Preliminary Results from Electric Arc Furnace Off-Gas Enthalpy Modeling

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ABSTRACT

This article describes electric arc furnace (EAF) off-gas enthalpy models developed at Oak Ridge National Laboratory (ORNL) to calculate overall heat availability (sensible and chemical enthalpy) and recoverable heat values (steam or power generation potential) for existing EAF operations and to test ORNL's new EAF waste heat recovery (WHR) concepts. ORNL's new EAF WHR concepts are: Regenerative Drop-out Box System and Fluidized Bed System. The two EAF off-gas enthalpy models described in this paper are:

1. Overall Waste Heat Recovery Model that calculates total heat availability in off-gases of existing EAF operations
2. Regenerative Drop-out Box System Model in which hot EAF off-gases alternately pass through one of two refractory heat sinks that store heat and then transfer it to another gaseous medium

These models calculate the sensible and chemical enthalpy of EAF off-gases based on the off-gas chemical composition, temperature, and mass flow rate during tap to tap time, and variations in those parameters in terms of actual values over time. The models provide heat transfer analysis for the aforementioned concepts to confirm the overall system and major component sizing (preliminary) to assess the practicality of the systems.

Real-time EAF off-gas composition (e.g., CO, CO_2, H_2, and H_2O), volume flow, and temperature data from one EAF operation was used to test the validity and accuracy of the modeling work. The EAF off-gas data was used to calculate the sensible and chemical enthalpy of the EAF off-gases to generate steam and power. The article provides detailed results from the modeling work that are important to the success of ORNL's EAF WHR project. The EAF WHR project aims to develop and test new concepts and materials that allow cost-effective recovery of sensible and chemical heat from high-temperature gases discharged from EAFs.

BACKGROUND

Oak Ridge National Laboratory (ORNL), in collaboration with E3M, Inc., and Toledo Engineering Company (TECO), is conducting research aimed at developing and testing new concepts and materials that allow cost-effective recovery of sensible and chemical heat from high-temperature gases discharged from electric arc furnaces (EAFs). The EAF melting process discharges a large amount of heat as high-temperature (>3,000°F) exhaust gases, or off-gases, that contain large amounts of condensable and non-condensable vapors, particulate matter, and corrosive gases (see Figure 1). EAFs use a batch or periodic process, so the mass flow and

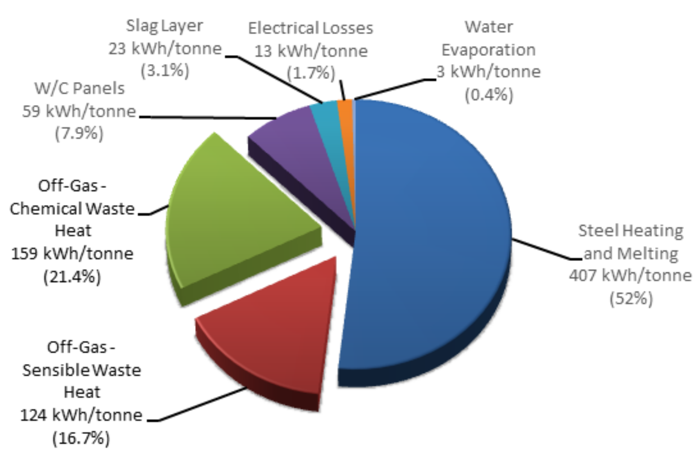

Figure 1: A large percentage (25–35%) of the total energy input for the EAF is lost as chemical and sensible heat.

composition of the off-gases vary during a cycle. At this time, not only is the energy contained in the gases wasted, but also much energy is used to handle and treat the gases before they are discharged into the atmosphere. Currently, for all EAFs used in the US steel industry, this loss is equivalent to approximately 31 trillion Btu/year, or approximately 3% of the total energy used by the US steel industry. The economic value of these losses is approximately $182 million US dollars per year. Existing waste heat recovery (WHR) systems (e.g., recuperators) have very short lives—usually 6 to 12 months—even if they are made of specially selected alloys, because of the highly corrosive, high-temperature operating environment.

The project goal is to develop a WHR system that uses appropriate innovative technology to enable the conversion of waste heat into usable energy. We aim to develop and/or improve a WHR system, equipment designs, and operating practices that can be applied to a large population of EAFs and in other areas of the primary and secondary steel melting industry where high-temperature contaminated gases are exhausted. The purpose of the project is to reduce the energy intensity of the US steel industry.

INTRODUCTION

During the 2014 AISTech conference in Indianapolis, ORNL researchers presented a study and review of available waste heat in high-temperature EAF off-gases and techniques/methods of recovering heat from these gases [1]. The 2014 paper detailed the quality and quantity of the sensible and chemical waste heat in a typical EAF exhaust gas; the energy savings potential from recovering part of the heat; a comprehensive review of currently used WHR methods; and the potential for using advanced designs to increase the level of heat recovery, including scrap preheating, steam production, and electric power generation. The paper included a review of the historical development of existing WHR methods, their operation, and their advantages/limitations. It also described a program to develop and test advanced concepts for scrap preheating, steam production, and electricity generation via recovery of chemical and sensible heat in EAF off-gases with a minimum amount of dilution or cooling air upstream of a pollution control system such as a bag-house. This paper describes EAF off-gas enthalpy models in detail and presents a real-life case study. Any steel plant could use the enthalpy models to calculate overall heat availability (sensible and chemical enthalpy) and recoverable heat values (steam or power generation potential) for an existing EAF and/or to test ORNL's WHR concepts for its particular EAF.

CURRENT PRACTICES TO MANAGE EAF OFF-GASES

The EAF is used to produce molten steel using scrap steel or other types of charge. More than 60% of US steel is produced by EAFs, and the proportion is likely to increase. An EAF melts steel using a batch process in which the charge material is loaded into a water-cooled furnace and energy is supplied to melt the material within 50 to 70 minutes. An EAF uses electricity and various fuels such as natural gas and carbon to supply energy to heat and melt the charge material. Various other materials such as fluxes, lime, carbon, and oxygen are also injected into the EAF during the melting cycle. A large volume of exhaust gases is discharged from the furnace at >3000°F during the melting operation. These gases contain products of incomplete combustion, including carbon dioxide (CO_2), water vapor (H_2O), carbon monoxide (CO), hydrogen (H_2), and other hydrocarbons. They also include small amounts of metallic and nonmetallic solid particles in various sizes.

In the vast majority (>90%) [2] of EAF installations, the common practice is to collect EAF exhaust gases, mix them with ambient air to combust the combustible materials, and then drop their temperature to less than 400°F (see Figure 2). These relatively lower-temperature gases are then passed through a bag-house before being discharged to the atmosphere. The capacity of these direct evacuation systems is typically 1,000 Nm^3/hour per ton of furnace capacity. The exhaust gas system may include a "drop-out" box to drop out large particles, a quench, and an exhaust fan that uses hundreds of horsepower of electrical energy. The entire exhaust gas direct evacuation system requires frequent cleaning and other maintenance. Moreover, fourth-hole direct evacuation systems do not always operate as designed. For example, changes in furnace pressure cause fumes to escape through doors, ports, roof-sidewall joints and electrode openings, bypassing the direct evacuation system. Hence many EAF systems also use a deep rectangular canopy hood over the furnace to capture fumes generated during charging, tapping, melting, and refining. These types of system typically have capacities of 340,000 to 850,000 Nm^3/hour per furnace and consume large amounts of electrical energy.

In some cases, the exhaust gases from the furnace are passed through a scrap preheating system, where the gases supply heat to the charge material to raise its temperature before charging it into the EAF vessel. Several charge preheating system designs are used. Charge preheating offers several benefits, including lower energy use in the EAF, reduced melt time, and increased productivity. The systems proposed and used at some plants include heating of scrap in buckets or shafts or on a conveyor specially designed to withstand high temperatures. In all cases, only part of the exhaust gas heat is transferred to the charge material, and a relatively large amount of heat remains in the exhaust gases leaving the charge preheater. Users have identified several other issues associated with currently available scrap heating systems. Commonly used scrap preheating systems require frequent maintenance and may heat scrap unevenly, with localized melting of steel on the conveyor itself resulting in operational problems. In many systems, operators prefer little or no preheating of scrap material to avoid heat deformation of the charging bucket and resulting maintenance issues, or white smoke or a bad smell produced by preheating. Some scrap preheating systems increase the combustion gas pressure under the furnace roof. In those cases, a highly sensitive furnace pressure control is required to avoid unacceptable pressure in the furnace, which would lead to CO escaping through any gaps in the furnace and associated plant equipment. Many of these problems are due to uncontrolled gas temperatures and the presence of combustibles, together with unpredictable air flow patterns that result in uncontrolled combustion of combustible gases. Hence, there is a need to develop systems that overcome the issues and problems associated with currently available designs and recover the maximum possible waste heat.

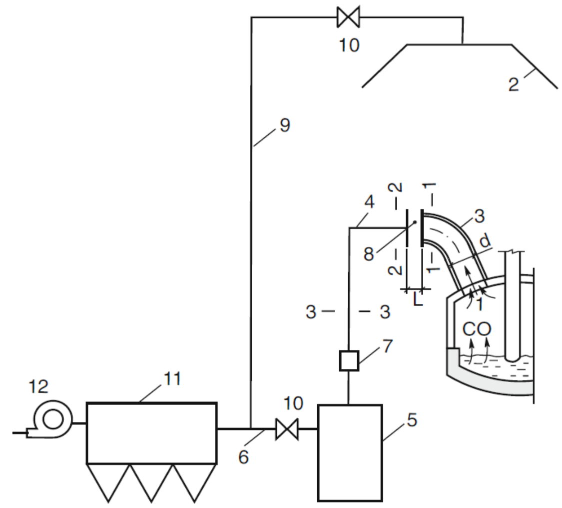

Figure 2 - Schematic diagram of evacuation and purification of gases from EAF [3].

1 – Opening in the furnace roof, 2 – the canopy hood, 3 – the roof elbow, 4 – the stationary gas duct, 5 – the drop out box, 6 – the gas duct, 7 – water quenching device, 8 – the air gap, 9 – the gas duct, 10 – off-gas flow rate control valves, 11 – the baghouse, and 12 – exhauster

ORNL is developing an innovative WHR concept that can recover >70% of off-gas heat to preheat scrap; generate steam; and, if economical, produce electrical power. The proposed WHR system aims to eliminate many of the problems associated with currently used practices and provide an opportunity to recover sensible and chemical heat through controlled burning of combustibles in the gases via integral heat recovery. The proposed WHR system also includes the removal of a large percentage of particulates, resulting in hot and relatively "clean" gases that can be used to preheat charge material and to produce steam and electrical power for use in the plant. The ORNL team expects to test one or more systems in collaboration with industrial partners and end users.

ORNL'S REGENERATIVE DROP-OUT BOX CONCEPT

The proposed WHR system includes several new features and differs from conventional systems in the following ways:

- It preconditions exhaust gases to process (or oxidize) combustible gases at a controlled temperature and removes a large percentage of particulates, resulting in clean or combustibles-free exhaust gases.
- It extracts off-gases from the furnace by keeping off-gas pressure under the furnace roof nearly constant.
- It controls temperature and gas composition while transferring heat.
- It uses heat recovery to reduce the exhaust gas temperature, as opposed to using a large volume of cooling air to do so.
- It uses a heat transfer system that provides heat accumulator capability to reduce the effect of variations in the sensible and chemical heat content of EAF exhaust gases during a heat or during the cycle.
- It preheats scrap using hot gases that contain no combustible materials and are at a controlled temperature, enabling convective heating of the entire mass of scrap before it is charged into the EAF.
- It uses clean exhaust gases in a steam generator that includes auxiliary fuel firing to deliver a fairly constant amount of steam for use in the plant.

- It uses steam to generate electrical power to offset some facility power costs, if economically justified.

DETAILED TECHNICAL DESCRIPTION OF THE PROPOSED SYSTEM

The proposed system for recovering sensible and chemical heat from EAF exhaust gases is shown in Figure 3 and described below.

1. A drop-out box regenerator (DB Regen 1) is used to condition EAF off-gases. It is designed to complete the combustion of gases containing chemical heat under controlled temperature using a minimum amount of combustion and cooling air. It consists of a heat source module that transfers heat from the off-gases to a regenerator with ceramic bricks that can withstand high temperatures and can store heat.
2. A heat transfer module (heat sink) transfers heat stored in the regenerator (Regen 2) to air or another fluid. In doing so, it also cools the regenerator in the heat source module so it can absorb more heat.
3. The system includes a particulate removal or dropping arrangement in or outside the heat transfer modules. It uses a proper geometrical configuration and/or a cleaning medium—such as compressed air, mechanical scrubbing, or other methods—to remove particulates attached to the regenerators.
4. A mixture of hot air from the heat sink module and hot and relatively clean gases—free of combustibles, vapors, and particulates—is used at a controlled temperature in the secondary WHR subsystem.
5. The secondary WHR system includes a scrap or charge preheater and/or a steam generator.
6. Gases are distributed to the scrap preheater and/or to a steam generator based on heat demand in the scrap preheater; excess gases go to the steam generator. The exact use, distribution, and control of the heat depend on specific plant requirements.
7. The system may recirculate scrap preheater exhaust gases to DB Regen 1, where the temperature is well above 982°C (1,800°F), to combust any combustible gases or volatile organic compounds mixed with heating gases in the scrap or charge preheater.
8. The steam generator uses the clean hot gases and air from Regen 2 to produce steam. It may use an auxiliary fuel, such as natural gas, to maintain constant steam production when the heat content of the hot gas and air is not adequate to deliver the desired steam production.
9. The steam can be used in the plant as process steam or for other applications as needed (e.g., vacuum degassing system, vacuum pumps) or for power generation using a conventional steam turbine generator system.
10. Clean, lower-temperature exhaust gases from the steam generator are directed to the bag-house or other pollution control system at a controlled temperature by using dilution air if necessary.
11. If necessary, a gas treatment method such as injection of activated carbon can be used to reduce the concentration of pollutants such as dioxin and furan to meet environmental control regulations.

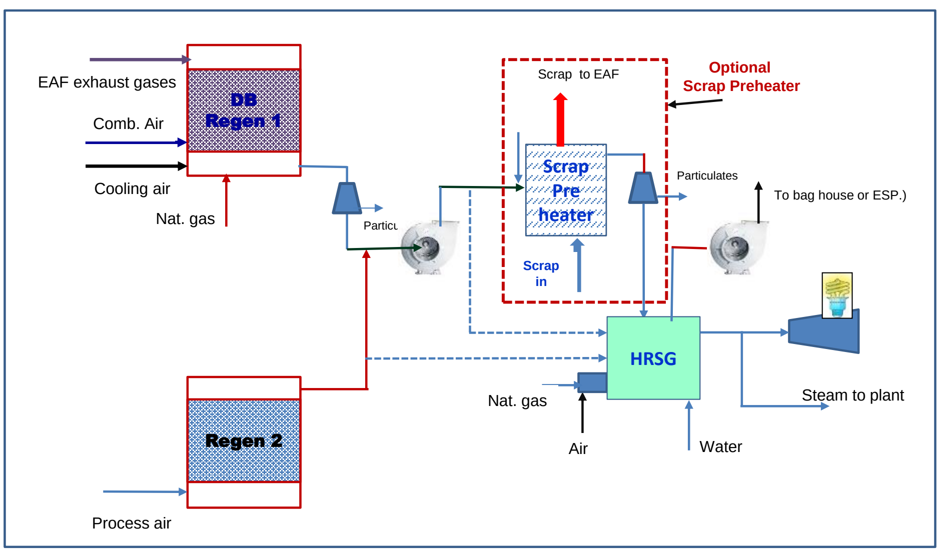

Figure 3 – Regenerative drop-out box heat recovery system for recovering sensible and chemical heat from EAF exhaust gases with integrated scrap preheating.

EAF OFF-GAS WASTE HEAT RECOVERY MODEL

EAF off-gases contain significant amounts of chemical and sensible heat that is not recovered or used for any productive purpose in the facility. Because of the batch or periodic nature of the process, mass and energy flow rates in the EAF are not steady-state but are time-dependent during a particular heat cycle. Mass and energy flow rates depend on variables such as electric power input, injection of oxygen and coal, firing rate of natural gas burners, and post-combustion injectors. These parameters affect the off-gas composition, percentage of combustibles, and mass flow rate and temperature, resulting in wide fluctuations in off-gas enthalpy or waste heat content. The issues of off-gas quantity and composition are highly complicated, because the waste heat quantity is very dependent on the design and operation of the EAF, as well as the type of charge material used.

In many cases, the off-gases react with air that enters the ductwork through openings between the furnace off-gas outlet (often referred to as the “fourth hole”) and the ducts leading to the off-gas or fume collection system. It is possible, although difficult, to measure the exact gas composition and temperature at this location. The current trend is to install a gas sampling probe in an off-gas duct close to the furnace where the gases do not have enough time to react with air entering the duct and hence are not completely combusted. However, because of the very high temperatures and the unpredictability of the combustion reaction at the point where a sampling probe would be located, it is difficult to install a long-lasting thermocouple and collect exact temperature data for the gases. The gas composition measured by a sampling probe is reported in percentages of CO, H_2, O_2, and CO_2. Along with the gas composition data, additional data are collected for the off-gas temperature and flow rates. Flow rate data are usually expressed as actual volume flow or cubic feet per minute (acfm) in English units or cubic meter per hour (m^3/hour).

Example off-gas composition, temperature, and flow rate data for a 145 ton batch EAF [4] are shown in Figures 4 and 5. As these figures show, there is wide variation in all parameters of interest for each heat cycle, and the values may change significantly from one cycle to another. Hence, it is necessary to account for these variations in considering potential WHR. The proposed ORNL model was developed to account for these variations.

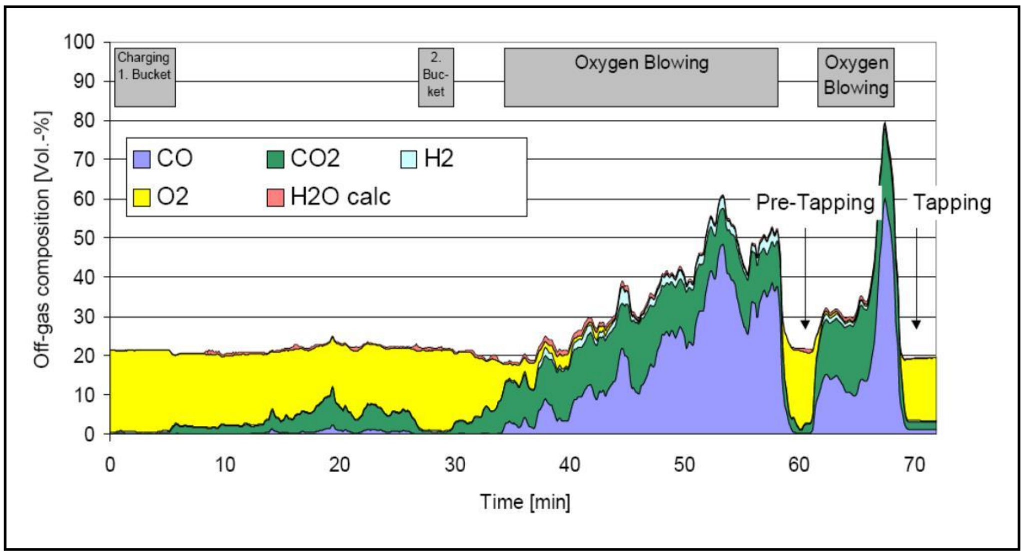

Figure 4 – Measured amounts of off-gas components from a 145 ton/batch EAF [4].

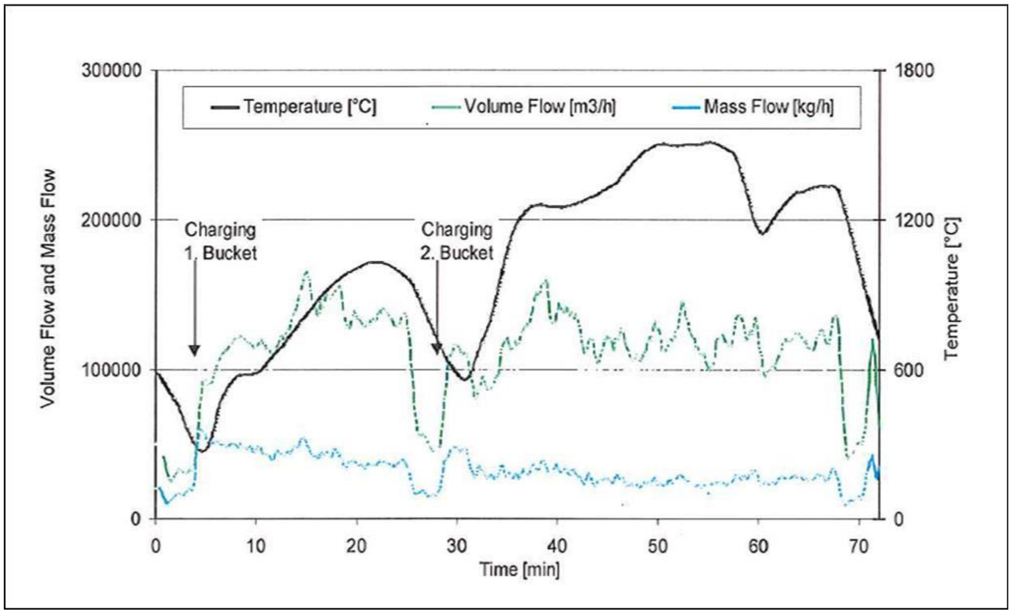

Figure 5 – Measured off-gas volume, mass flows, and temperature in a 145 ton/batch EAF [4].

DESCRIPTION OF THE ENTHALPY MODEL

The research team has developed an Excel-based enthalpy model for calculating overall heat availability (sensible and chemical) and recoverable heat values (steam or power generation potential) for the proposed WHR system. As input parameters, the model uses off-gas data collected using a commercially available off-gas monitoring system. It is designed to estimate steam generation and associated electricity production at several segments at predefined time intervals for a typical heat cycle, as well as for the total duration of the heat cycle, using two different modeling approaches.

The Overall Waste Heat Recovery Model uses the data to calculate steam generation and power generation based on the sensible and chemical heat of the off-gases when they are used directly in a steam generator. Obviously, this is a simple approach. However, it can be used to assess overall WHR potential and decide whether it is worthwhile to conduct a detailed analysis and investigate available WHR methods. The analysis requires no information regarding a heat recovery method. Figure 6 lists the data required to run the high-level Overall Waste Heat Recovery Model.

Because the direct use of off-gases containing variable amounts of particulates and combustibles at high temperatures is difficult, it is necessary to develop an alternate system that allows heat recovery from such gases. The second approach, the Regenerative Drop-out Box System Model, makes calculations for a regenerative drop-out box WHR system of the type described earlier. Using this system, it is possible to dampen or even eliminate wide fluctuations in the flow rates and composition of off-gases. The model also allows the use of auxiliary heat to produce a nearly constant amount of steam and electrical power, which is more practical for use in a plant. This analysis requires considerably more data related to the design and operating parameters for a regenerative drop-out box WHR system like the one described earlier. This model offers the option of using a scrap preheater as part of the WHR system. A list of the data required is provided in Figure 7.

Each of the two modeling approaches divides a typical heat, or cycle, into several time segments. Typically, 5 minute intervals are used for calculations. For each time segment, the following data are used for detailed heat recovery calculations:

- Average off-gas analysis in terms of CO, CO_2, O_2, H_2, and H_2O (if available)
- Average temperature of off-gases
- Average off-gas flow rate

High-Level Input Data for Overall Waste Heat Recovery Modeling

Heat Cycle Parameters
- Clock start time
- Time increment
- Total heat-cycle time

EAF Off-Gas Characteristics
- EAF off-gas temp.
- Off-gas volume flow rate
- Off-gas composition (% by volume): O_2, CO, H_2, CO_2, H_2O, and CH_4.

Operating Parameters
- Ambient temp.
- Air temperature for combustion and cooling

Parameters Used for Overall Performance Analysis:
- Percent of heat loss for EAF exhaust gases before approaching heat recovery system
- Heat to power conversion efficiency
- Desired or expected exhaust gas temperature from the system
- Heating value of natural gas

Economic Analysis Parameters:
- Purchased electricity unit price ($/kWh)
- Natural gas (fuel) cost ($/MMBtu)
- Credit for steam used in the plant ($/MMBtu)
- Allowance for maintenance & operating cost
- Number of heats per year
- Cost basis for the HRSG & generator system
- Cost basis for scrap preheater ($/ton of scrap)

Figure 6 – High-level input data for overall waste heat recovery modeling.

Detailed Input Data for Regenerative Drop out Box WHR Modeling

Regenerator Design Parameters:
- Refractory brick width, thickness, length, sp. Heat, sp. weight, % of surface exposed, total no. of bricks
- Heat loss from the regen system incl. ducts
- Allowable mixing temperature in regenerator
- Heat transfer coefficient
- Required Preheated Air Flow from Regenerator
- Maximum allowable regen material temperature

Scrap Preheater Design Parameters:
- Scrap charge rate
- Scrap inlet temp.
- Scrap specific heat average
- Temperature of gases entering in scrap preheater
- Fraction of regen preheated air used
- Scrap assumed plate thickness
- Scrap material density
-Overall heat transfer coefficient

Steam generator (HRSG) design parameters:
- Required steam production, pressure& temp.
- Feed water temperature to steam generator - boiler
- Heat loss in HRSG (% of heat input)
- Desired - design temperature for gases going to boiler
- Steam generator (HRSG) efficiency
- Steam used in the plant
- Steam power generation efficiency (excluding boiler efficiency)
- Boiler blow down loss as % of steam production

Figure 7 – Detailed input data for regenerative drop out box WHR modeling..

Most data collection systems collect data at very short time increments, as frequently as one data point per second. The result is a very large amount of data that can be difficult to handle using a simple model. Therefore, this Excel-based model uses average values for the required parameters. The average values for each segment can be obtained as an arithmetic average or by any other justifiable method of deriving average values. It is necessary to get the data at a single sampling point location and at a point where the gases have not had time to cool down. This requires the use of an advanced sampling and data collection system; equipment suppliers are capable of delivering this information.

A typical data input process uses the format shown in Table 1. Based on observations at several plants using two different methods of data collection, it is apparent that it is not always possible to collect all of these data at one sampling point. However, advanced in-situ laser-based systems (e.g. More's LINDARC system [5]) or off-gas extractive systems (e.g. Tenova Goodfellow's EFSOP system [6, 7] or Siemens' Lomas system [8]) can provide the required data with good accuracy. These data are used in the model to calculate potential electrical power generation and steam generation at 5 minute intervals. Note that the time interval can be selected by the user.

Table 1 – EAF off-gas enthalpy modeling - A typical data input format.

DATA INPUT					
EAF Off-Gas Characteristics	Data supplied by Company A - summarized by ORNL, March22, 2015				
Clock Time Start	1/22/2015 10:05	Time increment:	5	minutes	16
Total heat - cycle time	60	minutes per heat	Number of heats:		1
Heat No. 1					
Segment no.	1	2	3	4	5
Clock time	10:05 AM	10:10 AM	10:15 AM	10:20 AM	10:25 AM
Elapsed time: minutes	0:00:00	0:05:00	0:10:00	0:15:00	0:20:00
Elapsed time - hours	-	0.083	0.167	0.250	0.333
EAF off-gas temp Deg. F.	1440	1537	1333	1535	1594
EAF off-Gas volume flow rate acfh	7,491,295	9,946,110	9,378,111	9,481,778	9,357,497
Ex. Gas volume flow rate scfm	34,171	43,165	45,330	41,191	39,483
O2 % by volume (wet analysis)	1.21%	0.01%	10.88%	0.01%	0.03%
CO % by volume (wet analysis)	0.20%	3.30%	0.14%	12.12%	4.89%
H2 % by volume (wet analysis)	1.61%	1.86%	0.23%	7.46%	0.76%
CO2 % by volume (wet analysis)	0.32%	11.70%	0.61%	11.15%	13.37%
H2O % by volume	0.00%	0.00%	0.00%	0.00%	0.00%
CH4 and other combustibles % by volume	0.10%	0.11%	0.05%	0.38%	0.11%

Complete heat cycle 5-minute interval

The model calculates sensible and chemical heat contained in the off-gases, values of steam generation for a given pressure and superheat temperature, and electrical power generation at every time interval. Owing to large variations in gas flow and heat content, power generation varies considerably from one time segment to another. To calculate overall power production potential, an auxiliary fuel such as natural gas is used to maintain constant power production. In this case, the auxiliary fuel is used to deliver the peak power production rate. This requires a large amount of auxiliary heat that is calculated and reported in the results. For all practical purposes, this type of arrangement may not be possible and economically justifiable unless the auxiliary fuel is easily available in the required amount and relatively low in cost. These results are to be used only as a first step in evaluating the potential for power production using off-gas heat. The next step in the performance model uses a more realistic approach that allows the user to select the amount of steam and electrical power production.

Table 2 - Parameters used for economic calculations

Operating parameters			
Total heat or cycle time	60.00	Minutes	
EAF batch or heat weight	100.00	tons/heat	
Scrap charge - heating rate	100.00	tons/hour	
Reference temperature	Deg. F.	60	
Air temp for comb and gas cooling air	Deg. F.	80	
Parameters used for overall performance analysis			
Air temp ambient and cooling air	Deg. F.	80	
Percent of heat loss for EAF exhaust gases before approaching heat recovery system.	%	10%	
Heat to power conversion efficiency (overall)	%	25%	
Desired or expected exhaust gas temperature from the system	Deg. F.	350	
Heating value of natural gas	Btu/scf	1020	
Economic analysis parameters			
Purchased electricity cost incl. all charges	$/kwh	$0.08	
Natural gas (fuel) cost	$/MM Btu	$4.84	
Credit for steam used in the plant	$/1000 lb. steam	$8.00	
Allowance for maintenance and operating cost (added cost associated with WHR system operations)	% of cost savings	20%	
Number of heats per year	No.	8,000	
Cost basis for the system	$/kW produced	$	2,000.00
Cost basis for scrap preheater - Baseline for 100 tons/hour charge rate ($cap cost)	$/100 tons of scrap charged	$	10,000,000

The detailed Regenerative Drop-out Box System Model includes a heat storage and recovery system that dampens the fluctuations in the heat capacity of the off-gas heat and thus reduces the use of auxiliary fuel to produce stream and electrical power. The system offers two options:

1. In option one, off-gases are processed to use the chemical heat of the gases under controlled combustion and then used in a steam generator to produce steam. The steam can be used as process steam in the plant and/or used to generate electrical power using a steam turbine generator system.
2. Option two includes a scrap preheater in which the heat of off-gases at a controlled temperature is used to preheat scrap charged in the EAF. Gases from the scrap preheater are used in a steam generator to produce steam for use in the plant and/or to generate electrical power.

In both cases the regenerative drop-out box is used to completely oxidize the combustible components (CO and H_2) of the EAF off-gases and produce hot gases at a constant temperature.

Figure 7 provides a general list of the data required for the detailed model. Tables 2–4 gives examples of specific data used for the calculations discussed in this paper. Table 2 shows parameters used for economic calculations for the system. Table 3 lists design parameters used to design the steam generator and scrap preheater. Table 4 shows the regenerator design parameters.

Table 3 – Steam generator and scrap preheater design parameters

Heat recovery system design parameters - Regenerator System		
Steam generator (HRSG) design parameters		
Required (desired) steam production	lbs./hr	100,000
Required steam pressure	Psig	800
Required steam temperature	Deg. F.	700
Feedwater temperature to steam generator - boiler	Deg. F.	200
Heat loss in HRSG (% of heat input)	%	10%
Desired - design temp. for gases going to boiler	Deg. F.	1,600
Steam generator (HRSG) efficiency	%	75%
Steam used in the plant	lbs./hr	0
Steam power generation efficiency (excluding boiler efficiency)	%	33%
Boiler blow down loss as % of steam production	%	7%
Scrap preheater design parameters		
Scrap charge rate	tons/hr.	100
Scrap Inlet Temperature	Deg. F.	80
Scrap specific heat - average	Btu/(lb. - F)	0.135
Preheater Control Temperature	Deg. F.	1,700
Efficiency of EAF in transfer of electricity	%	50%
Fraction of regen preheated air used	%	100%
Scrap - assumed plate thickness	inch	0.75
Scrap material density	lbs./ft^3	480
Overall heat transfer coefficient	Btu/(hr. ft^2.	3.0

Table 4 – Regenerator design parameters

Regenerator (for each of the two sides) design parameters		
Sp. Heat of brick material	Btu/(lb. F)	0.225
Brick width	inch	4.50
Brick Thickness	inch	2.50
Brick Length	inch	9.00
Volume of the brick	ft^3	0.0586
Sp. Weight of the material	#s/ft^3	125.00
Weight per brick/piece	Lbs.	7.32
Surface area per brick	ft^2/brick	1.03
Exposure	%	90%
Ratio of surface area/volume for regen	ft^2/ft^3	6.00
Height/width ratio		4.00
width/length ratio		2.50
Total weight of the bricks	#s	200,000
Heat loss from the regen system incl. ducts	% of total	3.0%
Allowable mix temp in regen	Deg. F.	3,000
Heat transfer coeff	Btu/(hr-F-ft^2)	5
Required Preheated Air Flow From Regenerator	scfm	10,000
Maximum allowable regen material temperature	Deg. F.	2,500
Start temp for regen material (approximate to start calculations)	Deg. F.	1,435
ID Fan Control Temp	Deg. F.	1,700
Cycle time	Minutes	5

The analysis methodology includes the following steps.

1. Controlled combustion using appropriate amounts of combustion air and cooling air to control off-gas temperature at a predetermined value in a drop-out box. The analysis includes calculation of the required combustion air for combustible gases such as CO, H_2, and hydrocarbons and cooling air to bring the off-gas mixture to a desired temperature. Use of advanced ceramic and refractory materials would allow this temperature to be at a predetermined high value, typically a maximum of 2500°F.
2. Analysis of heat transfer in a regenerative heat exchanger system. The system includes two regenerative beds in which heat is transferred to and from the regenerator bed during heating and cooling cycles. Using design data for a regenerator bed, calculations are made of the heat transferred to a bed and the drop in off-gas temperature during a heating cycle. The regenerator bed provides a flywheel effect to reduce variations in the heat content of off-gases, since a percentage of the heat is transferred to and stored in the regenerator bed. Timing of the heating cycle depends on the regenerator size, type of material used, and other design parameters of the bed. In the calculations used in this paper, a heating cycle time of 5 minutes was assumed. During the cooling cycle, ambient air is used to cool the regenerator bed. The primary goal of the cooling cycle is to absorb as much heat as possible and cool the bed so that heat can be stored in the bed again during the heating cycle. The cooling air volume is controlled to achieve a desired exit air temperature. Heated air can be mixed with the off-gases discharged from the bed that is being heated or can be used in a steam generator. This air is used for combustion of auxiliary fuel and as a heat source for the steam generator.
3. The scrap preheater performance, when it is used, includes calculation of the average temperature of the scrap and of the exhaust gases from the scrap preheater. Hot gases from the regenerator bed and all or some portion of the regenerator cooling air are directed to the scrap preheater. The gas temperature entering the scrap preheater is controlled to a desired value between 1400 and 1600°F. Control of the temperature of the heating gases makes it possible to use convection heating and pass hot gases through the scrap bed. This is somewhat different from the commonly used heating system in which radiation is the main heat transfer mechanism. Convection heating allows more uniform heating and thus a substantial increase in the heat content of the preheated scrap. A forced-draft or an induced-draft fan can be used to provide sufficient gas velocity and overcome the pressure drop throughout the bed. The calculations are carried out by treating the

scrap preheater as a counter flow heat exchanger. It is also possible to account for any additional heat generated within the scrap preheater due to the presence of combustible materials, such as oil, in the scrap. Exhaust gases from the scrap preheater are taken to a steam generator to recover the remaining heat.

4. A heat recovery steam generator (HRSG) is included in the system to recover heat from hot gases from the regenerator and/or the scrap preheater and from heated cooling air from the regenerator bed. Calculations for steam generation are based on the practical value of the HRSG efficiency and specifications of steam pressure and temperature. The model does not include detailed calculations for HRSG design. Since the heat content of gases (temperature and mass flow rate) changes during a heat in an EAF, it is necessary to use an auxiliary heating source, such as natural gas, to maintain the required level of steam production. The model calculates the auxiliary heat required. In most cases, use of a duct burner may be adequate to provide the necessary heat, since the gases entering the HRSG contain enough air for combustion of an auxiliary fuel such as natural gas. However, the calculations include a check on the availability of enough oxygen for combustion of fuel and other combustibles in the hot gases. For the calculations presented in this paper, it is assumed that steam is delivered at 800 psig and 700°F; HRSG efficiency is assumed to be 75%. Steam can be used in the plant as process steam or to produce electricity generation using a steam turbine generator system. It is possible to specify and limit steam generation to a certain value, which is less than the steam generation at peak conditions when the amount of heat entering the HRSG is highest.
5. Potential electricity production using a steam turbine generator system is calculated by using the heat content of the steam used for the turbines. The calculations use a value of overall efficiency of electricity generation using a conventional turbine generator system. For the calculations in this paper, the conversion efficiency is 33% and does not include HRSG efficiency. The overall efficiency of the steam generator and electricity production is 24.75%, which is practically same as the value used for overall performance calculations discussed earlier.
6. Preliminary economic calculations use the energy cost and operating practices for the EAF. The calculations include credit for production of steam used in the plant, electricity produced, and reduction in energy use (mostly electricity) and related cost savings due to scrap preheating. No credit is taken for possible reduction in EAF heat time and increased production, since it depends on business conditions. Allowance is made for operating and maintenance cost as a percentage of the total savings. No attempt is made to calculate the project cost and hence the payback period. However, provision is made to enter user-defined capital costs and the resultant payback period.

The modeling results are reported on a separate page that includes user-defined values of economic and technical performance parameters. Table 5 shows typical results for a regenerative drop-out box system without a scrap preheater.

During the testing phase of the model, an attempt was made to calculate the payback period using very preliminary capital costs. The capital cost values could be debated since they are based on costs available in the literature for electrical power production and scrap preheating systems. The cost of the drop-box regenerator system was estimated based on the past experience of the team members. Using a capital cost of $2,500/kW installed capacity, an attempt was made to estimate total project cost and potential payback. However the numbers are very preliminary and should not be considered representative.

Table 5 – Typical performance results for regenerative drop-out box WHR system without scrap preheater

RESULTS - Regenerator System		
Performance Results		**Without Use of a Scrap Preheater**
See attached diagram for values of critical parameters for the system		
Average scrap temperature to the EAF	Deg. F.	N/A
Steam generated (average value)	Lbs./hr.	100,000
Steam used (exported) in the plant	Lbs./hr.	0
Electrical power generated (average value)	MW for the heat	11.301
Total electricity produced per heat	kwh per heat	11,301
Electricity savings due to scrap preheating	kwh per heat	0
Total electricity credit per heat	kwh per heat	11,301
Exhaust gas temperature at HRSG exit	Deg. F.	465
Preliminary cost parameters		
Credit for plant process steam	$/1000 lbs.	$8.00
Cost of natural gas	$/MM Btu	$4.84
Credit for incremental electricity	$/kwh	$0.08
No. of heats per year	No.	8,000
Natural gas consumption (average value)	MM Btu/heat.	17.42
Results - Savings and energy Use		
Maximum N. gas demand during a heat	MM Btu/hr.	62.10
Value of electricity produced	$/year	$7,232,842
Electricity cost savings related to scrap preheating	$/year	$0
Value of (credit for) steam used in the plant	$/year	$0
Cost of natural gas (fuel) used for the HR system	$/year	$838,780
Net savings	$/year	$6,394,062
Allowance for O&M cost	% of net savings	20%
O&M cost per year for the HR system	$/year	$1,278,812
Net cost savings per year	$/year	$5,115,250

Table 6 shows the system performance when a scrap preheater is used as an integral part of the heat recovery system.

In addition to the overall performance, the model also gives the flow rates and temperatures of various streams within the system at selected times. Figure 8 shows the locations of various streams numbered from 1 to 19. The model calculates these values at each time increment and allows the user to see their values at the user-selected time in the cycle.
An example in Table 7 shows the flow rate and temperature of the most important flow streams at midpoint in the cycle (10:25:00 a.m.).

The results of the analysis of two cases, one with and one without a scrap preheater, clearly show that using a scrap preheating system as an integral part of the overall WHR system offers relatively large savings. The savings do not include the potential benefits of a shorter heating time and an increased production rate.

Table 6 – Typical performance results for regenerative drop-out box WHR system – with scrap preheater

RESULTS - Regenerator System		
Performance Results	**With Use of a Scrap Preheater**	
See attached diagram for values of critical parameters for the system		
Average scrap temperature to the EAF	Deg. F.	1,248
Steam generated (average value)	Lbs./hr.	100,000
Steam used (exported) in the plant	Lbs./hr.	0
Electrical power generated (average value)	MW for the heat	11.301
Total electricity produced per heat	kwh per heat	11,301
Electricity savings due to scrap preheating	kwh per heat	22,664
Total electricity credit per heat	kwh per heat	33,965
Exhaust gas temperature at HRSG exit	Deg. F.	459
Preliminary cost parameters		
Credit for plant process steam	$/1000 lbs.	$8.00
Cost of natural gas	$/MM Btu	$4.84
Credit for incremental electricity	$/kwh	$0.08
No. of heats per year	No.	8,000
Natural gas consumption (average value)	MM Btu/heat.	21.22
Results - Savings and energy Use		
Maximum N. gas demand during a heat	MM Btu/hr.	75.55
Value of electricity produced	$/year	$7,232,842
Electricity cost savings related to scrap preheating	$/year	$14,504,963
Value of (credit for) steam used in the plant	$/year	$0
Cost of natural gas (fuel) used for the HR system	$/year	$985,824
Net savings	$/year	$20,751,982
Allowance for O&M cost	% of net savings	20%
O&M cost per year for the HR system	$/year	$4,150,396
Net cost savings per year	$/year	$16,601,585

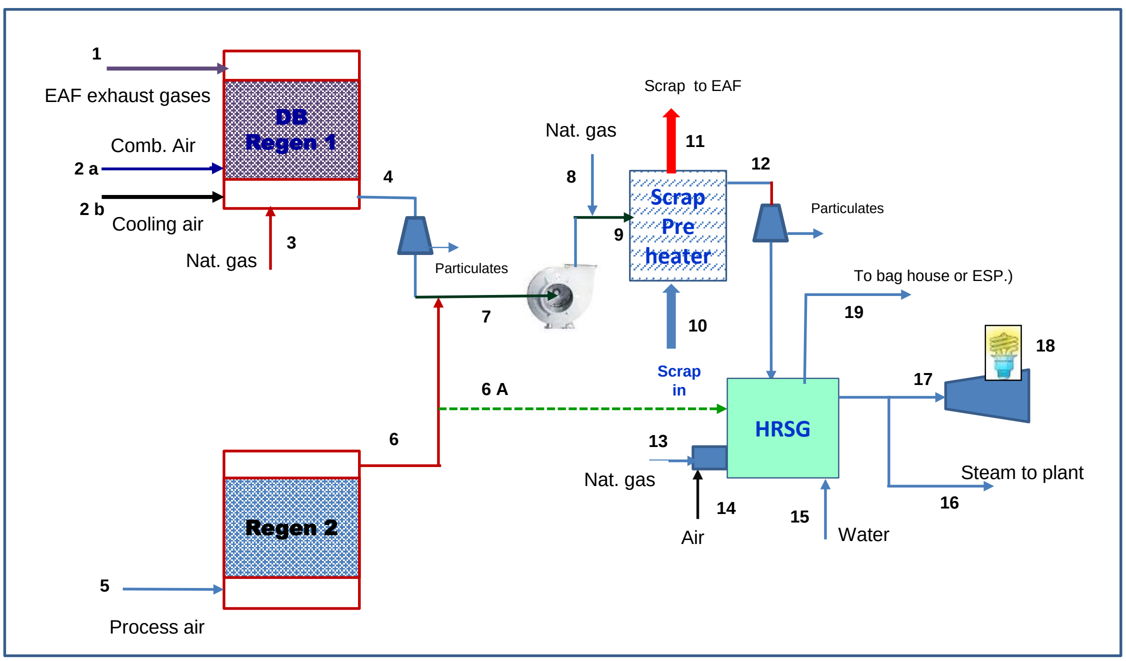

Figure 8 – Regenerative drop-out box heat recovery system—locations of various streams.

Table 7 – Flow and temperature of the most important flow streams at midpoint in the cycle (at 10: 25:00 AM)

Performance Parameters Table - Regenerator WHR System			
Time	Hours	10:25:00 AM	
Process parameter	No.	Flow rate	Temperature
		scfm or Lbs./hr.	Deg. F.
EAF exhaust gas	1	77,522	1,120
Combustion air to the regen unit	2 a	1,270	80
Cooling air to the regen unit	2 b	0	80
Natural gas to the regen unit	3	0	
Exhaust gases to scrap preheater	4	78,791	1,488
Cold air to the regenerator	5	10,000	100
Hot air from regen to scrap preheater	6	10,000	1,752
Hot air from regen to steam generator	6A	10,000	1,752
Total exhaust gases to scrap preheater	7	88,791	1,518
Natural gas added to scrap preheater	8	324	
Heating gases entering to scrap preheater	9	89,109	1,700
Scrap entering to preheater	10	200,000	80
Preheated scrap leaving scrap preheater	11	200,000	1,238
Exhaust Gases leaving scrap preheater	12	88,791	1,408
Natural gas to HRSG (boiler)	13	81	80
Combustion air to HRSG (boiler)	14	0	80
Feed water entering HRSG (boiler)	15	107,000	80
Mass flow of Steam Produced		64,015	
Steam to the plant	16	0	
Steam to the steam turbine	17	64,015	
Electric power	18	11.30	
Exhaust gases from HRSG (boiler)	19	57,176	392

The model is not designed to perform payback analysis, since it is difficult to obtain information on capital and installation costs for the system at any location. However, an attempt was made to obtain a very preliminary possible payback period for the location where the data were collected that were used in the calculations in this paper. Based on preliminary numbers, as shown in Table 8, the payback period can be as low as 1.5 years when the system includes a scrap preheater as part of the WHR system. These values are preliminary and should not be used to make firm conclusions about the justification for such a system.

Table 8 – Preliminary payback analysis

Simple payback - Based on prelimnary cost figures		
Estimated cost of the system	$	$32,602,631
Net credit or revenue	$/year	$16,601,585
Simple payback period	Years	1.96

USE OF THE MODEL

The primary objective of the development of the EAF enthalpy model is to enable EAF users to analyze the potential for steam and electrical power generation based on information obtained regarding off-gas composition and temperature. Since EAF steelmaking is a batch process in which off-gas composition and temperature vary continuously during a heating cycle, it is difficult to estimate the average and total values of recoverable heat wasted by the EAF. Use of this model allows users to estimate the peak values of waste heat, as well as potential for steam and/or electrical power generation. It also allows them to estimate the auxiliary heat required to maintain peak power production and the desired level of steam and electrical power production. Used for a case in which scrap is preheated using waste heat, the model enables the user to calculate the scrap preheat temperature and possible savings in electricity for charging hot scrap in the EAF. It is possible to define the temperatures of hot gases entering the scrap preheater to estimate the maximum temperature of scrap charged in the EAF.

In discussions of the results of the model with managers of the plant where the EAF was located, it became clear that many plant personnel do not realize the potential for generating steam and producing electrical power using EAF off-gas waste heat. With a proper WHR system and auxiliary heat from natural gas or other sources in a steam generator, it is possible to generate a large percentage of the total electrical power used in an EAF plant.

The most important requirement for using the model is to supply accurate data for off-gas analysis, primarily the levels of CO, H_2, and other combustibles along with the off-gas temperature and flow rate. Currently available off-gas monitoring systems promoted for the control of EAF operation can be used to provide inputs for this model.

FUTURE WORK

The enthalpy model is based on currently available information for the performance of regenerators and scrap preheaters. At this time, the project team continues to work with equipment suppliers and the steel industry to modify the model as more information is made available. In its current form, the model has been very useful in making industry personnel aware of the potential for WHR from EAF off-gases and the potential returns from a WHR system. The model will be modified to allow for industry requirements and additional information on materials and design.

CONCLUSION

A simple Excel-based model was developed to evaluate the recovery of chemical and sensible heat from EAF off-gases. The model can be populated with EAF off-gas data collected by commercially available off-gas monitoring systems. Such systems provide an off-gas analysis in terms of combustible gases such as CO, H_2, CH_4, and noncombustible gases such as O_2 and H_2O, along with off-gas flow rate and temperature data at or very near the EAF off-gas outlet. The model can be used to estimate scrap preheat temperature, steam generation, and electrical power generation using data taken at small time increments to allow for large variations in all the parameters. The calculations can be made at a high level when the WHR system performance is calculated at a high level, independent of the type of WHR system used. It can also be used to model a regenerative drop-out box WHR system being developed at ORNL. The model results give energy savings, scrap temperature at the outlet of a scrap preheater, possible steam generation, and electrical power production. It also estimates the economic benefits in terms of annual dollar savings for a given set of operating conditions. The research team has run this model using data obtained from a number of steel companies and is continuing to modify it as more data and component performance information become available.

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