Physical Ladle Tracking

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INTRODUCTION

This paper evaluates the results of a unique ladle tracking system that is successfully installed in two melt shops in North America, and one in India. The system uses a combination of thermally and mechanically protected equipment, Radio Frequency communication devices and custom software. A ROI case for a typical plant is presented, including highlights and real world situations that were collected during continuous operations for more than two years. The system has potential to revolutionize the way ladle tracking systems work, by implementing new hardware and software tools that complement existing software based tracking systems.

DISCUSSION

Ladle Tracking Motivation

Tracking the movement of ladles in a melt shop has become commonplace throughout North American plants. Ladle tracking systems provide several key benefits, including:

- Identifying the heat number at each station, an imperative for quality assurance.
- Acquiring accurate timestamps for ladle arrivals and departures and accurate transit times, which are useful for crane logistics analysis and planning
- Determining the exact contact time of each ladle which is used to evaluate the state of the refractory lining and other consumable parts
- Calculating heat losses for waiting time, and correct temperatures for tapping and heating
- Assigning steel weight, remaining weight and tare weight to the ladles, which is important for mass balance analysis.

During the last 20 years, most plants implemented "logical tracking" in their Level 2 systems, i.e. operators use HMI or Level 2 data entries to manually assign ladle number to heat numbers in the initial station (typically EAF or BOF) and then manually select the heat or ladle arrived at all subsequent stations, weigh scales, etc. Off-cycle activities such as cleaning, reheating, relining and soaking are also typically reported with manual data entries. All these highly repetitive manual inputs result in inevitable errors that can be very costly to the plant operation and negatively affect other activities such as planning and refractory performance evaluation.

Introducing Physical Ladle Tracking

In order to avoid the uncertainty and errors of the manual (logical) tracking systems, Physical Ladle Tracking (PLT) technology was developed based on Radio Frequency Identification (RFID). With PLT, each ladle is equipped with an RFID tag that is well-protected from thermal and mechanical damage. RFID reader stations are placed at the various ladle working, maintenance and storage stations. Antennas are placed throughout the shop to read the RFID tags and transmit the data to the system's central computer.

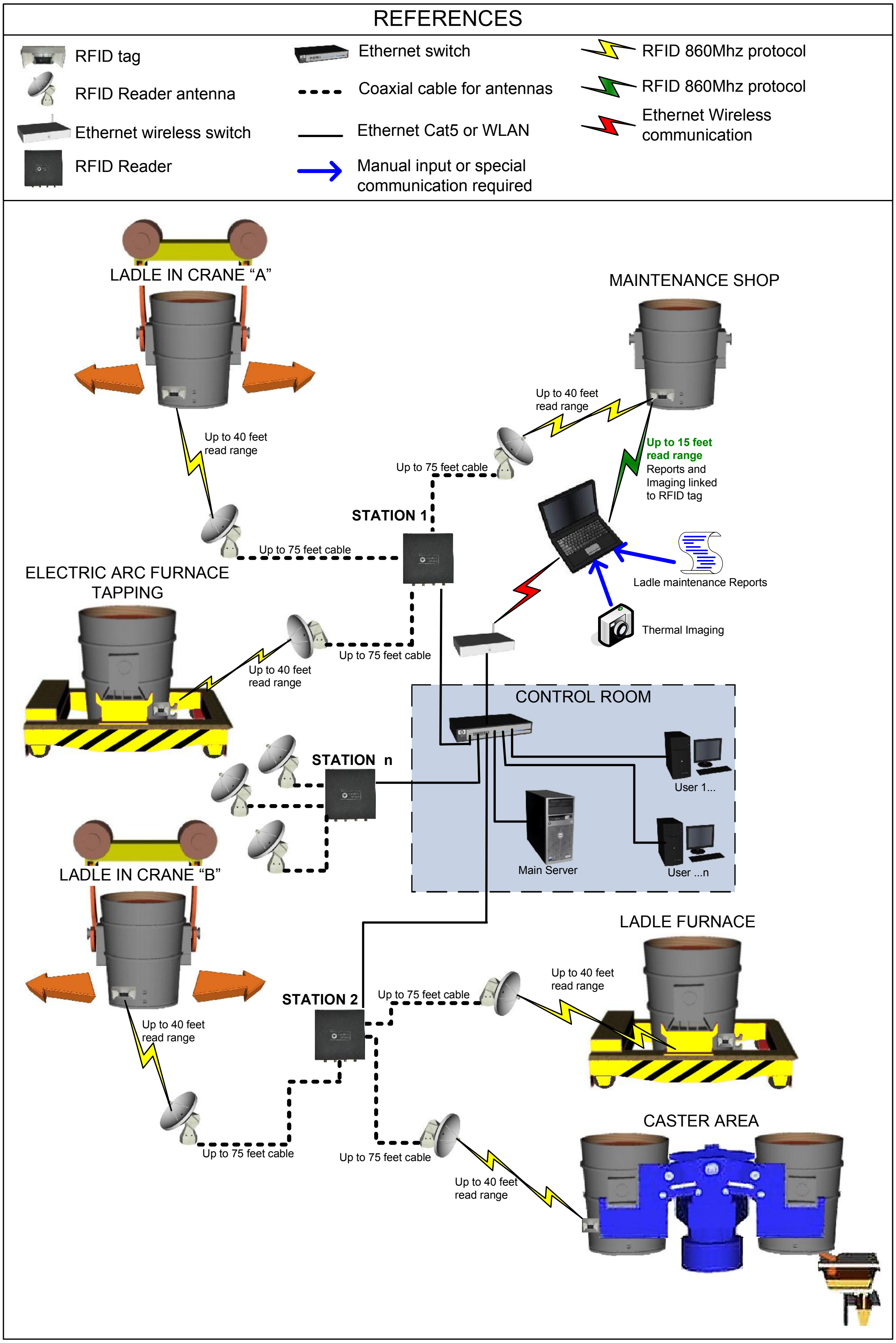

Figure 1: System Overview

RFID Tag

The PLT RFID tags are passive and use a modified form of the RFID reader's own signal to transmit data. This passive tag method is called "modulated backscatter".

Essentially, the tag reflects (or backscatters) the RF signal transmitted by the reader and embeds its unique ID by modulating that reflected signal.

The unique identification number will not change during the lifetime of the tag. It cannot produce false triggers, which means the only way to get the unique identification number sent by a particular tag is if that tag is present in a particular location.

The tags can be read from several feet away and they don't need to be on the line of sight of the reader. The system detection distance between sensors and antennas is recommended to be limited to 40 feet; however the detection distance has been site-tested up to 75 feet.

Figure 2: PLT RFID Tag

RFID Protection Armor

In order to protect the RFID Tag from both high temperature and collisions with other equipment, the RFID tags are installed inside a special protective cover, or armor, which is welded to the ladle wall.

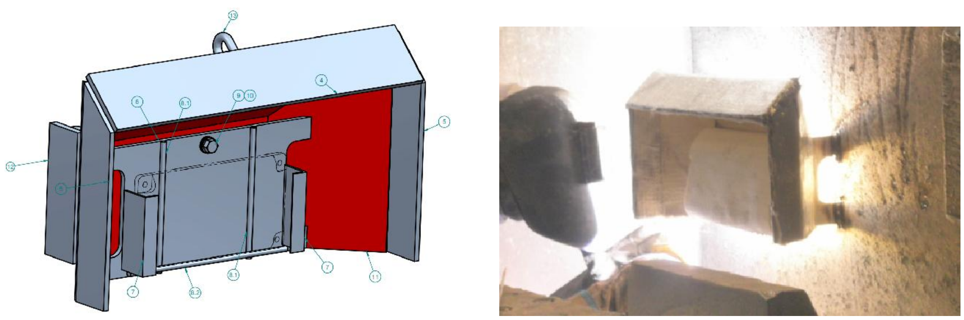

Figure 3: PLT Protection Armor and RFID Tag on ladle

The armor location on the ladle depends on ladle wall temperatures and where it will be safe from collisions and from signal interference. The armor keeps the sensors' temperature range within working levels to allow correct data transmission. The armor protects the sensors from collision damage, from hot metal splashes, and from slag falling from top of the ladle.

The armor is manufactured in carbon steel with several layers of insulation on the internal side where the RFID tag is located. 2000°F external reflective insulation is installed on the ladle side wall.

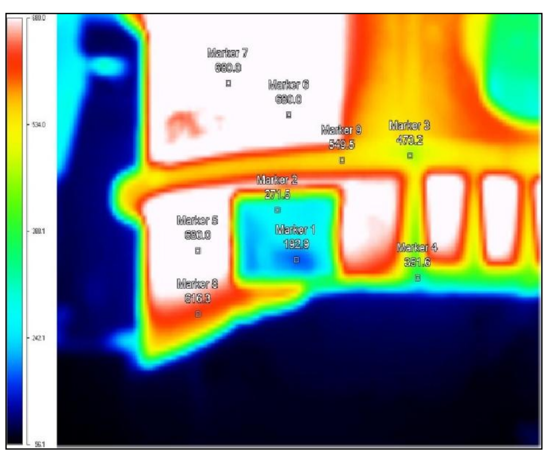

Figure 4: Thermal image of armor and sensor in ladle

Even with the protection armor, the RFID tags could be damaged by direct splashes, collision with plant equipment, etc. Thus the protection armor is designed for fast and simple exchange of either the protection armor and tag or just the tag itself. New tags are automatically recognized by the software and the complete process of changing and detecting a new tag will take no more than 4 minutes.

Stations and antennas

The RFID readers are installed inside the stations, which are NEMA 12 enclosures that protect the RFID readers from the environment. The stations have forced ventilation to keep the RFID reader within working temperature ranges and all necessary electrical distribution for powering and protecting the equipment. The RFID readers can manage up to 4 different antennas, which are individually connected to the reader with coaxial cable. The high gain, directional antennas are directed to the locations where the ladles need to be detected.

The antenna's gain, measured in dBi (decibels relative to isotropic radiator), is selected depending on cable length and the maximum distance between the antenna and the ladle location. Typically 3, 6, 9 and even 12dBi antennas can be used. During system installation, each antenna is carefully installed, oriented and calibrated to cover a defined area of the plant, which we call spots.

Typical spots in a melt shop are the tapping area, cranes, LF, ladle cars, caster turret arms, and preheaters.

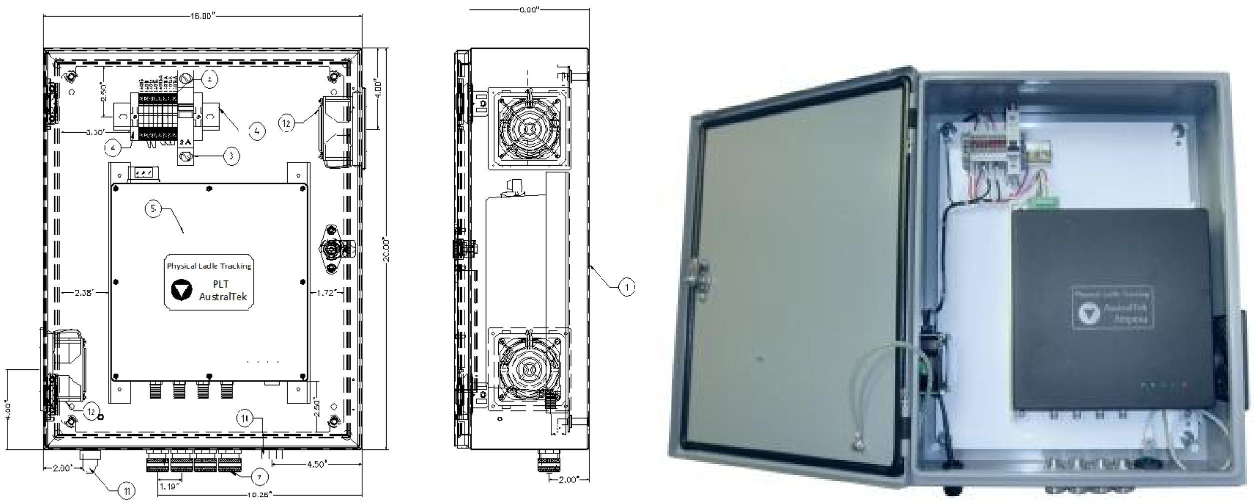

Figure 5: PLT Station Engineering Diagram and Picture

Server and software

Ethernet communication (wired or wireless) is used to connect the readers and the central computer (server), The server reads the identification number sent by the readers, collecting real-time information from all the stations to maintain a coherent internal state that represents all ladles and spots in the plant. This state is typically queried by client systems such as MES or Level 2 using Windows Communication Foundation (WPF) protocols. An OPC (Object Linking and Embedding for Process Control) version is being developed to allow direct communication with PLCs and HMIs.

System Design

Despite the simplicity of the concept, the correct implementation of a PLT system in melt shop environments comes with some engineering challenges:

The location of the armor on the ladle needs to be carefully chosen to prevent RF blockages from structures in all the spots, and at the same time be protective enough to prevent splashes and direct heat radiation sources throughout the process.

Stations should be installed close to the antennas because RF losses in the cables can be significant and might produce a large number of false negatives (i.e. no signal reception).

RF Gain must be adjusted in the antennas to target specific spots in the areas and prevent unwanted detection of more than one spot at the time or to avoid detection of transitory ladles (carried by a crane, for example).

RF transmission power and system impedance needs to be balanced as well to maximize the power transfer or minimize reflections from the antennas. This balance is performed by correct selection of antenna gain, cable impedance, and RF transferred power.

All these challenges require a complete site survey covering RF measurements at spots, potential station locations and thermal profile of ladles.

Usually a trial run is conducted where one ladle is equipped with armor and tag, a station is installed, and the ladle cycles are monitored for few days to confirm the feasibility of the envisioned system.

Temperature challenge
One of the most important issues to solve is the exposure of the tags to high temperatures, which affects both data transmission stability and maximum transmission distance.
The two system constraints that limit the use of the tags are the high temperature of the wall, and the time span the ladle wall is above certain temperature. In fact, the biggest problem is the radiation emitted by the ladle wall.
Standard commercial tags with long distance data transmission cannot withstand typical ladle wall temperatures (around 650°F), thus, the external protective armor was designed through thermal modeling software to keep the tags insulated from heat and keeping them cooled by convective air flow.

Thermal protection of the armor
Heat transfer to the armor is produced by convection, radiation, and conduction. Thermal conduction has been minimized by the structural design of the armor. Thermal convection is minimal in comparison with thermal radiation from the ladle wall. For a good approximation of the protection that the armor provides, we calculate the specific heat capacity of the armor and the net radiation loss rate. In order to successfully protect the tags, the temperature on the tags' side of the armor is not to exceed 400°F.

Specific heat:
The specific heat is the amount of heat per unit of mass required to raise the temperature of the material by one degree Celsius. The relationship between heat and temperature change can be expressed in the formula shown below.

$Q = m \times c \times \Delta T$

where:

ΔT= 174.44 °K	(400°F – 86°F expressed in °K, which is the armor's maximum allowable temperature increase from the ambient temperature to keep tags safe)
$c = 0.49 \frac{\text{KJ}}{\text{Kg}}$°K	(carbon steel specific heat)
m = 33lb = 14.968 Kg	(mass of steel of the armor)

Therefore, the amount of heat needed to raise the armor temperature to the ladle wall temperature is:
Q = 14.968 x 0.49 x 174.44 = **1,279,431.37 J**

Ladle wall radiation:
The ladle wall is constantly radiating energy to the armor, and its net radiation loss rate can be expressed as:

$\dot{Q} = \sigma \times \varepsilon \times A \times (T_H^4 - T_C^4)$

where:

$\sigma = 5.670373(21) \times 10^{-8} \frac{W}{m^2 \times K^4}$	(Stefan Boltzmann constant)
$A = 0.133966\ m^2$	(Armor steel area being directly affected by the ladle wall radiation)
ε = 0.5	(Very conservative emissivity estimate. Real emissivity of protective insulation for armor = 0.1)

$\dot{Q} = 5.670373 \times 10^{-8} \frac{W}{m^2 \times K^4} \times (0.5) \times (0.133966)\ m^2 \times (616.98^4 - 303.15^4)\ K^4 = \mathbf{516.0591} \frac{J}{s}$

Protection period:
Based on the armor specific heat, dividing $Q/\dot{Q}$ will give the time needed to reach the ladle wall temperature in the armor as:

$Q/\dot{Q} = \frac{1{,}279{,}431\ J}{516.05 \frac{J}{sec}}$ = 2479.23 sec = **41.32min**

For an emissivity of 0.4, the protection period will be 51.65min
For an emissivity of 0.3, the protection period will be 68.86min
For an emissivity of 0.1, the protection period will be 206.60min

As demonstrated, the armor deflects the direct heat from the ladle wall for a certain amount of time, which is strongly dependent on the emissivity of the material. If the internal plate of the armor reaches 400°F for more than 14 minutes, the RFID tag could be damaged.

The only way to lower the temperature on the tag side, once the armor is hot, is by cooling the armor or the tag with a colder air flow. In order to facilitate this cooling, the armor is designed to use part of the heat to create a convective air flow, which, together with the air flow produced by the normal movement of the ladle through the plant, will lower the outside temperature of the armor and dissipate the excess temperature on the tag side.

In addition to the armor protection, the RFID tags were redesigned to thermally insulate the RFID integrated circuit and to maintain the correct distance between antenna plates by keeping the antenna's dielectric in the correct position.

The combination of the armor and tag design, keeps the RFID tag safe for a long time and to be cooled by the normal movement of the ladle through the plant. If optional forced ventilation is used to direct air to the armor, then the RFID tag will be much better protected and completely safe against ladle wall high temperatures.

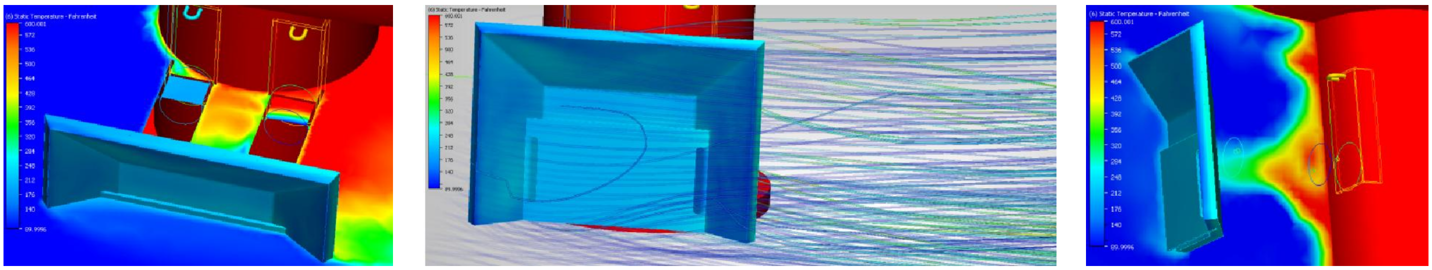

Figure 6: Thermal model images for convection cooling

Logic filters

One element to take into account, is that RFID technologies make false positives (i.e. detecting an object that is not there) almost impossible. On the other hand, sporadic false negatives (not detecting an object for a short time) are not uncommon, especially in industrial environments where interferences with heavy equipment movement can occur. In order to overcome this problem, the PLT system software uses a time-based, low pass filter that relies on the dynamics of ladles (heavy and slow objects).

Return of Investment (ROI)

A numeric evaluation of costs associated with improper ladle tracking in melt shops was developed. The typical problems that a physical ladle tracking solves, or at least improves, are the following:

Heat/Ladle Association Mistakes

This problem arises when the LMF, Caster or Crane operators make a mistake and receive, treat or move the wrong ladle leading to wasted alloys, fluxes, delays and quality missed heats. This problem is much more prevalent in regular-to-complex mills with more than one EAF or BOF, more than one secondary metallurgy station and especially more than one caster.

It is very hard to come up with an average Cost Per Incident, so for this calculation we assume that only the ferroalloys and fluxes are lost, no delays and thermal losses are calculated.
The ferroalloy and fluxes values sum up to 37.88 USD per steel ton according to [4] and using an average 120 ton heat size:

Cost Per Incident (cpi) = 37.88 * 120 = 4,545 USD

Yearly costs estimation of Heat/Ladle Association Mistakes:

Factor	Abbrev.	Value	Based on
Heats Per Day	hpd	40	Sample Meltshop
Running Days / Year	dpy	350	Average Meltshop
Human error rate	her	0.1%	From [1]
Average Cost Per Incident	cpi	4,545 USD	From [4]
Tracking Effectiveness	pe	90%	Conservative

By the use of these variables, the savings in one year would be:

hpd * dpy * her * acpi * pe = 57,264 USD

Improper Ladle Condition
Not knowing the condition of a ladle might lead to unexpected cold temperatures after tapping, heat losses and safety problems due to refractory wear and hot spots.

The typical way of assessing the condition of a ladle in cycle is counting tapped heats. This method provides a rough estimate at best. It is much more accurate to have a numeric value associated not only with the number of heats but also accurate contact time, preheater time and temperatures, tapping temperatures, tapping weights, free board, steel grade, slag basicity and type/brand of refractory.

A physical ladle tracking system provides an excellent framework to assess the condition of the ladle in real time.

According to SDI Roanoke's experience, the cost of tapping on a cold ladle is 10% to 15% of the refractory relining costs, or equivalently, it reduces the ladle life by 10% to 15%. The value of a relining was estimated at 22,000 USD.

Cost of Ladle Incident (cli) = 22,000 * 12.5% = 2,750 USD

They estimated an average of two ladle temperature events per month, 24 per year. Taking into account that SDI runs approximately 8000 heats a year that yields a 0.30% incidents rate.

Ladle Incidents Rate (lir) = 24 / 8000 = 0.30%

Although ladle tracking will not prevent all ladle incidents, it does create a manageable environment to analyze the different options for incident reduction. A very conservative estimation is that it will avoid 30% of these kinds of ladle incidents.

Yearly costs estimation for **Improper Ladle Condition:**

Factor	Abbrev.	Value	Based on
Heats Per Day	hpd	40	Average Meltshop
Running Days / Year	dpy	350	Average Meltshop
Ladle Incidents Rate	lir	0.30%	SDI estimation
Cost of ladle incident	cli	2,750 USD	SDI estimation
PLT Effectiveness	pe	30%	Conservative Estimation

By using these variables, the savings in one year would be:

hpd * dpy * lir * cli * pe = 34,650 USD

Operative practices and Heat Losses
A physical ladle tracking database and statistics, form an excellent foundation for the analysis of ladle movement logistics. It is expected that by analyzing the data, operational practices will change to improve scheduling performance.
Schedule issues generate two kinds of problems: heat losses due to idle time and delays.

In a test case, information was gathered by an installed PLT system for only one ladle on one given day. The operations report indicated no delays for that day. However, a review of the data delivered by the system displayed several differences in the arrival and departure times before entering the LMF, as well as dead time waiting in car. The difference in waiting time that the ladle spent in the transfer car on July 19th 2012 is detailed below:

7/19/12 1:38:14	0:03:54
7/19/12 5:52:37	0:04:10
7/19/12 6:57:50	0:15:10
7/19/12 7:37:21	0:01:45
7/19/12 11:22:38	0:02:33
7/19/12 12:01:41	0:03:50

7/19/12 16:49:26	0:06:35
7/19/12 17:14:20	0:02:33
7/19/12 18:21:05	0:05:31
7/19/12 22:19:50	0:12:50
7/19/12 23:16:39	0:02:13
TOTAL WAITING TIME	**1:01:04**

Based on above data, and supposing a small melt shop with 3 or more ladles in rotation, the total waiting time for one day would be:

1:01:04 * 3 = 3:03:02 = 3.05 hours

Heat radiation is the main cause of heat loss from a hot surface (metal or inner ladle) and is given by the following:

Factor	Abbrev.	Value	Based on
the emissivity of the molten steel	ε	0.50	[2]
Stefan-Boltzmann constant	σ	$5.67 * 10^{-8} W / m^2 * K^4$	Physical Constant
Temperature of hot steel	T_1	1,753 K	Typical liquids Temp
Air Temperature near ladle	T_2	500 K	Estimation
Total Waiting time per day	TWT	3.05 hours	From previous calculation
Days per year	DPY	360 days/year	Typical Year
Ladle emission area (only considering top liquid steel surface)	LEA	$9.6\ m^2$	Typical Ladle
Price of electricity	POE	0.0836 USD/KWH	[3]

The heat transfer per unit area is

$Q = \varepsilon * \sigma * (T_1^4 - T_2^4) = 175\ KW/m^2$

The total heat loss in one year of operation is:

THL = Q * LEA * TWT * DPY = 1.8 GWH

If we use an average price of industrial electricity in the USA as an estimator for the heat losses cost:

Cost of energy losses = THL * POE ~ 154,000 USD

Less operator intervention
Due to automatic detection, PLT removes the necessity of:

- Manual entry of ladle numbers on HMIs and Level 2 screens
- Communication between the crane operator and pulpit operator regarding the ladle number
- Operator checking the Level 2 screens to make sure he is receiving the proper ladle/heat
- Track tare, net weight and empty weight of the ladles for yield calculations

We estimate that these manual operations usually take 30 seconds of operator attention per heat, which in our sample Meltshop sums up to ~20 minutes a day. Although this cannot automatically be translated to savings, workload reduction is clearly a benefit.

CONCLUSIONS

The PLT is today installed in two plants in the US and it was installed in one plant in India. The system has helped to keep tracking of total steel contact in ladles, and detecting mistakes related to wrong ladle assignations and incorrect alloy additions.
The PLT has been running continuously for more than 30 months with an average RFID tag life of 8 months each, and no armors damaged or changed; with a total of more than 18,000 heats successfully tracked.
The system has been proven effective and reliable in several working conditions, making the PLT a very effective way to track ladles in the steel plant.

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