MELT LOSS EVALUATION

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Melt loss is generally recognized as one of the highest cost factors in an ingot plant. Its monitoring has evolved from simply being the closing figure in the metal balance into quantifying the melt loss figure for an entire ingot plant into analyzable process oriented data with a fairly high degree of accuracy. This paper will discuss the method of quantification and its use for monitoring and improving melt loss performance. A melt loss analysis of a hypothetical plant is included for the purpose of illustrating the methodology.

INTRODUCTION

The United States aluminum industry is approximately a seven-million-ton annual market with a 150-200 thousand ton reported melt loss. Even at today's depressed aluminum prices, this is a significant monetary loss and it represents a substantial portion of the total ingot manufacturing cost.

Yet, until recently, reported melt loss in most plants was one of the least controlled cost factors. Traditionally, the melt loss number represented all metal unaccounted for. That includes bookkeeping errors, metal lost during transport, and nonmetallic contaminants weighed in as part of the metal charge in addition to the true melt loss.

Before the 1973 energy crisis, metal units were relatively inexpensive and plentiful, resulting in melt loss being a low priority issue. However, rising energy cost and the increase in recycling of old scrap, especially beverage containers, have drastically changed that picture.

Melt loss reducing procedures and processes were introduced and melt loss tests were designed to quantify the effect of the intended improvements. Since actual melt loss results from the interaction of a large number of variables, the quantification process is rather complex and the results are often viewed with skepticism. Yet, it can be shown that the melt loss figure for an entire ingot plant can be quantified with a fairly high degree of accuracy using a relatively simple technique to analyze the data.

Furthermore, the analysis will point out that melt loss performance can be monitored and that changes introduced to improve performance can be quantified.

BACKGROUND AND DEFINITIONS

As stated above, melt loss was traditionally defined as the closing number in a metal inventory.

In order to be able to predict the metal shortage due to losses, arbitrary melt loss numbers were assigned to the scrap types which were remelted in the plant. By iteration and continually readjusting these "standards," the "missing" amount of metal could be approached more or less successfully.

The most simple and straightforward definition of melt loss is:

$$\text{Gross Melt Loss \%} = \frac{\text{Weight In} - \text{Weight Out}}{\text{Weight In}} \times 100\%$$

This definition was adequate, when only "clean" scrap was melted and skim was sold; but when the energy conservation drive started, melt loss reduction became a mandatory ingredient. Dirty, contaminated scrap that used to be sold was melted in-house and metal recovered from skim reentered the metal flow loop in the ingot plants. New processes were developed to reduce the high melt losses associated with these scrap types.

Quantification of melt losses became necessary to calculate the "cost of remelting dirty scrap," especially used beverage containers. Since huge amounts of skim were generated, from which a substantial portion was recovered, a new practical definition was introduced.

$$\text{System Loss \%} = \frac{\text{Scrap Weight In} - (\text{Metal Out} + \text{Skim Recovery})}{\text{Scrap Weight In}} \times 100\%$$

Since the dirt and contaminants are an integral part of the scrap, this definition does monitor the financial losses well, but is inadequate to determine the real metal losses, which is necessary if comparisons of effectiveness are made between different processes or procedures. For that purpose is introduced:

$$\text{True Melt Loss \%} = \frac{\text{Metal In} - (\text{Metal Out} + \text{Skim Recovery})}{\text{Metal In}} \times 100\%$$

Having eliminated all nonmetal contributions to melt loss, the largest factor determining the ultimate amount is skim generation. Since skim is generated in many places and for a number of reasons, it is appropriate to review the factors that cause skim generation during the entire melt operation.

FACTORS CONTRIBUTING TO SKIM GENERATION

1. Oxide Film on Scrap

Even if the scrap to be charged in a furnace is free of external contaminants, there will be an oxide film on the scrap which, depending on the total surface area, can be a noticeable amount. Alfaro[1], interested in quantifying the contribution to melt loss by the oxide on the scrap, designed a test to simulate an average charge to an open hearth furnace. By weighing the skim, then dissolving the aluminum and weighing the remaining oxide, he determined that 0.18% of an "average charge" consists of oxides. Freti et al.[2] have measured oxide films on foil directly and found the 50Å thick oxide film on capacitor foil to represent 0.11 wt.%. Using the dissolution method on beverage containers they found 0.22 wt.% oxide after chemical delacquering at room temperature and 0.82 wt.% oxide after thermal delacquering.

This is a reminder that different alloys under similar circumstances can have substantially different oxide skins and also that identical materials with different "histories" will enter the melt phase with different oxide contents.

Furthermore, it should be noted that the surface area to volume ratio of the mentioned materials is very different. It is obvious that a material with a relatively high surface area will be affected more by premelt oxidation than the same material with a low surface area.

2. Molten Metal Oxidation

In contrast with the vast literature on oxidation of solid state aluminum and its alloys, there are few publications on liquid aluminum oxidation.
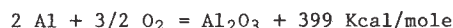
Sleppy[3] found that for pure aluminum the traditional logarithmic law is basically followed below 700°C and a modified parabolic law above 750°C. He emphasized the influence of the existing oxide film prior to melting on the behavior in the liquid state. Thiele[4], using thermal gravimetric test procedures and X-ray diffraction analysis of the oxidation product, proposed that the first oxide formed at any temperature is γ-Al$_2$O$_3$, a tight protective layer of spinel like cubic structure, which brings the oxidation quickly to a halt. After an incubation period, which is a function of temperature, the γ-Al$_2$O$_3$ transforms into the much denser hexagonal α-Al$_2$O$_3$. Stresses at grain boundaries or cracks in the layer will permit ionic transport and the oxidation will resume at rates not necessarily obeying any of the traditional laws. The higher the temperature is, the shorter the incubation time and the faster the growth rate.

Drouzy and Richard[7] conducted a comprehensive review of the influence of alloying elements on the oxidation behavior of aluminum. Many of the elements commonly used with aluminum, such as Cu, Fe, Mn and Si, do not have much impact. Zinc and magnesium, however, have a profound accelerating affect.

Thiele[4], Cochran et al.[5] and Belitskus[6] studied oxidation of liquid Al-Mg alloys under a variety of atmospheric conditions. Their general conclusion is that no protective film is formed at any stage. Early on, a crystalline, porous layer of MgO is formed preferentially, which later, as the aluminum oxidation increases, converts to spinel: MgO·Al$_2$O$_3$. The conversion nucleates on MgO crystals which leaves channels in between for metal transport to the surface. This results in the familiar cauliflower growth pattern of Al-Mg spinel above the metal surface.

In most remelt operations scrap is charged to entirely fill the furnace. The burners will strike the top and outside of the pile directly while the center remains cold. As the metal in the top melts, it will drip down and solidify on the cold metal underneath. Depending on the scrap type and charging method, this can happen several times before the entire charge is liquid. Every time, the oxide film will be broken and the exposed surface will form a new oxide skin. By the time the melting is complete, there is a mass of randomly oriented oxide skins with metal and gas trapped in between, floating on top of the melt (skim or dross).

At this stage most of the oxide trapping the metal inside the skim will be in the form of protective γ-Al$_2$O$_3$ films, and the entire layer can be relatively stable. If, however, through excessive heat input the temperature of the skim rises and/or the residence time exceeds the incubation time for conversion to α-Al$_2$O$_3$, oxidation of the trapped metal will resume. A large surface area in the skim is exposed to the atmosphere and since the skim layer with its trapped gasses is a poor heat conductor, dissipation of reaction heat is seriously impaired. This opens the way for a rapid increase in the skim temperature. The heat of formation of the two main high temperature reactions is:

$$2 \text{ Al} + 3/2 \text{ O}_2 = \text{Al}_2\text{O}_3 + 399 \text{ Kcal/mole}$$

and for T >2000°C:

$$2 \text{ Al} + \text{N}_2 = 2 \text{ AlN} + 131 \text{ Kcal/mole.}$$

Carrying this further, if 3% of a melt would oxidize, the heat generated is sufficient to raise the temperature of the entire melt 1500°C. Applying this to a skim layer containing 75% metal and assuming no heat loss to the surroundings, only 3% of the aluminum in the skim must "burn" to raise the temperature of the entire skim mass to well above 2000°C. At that point the nitride reaction will contribute to the continuation of this runaway situation until all the aluminum has been consumed.
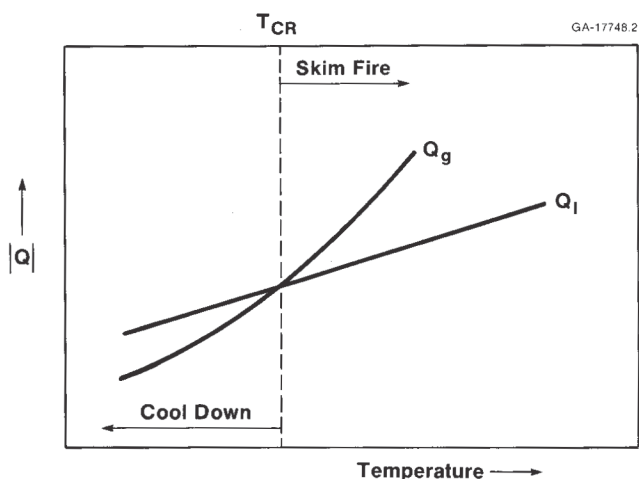
Critical Skim Temperature

Figure 1

Skim Formation by Cascading

Figure 2

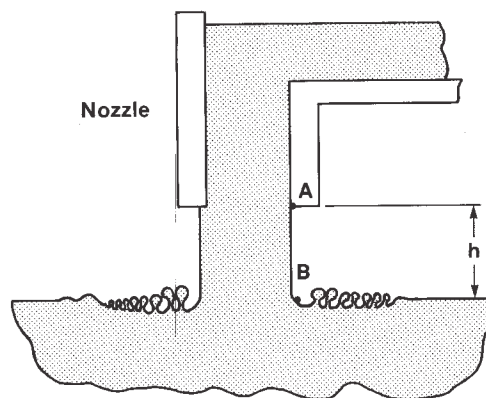Under most practical circumstances, there will be sufficient heat dissipation to the melt or through radiation to avoid the eruption of these "skim fires," but it should be realized that any skim mass has a critical temperature for the runaway reaction, as is qualitatively represented in Figure 1, in which Q_g is the generated reaction heat and Q_l the "heat loss" by dissipation to the surroundings at a given temperature.

The implications of the above are that molten metal oxidation is inevitable but that good management can contain the damage. It suggests that in furnaces containing substantial amounts of skim, the residence time and the temperature should be as low as practically possible.

3. Molten Metal Transport – "Cascading"

Whenever the protective oxide film on molten metal is ruptured, the freshly exposed metal will immediately start rebuilding it. The initially amorphous film has considerable flexibility. When it is ruptured and displaced (e.g., during mechanical stirring, gas fluxing or in a turbulent flow), it has a tendency to wrinkle and trap metal as well as air as shown in Figure 2.

Freti et al.[2] calculated the amount of oxide in a "skim ring" formed around the incoming flow of metal from a nozzle. By choosing the distance h between the bottom of the nozzle (A) and the metal level (B) such that the tensile strength of the film was exceeded and it ruptured at point A, the surface atoms of the cascade moved from A to B in Δt seconds and built an oxide film with thickness $d(\Delta t)$. At B the film is pushed down and out (see Figure 2). The amount of oxide in the skim after t seconds is:

$$M = 2\pi Rh\rho_{ox}d(\Delta t)\,\frac{t}{\Delta t}$$

in which ρ_{ox} is the density of $\gamma-Al_2O_3$.

It is assumed that the film growth stopped when point B was reached. The kinetics of film growth was determined experimentally by removing newly formed films with different time intervals from a well defined test surface and determining their weight by dissolving the metal.

The skim thus formed can initially contain up to 95% metal, but that decreases eventually to about 75%.

As will be shown later, there are many locations in an ingot plant where this "cascade" type of skim formation occurs.

SUMMARY OF THE SKIM GENERATING FACTORS

Oxides on Scrap

Oxide on scrap is usually a negligible quantity, but in cases of very fine scrap (foil) or preoxidized scrap (delacquered beverage cans) it can be a significant amount. More importantly, the amount of molten metal clinging to the oxide after melting will increase the total weight about three times based on the finding that skim is about 75% metal.

Molten Metal Oxidation

A protective film forms rapidly on the surface of most alloys, which if left undisturbed, will contain oxidation to small amounts. For some alloys, notably the higher magnesium alloys which do not develop a protective layer, continued oxidation of a still melt can be noticeable. Poor dissipation of "normal" oxidation reaction heat in skim layers causes higher reaction rates which can lead to runaway oxidation (skim fires). Maintaining minimum furnace temperature and skim residence time will help contain the losses.

Molten Metal Cascading

Molten metal cascading, or more broadly, any form of continuous rupturing of the protective film and displacing it, causes small amounts of oxide to trap large amounts of metal in the wrinkles. Level transfer and other nonsurface disturbing operating procedures can almost entirely eliminate this form of metal oxidation.

The above provides a qualitative framework to categorize the metal losses during molten metal processing according to the origin of the loss. Once a quantitative inventory has been made of the contributions by these categories to the total losses in a particular plant under normal operating conditions, two powerful tools have been created to manage melt loss: process related performance standards, and a base line for evaluating technological advances and measuring the effect.

INGOT PLANT MELT LOSS ANALYSIS

As stated in the Background, when plants started to monitor melt loss by scrap type, the discrepancies between the existing arbitrary standards and the values determined by melt loss tests were so large that it became clear that the impact of the "general" contributors--the skim generation not related to scrap type; for instance, from holding furnaces, filter boxes, metal transfer and casting pit cleanings--was much larger than was generally accepted.

With the above discussed considerations in mind, a practical model was created in which the total skim generation is composed of categorized, process related skim generating steps. Total skim generation is precisely known in most ingot plants because the skim is either sold or sent out for metal recovery. Therefore, it is an ideal focus point.

The metal recovered from skim treatment can be determined experimentally as one single percentage of total skim or, if there are large differences between the categories in recoverable metal content, as the weighted average of an appropriate number of assays.

The metal losses incurred in the course of preparing metal for melting or casting are a "legitimate" part of true melt loss and should be identified and quantified and appropriately interpreted in the computation. Furthermore, all apparent melt losses need to be identified and quantified to avoid misleading skim generation numbers and to bring to light process control deficiencies which do affect the measured skim generation.

SKIM GENERATION CATEGORIZATION

The following categories have been selected for identification purposes.

I. Cascading

This category consists of skim from metal transfer events during which oxide film rupture occurs and includes filling and emptying of crucibles, pumping and siphoning, troughing, furnace filling and draining, etc.

II. Melt Process

This includes the skim caused by the pre-existing oxide skim on the scrap and by such factors affecting molten metal oxidation as charge methods, firing rate, residence time temperature control, etc. For practical reasons these two basic skim generating factors have been combined.

III. Metal Quality

This pertains to skim generated during furnace fluxing and in-line metal treatment. This skim is categorized separately because it is the unfortunate by-product of a deliberate act to improve metal quality and should not be regarded automatically as a "loss that should be eliminated" as is definitely the case with the other categories.

IV. Metal Handling

This includes metal losses caused during preparation of scrap for melting or handling molten metal. Some of these losses are final, such as metal in floor sweepings going to the land fill. Others can be treated as "skim" because they are sent out or sold for metal recovery, such as ingot saw dust or casting pit cleanings.

V. Apparent Melt Losses

These include smelting bath in pot room crucibles which is incorrectly weighed in as metal and removed as "skim." By periodic quantification of the bath content in pot room crucibles, the average percentage can be established and subtracted from the skim as well as the incoming metal for the melt loss computation. Similar "losses" occur in scrap processing where sand, paint pigment, glass and other contaminants have the same effect if they are not removed prior to melting.

The objective of this step is to determine the weight of the skim as a percentage of the amount of metal involved for each skim generating event. Figure 4 is an example of a skim generation inventory sheet. For each event judged to have a noticeable impact on the total skim amount, a separate melt loss test is performed. These tests, when performed under standard operating conditions, should give accurate, reproducible numbers for these skim generating events. These experimentally established numbers provide the quantitative building blocks for composing the total melt loss number.

Flow Chart of Metal Losses

Figure 3

Figure 3 shows the metal flow in an ingot plant which receives pot room metal and processes both fabrication (new) scrap and consumer (old) scrap. Any expected significant melt loss contribution made during processing at a station or during transport to the next station is noted by category.

Even in this simple model the frequency of cascading events is evident. In large ingot plants in particular this can be a major contribution to total melt loss. These plants often have a number of "off-line" melt furnaces from which metal is periodically tapped or pumped into crucibles which carry the metal and cascade it into an empty on-line furnace. This double cascading alone (with up to two meters of metal level difference) can cause skim generation in the order of 2.5%.

As is to be expected, most of the apparent and handling losses are in the scrap collection, transportation and preparation area where not all contaminants can be removed entirely and some metal will inevitably leave the scrap with the removal of contaminants.

In setting up a model for an actual plant, special attention needs to be paid to the potential impact of specific procedures. For instance, when substantial amounts of salt flux are used in the melt process, this should be treated in the analysis as an apparent melt loss and the salt weight* should be subtracted from the skim weight for the true melt loss calculation.

The flow chart (Figure 3) shows that the true melt loss is the sum of the oxides and unrecovered metal from skim treatment and the handling losses.

Comprehensive Skim Generation Inventory

	Event	Skim Category	Metal Weight (in kg)	Skim (Weight Percentage)
1.	Syphon Into Crucible	I/A	—/—	—/—
2.	Tap Crucible in Furnace	I	—	—
3.	Add Alloying Material	I/III	—/—	—/—
4.	Transfer to Holder	I	—	—
5.	Flux or Metal Treatment Unit	III	—	—
6.	Cast	IV	—	—
*7.	Collect Scrap	IV/A	—/—	—/—
8.	Prepare Scrap	IV/A	—/—	—/—
9.	Transport Scrap	IV	—	—
10.	Charge Scrap (Join Steps 3-6)	I/II	—/—	—/—
11.	Oxidizing Skim to Skimhouse	III	—	—
12.	Skim Treatment	II	—	—
13.	Metal to Remelter	II	—	—

*Steps 7-10 Need Scrap Oriented Approach (eg. UBC's, Scalper Chips, Light Trim, Painted Scrap, Heavy Scrap, etc.)

Figure 4

In many cases these data are available or readily-obtainable. For instance the metal content of a pot room crucible is known. Thus, collecting and weighing the skim after one or two crucibles have been charged without performing any other skim generating act (and of course starting with a clean furnace and crucible) will provide adequate information for a first approach. Alloy sensitivity of a skim generating event may require separate determinations for each alloy.

Process steps may differ significantly for different scrap types. Some plants have side well melters for light scrap and regular reverberatory furnaces for heavy scrap. In most cases sufficiently accurate data can be obtained by grouping scrap types of similar skim generating behavior.

Other process steps may be different for various end products. For example, when gas fluxing in a holding furnace or on-line metal treatment is required, the skim generation in the metal quality category will be much higher than for products not requiring such treatment.

*Assuming that salt fuming is negligible.

Finally, concerning metal handling losses, a distinction should be made between irretrievable and recoverable losses. For instance, metal fines, heavily oxidized during UBC* delacquering, are most likely completely lost, but casting pit cleanings and screened out fines from scalping chips are collected and represent a certain recoverable metal value. If the product is sold for a fraction X of the nominal metal value, it should be considered an apparent melt loss (1-X) times the actual amount removed from the production process. If the product has recoverable value similar to that of average skim, it should be handled and reported as skim.

CLOSING THE LOOP

In order to achieve the ultimate objective of this exercise, the individual contributors have to be related proportionally to "compose" the total skim generation for a given period.

This composed total skim generation number should be in agreement with the actual reported number for the period. If the numbers are more than 2% apart, a review of the impact of the individual contributors has to be made and additional melt loss tests may be required to get satisfactory agreement.

Once this process has been completed, a change in skim generation due to a different scrap mix can be predicted. Also, when new technology is introduced to replace existing process steps, a single melt loss test for the new process or equipment will set a new standard. This standard can be readily integrated into a newly predicted total melt loss performance.

This can be illustrated by conducting a performance analysis of a hypothetical plant and then introducing improved technology and operating procedures. The numbers for present and projected performance are chosen for illustration purpose and will therefore appear more dramatic than can be expected in a real life situation. The scenario for plant X is as follows.

A representative melt consists for 40% of pot room metal and the remaining 60% of three scrap type groups with very different skim generating characteristics. The heavy and light scrap is melted in on-line furnaces. The chips are charged into an off-line melter, from which the metal is pumped into a crucible and from there cascaded into an on-line furnace contributing 22 wt.% to the melt. Half of the molten metal is to be used in a high quality product requiring extensive fluxing and filtering, while the other half is utilized in products requiring little metal treatment. Fines are generated during preparation of part of the scrap and are removed before melting. Their weight represents .1% of the melt.

Melt loss tests have indicated that the fines generate 20% of skim in the induction furnace. Furthermore, the metal recovery from skim can be slightly improved.

Management of the plant is concerned about present melt loss performance and is considering a number of improvements, among which is a special metal transfer technology, purchasing a tilt furnace for chip melting and strict new operating procedures which will reduce melt furnace skim and even some holder skim.

Table I shows the analysis of the present melt loss performance of plant X and the projected numbers based on the introduction of the proposed technologies and procedures.

In the previous discussion, it has been suggested that certain skim generating events can be grouped without compromising accuracy and that, on the other hand, other seemingly single events actually need to be split up to recognize different behavior of alloys or style of treatment.

The pot room metal is subjected to a "single" cascading crucible emptying event in addition to the other transfer steps between stations. Together, these events generate 1% skim, leading to a .40% contribution to the total, as is shown in Table I under cascading (S) in category I. The "double" cascading of the chip melter metal causes its number to be 2.1% and is therefore listed separately as cascading (D).

The melt process skim (category II) consists of three grouped contributors reflecting the difference in skim generating characteristics.

The splitting up of category III reflects the fact, stipulated in the scenario, that half of the metal requires heavy fluxing and the other half only little skim generating metal treatment.

The fines (category IV) are presently treated as skim. This means that 40% recovery will be reported after skim treatment. Presumably, a melt loss test has established that with the present melt facilities no better result can be obtained.

Table I demonstrates that the melt loss performance of an entire plant can be "captured" and monitored with a relatively small framework of key, process oriented numbers.

Not only are the "contribution to total skim generation" numbers a direct reference for expected melt loss performance but, in certain combinations, they can be used as a diagnostic tool. For instance, the total holder/in-line treatment skim should be a constant percentage of the melt if the product mix of the plant does not change. Therefore, if, in the case of plant X where the holder skim is about 15% of total skim, total skim would increase unexpectedly, a quick check of the ratio holder skim/total skim will indicate in which direction to search for the cause of the deviation.

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*UBCs are used beverage containers.

Metal Loss Analysis - Plant X

Skim Generation Contribution Groups	Categories	Present			Projected		
		Skim Weight Percentage	Quantity Percentage of Melt	Contribution to Total Skim Generation Percentage	Skim Weight Percentage	Quantity Percentage of Melt	Contribution to Total Skim Generation Percentage
Cascading (S)	I	1.0	40	0.40	0.2	40	0.08
Cascading (D)	I	2.1	22	0.45	0.41	22	0.09
Heavy Scrap	II	0.5	30	0.15	0.5	30	0.15
Light Scrap	II	3.5	8	0.29	1.5	8	0.12
Chips	II	7.8	22	1.72	4.0	22	0.88
Holding/ILT	III	0.3	50	0.15	0.3	50	0.15
Holding/ILT	III	0.8	50	0.40	0.5	50	0.25
Fine Removal	IV	—	0.1	0.10	20.0	0.1	0.02
Total Skim Generation				3.66			1.74
Skim Recovery		40% of 3.66		— 1.46	45% of 1.74		— 0.78
True Melt Loss				2.20			0.96

Table I

The calculated true melt loss should also be in close agreement with the reported administrative true melt loss. If the skim numbers are identical and the true melt loss numbers show a discrepancy, it is almost certain that an administrative error caused the difference and that will show up in a metal inventory audit. This is a complete turnabout from when the inventory adjustments were used to change the "melt loss standards."

The calculations of the projected improvements in plant X follow the same pattern and are self-explanatory if one assumes that the contributions of the individual skim generating events have been established by conducting melt loss tests.

The change in treatment of the fines is included in this exercise to point out that introduction of new technology may have benefits in unexpected areas. In this case, melting the fines in the new induction chip melter gives, in spite of a high skim generation, a significant ultimate melt loss reduction.

This exercise demonstrates that the use of process oriented loss factors enables one to monitor the losses at a high level of accuracy once a network of reproducible numbers has been established.

CONCLUSION

Traditionally, melt loss was determined as the closing number in a metal balance inventory. Quantitative evaluations lacked credibility because nonrelevant factors and administrative errors were included in the total number. It was demonstrated that by basing the calculations on skim generation, a framework of process related quantifiable contributors to total skim generation can be established. By proportionally relating the contributors to the total metal flow through the ingot plant, total skim generation can be determined. Once established, the network becomes the set of standards for monitoring melt loss performance and quantifying changes.

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