

## Appendix C

**Table C-1** Literature review list for slag refining with crude silicon. Adapted from Zhu (2021).

| Author                           | Furnace type                     | Crucible type | Temperature (°C) | Si Source/<br>Initial B | Metal system | Slag system          | Gas phase                       | Slag/ metal mass ratio | Holding time (h) | $L_B$         |
|----------------------------------|----------------------------------|---------------|------------------|-------------------------|--------------|----------------------|---------------------------------|------------------------|------------------|---------------|
| (Suzuki and Sano, 1991)          | Resistance                       | Graphite      | 1450–1550        | MG-Si<br>B: 30–90 ppmw  | Si           | CaO–SiO <sub>2</sub> | Ar, CO,<br>Ar + CO <sub>2</sub> | 1                      | 2                | 0.31–<br>1.15 |
| (Weiss and Schwerdtfeger, 1994)  | Resistance                       | Quartz        | 1500             | MG-Si                   | Si           | CaO–SiO <sub>2</sub> | Ar                              | 2.5                    | 4, 6.5           | 5.5           |
| (Fujiwara <i>et al.</i> , 2005)  | Induction + mechanical stirring  | Alumina       | 1600             | B: 7.6 ppmw             | Si           | CaO–SiO <sub>2</sub> | Ar                              | -                      | -                | -             |
| (Teixeira <i>et al.</i> , 2009)  | Resistance                       | Graphite      | 1550             | B: 150 ppmw             | Si           | CaO–SiO <sub>2</sub> | Ar                              | 2.2                    | 18               | 2–5.5         |
| (Luo <i>et al.</i> , 2011)       | Induction 200 kW–3000 Hz         | Quartz        | 1550–1600        | B: 15 ppmw              | Si           | CaO–SiO <sub>2</sub> | Ar                              | 0.1                    | 0.5–2            | 2.2           |
| (Ding <i>et al.</i> , 2012)      | Induction                        | Graphite      | 1550             | MG-Si<br>B: 22 ppmw     | Si           | CaO–SiO <sub>2</sub> | Ar                              | -                      | -                | 1.02          |
| (Nishimoto <i>et al.</i> , 2012) | Resistance                       | Graphite      | 1550             | B: c.a. 300 ppmw        | Si           | CaO–SiO <sub>2</sub> | Ar                              | 1.25–2.5               | 3                | 2.16          |
| (White and Sichen, 2014)         | Resistance + mechanical stirring | Graphite      | 1550             | EG-Si                   | Si           | CaO–SiO <sub>2</sub> | -                               | 1                      | 0.17             | 1.98,<br>2.45 |

| Author                         | Furnace type | Crucible type | Temperature (°C) | Si Source/<br>Initial B | Metal system | Slag system              | Gas phase                    | Slag/ metal mass ratio | Holding time (h) | $L_B$     |
|--------------------------------|--------------|---------------|------------------|-------------------------|--------------|--------------------------|------------------------------|------------------------|------------------|-----------|
| (Wei <i>et al.</i> , 2015)     | Induction    | Graphite      | 1550             | B: 22 ppmw              | Si           | CaO–SiO <sub>2</sub>     | Ar                           | -                      | 0.5–3            | 0.7–1.6   |
| (Jakobsson and Tangstad, 2015) | Resistance   | Graphite      | 1600             | -                       | Si           | CaO–SiO <sub>2</sub>     | Ar                           | 1                      | 0.6–18           | 2.13–2.52 |
| (Jakobsson and Tangstad, 2015) | Resistance   | Graphite      | 1600             | -                       | Si           | MgO–SiO <sub>2</sub>     | Ar                           | 1                      | 0.6–18           | 1.92–2.41 |
| (Safarian, 2019)               | Induction    | Graphite      | 1500–1600        | Si–B alloy, B: 500 ppmw | Si           | BaO–SiO <sub>2</sub>     | Ar                           | -                      | 2                | 0.9–1.35  |
| (Suzuki and Sano, 1991)        | Resistance   | Graphite      | 1450             | MG–Si B: 30–90 ppmw     | Si           | CaO–MgO–SiO <sub>2</sub> | CO                           | 1                      | 2                | 1–1.6     |
| (White <i>et al.</i> , 2013a)  | Resistance   | Graphite      | 1600             | EG–Si                   | Si           | CaO–MgO–SiO <sub>2</sub> | CO (0.6, 0.8, 1 atm)         | 3.3                    | 48               | 2.3–3.45  |
| (White <i>et al.</i> , 2013b)  | Resistance   | Graphite      | 1600             | EG–Si                   | Si           | CaO–MgO–SiO <sub>2</sub> | Ar + CO, CO + N <sub>2</sub> | 3.3                    | 48               | 1.3–3.4   |
| (Jakobsson and Tangstad, 2015) | Resistance   | Graphite      | 1600             | -                       | Si           | CaO–MgO–SiO <sub>2</sub> | Ar                           | 1                      | 0.6–18           | 1.84–2.52 |
| (Suzuki and Sano, 1991)        | Resistance   | Graphite      | 1450             | MG–Si B: 30–90 ppmw     | Si           | CaO–BaO–SiO <sub>2</sub> | CO                           | 1                      | 2                | 1.5–2     |
| (Safarian, 2019)               | Induction    | Graphite      | 1500–1600        | Si–B alloy B: 500 ppmw  | Si           | CaO–BaO–SiO <sub>2</sub> | Ar                           | -                      | 2                | 1.9–2.2   |

| Author                       | Furnace type | Crucible type | Temperature (°C)   | Si Source/<br>Initial B | Metal system | Slag system                                | Gas phase   | Slag/ metal mass ratio | Holding time (h) | $L_B$     |
|------------------------------|--------------|---------------|--------------------|-------------------------|--------------|--------------------------------------------|-------------|------------------------|------------------|-----------|
| (Suzuki and Sano, 1991)      | Resistance   | Graphite      | 1450               | MG-Si<br>B: 30-90 ppmw  | Si           | CaO-SiO <sub>2</sub> -CaF <sub>2</sub>     | CO          | 1                      | 2                | 1-1.7     |
| (Teixeira and Morita, 2009)  | Resistance   | Graphite      | 1550               | -                       | Si           | CaO-SiO <sub>2</sub> -CaF <sub>2</sub>     | Ar          | 2.2                    | 18               | 1-2.4     |
| (Cai <i>et al.</i> , 2011)   | Induction    | Graphite      | 1600,<br>1500-1700 | B: 6-9 ppmw             | Si           | CaO-SiO <sub>2</sub> -CaF <sub>2</sub>     | Ar          | 3                      | 1                | 2.86-4.61 |
| (Cheng <i>et al.</i> , 2018) | Induction    | Graphite      | 1550               | -                       | Si           | CaO-SiO <sub>2</sub> -CaF <sub>2</sub>     | Ambient air | 2.2                    | 2                | -         |
| (Cheng <i>et al.</i> , 2019) | Induction    | Graphite      | 1600               | -                       | Si           | CaO-SiO <sub>2</sub> -CaF <sub>2</sub>     | Ambient air | 1-3                    | 0.25-0.5         | 1.2-1.8   |
| (Suzuki and Sano, 1991)      | Resistance   | Graphite      | 1450               | MG-Si<br>B: 30-90 ppmw  | Si           | CaO-MgO-SiO <sub>2</sub> -CaF <sub>2</sub> | CO          | 1                      | 2                | 1-1.4     |
| (Suzuki and Sano, 1991)      | Resistance   | Graphite      | 1450               | MG-Si<br>B: 30-90 ppmw  | Si           | CaO-BaO-SiO <sub>2</sub> -CaF <sub>2</sub> | CO          | 1                      | 2                | 1.2-6     |
| (Ding <i>et al.</i> , 2012)  | Induction    | Graphite      | 1550               | MG-Si<br>B: 22 ppmw     | Si           | CaO-SiO <sub>2</sub> -LiF                  | Ar          | 0.5-5                  |                  | 1.0-2.77  |
| (Y. Li <i>et al.</i> , 2014) | Induction    | Graphite      | 1550               | -                       | Si           | CaO-SiO <sub>2</sub> -LiF                  | Ar          | 1                      | 0.25-3           | 1.8       |
| (Wang <i>et al.</i> , 2016)  | Induction    | Graphite      | 1550               | B: 13 ppmw              | Si           | CaO-ZnO-SiO <sub>2</sub>                   | Ar          | 1                      | 1                | 1.8-3.04  |

| Author                          | Furnace type | Crucible type    | Temperature (°C) | Si Source/ Initial B | Metal system | Slag system                                     | Gas phase   | Slag/ metal mass ratio | Holding time (h) | $L_B$     |
|---------------------------------|--------------|------------------|------------------|----------------------|--------------|-------------------------------------------------|-------------|------------------------|------------------|-----------|
| (Lai <i>et al.</i> , 2016)      | Induction    | Graphite         | 1700             | -                    | Si           | $\text{Li}_2\text{O}-\text{SiO}_2$              | Ambient air | 0.5–3                  | 0.17–0.5         | -         |
| (Y. Li <i>et al.</i> , 2014)    | Induction    | Graphite         | 1550             | -                    | Si           | $\text{Li}_2\text{O}-\text{CaO}-\text{SiO}_2$   | Ar          | 1                      | 0.25–3           | 1.4       |
| (Lai <i>et al.</i> , 2016)      | Induction    | Graphite         | 1700             | -                    | Si           | $\text{Li}_2\text{O}-\text{SiO}_2-\text{CaF}_2$ | Ambient air | 1                      | 0.17–1           |           |
| (Ding <i>et al.</i> , 2012)     | Induction    | Graphite         | 1550             | MG-Si B: 22 ppmw     | Si           | $\text{Li}_2\text{O}-\text{CaO}-\text{SiO}_2$   | Ar          | 0.5–5                  | 0.5–4            | 1.0–2.0   |
| (Wu <i>et al.</i> , 2012)       | Induction    | Graphite         | 1600             | -                    | Si           | $\text{Li}_2\text{O}-\text{CaO}-\text{SiO}_2$   | Ar          | 0.5–4                  | 2                | 0.82–1.56 |
| (Safarian <i>et al.</i> , 2013) | Induction    | Graphite         | 1500, 1550       | -                    | Si           | $\text{Na}_2\text{O}-\text{SiO}_2$              | Ar          | 2                      | 0.25–0.75        | 0.3–1     |
| (Fang <i>et al.</i> , 2014)     | Induction    | Graphite         | 1550–1750        | -                    | Si           | $\text{Na}_2\text{O}-\text{SiO}_2$              | Ambient air | 0.5–2.5                | 0.5              | -         |
| (Li <i>et al.</i> , 2018)       | Induction    | Graphite         | 1600             | -                    | Si           | $\text{Na}_2\text{O}-\text{SiO}_2$              | -           | 0.5–1.5                | 0.17–1           | -         |
| (Teixeira and Morita, 2009)     | Resistance   | Graphite         | 1550             | -                    | Si           | $\text{Na}_2\text{O}-\text{CaO}-\text{SiO}_2$   | Ar          | 2.2                    | 1                | 1.6–2.3   |
| (Zhang <i>et al.</i> , 2013)    | Induction    | Graphite, Quartz | 1500             | -                    | Si           | $\text{Na}_2\text{O}-\text{CaO}-\text{SiO}_2$   | Ar          | 0.2                    | 1                | 2.12–5.81 |
| (Safarian <i>et al.</i> , 2015) | Induction    | Graphite         | 1600             | -                    | Si           | $\text{Na}_2\text{O}-\text{CaO}-\text{SiO}_2$   | Ar          | 1–3                    | 0.17–2           | 2.4, 2.6  |
| (Y. Li <i>et al.</i> , 2014)    | Induction    | Graphite         | 1550             | -                    | Si           | $\text{K}_2\text{CO}_3-\text{CaO}-\text{SiO}_2$ | Ar          | 1                      | 0.25–3           | 1.9       |

| Author                         | Furnace type | Crucible type   | Temperature (°C) | Si Source/<br>Initial B | Metal system | Slag system                                                                        | Gas phase      | Slag/ metal mass ratio | Holding time (h) | $L_B$              |
|--------------------------------|--------------|-----------------|------------------|-------------------------|--------------|------------------------------------------------------------------------------------|----------------|------------------------|------------------|--------------------|
| (Wu <i>et al.</i> , 2016)      | Induction    | Graphite        | 1550             | -                       | Si           | $K_2CO_3$ -<br>CaO-SiO <sub>2</sub>                                                | Ar             | 1                      | 0.5-5            | 1.17-<br>2.08      |
| (Jakobsson and Tangstad, 2018) | Resistance   | Graphite        | 1600             | -                       | Si           | CaO-<br>Al <sub>2</sub> O <sub>3</sub> -SiO <sub>2</sub>                           | Ar             | 1                      | 6-9              | 1.33-<br>2.08      |
| (J. Li <i>et al.</i> , 2014)   | Induction    | Graphite        | 1800             | -                       | Si           | CaO-<br>Al <sub>2</sub> O <sub>3</sub> -<br>SiO <sub>2</sub> -CaF <sub>2</sub>     | Ambient<br>air | 0.4-1                  | 0.5-2            | 1.0-<br>2.2        |
| (Johnston and Barati, 2010)    | Resistance   | Alumina         | 1500             | B: 0.19-<br>0.26wt%     | Si           | BaO-<br>Al <sub>2</sub> O <sub>3</sub> -<br>SiO <sub>2</sub>                       | Ar             | 1.4                    | 2                | 0.1-<br>0.5        |
| (Jakobsson and Tangstad, 2018) | Resistance   | Graphite        | 1600             | -                       | Si           | MgO-<br>Al <sub>2</sub> O <sub>3</sub> -<br>SiO <sub>2</sub>                       | Ar             | 1                      | 6-9              | 1.8                |
| (Johnston and Barati, 2010)    | Resistance   | Alumina,<br>MgO | 1500             | B: 0.19-<br>0.26wt%     | Si           | CaO-<br>MgO-<br>Al <sub>2</sub> O <sub>3</sub> -<br>SiO <sub>2</sub>               | Ar             | 1.4                    | 2                | 0.9-<br>1.8<br>1-2 |
| (Yin <i>et al.</i> , 2011)     | Induction    | Graphite        | 1600-1750        | -                       | Si           | Na <sub>2</sub> O-<br>CaO-<br>Al <sub>2</sub> O <sub>3</sub> -<br>SiO <sub>2</sub> | -              | 0.1-0.5                | 0-4              | -                  |
| (Wang <i>et al.</i> , 2014)    | Resistance   | Graphite        | 1450             | -                       | Si           | CaO-SiO <sub>2</sub> -<br>CaCl <sub>2</sub>                                        | Ar             | 2                      | 12               | 0.23-<br>2.4       |

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**Table C-2** Review list of literature on gas refining of Si for boron removal with  $H_2$ -x%  $H_2O$  gases. Adapted from Hoseinpur (2021).

| Author                             | Furnace type                     | Crucible                                                              | Temperature(°C)                    | Si- Material                                                                                                          | Gas composition                                    | Gas flow rate (NL/min)                                                                                          | Holding time (h)     | $k_i$ ( $\mu\text{m/s}$ ) |
|------------------------------------|----------------------------------|-----------------------------------------------------------------------|------------------------------------|-----------------------------------------------------------------------------------------------------------------------|----------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|----------------------|---------------------------|
| (Altenberend <i>et al.</i> , 2017) | Inductively coupled plasma torch | a. Cold crucible (copper)<br>b. Silica plates<br>c. Graphite crucible | a. 1410<br>b. 1500<br>c. 1500–1700 | a. UMG-Si with 30 ppmw B<br>b. UMG-Si with 30 ppmw B<br>c. EG-Si with 30 ppmw B                                       | Ar, $H_2$ and $O_2$                                | a. 7.2–7.6 ( $\text{Nm}^3/\text{h}$ )<br>b. 7.7 ( $\text{Nm}^3/\text{h}$ )<br>c. 7.6 ( $\text{Nm}^3/\text{h}$ ) | a. 6<br>b. -<br>c. - |                           |
| (Hoseinpur <i>et al.</i> , 2020)   | Vacuum induction                 | Graphite                                                              | 1500                               | Mixture of commercial-grade silicon HQ-Silgrain, purity 99.76%, and FBR silicon, with 11.76 ppmw B                    | $H_2$ -3% $H_2O$                                   | 3 NL/min                                                                                                        | 1.67                 | 17.33                     |
| (Hoseinpur <i>et al.</i> , 2022)   | Vacuum induction                 | Graphite<br>Alumina                                                   | 1450, 1500, 1600                   | 213 g Si, mixture of 50 wt% FBR polysilicon, 8N purity, and 50 wt% Silgrain HQ micron cut; initial B about 15–20 ppmw | $H_2$ or $H_2$ -3% $H_2O$ ; with Ar, He, or vacuum | 3 NL/min                                                                                                        | 0.83–2               | 0.9–23.3                  |

| Author                          | Furnace type         | Crucible                              | Temperature(°C)           | Si- Material                                        | Gas composition                                                                    | Gas flow rate (NL/min)                                              | Holding time (h) | $k_i$ (μm/s) |
|---------------------------------|----------------------|---------------------------------------|---------------------------|-----------------------------------------------------|------------------------------------------------------------------------------------|---------------------------------------------------------------------|------------------|--------------|
| (Nakamura <i>et al.</i> , 2004) | Steam added plasma   | Silica<br>Graphite                    | 1600–1700<br>1550–1600    | UMG–Si with 5–10 ppmw B<br>HP–Si with 0.7–30 ppmw B | Ar, Ar + He,<br>Ar + H <sub>2</sub> ,<br>with<br>H <sub>2</sub> O + H <sub>2</sub> | 2.5*10 <sup>-4</sup> – 7.1*10 <sup>-2</sup><br>(Nm <sup>3</sup> /s) | 8.33             | -            |
| (Nordstrand and Tangstad, 2012) | Vacuum induction     | Graphite                              | 1450, 1500, 1550,<br>1600 | EG–Si with 50/130/150 ppmw B                        | H <sub>2</sub> O, H <sub>2</sub> and Ar                                            | 3                                                                   | 2, 4.5           | 1.2–13       |
| (Safarian <i>et al.</i> , 2016) | Induction            | Graphite, high-purity quartz, alumina | 1460, 1500, 1530          | EG–Si with 10–25 ppmw B                             | H <sub>2</sub> and H <sub>2</sub> O                                                | 0.5, 1, 1.5, 3, 6, 9                                                | 1, 3.25          | 1.5–25       |
| (Sortland and Tangstad, 2014)   | Induction Resistance | Graphite                              | 1500                      | EG–Si with 36 to 128 ppmw B                         | H <sub>2</sub> O, H <sub>2</sub> and Ar                                            | 0.5–16                                                              | 0.6–2.5          | 0.1–51.1     |

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**Table C-3** Review list of literature on slag refining with silicon alloy. Adapted from Zhu (2021).

| Author                                    | Furnace type | Crucible | Temperature (°C) | Metal system | Alloy composition | Slag system                                                                | Gas phase   | Slag / Metal mass ratio | Holding time (h) | $L_B$            |
|-------------------------------------------|--------------|----------|------------------|--------------|-------------------|----------------------------------------------------------------------------|-------------|-------------------------|------------------|------------------|
| (Ma <i>et al.</i> , 2013)                 | Induction    | Graphite | 1400             | Si-Sn        | 0–82.4 mol% Sn    | CaO–SiO <sub>2</sub> –CaF <sub>2</sub>                                     | Ar          | 3                       | 18               | 2.3–200          |
| (Li <i>et al.</i> , 2016)                 | Resistance   | Graphite | 1450             | Si-Sn        | 0–50 mol% Sn      | Na <sub>2</sub> SiO <sub>2</sub> –CaO–SiO <sub>2</sub>                     | Ar          | 1–2                     | 0.5–3            | -                |
| (Al-Khazraji <i>et al.</i> , 2018)        | Resistance   | Graphite | 1500             | Si-Sn        | 25 wt% Sn         | CaCl <sub>2</sub> , CaO/SiO <sub>2</sub> = 0.5–2                           | Ar          | 1, 2                    | 0–1              | -                |
| (Li <i>et al.</i> , 2014)                 | Resistance   | Alumina  | 1500             | Si-Cu        | 70 wt% Cu         | Na <sub>2</sub> O–CaO–Al <sub>2</sub> O <sub>3</sub> –SiO <sub>2</sub>     | Ar          | 10                      | 0.17             | 0.7–46.8         |
| (Huang <i>et al.</i> , 2016)              | Induction    | Graphite | 1550             | Si-Cu        | 30–70 wt% Cu      | CaO–SiO <sub>2</sub> –CaCl <sub>2</sub>                                    | Ambient air | 1                       | 0.5              | -                |
| (Jakobsson, 2013)                         | Resistance   | Graphite | 1600             | Si-Fe        | 0–50 wt% Fe       | CaO–SiO <sub>2</sub>                                                       | Ar          | 1                       | 6                | 2.6–3.0          |
| (Krystad <i>et al.</i> , 2017)            | Resistance   | Graphite | 1600             | Si-Fe        | 0–85 wt% Fe       | CaO–SiO <sub>2</sub>                                                       | Ar          | 0.57                    | 0–3              | 2.4–6.0          |
| (Hosseinpour and Tafaghodi Khajavi, 2018) | Resistance   | Alumina  | 1600             | Si-Fe        | 20 wt% Fe         | CaO–Al <sub>2</sub> O <sub>3</sub> –SiO <sub>2</sub>                       | Ar          | 1                       | 0–8              | 0.8–11.4         |
| (Zhu <i>et al.</i> , 2021)                | Induction    | Graphite | 1600±20          | Si-Sn        | 10 wt% Sn         | CaO–SiO <sub>2</sub> –CaO–La <sub>2</sub> O <sub>3</sub> –SiO <sub>2</sub> | Ar          | 1                       | 1                | 2.93, 3.33, 3.65 |

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