VOD Process Simulation

(**V**acuum **O**xygen **D**ecarburization)

MIME 572
Computational Thermodynamics

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1. Basic concept of VOD

1) Main purpose
2) Process
3) Importance

1-1 Main Purpose

Achieve

Extremely low carbon content in a molten steel
(mostly less than 0.04 wt%, ultra low less than 0.005 wt%)

Lower amount of undesired elements (such as nitrogen, oxygen, etc)

Demanded composition of desired element (such as Chromium)

Focus

Low Carbon and Nitrogen content at the same time (<80ppm)

→ Improving Mechanical Property

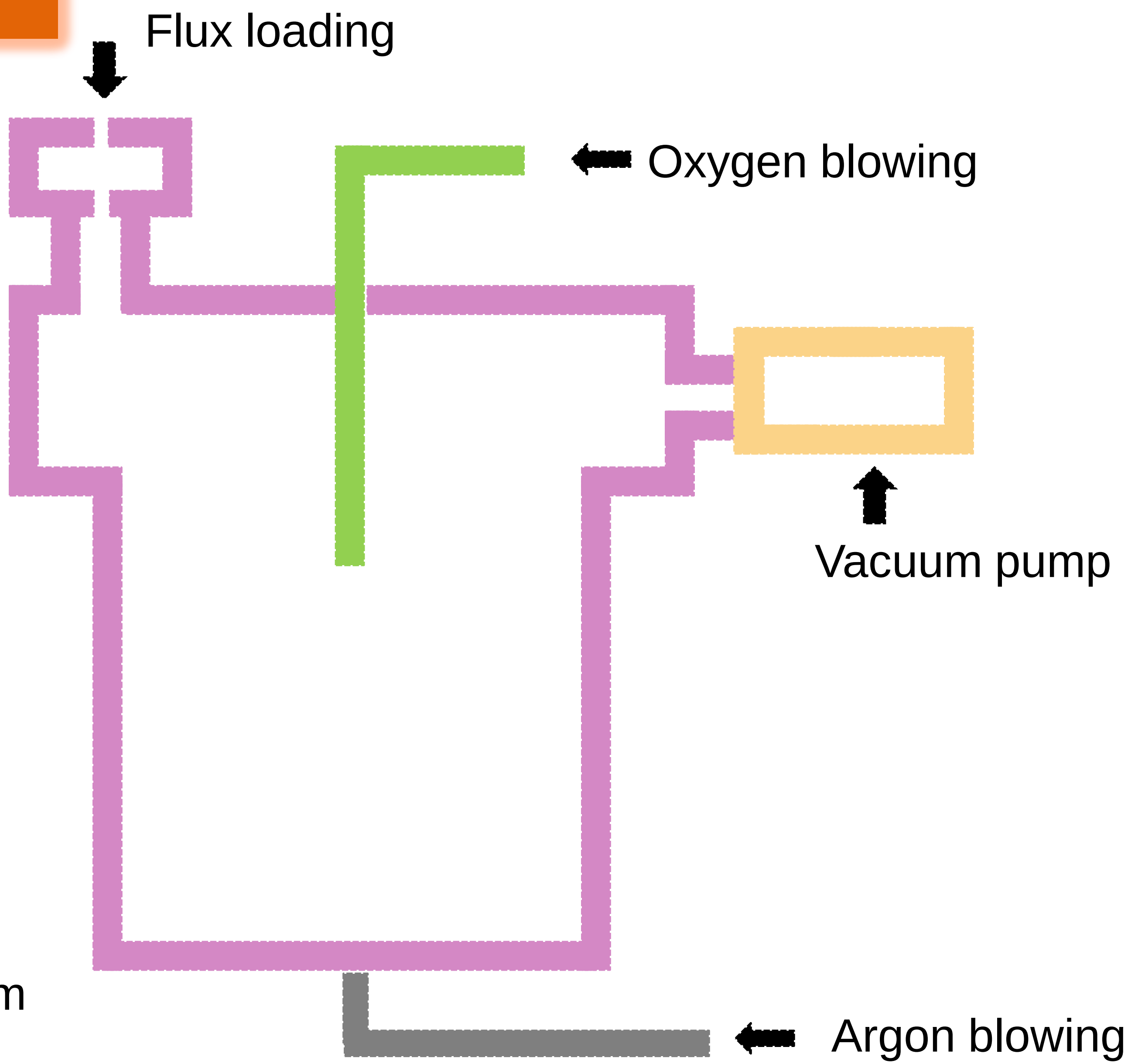
Chromium content as 18 wt%

1-2 Process

Three stages of VOD process

1) Oxygen blowing stage
2) Degassing stage
3) Reduction stage

1-2 Process



Flux loading

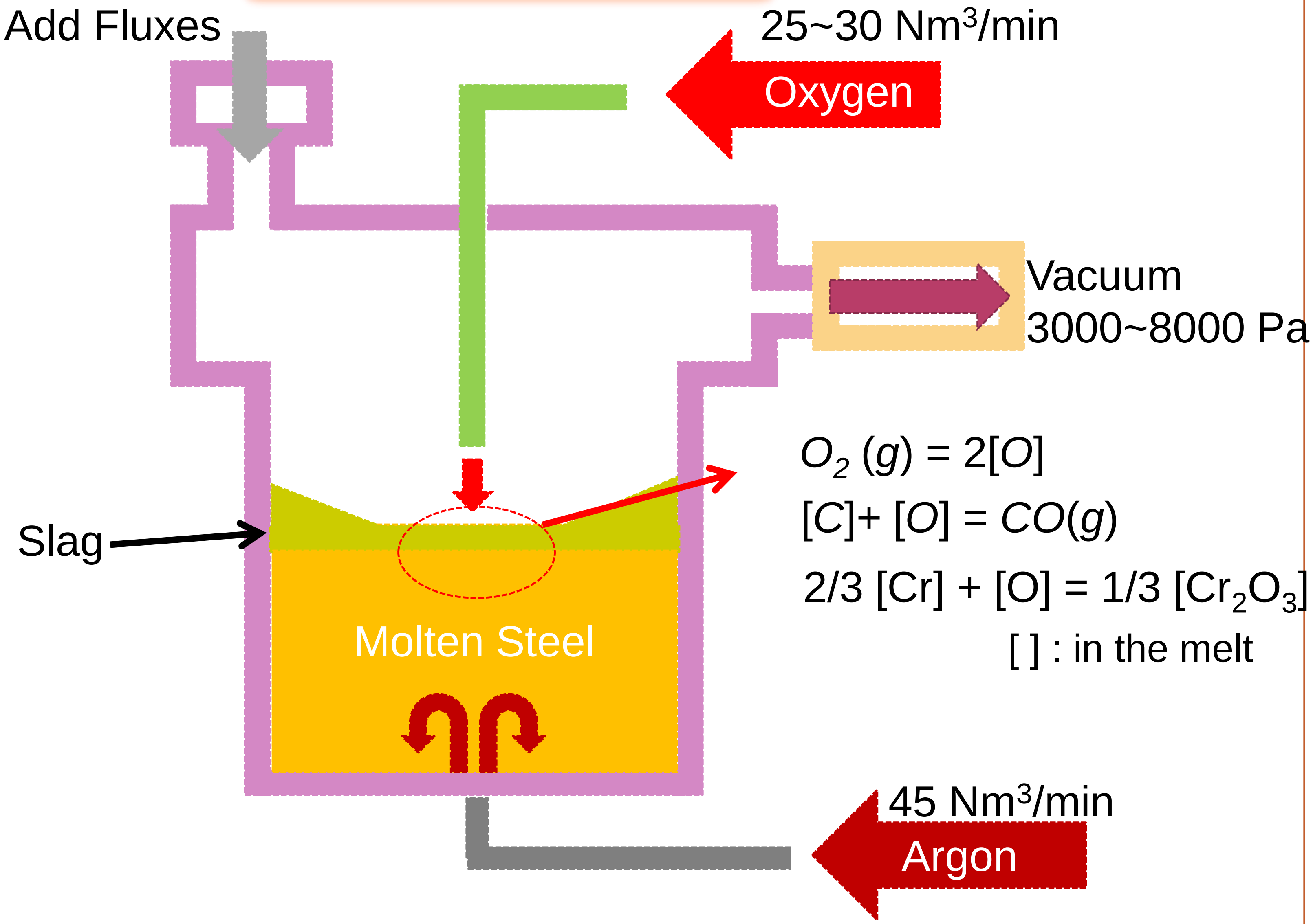
Oxygen blowing

Vacuum pump

Argon blowing

Schematic diagram
VOD vessel

Oxygen Blowing stage



$O_2(g) = 2[O]$

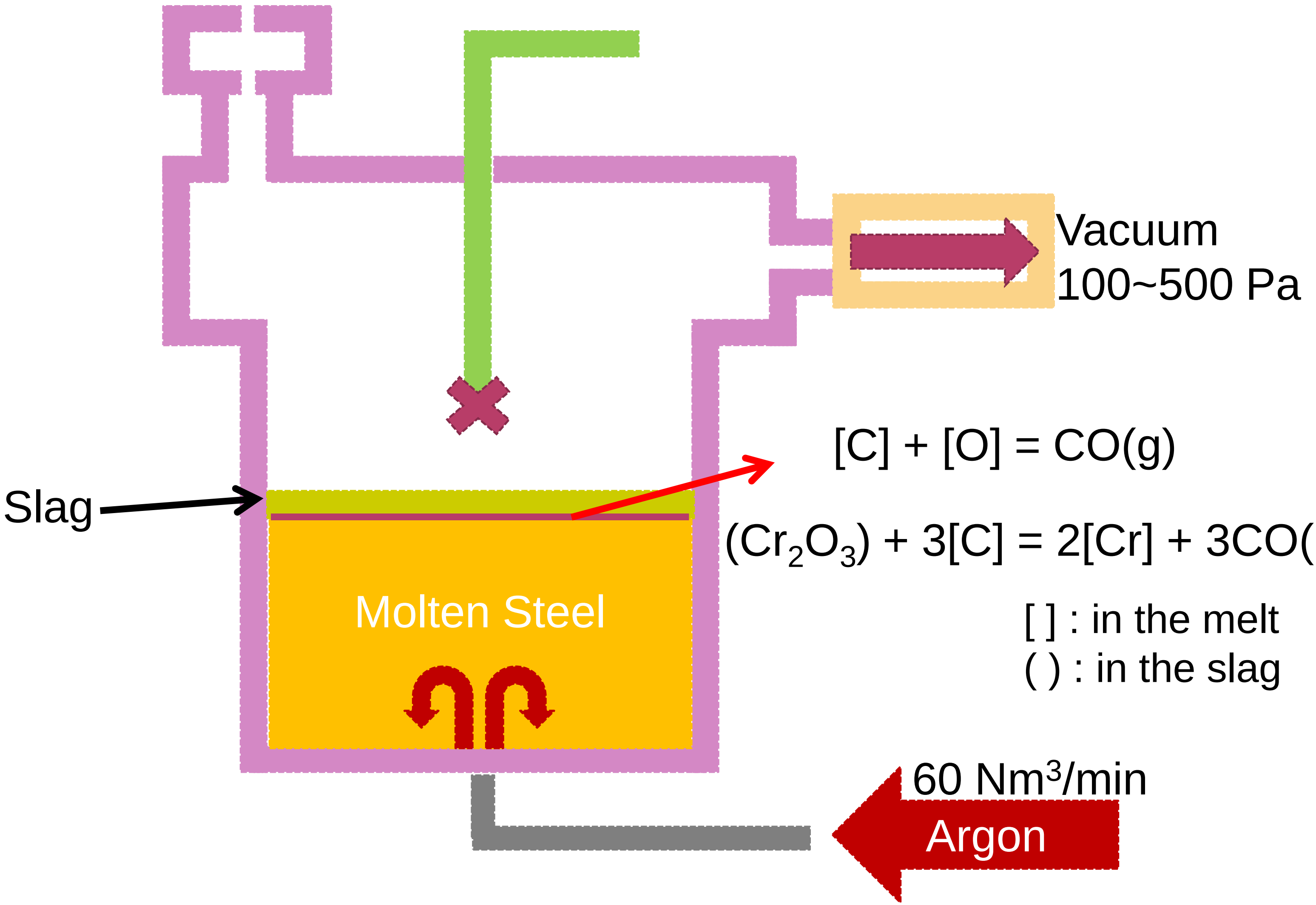
$[C] + [O] = CO(g)$

$2/3\ [Cr] + [O] = 1/3\ [Cr_2O_3]$

[ ] : in the melt

1-2 Process

Degassing stage

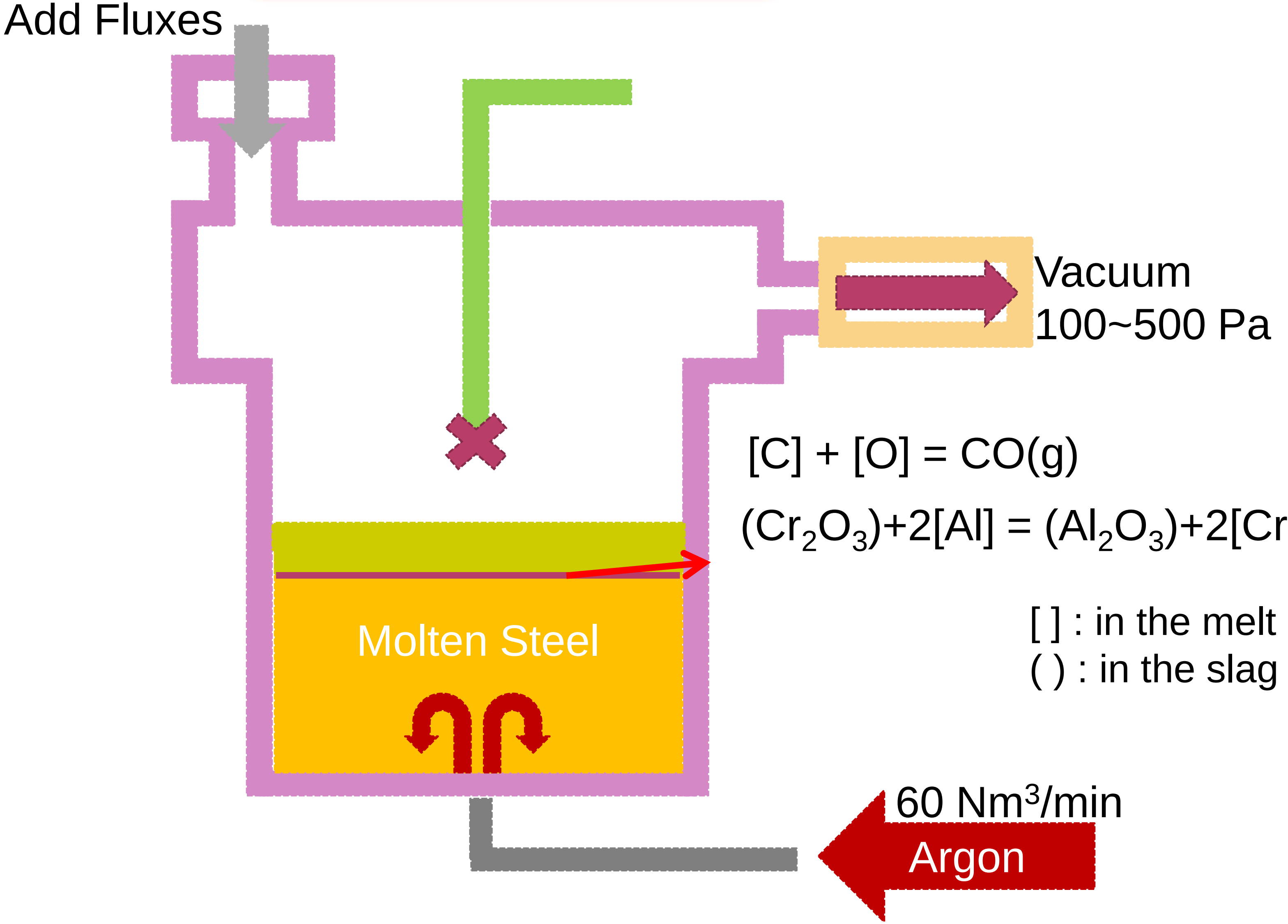


$[C] + [O] = CO(g)$

$(Cr_2O_3) + 3[C] = 2[Cr] + 3CO(g)$

[ ] : in the melt
( ) : in the slag

Reduction stage



$[C] + [O] = CO(g)$

$(Cr_2O_3)+2[Al] = (Al_2O_3)+2[Cr]$

[ ] : in the melt
( ) : in the slag

1-3 Importance

VOD process can achieve ultra low carbon and nitrogen content ([C]+[N] = 60~90 ppm)

Lower consumption for Argon and Silicon (60 to 90 ppm)

Stainless steel production grows steadily

High demand for ferritic stainless steel grades (e.g. AISI409, 439) which require lower carbon content

VOD process has not been understood well

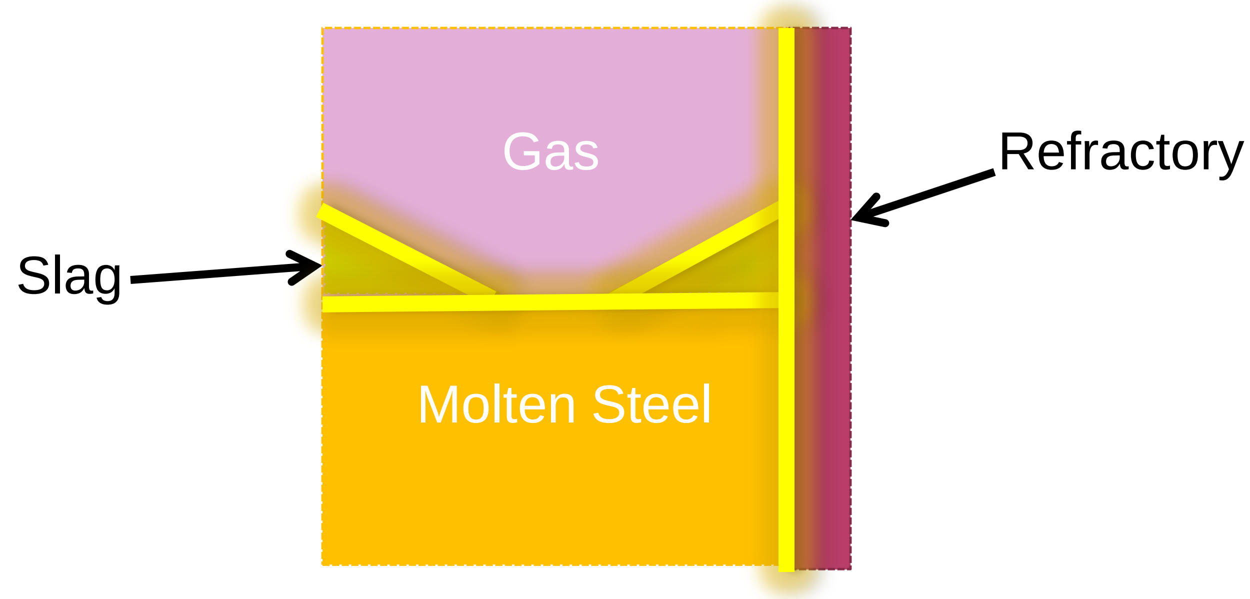
Because its complexity of reactions and harsh condition in vacuum

2. Simulation strategy

1) Parameters
2) Calculation plan
3) Understanding of relation
   Time, Temperature, Carbon content

2 – 1 Parameters

Considering Reactions



Molten steel / Slag / Solid oxides / Gases / Refractories

2 – 2 Calculation Plan

Initial Composition (wt%) :
[C] 0.25 [Cr] 18 [N] 0.015 [O] 0.02 [Si] 0.21 [Mn] 0.6

Temperature (℃) : 1600

$\Delta T = 5$ min

Vessel = 120 ton of melt

Oxygen blowing = 30 Nm^3 / min

*Data from **Bao Steel, ALZ** (Stainless steel making companies)*

2 – 3 Understanding of relation among Time, Temperature, Carbon content

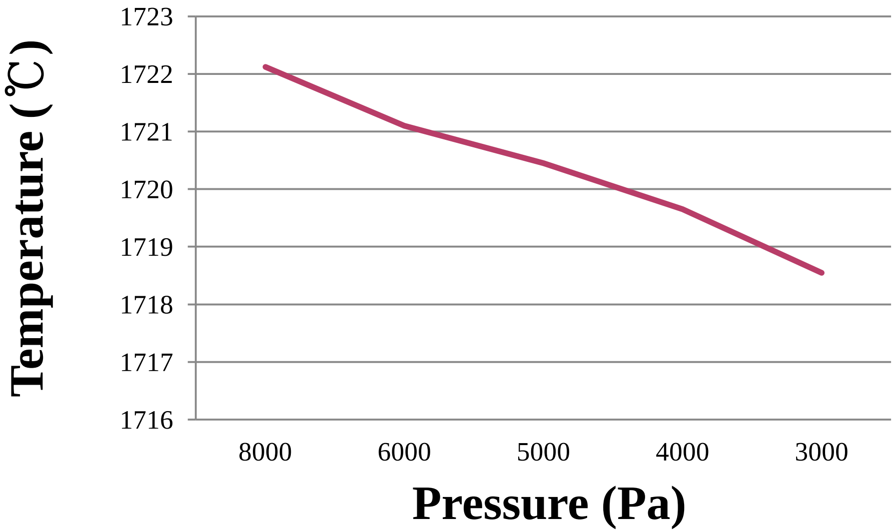
Purpose

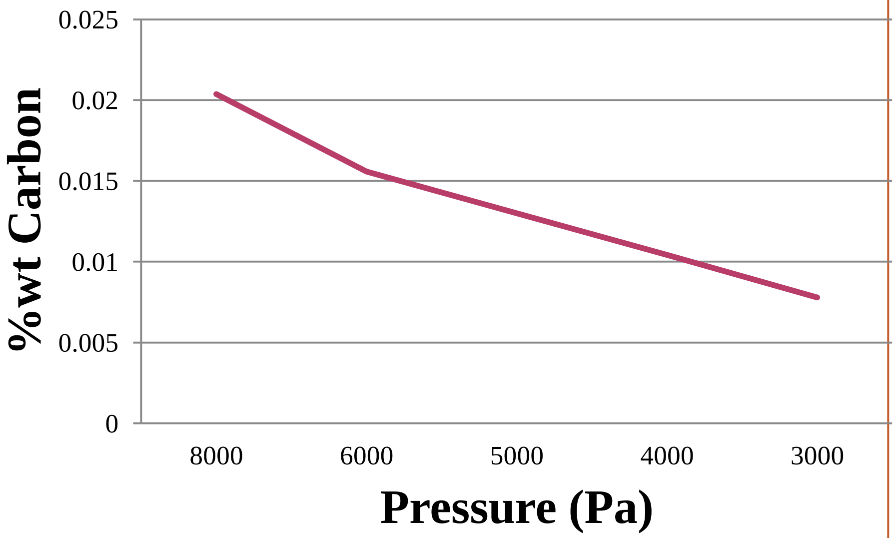
Find → 1. Suitable Reacted oxygen amount with melt

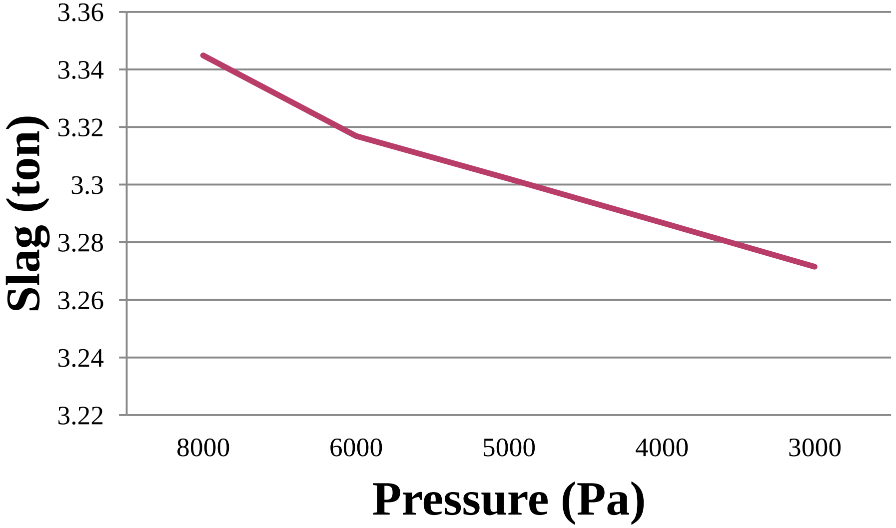
2. Slag amount
3. Vacuum condition
4. Flux amount

2 – 3 Understanding of relation among Time, Temperature, Carbon content

Fixed Reacted oxygen, Fluxes







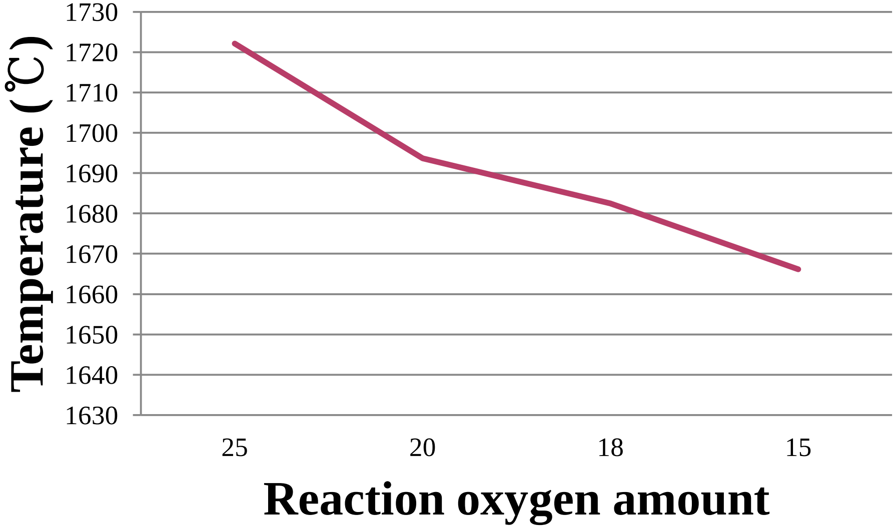
Pressure ↘ = Final Temperature ↘

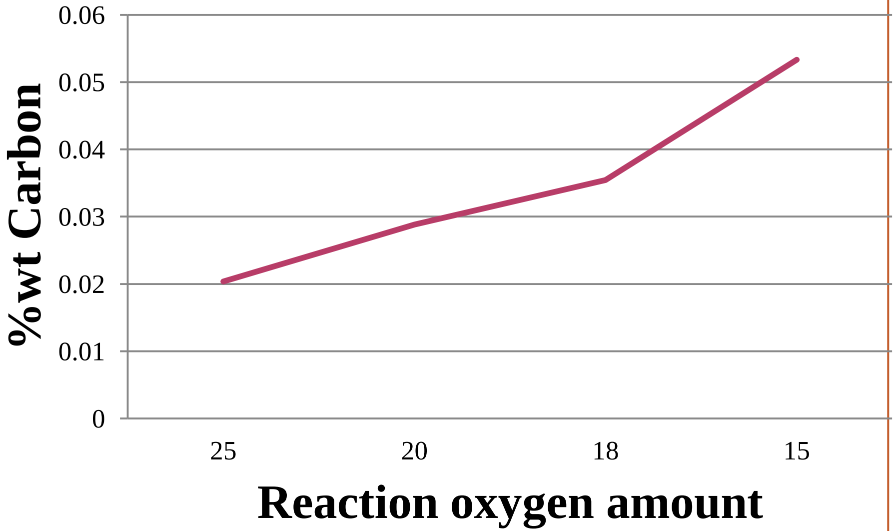
Pressure ↘ = wt% Carbon ↘

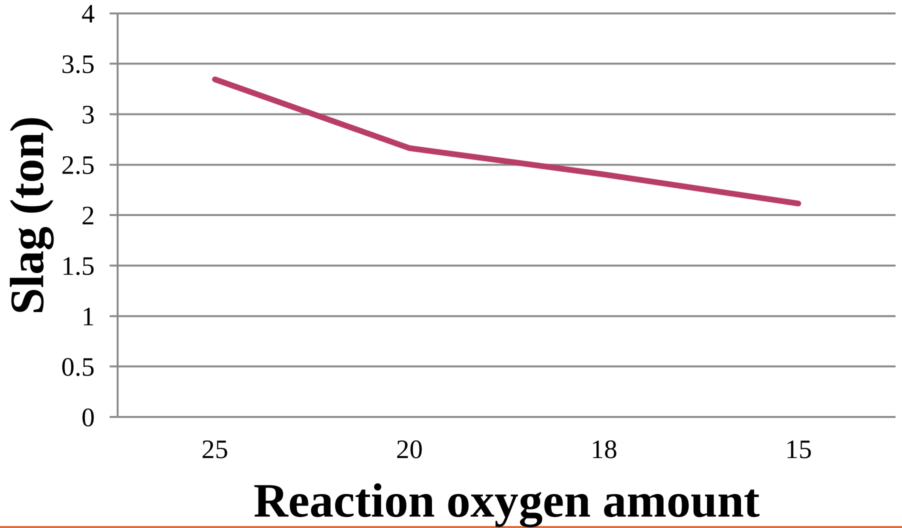
Pressure ↘ = Slag amount ↘

2 – 3 Understanding of relation among Time, Temperature, Carbon content

Fixed Vacuum, Fluxes







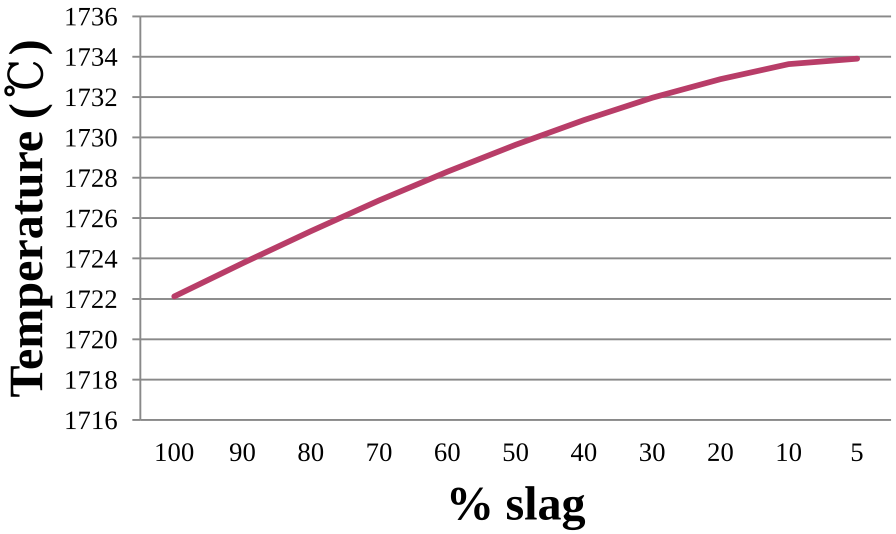
Oxygen ↘ = Final Temperature ↘

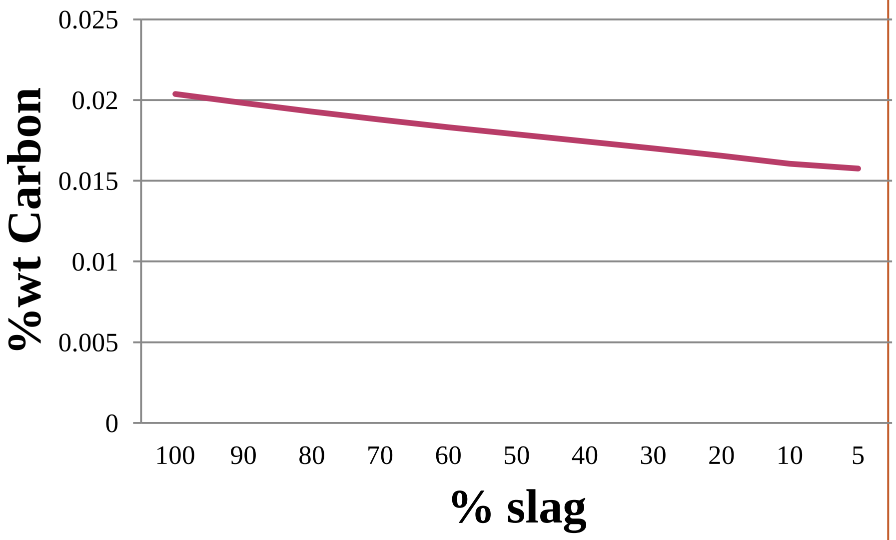
Oxygen ↘ = wt% Carbon ↗

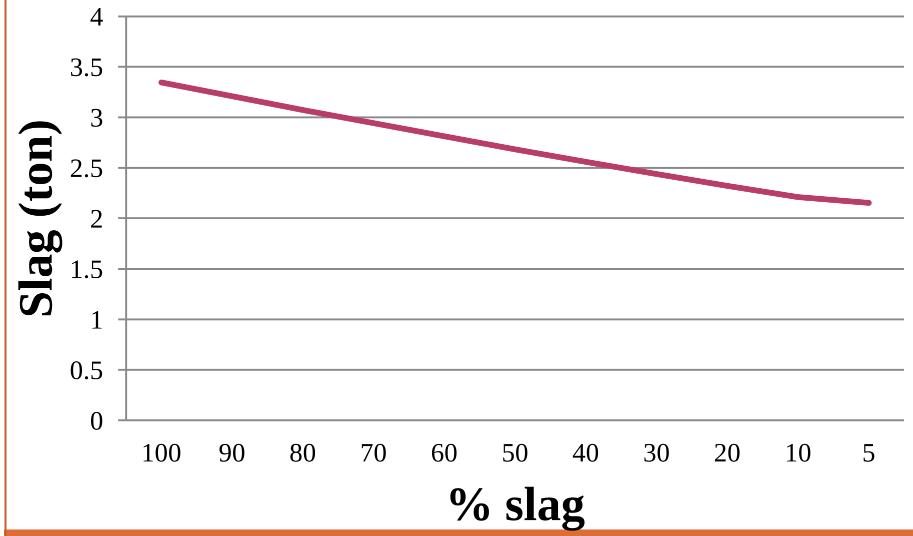
Oxygen ↘ = Slag amount ↘

2 – 3 Understanding of relation among Time, Temperature, Carbon content

Fixed Vacuum, Reacted oxygen







Slag ↘ = Final Temperature ↗

Slag ↘ = wt% Carbon ↘

Slag ↘ = Slag amount ↘

3. Preliminary calculation

1) Condition
2) Result & Modification

3 – 1 Condition

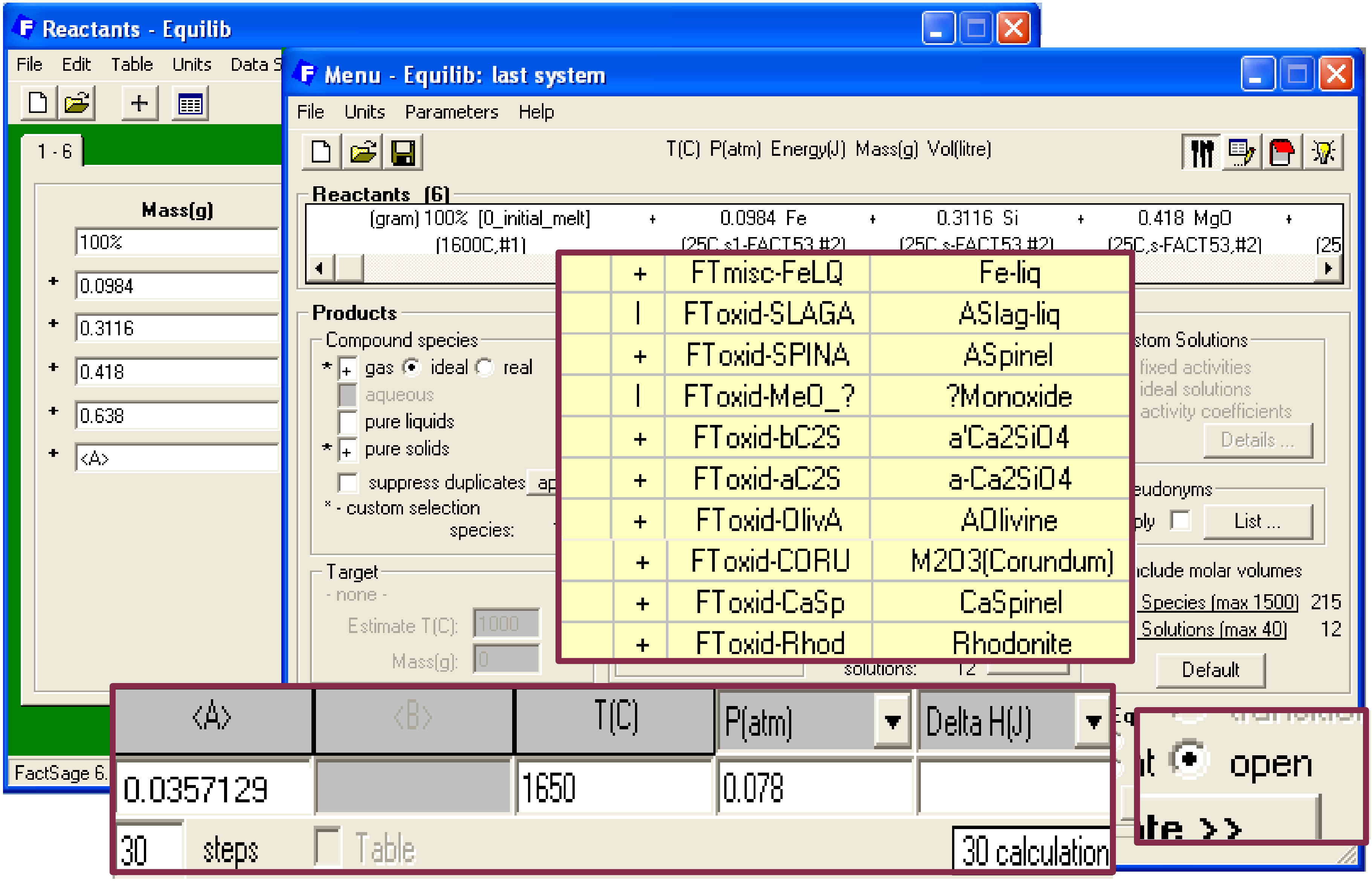
For Oxygen blowing stage

Reacted oxygen amount = 25 Nm^3/min (83%)

Vacuum condition = 0.078 atm (8000Pa)

Fluxes = FeSi (76% Si)
Dolomitic lime (38%MgO, 58% CaO)

3 – 1 Condition



Mass(g)

100%
+ 0.0984
+ 0.3116
+ 0.418
+ 0.638
+ <A>

Reactants (6)

(gram) 100% [0_initial_melt] (1600C,#1) + 0.0984 Fe (25C,s1-FACT53,#2) + 0.3116 Si (25C,s-FACT53,#2) + 0.418 MgO (25C,s-FACT53,#2) + (25

Products

Compound species
- * ☒ gas ● ideal ○ real
- ☐ aqueous
- ☐ pure liquids
- * ☒ pure solids
- ☐ suppress duplicates
- * - custom selection

Target
- none -
Estimate T(C): 1000
Mass(g): 0

Custom Solutions: fixed activities, ideal solutions, activity coefficients

Pseudonyms apply ☐

include molar volumes

Species (max 1500) 215
Solutions (max 40) 12

	+	FTmisc-FeLQ	Fe-liq
	I	FToxid-SLAGA	ASlag-liq
	+	FToxid-SPINA	ASpinel
	I	FToxid-MeO_?	?Monoxide
	+	FToxid-bC2S	a'Ca2SiO4
	+	FToxid-aC2S	a-Ca2SiO4
	+	FToxid-OlivA	AOlivine
	+	FToxid-CORU	M2O3(Corundum)
	+	FToxid-CaSp	CaSpinel
	+	FToxid-Rhod	Rhodonite

<A>	<B>	T(C)	P(atm)	Delta H(J)
0.0357129		1650	0.078	

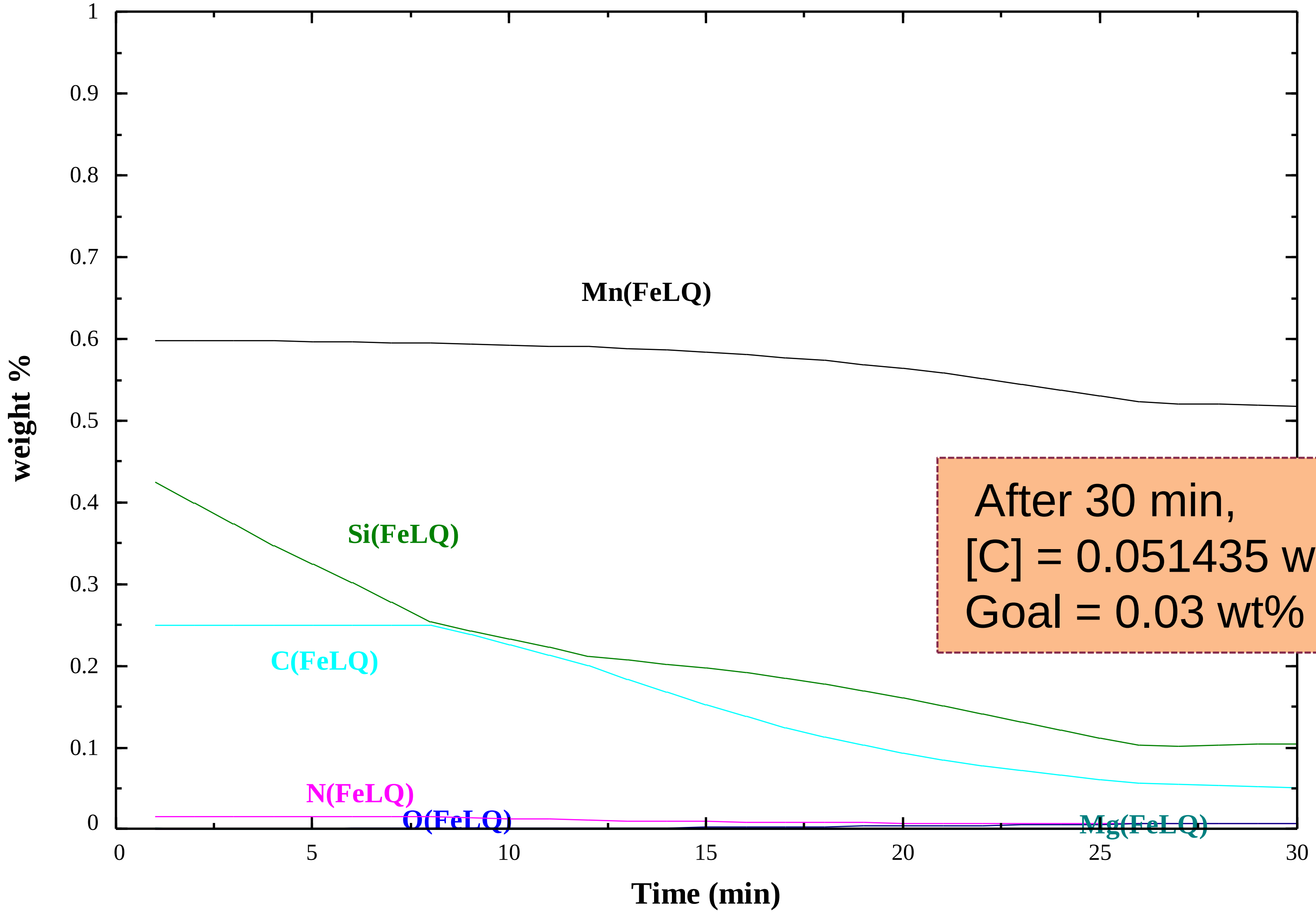
30 steps ☐ Table 30 calculation

● open

...te >>

3 – 2 Result & Modification

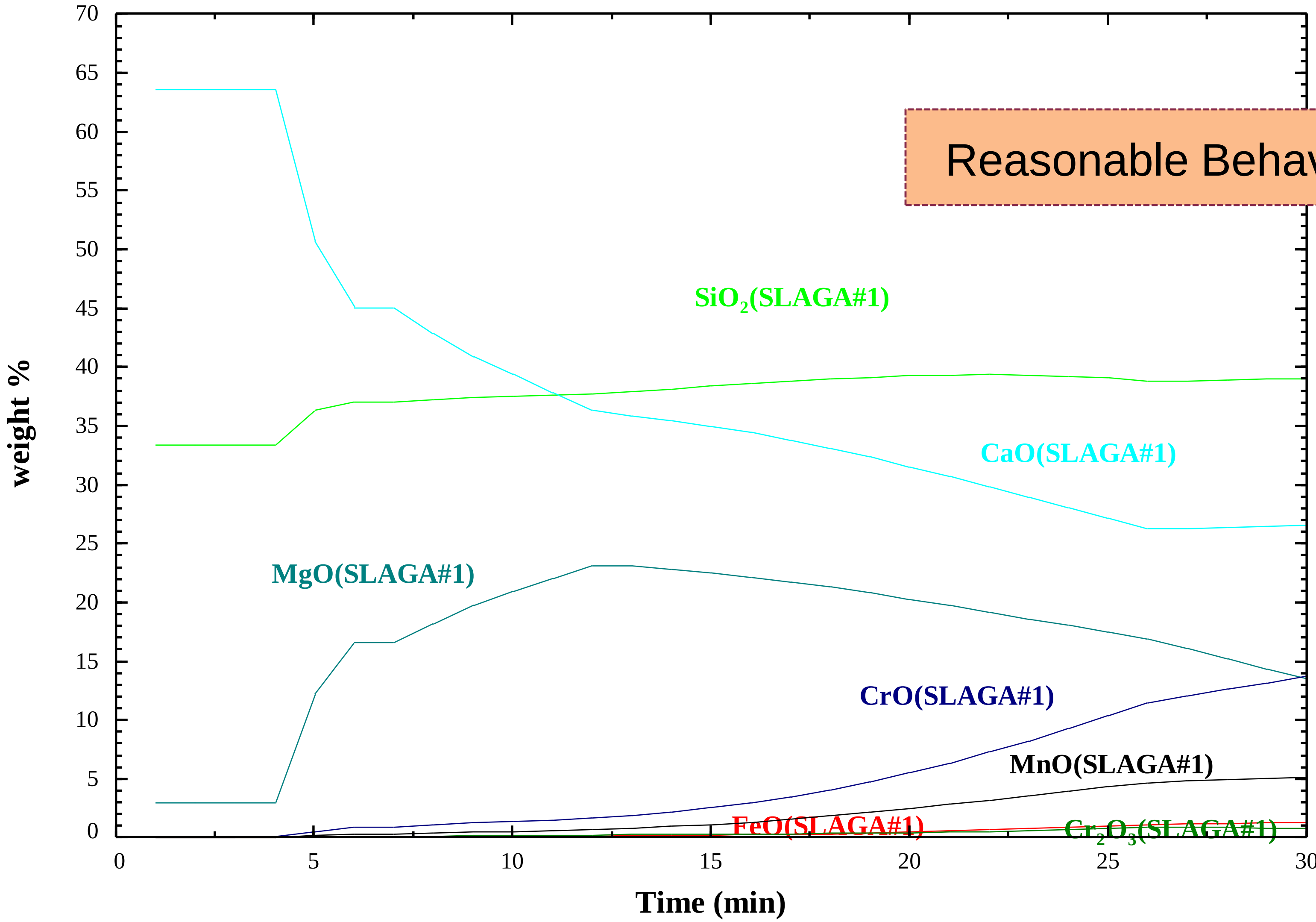
[C], [N], [O], [Si], [Mn], [Mg] in the melt



After 30 min,
[C] = 0.051435 wt%
Goal = 0.03 wt%

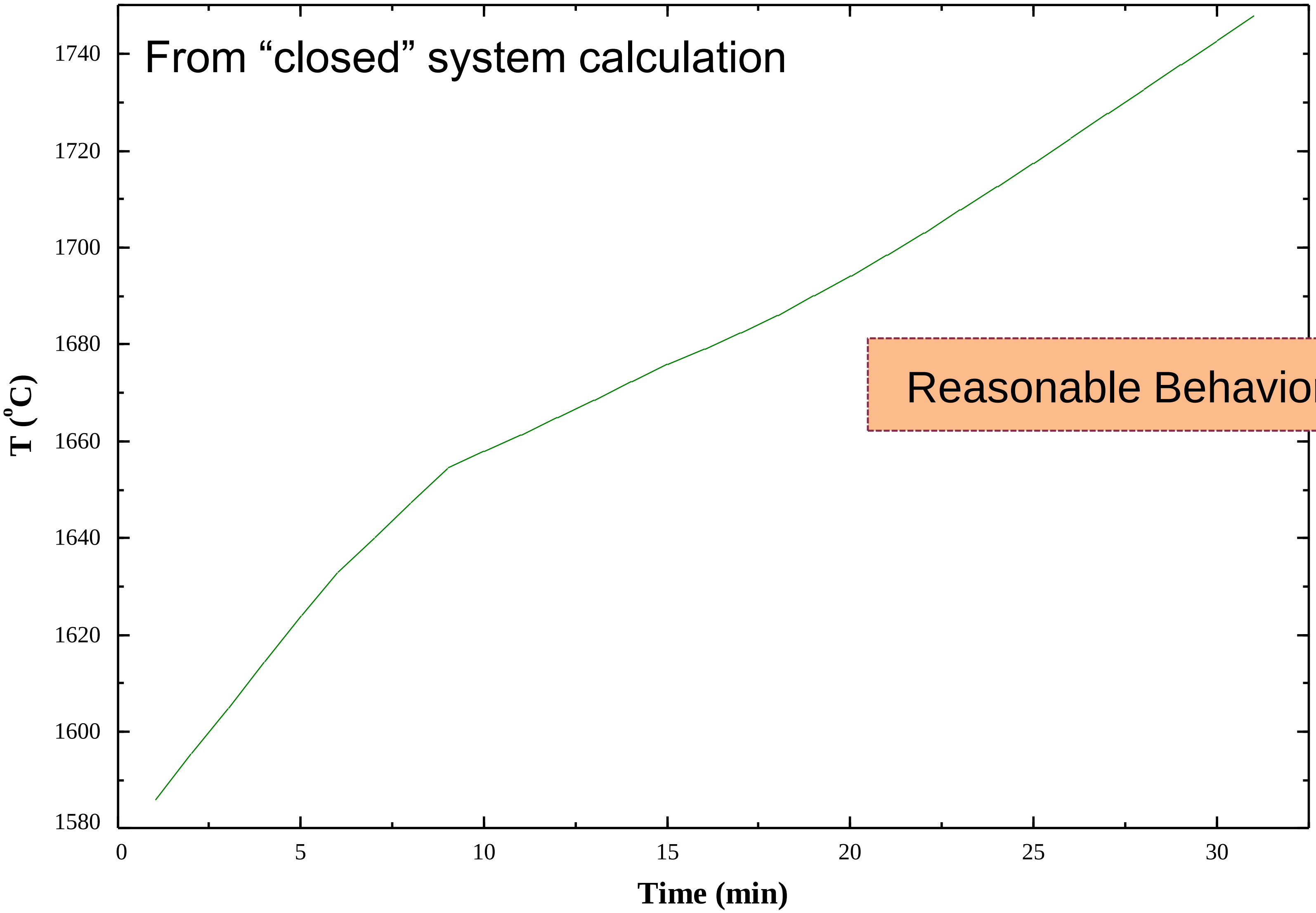
3 – 2 Result & Modification

Slag Composition



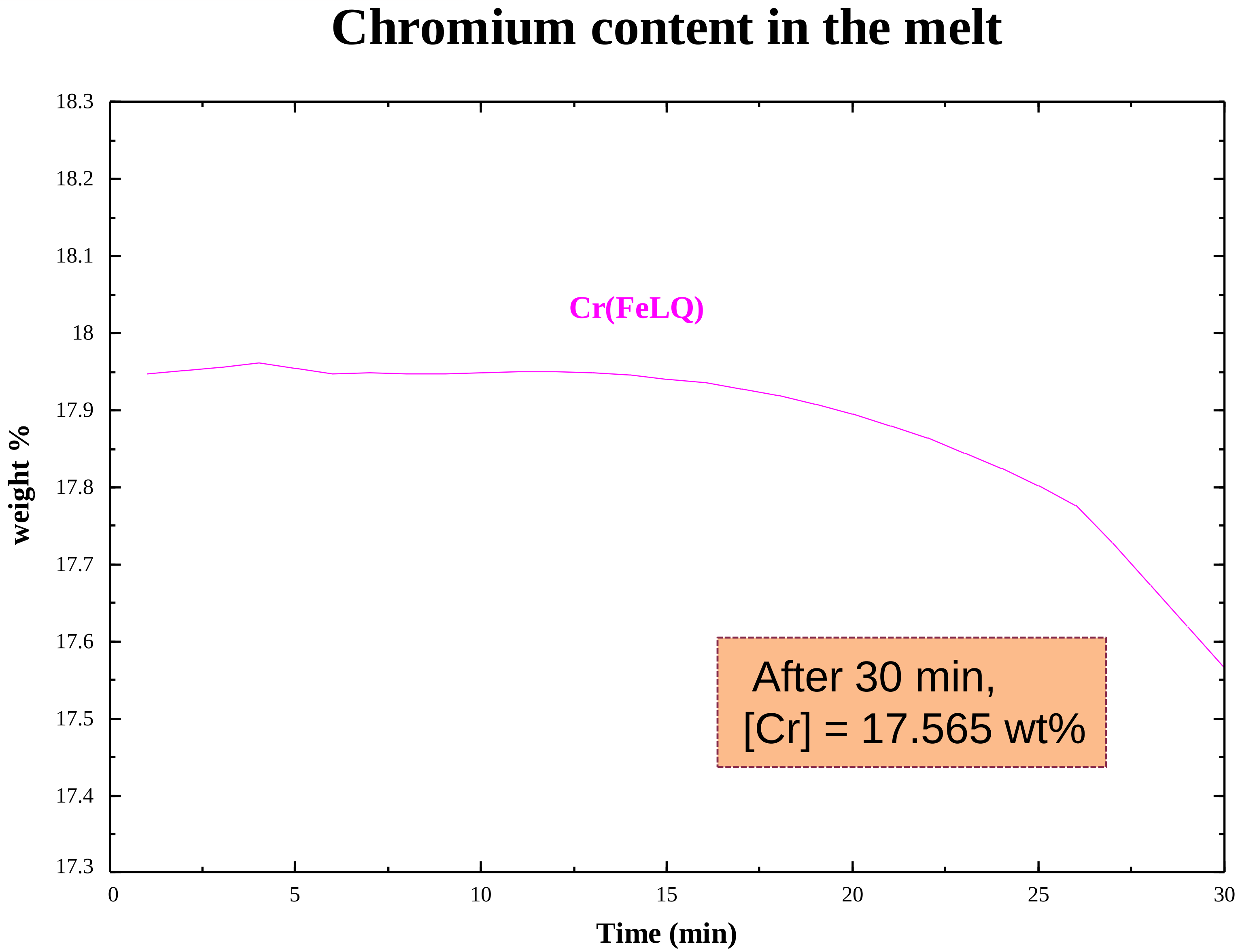
Reasonable Behavior

Temperature



Reasonable Behavior

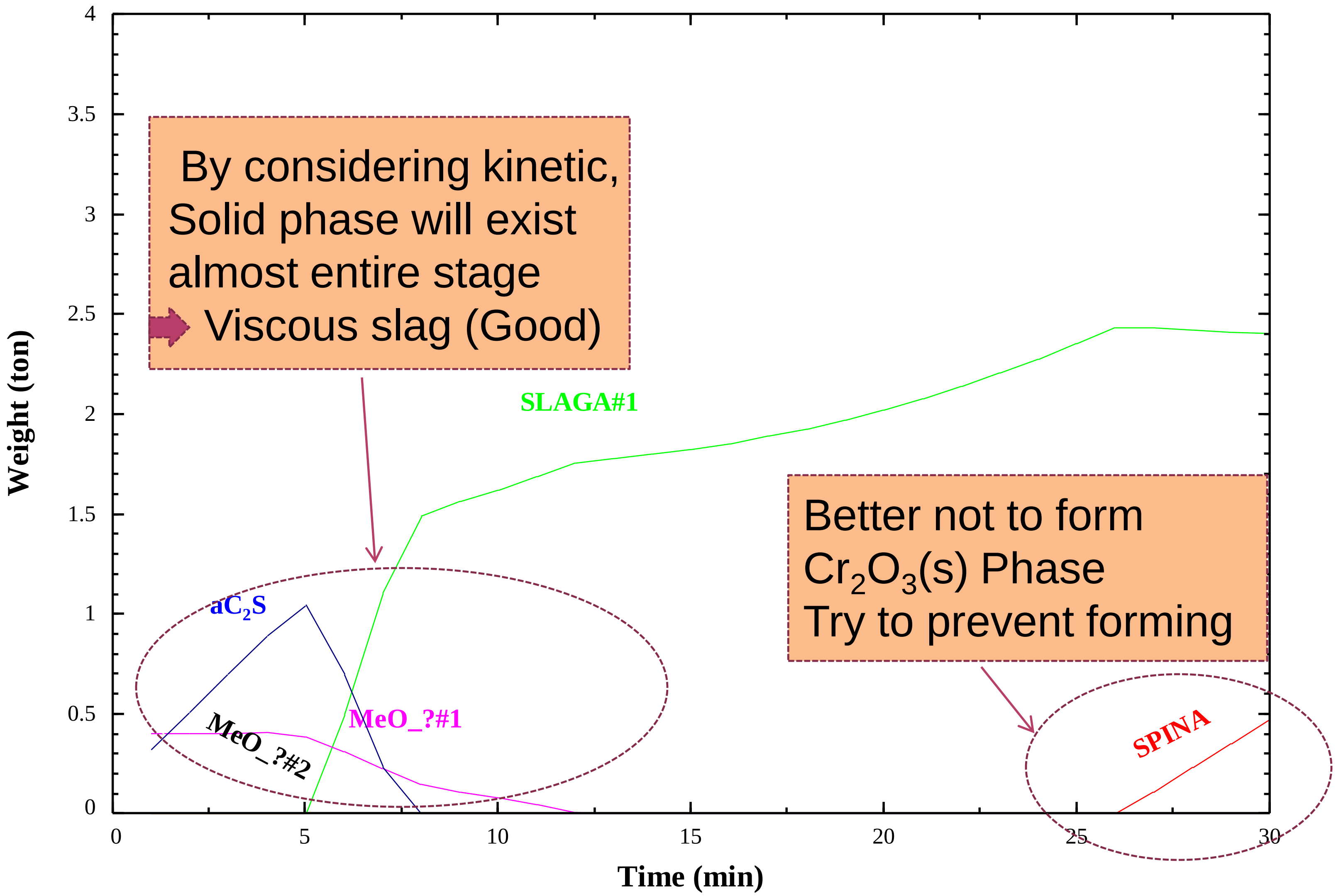
3 – 2 Result & Modification



After 30 min,
[Cr] = 17.565 wt%

3 – 2 Result & Modification

Solid phases



By considering kinetic, Solid phase will exist almost entire stage

➡ Viscous slag (Good)

Better not to form Cr_2O_3(s) Phase

Try to prevent forming

3 – 2 Result & Modification

From Previous calculations (section 2)
and
industrial data from Baosteel (09Xu)

More time for this stage (> 30min)

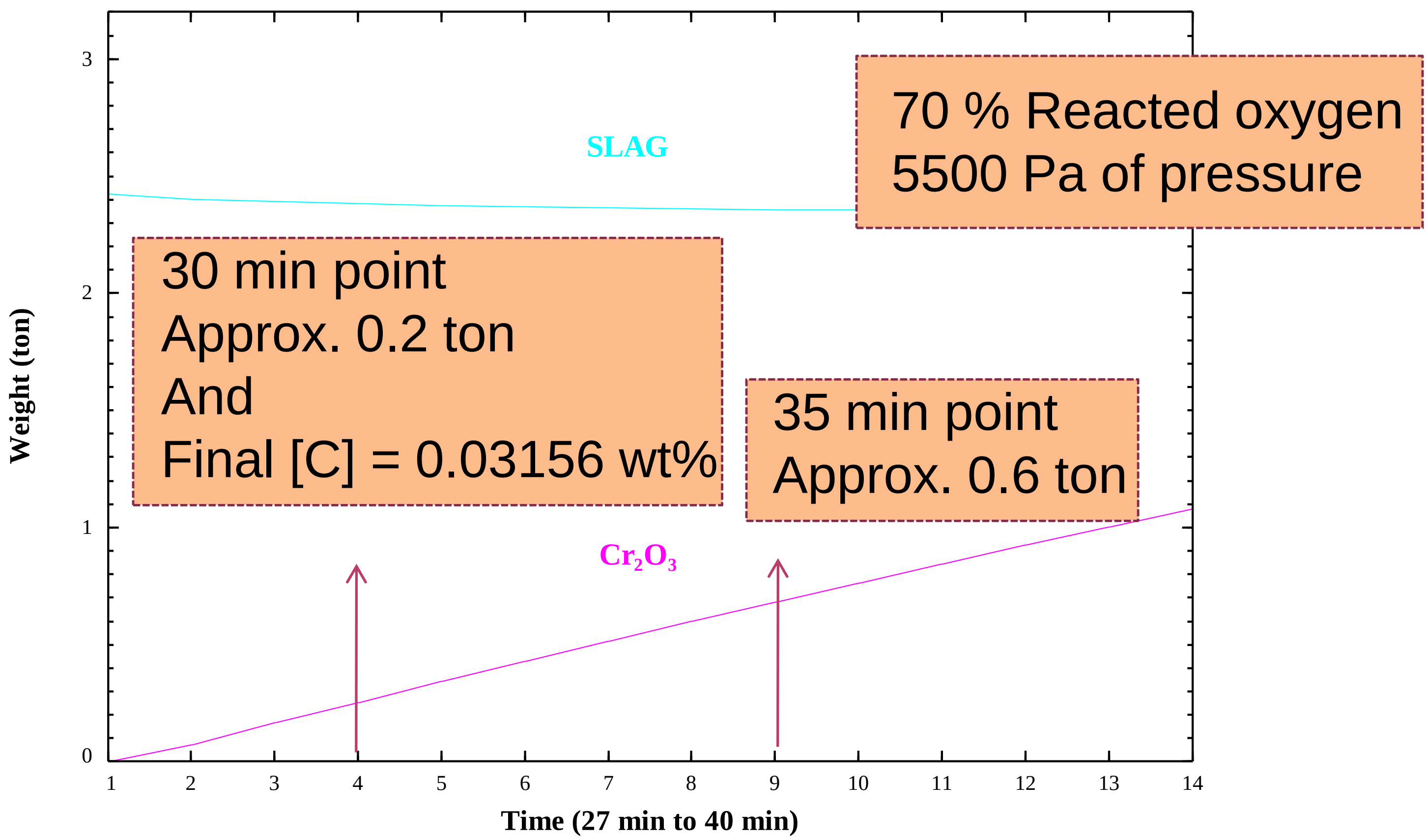
Reduce oxygen blowing to minimize Cr_2O_3(s) phase (Between 26 – 27 min Cr_2O_3(s) formed)

Reduce pressure to minimize slag amount

Keep flux amount (for reduction stage)

3 – 2 Result & Modification

Approximation for reducing Cr_2O_3(s) phase



Cr_2O_3 (s) phase

70 % Reacted oxygen
5500 Pa of pressure

30 min point
Approx. 0.2 ton
And
Final [C] = 0.03156 wt%

35 min point
Approx. 0.6 ton

3 – 2 Result & Modification

For Reduction stage

By considering slow reaction between slag and melt, divide 8 small portion of reaction fluxes amounts

Vacuum condition = 0.0019 atm (200Pa)

Initial fluxes =
FeSiMn (28.8%Si, 63.7%Mn) : 900kg
Al (99.5% Al) : 160kg
Dolomitic Lime (38%MgO, 58%CaO) : 200kg

3 – 2 Result & Modification

Result from approximate calculation

➡ + 9.4648E-06 wt.% C
+ 17.868 wt.% Cr
+ 7.1622E-04 wt.% N
+ 0.11470 wt.% Si
+ 1.0569 wt.% Mn

Modification

To achieve

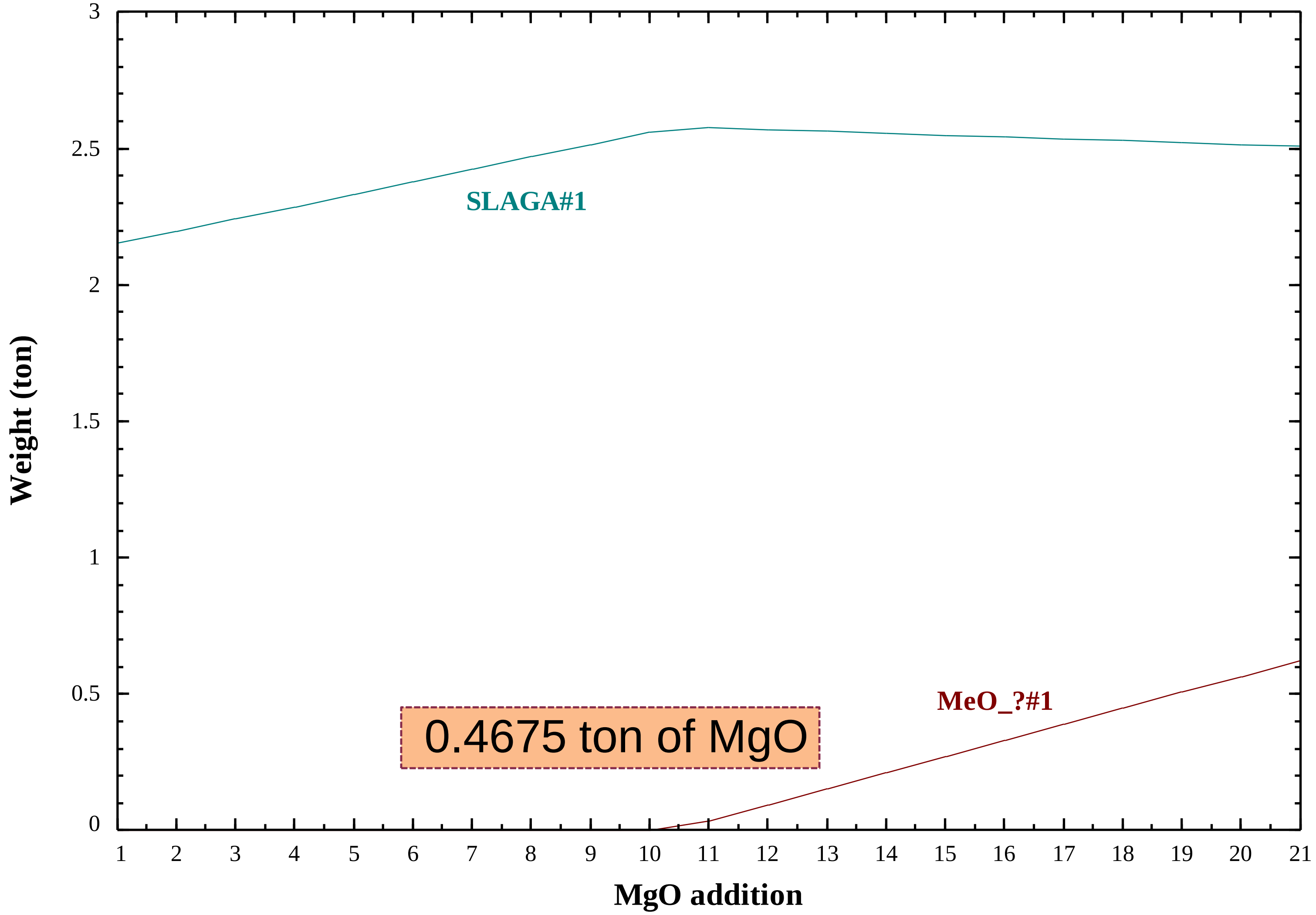
➡ Fe, <0.12% C, 16-18% Cr, <0.75% Ni, <1.0% Mn, <1.0% Si,

<STS grade 430 From Azon.com>

➡ Add SiCr to adjust final [Cr]
Add more MgO to saturate MgO in the slag to prevent reaction between slag and refractories
(assume refractories are mainly consist of MgO-rich phase)

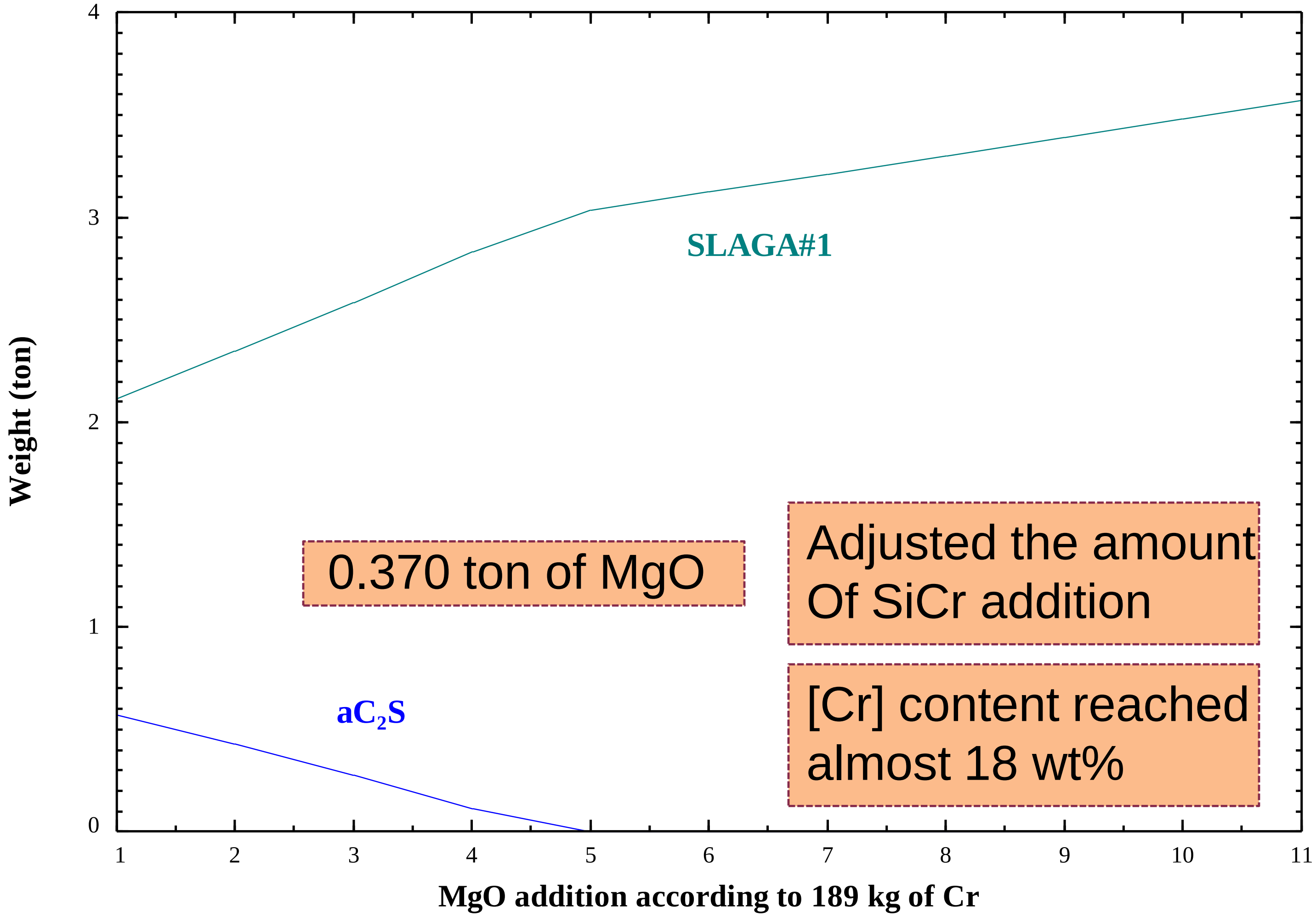
3 – 2 Result & Modification

Find MgO saturation point



0.4675 ton of MgO

Preventing solid phase forming (because of Si)



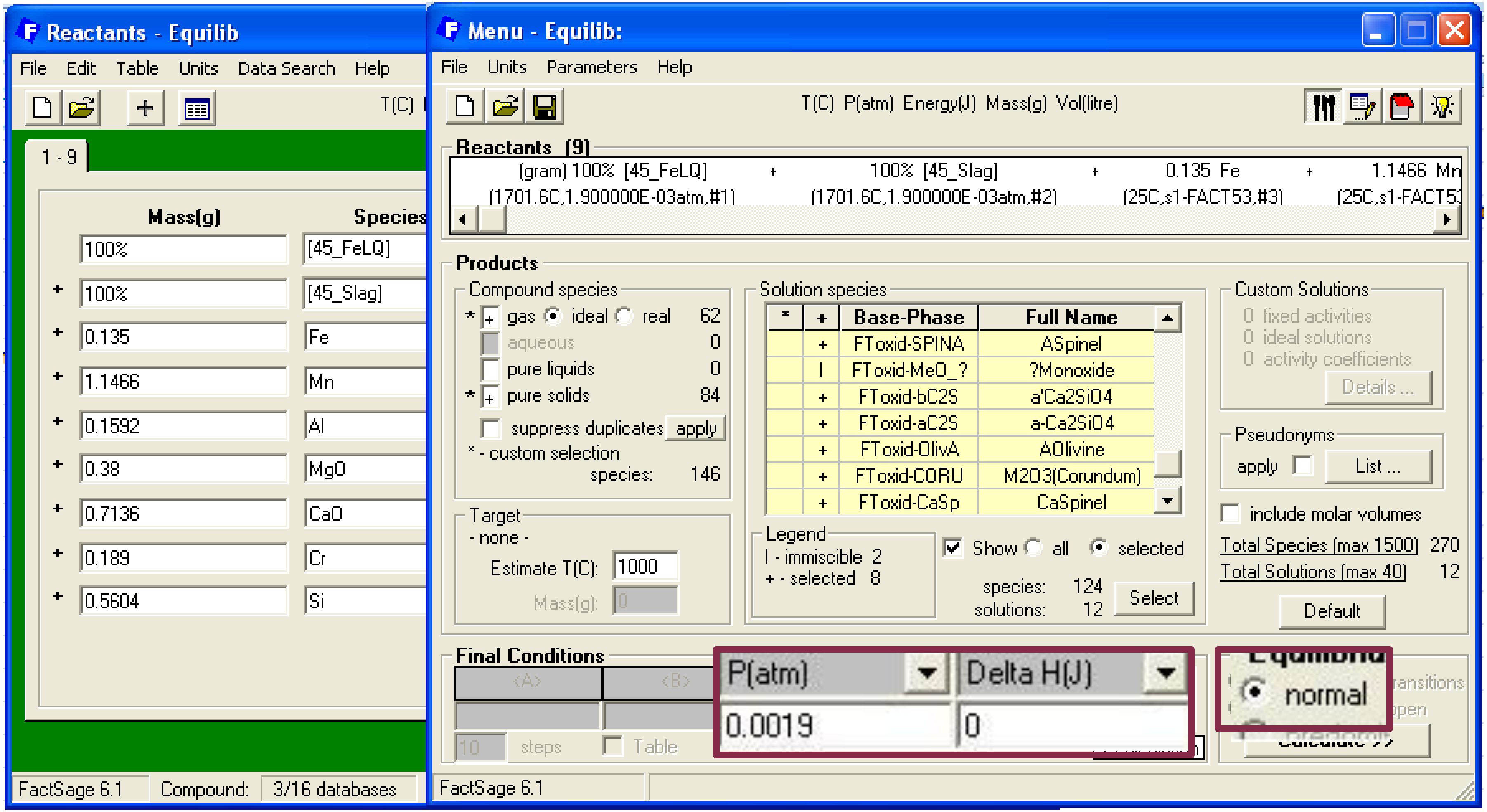
0.370 ton of MgO

Adjusted the amount Of SiCr addition

[Cr] content reached almost 18 wt%

3 – 2 Result & Modification

Estimation calculation for Reduction stage



Reactants - Equilib

	Mass(g)	Species
	100%	[45_FeLQ]
+	100%	[45_Slag]
+	0.135	Fe
+	1.1466	Mn
+	0.1592	Al
+	0.38	MgO
+	0.7136	CaO
+	0.189	Cr
+	0.5604	Si

FactSage 6.1 Compound: 3/16 databases

Menu - Equilib:

Reactants (9)

(gram) 100% [45_FeLQ] + 100% [45_Slag] + 0.135 Fe + 1.1466 Mn
(1701.6C,1.900000E-03atm,#1) (1701.6C,1.900000E-03atm,#2) (25C,s1-FACT53,#3) (25C,s1-FACT5

Products

Compound species

*	☐+	gas ● ideal ○ real	62
	☐	aqueous	0
	☐	pure liquids	0
*	☐+	pure solids	84

☐ suppress duplicates apply
* - custom selection
species: 146

Solution species

*	+	Base-Phase	Full Name
	+	FToxid-SPINA	ASpinel
	I	FToxid-MeO_?	?Monoxide
	+	FToxid-bC2S	a'Ca2SiO4
	+	FToxid-aC2S	a-Ca2SiO4
	+	FToxid-OlivA	AOlivine
	+	FToxid-CORU	M2O3(Corundum)
	+	FToxid-CaSp	CaSpinel

Legend
I - immiscible 2
+ - selected 8

☑ Show ○ all ● selected
species: 124
solutions: 12
Select

Custom Solutions
0 fixed activities
0 ideal solutions
0 activity coefficients
Details ...

Pseudonyms
apply ☐ List ...

☐ include molar volumes
Total Species (max 1500) 270
Total Solutions (max 40) 12
Default

Target
- none -
Estimate T(C): 1000
Mass(g): 0

Final Conditions

P(atm)	Delta H(J)
0.0019	0

10 steps ☐ Table

Equilibrium
● normal
transitions
open
Calculate >>

FactSage 6.1

3 – 2 Result & Modification

Result - Melt

```
+ 120.81     gram  Fe-liq
   (120.81 gram, 2.2034 mol)
        (1625.71 C, 1.9000E-03 atm,     a=1.0000)
        ( 80.467     wt.% Fe                                   FTmisc
        + 1.9321E-03 wt.% Al                                   FTmisc
        + 1.9204E-05 wt.% C                                    FTmisc
        + 4.2150E-08 wt.% Ca                                   FTmisc
        + 17.965     wt.% Cr                                   FTmisc
        + 1.0346     wt.% Mn                                   FTmisc
        + 6.3495E-04 wt.% N                                    FTmisc
        + 6.0079E-04 wt.% O                                    FTmisc
        + 0.51398    wt.% Si                                   FTmisc
        + 3.2650E-05 wt.% Mg                                   Ftmisc
                      .
```

➡ Fe, <0.12% C, 16-18% Cr, <0.75% Ni, <1.0% Mn, <1.0% Si

3 – 2 Result & Modification

Result - Slag

```
+ 3.0180     gram  ASlag-liq#1
  (3.0180 gram, 5.2305E-02 mol)
          (1625.71 C, 1.9000E-03 atm,     a=1.0000)
          ( 9.8177     wt.% Al2O3                        FToxid
          + 33.583     wt.% SiO2                         FToxid
          + 44.746     wt.% CaO                          FToxid
          + 5.9575E-02 wt.% FeO                          FToxid
          + 2.1620E-04 wt.% Fe2O3                        FToxid
          + 10.540     wt.% MgO                          FToxid
          + 0.65223    wt.% MnO                          FToxid
          + 0.55160    wt.% CrO                          FToxid
          + 5.0136E-02 wt.% Cr2O3                        FToxid
          + 7.7029E-05 wt.% Mn2O3                        FToxid)
```

Almost same result from paper (01Jon)

4. Main calculation (by using stream function)

1) Condition
2) Calculation
3) Result & Discussion

4 – 1 Condition

Oxygen Blowing Stage

Time(min)	0-5	6-10	11-15	16-20	21-25	26-30	31-35
Oxygen(Nm^3/min)	20	20	20	20	20	15	10
Vacuum(Pa)	8000	8000	8000	8000	8000	6750	5500

Initial fluxes =

FeSi (76% Si) 410kg
Dolomitic lime (38%MgO, 58% CaO) 1100kg

Degassing Stage

Time(min)	36-40	41-45
Oxygen(Nm3/min)	0	0
Vacuum(Pa)	250	200

No fluxes added

4 – 1 Condition

Reduction Stage

Time(min)	46-50	51-55	56-60	61-65	66-70	71-75	76-80
Oxygen(Nm^3/min)	0	0	0	0	0	0	0
Vacuum(Pa)	200	200	200	200	200	200	200

Fluxes	**Composition**	**Total amount**
FeSiMn	28.8%Si, 63.7%Mn	787.5kg
SiCr	31.5%Cr, 50.2%Si	525kg
Al	99.5% Al	140kg
Dolomitic Lime	30.9%MgO, 58%CaO	1076.25kg

Assume that 1/7 of fluxes react with melt on each time interval

4 – 1 Condition

Stream calculation

1. Calculate first step

Save as stream files

Result – liquid steel, slag, solid, gas formed

Take all of formed phase except gas phases

2. Calculate second step

Liquid steel
Slag
Solid phases

→

In condition of second step
(e.g. different pressure)

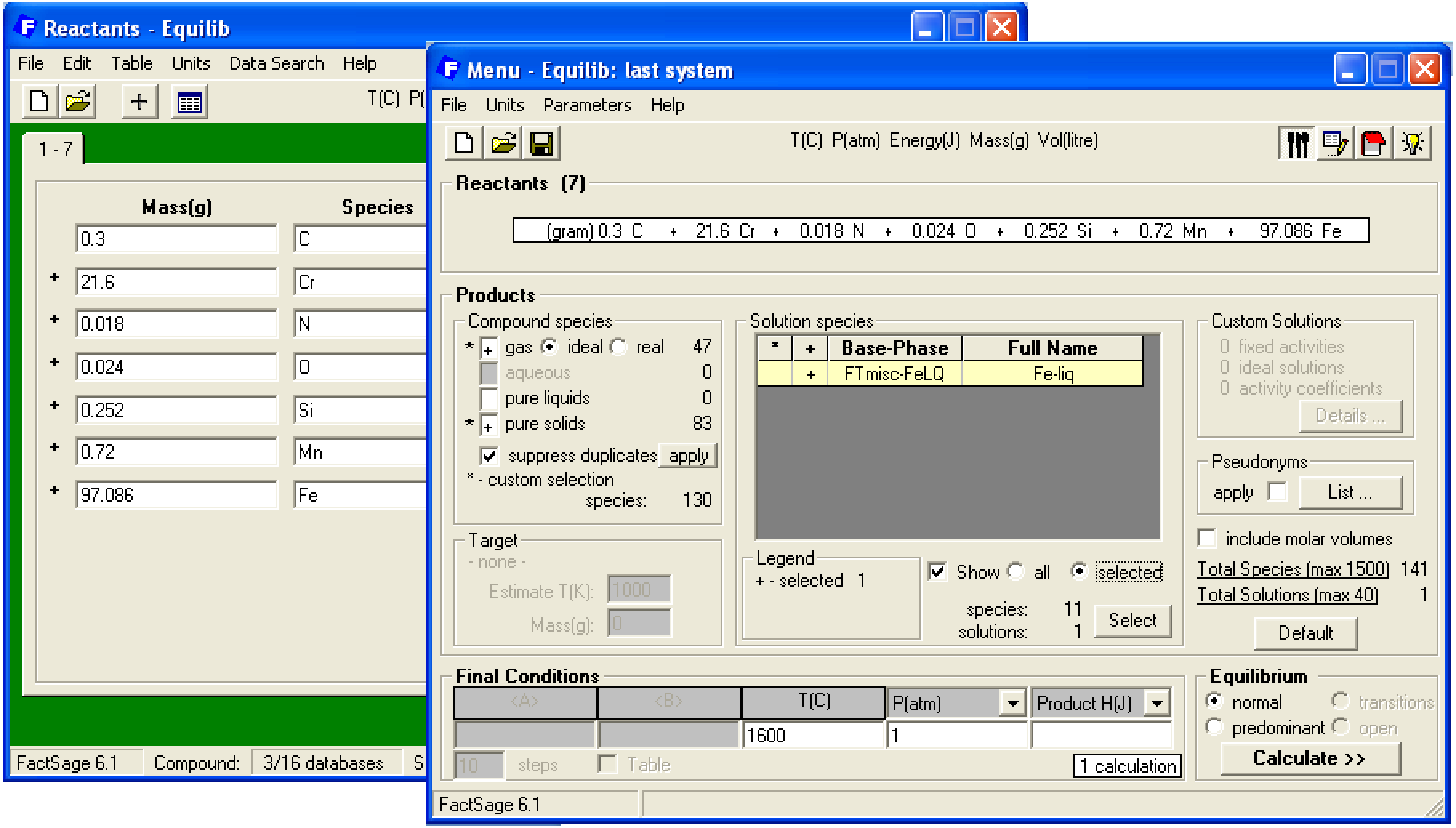
Result – liquid steel, slag, solid, gas formed

Take all of formed phase except gas phases for next step calculation

3. Calculate third step as done on second step

4 – 2 Calculation

Initial steel



Reactants - Equilib

	Mass(g)	Species
	0.3	C
+	21.6	Cr
+	0.018	N
+	0.024	O
+	0.252	Si
+	0.72	Mn
+	97.086	Fe

FactSage 6.1 Compound: 3/16 databases

Menu - Equilib: last system

Reactants (7)

(gram) 0.3 C + 21.6 Cr + 0.018 N + 0.024 O + 0.252 Si + 0.72 Mn + 97.086 Fe

Products

Compound species

- * ☐+ gas ● ideal ○ real 47
- ☐ aqueous 0
- ☐ pure liquids 0
- * ☐+ pure solids 83
- ☑ suppress duplicates apply
- * - custom selection
- species: 130

Solution species

*	+	Base-Phase	Full Name
	+	FTmisc-FeLQ	Fe-liq

Legend: + - selected 1

☑ Show ○ all ● selected

species: 11
solutions: 1
Select

Custom Solutions
0 fixed activities
0 ideal solutions
0 activity coefficients
Details ...

Pseudonyms: apply ☐ List ...

☐ include molar volumes

Total Species (max 1500) 141
Total Solutions (max 40) 1

Default

Target
- none -
Estimate T(K): 1000
Mass(g): 0

Final Conditions

<A>	<B>	T(C)	P(atm)	Product H(J)
		1600	1	

10 steps ☐ Table 1 calculation

Equilibrium

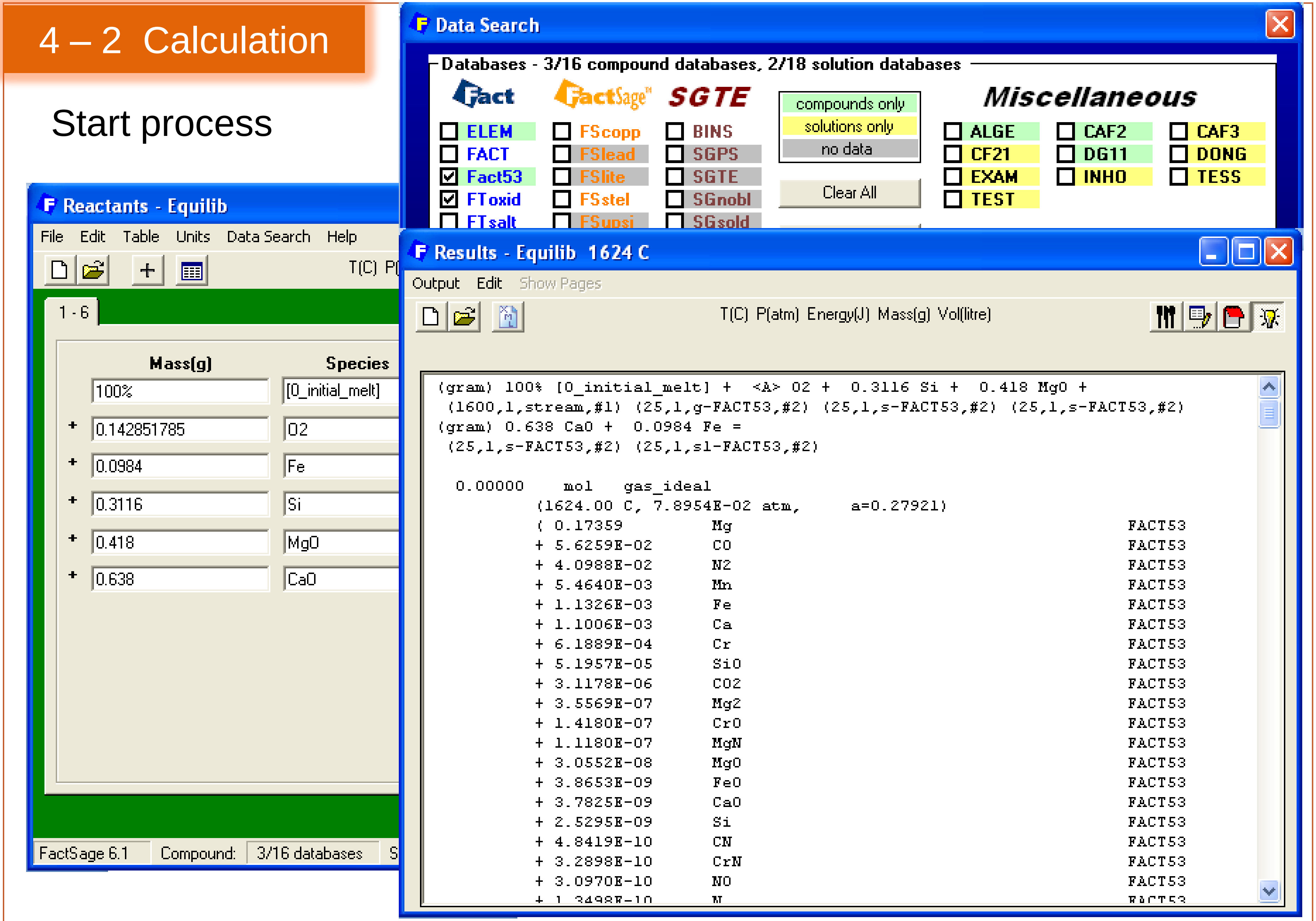
● normal ○ transitions
○ predominant ○ open

Calculate >>

FactSage 6.1

4 – 2 Calculation

Start process



Databases - 3/16 compound databases, 2/18 solution databases

☐ ELEM
☐ FACT
☑ Fact53
☑ FToxid
☐ FTsalt

☐ FScopp
☐ FSlead
☐ FSlite
☐ FSstel
☐ FSupsi

☐ BINS
☐ SGPS
☐ SGTE
☐ SGnobl
☐ SGsold

☐ ALGE
☐ CF21
☐ EXAM
☐ TEST

☐ CAF2
☐ DG11
☐ INHO

☐ CAF3
☐ DONG
☐ TESS

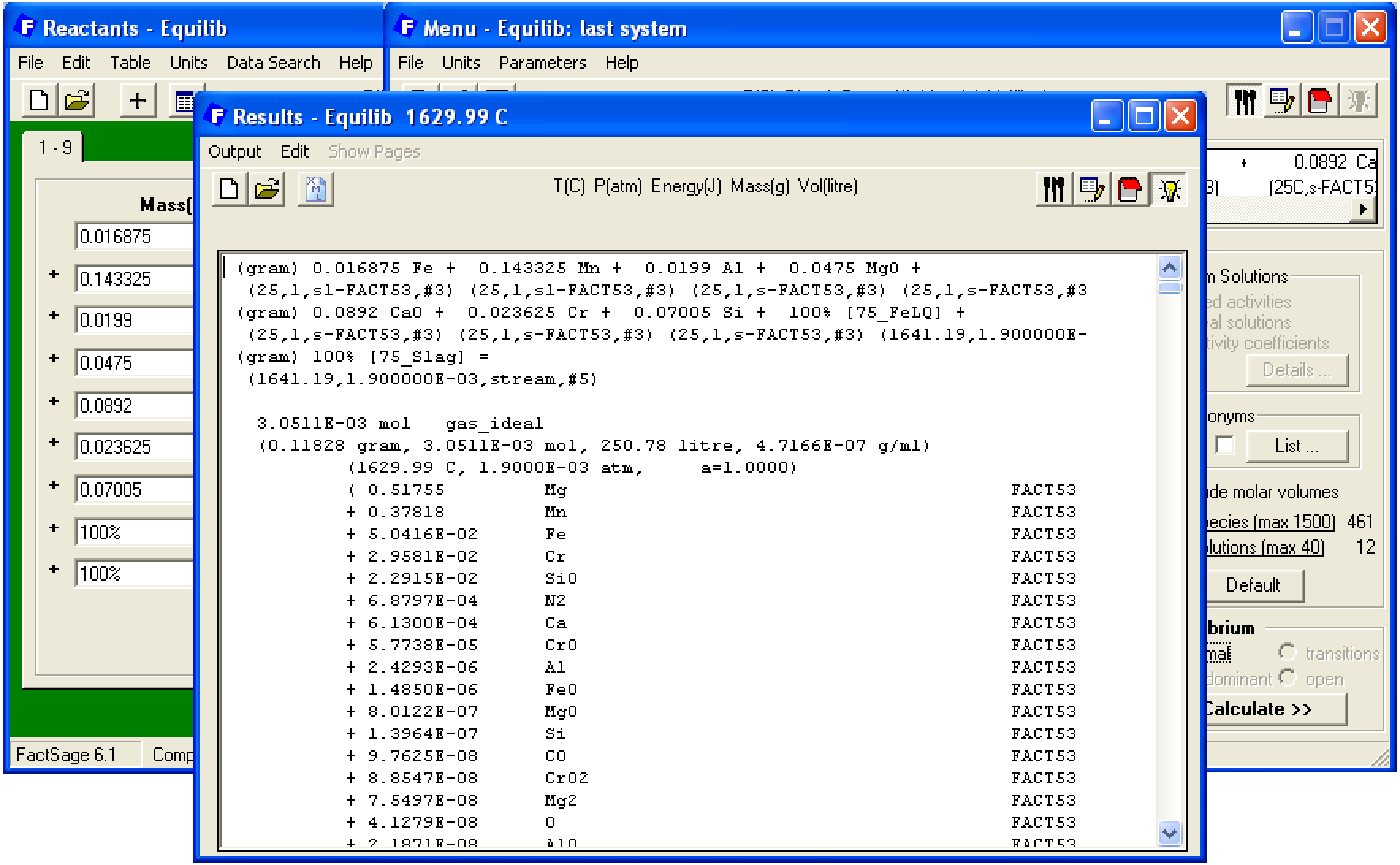
	Mass(g)	Species
	100%	[0_initial_melt]
+	0.142851785	O2
+	0.0984	Fe
+	0.3116	Si
+	0.418	MgO
+	0.638	CaO

```
(gram) 100% [0_initial_melt] +  <A> O2 +  0.3116 Si +  0.418 MgO +
 (1600,1,stream,#1) (25,1,g-FACT53,#2) (25,1,s-FACT53,#2) (25,1,s-FACT53,#2)
(gram) 0.638 CaO +  0.0984 Fe =
 (25,1,s-FACT53,#2) (25,1,sl-FACT53,#2)

  0.00000    mol   gas_ideal
          (1624.00 C, 7.8954E-02 atm,     a=0.27921)
          ( 0.17359        Mg                                         FACT53
          + 5.6259E-02     CO                                         FACT53
          + 4.0988E-02     N2                                         FACT53
          + 5.4640E-03     Mn                                         FACT53
          + 1.1326E-03     Fe                                         FACT53
          + 1.1006E-03     Ca                                         FACT53
          + 6.1889E-04     Cr                                         FACT53
          + 5.1957E-05     SiO                                        FACT53
          + 3.1178E-06     CO2                                        FACT53
          + 3.5569E-07     Mg2                                        FACT53
          + 1.4180E-07     CrO                                        FACT53
          + 1.1180E-07     MgN                                        FACT53
          + 3.0552E-08     MgO                                        FACT53
          + 3.8653E-09     FeO                                        FACT53
          + 3.7825E-09     CaO                                        FACT53
          + 2.5295E-09     Si                                         FACT53
          + 4.8419E-10     CN                                         FACT53
          + 3.2898E-10     CrN                                        FACT53
          + 3.0970E-10     NO                                         FACT53
          + 1.3498E-10     N                                          FACT53
```

4 – 2 Calculation

End of calculation



0.016875
+ 0.143325
+ 0.0199
+ 0.0475
+ 0.0892
+ 0.023625
+ 0.07005
+ 100%
+ 100%

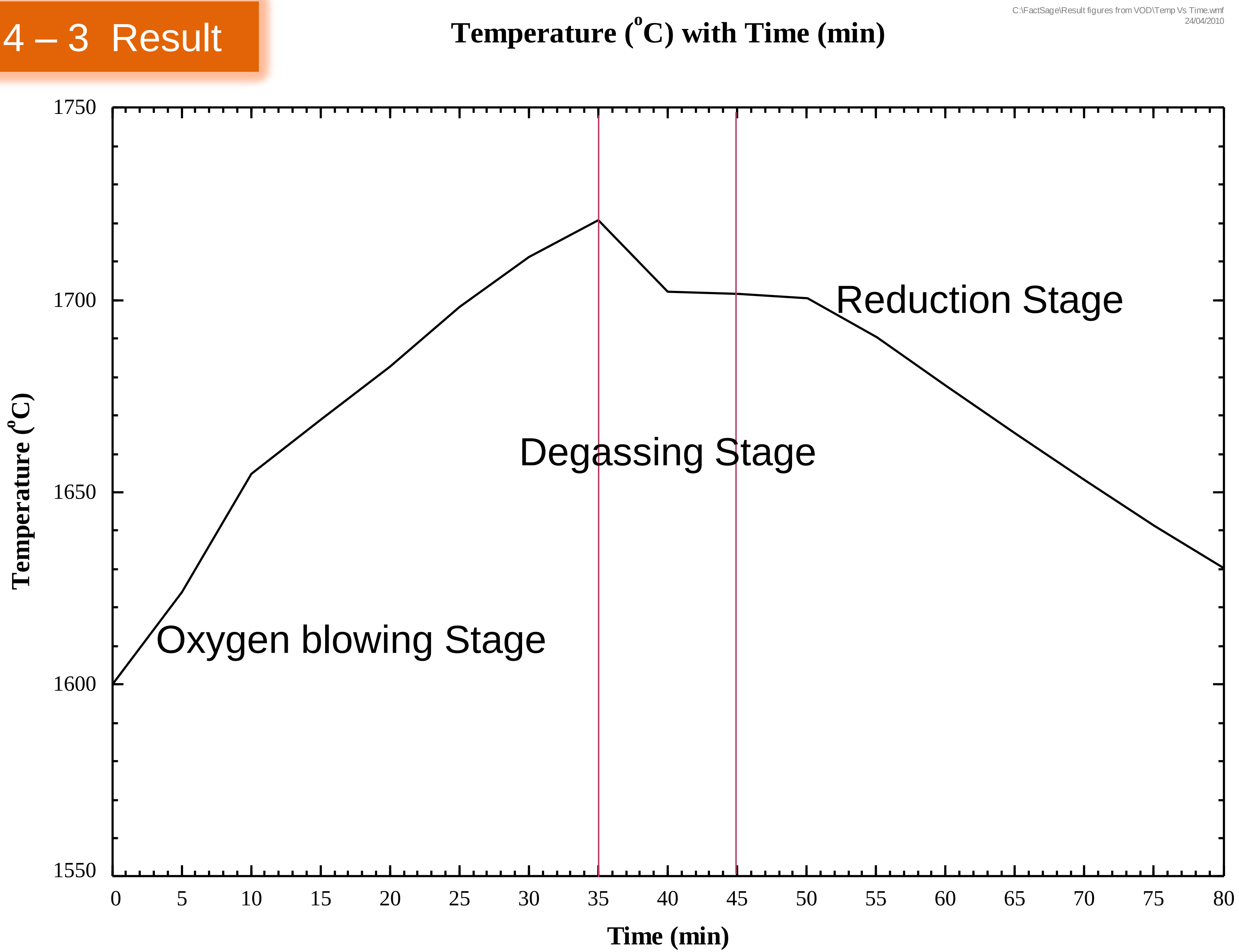
```
(gram) 0.016875 Fe +  0.143325 Mn +  0.0199 Al +  0.0475 MgO +
 (25,1,sl-FACT53,#3) (25,1,sl-FACT53,#3) (25,1,s-FACT53,#3) (25,1,s-FACT53,#3
(gram) 0.0892 CaO +  0.023625 Cr +  0.07005 Si +  100% [75_FeLQ] +
 (25,1,s-FACT53,#3) (25,1,s-FACT53,#3) (25,1,s-FACT53,#3) (1641.19,1.900000E-
(gram) 100% [75_Slag] =
 (1641.19,1.900000E-03,stream,#5)

  3.0511E-03 mol   gas_ideal
  (0.11828 gram, 3.0511E-03 mol, 250.78 litre, 4.7166E-07 g/ml)
         (1629.99 C, 1.9000E-03 atm,     a=1.0000)
         ( 0.51755         Mg                                   FACT53
         + 0.37818         Mn                                   FACT53
         + 5.0416E-02      Fe                                   FACT53
         + 2.9581E-02      Cr                                   FACT53
         + 2.2915E-02      SiO                                  FACT53
         + 6.8797E-04      N2                                   FACT53
         + 6.1300E-04      Ca                                   FACT53
         + 5.7738E-05      CrO                                  FACT53
         + 2.4293E-06      Al                                   FACT53
         + 1.4850E-06      FeO                                  FACT53
         + 8.0122E-07      MgO                                  FACT53
         + 1.3964E-07      Si                                   FACT53
         + 9.7625E-08      CO                                   FACT53
         + 8.8547E-08      CrO2                                 FACT53
         + 7.5497E-08      Mg2                                  FACT53
         + 4.1279E-08      O                                    FACT53
         + 2.1871E-08      AlO                                  FACT53
```

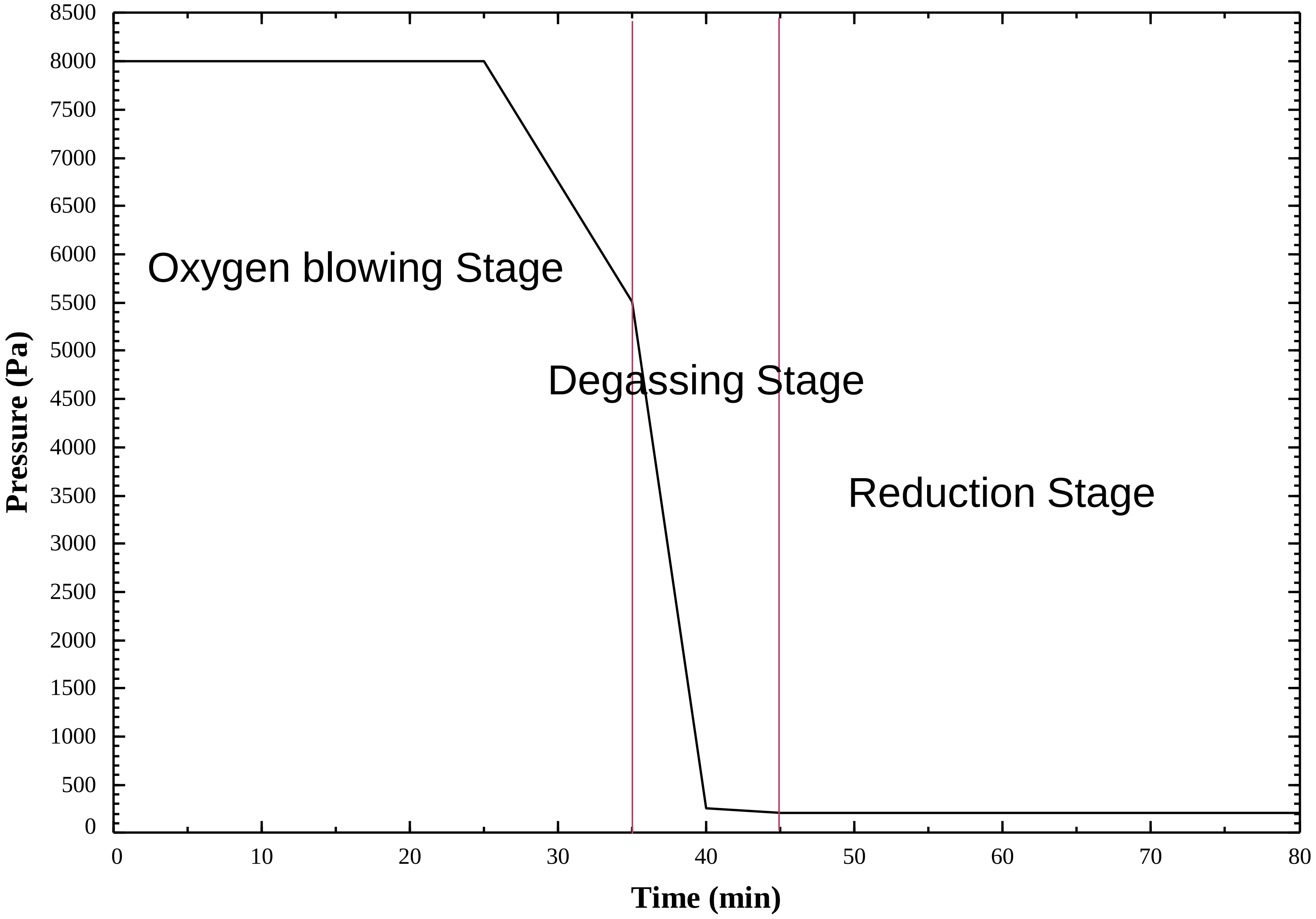
Result

Vacuum, Temperature, Reacted oxygen

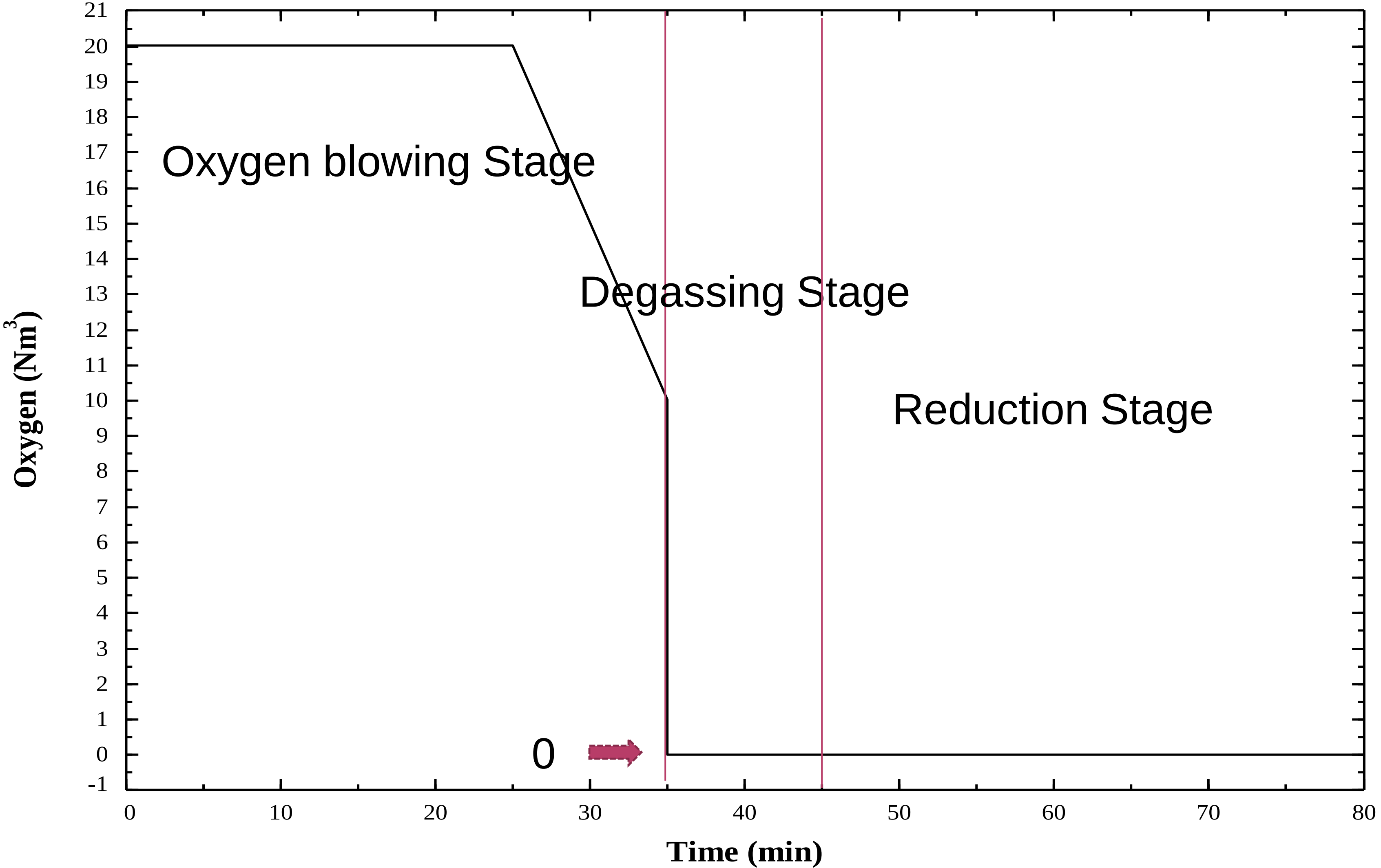
4 – 3 Result


C:\FactSage\Result figures from VOD\Temp Vs Time.wmf
24/04/2010
Temperature (°C) with Time (min)
Temperature (°C)
1750
1700
1650
1600
1550
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
Time (min)
Oxygen blowing Stage
Degassing Stage
Reduction Stage

Pressure (Pa)


Pressure (Pa)
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
80
Time (min)
Oxygen blowing Stage
Degassing Stage
Reduction Stage

Reacted Oxygen (shows blowing oxygen ratio)

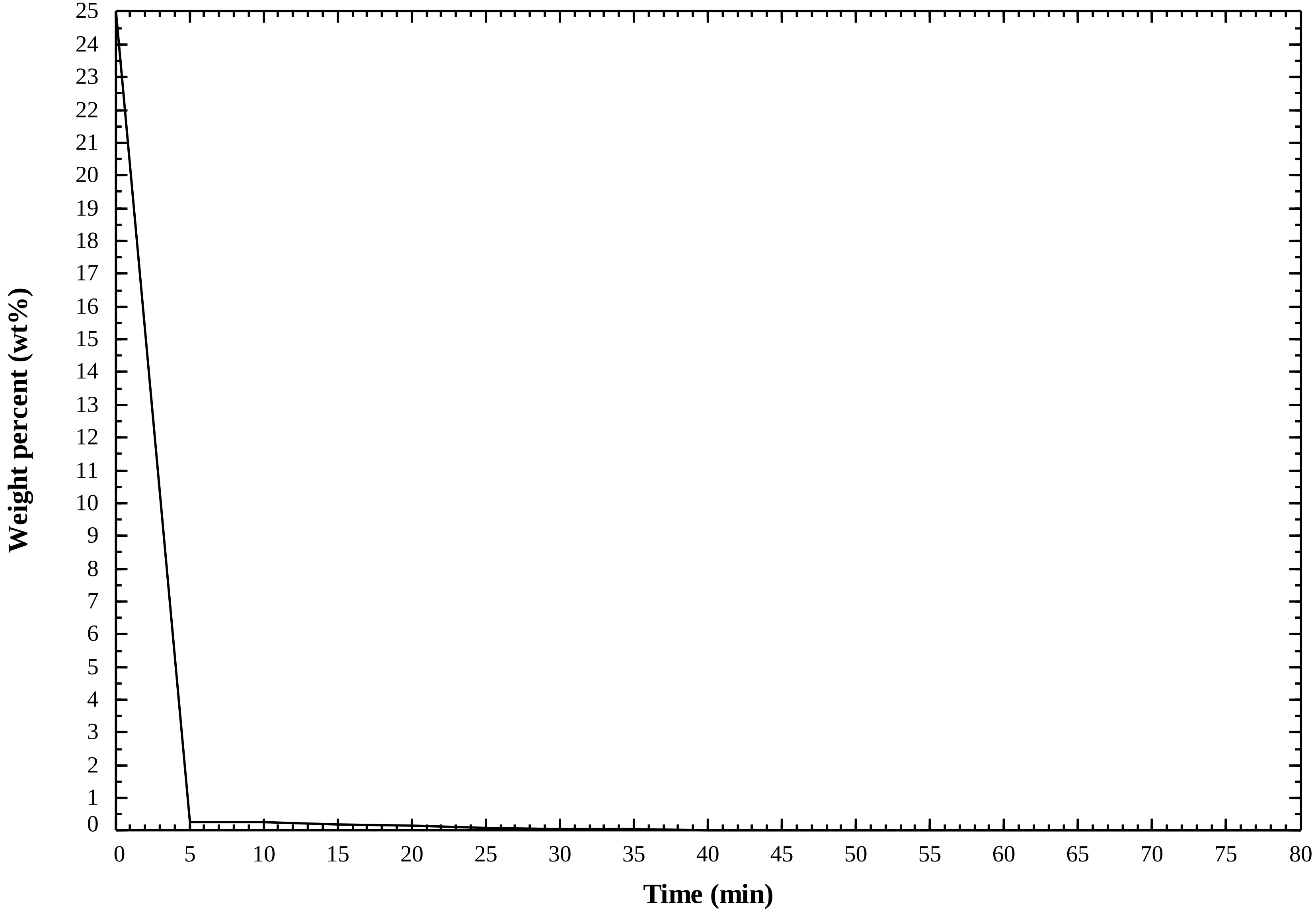


Result

Liquid steel composition

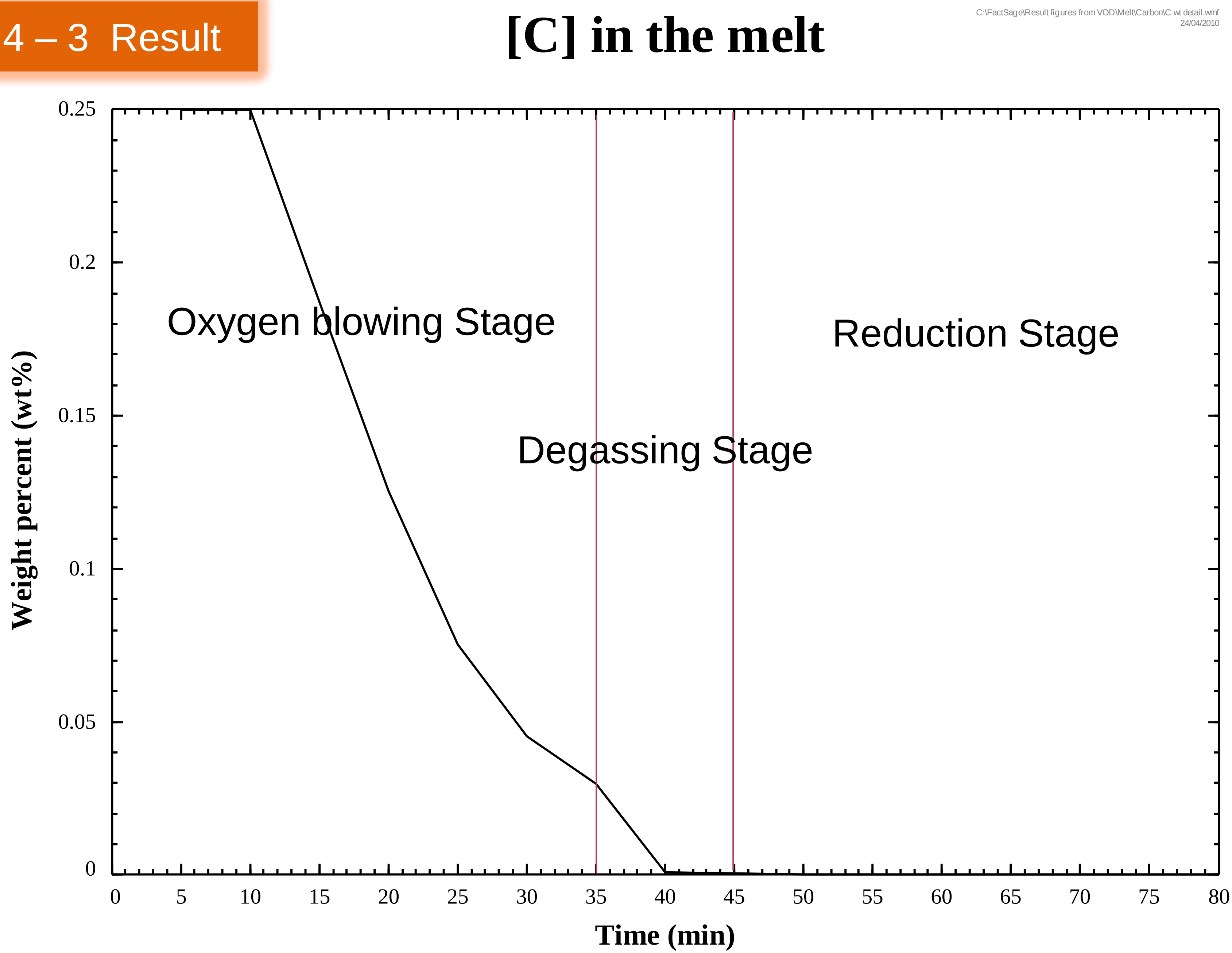
4 – 3 Result

[C] contents in the melt



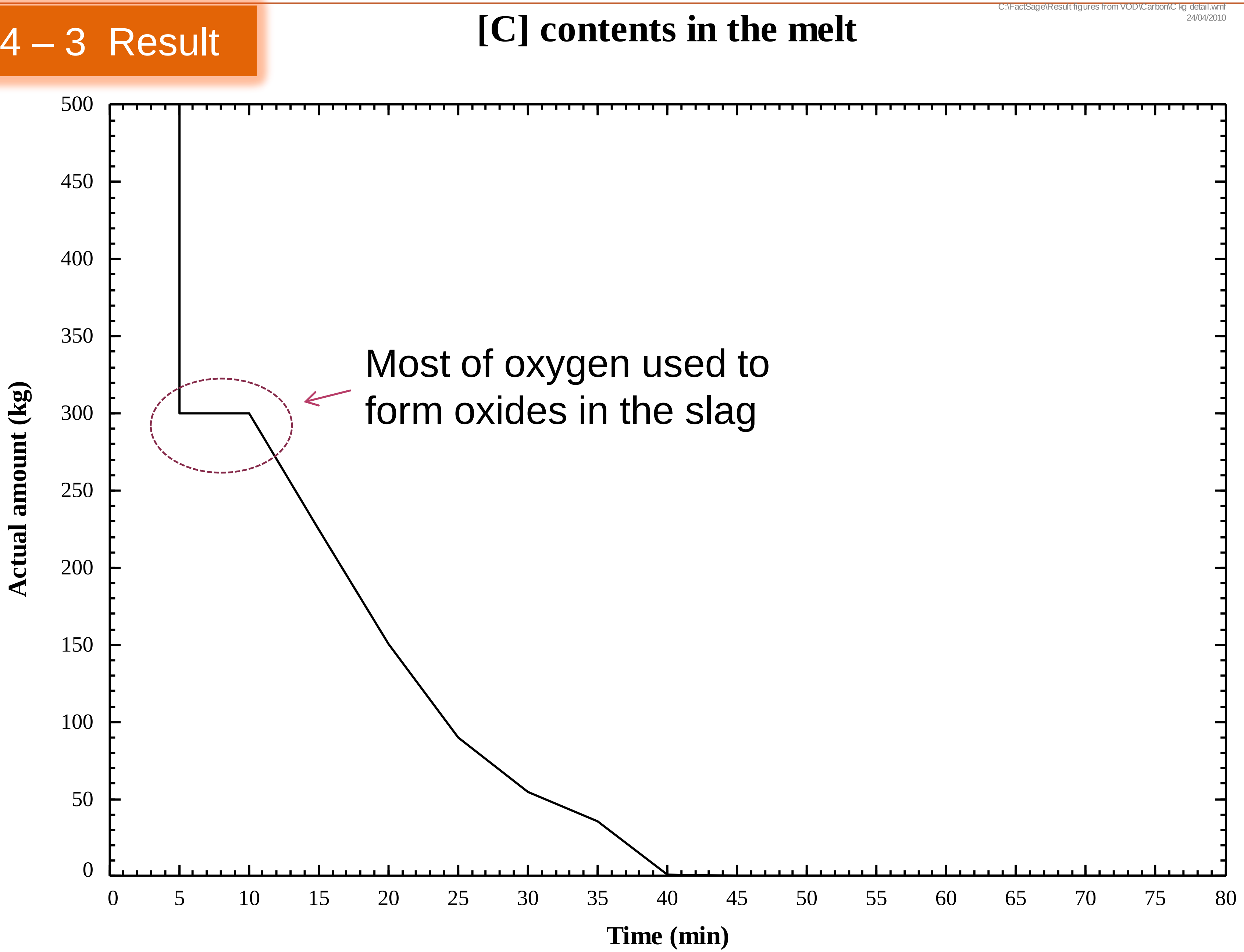
4 – 3 Result

[C] in the melt



4 – 3 Result

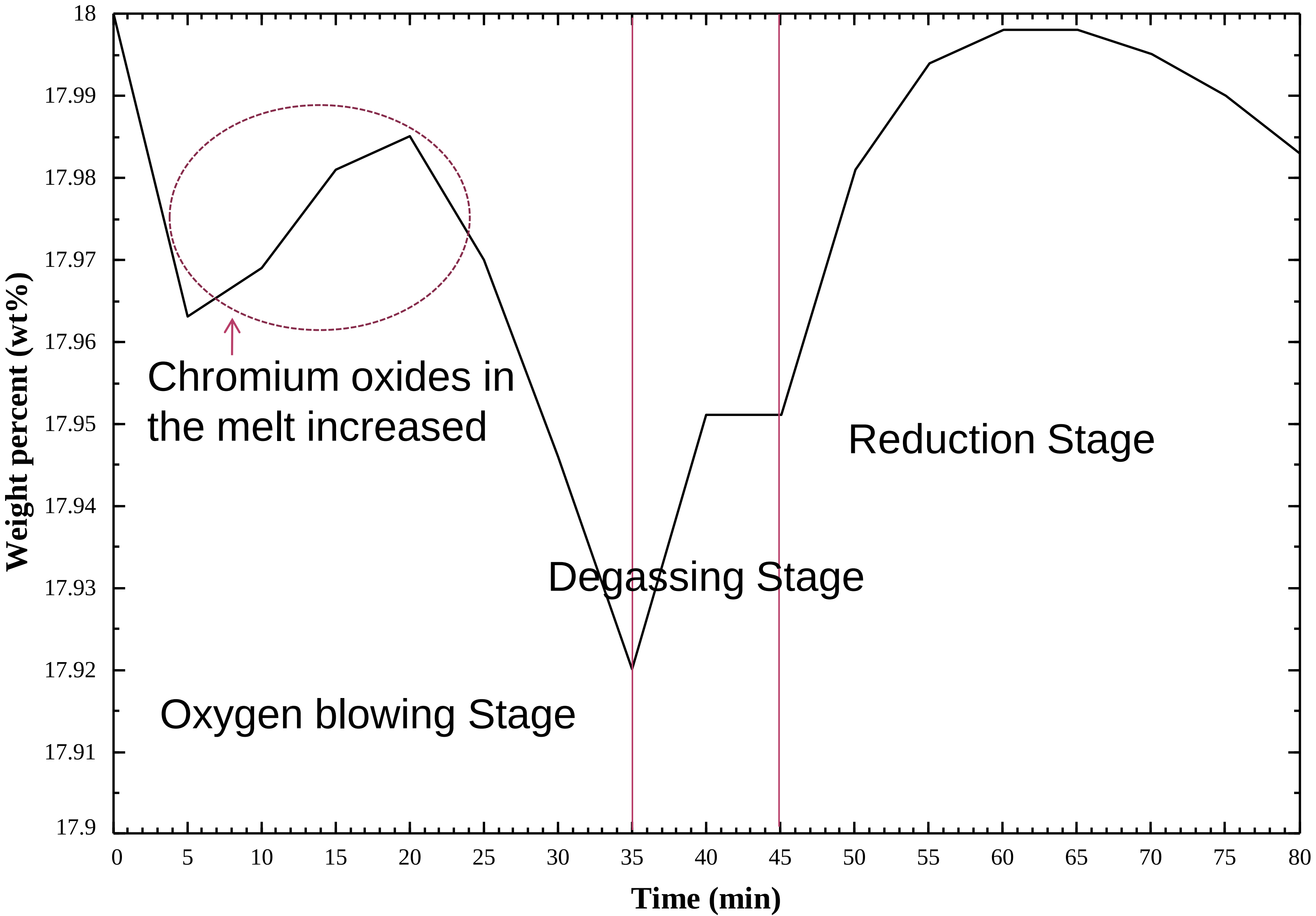
[C] contents in the melt



Most of oxygen used to form oxides in the slag

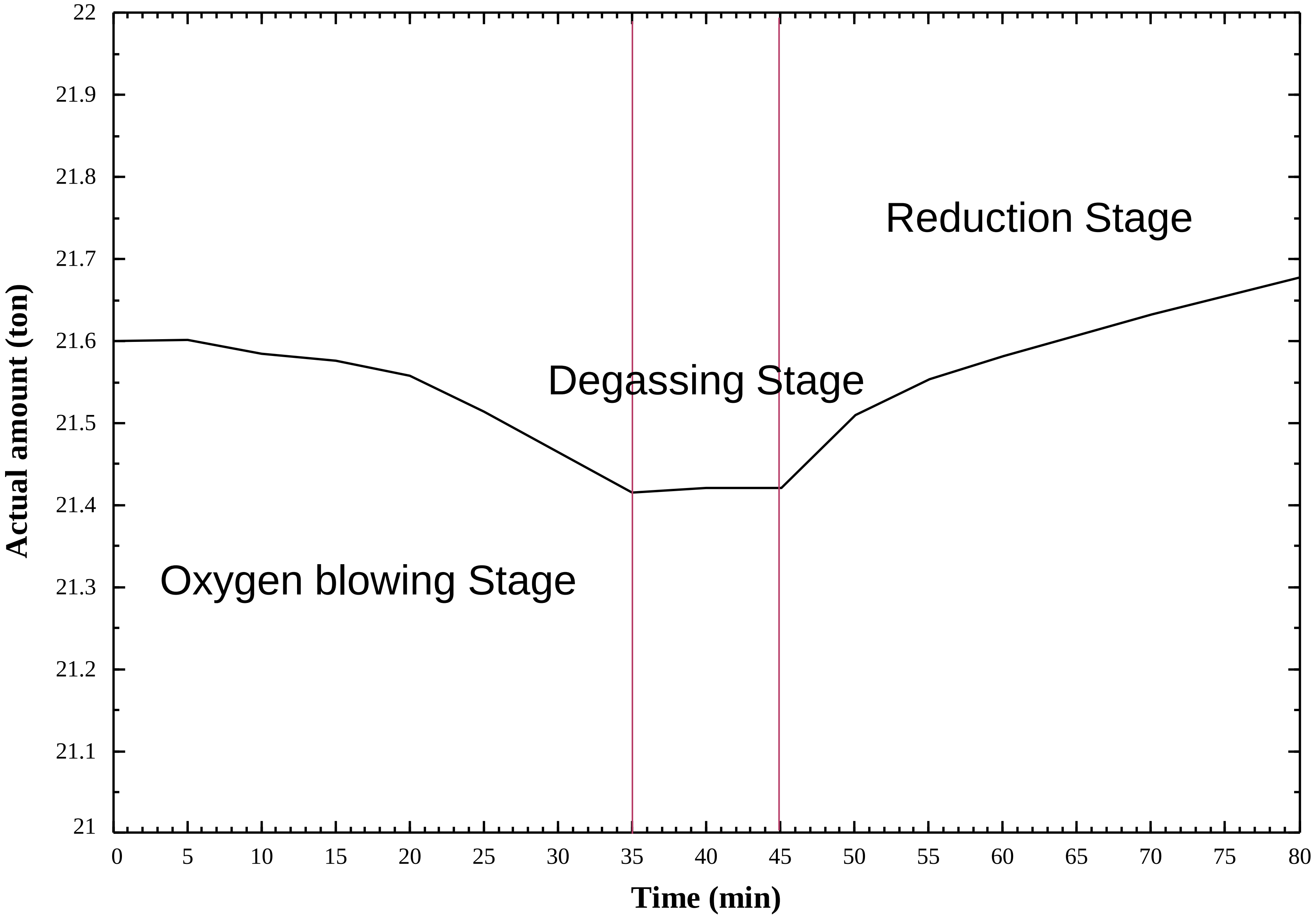
[Cr] in the melt

C:\FactSage\Result figures from VOD\Melt\Chromium\Cr wt.wmf
24/04/2010



Chromium oxides in the melt increased

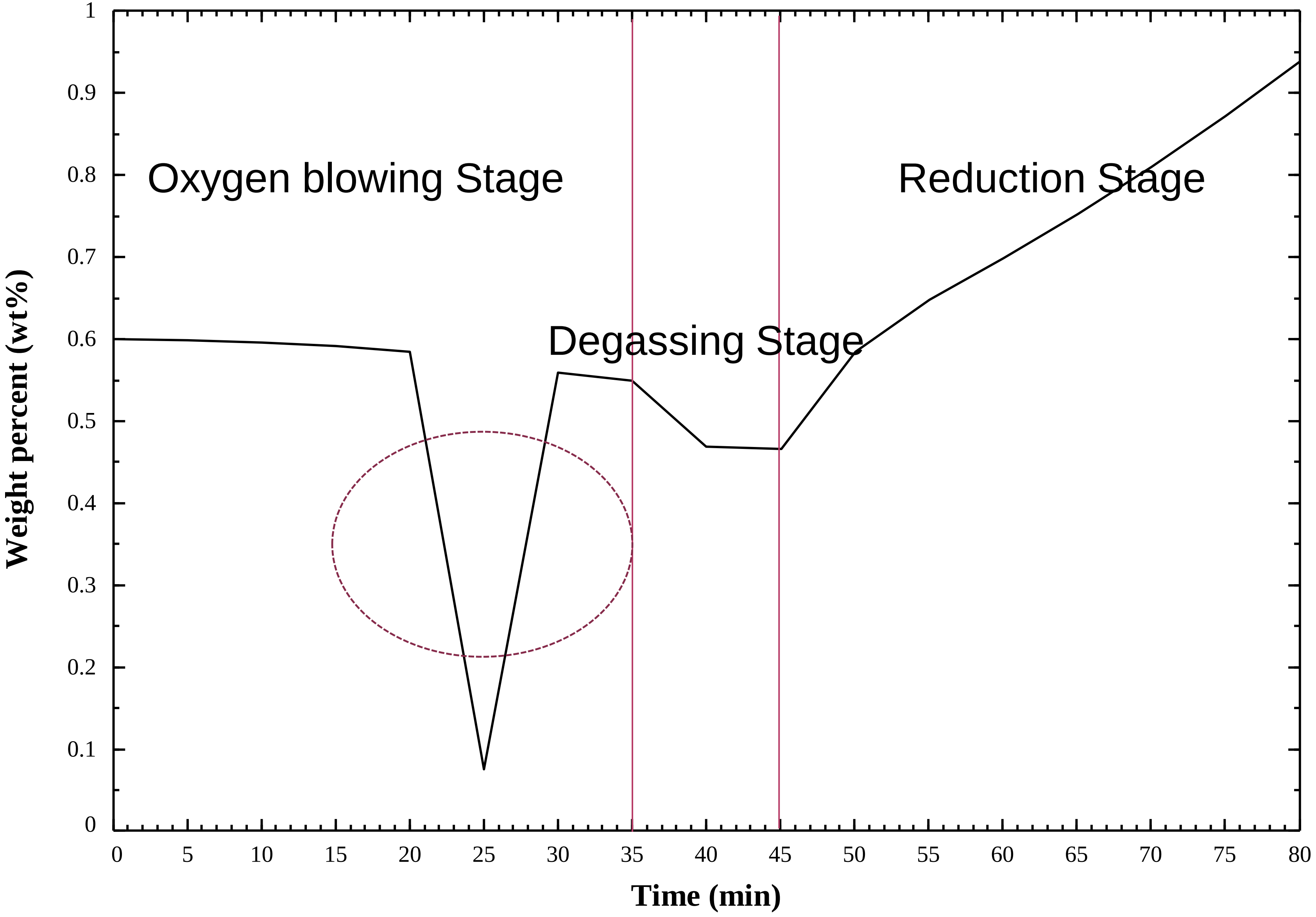
[Cr] in the melt



4 – 3 Result

[Mn] in the melt

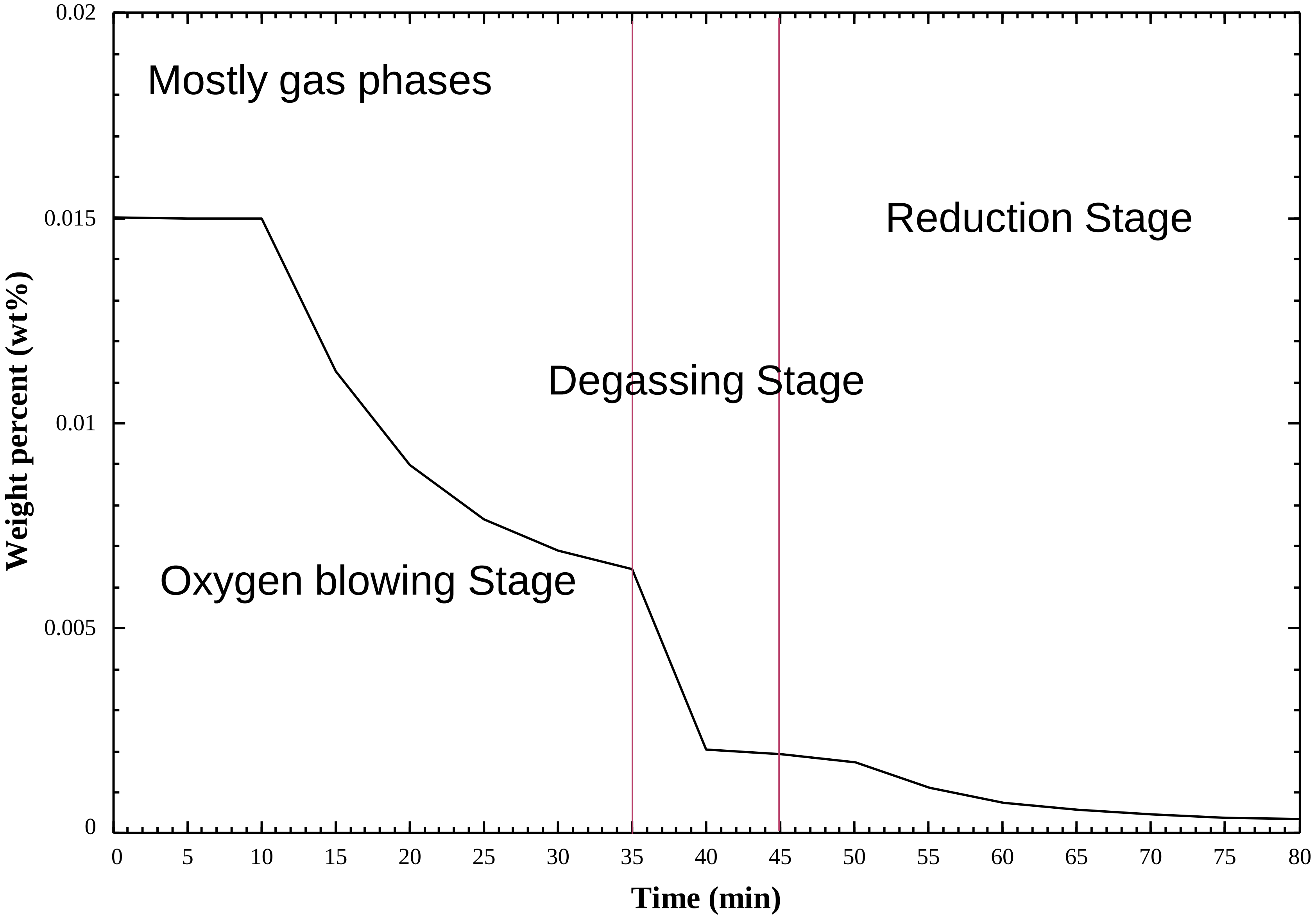
C:\FactSage\Result figures from VOD\Melt\Manganese\Mn wt.wmf
24/04/2010



4 – 3 Result

[N] in the melt

C:\FactSage\Result figures from VOD\Melt\Nitrogen\N wt.wmf
24/04/2010



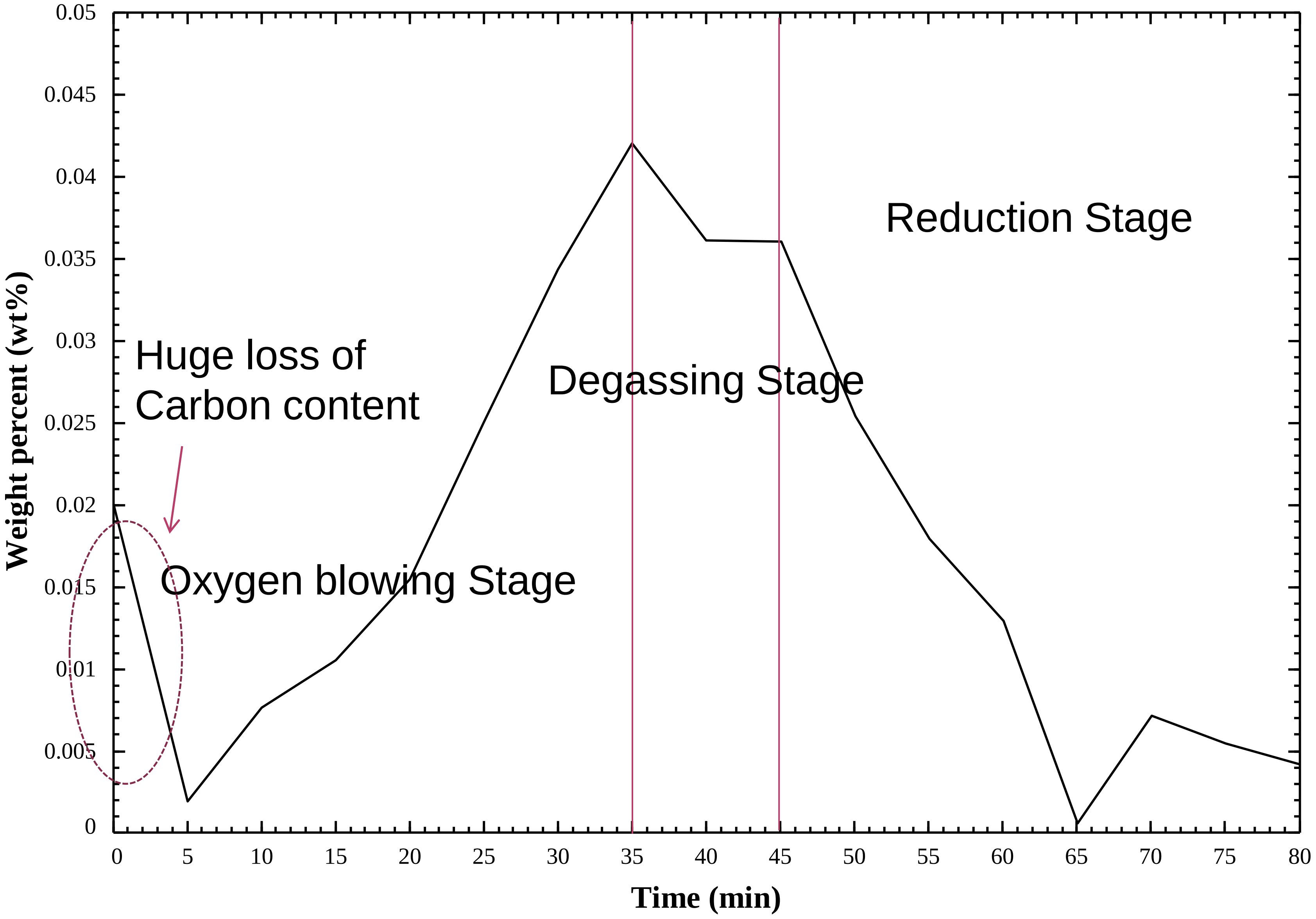
Mostly gas phases

Reduction Stage

Degassing Stage

Oxygen blowing Stage

[O] in the melt



Huge loss of Carbon content

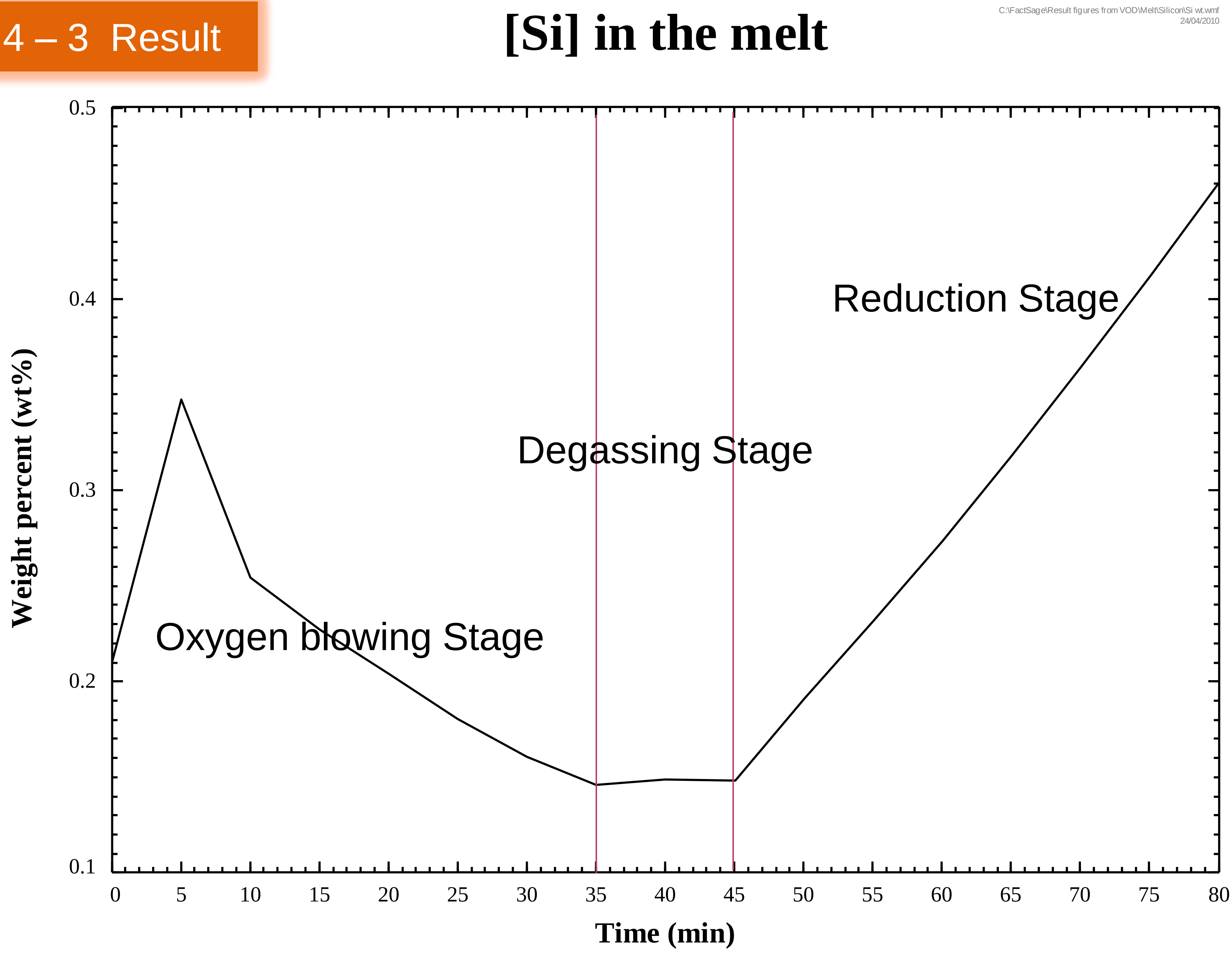
Oxygen blowing Stage

Degassing Stage

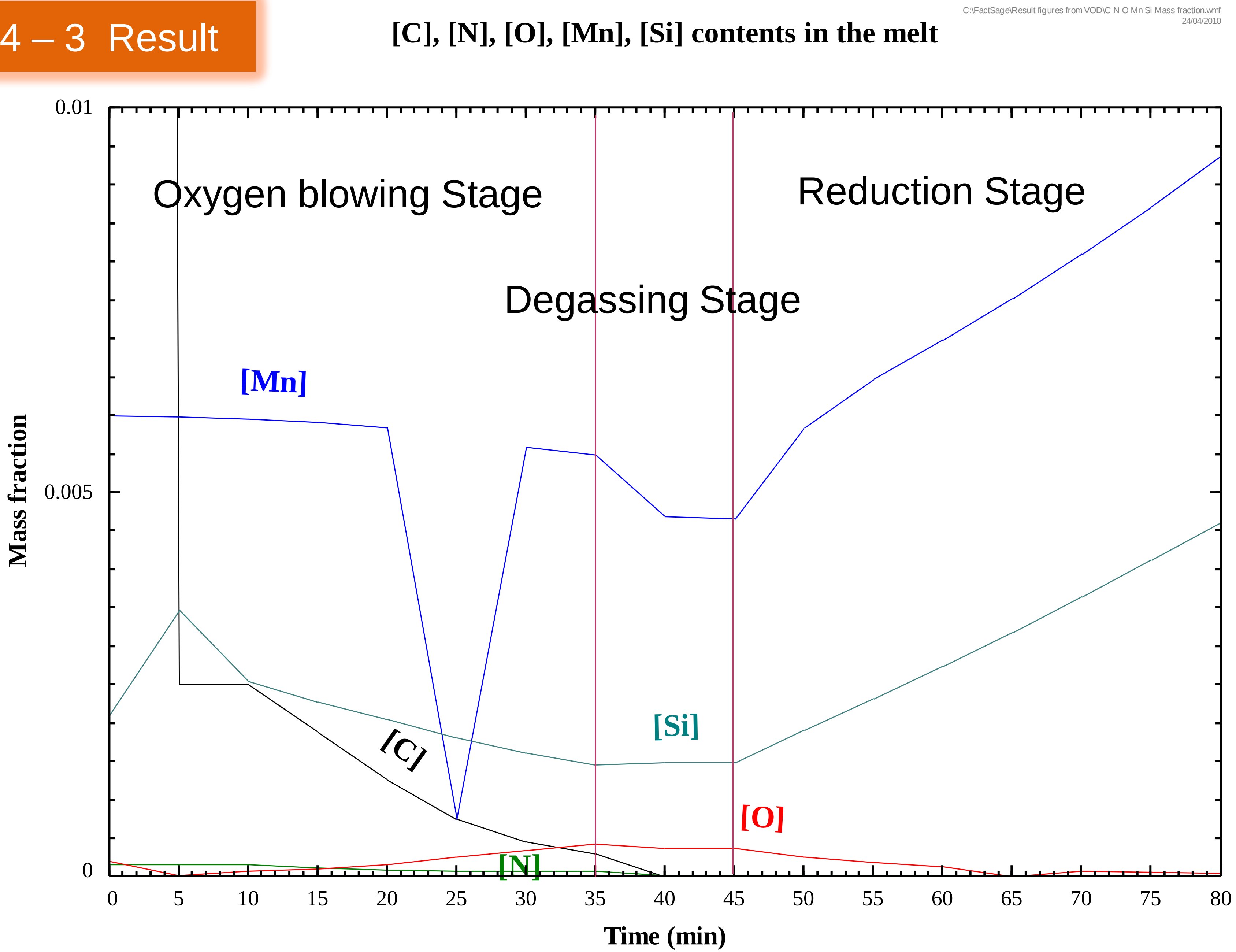
Reduction Stage

4 – 3 Result

[Si] in the melt



4 – 3 Result



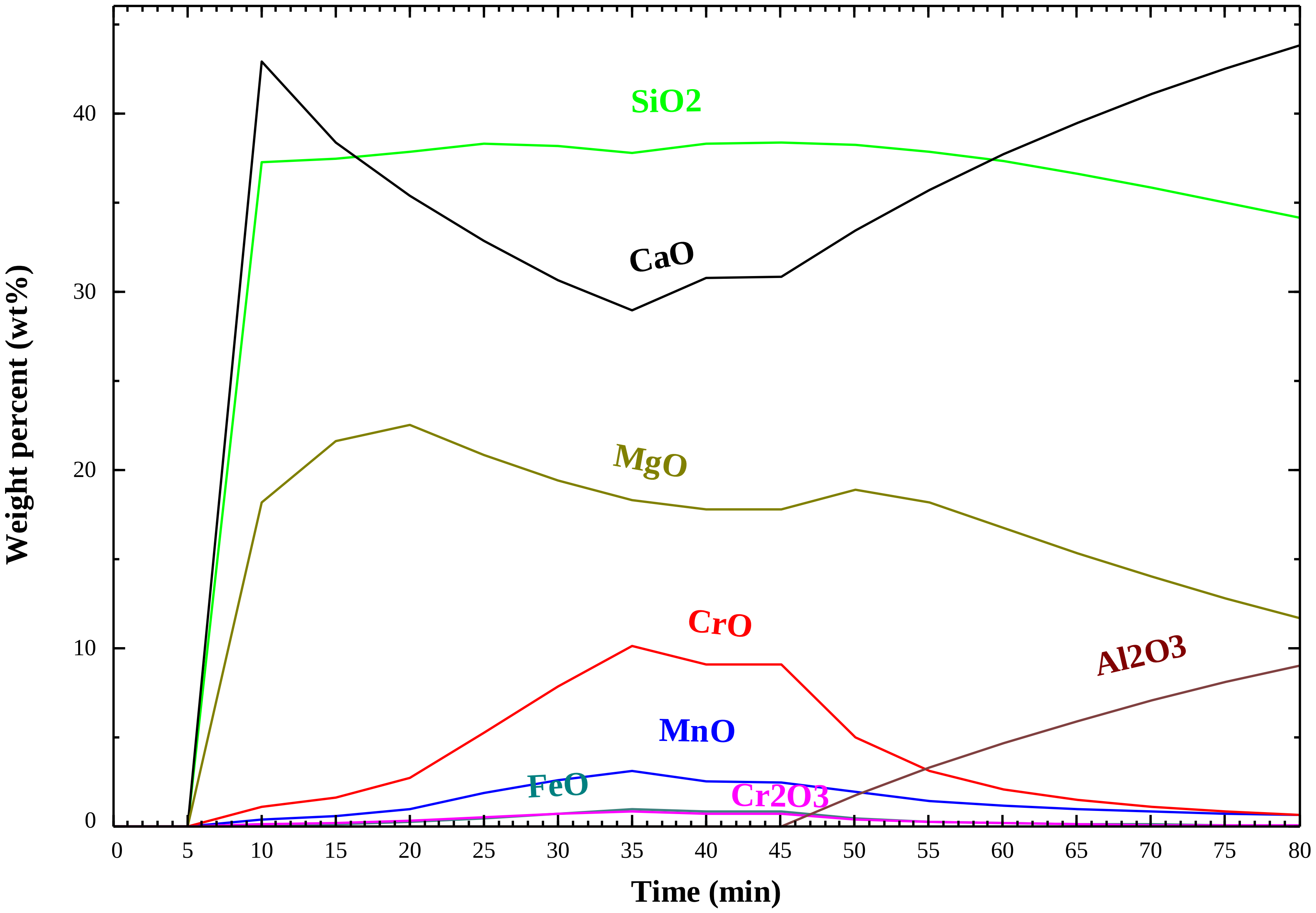
[C], [N], [O], [Mn], [Si] contents in the melt

Result

Slag composition

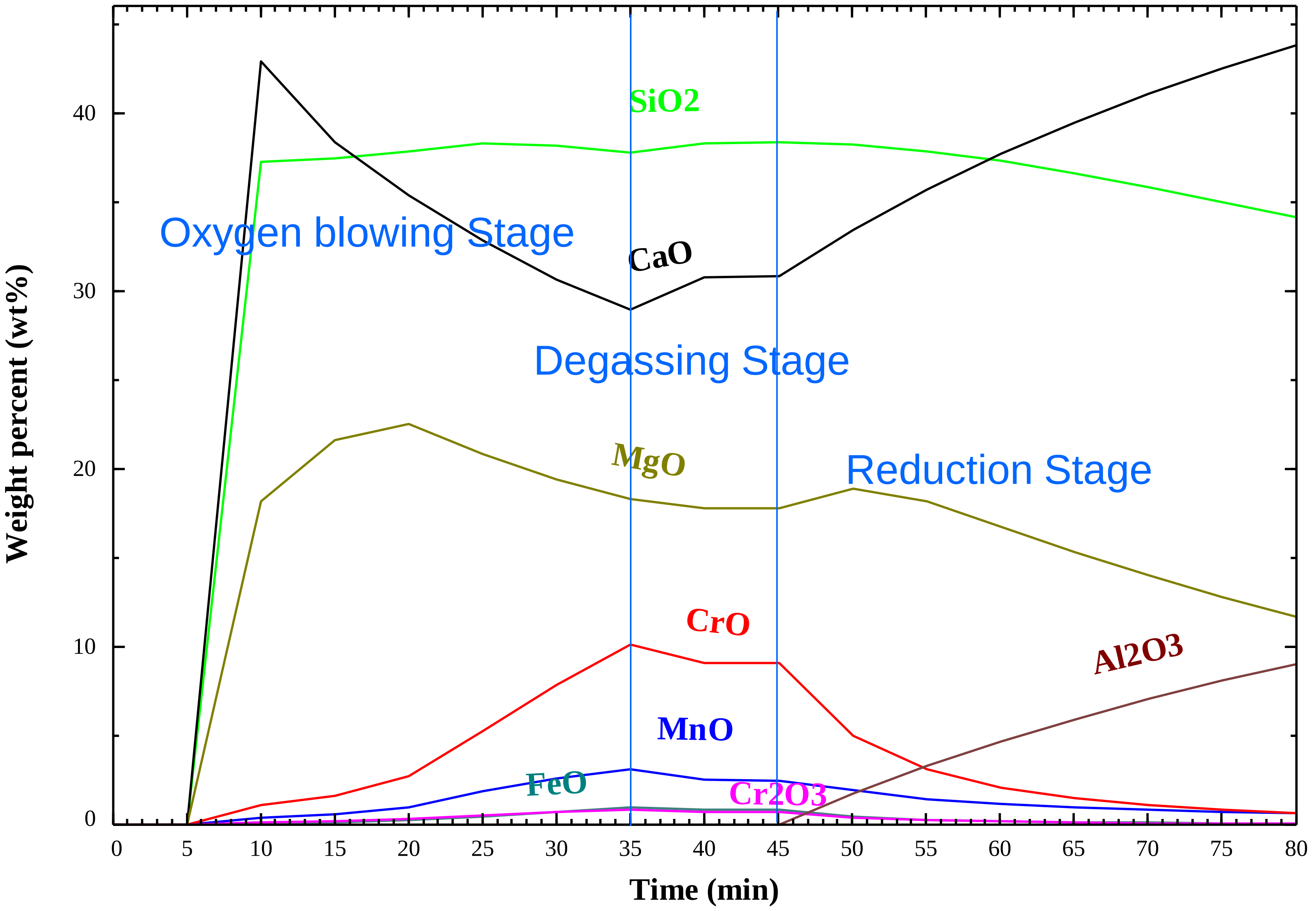
Slag composition

C:\FactSage\Result figures from VOD\Slag\Slag compo.wmf
24/04/2010



Slag composition

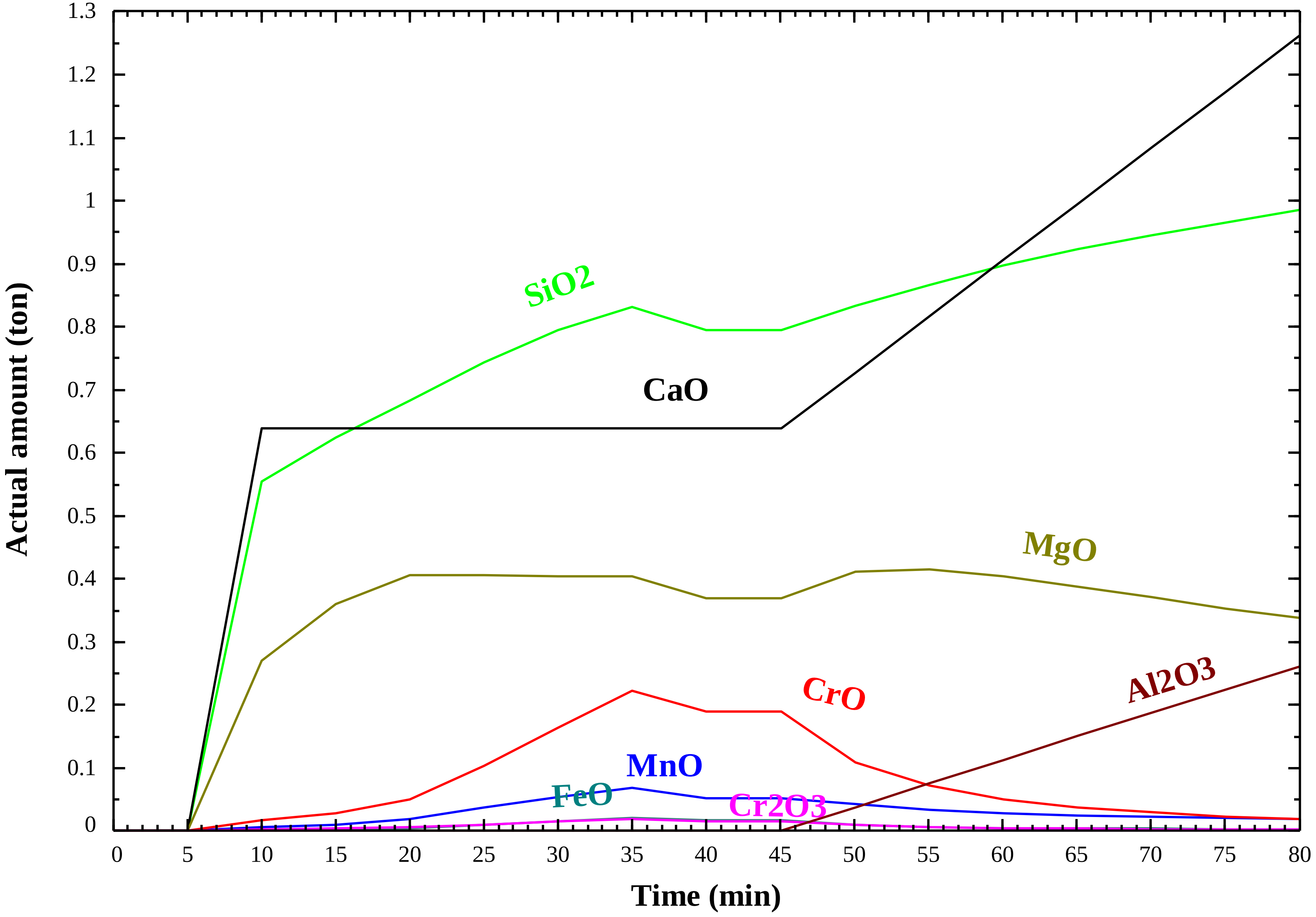
C:\FactSage\Result figures from VOD\Slag\Slag compo.wmf
24/04/2010



4 – 3 Result

Slag amount (ton)

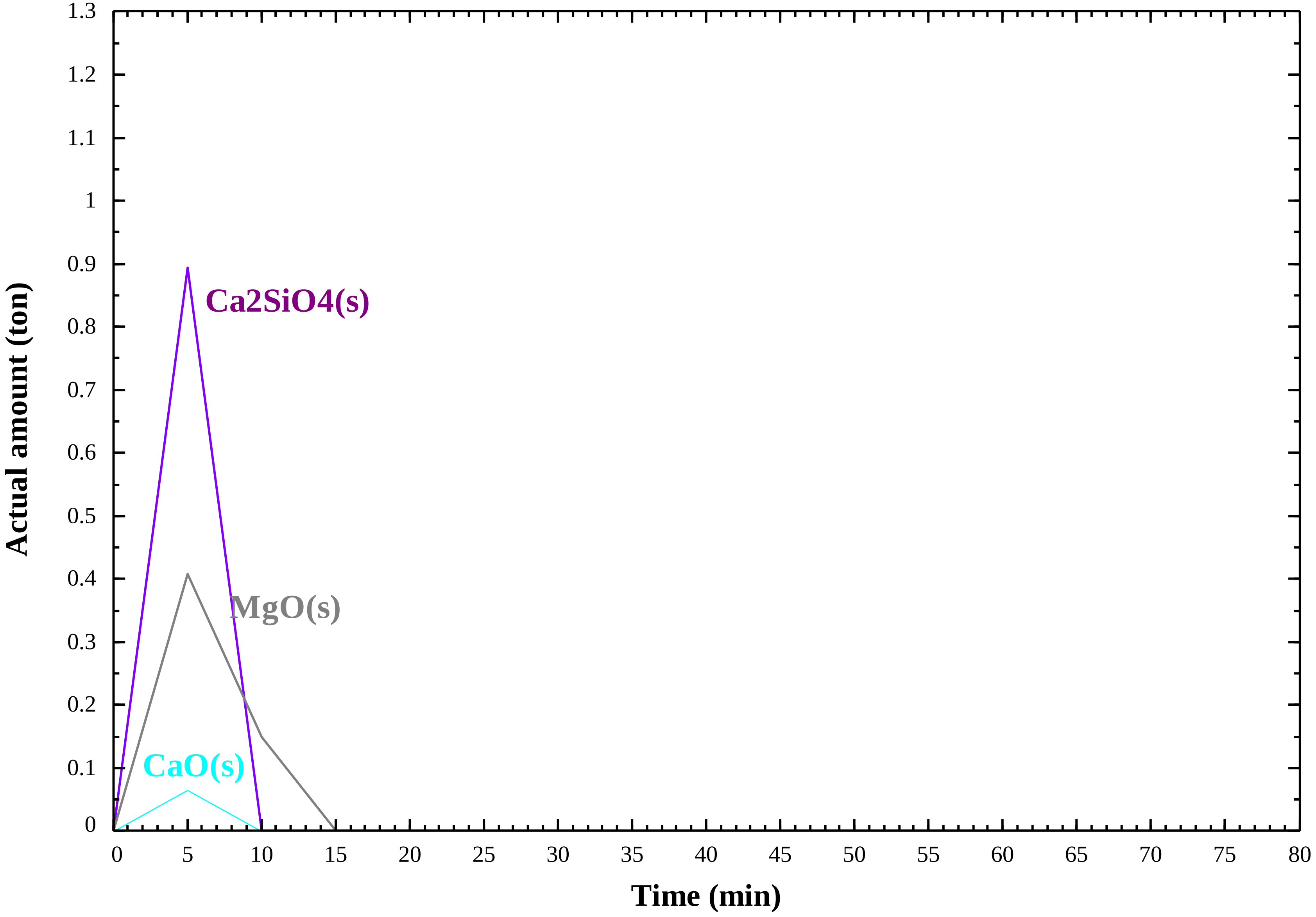
C:\FactSage\Result figures from VOD\Slag\Slag amount ton.wmf
24/04/2010



4 – 3 Result

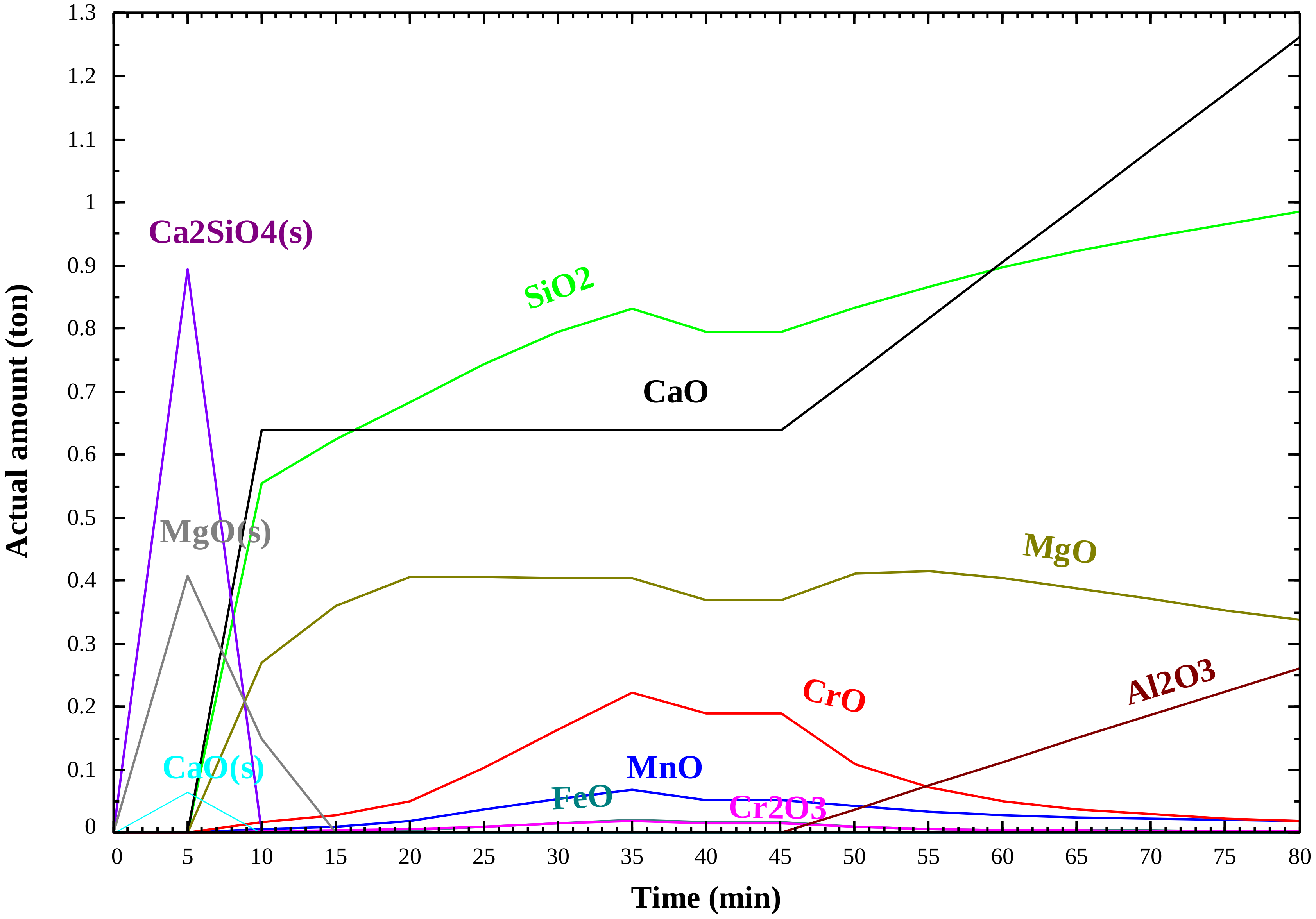
Solid phases (ton)

C:\FactSage\Result figures from VOD\Slag\Solid phases.wmf
24/04/2010



Slag amount and Solid phases

C:\FactSage\Result figures from VOD\Slag\Slag amount and Solid phases.wmf
24/04/2010



4 – 3 Result

Slag composition from ALZ

11.6 ±1.1 MgO
43.5 ±2.9 CaO
6.1 ±0.4 Al2O3
1.8 ±0.6 Cr2O3
1.4 ±0.5 MnO
0.6 ±0.4 FeO
35.0 ±1.6 SiO2

Slag composition from calculation

+ 11.694 wt.% MgO
+ 43.770 wt.% CaO
+ 9.0111 wt.% Al2O3
+ 5.8075E-02 wt.% Cr2O3
+ 0.64123 wt.% MnO
+ 6.6040E-02 wt.% FeO
+ 34.133 wt.% SiO2

Almost same for Slag basicity, MgO saturation

Less Cr2O3, FeO amount

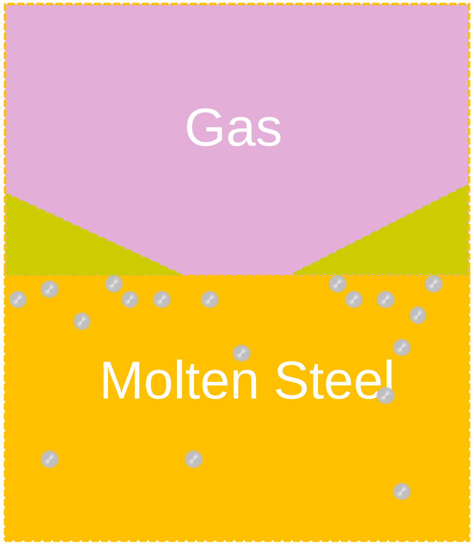
5. Optimization for the gas reaction

Consider about gas equilibrium with melt

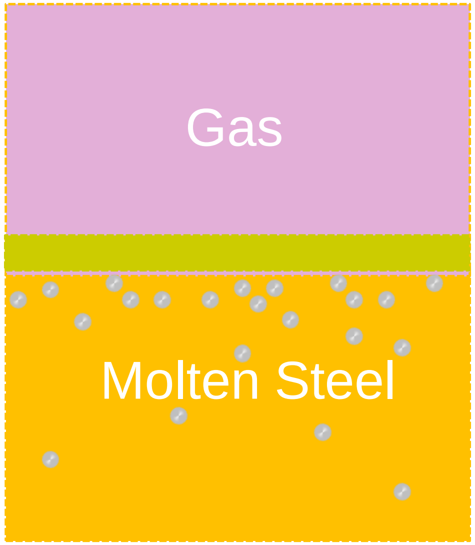
- Comparison for the whole ‘oxygen blowing stage’
- Comparison for the whole ‘reduction stage’

Purpose

Because in reality, there are a lot of gas bubbles in the melt so some of the portions of gas phase should be take into account for the calculation

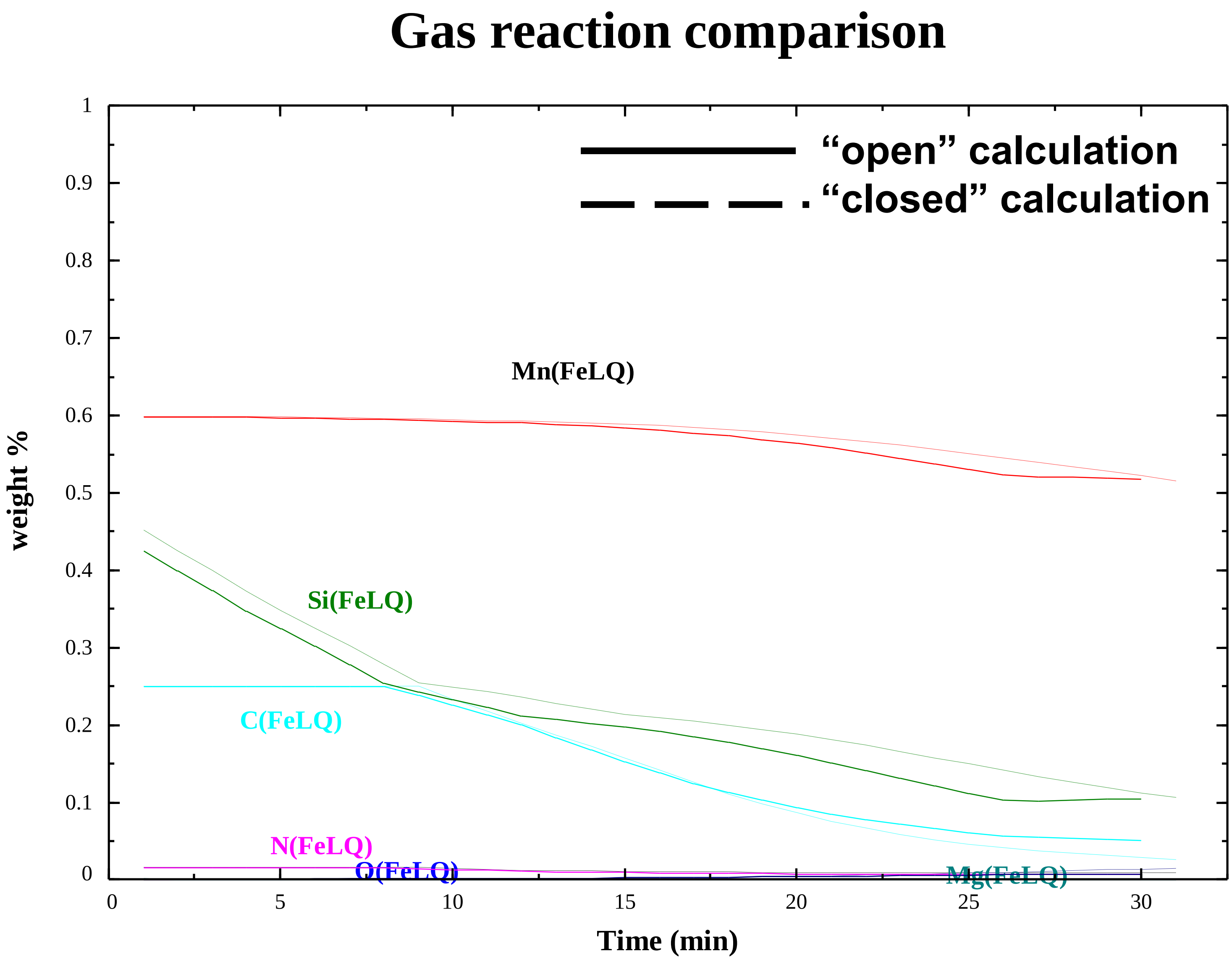


Oxygen blowing stage



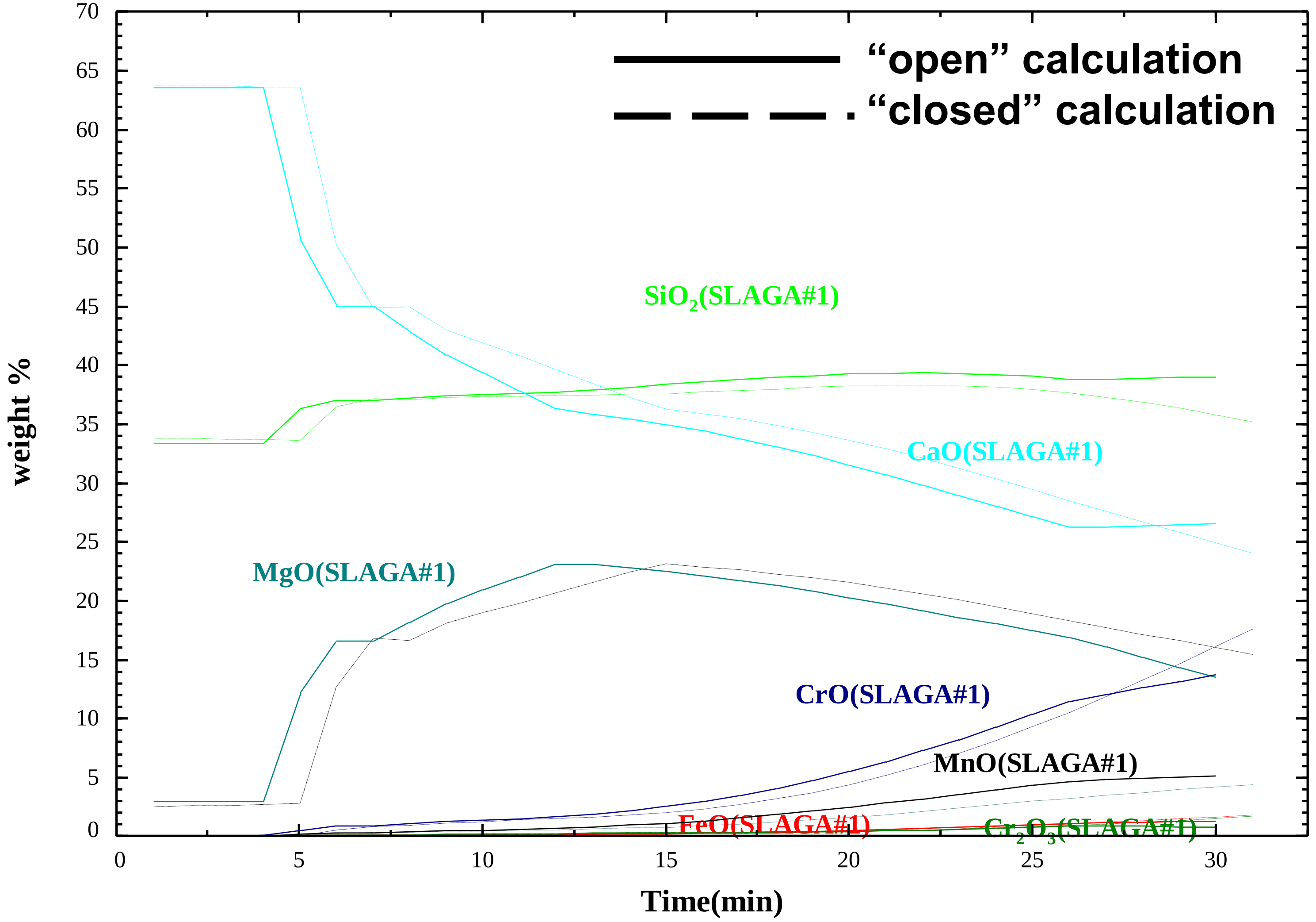
Reduction stage

Oxygen blowing stage



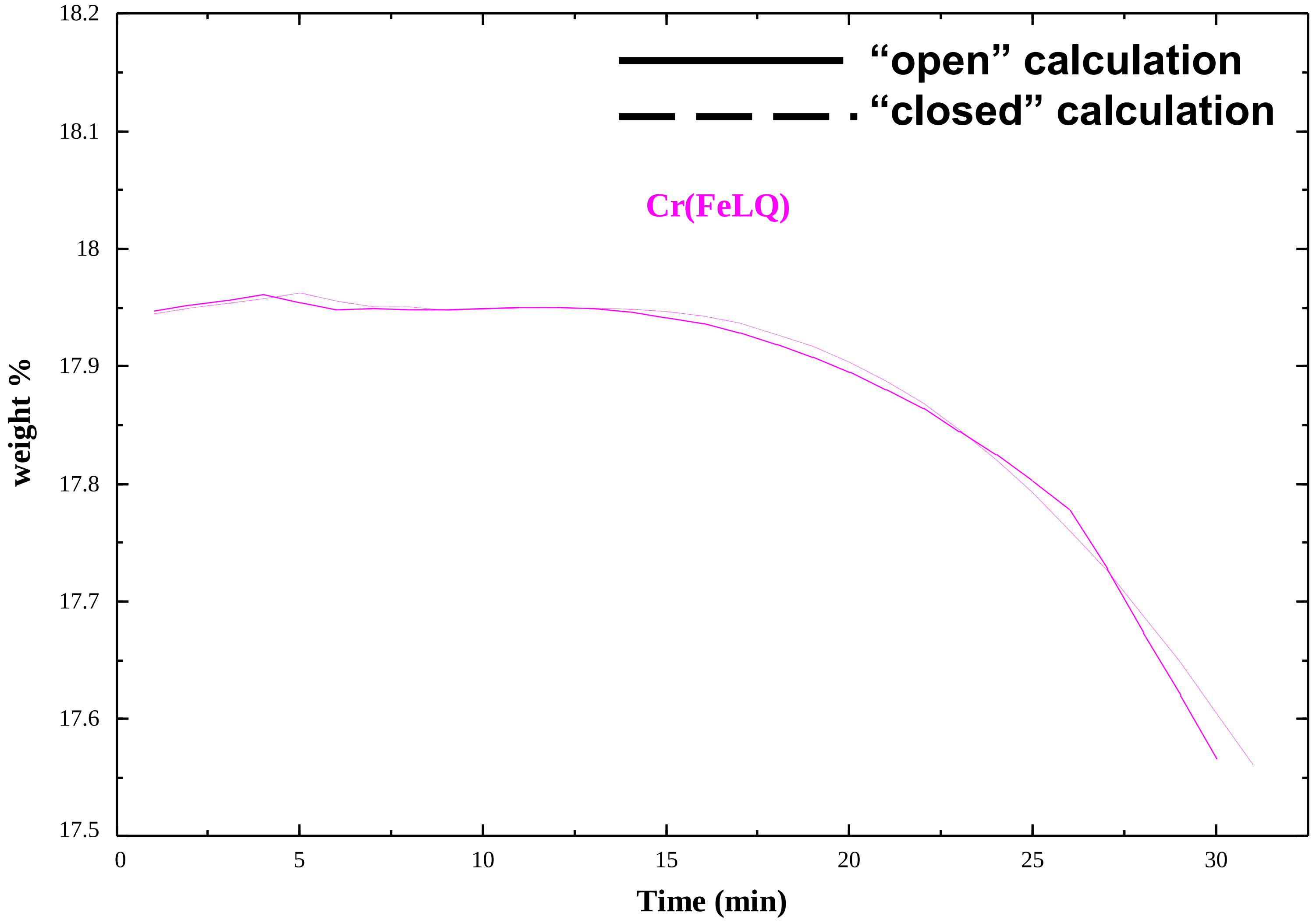
Oxygen blowing stage

Gas reaction comparison



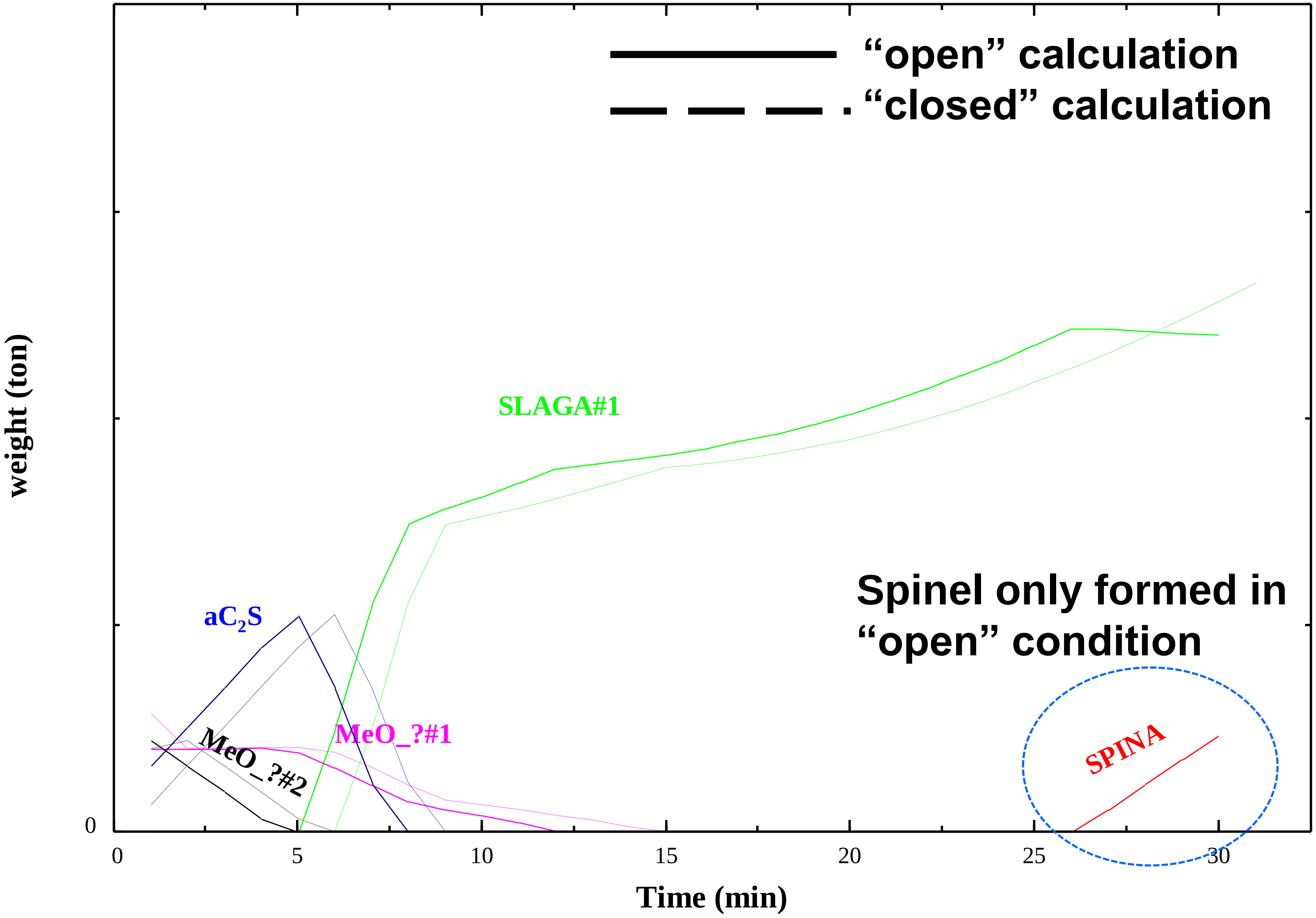
Oxygen blowing stage

Gas reaction comparison



Oxygen blowing stage

Gas reaction comparison

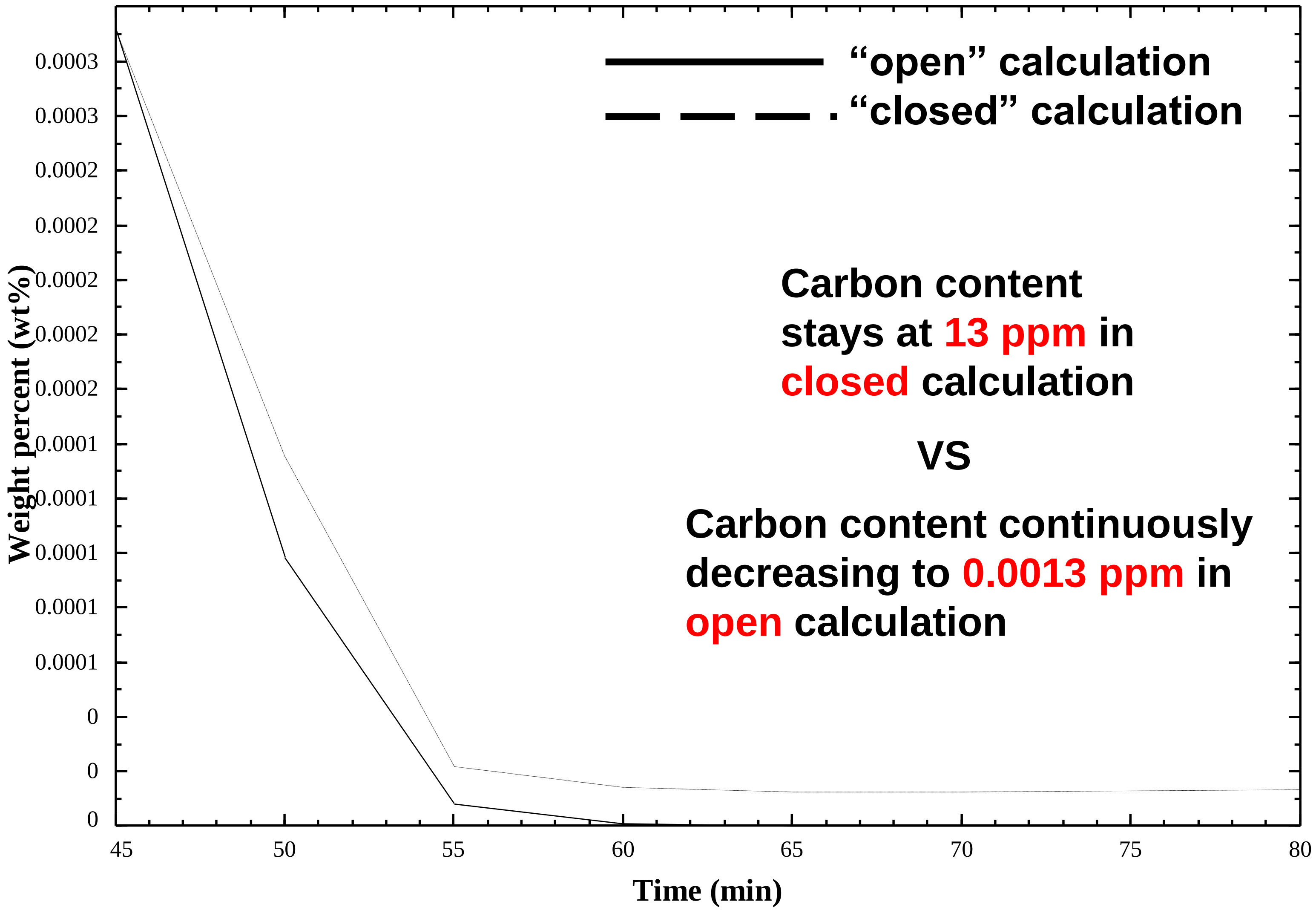


Spinel only formed in "open" condition

Reduction stage

[C] in the melt

C:\FactSage\Result figures from VOD\open closed\C wt open closed com.wmf
30/04/2010



Carbon content stays at 13 ppm in closed calculation

VS

Carbon content continuously decreasing to 0.0013 ppm in open calculation

Conclusion for comparison

From these two calculations,

We can see significant difference in final carbon content in the melt.
Also, we found that even it is very small amount, it still has noticeable effect on phase equilibrium according to spinel phase

→ **For more accurate calculation, we need to consider gas phase equilibrium and it should be well defined by kinetic point of view and the activation energy for CO bubble forming is one of the important factor in estimation .**

6. Summary and Conclusion

Summary

- VOD (Vacuum Oxygen Decarburization) is mainly for reducing Carbon, Nitrogen content and keep Cr content in the Liquid steel.
- Product quality from VOD is highly dependent on its vacuum condition, oxygen blowing rate, argon blowing rate(to reach equilibrium), fluxes, processing time.
- Melt, Slag compositions are well predicted by FactSage stream calculation.

Conclusion

- Final composition estimations displayed quite reasonable result so that we can predict the final grade of molten steel from VOD process by using FactSage.
- From the result, we can track each compositions of slag by time. This help us to understand reactions in the VOD process and to develop better synthetic slag composition for reducing.
- Futher calculations with other elements such as phosphorous, sulfur and fluorides are possible.
- By understanding of slag composition changes, we can minimize dissolution amount from refractories.
- In terms of processing time, it could not show us good result, more work should be done for the kinetic part if we want get better result.

Future work

- Developing database which include sulfur, phosphorus, CaF_2 in the slag and melt
- Calculation by using kinetic modeling program and FactSage at the same time
- Study economic aspects of VOD and process modification

Acknowledgement

Sincere thanks to

- Prof. In-Ho Jung
- Marie-Aline Van Ende
- Manas Paliwal
- Gabriel Garicia Curiel

and all of our group members

References

[92Pre] : V. Presern, Vacuum, 43 (1992).

[94Tsu] : R. Tsujino et al., Nippon steel technical report, 61 April (1994).

[99]Cho : R. J. Choulet, AISE Seminar on June 5, Detroit (1997).

[00Din] : R. Ding et al., Metall. Mater. Trans. B, 31B (2000).

[01Kor] : B. Korousic et al., Berg- und Huettenmaennische Monatshefte, 146(7) (2001).

[01Jon] : P. T. Jones, Doctoral Thesis of Katholieke Universiteit Leuven, *België* (2001).

[03Jun] : In-Ho Jung, Doctoral Thesis of Ecole Polytechnique, *Montreal* (2003).

[05Pet] : J. Peter et al., Proceedings of the Iron & Steel Technology Conference., May 9-12 (2005).

[07You] : Xinag-mi You et al., J. Iron. Steel Res. Int., 14(4) (2007).

[09Xu] : Y. Xu et al., Metall. Mater. Trans. B, 40B (2009).

Thank you for your attention!

Questions?