Optimization of Commercial Aluminum Alloy Melting in Reverberatory Furnaces

PURDUE MATERIALS ENGINEERING

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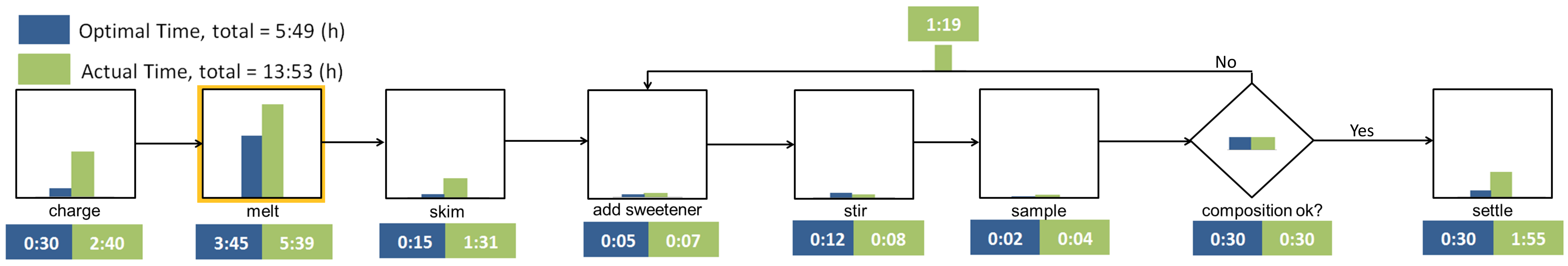
ALCOA

Alcoa Lafayette uses reverberatory furnaces to melt aluminum for casting. The furnaces are a bottleneck due to long melt cycle times. Improvements to the melt cycle time would increase capacity and directly impact revenues for the plant. The melting of the aluminum is a time consuming task which is not easy to monitor. No method exists to predict when the bath is melted. For this reason, our team focused on methods to predict accurate melt times to reduce time spent in the melt section of the flow path.



Melt operation sub-process flowchart displaying steps within the melt cycle with actual run time and optimal value added times.

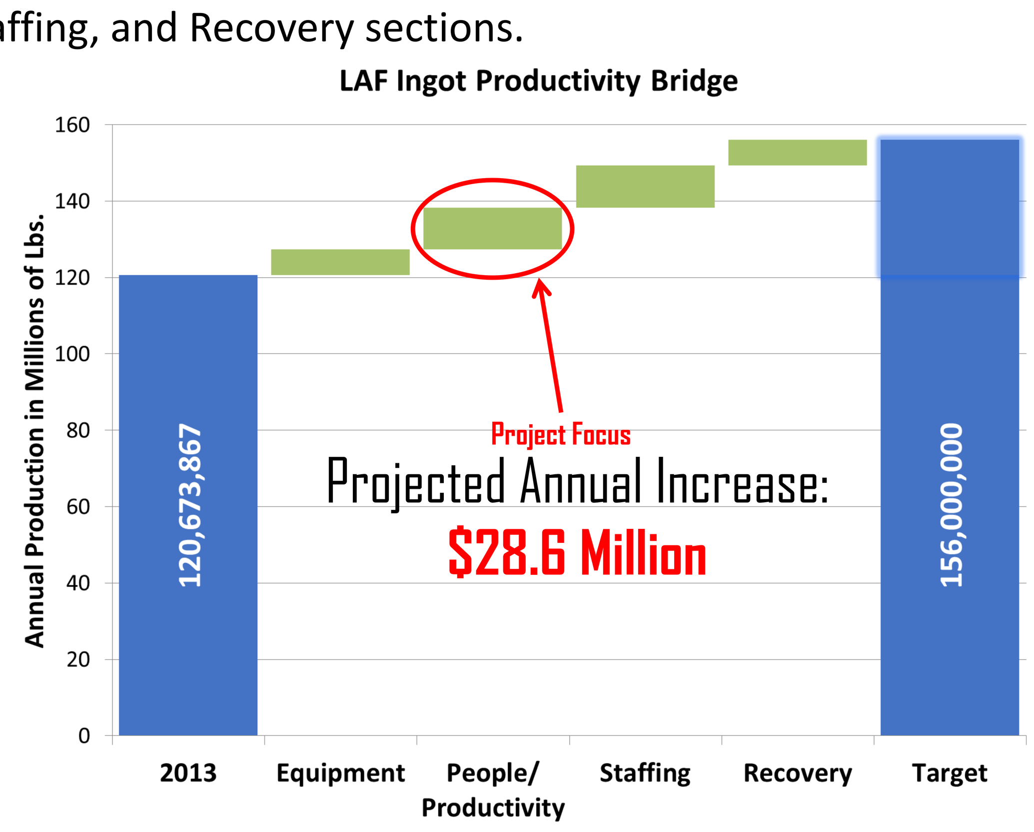
Project Background

Introduction

Alcoa Lafayette Operations cast and extrude components for the aerospace, oil and gas, and automotive industries. The operation of its ingot plant is described by the flowchart below:

MELT ➡ DEGAS ➡ FILTER ➡ CAST

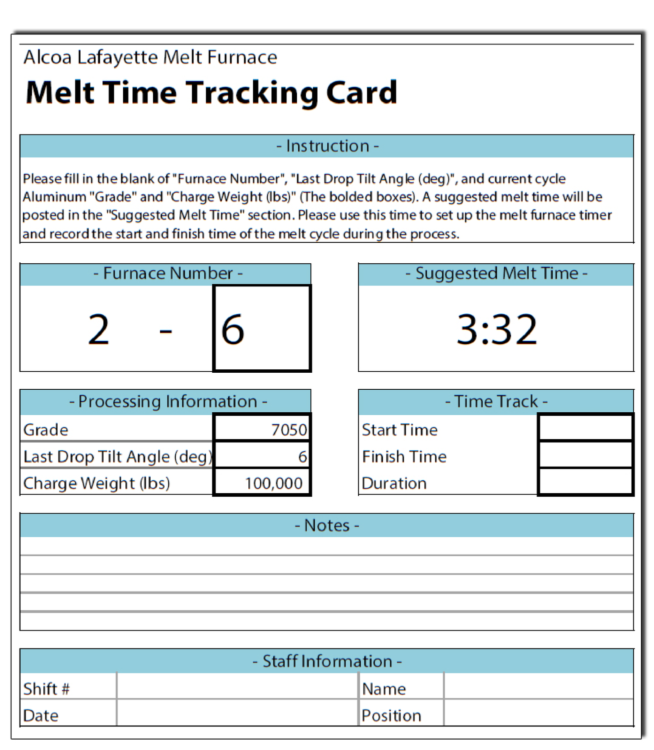
At the beginning of 2014, Alcoa Lafayette Operations ingot plant set up a productivity improvement plan in order to increase annual production by 36 million pounds, which would result in a $63.7 million increase in annual revenue. The improvement comes from Equipment, People/Productivity, Staffing, and Recovery sections.



The senior design project focus is on the People/Productivity section, where the target production increase is 11 million pounds. The goal of this project is to provide recommendations to help Alcoa achieve the improvement plan by increasing the melt efficiency.

Deliverable

A melt time tracking card was developed based on an empirical model and provided to Alcoa to determine an accurate melt time. An improved theoretical estimate will be obtained once a theoretical model is implemented. Using the card could reduce time spent in melt which would lead to the below savings.



	Monetary Value		Output Increase (lbs)		Percent of Target Achieved
	Alcoa's Goal	Projected	Alcoa's Goal	Projected	
Furnace 2-6	$7.3 Million	$10.9 Million	4.2 Million	6.1 Million	150.1%
All Furnaces	$19.5 Million	$28.6 Million	11.0 Million	16.1 Million	146.7%

Problem Identification

Flowchart

- Melt cycle is illustrated by the flowchart on the upper right.
- The team analyzed a large furnace which contributed 37.9% of the total production in 2013.
- **The melt step is the bottleneck** in the cycle because it constrains casting, and takes the longest amount of time.

Bottleneck Causation - Two main traits lead to long melt times

- Opening of the furnace door at incorrect times.
- Not moving to the next step once bath is molten.

Bottleneck Reduction - Two models were developed

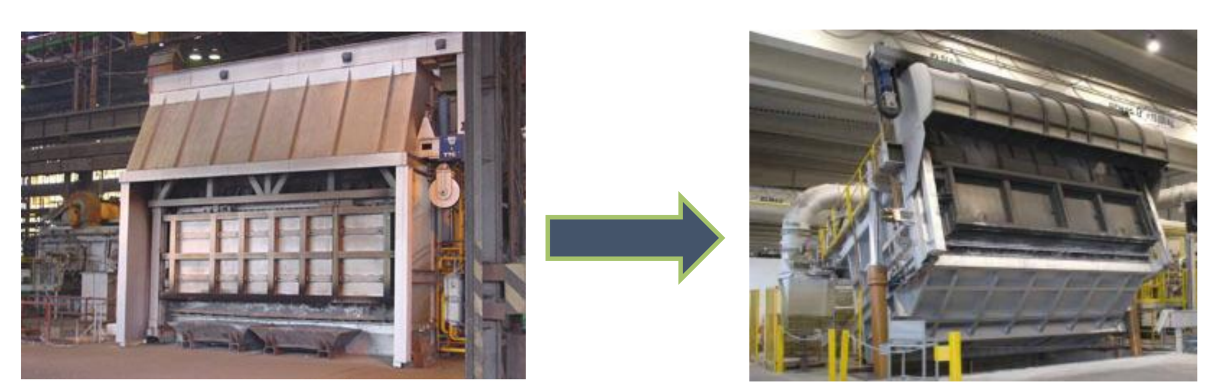
1. **Empirical model based on the amount of charge and the metal left from the previous casting drop.**
2. **Theoretical model based on furnace flue temperature.**

Empirical Model

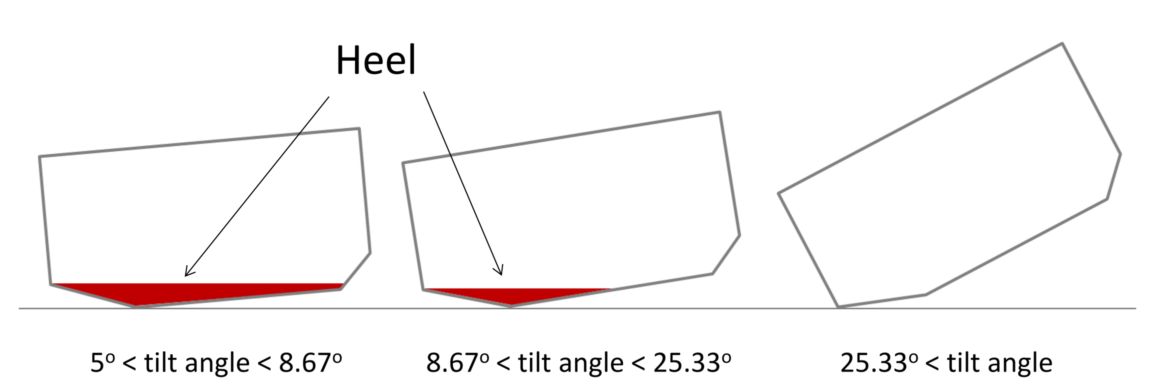
Alcoa and the team believed the following three factors to have the most influence on melt time: heel weight, amount of scrap used, and total charge weight. The results from examining these factors and developing our empirical model met Alcoa's need in increasing efficency.

Heel Model

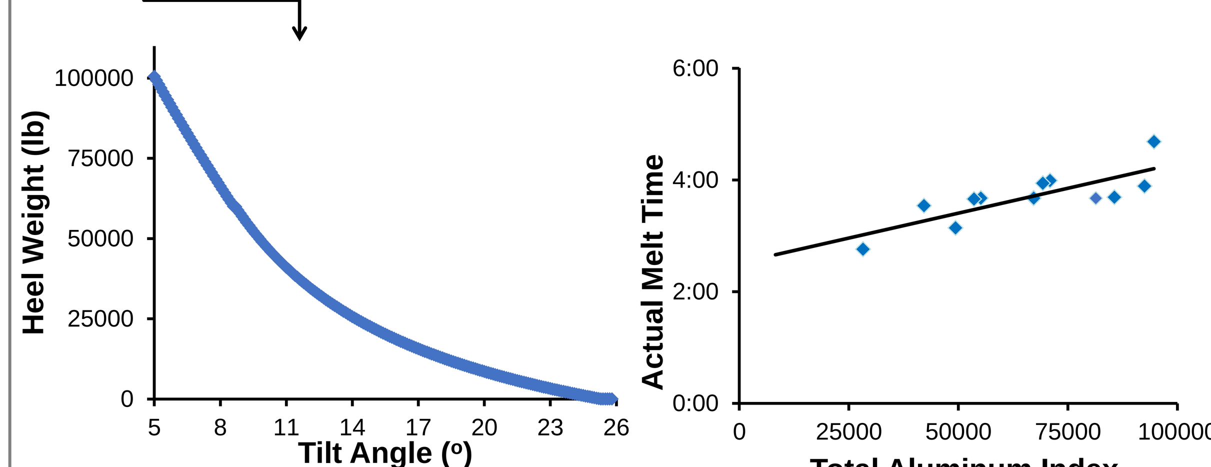
- The furnace tilts to pour the metal.
- Liquid metal remaining after pouring is known as the heel.



melting position to casting position



$$\text{Heel Weight}=\begin{cases}367029*\dfrac{\sin(8.67-\text{tilt angle})}{\sin(29.61+\text{tilt angle})}+59548 & 5.00^{o}<\text{tilt angle}<8.67^{o}\\ 13603*\dfrac{1}{\tan(\text{tilt angle})}-28779 & 8.67^{o}<\text{tilt angle}<25.33^{o}\\ 0 & \text{tilt angle}>25.33^{o}\end{cases}$$



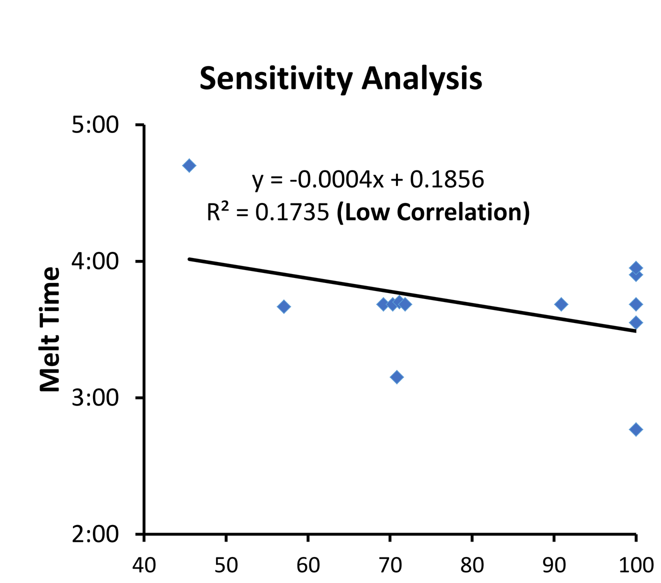
Estimated Melt Time = 7E-07*(0.8*total charge weight-0.2*heel weight) + 0.1
$R^2 = 0.6321$

Estimated Melt Time

- 42 cycles were analyzed, and 12 were deemed ideal to use for the empirical model.
- The total aluminum index was calculated based on the total charge weight and heel weight.
- Coefficients were inserted and optimized for the best correlation.
- The regression line outputs estimated melt time.
- The estimated time equation had a regression of 0.6321.

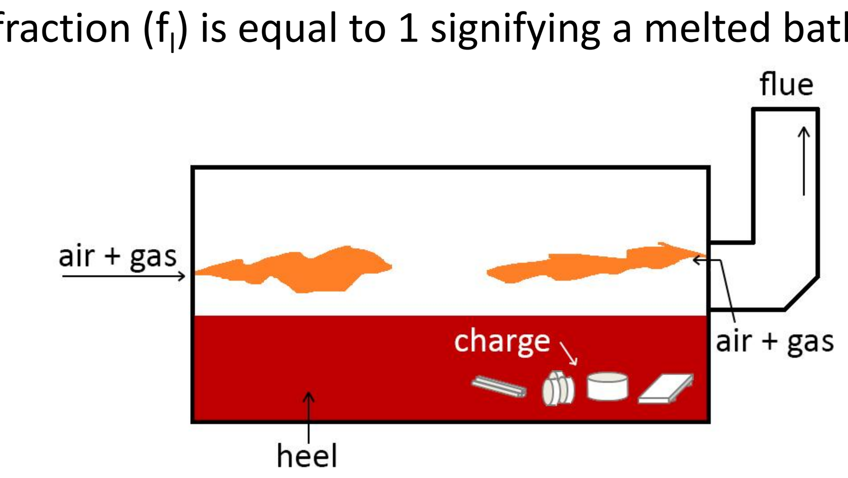
Percent Scrap Analysis

- Scrap usage did not have as large of an impact on the melt time as heel weight or total charge weight.
- Proves that heel weight and weight of material charged were the main factors determining melt time.



Theoretical Model

Thermodynamic balance of furnace to determine when liquid fraction (f_l) is equal to 1 signifying a melted bath.



$$f(T)=Q_{comb}+(mh_{air})_{in}+(mh_{gas})_{in}-(mh_{flue})_{out}=\left(\frac{\partial H}{\partial t}\right)_{charge}$$

$$H=m(cT+L_f f_l)$$

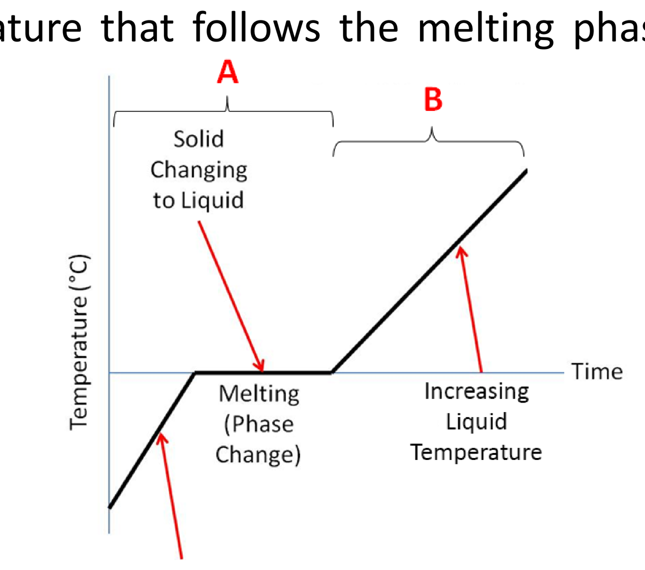
Assume all metal is initially solid:

$$H(t_o)=H_{heel}+H_{charge}=mT_o+cT_o \quad \text{with } T_o<T_f$$

A	B
When solid: $H_{solid}=mcT$ @ $T(t=0)=T_0$ When $T=T_o<T_f$ ($f_s=1$): $\frac{\partial H}{\partial t}=mc\frac{\partial T}{\partial t}=f(T)$ $T=(\Delta t/mc)f(T)+T_{old}$ $f_l=f_{l\_old}+(\Delta t/mL_f)f(t)$, till $f_l=1$	When liquid: $\frac{\partial H}{\partial t}=mL_f\frac{\partial L_f}{\partial t}=f(t)$

m=mass of metal, c=sensible heat, L_f=latent heat, f_l= liquid fraction , Q= heat of combustion, h= heat transfer coefficient, H= enthalpy, T= temperature, Δt= change in time

These set of equations can be graphically illustrated by a typical metal heating curve. If temperatures of the flue gas are monitored throughout the melt, the changes in slope will identify phase transitions of the aluminum from solid to liquid. The goal is to have the Programmable Logic Controller (PLC) signal the burners to turn off during the rapid change in slope/temperature that follows the melting phase to prevent overheating.



Summary and Future Work

Based on limited data, the Melt Time Tracking Card could potentially save up to 1 hour 10 minutes and 2 hours 13 minutes per cycle for small and large furnaces respectively. Time is saved by improving accuracy of the timer, which increases efficiency by not opening the door at inappropriate times and reduction of non-value-added time. This change can result in an annual production increase of 13.4% which is 16.2MM pounds or $28.6MM in revenue. Our theoretical model provides a scientific approach to determine whether the metal is fully melted or not.

Alcoa decided to implement the Tracking Card in their future furnace operations. A more accurate empirical estimated melt time will be updated once more data is acquired. Additional analysis of continuous flue temperature data will be used to optimize the theoretical model to better match actual conditions of the furnaces at Alcoa Lafayette Operations.