Hydrogen control of large bottom poured forging ingots at Ellwood Quality Steels

Bjorn Gabrielsson¹, Brendan Connolly², Steve Lubinski², Sean Cowden², Hongliang Yang³
¹Ellwood Group, Inc. - New Castle, PA, USA
²Ellwood Quality Steels - New Castle, PA, USA
³ABB R&D Metallurgy - Vasteras, Vastmanland, Sweden

Abstract
Ellwood Quality Steels (EQS) produces high-quality bottom poured ingots for the open die forging and ring rolling industries. Significant research and development efforts at EQS have expanded the ingot production capabilities from a maximum 47 Mton ingot in 2007 up to a maximum 170 Mton ingot by 2017. The multiladle sandwich pouring process was implemented to produce ingots which are greater than the nominal heat size of 47 Mton.

Hydrogen control is critical for the grades and sizes produced at EQS to prevent defects such as hydrogen flake in the forgings. EQS utilizes combined ladle Electromagnetic Stirring (EMS) and argon gas stirring during vacuum treatment at low pressure to quickly reduce the hydrogen content of the liquid steel to less than 1 ppm. After vacuum treatment and during bottom pouring, it is imperative to minimize hydrogen pick-up into the liquid steel bath by implementing the appropriate countermeasures to potential hydrogen sources such as moisture.

The combined EMS and argon ladle stirring during deep vacuum treatment is reevaluated in this work. A comparison of a stronger 1350A EMS stirrer versus previously published results detailing a 1000A EMS stirrer is presented. Additionally, this work examines the effect of hydrogen sources on the hydrogen pick-up that occurs during bottom pouring of large steel ingots. Various methods were used in order to differentiate sources of hydrogen pickup after vacuum treatment.

The results of this work indicate that the Ultra-Low Hydrogen Practice implemented at EQS allows for consistent production of high-quality, large cross-section bottom poured steel ingots with hydrogen content of less than 1.5 ppm.

1. Introduction
The Ellwood Group operates two separate Electric Arc Furnace (EAF) melt shops, each with a maximum heat size of 47 Mton:

- Ellwood Quality Steels (EQS) in New Castle, Pennsylvania, with a capacity of 390,000 Mton of plain carbon, low and medium alloy steel, tool steels and martensitic stainless. Maximum ingot weight at EQS is 170 Mton.
- Ellwood National Steels (ENS) in Irvine, Pennsylvania, with a capacity of 80,000 Mton of high alloyed, low carbon stainless, Ni-based and other sophisticated alloys[3]. Maximum ingot weight at ENS is 90 Mton.

The EQS melt shop was commissioned in late 1985 with a maximum heat size of 40 Mton[2]. The heat size increased gradually to 47 Mton with the following modifications:

- Original 1985 runner tap EAF replaced with enlarged EBT
- Lengthening of the original ASEA-SKF ladles
- Optimization of ladle refractory thickness

With these heat size improvements the maximum as-cast bottom poured forging ingot weight increased to
47 Mton from a single heat. Production flow at the EQS melt shop is shown in Figure 1.

The EQS melt shop has produced roughly 8,300,000 Mton of forging and ring rolling ingots since start up in December 1985. There are two teeming bays at EQS:

- West Teeming Bay for 24 – 47 Mton ingots teemed by overhead crane
- East Teeming Bay for 2 – 24 and 60 – 170 Mton ingots

The EAF, Ladle Furnace No. 1 (LF1), Vacuum Station, Ladle Furnace No. 2 (LF2) and chemical laboratory (located between EAF and LF1) are very compact with a total steel making platform length of only 85 m. Both ladle furnaces are equipped with EMS in order to allow for short-arc reheating under a fully liquid reducing slag cover. This makes it possible for EQS to consistently produce extremely clean steel with very tight composition control while maintaining high productivity\(^\text{[6]}\). Table 1 lists some key performance indicators (KPI) for 2017.

The sandwich pouring process was implemented at EQS in 2015 in order to produce up to 170 Mton ingots using four ladles of liquid steel. Sandwich pouring is shown schematically in Figure 2. The development work and excellent quality results of sandwich poured, large cross-section ingots at EQS are well documented\(^\text{[4]}\).

<table>
<thead>
<tr>
<th>KPI</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAF Gross T-T-T</td>
<td>52.7 minutes/heat</td>
</tr>
<tr>
<td>EAF Power On Time</td>
<td>36.1 minutes/heat</td>
</tr>
<tr>
<td>EAF Power Off Time</td>
<td>16.6 minutes/heat</td>
</tr>
<tr>
<td>Productivity</td>
<td>27.3 heat/day</td>
</tr>
</tbody>
</table>

Table 1. Key performance indicators, 2017

2. **Hydrogen In Steel**

It was recognized in the early 20\(^{th}\) century that certain internal hairline cracks in large steel forgings were related to hydrogen\(^\text{[9]}\). These cracks have been termed “hydrogen flakes” and extensive research on their formation and prevention has been performed by both academia and industry.

Hydrogen is present in steel as a monatomic species with high diffusivity and low solubility in low temperature transformation products. The mechanism for hydrogen flake formation remains controversial, however calculations have been performed\(^\text{[9]}\) to show that the pressure buildup due to hydrogen within a steel matrix is easily high enough to exceed that which even a high-strength steel is able to withstand. The
atomic fraction of hydrogen in equilibrium with H₂ gas at pressure P (atm) is given as\[^{[7]}\]:

\[
C_v = 0.00185 \sqrt{P} e^{-\frac{114.0}{T}}
\]

where \( C_v \) is the atom fraction of hydrogen and \( T \) is in Kelvin. \( P \) must be replaced by fugacity at the pressures being considered. An approximation of the Taylor expansion can be used to estimate fugacity, \( f \):

\[
f \approx \frac{P \bar{V}}{RT}
\]

where \( \bar{V} \) is the molar volume and \( R \) is the gas constant. In order to determine the molar volume, the van der Waals equation of state for one mole of gas can be used:

\[
(p + \frac{a}{V^2})(V - b) = RT
\]

\[
a = \frac{27RT_{\text{crit}}^2}{64P_{\text{crit}}}
\]

\[
b = \frac{RT_{\text{crit}}}{8P_{\text{crit}}}
\]

After determining the fugacity, the pressure and molar volume can be simultaneously solved. Figure 3 shows the internal pressure buildup versus various amounts of hydrogen in the steel matrix at different temperatures. Figure 4 shows the difference in relative volumes of steel, hydrogen gas and water at standard temperature and pressure.
The important point from Figures 3 and 4 is that even at a hydrogen content of 1 ppm, coming from a very small relative volume of water, the matrix will be unable to withstand the high internal pressure buildup at room temperature. The hydrogen present within the steel must be accommodated in some fashion. Hydrogen accumulates at voids and interfaces within the steel, thereby lowering the hydrogen dissolved within the matrix. Grain boundaries, dislocations, microporosity and inclusions are all potential trapping sites where hydrogen is able to diffuse out of the matrix and remain in these traps without detrimental flakes occurring[7]. Fully dense forgings with low inclusion content are more susceptible to hydrogen flaking due to the reduced availability of trapping sites.

Hydrogen can be removed from steel forgings by sub-critical diffusion annealing in order to prevent hydrogen flaking. However, the diffusion annealing practice is both time-consuming and expensive. Figure 5 shows the required diffusion annealing time versus the forging diameter for removal of 50% of the original hydrogen content at 650°C according to Thelning’s calculation[8]. The diffusion annealing time required for hydrogen removal in large cross-section forgings is prohibitively long.

![Diagram of diffusion time for 50% hydrogen removal](image)

**Figure 5** Diffusion time for 50% hydrogen removal

3. **EQS Vacuum Station**

The secondary steelmaking operation at EQS utilizes a vacuum hood degassing station with combined argon gas and EMS stirring for fast and efficient hydrogen removal from the liquid steel. The EMS stirrer was upgraded from 1000A max current to 1350A max current in 1998. The EQS vacuum station is shown schematically in Figure 6.

![Schematic of vacuum hood degassing station at EQS](image)

**Figure 6** Schematic of vacuum hood degassing station at EQS

Typical operating pressure of less than 1 mbar above the liquid steel bath is consistently achieved using a 4-stage steam ejector vacuum pump. The 4-stage steam ejector vacuum pump utilizes parallel ejectors in the first two pumping stages in order to achieve the highest possible pumping capacity and reach operating pressure in less than four minutes.
It is common for steam ejector pumps used in the vacuum treatment of liquid steel to require periodic high-pressure water-jet cleaning in order to remove the buildup of concrete-like deposits of process dust inside the pump itself. EQS installed an in-line vacuum bag filter in 2004 between the vacuum station and the vacuum pump in order to separate the process dust that is generated by evaporation and condensation of low vapor pressure elements such as magnesium, zinc and manganese. The dust is highly pyrophoric and will combust readily if it is exposed to oxygen. The bags are cleaned by nitrogen pulse jet after each vacuum treatment and the dust is collected in a nitrogen pneumatic ejection dispenser at the bottom of the bag filler. At the end of the bag cleaning cycle, the dust is ejected into the ladle furnace offgas system where it is combusted and then captured by the ladle furnace baghouse. The in-line vacuum bag filter has provided several advantages for the EQS secondary steelmaking operation:

- No degradation of vacuum capacity or vacuum pressure due to dust buildup in the pump over time
- No cleaning (downtime) of the vacuum pump is required
- No manual handling of the pyrophoric dust is required

4. **Hydrogen Sampling**

EQS performs hydrogen sampling a minimum of two times for every heat produced. The first sample is taken from the ladle after vacuum treatment to ensure the process achieved the necessary low hydrogen content prior to bottom pouring. The final sample, which is used for certification, is taken from the ingot mold when the mold is almost full to ensure that the hydrogen content reported to customers is accurate and includes any hydrogen pickup that occurs during post-vacuum treatment secondary steelmaking operations and bottom pouring.

Standard hydrogen sampling and analysis at EQS has been previously described and proven to be an accurate method. The standard method at EQS is summarized below:

- Liquid metal sampling by evacuated 6 mm diameter glass pin tube
- Immediate, rapid quenching of the pin with cold, clean water
- Storage of the pin in dry ice until analysis (analyzed within 24 hours)
- 3 – 5 gram samples broken from the pin while cold
- Hot extraction analysis at 1100°C using LECO hydrogen analyzer

5. **Hydrogen Removal**

The amount of hydrogen dissolved in liquid steel is proportional to the square root of the partial pressure of hydrogen in contact with the liquid steel according to Sievert's Law. Removal of hydrogen from the liquid steel is achieved by exposing the liquid steel to an atmosphere of reduced hydrogen partial pressure. The amount of hydrogen removed from the liquid steel depends on the following factors:

- Mass transfer coefficient of hydrogen, \( k_{H} \), which depends on flow conditions in the liquid steel
- Ratio between the free metal surface area and the volume of liquid steel
- Vacuum treatment time
- Hydrogen concentration difference relative to equilibrium with the partial pressure above the liquid steel according to Sievert's Law
- Stirring gas flow rate and hydrogen concentration difference relative to equilibrium with the partial pressure in the stirring gas according to Sievert's Law
- Concentration of surface active elements such as sulfur and oxygen in the liquid steel
5.1 CFD Simulations

Stirring power density due to Ar-gas and EMS stirring during vacuum treatment affects several of the factors listed above. Simulations were performed by ABB R&D Metallurgy to evaluate how different stirring parameters will influence the important factors for hydrogen removal. Three cases were simulated as shown in Table 2.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>CASE 1</th>
<th>CASE 2</th>
<th>CASE 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat size, Mton</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>EMS type</td>
<td>None</td>
<td>ORT34</td>
<td>ORT34</td>
</tr>
<tr>
<td>EMS Current, A</td>
<td>0</td>
<td>1000</td>
<td>1350</td>
</tr>
<tr>
<td>EMS stir direction</td>
<td>Up</td>
<td>Up</td>
<td>Up</td>
</tr>
<tr>
<td>Vacuum pressure, mbar</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Ar flow rate, NL/min</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Slag amount, kg</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
</tbody>
</table>

Table 2: CFD modeling parameters

Figure 7 shows the argon gas plug location, ladle geometry and location of the ORT34 EMS stirrer. The Ar-gas plug is located on the EMS side. ½ radius of the working lining inside diameter.

Figure 8 shows the results of the CFD simulation for the top surface of the liquid slag and steel for Cases 1 - 3. Figure 9 shows the liquid metal velocity vectors through the ladle cross section for Cases 1 - 3. The benefits of combined argon gas and EMS stirring with the maximum EMS current (1350A) are as follows:

- Free metal surface exposure to the low pressure atmosphere is increased
- Liquid metal velocity at the free metal surface is increased
- Bulk liquid metal flow (mixing) is increased
The increased liquid metal velocity for Cases 2 and 3 also aids in dispersing argon gas bubbles throughout the liquid metal. Figure 10 shows the argon bubble distribution within the liquid steel, with the color of each bubble indicating its velocity. Dispersion of the argon bubbles throughout the melt is beneficial for the hydrogen removal process for the following reasons:

- Maximization of the bubble retention time to achieve, as close as possible, equilibrium hydrogen content in each bubble according to Sievert’s Law
- Exposure of bulk liquid to the argon bubbles rather than only in a narrow stream of argon

The results of ABB’s CFD modeling are summarized in Table 3. The combined argon-gas and EMS stirring at 1350A provides superior conditions for hydrogen removal during vacuum treatment.
5.2 CFD Model Verification

Several verification tests were performed in order to confirm the results of the CFD modeling:

5.2.1 Mixing Time Comparison

A mixing time comparison of combined argon and EMS stirring versus argon-only stirring was performed by Gabrielsson and Lubinski in 1988[10] using a 1000-amp EMS stirrer. The comparison is extended in this work to include the 1350-amp EMS stirrer currently installed at EQS. The mixing time study was performed with Cu as a tracer element. 5 kg Cu / t steel was added to the ladle followed by chemical sampling every 10 seconds. Due to the practical limitations of obtaining chemical samples during vacuum treatment, the mixing time must be performed at atmospheric pressure. The argon gas flow rate was adjusted to compensate for the loss of mechanical stirring power of the Ar-gas expansion at a vacuum pressure of 2 mbar for consistency with the previous work. Sundberg’s formula[11] for calculating power through isothermal expansion of the gas:

\[ P_{\text{mech}} = \frac{387Q(T_1 - T_0)}{M_L} \left(1 + \frac{T_0}{T_1} + \ln \frac{P_1}{P_2}\right) \]

where \( P_{\text{mech}} \) is the mechanical stirring power density (W/t), \( Q \) is the argon gas flow rate (Nm³/sec), \( T_1 \) is the steel temperature (K), \( T_0 \) is room temperature (K), \( P_1 \) is the pressure at the ladle bottom (Pa), \( P_2 \) is the pressure above the liquid surface (Pa) and \( M_L \) is the liquid metal weight (ton). Figure 11 shows the results of the mixing time trials. These experimental results confirm superior liquid steel mixing with combined Ar-gas and 1350A EMS currently installed at EQS, as predicted by the CFD modeling.

![Figure 11: Copper tracer mixing time results](image)

5.2.2 Free Metal Surface Comparison

The CFD modeling results for free metal surface were tested with trials at the EQS vacuum station using the stirring parameters as indicated in Table 2, with the exception of argon flow rate. Due to the camera view angle at the EQS vacuum station, it is not possible to see the entire liquid surface during vacuum treatment. At typical argon flow rate of 80 Ni/min the visible area shows nearly 100% exposed liquid steel. In order to show the difference in surface area exposure, the argon flow rate for this trial was reduced to 60
Images from the vacuum station for each case (and also without Ar-gas or EMS stirring) are shown in Figure 12, where the increased free metal surface for combined induction and argon stirring was recorded utilizing a CCTV mounted in the vacuum hood, see Figure 6.

![Figure 12: Camera view images for different stirring at EQS vacuum station](image)

### 5.2.3 Hydrogen Removal Comparison
85 heats were produced without the use of EMS during vacuum treatment. The trial parameters were as follows:

- Vacuum pressure < 1.0 mbar
- Vacuum treatment time minimum 20 minutes

Table 4 shows the results of this trial compared to heats using EMS that met the same parameter requirements above during 2017. A histogram of the hydrogen values after vacuum treatment is shown in Figure 13. The average vacuum pressure was slightly lower for the case of combined Ar-gas + EMS stirring, however this would only account for about 0.02 ppm difference in equilibrium hydrogen according to Sievert’s Law. Combined Ar-gas and EMS stirring significantly improves the exposed liquid steel surface, bulk mixing and Ar-gas bubble retention time, giving consistently lower post-vacuum hydrogen content.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ar-gas only (No EMS)</th>
<th>Combined Ar-gas + EMS 1350A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of heats</td>
<td>85</td>
<td>3256</td>
</tr>
<tr>
<td>Average pressure, mbar</td>
<td>0.77</td>
<td>0.72</td>
</tr>
<tr>
<td>Average time, minutes</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>Average H after vacuum treatment, ppm</td>
<td>1.05</td>
<td>0.59</td>
</tr>
</tbody>
</table>

*Table 4: Results of Ar-gas only stirring trial vs Combined Ar-gas + EMS 1350A*

![Figure 13: Post-vacuum treatment hydrogen for Ar-gas only stirring trial vs Combined Ar-gas + EMS](image)
5.3 Hydrogen Removal Results
Vacuum treatment (typically at < 1 mbar pressure) is performed on every heat produced at EQS. Vacuum treatment time ranges from 10 – 30 minutes depending on the steel grade and cross section being produced. The average hydrogen content in the ladle after vacuum treatment with combined Ar-gas and EMS stirring at EQS is shown from 2014 – 2018 YTD in Figure 14. Continuous improvement efforts by EQS Steelmaking and Maintenance departments have been effective in maximizing the vacuum station efficiency.

![Average hydrogen after vacuum treatment by year](image)

**Figure 14.** Average hydrogen after vacuum treatment by year

6. Hydrogen Pickup
After vacuum treatment is complete the liquid steel must be protected from hydrogen sources such as moisture and hydrocarbons. In the secondary steelmaking operation at EQS, the primary hydrogen sources after vacuum treatment are atmospheric moisture and moisture present in alloying additions. Atmospheric moisture is controlled by maintaining complete coverage of the bath with a liquid slag layer during post-vacuum secondary steelmaking operations. This is possible even during reheating at the ladle furnace due to EMS stirring without breaking the slag cover. All potential sources of hydrogen such as argon stirring, alloying additions and slag additions are strictly controlled after vacuum treatment.

Hydrogen is tested after vacuum treatment for every heat produced at EQS in order to ensure that the necessary hydrogen removal was achieved. An additional hydrogen test was taken from the ladle just prior to bottom pouring on 190 heats and compared to the test taken immediately after vacuum treatment in order to verify that the post-vacuum treatment secondary steelmaking operations do not make a significant contribution to the hydrogen pickup. The results of this trial showed an average of <0.1 ppm higher hydrogen in the test just prior to bottom pouring, which confirms that there is no significant hydrogen pickup during the post-vacuum treatment secondary steelmaking processes at EQS.

During the teeming operation there are several sources of hydrogen pickup:

- Ladle slide gate refractory components
- Atmospheric moisture
- Bottom pour tile and mortar cover
- Teeming flux

The influence of these various hydrogen sources on hydrogen pickup during bottom pouring were investigated in detail using data collected and analyzed for over 30,000 heats produced at EQS.
6.1 Ladle slide gate refractory components
The ladle slide gate refractory components include the ladle inner nozzle, slide gate plates and collector nozzle. Typical life for various ladle and slide gate refractory components are listed in Table 5.

<table>
<thead>
<tr>
<th>Component</th>
<th>Component life (heats per replacement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ladle brick (barrel + slagline)</td>
<td>80</td>
</tr>
<tr>
<td>Inner nozzle</td>
<td>15-20</td>
</tr>
<tr>
<td>Slide gate plates</td>
<td>5</td>
</tr>
<tr>
<td>Collector nozzle</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5: Typical replacement life for ladle and slide gate refractory components

Figure 15 shows the average relative hydrogen pickup for the first five heats on a new ladle (all components from Table 5 replaced for 1st heat on ladle) and for heats where only the inner nozzle or slide gate plate / collector were replaced. Note that the slide gate plates and collector nozzle are always replaced when the inner nozzle is replaced.

Hydrogen pickup for a brand new ladle compared to a new inner nozzle and slide gate plates is identical, which indicates that the newly refined ladle has no impact beyond the new inner nozzle and slide gate components. This is due to vacuum treatment after initial exposure of the barrel and slagline to the liquid steel. The largest contribution to hydrogen pickup from these refractory components is due to changing the slide gate plates and collector nozzle, accounting for up to 17% of the hydrogen pickup. EQS has specific ladle refractory requirements in place for hydrogen-critical heats as part of the “Ultra-Low Hydrogen Practice” in order to ensure minimal hydrogen pickup from new refractory components.

![Graph showing contribution to hydrogen pickup](image)

Figure 15: Effect of slide gate refractory status on hydrogen pickup

6.2 Atmospheric moisture
Atmospheric moisture can have a significant contribution to hydrogen pickup during bottom pouring if the liquid steel stream is not protected from contact with the atmosphere. Argon shrouding is performed on all heats produced at EQS, with the exception of specific grades where particular customer requirements will not allow this practice.

The benefits of argon shrouding are more pronounced during hot, humid weather due to the additional moisture in the atmosphere. The relative hydrogen pickup for non-shrouded and shrouded heats produced since 2015 are shown by month along with average monthly humidity in Figure 16. Relative hydrogen pickup is expressed as percentage of average (100% being the average of all heats). Argon shrouding results, on average, gave 35% lower hydrogen pickup compared to non-shrouded heats.
The EQS argon shroud design was improved significantly at the end of 2015. The new argon shroud design allows for 100% sealing of the liquid metal stream from the atmosphere and positive pressure of argon within the shroud. Oxygen testing within the argon shroud during actual teeming operations confirmed oxygen levels below 0.5%, indicating that atmospheric exposure is reduced by more than 97% when the EQS shroud is utilized.

In the production of large ingots (> 47 Mton) where the sandwich pouring process is used to pour more than one ladle of liquid steel into a single mold, the liquid stream from the top ladle(s) is completely protected from the atmosphere by a ladle-to-ladle shroud. The shroud is submerged into the liquid bath of the lower ladle for the entire duration of pouring from the upper ladle46.

6.3 Bottom pour tile and mortar cover

Refractory bottom pour tile contains some small amount of moisture that is absorbed after production during packaging, transport and storage. Moisture content testing of EQS bottom pour tile confirmed that the practice of sealed pallet, dry storage prevents any significant moisture pickup in the bottom pour tile during storage.

One source of moisture to the bottom pour tile is the refractory mortar that is used for compression of the tiles once they are set in the sprue plate. The refractory mortar is an olivine-based material that is mixed with 5 – 10% water in the bottom pour plate preparation area and evenly applied on top of the runner brick channel after bricks have been set. When the refractory mortar is cured by the hot sprue plate it turns very hard, locking all of the bottom pour tiles together and assisting in compression.

A hygrometer was placed inside the bottom pour tile in order to measure the specific humidity (g H\textsubscript{2}O / kg air) within the bottom pour setup. A separate hygrometer was placed in the open atmosphere for comparison. Figure 17 shows that the humidity inside bottom pour tile initially is decreasing when the tiles are first set, likely due to the heating of the tiles by the hot sprue plate driving off residual moisture. When the mortar is applied to the brick there is a significant increase in the specific humidity.
This increase in specific humidity within the bottom pour system presented a potential source of hydrogen pickup. Ohmori et al. found that preheating the bottom pour tile with dry forced air can reduce the moisture content of the refractory and reduce hydrogen pickup. EQS has developed and implemented a bottom pour tile preheating system that is used for the production of all large (>47 Mton) ingots. The preheating system is capable to reach air temperatures of 500°C in order to drive all moisture out of the refractory bottom pour system.

6.4 Teeming flux

The teeming flux used during bottom pouring at EQS contains approximately 0.25% moisture by weight according to recent analyses. At EQS the teeming flux addition is based on the ingot cross-section and total volume. Figure 18 shows the average grams of hydrogen pickup versus the grams hydrogen present in the teeming flux moisture for various ingot sizes produced at EQS. The dataset excludes heats with new slide gate or inner nozzle refractory components. Hydrogen pickup correlates strongly with the hydrogen present in the teeming flux.

![Graph showing the relationship between hydrogen pickup and hydrogen present in teeming flux](image)

Figure 18: Hydrogen pickup vs hydrogen present in teeming flux

When using molds that have been adequately preheated, EQS has found that application of flux by pouring directly into the hot mold allows removal of some residual moisture from the flux and results in ~8% reduction in the hydrogen pickup. This flux application method has been incorporated into the Ultra-Low Hydrogen Practice.
7. Results and Conclusion

The EQS secondary steelmaking processes consistently deliver high-quality, low hydrogen liquid steel to the teeming bay. Standard practices in the bottom pouring operation minimize hydrogen pickup during routine operation. In the production of large ingots (> 47 Mton) where sensitivity to hydrogen becomes even more significant, special Ultra-Low Hydrogen Practices are in place to ensure < 1.5 ppm H in the final ingot:

- Specific ladle scheduling rules to ensure previous liquid steel exposure to inner nozzle, slide gate and collector nozzle
- Vacuum treatment at < 1 mbar pressure with combined EMS and Ar-gas stirring
- Strict limitations on alloying and slag additions after vacuum treatment
- Argon shrouding of the lower ladle stream
- Ladle-to-ladle shrouding of the upper ladle stream(s)
- Preheating of bottom pour refractory to 500°C
- Proper preheating of mold
- Flux addition by pouring directly into hot mold for residual moisture removal

The Ultra-Low Hydrogen Practices have resulted in an average of 35% reduction in hydrogen pickup during bottom pouring. Figure 19 shows the hydrogen pickup for standard processing (including testing just prior to bottom pouring for comparison) and the Ultra-Low Hydrogen Practice. Figure 20 shows the distribution of final hydrogen analyses from sandwich poured ingots at EQS, as reported previously[4].

![Figure 19: Hydrogen pickup for standard and ultra-low hydrogen practice](image1)

![Figure 20: Histogram of final hydrogen content in sandwich-poured ingots at EQS](image2)
8. References


