm{K}\right) \quad(\mathrm{D} .10)
$$

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

$$
\begin{array}{r}
k_{p}=4.08 \times 10^{-12} \mathrm{~d} \cdot \mathrm{~T}^{3}+3.04 \times 10^{-4}\left[1-\exp \left(-7.65 \times 10^{-4} \mathrm{~T}\right)\right] \\
\left(\mathrm{Cal} / \mathrm{cm} \cdot \mathrm{sec} \cdot{ }^{\circ} \mathrm{K}\right) \quad(\mathrm{D} .11)
\end{array}
$$

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: ${ }^{79}$
where $\mathrm{k}_{M}$ is the thermal conductivity of constituent $M$. The volume fraction of $M$ denoted by $\psi_{M}$ is assumed to be proportional to the weight fraction of $M$ designated by $W_{M}$ :

$$
\begin{equation*}
\psi_{M}=W_{M}\left(1-\psi_{P}\right) \tag{E.2}
\end{equation*}
$$

For simplicity, the change of $\psi_{p}$ when DRI pellets are heated is assumed negligible.

The heat of fusion of $D R I$ materials, $\Delta H$, 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, $\Delta H$ can be calculated from the following equation:

$$
\begin{equation*}
\Delta \mathrm{H}=\mathrm{W}_{\mathrm{Fe}} \Delta \mathrm{H}_{\mathrm{Fe}}+\mathrm{W}_{\mathrm{Al}_{2} \mathrm{O}_{3}} \Delta \mathrm{H}_{\mathrm{Al}_{2} \mathrm{O}_{3}}+\mathrm{W}_{\mathrm{SiO}_{2}} \Delta \mathrm{H}_{\mathrm{SiO}_{2}} \tag{E.3}
\end{equation*}
$$

in which $\Delta H_{M}$ 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: ${ }^{58}$

$$
\begin{gather*}
\dot{Q}=\chi A_{1} F \sigma\left(T_{W, j}-T_{b, j}\right)+y A_{2} k\left(T_{W, j}-T_{b, j}\right) / \Delta r  \tag{E.4}\\
T_{b, j+1}=T_{b, j}+\dot{Q} \Delta t / m C_{p} \tag{E.5}
\end{gather*}
$$

where $X A_{1}$ 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:

$$
\begin{equation*}
F=1 /\left(1 / \varepsilon_{W}+1 / \varepsilon_{b}-1\right) \tag{E.6}
\end{equation*}
$$

where $\varepsilon_{w}$ and $\varepsilon_{b}$ 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:

$$
\begin{align*}
& \dot{Q}=A\left(T_{w \cdot j}-T_{b, j}^{4}\right)+B\left(T_{w, j}-T_{b, j}\right)  \tag{E.7}\\
& T_{b, j+1}=T_{b, j}+\dot{Q} \Delta t / D \tag{E.8}
\end{align*}
$$

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

$$
\begin{align*}
& A \equiv X A_{1} F \sigma  \tag{E.9}\\
& B \equiv y A_{2} k  \tag{E.10}\\
& D \equiv m C_{p} \tag{E.11}
\end{align*}
$$

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

| Coefficient | Nickel Sphere |  | DRI Pellet |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Sma11 | Large | E | D |
| A, $10^{14} \mathrm{Cal} / \mathrm{sec} .{ }^{\circ} \mathrm{K}^{4}$ | 2 | 6 | 1 | 1 |
| B, $10^{4} \mathrm{Cal} / \mathrm{sec} .{ }^{\circ} \mathrm{K}$ | 3 | 1 | 6 | 6 |
| D, $\mathrm{Cal} /{ }^{\circ} \mathrm{K}$ | 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 $\mathrm{F}-1$ ). 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" $\left(\mathrm{SiO}_{2}+\mathrm{Al}_{2} \mathrm{O}_{3}\right)$, 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 axygen and carbon are in form of " $\mathrm{FeO}^{\prime}$ " and $\mathrm{Fe}_{3} \mathrm{C}$ chemical compounds. The reaction between these compounds below the carbide decomposition temperature $\mathrm{T}_{\mathrm{a}}$ (see Figure $\mathrm{F}-1$ ) may be written as follows:

$$
\begin{gather*}
\mathrm{FeO} \mathrm{O}+\mathrm{Fe}_{3} \mathrm{C}=3.95 \mathrm{Fe}+\mathrm{CO}  \tag{F.1}\\
2^{\prime \prime} \mathrm{FeO}^{\prime \prime}+\mathrm{Fe}_{3} \mathrm{C}=4.9 \mathrm{Fe}+\mathrm{CO}_{2} \tag{F.2}
\end{gather*}
$$

For a gaseous product composed of $90 \% \mathrm{CO}$ and $10 \% \mathrm{CO}_{2}$, the stoichiometric quantities of reactants and products are as demonstrated in Eq. (F.3):

$$
\begin{aligned}
& 1.1 \mathrm{NFeO}^{\prime}+\mathrm{Fe}_{3} \mathrm{C}=4.05 \mathrm{Fe}+0.9 \mathrm{CO}+0.1 \mathrm{CO}_{2} \\
& 3.53 \times 10^{-3} \mathrm{~g}+8.02 \times 10^{-3} \mathrm{~g}=1.01 \times 10^{-2} \mathrm{~g}+1 \mathrm{~cm}^{3}
\end{aligned}
$$

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

$$
\begin{gather*}
\mathrm{W}_{\mathrm{Fe}}=\mathrm{W}_{\mathrm{i}, \mathrm{Fe}}-(-1.01 \mathrm{E}-2) \mathrm{V}  \tag{F.4}\\
\mathrm{~W}_{{ }^{\prime \prime} \mathrm{FeO}}=\mathrm{W}_{\mathrm{i}, \mathrm{FeO}}{ }^{\prime}-(3.53 \mathrm{E}-3) \mathrm{V}  \tag{F.5}\\
\mathrm{~W}_{\mathrm{Fe}_{3} \mathrm{C}}=\mathrm{W}_{\mathrm{i}, \mathrm{Fe}_{3} \mathrm{C}}-(8.02 \mathrm{E}-3) \mathrm{V} \tag{F.6}
\end{gather*}
$$

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:

$$
\begin{gather*}
\mathrm{CM}=\mathrm{W}_{\mathrm{Fe}} \cdot \mathrm{C}_{\mathrm{Fe}}+\mathrm{W}_{\mathrm{NFeO}^{\prime \prime}} \cdot \mathrm{C}_{\mathrm{FFeO}^{\prime \prime}}+\mathrm{W}_{\mathrm{Fe}_{3} \mathrm{C}} \cdot \mathrm{C}_{\mathrm{Fe}_{3} \mathrm{C}}+ \\
\mathrm{W}_{\mathrm{Al}_{2} \mathrm{O}_{3}} \cdot \mathrm{C}_{\mathrm{Al}_{2} \mathrm{O}_{3}}+\mathrm{W}_{\mathrm{SiO}_{2}} \cdot \mathrm{C}_{\mathrm{SiO}_{2}} \tag{F.7}
\end{gather*}
$$

Table F-1. Specific Heat of Materials. ${ }^{94}$

| Material | Relationship ( $\mathrm{Cal} .{ }^{\circ} \mathrm{K}^{-1} \cdot \mathrm{~g}^{-1}$ ) | Temp. Range $\left({ }^{\circ} \mathrm{K}\right)$ |
| :---: | :---: | :---: |
| $\mathrm{Fe}_{\alpha}$ | $7.48 \mathrm{E}-2+1.06 \mathrm{E}-4 \mathrm{~T}$ | 273-1033 |
| $\mathrm{Fe}_{\beta}$ | $1.61 \mathrm{E}-1$ | 1033-1181 |
| $\mathrm{Fe}_{\gamma}$ | 3.29 E-2 + 8.34 E-5T | 1191-1674 |
| $\mathrm{Fe}_{0.95}{ }^{0}$ | $1.69 \mathrm{E}-1+2.90 \mathrm{E}-5 \mathrm{~T}-9.70 \mathrm{E} 2 \mathrm{~T}^{-2}$ | 298 - m.p. |
| $\left.\mathrm{Fe}_{3} \mathrm{C}\right)_{\alpha}$ | $0.109+1.11 \mathrm{E}-4 \mathrm{~T}$ | 273-463 |
| $\left.\mathrm{Fe}_{3} \mathrm{C}\right)_{\beta}$ | $0.143+1.67 \mathrm{E}-5 \mathrm{~T}$ | 463-1500 |
| $\mathrm{Al}_{2} \mathrm{O}_{3}$ | $0.25+4.17 \mathrm{E}-5 \mathrm{~T}-6.69 \mathrm{E} 3 \mathrm{~T}^{-2}$ | 298-1800 |
| $\left.\mathrm{SiO}_{2}\right)_{\alpha}$ | $1.87 \mathrm{E}-1+1.36 \mathrm{E}-4 \mathrm{~T}-4.49 \mathrm{E} 3 \mathrm{~T}^{-2}$ | 298-848 |
| $\left.\mathrm{SiO}_{2}\right)_{\beta}$ | $2.40 \mathrm{E}-1+3.23 \mathrm{E}-5 \mathrm{~T}$ | 848-2000 |

## 2. Enthalpy of Reactions

Equation (F.3) illustrates the final reduction of the sponge material below the carbide decomposition temperature $T a$ (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.

$$
\begin{equation*}
1.1{ }^{\prime \prime} \mathrm{FeO}^{\prime}+\underline{\mathrm{C}}=1.05 \mathrm{Fe}+0.9 \mathrm{CO}+0.1 \mathrm{CO}_{2} \tag{F.8}
\end{equation*}
$$

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:

$$
\begin{equation*}
G(T)=\partial V / \partial T \simeq V_{T+0.5} V_{T-0.5} \tag{F.9}
\end{equation*}
$$

| Temp. Range ( ${ }^{\circ} \mathrm{K}$ ) | Table F-2 |  | Enthalpies and Free Energies of Reactions |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\begin{aligned} & \text { Enthalpy } \\ & \text { (Cal. } \mathrm{cm}^{-3} \text { ) } \end{aligned}$ |  | $\begin{aligned} & \text { Standard Free Energy } \\ & \left(\mathrm{CaI} . \mathrm{cm}^{-3}\right) \\ & \hline \end{aligned}$ |  | $\begin{gathered} C_{R} \\ \left(\mathrm{Cal}^{-1} \cdot \mathrm{k}^{-1}\right) \end{gathered}$ |
|  | (F.3) | (F.8) | F.3) | (F.8) |  |
| $\mathrm{T}<\mathrm{T}{ }_{\mathrm{a}}$ | 1.29 | - | - | - | $1.29 \mathrm{G}(\mathrm{T})$ |
| $\mathrm{T}_{\mathrm{a}} \leq \mathrm{T} \leq \mathrm{T}{ }_{\mathrm{a}}+8$ | 1.35 | - | -0.02 * | $0.22 *$ | $1.35 \mathrm{G}(\mathrm{T})$ |
| $\mathrm{T}_{\mathrm{a}}+8<\mathrm{T}<\mathrm{T}_{\mathrm{b}}$ | 1.47 | - | $-0.60{ }^{\text {F }}$ | $-0.24^{\neq}$ | $1.47 \mathrm{G}(\mathrm{T})$ |
| $T \geq \mathrm{T}_{\mathrm{b}}$ | - | 1.35 | - | - | $1.35 \mathrm{G}(\mathrm{T})$ |
| ${ }^{*}$ Calculat | d at | ${ }^{\circ} \mathrm{K}$. | ${ }^{\prime}$ Calculated | $1400^{\circ} \mathrm{K}$ |  |

## 3. Heat of Phase Transformation

The formation of Austenitic iron phase in $D-R$ sponge pellets at eutectoid temperature, $T_{a}$, is exothermic: ${ }^{77}$

$$
\begin{equation*}
\mathrm{Fe}_{3} \mathrm{C}=3 \mathrm{Fe}+\underline{\mathrm{C}}-1.23\left(\mathrm{cal} \cdot \mathrm{~g}_{\mathrm{Fe}_{3}} \mathrm{C}^{-1}\right) \tag{F.10}
\end{equation*}
$$

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

The fron 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, $\mathrm{Fe}_{3} \mathrm{C}$, at the eutectoid temperature can be calculated from Eq. (F.13):

$$
\begin{align*}
& \mathrm{W}_{\mathrm{i}, \mathrm{Fe}_{3} \mathrm{C}}=(\mathrm{CA}-0.02) / 6.66  \tag{F.11}\\
& \mathrm{~W}_{\mathrm{Fe}_{3} \mathrm{C}}=(\mathrm{CA}-0.77) / 5.92  \tag{F.12}\\
& \Delta \mathrm{~W}_{\mathrm{Fe}_{3} \mathrm{C}}=1.88 \times 10^{-2} \mathrm{CA}-0.127 \tag{F.13}
\end{align*}
$$

in which $C A$ 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.

$$
\begin{equation*}
C_{T}=2.89 \times 10^{-3} \mathrm{CA}-1.95 \times 10^{-2} \tag{F.14}
\end{equation*}
$$

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.


Fig. F-1 Schematic $\mathrm{Fe}-\mathrm{Fe}_{3} \mathrm{C}$ Phase Diagram and DRI Extraction Path.

## 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 $\mathrm{T}_{\infty}$ 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:

$$
\begin{equation*}
-k\left(\frac{\partial T}{\partial r}\right)_{i}+h\left(T_{\infty}-T_{i}\right) \tag{G.1}
\end{equation*}
$$

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

$$
\begin{equation*}
\delta_{\mathrm{T}}=2(\mathrm{R}+\theta) / \mathrm{Nu} \tag{G.2}
\end{equation*}
$$

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

## Appendix H

## Conduction Heat Transfer

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

$$
\begin{equation*}
\frac{\partial T}{\partial t}=\alpha\left[\frac{\partial^{2} T}{\partial r^{2}}+\frac{2}{r} \frac{\partial T}{\partial r}\right] \tag{H.1}
\end{equation*}
$$

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

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

where:

$$
\begin{array}{ll}
\xi=0 & t=0 \\
\xi=(R+\theta)\left(T_{i}-T_{\infty}\right) & r=R+\theta \tag{H.4}
\end{array}
$$

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

$$
\begin{equation*}
T-T_{\infty}=\left(T_{i}-T_{\infty}\right) \frac{R+\theta}{r} \operatorname{erfc} \frac{r-R-\theta}{\sqrt{\pi \alpha t}} \tag{H.5}
\end{equation*}
$$

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

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

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

$$
\begin{equation*}
h=k\left[\frac{1}{R+\theta}+\frac{1}{\sqrt{\pi \alpha t}}\right] \tag{H.7}
\end{equation*}
$$

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

$$
\begin{equation*}
N u=2+2(R+\theta) / \sqrt{\pi \alpha t} \tag{H.8}
\end{equation*}
$$

## 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:

$$
\begin{equation*}
n=f \frac{\ell}{v} \tag{I.1}
\end{equation*}
$$

where $f$ and $v$ are frequency and velocity of gas bubbles and $\ell$ 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:

$$
\begin{equation*}
P=N \frac{f l}{6 v}\left(\frac{D_{b}}{D}\right)^{2} \tag{I.2}
\end{equation*}
$$

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.

## 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.

```
C.............INPUT UATA
        REAL IOT,IOR,NU ,K2,K3,K4,K5
        COMMON VG(20), GG(2Ј),PS,TA,CA,TB,F1,F2,F3,F4,F5,W1,W2,W3
        C,S,CKS ,CKL, DP,DB ,K2,K3,K4,K5 ,DDD,FF2
        OIMENSION A(99),V(99),1(99),E(99), EV(99),TT(99),GV(99)
        AF=0
2) IF(AF.EQ.0) 60 TO 77
            IF(AF-CJ)66,98,71
        AF=0
        READ(5,1SOINO, NUT, 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,
        CNi),CKS,F, PS, (GG(I),I=1,N1),DS1, ACRM,GNU,AA,H,DDD,K4, K5 ,TTT
        IF(NO.EQ.O.)GO TO 2U:
1)0 FORMAT(4I5/ (bF10.4))
        WRITE(G,111INO,NOT, NOS,N1,IDR,IDT,BB,TO,TMS,TMSP,CA,K3,S,R,D,K2,
    CCPL,CPS,U,XX,OL,TM,DD,ZT ,CJ,DSS,RR,TR,CB, TA, TB, (VG(I),I=1,
    CNL),CKS,F, PS, (GG(I),I=1,N1),DS1 , ACRM,GNU,AA,H, DDD,K4, K5, TTT
        FURMATI4I5/5X,'IDR',T15,'IDT',T25,'BB',T35,'TO',T45,'TMS',T55,'TMS
        CP',T65,'CA',T75,'K3'/8F1G.4/5X,'S',T15,'R',T25,'D',T35,'K2',T45,'C
        CPL',T55,'CPS',T66,'U',T75,'XX'/8F1%.4/5X, 'DL',T15,'TM ',T25,'DD',
        CT35,' LT',T45,'CJ',T55,'USS',T65, 'RR',T75,'TK'/8F10.4/5X, 'CB'
        C,T15,'TA',T25,'TB',T35,'VG(1)',T45, '2',T55,'3',T65,'4',T75,'5''
        C/8F10.4/5X,'6',T:5,'7',T25,'8',T35,'9',T45,'10',T55,'11',T65,'12'
        C,T75,'13'/8F1.4/5X,114 ..... 15 ..... 16 .... CKS .... F.
        C...PS .....GG(1) .. 2'/8F13.4/5X,13',9X,14 ...... 5 ...... 6
        C ..... 7 .... 8 ...... 9 ..... lv'/ofl0.4/5x,ilil, 9x,iliz
        C ... 13 .... 14 ..... 15 ...... 16 ......DS1.... ACRM'/8F1u.4/
```



```
        REAO(5,IU) Fi,F2,F3,F4,F5,TI,CKL,YYY,FF2 ,FNU,TMS,TMSP,NU,DP,FR,WT
        C,R
1) FORMAT(8F10.4)
        IF(F1 1201,2.)1,1i
IL WRITE(G,12) Fl,F2,F3,F4,F5,TI,CKL,YYY,FF2,FNU,TMS,TMSP,NU,DP,FR,WT
        C,R
i2 FORMATI//// 5X,'PELLET COMPOSITICN:',N,NF1.4/ (12F10.4))
```

```
C.............calculaile cQnstants
    DR=(R-RR )/(NO-NOS )
    Xx=DR
    DS=DS1* (1.-S)
    AF=AF+1
    NOM=NO-1
    MN=NOS+1
    M=NOS-1
C............INITIALIZE variables
    KL=')
    LLL=0
    TFN=5.
    TGV=0
    J=0
    TIME1=0
    GK=0
    TGV1=0.
    Y=0.
    WI=F1
    w2=F2
    W 3 F F 3
c..............initialize cas volumes ano temperatures ,
C............AND CALCULATE AREA ANO vOLUMES OF ELEMENTS
    DO 400 I = 1,NO
    GV(I)=1.
    400 EV (I)=0.
    DO 1,1) N=1,M
    I(N)=TMS
    E(N)= TMS
    A(N)=((N-.5)*(0R+R)**2
101V V(N)=.333*((N-.5)*IDR+R)**3-.333*((N-1.5)*IDR+R)**3
    A(1)=A(i)*F
    DC 102 N=NOS,iNUM
    r(N)= TO
    TT(N)=T0
    A(N)=((N-NOS-.5)*DR+RK )***2
102 V(N)=.333*((N-NOS-.5 )*DR+RR)**3-.333*((N-NOS-1.5)*DR+RR )**3
    V(NOS+1)=((RK+1)R/2)**3-RR**3)/3
```

```
        T(NO)=TO
        TT(NO)=TO
        T(1)=T0
        A(NO)=(R-XX/2)**2
        V(NO)=(R** 3-(R-XX-DR/2)**3)/3
C.............SET INITIAL SHELL THICKNESS
    BUND=R
    X=.10*IDR
    DM = X
    XN=X
    TIME=0.
C............CALCULATION OF HEAT TRANSFER COEFFICIENT
88 ENU= GNU
    PNU=0.
    IF(TIME.LT.TTT) PNU=FNU*(1-TIME/TTT)
    IF (TIME.GI.O)ENU=2*BOND/(3.1416* CKL/ DL/CPL*TIME)**.5+2+PNU
    IF IENU.LT. NU ) ENU=NU
    HTRANS=ENU* CKL /BOND/2.
    BCND=ROND+XN
    TIME= J * IDT
87 IFIT(I)-TI)85,90,9,
35 IF(T11) 90,90,84
?O WRITE(6,73) TIME,T(1),T(NC),T(NOS)
13 FCRMAT(' CHANGED 1,4F12.4)
    CO 1O 20.3
    KL = KL + i
    J= J +1
    IHICK=BOND-R
G IF(TIMF .LT.Y) 6O TO 4
    Y=Y+1
:5 IF (TIME-TIME.1) 16,16,17
O...........CALCULATIOA OF VQLUME ANU RATE OF EVOLUTICN OF GAS
    TGV = \an I=NM,NO
    Ev(I) = vVV(T(I))
    GV(I) = EV(I) *3 *V(I)/(R**3-RR**3)
    TGV = TCV+GV(I)
```

```
300 TT(I)=T(I)
    GR=(TGV-TGVI)/(TIME-TIMEI)*60.
    TGVL=TGV
    TIMEI = IIME
    IHICKN =(THICK )*1OO.
    WW1=W1*1%0.
    WW2=W2*1CO
    WW3=W3*100.
    WRITE(6,70)TIML, IHICKN,TGV,GR,(T(I),I=1,NO),(GV(I),I=MM,NO), TFM
    C,hWl,hw2,hh3, ENU
1) FORMAT(/(1)F:2.2))
    IF(T(NOS).GE.1373.AND.TI.LT.1773.) GC TO 200
C............CALCULATIUN OF TEMPERATURE OF THERMCCOUPLE
```



```
4 HIN=AA*IE-14*(T(NOS+1)**4-T(NOS)**4) + BB*1E-4*(T(NOS+1) -T(VOS))
    E(NOS)=HIN*IDT/ DE + T(NOS)
    CALL FFF (CPN,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* %/((DR*.5+RR)**3-RR**3)/CPN/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 )
I1 E(N)=T(N) +CKM/D/CPM*IDT/V(N) / DR*(HIN+HOLT)
    CALL FFF (CPM,T(NO) , CKM,CS )
    HIN=-HOUT*CKN/OR
    HOUT =A(NO) *CS:(T(1)-T(NO))/XX
    CPC=CPM
    VV = (CPM* O*((R-XX)**3-(R-XX-DR/2)**3)+CPO*DSS*((R-XX/2)**3-(R-XX)
    S*23)//3
    E(NO)=(HIN+HOUT )
    N=1
C...........CALCULATIUN UF TEMPERATURE AT SURFACE OF PARTICLE
        If (R+IDR-BCND)IC&,103,103
193
    HIN=-HOUT
    CALL FFF (CPU,T(1), CKN ,CS)
    VU = (DS*CPS*((R+X/2)**3-R***3)+CPO*DSS*(R**3-(R-XX/2) ** 3) )/3
```

```
    IF (BOND-R) 1,2,3
    BOND=R
    XN=O.
    x=0.
    IF (T(1)-TM) lv07,1%:,8,1008
1)7 HOUT = R**2*HTKANS* (TI-T(1))
    E(1)=(HIN+HOUT)*IDT/VU+T(1)
    IF (E(1)-TM) 2:3,2(3,1009
C............CALCULATIGN OF MELTED FRACIION OF PARTICLE
1009 QR = (E(1)-TM)*VU/IDT
    GO TO 1010
1):8 QR=R**2*HTRAVS*(TI-TM)+HIN
i) 10 FM=QR*IDT*3/(R**3*0*ACRM)
    TFM=TFM+FM
    IF (TFM.LT.U.) E(I) =TM+QR*TFM/FM*IDT/VU
    IF (TFM.GE.O.) E(1) =TM
    IF (TFM-1.) 2,3,15,5,1:105
10'5 WRITE (6,1?0G) TIME,TFM
1006 FCRMAT(////10x,'TOTAL MELTING TIME = 0,2F10.2)
    GO TO 2C0
C............CALCULATIUN OF TEMPERATURE AI SURFACE OF PARTICLE
C.............WITH SLAG SHELL THICKNESS LESS THAN IDR
3 Al=(R+.5*X)**2
    HOUT=A!*F*(TMS -T(1))*CK(T(1))/X
    E(1)=(|INN+HOUI)*IOT/VU +T(1)
    IF(E(1)-E(NO) 129,3\therefore,30
    E(1)=E(NO)
3) XN=-IDT/H/DS*(CK(T(1))*(E(1)-TMS)/X + (TI-TMSP) *HTRANS)
        IFITIME.LE. WT.ANO.YYY.GT.S.I XN=XN*FR
    BA=BONO+XN-R
    L=BA/IDR
    X=IDR*(BA/IDR-L)
    If(UM - IDR/1:.)9,3,8
    UM = IOR/1%.
    IF(X-IOR/1O)7,203,2J3
    X = IUR/10.
    IF(NOT - KL)?.,2%.,99
```



```
99 DO 705 K=1,NO
7.)5 T(K)=E(K)
    G0 ro 88
c.............calculatiun of temperature at surface of particle
C..............AND thruUGHOUT SOLID Slag Shell
108 HIN=-HOUT
    HOUT=A(1)*(T(2)-T(i))* CK(T(1))/IDDR
    CALL FFF (CPG,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)}\becauseIDT/VOL +T(1
299 N=N+1
    IF (R+(N )*IDR-BCND)115,115,110
110 AX=(8OND-X/2.): (BOHD-X/2.)
    VX=.333*(BOND-X/2)**3-.333*(BOND-IOR/2-X)**3
    HIN=A(N-1)*(T(N-1)-T(N))/IDR
    HOUT=AX*(TMS -T(N))/X
    E(N)=(HIN+HOUT)* CK(I(H))/OS/ CPS*IDI/VX+I(N)
    QG=(E(N)+TMS)/2.
    XN= -IDT/H/DS *(CK(UQ)*(E(N)-TMS) / X+ (II-TMSP)* HTRANS)
    IFITIME.LE. WT.ANC.YYY.GT.O.) XN=XN:FFR
    BA=BOND+XN-R
    L=BA/IDR
    X=IDR*(BA/IDR-L)
    IF(DM - IDR/1.ly, &,8
115 IF(N-NOS+1)116,9(,90)
116 A9 = (T(N+1)-T(N))*A(N) - (T(N)-T(N-1))*A(N-I)
    E(N) =CK(T(N))/DS/CPS/V(N) * IDT/ IDR*A9+ T(N)
    IF(EINI-TMS I109,109,402
402 E(N)=TMS
    gu ro 10g
201 STOP
    END
```

2. Subprogram 1
```
C.............VOLUME OF GAS EVOLVED AT TEMP. Q
    FUNCTION VVV(G)
    COMMON VG(2C),GG(2H),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.I.OR.F3.LE.O) GO TO 1011
    I=1 Q-273. )/ 10U.
    IF (I.GT.O.)VVV=(VG(I)+(VG(I+L)-VG(I))*((Q-273.)/1.10.-I))*FF2/FF2
    IF (I.EO.O.) VVV=VO(1)*(Q-273.1/100.
    RETURN
:111
    VVV=O.
    RETURN
    END
```

3. Subprogram 2
```
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,Fi,F2,F3,F4,F5,W1,W2,W3
    C,S,CKS ,CKL, DP,DES,K2,K3,K4,K5 ,DDD,FF2
        J=Q/10%.-1.
        CHECK=CM(Q)
        OU = 3.04E-4*(1-EXP(-7.65E-4*(Q))+4.%8E-12*Q**3*DDD
    CKM= OO**PS*GG(J)**(W1*(1-PS))*K2** (W2*(1-PS))*K3**(W3*(1-PS))
    C*K4**(F4*(1-PS))*Kり必*(F5*(1-PS))
    CS = CKM
    G=VVV(Q+.5) - VVV(Q-.5)
    IF(Q-TA)10S1,1002,i)u2
1OO1 CPM = CHECK+1.29:G
    RETURN
1002 IF(Q-(A-8)1003,1003,1004
1003 CPM = CHECK+1.35%C+2.89E-3*CA-1.95E-2
    RETURN
1004 IF( Q.LT.TB) CPM=CHECK+1.47*G
    IFI Q.GE.TB ) CPM=CHCCK+1.35*G
    RETURN
    END
```

4. Subprogram 3
```
C.............SPECIFIC HEAT OF MATERIALS USED IN CALCULATION
C.............OF SPECIFIC HEAT OF DRI PELLET
    FUNCTION CM(Q)
    COMMON VG(20), GG(2j),PS,TA,CA,TB,F1 ,F2,F3 ,F4,F5,W1,W2,W3
    C,S,CKS ,CKL, DP,DE ,K2,K3,K4,K5 ,ODD,FF2
        Wl = Fl+1.01E-2*VVV(Q)
        W2 = F2-3.53E-3*VVV(0)
        W3 = F3-8.\cup2E-3* VVV(Q)
        IF (Q.LE.1O33) Cl=7.48E-2+1.06E-4*Q
        IF (Q.GT.lO33.ANU.Q.LE.1181) Cl=.161
        IF (Q.GT.1181) Ci= 3.29E-2
        +8.34E-5*()
    C2 =.169+2.9 E-5*Q-9.7E2/Q**2
    IF (Q.LE.463) C3=.109+1.11E-4*Q
    IF (Q.gT.463) C 3=.143+i.67E-5*Q
    C4 =. 25+4.17E-5*Q-t.69E 3/Q**2
    IF (Q.LE.84B) C5=1.87E-1+1.36E-4*Q-4.47E3/Q**2
    IF (Q.OT.848) C5= 2.4 E-1+3.23E-5%(L
    CM =W1*C 1+W2*C2+W3*C 2 FF4*C4+F5*C5
    RETURN
    END
```


## 5. Subprogram 4

```
C............CUNDUCTIVITY OF SOLID SLAG SHELL FUNCTICN CK(Q)
COMMON VG(20), GG(2,),PS,TA,CA,TB,F1,F2,F3,F4,F5,W1,W2,W3
C,S,CKS ,CKL, DP,DU ,K2,K3,K4,K5 ,DOD,FF2
\(P C=3.04 E-4 *(1-E X P(-7.65 E-4 * Q))+4.38 E-12 * Q * 3 * D P\)
\(C K=\) CKS ** \((1-S) * P C \div 5\)
RETURIV
END
```

6. Subprogram 5
```
r............succIFIC HEAT mvU THEwAA_ CUNDUCTIVITY OF NI PARTILL
    cijpRUUTINE FFF (CLA,O, iKM, CS)
```




```
    J=0/100.-1.
```



```
    CKM=U0**:N =*6G(1):**(1-b)
    CS = CAM
```




```
    DFHUJK:
    EM!I)
```


## 7．Definition of Terms

```
A(V) = AREA RETNEEN NODES N AND N+1 AT DISTANCE IDR/2
AA}= CONSTANT FOR HEAT TKANSFER TO THERMOCOUPLE
Aこ२M =HEAT OF FJSION OF PARTICLE
ALL = TERMAL DIFUSIVITY UF LIQ. SLAG
AL? = TERMAL DIFUSIVITY UF SOLID SLAG
```

B3 = CONSTANT FOR hEAT TRANSFER TO THERMOCOUPLE
B< =THERMAL CUNDUCTIVITY OF POROUS LIQ. SLAG
EJVD $=2+$ THICKNESS OF SHELL

| Cl | $=$ | SPECIFIC | －heat | OF | IRON |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| C2 | $=$ | SPECIFIC | c heat | OF | ＂FEO＂ |  |  |
| $0 \cdot$ | $=$ | SPECTFIC | －heat | OF | FE3C |  |  |
| $\mathrm{C}_{4}$ | $=$ | SPFCTFIC | －heat | OF | AL203 |  |  |
| C5 | $=$ | SPECIFIC | －heat | OF | SIO2 |  |  |
| cas | $=$ | CARZON | CONTENT | OF | PARTICLE | AT | TEMP． |
| C3 | $=$ | CAREON | content | OF | PARTICLE | AT | TEMP． |
| CC | ＝ | constant | FOR HE | EAT | TKANSFER TO |  | HERMOC |
| C |  | THERMAL CON | conductiv | VITY | UF POROUS S |  | SHELL |
| CくL |  | THERMAL CJN | JNOUCTIVI | ITY | JF LIQ．SLAG |  |  |
| c＜4 |  | THERMAL COND | ONDUCTIVI | ITY | of particle |  |  |
| C＜ 5 |  | THERMAL CJI | Jnductivi | ITY | jr Solid Sla |  |  |
| Cu | $=$ | SPECIFIC | C HEAT | OF | U－R yateri | I AL |  |
| cコl |  | SPECIFIC te | ieat of l | LIQ． | slag |  |  |
| con |  | SPECIFIC HEA | heat of pa | PART | IClE |  |  |
| coo |  | SOECIFIC HEA | HEAT OF EX | EXTE | －ival Element | T OF | Parti |
| cos |  | SDECIFIC HEA | HEAT OF S | SOLI | ）SHELL |  |  |
| Cs |  | CONDUCTIVI | ITYT OF EX | EXTE | rval Element |  | PARTI |

0 = DENSITY OF PARTICLE
D3 = PORE MIAMETER IN LIQ. SLAG
D) = CONSTANT FOR HEAT TRANSFER TO THERMOCOUPLE
$D J D=$ PORE DIAMETER IN PARTICLE
DL = DENSITY OF LIQ. SLAG
DD = OORE DIAMETER IN SOLIU SLAG
D₹ $=W I D T H$ OF $A N$ ELEMENT IV PARTICLE
DS = DENSITY OF POROUS SOLID SHELL
DSI = DENSITY OF SOLID SLAG
$0: S$ = DENSITY OF EXTERNAL ELEMENT OF PARTICLE
$E(V)=$ TEMD. $A T$ NODE $N$ FOR OKESENT TIME
EE = CONSTANT FOR hEAT TKANSFER TO THERMOCOUPLE
EV $(N)=G A S$ VOL. PER GRAM OF SPONGE ELEMENT $N$

```
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|}
\hline F & \(=\) & CO & & FACTOR & FOR & & TICLE & SL & \multicolumn{2}{|r|}{INTERFACF} \\
\hline F] & = & INITIAL & WT. & FRACT & IUN & OF & IRON & IN & D-P & PELLET \\
\hline F? & = & INITIAL & WT. & FRACT & ION & 05 & "FEO" & IN & D-R & PELLET \\
\hline \(F 3\) & = & INITIAL & WT. & FRACT & IUN & OF & FE3C & IN & D-R & PELLET \\
\hline F'4 & = & WEIGH & & FRaC & ION & OF & AL203 & IN & D-R & PELLET \\
\hline F'j & \(=\) & WEIGH & & FRACT & UN & OF & SIO2 & IN & D-R & PELLET \\
\hline FiU & \(=\) & NUSSELT & & ER & & & & & & \\
\hline
\end{tabular}
G = SPECIFIL GAS VOLUME
GG = THERMAL CONDUCTIVITY OF METAL AS A FUN. OF TEMP.
GZ = RATE OF GAS EVOLUTION FROY PARTICLE
GV(I)= VOL. FZACTION OF GAS EVOLVED FROM ELEMENT I
H =HEAT OF FJSION OF SLAG
Hl = HEAT OF FUSION OF IRON
H? = HEAT OF}\mathrm{ FUSION OF 'FEO'
H3 = HEAT OF FUSION OF FE3C
H'4 = HEAT OF FUSION OF AL2O3
45 = HEAT OF FUSION OF SIOZ
HTRANS= HEAT TRANSFER COEFFICIENT
Iว2 =WIDTH OF AN ELEMENT IV SLAG
IJT = LENGTH OF a time elevevt
K> = THERMAL CONDUCTIVITY OF 1FEO'
K3 = THFRMAL CONDUCTIVITY OF FE3C
K'4 = THERMAL COVDUCTIVITY OF AL2O3
Kミ = THERMAL CUVDUCTIVITY DF SIOZ
NI = NO. OF TEMP. IVTEKVALS FOR GG AND VG
NO = NO. OF VODES
NOS = NO. OF NOOES IN SLAS
NOT = NO. OF TIME STEPS ALLOWABLE
00 = THERMAL CONDUCTIVITY OF PARTICLE PORES
TSV = TOTAL GAS VOL. EVOLVED FROM PELLET
PG = POROSITY OF PARTICLE
Q = TEMPFRATURE OF SPJNGE
Q2 = FLOW OF HEAT FOR MELTING PARTICLE
R = RADIUS OF PARTICLE
RZ = RADIUS JF THERMOCOJPLE HOLE
```

```
S = POROSITY OF SLAG SHELL
SS = POROSITY OF LIQ. SLAG
T'(y) = TEMP. AT NODE N FOR בAST TIME
TA = TEMP. AT WHICH SOLID-SOLID TRANSFORMATION STARTS
T3 = TEMP. AT WHICH SULID-SOLID TRANSFORMATION ENDS
TFM = VOL. FRACTION OF PARTICLE MELTED
TI = TEMP. OF BULK LIQ. SLAG
TIME = TIME AFTER IMMESION UF PARTICLE
TM = MELTING TEYD. OF PARTICLE
TUS = SOLIDUS TEMP. OF SLAG
TUSP = LIQUIDUS TEMP. OF SLAG
TO = INITIAL TEMP. OF PARTICLE
Tz = mELTING RANGE OF SLAG
U = VISCOSITY OF SLAG, POISE
V(V) = VOL. AT NODE N
VO(I)= VOL. OF GAS EVOLVED FROM 1 GRAM OF SPONGF AT TEMP. T(I)
VOL = HALF OF TOTAL VOL. OF EXTERNAL ELEMENT ON PARTICLE AND
    adjacent Element in slag
VVV = VOL. OF GAS EVOLVED FROM I GRAM OF DRI
WI = WT. FRACTION OF IROV IN D-R PELLET
W\nu = WT. FRACTION OF IFEO' IN D-R PELLET
wz = WT. FRACTION OF FE3C IN D-R PELLET
x = DIS. FRUM FURTHEST ELEMENT TO THE MOVING BOUNDARY
xv = THICKNESS CHANGE IN ONE TIME STEP
XX = THICKNESS OF EXTEZNAL ELEMENT OF PARTICLE
YYY = GAS BUB3LING CONTROLLER - 1 . BUBBLING
- 0 . NO BUBBLING
```

