The effectiveness of current control of submerged arc furnace electrode penetration in selected scenarios

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Synopsis

The electrical control of three-electrode submerged-arc furnaces suffers from a number of complexities, mostly due to the nature of the furnace electrical circuit providing power to the furnace where the three electrodes are interconnected within the furnace through the molten metal bath. This gives rise to what is known as the interaction effect[2], where variations in one electrode's current can cause comparable changes to the currents in the other electrodes, particularly in larger furnaces with low power factor.

Resistance-based control of the electrode penetration has largely alleviated these problems, since the resistance encountered by each electrode is predominantly dictated by the length and conductivity of the current path from the electrode's tip to the molten metal bath, which acts as the three-phase circuit's floating neutral point. Hence resistance changes due to tip position or conductivity changes beneath one electrode do not affect the resistances beneath the others, effectively decoupling the control of the individual electrodes[1].

Although resistance-based control is therefore generally accepted as superior to current-based control for the regulation of submerged-arc furnace electrode penetration, a few furnace operators still prefer to use current control under specific furnace conditions. This paper presents the results of analysing the performance of both current and resistance-based control in typical scenarios encountered on industrial furnaces, taking into account a number of factors including electrode penetration, power distribution, efficiency and asymmetry of the electrode currents. In order to accomplish this, three typically encountered scenarios were simulated.

The results obtained show that resistance control provides more benefit in all cases, however, the uneven electrode current distribution generated by resistance control when electrodes are on top stops may cause some concern if baking of the electrodes is required in this scenario.

Introduction

In three-electrode submerged-arc furnaces, the electrodes are typically powered by a delta connection of power transformer secondary windings, with each corner of the delta connection feeding power to an electrode. The electrodes themselves form a star circuit load, and are interconnected with each other through the molten metal bath in the furnace, with the bath forming the circuit floating neutral point.

Figure 1 shows how this appears electrically. It can be seen that for any single electrode current, the return path to the power supply has to be via the other two electrodes, since there is no other electrical path out of the furnace. The consequence of this is that any movement of, or disturbance under an electrode causing a change in current in that electrode, will affect the currents in the other two electrodes as well. This is referred to as the interaction effect[2], and can lead to operational and metallurgical problems on the furnace. The interaction effect is particularly severe on larger furnaces with lower power factor, and when one electrode is short and continuously sitting on bottom limit of the electrode hoist travel.

Submerged-arc furnaces usually make use of Soderberg 'self-baking' electrodes, which comprise cylindrical steel casings welded together to form an electrode column shell, which is then loaded with electrode paste. This paste is melted and baked solid by the increasing heat generated by the electrode's current as the paste moves closer to the electrode contact clamps where the currents enter the electrode from the transformer connections. In order to bake the paste properly, the appropriate levels of current are required to provide the heating to solidify the electrode paste at the correct rate[3], which is proportional to the square of the electrode current. Further, to counteract the effect of erosion of the electrode tips within the furnace, the electrodes are slipped through the electrode hoist holders using a pair of slip rings at regular intervals to maintain their lengths. If the current levels are too low, the paste takes longer to bake. This can result in a short

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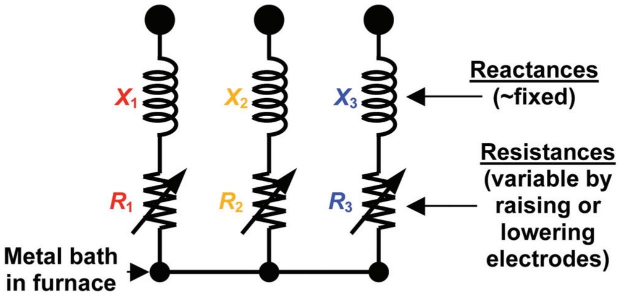

Figure 1—Simplified equivalent circuit of a submerged-arc furnace

electrode if operators are forced to reduce the slipping rate to prevent the baked paste level dropping too far below the electrode contact clamps, or at the extreme, a green break, where the electrode breaks off completely due to poor baking.

Besides being crucial from a power optimization point of view, electrical balance is therefore also critical for electrode management to ensure sustained furnace performance and availability, as all three electrodes need to be slipped and baked at equal rates as far as possible to ensure the lengths do not vary too significantly, and are maintained close to their ideal lengths to ensure they fall within the travel range of the electrode hoists.

Resistance control of electrodes is generally considered superior to current control[4,5] as it eliminates the interaction effect, which gives rise to unnecessary electrode movement under current control. In extreme circumstances, furnace operators may choose to revert to manual or current control in order to attempt to balance the furnace, invariably using the electrode currents as reference when operating manually.

Tests were conducted to see whether this course of action is justified by testing three extreme scenarios on a furnace simulator, and comparing the performance of current and resistance controllers with identical characteristics.

Experimental procedures

Test conditions

In order to eliminate any effects caused by metallurgical conditions, and purely evaluate the electrical behaviour, the tests were undertaken on an ideal furnace simulator. This is a software simulator developed at Mintek that models the entire furnace electrical circuit. Disturbances are simulated by adjusting a simulated metal bath level beneath each electrode, effectively altering the electrode resistance. These bath level changes can be automated by specifying a resistance range and rate of change for bath movement, and can be adjusted independently for each electrode.

Current control was achieved by manipulating the resistance controller's setpoints to achieve the corresponding current setpoint. This results in the two controllers having identical tuning characteristics in terms of deadbands and control action responses and allows for directly comparable results.

Scenarios tested

Three typical scenarios encountered on furnaces were tested, under various conditions:

- *All electrodes free* (FR)—The 'free travel' scenario is when all the electrodes are free to move, which is normally the case in practice when all electrodes are near their correct, ideal lengths. In this simulation, all three electrodes are assumed to have ideal and equal length. One electrode is moved up and down in response to fluctuations in the metal bath position of the simulator.
- *One electrode on bottom stops* (BS)—In the 'bottom stops' scenario all the electrodes are free to move, except for one electrode which is forced to the bottom of its hoist travel range in response to the metal bath position of the simulator falling. This is analogous to having one short electrode on an industrial furnace, which results in the electrode being lowered all the way to the bottom of its travel range in order to achieve the setpoint for resistance or current. The remaining two 'free' electrodes are assumed to be at the ideal length, corresponding to mid range of the hoist travel when at setpoint and zero metal bath deviation.
- *One electrode on top stops* (TS)—In the 'top stops' scenario all the electrodes are free to move, except for one electrode which is forced to the top of its hoist travel range in response to the metal bath position of the simulator rising. This is analogous to having one long electrode on an industrial furnace, which results in the electrode being lifted all the way to the top of its travel range in order to achieve the setpoint for resistance or current. Similar to the 'bottom stops' scenario, the remaining two 'free' electrodes are assumed to be at the ideal length.
- *Rate of bath change*—Each of the above scenarios was tested for both a slow and a fast rate of change in the simulated metal bath level. In practice, the slow rate represents typical build up and wash out of metal over a tapping cycle, while the fast rate of change represents rapidly changing, unstable furnace conditions.
- *Type of control*—All the scenarios were tested with both resistance and current control.

Scenario parameters

Resistance control tests were performed at a typical operating point of an average sized Ferrochrome furnace. For resistance control, a resistance setpoint of 2 mΩ was used, while for the current control tests a setpoint of 78 kA was used. The power setpoint was 35 MW in both cases.

It is important to note that the tests were carried out on a furnace operating at a reasonably high power factor of 0.85. Larger modern ferrochrome furnaces, as well as those producing other types of ferroalloys, are likely to operate at significantly lower power factors, where the adverse effects of the interaction effect are more severe.

The relevant furnace simulator and controller limits were configured as follows:

Transformers:	48 MVA (3 x 16 MVA transformers, differential tapping enabled)
Electrode current limit:	88 kA
Power factor:	0.85
Resistance deadband:	± 0.5 mΩ (≈ ± 1.0 kA at setpoint)

Results

Figures 2 to 7 compare the results obtained for the resistance and current control tests in each scenario. For clarity, results are displayed only for a slow rate of change in the simulated metal bath, as the results for a fast rate of change were not significantly different in most cases. However, vastly increased current asymmetry (24%) was observed under current control in the 'free travel' scenario when the bath levels were changing rapidly.

Figure 7 gives an indication of the sum of squares deviation of the electrode current from the normal operating value to demonstrate the effect the unbalance has on baking of the electrodes, which is proportional to the square of the current.

Discussion

Electrodes in free travel (FR)

As is evident from the figures, under normal operation where

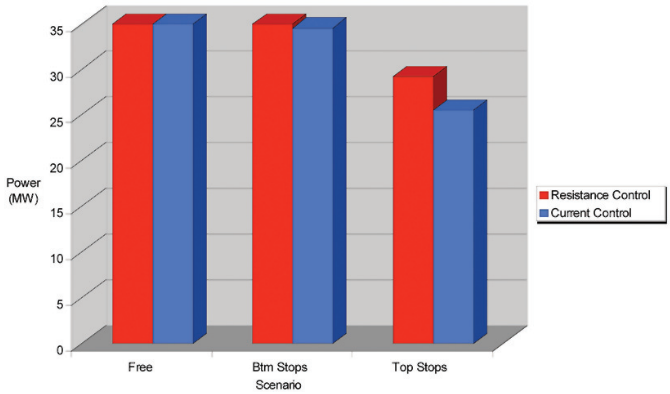

Figure 2—Power input

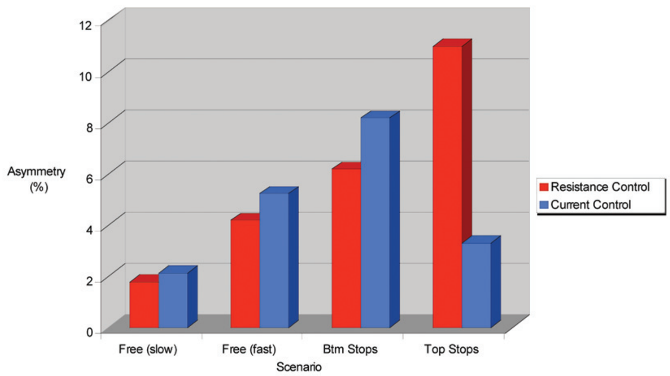

Figure 3—Electrode current asymmetry

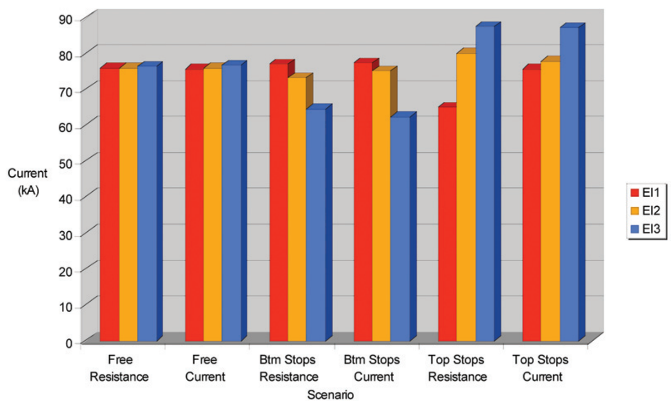

Figure 4—Electrode current distribution

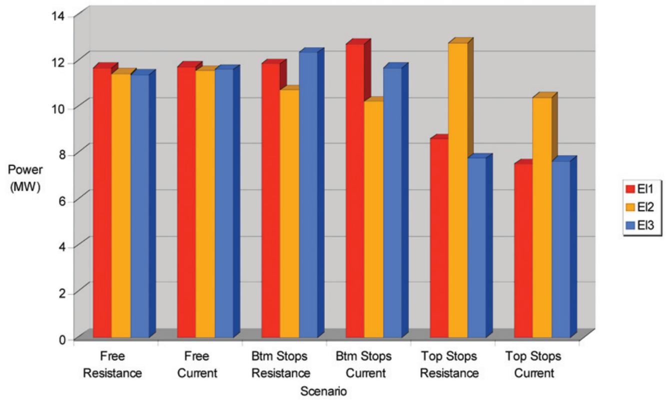

Figure 5—Electrode power distribution

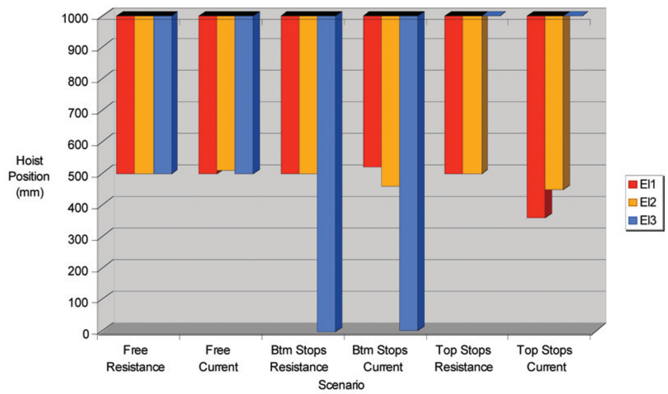

Figure 6—Steady state hoist positions

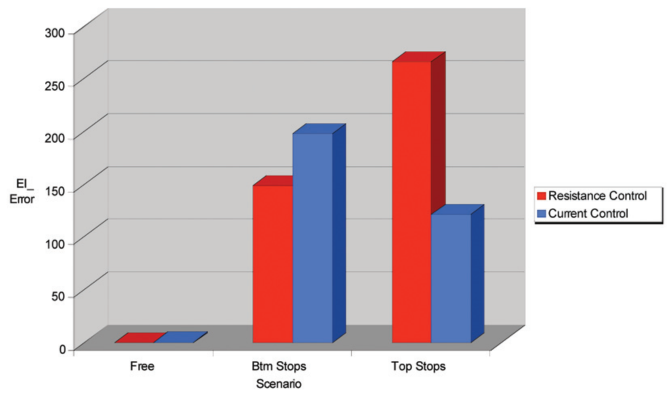

Figure 7—Sum of squares electrode current error

both electrodes are free to move, and the controllers are able to correct any drift in a single control action, there is not much notable difference between resistance and current control, with both successfully maintaining the power setpoint and the load balanced evenly between electrodes. When all electrodes are free to move under fairly stable conditions, current and resistance control are essentially identical. This is because the current controller can correct deviations from an electrode's setpoint quickly enough that the disturbance caused by current interaction on the others, which will be of smaller magnitude at a power factor above 0.5, will be corrected before the controllers on the other electrodes need to take action.

However, when the furnace is unstable and conditions are changing rapidly beneath any electrode and the current controller cannot correct for the disturbance immediately, the resulting net change in the electrode's current begins having a noticeable sustained effect on the currents of the remaining electrodes, and their current controllers begin responding, causing the electrodes to begin 'hunting' for the setpoint.

This is evident in the increased current asymmetry in Figure 3's current control for FR (fast). The consequence of this 'hunting' is unnecessary movement of the electrode hydraulics, causing increased electrode erosion and unnecessary upset of the furnace reaction zone, resulting in poorer recovery and efficiency.

Electrodes on top stops (TS)

With one electrode limited to the upper limit of its travel, neither resistance nor current control is able to meet the power setpoint, but resistance control yields a significantly higher power delivery than current control. The reason why neither meets setpoint is because when the one electrode (electrode 3) reaches top stops, the electrode's resistance decreases rapidly as the bath level continues to rise. This causes the current in this electrode to rise above its maximum limit. This is analogous to having a long electrode, or a high conductivity over-carboned state under one electrode. In response, the controller is forced to tap the furnace transformers down several times to reduce this electrode current to within its limit. This tapping down reduces the input power to below setpoint.

The reason resistance control produces higher power delivery than current control in this scenario is that with current control, as the transformers are tapped down to reduce the electrode current in the electrode at top stops, the currents of the remaining electrodes are also reduced. In response, the current controller lowers these electrodes to increase their current to setpoint once more. However, due to the interaction effect, this causes the electrode current in the electrode at top stops to increase even further above its maximum limit. This means that the transformers must be tapped down further to reduce this electrode current once more to within its limit.

These additional tap down actions reduce the power obtained with current control to below that obtained with resistance control. Figures 8 and 9 are screenshots of scenario TS for resistance and current control respectively. Under resistance control it is possible to maintain the transformers at tap 8 without exceeding the electrode current limit, while under current control the transformer taps are reduced to tap 4.

Although current control results in 5 MW (14%) less power input than resistance control in this case, it does produce deeper penetration of electrodes 1 and 2 (see the right-hand side of Figure 6 above). In practice, this should reduce heat losses from the top of the furnace marginally, but not to any extent sufficient to make an impact on the 5 MW loss in overall power input. Current control does, however, significantly reduce electrode current asymmetry (see Figure 3) and sum of squares error (Figure 7) compared to resistance control, which might be an important consideration from an electrode slipping or baking point of view. However, in practice, the 'top stops' scenario is usually associated with a long electrode, so it is highly unlikely that baking or slipping would be of major relevance when this scenario is encountered in practice.

Electrodes on bottom stops (BS)

In the case where one electrode is at the bottom limit of its travel, which could be encountered as a result of a short electrode, or low conductivity under-carboned state beneath one electrode, it is evident from Figure 3 that resistance control results in lower current asymmetry than current control. Further, current control applies more power to the 'free' electrode whose tip is closest to the surface of the furnace (see Figure 6), resulting in increased heat losses and most likely lower furnace efficiency.

In this case, the interaction effect actually results in a poorer sum of squares deviation for current control than resistance control despite the current control distribution of the electrode currents visually seeming better. This is mainly due to the lower current value obtained in the short electrode

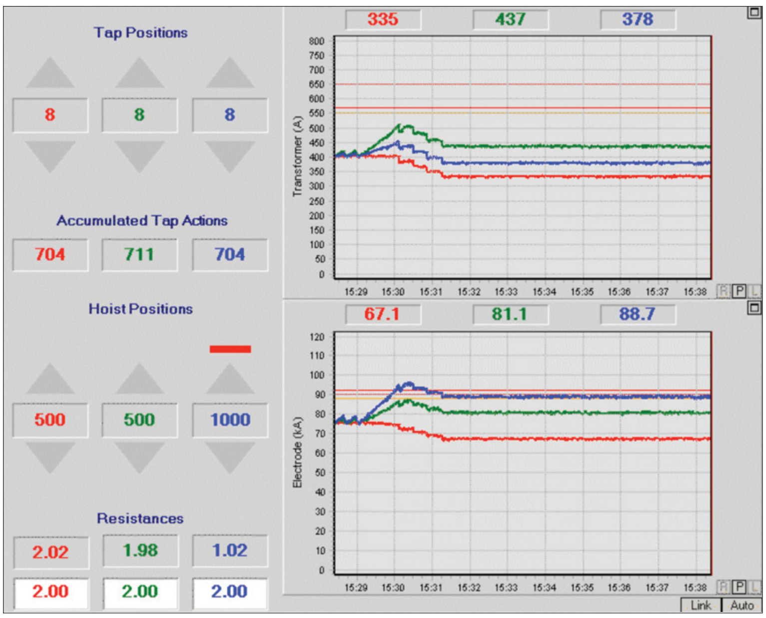

Figure 8—Transformer tapping for resistance control of top stops scenario

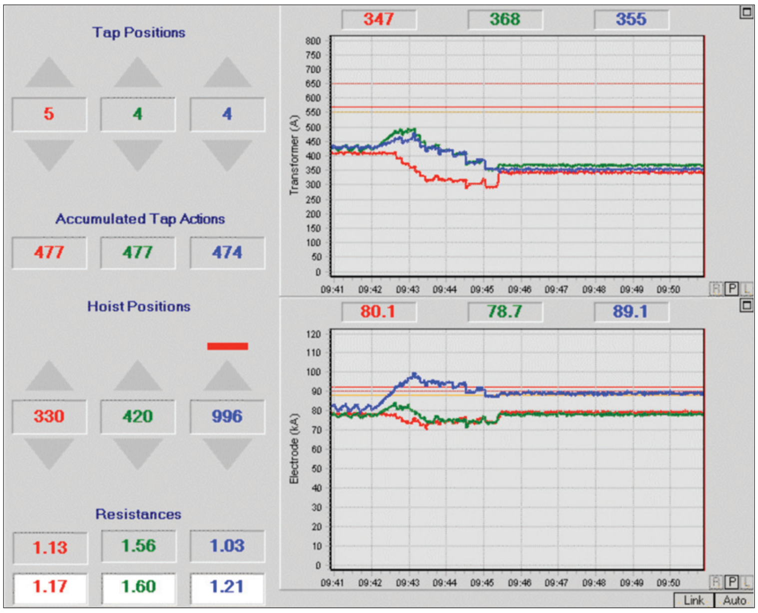

Figure 9—Transformer tapping for current control of top stops scenario showing the lower tap positions (and hence power) in this scenario compared to that in Figure 8 for resistance control

3 on bottom stops under current control when compared to resistance control. The cause of this is as follows—as electrode 3 reaches the lower limit of its travel and the electrode cannot be moved down further to curb the further decrease in current, electrode 3's decreasing current causes electrode 2's current to start decreasing too. In response, the current controller lowers electrode 2 to increase the current back to setpoint, which in turn increases electrode 1's current. The current controller subsequently lifts electrode 1 to reduce the current in electrode 1 again, and this in turn further reduces the already low current in the problematic short electrode 3 which is on bottom stops. The resulting lower current in electrode 3 hinders the rates of baking and slipping of this short electrode, which are proportional to the square of the current, that are required in order to recover its length.

Furthermore, Figures 5 and 6 show that under current control, electrode 1, which has unnecessarily been raised, has by far the highest power consumption. This results in increased heat losses and poor efficiency of this electrode, and a significantly increased electrode burn-off or consumption rate for this electrode. Simultaneously, furnace operators unaware of the electrical reasons behind electrode 1 rising in the furnace, may be inclined to interpret the rise in electrode 1's hoist position as an indication that electrode 1 is becoming long, and may decrease its slipping rate in response. The combination of a decreased slipping rate and dramatically increased consumption rate results in an electrode which gets short very rapidly. When electrode 3, which was the original short electrode, finally recovers, electrode 1 is now likely to have become short, and so the problem shifts from one electrode to the next. This phenomenon is what is known as chronic imbalance[2].

Resistance control reduces the chances of this ongoing problem by maintaining the other two electrodes at their correct penetrations, and more balanced power distribution, so that they are slipped correctly and consumed more equally.

Conclusion

Where electrodes are allowed to move freely, current and resistance control appear to produce very similar results overall, provided the conditions within the furnace are not changing too rapidly. Where upset conditions are present, resistance control surpasses current control in that it does not move unaffected electrodes unnecessarily.

Resistance control also results in lower current asymmetry and more even power distribution when one electrode is at bottom stops. Current control applies more power to the electrode that is highest in the furnace, resulting in poor efficiency and possibility of prolonged chronic imbalance.

The power obtained by resistance control with an electrode on top stops was below setpoint, but significantly higher than that obtained by current control. Although electrode penetration is deeper for current control in this scenario, the efficiency improvement is unlikely to counter the significant loss of power to any extent. The current asymmetry under resistance control when on top stops is higher than that obtained for current control, which could potentially impact negatively on electrode baking. However, in this scenario, it is unlikely that baking should be an issue since in this case, the electrode is long.

It is therefore clear that operating a furnace under current control when an electrode is limited in its travel can have detrimental effects on the furnace performance in both the short and long-term. On consideration of all the data it is clear from an electrical point of view to be better to use resistance control in all scenarios. However, the uneven electrode current distribution generated by resistance control when an electrode is at its top limit may cause some concern if baking of the electrodes is required.

Optimal furnace performance is a fine balance of the contributions of a number of competing electrical factors including total power input, power distribution between electrodes, electrode penetration, and electrode baking current, many of which have direct impact on one another. The above analyses show that there is no single electrical parameter that can be used to measure and control furnace performance optimally. Many furnace operators have limited experience and understanding of the complex trade-offs that occur within a submerged-arc furnace three-phase electrical circuit and how they affect furnace performance. As a result, inexperienced operators may resort to the simplest and most familiar form of control, electrode current, when faced with an abnormal furnace condition, and believe that they are controlling the furnace more effectively based on the electrode current values alone.

The analyses show that this is not the best course of action, and could result in long-term negative impact on furnace performance. Work is currently underway at Mintek to develop key performance indicators specifically for submerged-arc furnaces that provide a more holistic measure of furnace performance, which will make the negative impact of poor control practice on furnace performance obvious to even inexperienced operators.

A further consideration is that the definition of optimal furnace performance is likely to change depending on furnace condition and other external factors such as feed or energy supply restrictions. An advanced control system should thus accept input from the operators to indicate the main objective, and determine the most appropriate course of action for the present conditions. Simulating alternate furnace operating points and control actions in real time will assist in determining the optimum furnace operating point for the given objective.

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