Transient Kinetics of Slag Metal Reactions

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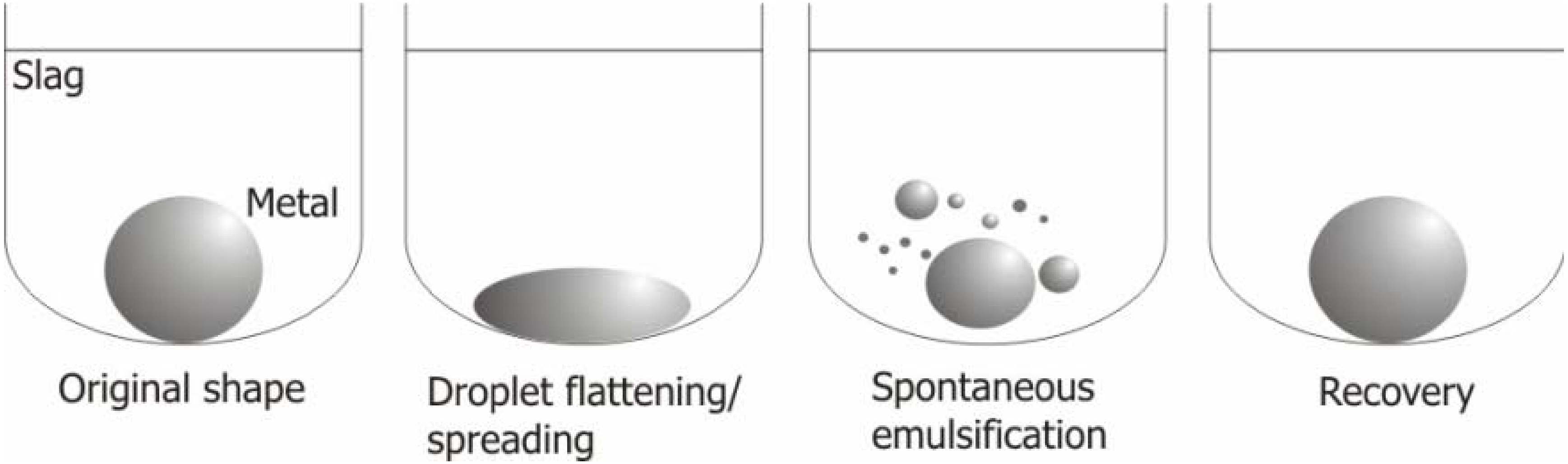
SWINBURNE UNIVERSITY OF TECHNOLOGY

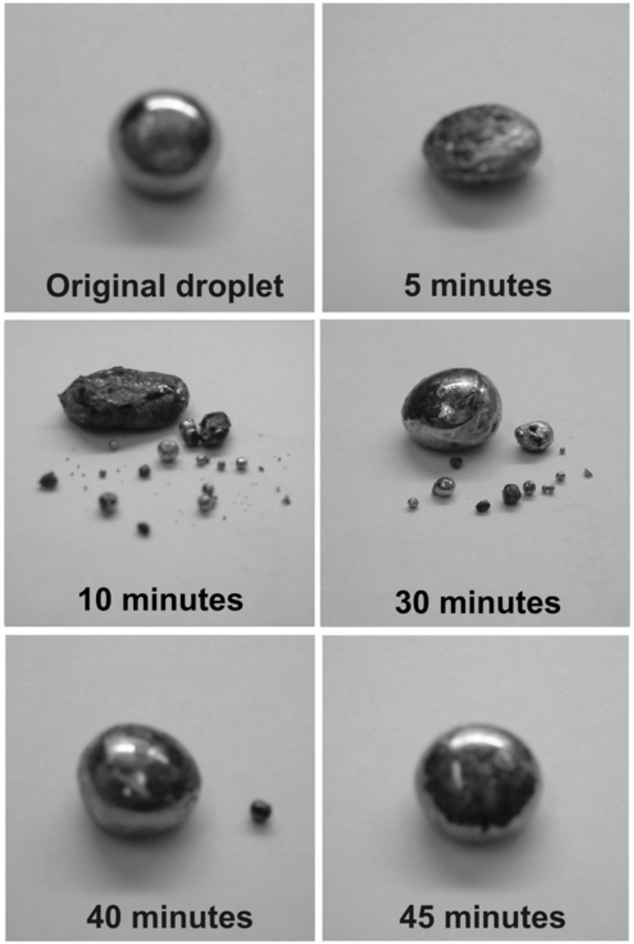
Exploding Droplets !!!

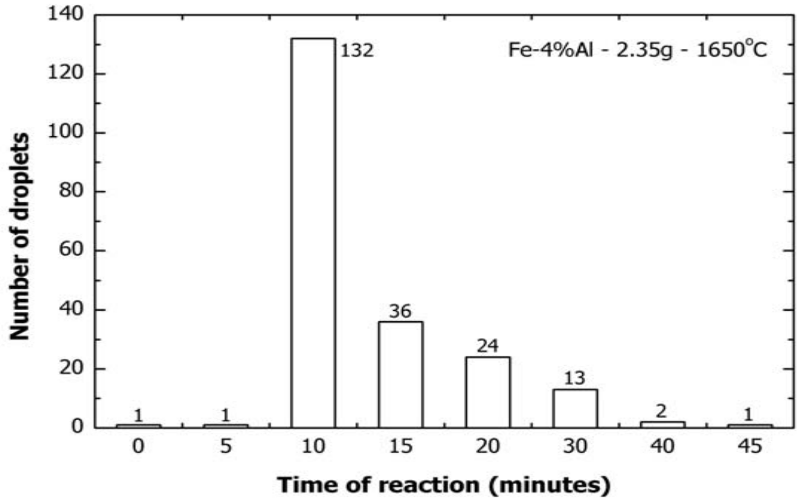


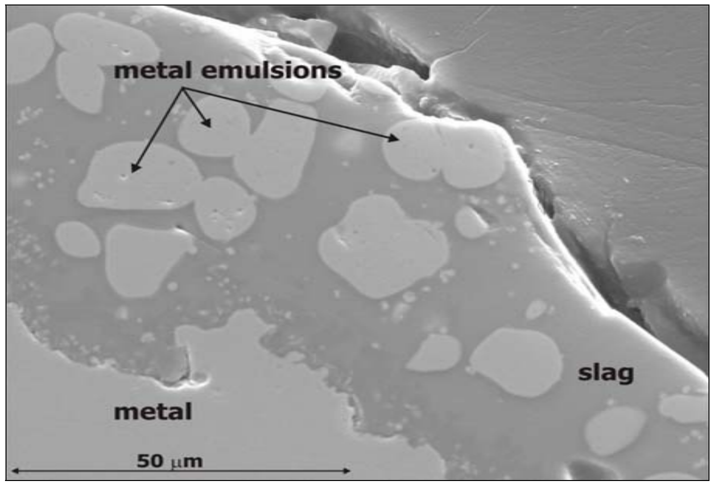
Observed by Kozakevitch et al. (1955), Riboud and Lucas (1981), Chung and Cramb (1998,2000) and others, for

Fe-Al, Fe-C-S, Fe-Ti, Fe-P, Fe-B, Fe-Cr and Fe-Si

Experimental Work



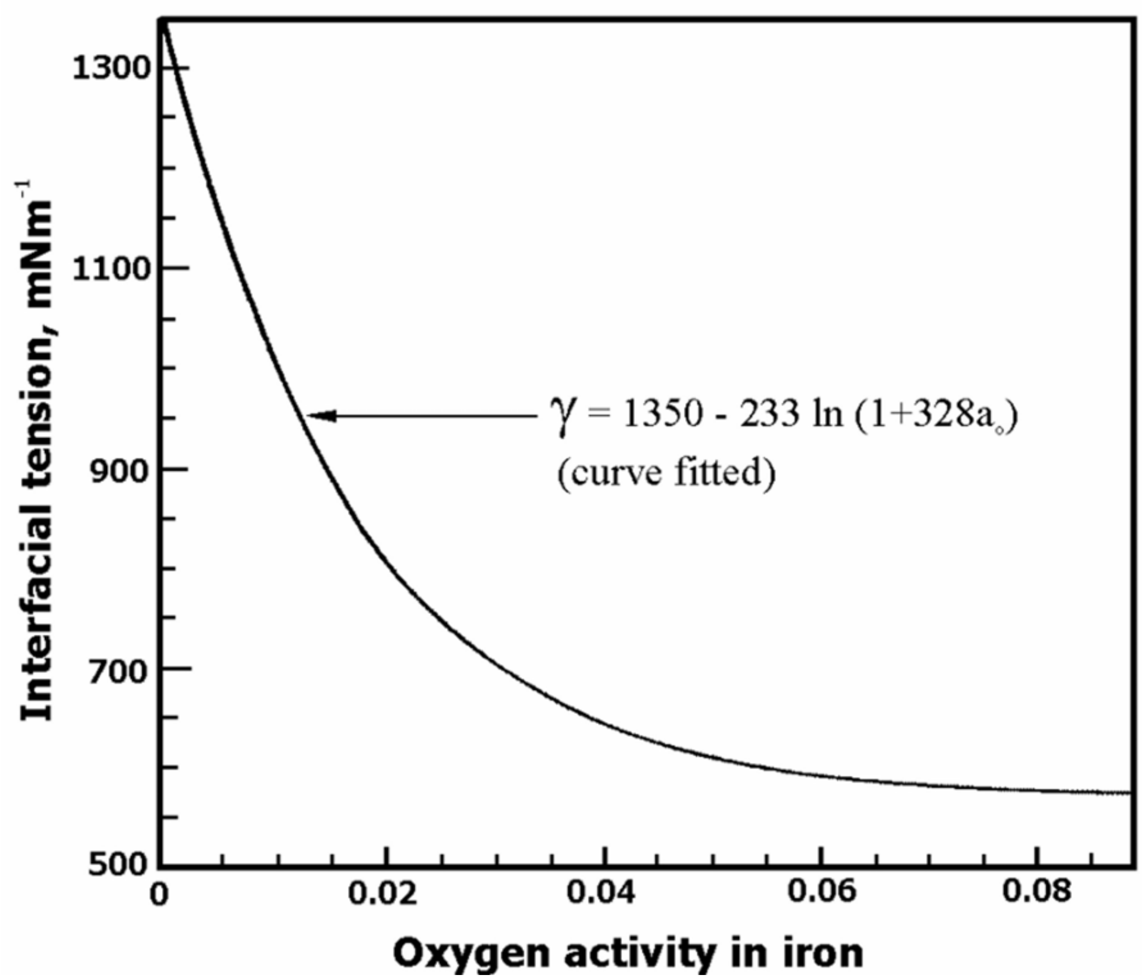




2.35g Fe-4wt.%Al and CaO-SiO2-Al203 at 1650 C

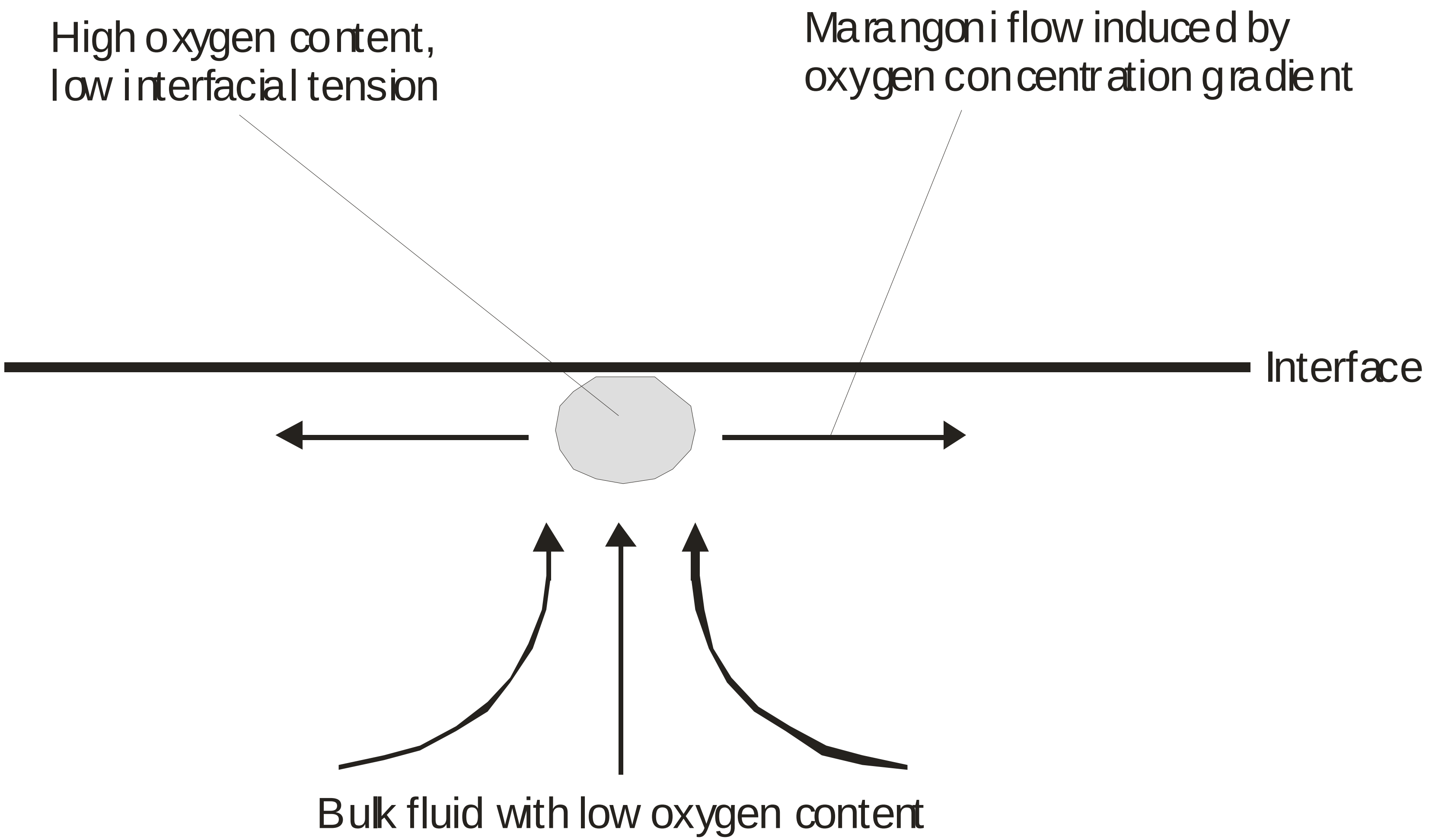
Rhamdhani, Brooks and Coley, Met. Mat. Trans. B, 2005

Interfacial Tension



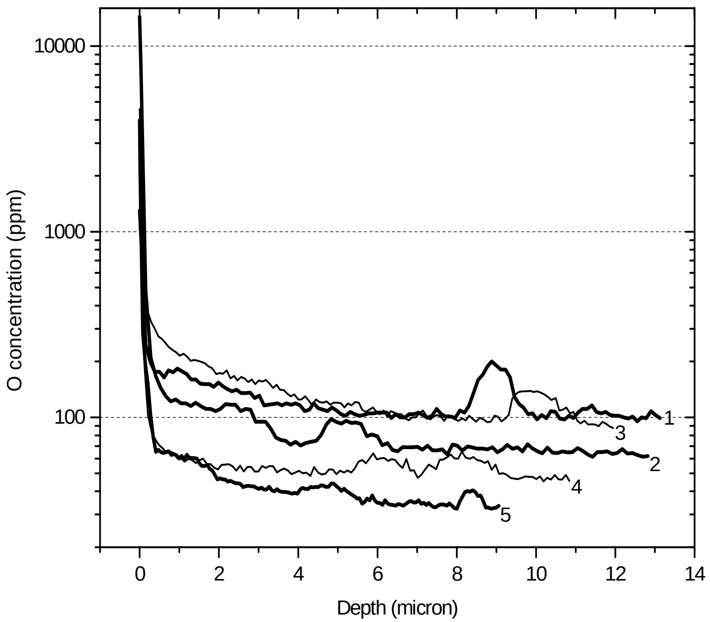
Gaye et al. (1984)

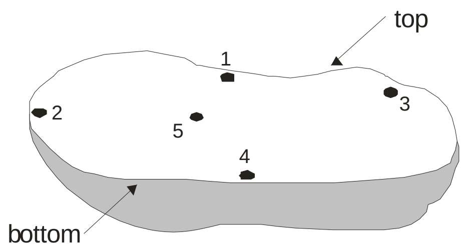
Scale of Disturbance



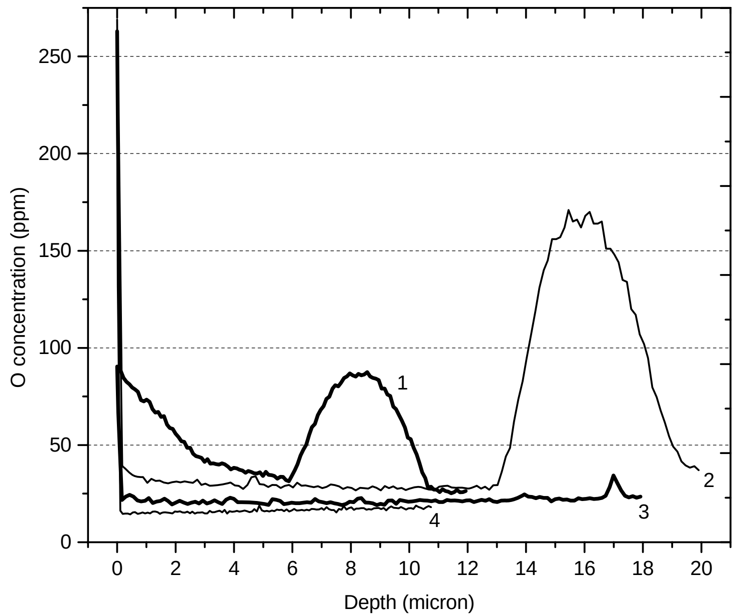
SIMS Analysis

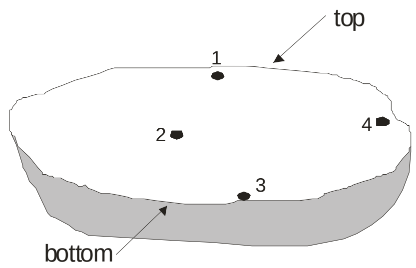
9 minute sample





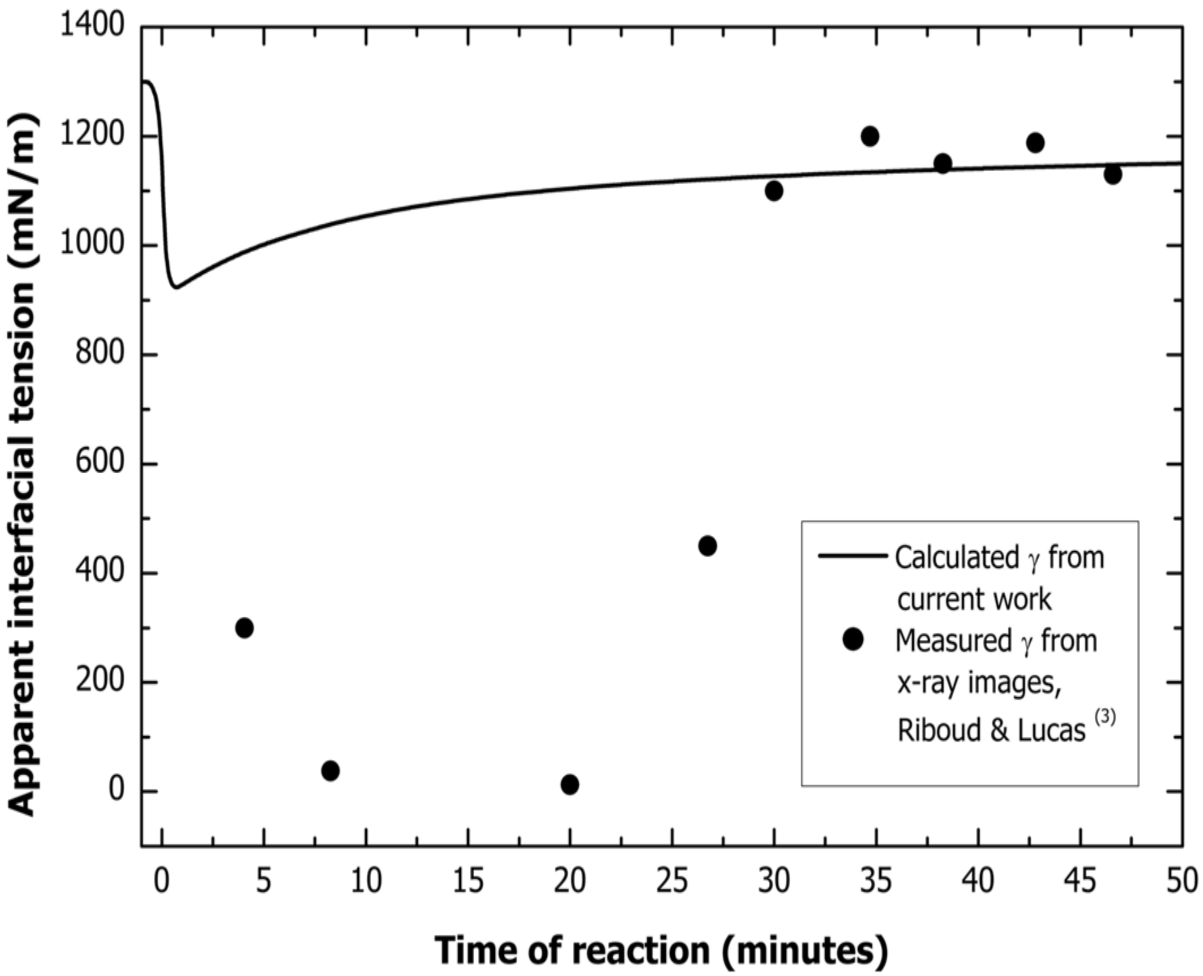
30 minute sample





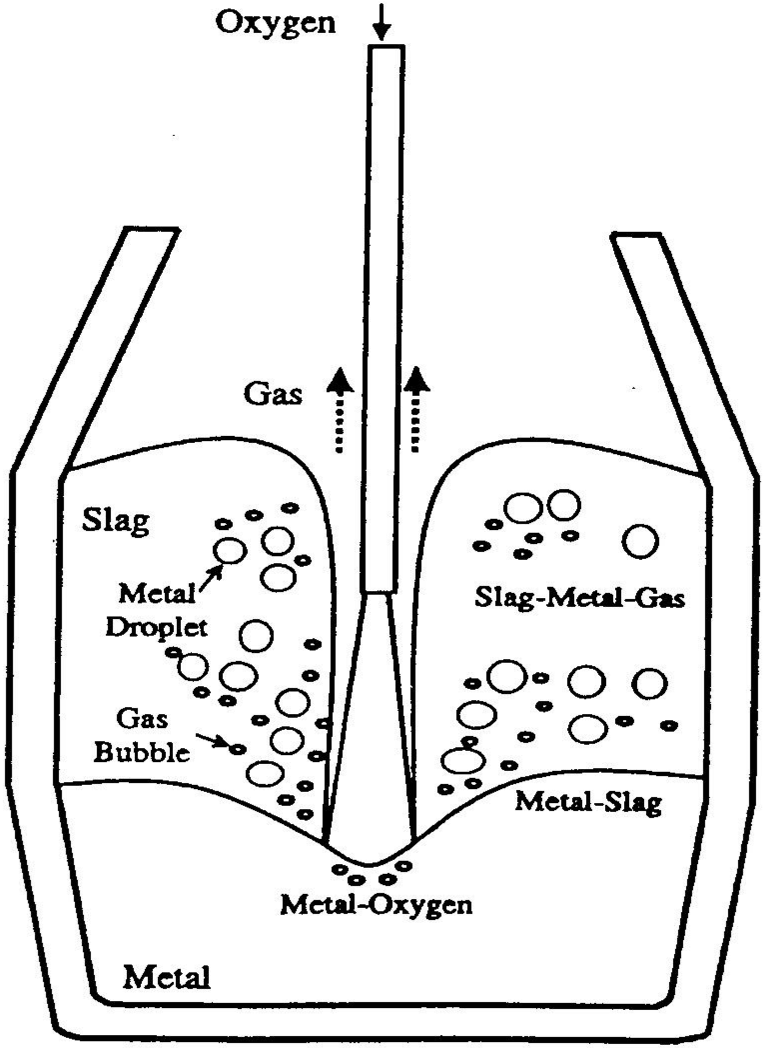
Rhamdhani and Brooks, Met. Mat. Trans B, 2003

Not the whole story !!



Rhamdhani, Coley and Brooks, Met. Mat. Trans. B, 2006

Oxygen Steelmaking



Hot Zone

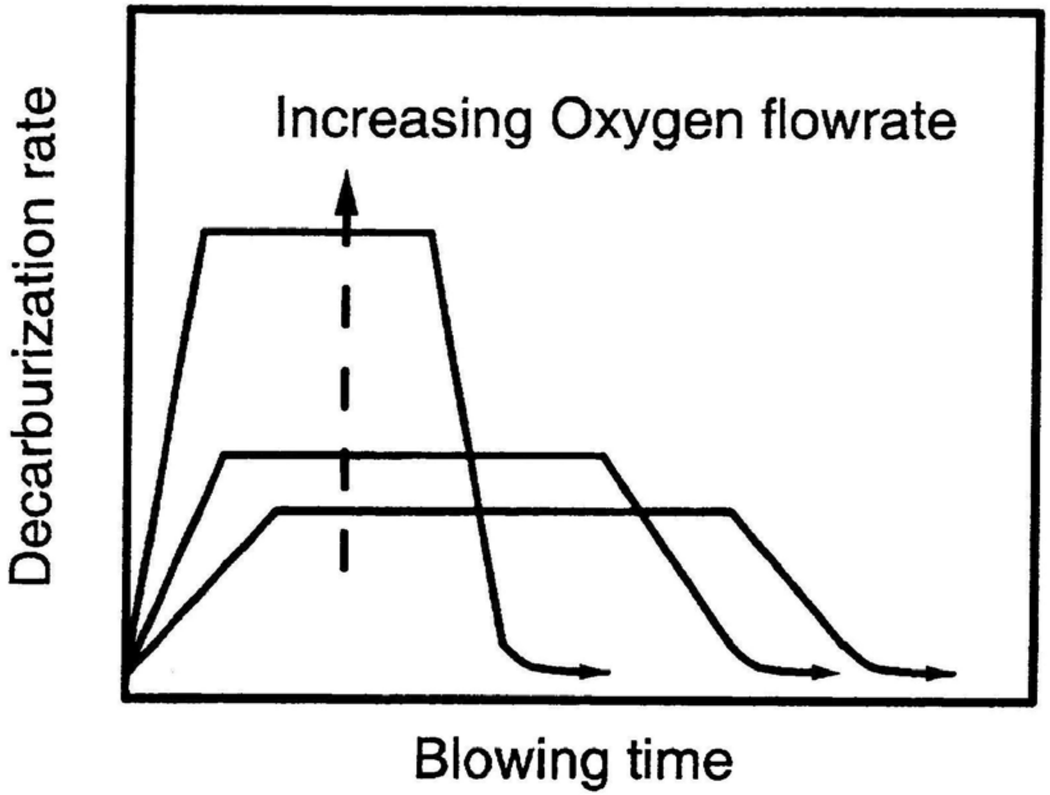
$O_2(g) = 2\underline{O}$

$\underline{O} + \underline{C} = CO(g)$

Emulsion

$(FeO) + \underline{C} = Fe + CO(g)$

Decarburization



Rate of decarburization during a typical oxygen steelmaking heat (after Deo & Boom)

How Fast ?

$$\frac{dC_b}{dt} = \frac{\left(\frac{A}{V}\right)\left(C_b - C_i\right)}{\left(\frac{1}{k}\right)} = \left(\frac{\text{Area}}{\text{Volume}}\right) \cdot \frac{\text{Drive}}{\text{Resistance}}$$

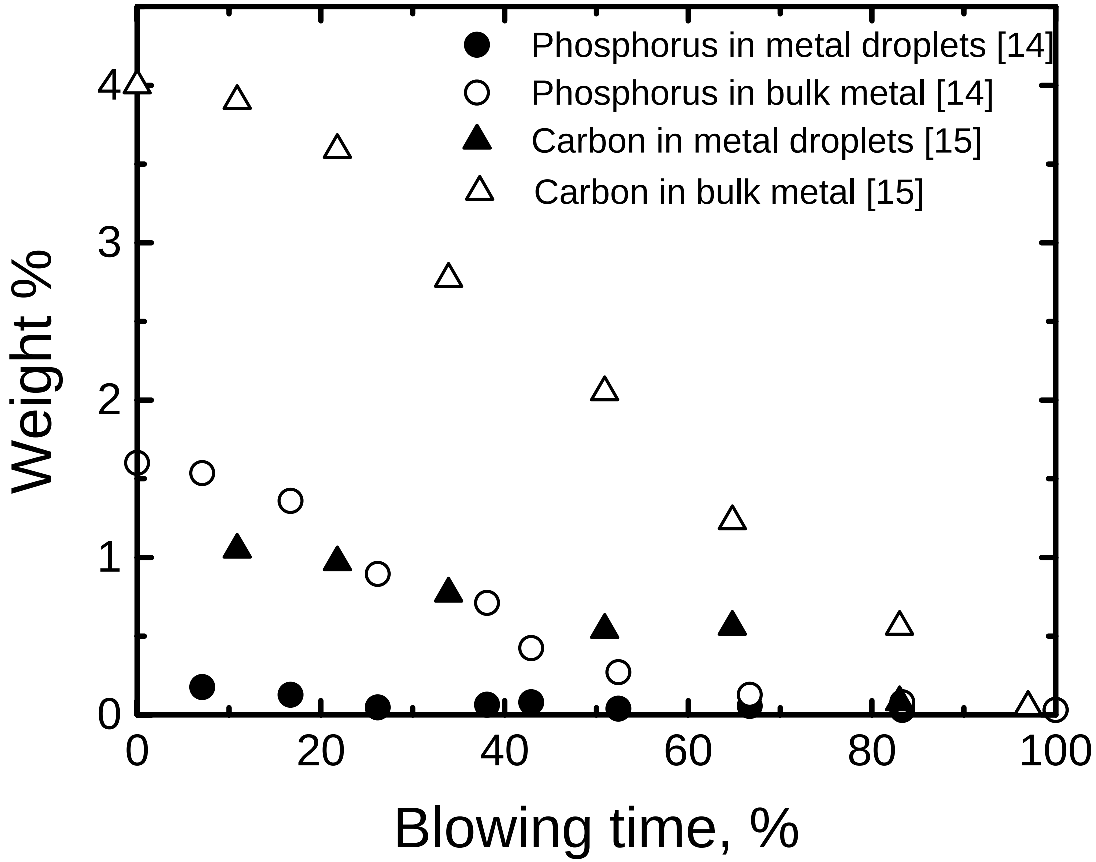
Gas Injection & Kinetics

- wide range of droplet sizes
- energy imparted to each droplet will vary
- rate at which droplets react likely to vary
- surface tension effects influence kinetics

Gas Injection & Kinetics

- gas generation influences properties & buoyancy
- trajectory & residence time of droplets will vary
- steady state assumption kinetics not justified.

Reactions in the Droplets



Subagyo, Brooks and Coley, 2002

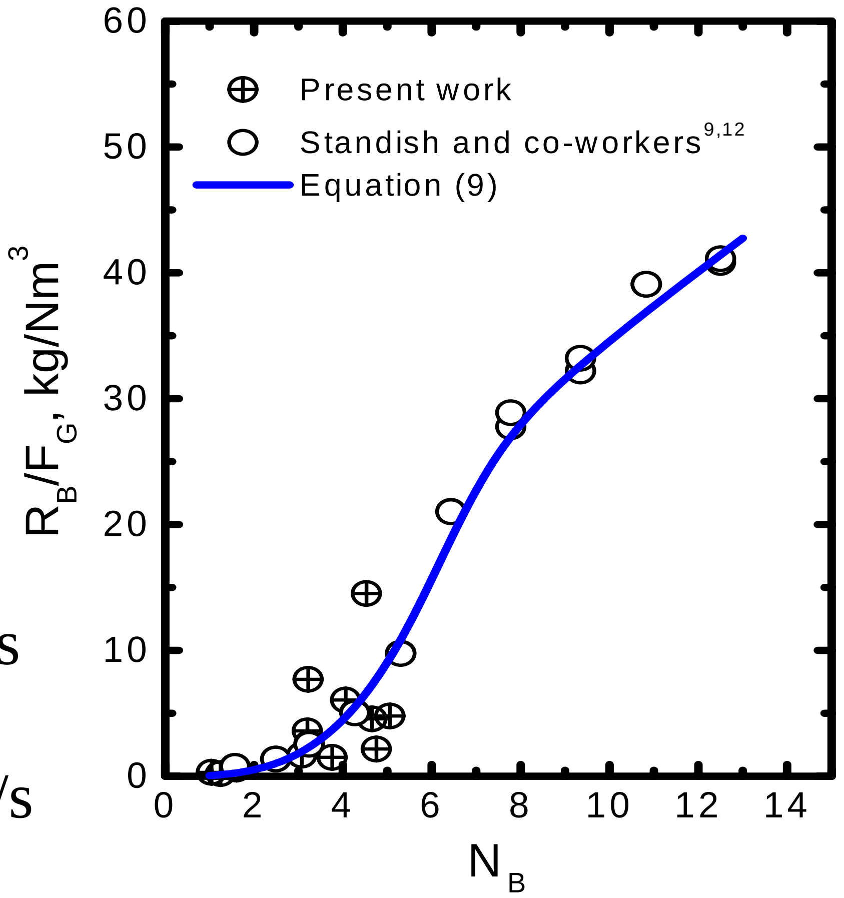
Transient Kinetic Theory

$$J_{overall} = \sum_{i=1}^{i=m} \frac{\partial C_i}{\partial t} \frac{V_i}{A_i}$$

Droplet Generation

Kelvin-Helmholtz Instability Criteria

$$N_B = \frac{\rho_G u_G^2}{2\sqrt{\sigma g \rho_L}}$$

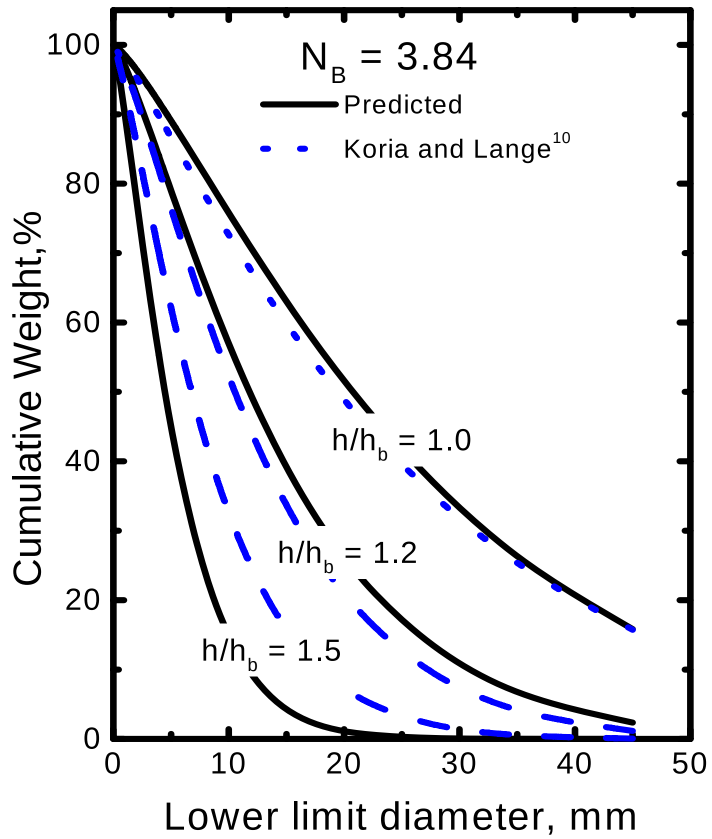


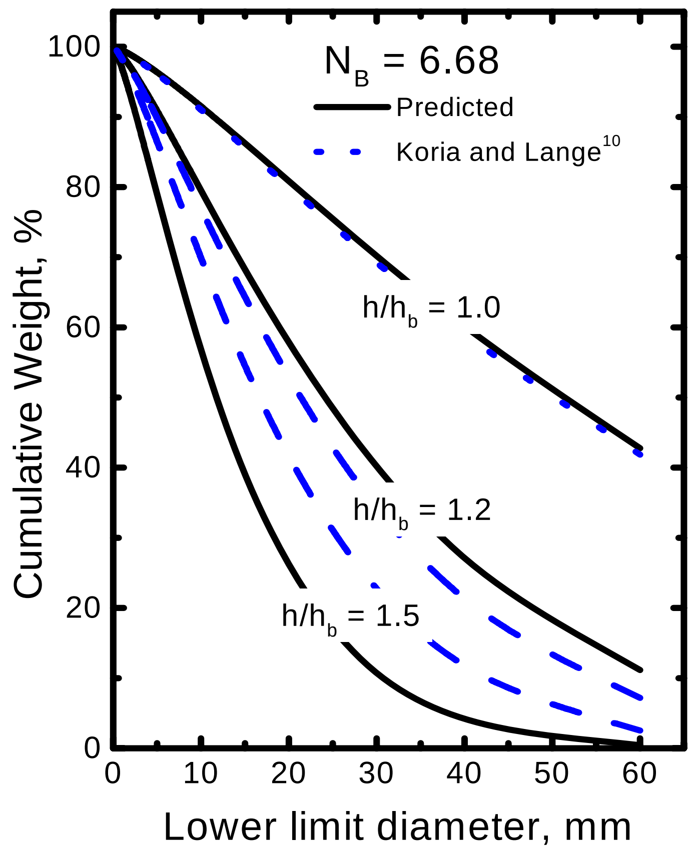
R_B = droplet generation rate, kg/s

F_G = gas flow at lance exit, Nm^3/s

Subagyo, Brooks, Coley and Irons, ISIJ, 2003

Size Distribution





Subagyo, Brooks and Coley, Can. Met. Quarterly, 2005

Blowing Number

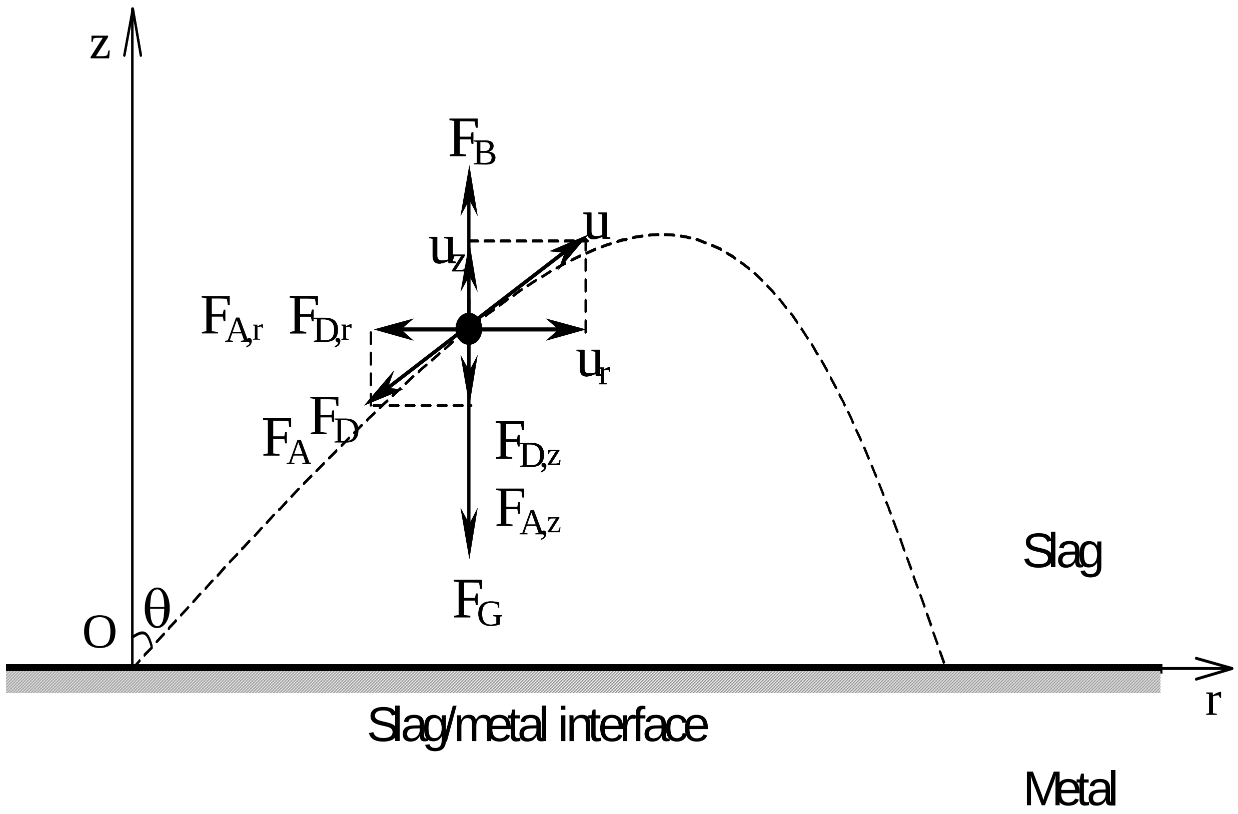
$$R_B = \frac{F_G N_B^{3.2}}{\left[2.6\times10^6 + 2.0\times10^{-4} N_B^{12}\right]^{0.2}}$$

$$R = 100\exp\left[-\left(\frac{d}{12.0 N_B^{0.82}}\right)^{1.44}\right]$$

R = wt.% droplets with diameters > d

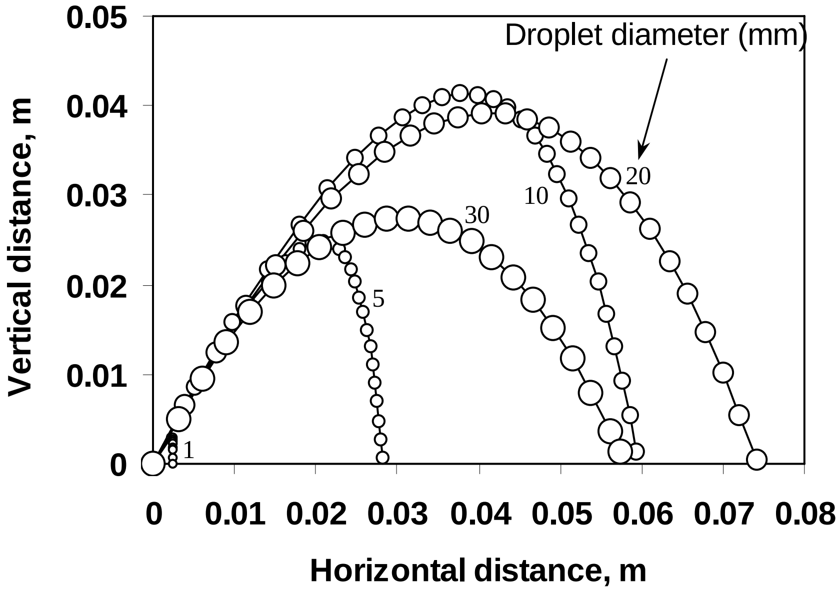
Subagyo, Brooks and Coley, Can. Met. Quarterly, 2005

Droplet Ballistics

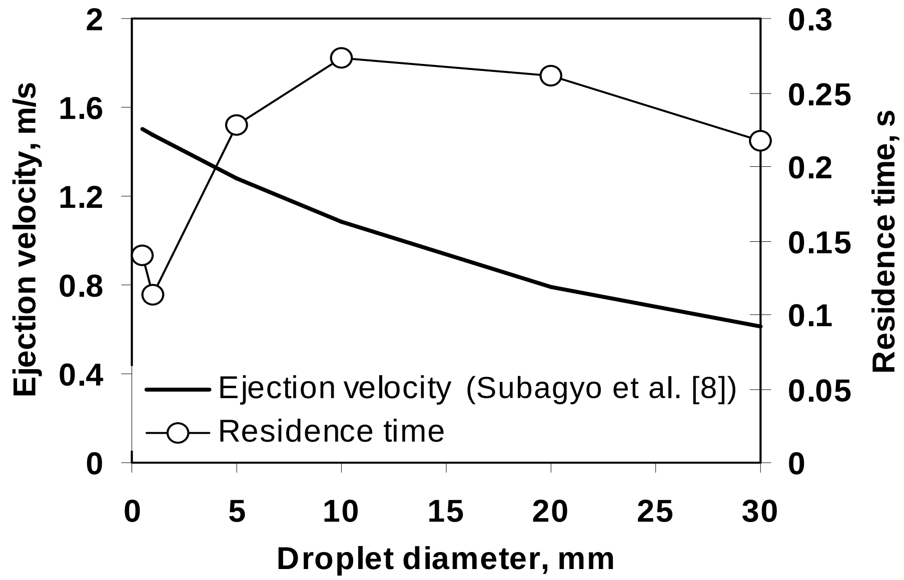


Brooks, Pan, Subagyo, Coley, Met. Matl. Trans B, 2005

Dense Droplets



(a) Trajectory of dense metal droplets



(b) Ejection velocity and residence time of dense metal droplets

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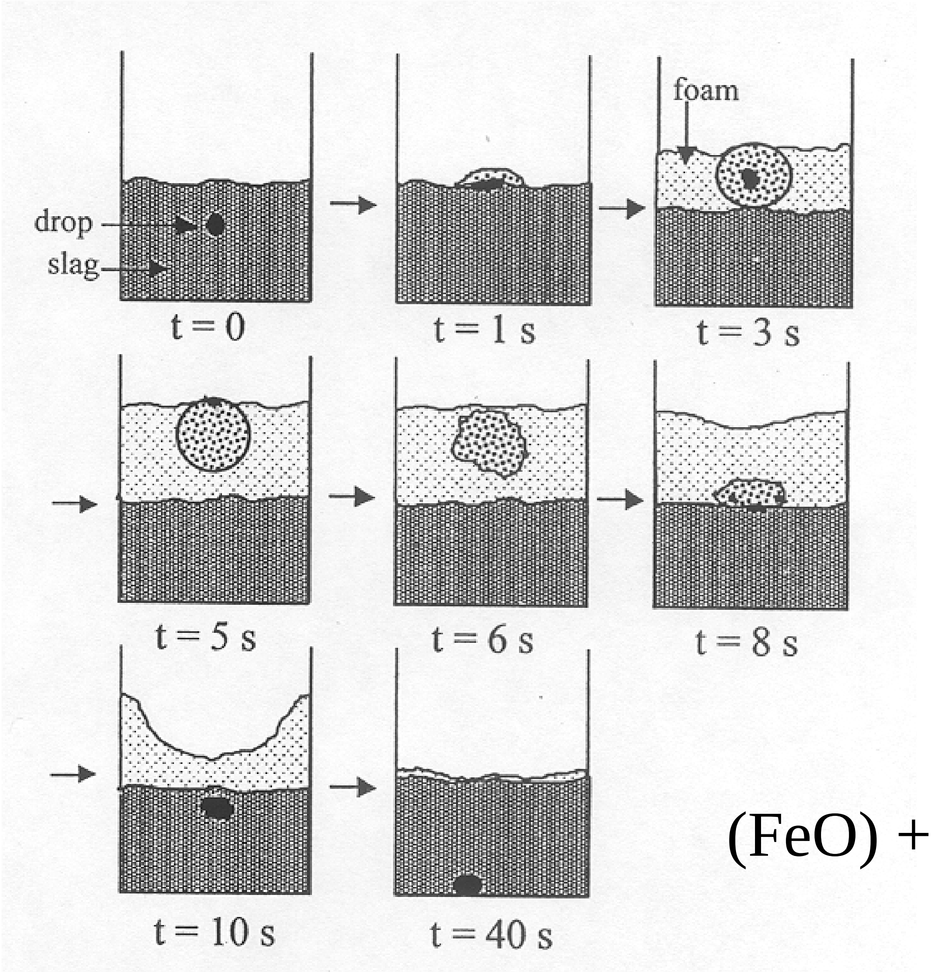
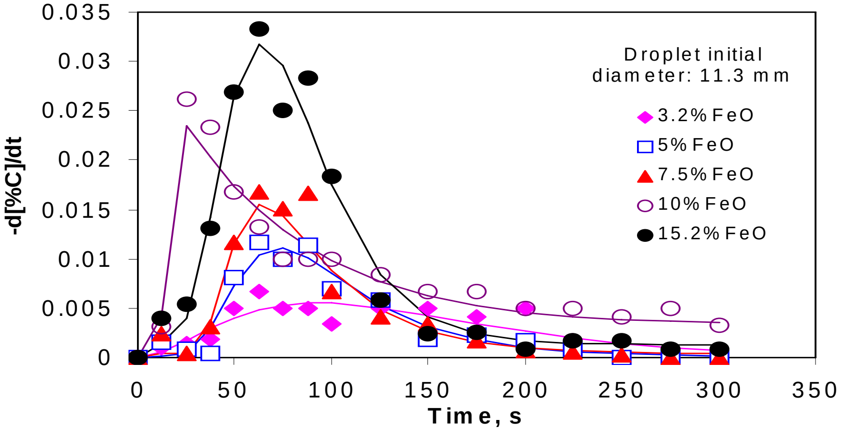
“Bloated” Droplets



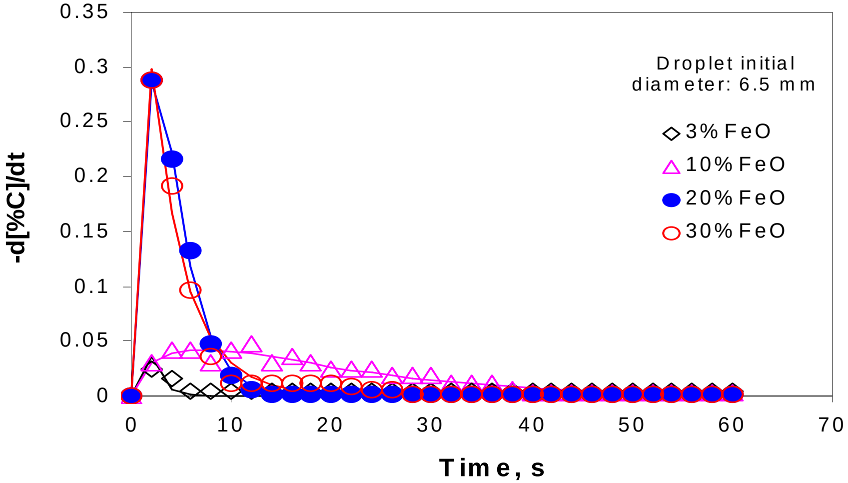
(FeO) + C = Fe + CO(g)

X-ray fluoroscopy of a Fe-C drop
Slag with 20 wt.% FeO (after Molloseau & Fruehan)

Decarburization in Bloated Droplets

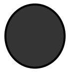


(a) Decarburization rates for experimental cases of Min and Fruehan [16]

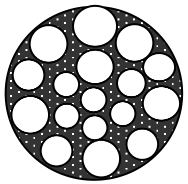


(b) Decarburization rates for experimental cases of Molloseau and Fruehan [17]

Variation of Density in Bloated Droplets



$$\rho_d = \rho_{d0}$$ (if $r_c \le r_c^*$)



$$\rho_d = \rho_{d0} \frac{r_c^*}{r_c}$$ (if $r_c > r_c^*$)

$$r_c^* = 2.86 \times 10^{-4} (\%FeO)$$

Brooks, Pan, Subagyo, Coley, Met. Matl. Trans B, 2005

Kinetic Equation

$$r_c = -\frac{d[\%C]}{dt} = k_{eff}\frac{A_{app}}{V_{app}}\left([\%C]-[\%C]_e\right)$$

Higbie Penetration Theory for Mass Transfer:

$$k_{eff} = 2\sqrt{D_c u_d/(\pi D_{d,app})}$$

Notations:

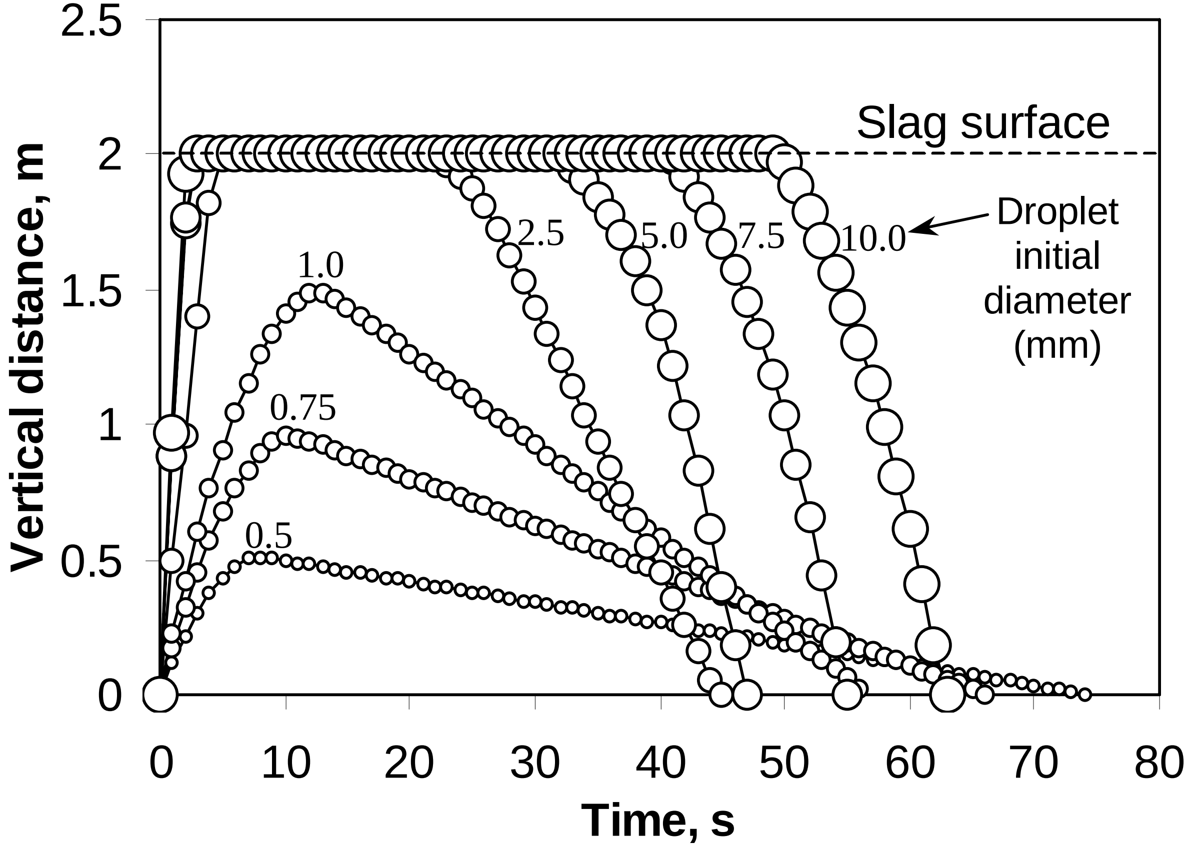
k_{eff}: effective rate constant

D_c: effective diffusivity of carbon in liquid iron

$D_{d,app}$: apparent diameter of droplet

u_d: overall velocity of droplet

Droplet Residence



Initial C = 4.0 wt.% FeO = 15 wt.%

Brooks, Pan, Subagyo, Coley, Met. Matl. Trans B, 2005

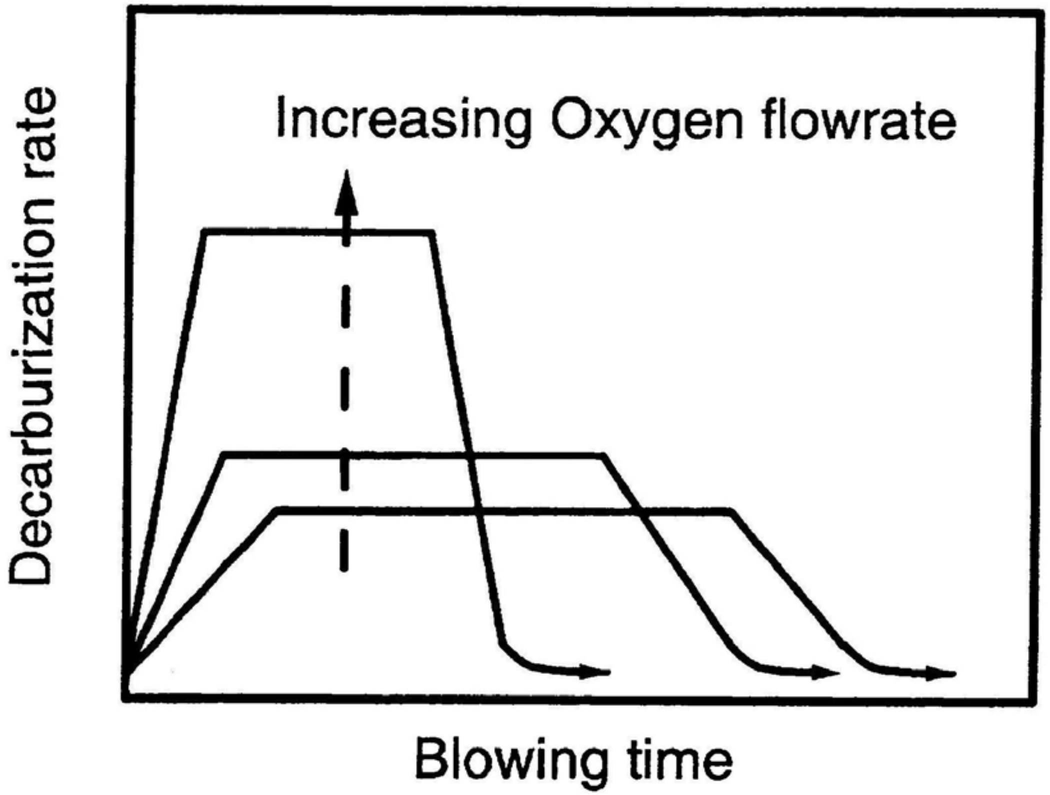
Comparisons

Table II Comparisons of bloated droplet motion model predictions with laboratory and industrial observations on the residence time of metal droplets in slag in top blown oxygen steelmaking.

Investigators	Methods	Residence time (s)
Schoop et al. [12]	Indirect plant measurement from which the residence time was calculated based on chemical analysis and kinetic model.	~ 60
Price [13]	Plant measurement with radioactive gold isotope tracer technique.	120 ± 30
Kozakevitch [20]	Prediction based on the carbon and phosphorus contents in metal droplet from plant measurement.	60-120
Present work	Bloated droplet motion model predictions on experimental cases of Molloseau and Fruehan [17] and Min and Fruehan [16] (c.f., Fig. 6)	10 – 200
Present work	Bloated droplet motion model predictions on residence time of metal droplets with 4.0 wt.%[C] in slag containing 15 wt.%FeO (c.f., Fig. 7(b))	45 – 75

Pan, Brooks, Coley and Subagyo, 2006

Decarburization



Rate of decarburization during a typical oxygen steelmaking heat (after Deo & Boom)

Bloated Droplet Summary

Strong link between droplet residence time and gas generation

Droplet motion in oxygen steelmaking is dominated by buoyancy

Bloated droplet model is promising

Incorporation of kinetics of decarburization and fluid mechanics

My major points

(i) Slag metal systems are fundamentally transient

(ii) We need to study how interfacial area and concentration gradients change with time

My co-workers and supporters

Subagyo, Ken Coley, Yuhua Pan, Gord. Irons and Akbar Rhamdhani

McMaster University, Swinburne University of Technology, CSIRO, NSERC, ARC, Bluescope Steel, Dofasco, Stelco and IPSCO

Questions please

"If there is an original idea out there, I could use it right now"

Bob Dylan