Process Heating Assessments Using DOE's Manufacturing Energy Assessment Software for Utility Reduction (MEASUR) Tool Suite

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ABSTRACT

Process heating is the most energy-intensive manufacturing process for most sectors of industry. To quantify energy savings from various energy conservation measures, the Department of Energy (DOE) sponsored the development of the Process Heating Assessment and Survey Tool (PHAST) and similar tools for other industrial systems in the early 2000s. It has been used extensively in the Save Energy Now Program's Energy Savings Assessments and the Better Plants Program's In-Plant Trainings. Since the initial development of the legacy tools, both computer operating systems and software development have evolved significantly. Thus, DOE has invested in the modernization of PHAST and other legacy software tools to create the Manufacturing Energy Assessment Software for Utility Reduction (MEASUR) tool suite. MEASUR offers a collection of software tools that can aid manufacturing facilities in improving the efficiency of energy systems and equipment (specifically pumps, fans, steam, and process heating) and in conducting "Energy Treasure Hunts". Eventually, the tool will also add compressed air and process cooling systems.

The Process Heating Assessment (PHA) module of MEASUR is an upgrade of the PHAST tool. PHA provides the means to model fuel-fired, steam-based, and electric process heating systems, covering process heating for most industrial plants in manufacturing sector. It also includes several key upgrades, including the ability to consider multi-component charge loads and account for several different areas of energy losses. The new tool includes a comprehensive flue gas calculator to quantify available heat and heat loss for various gaseous, liquid, and solid fuels and new heat loss calculators. It generates a report and a dynamic Sankey diagram to show the energy consumption in various areas of energy use. MEASUR has significantly improved the user experience by adopting a modern software design. This paper details the structure and workflow of PHA and presents a real-world case study to demonstrate energy savings quantification and MEASUR's outstanding reporting capabilities.

Keywords: Industrial energy efficiency, process heating, electrotechnology, heat balance, waste heat recovery

INTRODUCTION

Process heating operations supply thermal energy to transform materials like metal, plastic, rubber, limestone (cement), glass, ceramics, and biomass into a wide variety of industrial and consumer products. Industrial heating processes include drying, heat treating, curing and forming, calcining, and smelting, among others. Process heating systems include furnaces, ovens, dryers, heaters, and kilns. Process heating accounts for about 70% of all process energy (energy used to convert material into manufactured products) used in the U.S. manufacturing sector. This is equivalent to a total of 7.5 quadrillion BTU (quad) of energy. Energy losses at individual subsector levels vary, but on average the percent of process heating energy lost in the entire manufacturing sector is estimated at 34%, or 2.55 quad [1]. Energy audits and assessments can help reduce the energy consumed by process heating equipment by identifying areas of energy use and loss and taking action to reduce the losses.

To help identify and quantify such savings, the Department of Energy (DOE) sponsored the development of the Process Heating Assessment and Survey Tool (PHAST, first released in 2010), which was used extensively in the Save Energy Now Program's Energy Savings Assessments, the Better Plants Program's In-Plant Trainings [2], and internationally [3], [4]. More recently, in response to the tremendous evolution of computer operating systems and improvements in software development, DOE has modernized PHAST and other DOE energy analysis tools and combined them to create the Manufacturing Energy Assessment Software for Utility Reduction (MEASUR) Tool Suite.

MEASUR, first released in 2018, is a collection of updated software tools developed to aid manufacturing facilities in improving the efficiency of energy systems and equipment [5]. Based on the original DOE software tools, MEASUR contains the capability to analyze four major support systems found within manufacturing facilities (pumps, fans, steam, and process heating), as well as a Treasure Hunt Module. Eventually, the tool will also add compressed air and process cooling systems. MEASUR combines more than 50 equipment and property calculators for simple energy-related calculations and analyses. It is available for Windows, Mac, and Linux, and is open source and open access, with the code bases and program available for free download and use [6].

This paper focuses specifically on the use of the new Process Heating Assessment (PHA) tool in MEASUR, which replaces PHAST.

WHAT IS THE PROCESS HEATING ASSESSMENT TOOL?

The PHA tool in MEASUR was developed to conduct energy assessments/audits of the process heating equipment used in many industries. PHA can be used to perform heat balances to identify major areas of energy use/loss under various operating conditions and test various "what-if" scenarios for reducing energy use. Previous versions of the tool have been used in industrial plants around the world to identify and estimate energy use distribution and losses and to analyze potential energy savings from applying commonly recommended energy savings measures. PHA is specifically designed to enhance the capabilities of older versions of PHAST (PHAST 3.0, and PHASTEx, released in 2016), including a major update of the electrotechnology section that allows users to choose among several electric or fuel-fired systems. Updates also allow for the consideration of multi-component charge-loads and account for a variety of energy losses.

PHA serves three specific purposes:

1. Estimate annual energy use and costs for process heating equipment, such as furnaces, ovens, heaters, kilns, and boilers.
2. Perform detailed heat balance and energy-use analysis to identify areas of energy use and energy losses for a furnace or a boiler.
3. Perform "what-if" analyses for possible energy-reduction and energy-efficiency improvements through changes in operation and maintenance and retrofits of components and systems.

USING THE PROCESS HEATING ASSESSMENT TOOL

Collecting Baseline Data
Using PHA requires that certain critical data for heating equipment be collected, preferably when the heating equipment is operating at typical or average production conditions. The type of data needed and where they are collected depend on the design and operation of the heating system. The data collection process in most cases does not disturb production and can be conducted by the plant personnel or an outside consulting organization. However, it may be necessary to install or use process monitoring instruments in selected areas of the heating system. It is also necessary to collect information on the products (charge materials) and fuel used for the equipment, which is usually easily available from the plant personnel, installed data collection equipment, or records.

PHA consists of several calculators; each calculator is designed to estimate heat loss or heat use for process heating equipment under current operating condition (see "Baseline Heat Balance" section below). The estimates for a piece of equipment are consolidated into an overall heat balance for the equipment, expressed in various forms (i.e., pie charts, bar charts, Sankey diagrams, and tables). PHA also includes suggestions for possible energy saving measures for specific energy uses, allowing for the creation of "what-if" scenarios in which users can change opportunity-specific parameters and quantify potential savings. The PHA report displays each of these energy saving measures, alongside the baseline.

Areas of energy use within a typical heating system that are represented in PHA are listed in Figure 1
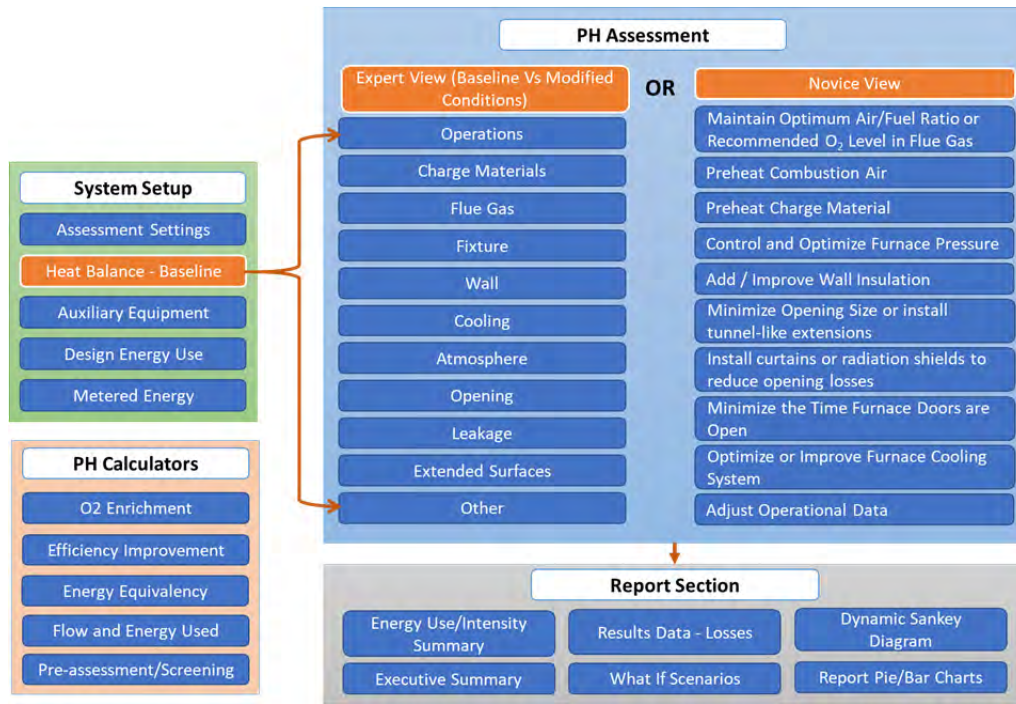
Figure 1. Overview of the MEASUR Process Heating Assessment Module Capabilities.

System setup

The PHA System Setup page is where the user defines a system, establishes its baseline energy losses/uses, and compares the energy use calculated by PHA to fuel use meters or design specifications. The different components of the System Setup menu are shown in Table I.

Table I. Components of System Setup

Assessment Settings	Define the units of measure (imperial, metric, or custom), energy source type (i.e., fuel-fired, electrotechnology, or steam-based) Add equipment notes and document the operating conditions at time of assessment
Heat Balance	Enter primary data and preform calculations for the PHA baseline heat balance (described in "Baseline Heat Balance" section)
Aux Equipment	Inventory the other systems associated with heating systems (such as electric motors) that consume significant energy
Design Energy Use	Compare PHA output with expected energy use calculated from design specifications (total rated capacity of burners [MMBtu/kWh], annual operating hours, percentage of rated capacity used, and duty cycle)
Metered Energy	Compare PHA output with expected energy use calculated from a meter reading

Baseline Heat Balance

The PHA baseline heat balance for fuel-based process heating equipment consists of nine loss/use calculators, plus pages for operating parameters (operating hours and energy unit costs) and other known heat losses. PHA requires the use of three calculators—Operations, Charge Material, and Flue Gas—before advancing to the what-if analysis. The use of all other calculators is optional.

Charge Material calculates the heating energy required to increase the temperature of the material (often referred to as a "load" or a "charge") from inlet to outlet conditions to melt, heat or dry (see Figure 2). Phase changes, water evaporation, and reactions (exothermic and endothermic) can all be accounted for with proper data. Users can choose multiple charge

materials from lists of predefined solid, liquid, or gaseous charge materials, or can create their own using relevant material properties.
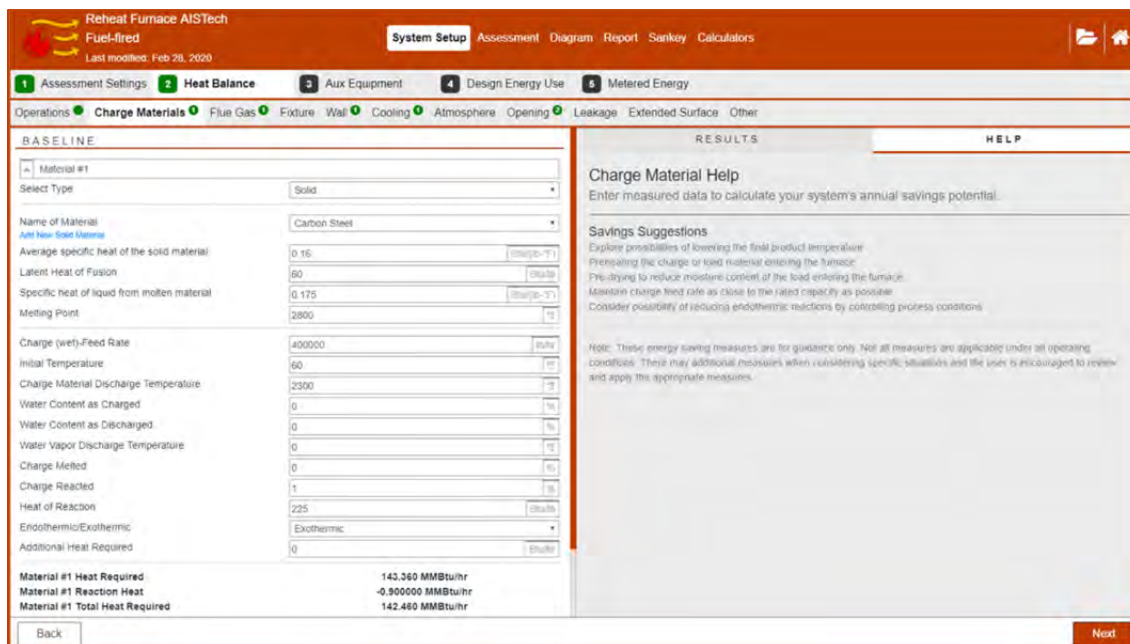

Figure 2. Reheat Furnace Baseline—Charge Materials with help text

Flue Gas quantifies energy lost through the flue or "chimney" of the furnace and is normally the largest loss in a fired process heating system (see Figure 3). For industrial heating systems, it is difficult and impractical to measure the quantity of each combustion component in order to calculate the total heat content of the flue gases. Instead, PHA uses an indirect method known as "available heat method" to calculate heat losses from a heating system. Users can choose from lists of predefined fuels or create their own using the mass or volumetric composition of their fuel.
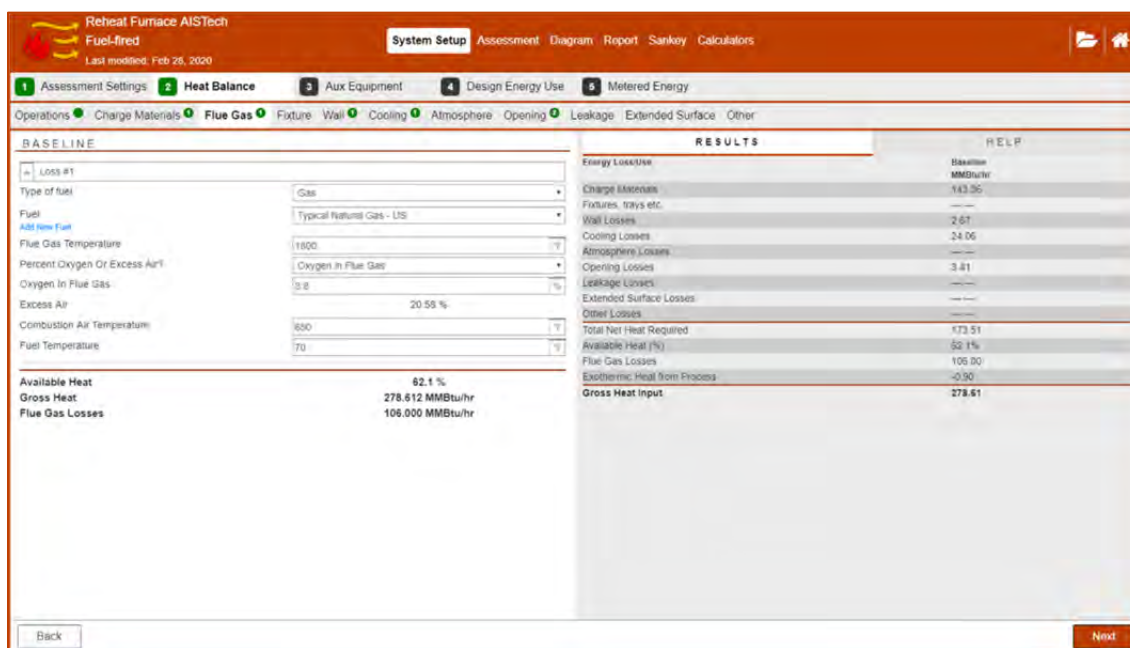

Figure 3. Reheat Furnace Baseline—Flue Gas with results.

There are seven additional calculators that can be used to identify and quantify heat losses in process heating equipment, shown in Table II. Users can model multiple losses for each loss type (e.g., multiple openings of different sizes, a loss entry

for each wall of the furnace). Each calculator has a bar on the right that displays the total energy use or loss from the calculators (see Figure 3) or field-by-field help text to assist users in data collection and provide realistic ranges for parameters (see Figure 2).

Table II. PHA Additional Heat Loss Calculators

Fixture	Estimates the energy used to heat fixtures (e.g., trays, conveyor belts, product hangers) used to transport the charge material through the heating chamber
Wall	Estimates the energy loss due to heat transferred (radiation and convection) from the outer surface of the walls or casing of process heating equipment to the surroundings
Cooling	Estimates the energy loss due to required cooling to protect the equipment from the hot environment
Atmosphere	Estimates the energy loss from replacing the lost warm atmosphere gas (i.e., gas in furnace to provide an inert or specialized environment) with cooler gases
Opening	Estimates the energy loss due to heat transfer from the openings on process heating equipment walls (radiation from hot furnace to ambient, and convection from infiltration/exfiltration due to pressure differences between the furnace and ambient)
Leakage	Estimates the energy loss specifically due to hot gas leaving the furnace or cold gas entering the furnace
Extended Surface	Estimates the energy loss specifically due to heat transfer from extended surfaces

What-if Analyses: Assessment

All MEASUR assessments, including PHA, assist in quantifying the savings potential of energy reduction opportunities using "what-if" assessments in the Assessment Tab. These assessments use either Expert View—Modify All Conditions, or Novice View—Explore Opportunities. The Novice View, shown in Figure 4, provides users with a list of common energy reduction projects [7] and the fields that are associated with modeling the implementation of the project. For example, a common process heating project is preheating charge material; selecting this project will display the baseline initial charge material temperature and allow the user to input the initial temperature for the modification. This allows users to quickly set up new scenarios without having to navigate the entire heat balance.
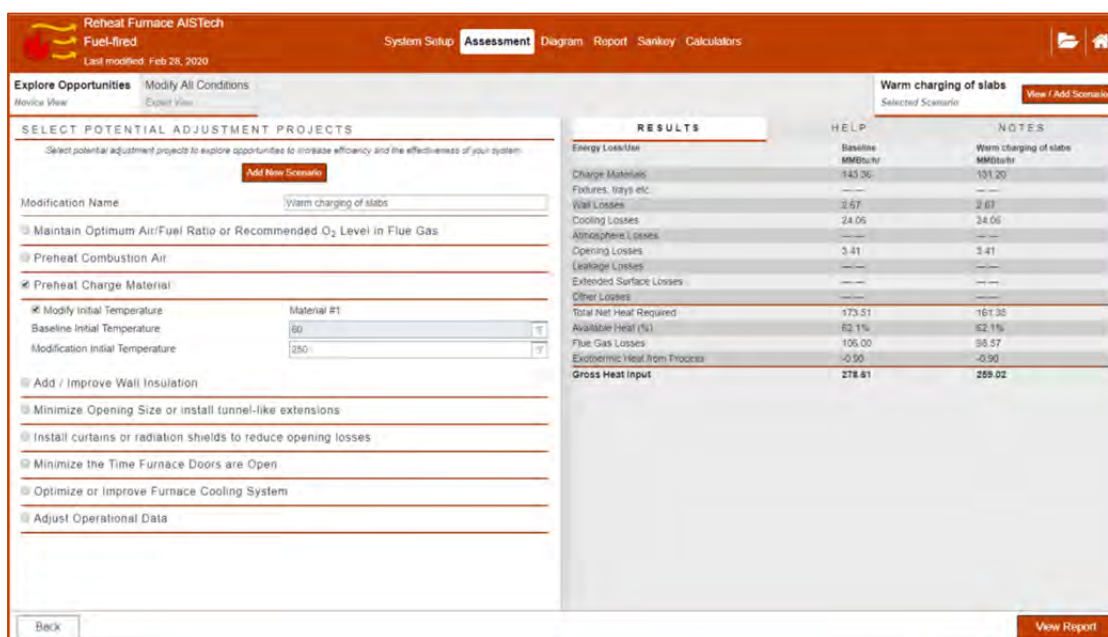

Figure 4. Reheat Furnace Assessment—Novice View with results.

The Expert View gives the user the same forms completed for the baseline, and the user can directly choose which parameter fields to adjust to model the opportunity. The PHA helps users quickly assess what has been modified in each scenario, using visual cues such as color-changing badges and field highlighting (with different colors representing whether a change has been made or if there is an error in the calculator). Also, on the Operations page of Expert View is a field where users can enter a project Implementation Cost to model simple payback. In Expert View, the bar at the right still shows the results (comparing the baseline with the current scenario) or the help text; there is also a notes tab to allow users to detail their modifications, which will be transferred to the report (see Figure 5).
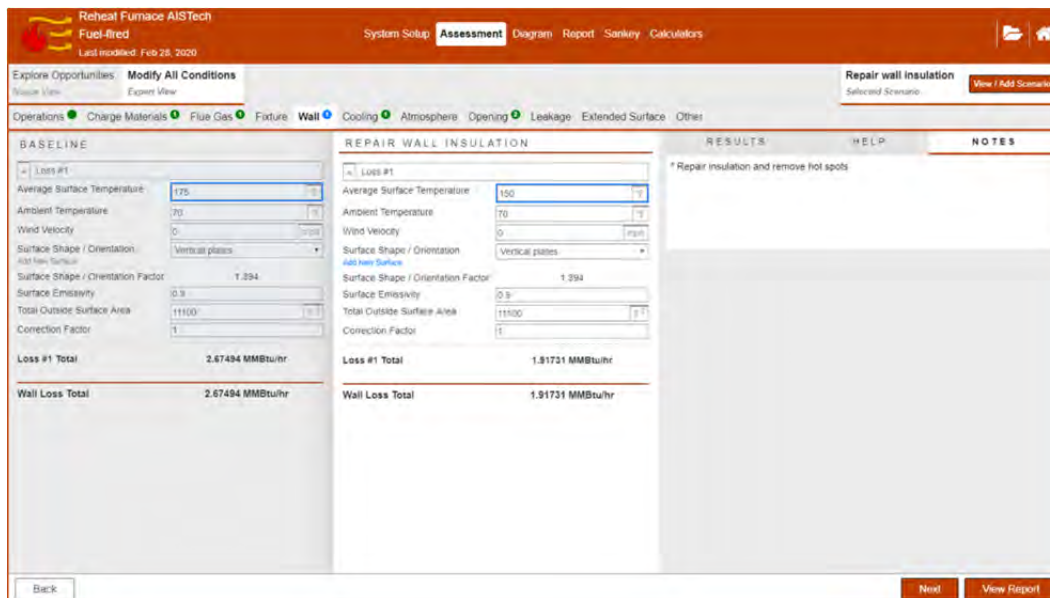
Figure 5. Reheat Furnace Assessment—Expert View with notes.

Assessment Report

The PHA report provides several tables and graphs to help the user understand the baseline heat balance and compare the different energy savings opportunities. There are five main report sections (Table III) plus a review of the input data and facility information inherited from the MEASUR file structure.

The energy units in which the results are reported can be set in the System Setup, independent of the overall unit system chosen (i.e., imperial or metric) and can include hourly MMBTU, Btu, GJ, kJ, kcal, kilogram coal equivalent (kgce), kilogram oil equivalent (kgoe), and kWh.

Table III. Components of PHA Report

Energy Used	Provides an overall summary of the quantity of energy used and comparison of the PHA calculated value with the metered analysis or design specifications	Figure 6
Executive Summary	Outlines the energy intensity (energy per charge material mass), annual energy use and cost, and energy use and cost savings for the baseline and scenarios	Figure 7
Result Data	Outlines the energy loss and use determined by each calculator for baseline and scenarios	Figure 8
Report Graphs	Illustrates the heat balance with pie and bar charts to compare the baseline and scenarios	Figure 9
Sankey	Illustrates the heat balance with a Sankey diagram, dynamically based on the actual results, with the width of each arrow proportional to the total energy requirements (Gross Heat)	Figure 10

Reheat Furnace AISTech
Fuel-fired
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Energy Used | Executive Summary | Result Data | Report Graphs | Sankey | Input Summary | Facility Info

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Summary of Energy Sources Used
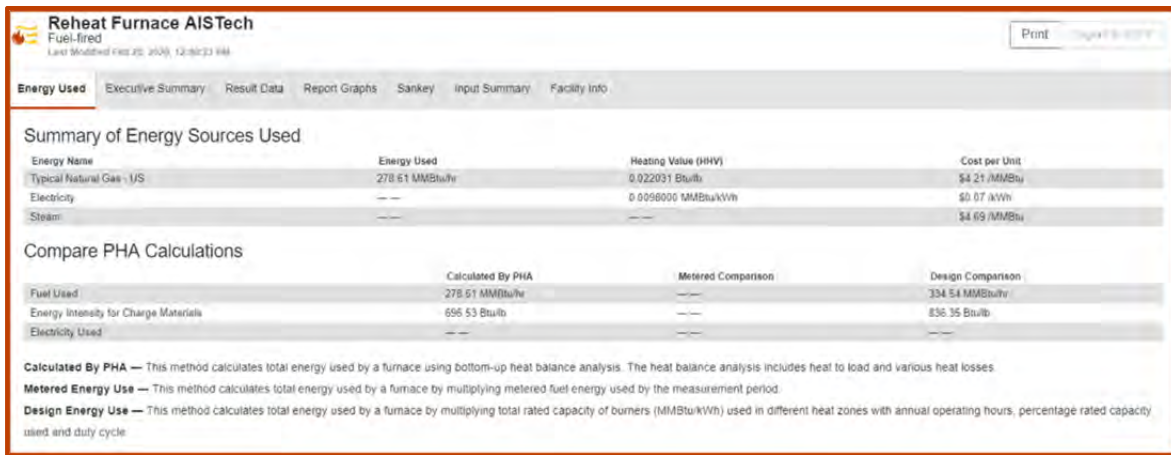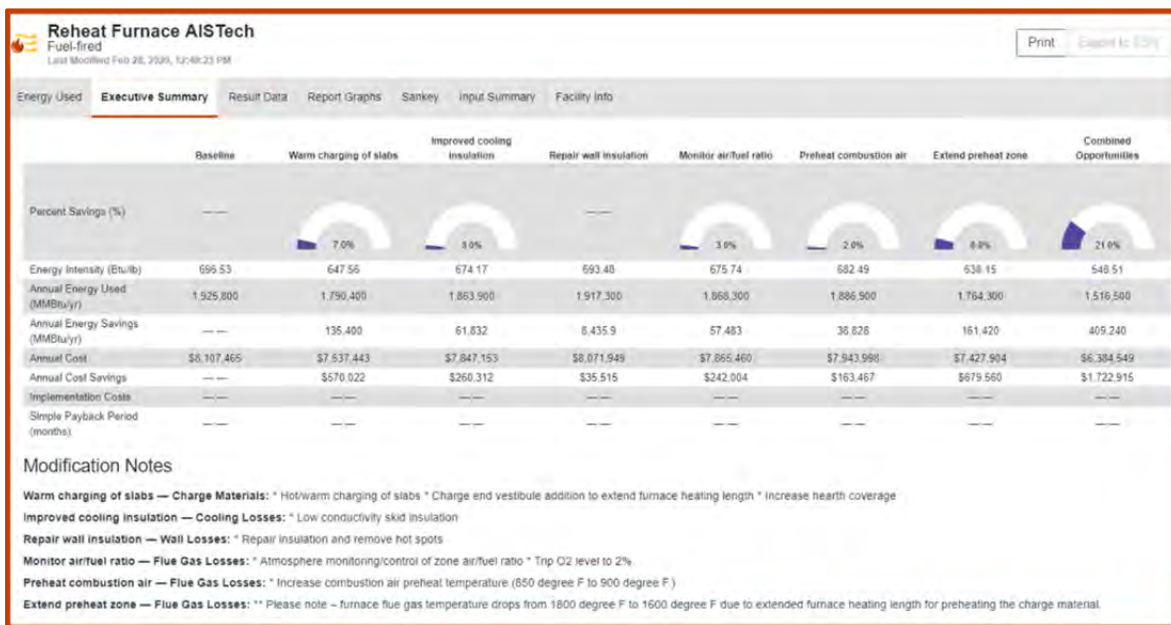
Energy Name	Energy Used	Heating Value (HHV)	Cost per Unit
Typical Natural Gas - US	278.61 MMBtu/hr	0.022031 Btu/lb	$4.21 /MMBtu
Electricity	——	0.0098000 MMBtu/kWh	$0.07 /kWh
Steam	——	——	$4.69 /MMBtu

Compare PHA Calculations

	Calculated By PHA	Metered Comparison	Design Comparison
Fuel Used	278.61 MMBtu/hr	——	334.54 MMBtu/hr
Energy Intensity for Charge Materials	696.53 Btu/lb	——	836.35 Btu/lb
Electricity Used	——	——	——

Calculated By PHA — This method calculates total energy used by a furnace using bottom-up heat balance analysis. The heat balance analysis includes heat to load and various heat losses.

Metered Energy Use — This method calculates total energy used by a furnace by multiplying metered fuel energy used by the measurement period.

Design Energy Use — This method calculates total energy used by a furnace by multiplying total rated capacity of burners (MMBtu/kWh) used in different heat zones with annual operating hours, percentage rated capacity used and duty cycle.

Figure 6. Reheat Furnace Results—Energy Used.

Reheat Furnace AISTech
Fuel-fired
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Energy Used | **Executive Summary** | Result Data | Report Graphs | Sankey | Input Summary | Facility Info

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	Baseline	Warm charging of slabs	Improved cooling insulation	Repair wall insulation	Monitor air/fuel ratio	Preheat combustion air	Extend preheat zone	Combined Opportunities
Percent Savings (%)	——	7.0%	3.0%	——	3.0%	2.0%	8.8%	21.0%
Energy Intensity (Btu/lb)	696.53	647.56	674.17	693.48	675.74	682.49	638.15	548.51
Annual Energy Used (MMBtu/yr)	1,925,800	1,790,400	1,863,900	1,917,300	1,868,300	1,886,900	1,764,300	1,516,500
Annual Energy Savings (MMBtu/yr)	——	135,400	61,832	8,435.9	57,483	38,828	161,420	409,240
Annual Cost	$8,107,465	$7,537,443	$7,847,153	$8,071,949	$7,865,460	$7,943,998	$7,427,904	$6,384,549
Annual Cost Savings	——	$570,022	$260,312	$35,515	$242,004	$163,467	$679,560	$1,722,915
Implementation Costs	——	——	——	——	——	——	——	——
Simple Payback Period (months)	——	——	——	——	——	——	——	——

Modification Notes

Warm charging of slabs — Charge Materials: * Hot/warm charging of slabs * Charge end vestibule addition to extend furnace heating length * Increase hearth coverage

Improved cooling insulation — Cooling Losses: * Low conductivity skid insulation

Repair wall insulation — Wall Losses: * Repair insulation and remove hot spots

Monitor air/fuel ratio — Flue Gas Losses: * Atmosphere monitoring/control of zone air/fuel ratio * Trip O2 level to 2%

Preheat combustion air — Flue Gas Losses: * Increase combustion air preheat temperature (850 degree F to 900 degree F)

Extend preheat zone — Flue Gas Losses: ** Please note – furnace flue gas temperature drops from 1800 degree F to 1600 degree F due to extended furnace heating length for preheating the charge material.

Figure 7. Reheat Furnace Results—Executive Summary.

Reheat Furnace AISTech
Fuel-fired
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Energy Used | Executive Summary | **Result Data** | Report Graphs | Sankey | Input Summary | Facility Info

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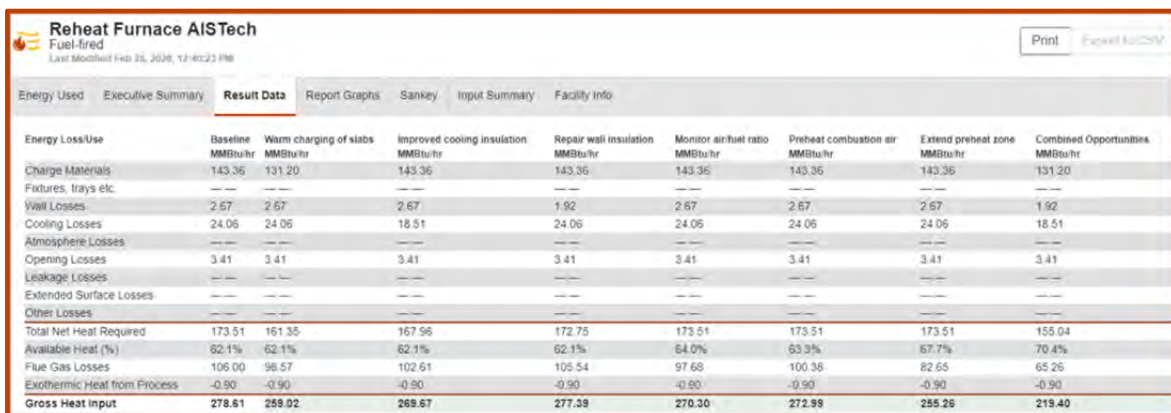| Energy Loss/Use	Baseline MMBtu/hr	Warm charging of slabs MMBtu/hr	Improved cooling insulation MMBtu/hr	Repair wall insulation MMBtu/hr	Monitor air/fuel ratio MMBtu/hr	Preheat combustion air MMBtu/hr	Extend preheat zone MMBtu/hr	Combined Opportunities MMBtu/hr
Charge Materials	143.36	131.20	143.36	143.36	143.36	143.36	143.36	131.20
Fixtures, trays etc.	——	——	——	——	——	——	——	——
Wall Losses	2.67	2.67	2.67	1.92	2.67	2.67	2.67	1.92
Cooling Losses	24.06	24.06	18.51	24.06	24.06	24.06	24.06	18.51
Atmosphere Losses	——	——	——	——	——	——	——	——
Opening Losses	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41
Leakage Losses	——	——	——	——	——	——	——	——
Extended Surface Losses	——	——	——	——	——	——	——	——
Other Losses	——	——	——	——	——	——	——	——
Total Net Heat Required	173.51	161.35	167.96	172.75	173.51	173.51	173.51	155.04
Available Heat (%)	62.1%	62.1%	62.1%	62.1%	64.0%	63.3%	67.7%	70.4%
Flue Gas Losses	106.00	98.57	102.62	105.54	97.68	100.38	82.65	65.26
Exothermic Heat from Process	-0.90	-0.90	-0.90	-0.90	-0.90	-0.90	-0.90	-0.90
Gross Heat Input	278.61	258.02	269.67	277.39	270.30	272.99	255.26	219.40

Figure 8. Reheat Furnace Results—Result Data.

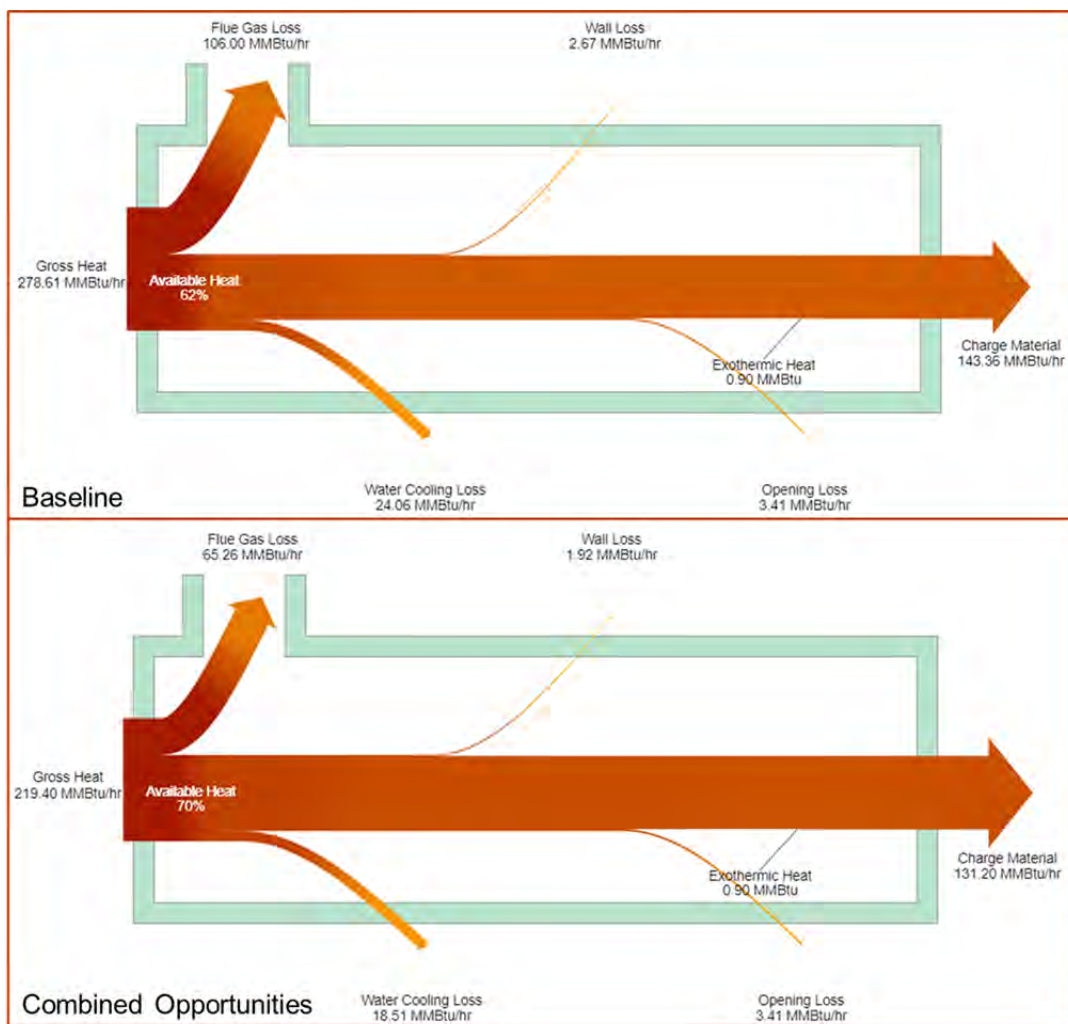Figure 9. Reheat Furnace Results—Report Graphs.

Figure 10. Reheat Furnace Results—Sankey diagrams (Top – Baseline, Bottom – Combined Opportunities Scenario).

Process Heating Calculators

MEASUR hosts over 50 equipment and property calculators for performing simple energy-related calculations and analyses; four of these are process heating specific (outlined in Table IV) and can be accessed directly in PHA, along with the Pre-assessment/Screening tool. Please note that some of these calculators are valid only for natural gas fuels in North America.

Table IV. MEASUR Process Heating Calculators

O₂ Enrichment	Estimate available heat and fuel savings for fuel-fired furnaces via adjusting the oxygen content of combustion and flue gases
Efficiency Improvement	Explore potential fuel savings from adjusting burner operating conditions
Energy Equivalency	Estimate required heat input when switching heat source from fuel-fired to electric or vice versa
Flow and Energy Used	Calculate the energy flow into the furnace by calculating the gas flow from data obtained by an orifice meter
Pre-assessment/ Screening Tool	Compare the relative energy use of equipment before conducting an assessment to prioritize energy evaluations and opportunities using meter data or design specifications (similar to Metered Data and Design Energy Use)

Assessment Summaries and Dashboard

Process heating assessments are stored with all other assessments in MEASUR's folder structure in which each folder can be used to represent a facility. Users can enter facility information (e.g., company and facility name, address) and establish settings to be inherited throughout the folder (e.g., unit system and energy unit costs). This approach also allows users to quickly view a summary of all the assessments in the folder (number, annual energy used, and costs of each assessment type). This is also where users can import and export assessment files. Users can also generate "Rollup" reports for several assessments showing the total energy use and cost by type, chosen opportunity scenario, and estimated savings for all assessments included in the report. Other key features of MEASUR are outlined in Table V.

Table V. Other Features of MEASUR

Settings	Set units of measure and energy unit costs for all new assessments (globally or by assessment type)
Custom Materials	Manage, export, and import user-generated custom materials
Tutorials	View quick tutorials explaining how to navigate and use MEASUR
About	Provides more information about each module of MEASUR
Feedback	Provides links to feedback survey and bug reporting
Acknowledgements	Lists major MEASUR contributors
Translate	Provides translate functionality using Google Translate (requires active internet connection)
Version Number	Provides details about the latest update

REHEAT FURNACE CASE STUDY

In this section, the PHA module within MEASUR (v.0.6.5) is highlighted using a reheat furnace case study, based on data collected at a process heating assessment at an iron and steel manufacturing plant in 2013. There are two basic types of reheat furnaces, defined by how the product passes through the furnace. The product is either pushed through the furnace in a continuous motion (in a pusher furnace) or carried through the furnace via incremental motions (in rotary and walking-beam furnaces.)

- A pusher furnace can be top-fired if the work is pushed through the furnace on the refractory hearth or floor. The front section of the furnace can be both top- and bottom-fired if the work is pushed on rails and then onto the hearth.
- In a rotary furnace, the work is placed on the hearth and then carried as the hearth rotates 360°. The work is extracted just before returning to the charge position.
- In a walking hearth furnace, the work is placed on a combination walking and stationary hearth configuration. It is then "walked" to the discharge end by the stepwise motion of the walking hearth. A walking hearth is therefore a top-fired type of furnace.
- In a walking beam furnace, the work is placed on a combination of walking and stationary rails or water-cooled beams and then walked to the discharge end by the motion of the walking rails. The walking beam is therefore a top- and bottom-fired type of furnace.

Figure 11demonstrates the heating throughput range of the various reheat furnace types. All five furnace types can accommodate a system requiring 100 tons per hour (tph) steel production or less, although 5-zone pusher furnaces or walking beam furnaces are significantly less efficient at low tph. Walking hearth, 3-zone pusher, and rotary type furnaces can all process lower rates, from near zero (for rotary furnaces) to about 150 tph. Five-zone pusher and walking beam furnaces can process from 100 tph up to 250 or 350 tph and therefore dominate the plate and hot strip mill applications[10].
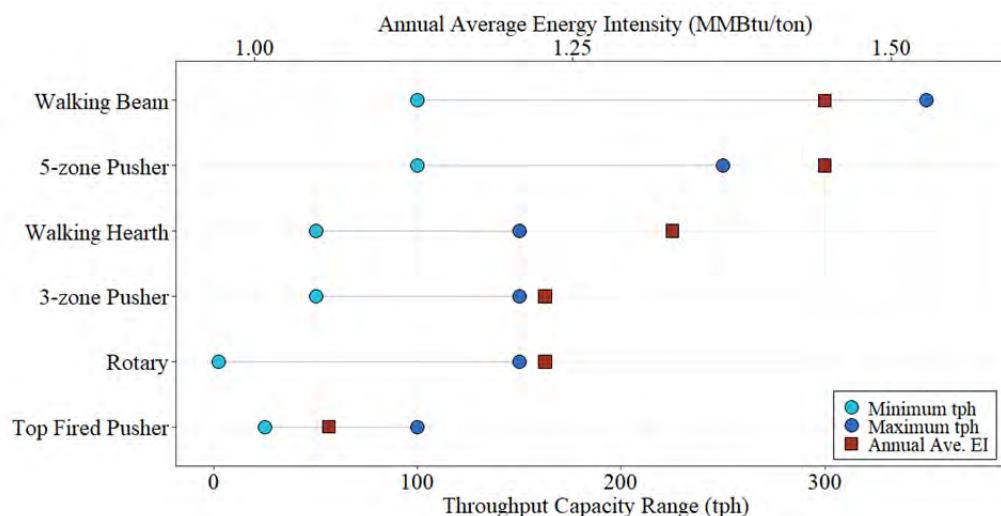
Figure 11. Throughput capacity (tph) and average annual energy intensity (MMBtu/ton) of common reheat furnaces[10]

The type of furnace selected defines the level of furnace efficiency in terms of the design energy intensity (EI; MMBtu/ton level). The design EI is a calculated value based on a rigorous heat balance conducted at the design heating capacity of the furnace, both during design and later using actual energy consumption measurements during operations. A furnace with high casing losses (like a small rotary furnace) or high water-cooled losses (like a top- and bottom-fired pusher furnace or a walking beam furnace) will have a higher design EI. The annual average EI (also shown in Figure 11) addresses delays, inefficient operating levels, and typical day in-day out occurrences of operations that are less than ideal and is higher for furnace types with high heat losses. Figure 11 shows that the walking beam and 5-zone pusher furnaces, with their large amounts of water-cooled heat losses, have the highest annual average EIs and hourly energy use.

Data Collection
The furnace in this case study was a 5-zone pusher type processing around 200 tph of steel. Furnace operational data were collected both before and during the in-plant training event by the plant personnel and training participants. These data (see Table VI) were measured by using in situ and handheld equipment and collected from some furnace operation manuals and notes. A more recent (2018) unit cost of $4.21/MMBTU of natural gas was used for the energy cost estimations [8].

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Table VI. Collected reheat furnace operational data

Parameter	Value	Parameter	Value
Furnace max (average) production rate	250 tons/h (200 tons/h)	Furnace max heat input	598 MMBtu/h
Slab dimensions	7.5–10 in. × 30–75 in. × 212–388 in.	Slab temperature before reheat	70°F
Slab temperature after reheat	2300°F	Flue gas temperature entering recuperator	1800°F
Average flue gas oxygen content (dry basis)	3.8%	Preheated combustion air temperature at the burner	850°F
Annual operating hours	6912 h/year	Average furnace wall temperature	175°F

Baseline Data Entered into PHA

The data from the assessment was entered in the PHA using the Charge Materials, Flue Gas, Wall, Cooling, and Opening calculators. All calculators had only one loss except Opening, which had one loss each for the fixed (always) and variable (intermittently) openings. In case of the wall heat loss, the users can model multiple walls with different average surface temperatures and orientations or, as in this case, model a single wall loss using an overall average surface temperature. Table VII provides almost all the values entered in the PHA baseline: if a field was not listed in the table, it was left as the default value (all correction factors were left as one, all others were zero).

The heating of the charge materials required the most energy for the baseline (143 MMBtu/h) and the flue gas required the second most (106 MMBtu/h). All other losses were 30.1 MMBtu/h, with 0.9 MMBtu/h being generated by the exothermic reaction of the oxidation of steel producing scale. Figure 2 (in the "Baseline Heat Balance" section) shows the Charge Material data entry page for the case study and Figure 3 shows the Flue Gas data entry page.
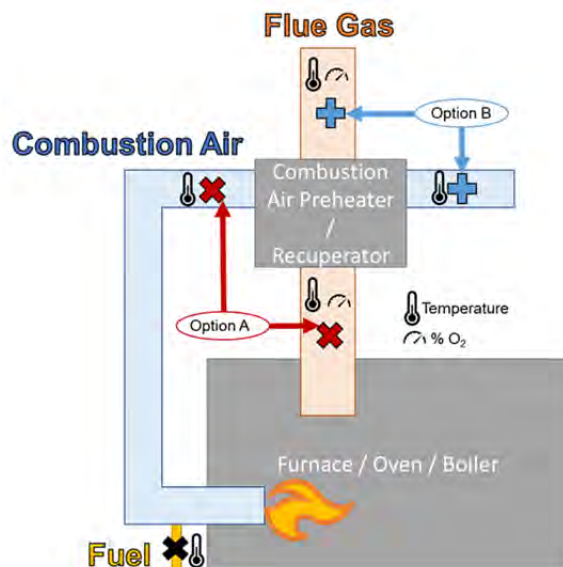

Figure 12. PHA help illustration depicting how to properly measure temperature and oxygen levels

Figure 12 is a help text figure from PHA which illustrates the control volume (CV) used for the analysis. The CV did not include the recuperator (Option A in the figure), therefore the flue gas temperature and oxygen levels were estimated before the recuperator and the combustion air temperature was taken after it had been heated by the recuperator. It is also valid to include the recuperator, but then the flue gas properties must be measured after the recuperator and the combustion air temperature, before.

Table VII. Reheat furnace case study baseline data

FIELD	VALUE	FIELD	VALUE
OPERATIONS		**COOLING (LOSS #1)**	
Operating hours	6912 h/year	Cooling medium	Water
Fuel costs	4.21 $/MMBTU	Name of cooling medium	Water
Steam costs	4.69 $/MMBTU	Average specific heat	1 Btu/lb·°F
Electricity costs	0.066 $/kWh	Density	8.338 lb/gal
		Liquid flow	3700 gal/min
CHARGE MATERIAL #1		Inlet temperature	87 °F
Select type	Solid	Outlet temperature	100 °F
Name of material	Carbon Steel		
Charge (wet) feed rate	400000 lb/h	**OPENING (LOSS #1)**	
Initial temperature	60 °F	Select type	Rectangular
Charge material discharge temp.	2300 °F	Number of openings	1
Charge reacted	1 %	Furnace wall thickness	16 In.
Endothermic/exothermic	Exothermic	Length of openings	420 In.
Heat of reaction	225 Btu/lb	Height of openings	6 In.
		View factor (calculated)	0.47
FLUE GAS		Avg. zone or radiation source temp.	2275 °F
Type of fuel	Gas	Ambient temp.	70 °F
Fuel	Natural gas	Emissivity of the source	0.9
Flue gas temperature	1800 °F	% time open	100 %
Percent oxygen or excess air	Oxygen in flue gas		
Oxygen in flue gas (dry gas analysis)	3.8 %	**OPENING (LOSS #2)**	
Combustion air temperature	850 °F	Select type	Rectangular
Fuel temperature	70 °F	Number of openings	1
		Furnace wall thickness	16 In.
WALL (LOSS #1)		Length of openings	420 In.
Average surface temperature	175 °F	Height of openings	60 In.
Ambient temperature	70 °F	View factor (user defined)	1
Wind velocity	0 mph	Avg. zone or radiation source temp.	2400 °F
Surface shape/orientation	Vertical plates	Ambient temp.	70 °F
Surface emissivity	0.9	Emissivity of the source	0.9
Total outside surface area	11100 ft^2	% time open	15 %

Modifications and Scenarios

Six energy conservation measures were identified during the assessment and PHA was used to analyze the savings. The results are presented in the next section.

1. ***Warm charging of slabs***: The slabs were produced in a continuous caster in the same plant but needed to travel a long distance to the reheat furnace. In some instances, the slabs were stored outside for hours to days before sent to the reheat furnace. Participants observed that by the time the slabs arrived at the reheat furnace, they were not much above the ambient temperature. It was recommended that the slab transportation routes and methods be revised to keep the slabs as hot as possible. This measure was modeled by increasing the Charge Material Initial Temperature to 250°F.

2. ***Improved cooling insulation:*** The heat loss through the water-cooled skid pipes was estimated around 24.1 MMBtu/h (9% of total heat). Improving the quality or quantity of insulation for the water-cooled parts in the furnace would reduce this heat loss. This measure was modeled by decreasing the Cooling Outlet Temperature to 97°F.

3. ***Repair wall insulation:*** During the assessment, furnace wall temperatures were measured at several locations and showed significant variation, ranging between 150°F to 200°F (the baseline was estimated to be 175°F). Some insulation improvement was recommended to reduce heat losses. This measure was modeled by reducing the Wall Average Surface Temperature to 150°F.

4. ***Extend preheat zone length***: Before flue gas enters the recuperator, cold (dilution) air is mixed with the exhaust gases to control the gas temperature. Adding an unfired preheat zone to the furnace was suggested, using exhaust gas to preheat the slab before the gas was mixed with dilution air. This measure was modeled by reducing the Flue Gas Temperature to 1600°F to represent the reduced exhaust temperature after the preheat zone was added.

5. ***Monitor air/fuel ratio:*** It was recommended that monitoring of the furnace air/fuel ratio be enhanced, and the flue gas oxygen content reduced from 3.8% to 2.0% (dry basis) to improve combustion efficiency.

6. ***Preheat combustion air***: It was observed that the operation or design of the recuperator could be reconfigured to provided hotter combustion air (temperature increased from 850°F to 900°F) to improve combustion efficiency. For example, the surface temperature for some areas of the recuperator was more than 500°F, and well above the average surface temperature of 400 °F. Some insulation improvement was recommended to reduce heat loss. Using better insulation for hot air piping could cause the air temperature at the burner to increase by around 10 °F - 20°F, improving the furnace performance.

Table VIII shows the values changed for each scenario. The Combined Opportunities scenario was created using each of the modifications from the other opportunities. Figure 5 shows the data entry for the scenario modifying repairing the furnace wall insulation, using the Expert View. It also shows the notes entered to remind the user what is being modeled. Figure 4 shows the data entry for the scenario modeling preheating of the charge materials, in Novice View.

Table VIII. Reheat furnace case study scenario data

FIELD	BASELINE VALUE	OPPORTUNITY VALUE
Warm charging of slabs Charge materials - initial temperature	60 °F	250 °F
IMPROVED COOLING INSULATION Cooling—outlet temperature	100 °F	97 °F
REPAIR WALL INSULATION Wall—average surface temperature	175 °F	150 °F
MONITOR AIR/FUEL RATIO Flue gas—oxygen in flue gas	3.8 %	2.0 %
PREHEAT COMBUSTION AIR Flue gas—combustion air temperature	850 °F	900 °F
EXTEND PREHEAT ZONE Flue gas—flue gas temperature	1800 °F	1600 °F

Results of MEASUR

As stated earlier, the PHA results are displayed in several tables and graphs. The first is an overview of the energy used by the process heater, in this case a natural gas reheat furnace. PHA calculated that about 280 MMBtu/h is required to heat the 400,000 lb/h (200 tph) of carbon steel, resulting in an energy intensity of 697 Btu/lb or 1.39 MMBtu/ton. This is much less than the 335 MMBtu/h (836 Btu/lb, 1.67 MMBtu/ton) estimated from the design specifications (Figure 6), indicating an error in the estimation of either fraction of rated capacity used (40 – 80% depending on the burner location), the fraction of operating hours the burners were on (88%), or some of the data used by PHA. This is also lower than the average EI for 5-zone pusher type furnaces (1.44 MMBtu/ton). It should be noted that the PHA only provides an estimation of a single data collection time, which is why it is recommended that data collection should be undertaken on a typical production day.

The Executive Summary (shown in Figure 7) allows for a comparison of the six different opportunities and the combined opportunity scenario (which describes an integrated system including interaction of all individual energy saving opportunities). Extending the preheat zone and warm-charging the slabs shows the largest impacts of all the opportunities (8% and 7% savings), with the other opportunities each providing 2–3% additional savings. It is important to also model a combined opportunity, as many of the opportunities are interconnected and implementing some opportunities would reduce the impact of others. In this case, implementing all the modeled opportunities could result in a total of 21% (over 409 TBtu/year) energy savings, reducing the energy intensity from 697 Btu/lb to 549 Btu/lb (1.39 MMBtu/lb to 1.10 MMBtu/lb). The Executive Summary page also shows all the notes entered in the scenarios.

The Result Data tab (Figure 8) shows the energy lost or used for each segment of the furnace. For all scenarios, the charge materials consume the most energy (131.2–143.36 MMBtu/h); however, 29.6–37.9% of the total energy required is still lost up the flue (155 – 174 MMBtu/h). The Results Data tab also calls out the exothermic heat energy created from the oxidation of iron to iron oxide (0.9 MMBtu/h) after the calculation of available heat. This is because it is produced within the system (none of its heat energy escapes via the flue) and is therefore not affected by flue gas loss (or available heat). It is modeled by subtracting it from the final gross heat calculation. The relative loss size can also be seen in the Report Graphs (Figure 9), which include a pie chart of all energy use and losses as well as a bar chart comparing the baseline with a chosen scenario. The Sankey diagrams also graphically show the energy losses, using arrows of relative sizes to represent each loss of the system (Figure 10). PHA lets the user examine all these figures quickly, and they can be easily exported using the download icon.

DISCUSSION AND CONCLUSION

The PHA module of the MEASUR tool suite was created to replace the PHAST tool (released in 2010) and the PHASTEx tool (released in 2016). The PHA module provides an improved user experience and some requested features and capabilities [6]:

- **Accessibility:** The capabilities of the legacy DOE software tools, including PHAST, are now available in a single software download tool, MEASUR. This tool is open-source and cross-platform compatible (Windows, Mac, Linux and soon web-based).
- **Algorithm:** The algorithms used by the PHA modules are based on previous versions of PHAST (which were based on physics and engineering fundamentals) and were validated by analyzing case studies. This tool also improved the accuracy of previous incarnations by considering the impacts of additional parameters (e.g., fuel temperature, wind, surface emissivity) and improvements in the calculation of available heat [6].
- **Data Entry:** PHA streamlines the workflow by using a Tab UI design. The three major analysis steps (baselining in Systems Setup, what-if-analysis in Assessment, and the Report) and their sub-steps can all be accessed on the same window, and the user can switch among the steps by clicking on their dedicated tabs. Results are displayed dynamically with user entry, allowing for immediate feedback and reducing the chance of error in exploring data entry. Also, help information (e.g., insight into data collection, reasonable ranges for values) is always available in the right panel and is easy to find.
- **Results:** A variety of graphs and tables are generated to easily compare baseline and opportunity scenarios. The Sankey chart effectively shows how much heat is lost in each possible area by dynamically sizing the respective arrows to the sizes of the losses. MEASUR generates a report, but users can easily copy the input data and analysis results (as both numerical tables and graphics) to generate their own reports.
- **Simple Calculators:** To facilitate simple analyses, individual calculators are included in this tool: calculations of savings from oxygen enrichment, excess air calculation, air and fuel flow rate calculation, pre-assessment screening, with more to come.
- **Third-party Expansion:** As an open-source software suite, MEASUR provides interfaces and calculation capabilities that third parties can use to develop customized software to import their real-time data.

Currently, PHA, like most of the MEASUR modules, is limited to a single moment of data collection: variations in energy use and production throughout a year are not accounted for and could impact savings calculations. Although PHA can model electric process heating, there are still outstanding tasks to improve the calculations and workflow. MEASUR is still in development, and users could experience some failures and anomalies due to coding errors. The development team is taking error reports, comments, and feedback and will continue to improve the tool. DOE's Better Plants program will use MEASUR in the coming process heating in-plant trainings to analyze more real-world cases and collect more user feedback. The PHA module is available in the latest version of MEASUR, which can be downloaded from DOE's Software Tools webpage [9].

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