FINAL REPORT

Aluminum Bronze Alloys to Improve the System Life of Basic Oxygen and Electric Arc Furnace Hoods, Roofs and Side Vents.

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EXECUTIVE SUMMARY

Energy Industries of Ohio was the lead organization for a consortium that examined the current situation involving the service life of electric arc and basic oxygen furnace hoods, roofs and side vents. This equipment is a major source of lost productivity and energy inefficiency in steel operations as a result of the continual maintenance required to insure the safety and operability of steel making systems. The overall goal of the project was to double current hood, roof, and sidewall system-life; reduce overall system costs by 20% and reduce furnace downtime related to hood, roof, and sidewall problems by 95%.

Initial project activities surveyed the state of hood, roof, and sidewall systems within the project participants; identification of potential alternative materials of construction; and thermal, stress and corrosion modeling of selected candidate materials. These activities resulted in the identification of aluminum bronze (Al-Bronze) alloy as a viable alternative to carbon steel construction for this equipment. Republic Engineered Products (REP), one of the project partners, volunteered to install a full-scale Al-Bronze “skirt” in their BOP system at their Lorain OH facility, the first such installation of this alloy in BOF service. Installation on REP’s back-up vessel was completed in October 2004 with the first heat processed on 11/10/04. As of the end of October 2006, the skirt has been in operation in back-up service for 9 months and as the primary production vessel for 15 months. During this time a total of 4,563 heats of steel have been processed.

The performance of the Al-Bronze skirt has been extremely successful. Current estimates place the overall life the Al-Bronze skirt at as much as five times the life of comparable carbon steel versions of this equipment. In 24 months of operation, the Al-Bronze skirt has required only 2 shutdowns for maintenance, both related to physical damage inflicted on the skirt through operational mishaps. Historically, carbon steel skirts would have undergone 40 to 50 maintenance shutdowns for corrosion and thermal stress cracking during the same period of time. The project’s ultimate success is demonstrated by the fact that REP has already replaced their carbon steel “flux chutes” with Al-Bronze alloy chutes and are currently bidding entire Al-Bronze alloy lower hood sections for installation. In recognition of the excellent results, this project was selected as the winner of the Ohio’s 2006 Governor’s Award for Excellence in Energy, the state’s award for outstanding achievements in energy efficiency.

Calculations performed at Oak Ridge National Laboratory indicate that the energy savings attributable to the skirt’s improved performance at REP is approximately 11.06 trillion Btu per year by 2025 assuming a 2% adoption rate of this technology for BOF skirts, lower hood portions and flux chutes; and the use of Aluminum Bronze in EAF roofs and side vents. Additional benefits are expected in the reduction by 2025 of 657,000 tons per year of CO2 emissions to the environment as well as a projected $240 million per year in project economic benefit resulting from reduced maintenance and operating costs and increased productivity.

INTRODUCTION

Modern steel making is an extremely competitive international business. The economic health of any particular facility depends, in large measure, on the productivity of the facility. Areas of the process that require interrupting the operation for required maintenance are prime candidates for investigations that can mitigate or eliminate this source of lost productivity. Should these areas be such that continual maintenance is necessary, serious productivity issues can result. In addition to the loss of productivity, the energy efficiency of the steel making process suffers from interruptions in the process as a result of the elevated temperatures needed in steel making and the loss of temperature while maintenance is being completed.

One such area in a modern steel making facility is the steel making process itself. With the advent of continuous casting technology, interruptions in the steel making process affect the productivity and energy efficiency of both the steel furnace and the continuous caster. The work undertaken in this program was designed to identify methods of reducing need for maintenance in steel making operations.

BACKGROUND

Steel Making Processes

Steel is produced in two processes – the basic oxygen furnace (BOF) and the electric arc furnace (EAF). While these process differ significantly in their operation, the equipment used has a number of striking similarities. The following discussion provides a general overview of these operations.

In its simplest form, the EAF is a scrap-based process, producing steel by melting recovered steel scrap using electric current. Furnace designs vary considerably. A schematic of one such design appears in Figure 1. The furnace itself is a refractory-

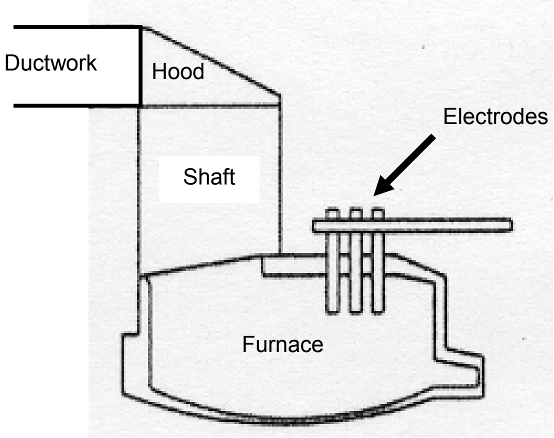


Figure 1. EAF Schematic

lined vessel. The roof of the vessel, the shaft, hood and ductwork are usually constructed of carbon steel or a steel alloy with some means of water cooling incorporated into the design so that the extreme heat in the process does not melt the equipment. In the design shown in the diagram, the shaft, hood and ductwork have the primary function of transporting the gases generated in the process to treatment equipment that cools and cleans the gas prior to discharge.

Scrap steel, fluxes, and other batch components are charged into the vessel either by lifting and rotating the entire vessel roof or (as is the case in the schematic) by lifting and rotating the hood and charging through the shaft. Once charged, electricity is run through the batch to melt the scrap steel. Finished steel and slag are periodically discharged from the vessel once the process is complete. Cycle times for the process are typically in the range of 75 minutes depending on shop practices.

BOF's produce steel as part of integrated steel making operations. A simplified schematic of this process is shown in Figure 2.

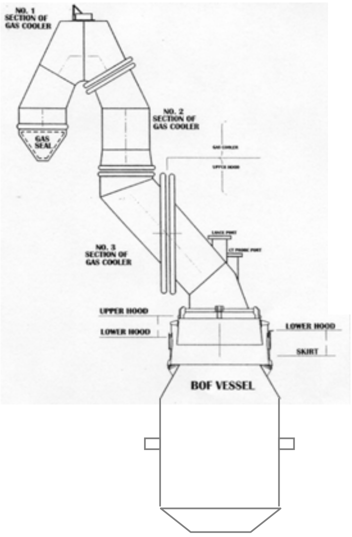


Figure 2. BOF Schematic

The BOF Vessel is refractory lined and mounted on a trunnion that allows that vessel to be tilted for charging raw materials and to discharge finished steel and slag. A movable skirt is located immediately above the vessel. The skirt can be raised to allow the vessel to rotate or it can be lowered to contain the gases generated during the steel making process. A water-cooled oxygen lance passes through the opening located on the centerline off the vessel. The lance can be lowered into the vessel to blow oxygen into the molten iron to produce steel and can be raised after the "heat" (batch) is finished to allow discharge. A flux chute is also located in the hood system to allow the addition of fluxes and other batch additions. The entire upper portion of the system – skirt, lower and upper hood, flux chute, oxygen lance and lance opening, and the remaining ductwork is typically constructed of water-cooled carbon steel or steel alloy in a manner similar to that in EAF systems.

The process of producing steel in the BOF involves charging a portion of the iron values (~20%) to the furnace as steel scrap followed by the remainder of the iron values in the form of "hot metal" (molten iron) from the blast furnace. Fluxes and other batch additions are then added through the flux chute and mixed into the batch. After flux addition the oxygen lance is lowered into the batch and pure oxygen in blown through the melt. This oxygen burns out carbon, silicon and other unwanted metal constituents, converting the molten iron to steel. Once complete, the molten steel is removed through a tap hole in the side of the vessel. Slag is removed by inverting the vessel after the molten steel has been tapped off.

PROJECT DESCRIPTION

One of the major causes of continual maintenance shutdowns, productivity loss and reduced energy efficiency in either steel making process is the need to repair leaks in the water-cooled portions of the equipment. Severe equipment damage, personnel injuries and fatalities have resulted from "steam explosions" that resulted from water entering equipment that processes molten metals including these steel making operations.

The need for water cooled hoods, roofs, side vents and ductwork is undeniable. The gases vented from steel making are produced at temperatures that are ≥ 3000°F. Lack of water cooling would quickly result in this equipment melting in the heat provided by the process off gases. Three additional characteristics of the off gas add to the difficulties inherent in maintaining this water cooled equipment. First, significant volumes of exhaust gases are produced from either process. These gases entrain particulate matter from the process which causes abrasive wear in the hoods, roofs and ductwork. Second, the process gas can contains significant levels of carbon monoxide, especially in BOF operations. Hood systems for BOF fall into two general categories – excess air hoods and suppressed combustion hoods. Excess air hoods have a fixed lower hood section that allows excess air to be drawn into the exhaust gas. This causes the carbon monoxide to burn, greatly increasing the temperature in the exhaust gas. Gas temperatures in the 4000 to 5000°F range are not unusual in these types of installations. Suppressed combustion hoods have a moveable "skirt" in the lower hood. Positioning this skirt properly restricts the amount of excess air entering the process greatly reducing exhaust gas temperatures and volumes. Improper positioning results in the same elevated temperature conditions that prevail in excess air hoods. Finally, the exhaust gases can contain corrosive materials, such as sulfur dioxide, that are capable of reacting with and corroding the metals in the equipment. Entrained particulates and corrosive compounds can result in significant metal loss in the water cooled sections of the process which eventually results in leaks. A cross section of a typical carbon steel tube exposed to these conditions appears in Figure 3. Combined with the extreme temperatures, corrosive nature and entrained solids in the exhaust gases are two other system characteristics – continuous thermal cycling and water-side tube fouling.

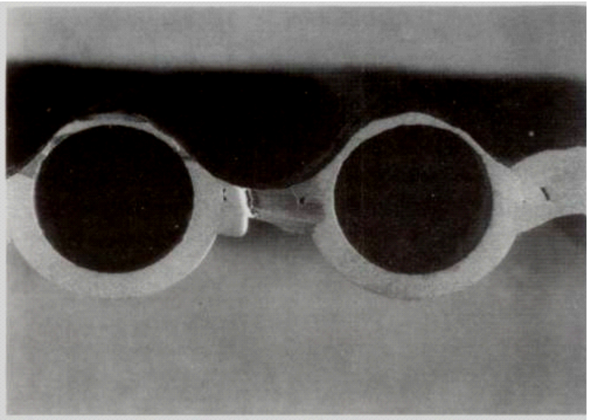


Figure 3. Cross section of tubes showing severe wall thinning attributed to process-side corrosion. Initial wall thickness of 0.20”. (from Betz Dearborn Technical Paper 399-9906).

Steel making processes can cycle as frequently as once an hour. While there isn’t sufficient time for the furnace to become cold, the water cooled equipment does cool significantly only to be exposed to +3000°F temperatures during the next heat. This cycling contributes to thermal stress in the metal and eventual thermally induced cracking. Water-side fouling and corrosion can also lead to reduced service life in carbon steel systems. Scaling and oxide deposits, frequently iron-based corrosion products from the cooling system, aggravate thermal stress cracking by causing uneven cooling and hot spots in the equipment. Corrosion, both general and dissolved oxygen related pitting, can lead to further loss of tube wall thickness and increases in the need for leak repairs.

As proposed, this project sought to identify, evaluate and test materials that had the potential to extend the life of water-cooled BOF and EAF hood and roof systems. The project involved three major activities. The first of these involved a survey of the literature and participating companies to identify operating practices and experience and to secure data and samples from operating equipment for failure analysis. The second activity involved identifying possible alternative materials and evaluating these materials against those in current use for suitability in the proposed service. This evaluation would be conducted through heat transfer, corrosion and thermal stress modeling. The third portion of the project was to test selected materials under operating conditions in an operating furnace.

OPERATING SURVEY

A company survey, a literature survey, and interviews with participating plants suppliers of materials were conducted to assess the current state of the art in the construction of hoods, roofs and side walls for BOF and EAF operations.

The company survey of the participating companies was conducted in late 2002 and early 2003. Since the sample size was expected to be fairly small, given the limited number of companies involved in the project, the results obtained were compared to the results published by the Association of Iron and Steel Engineers (AISE) in their 1999 study of steel making processes. The results for the questions most applicable to the current work are shown in Figures 4, 5, 6 and 7 on the following page.

Figure 4

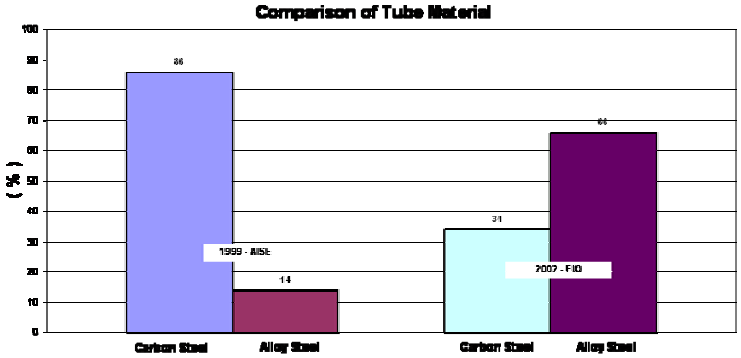


Figure 5

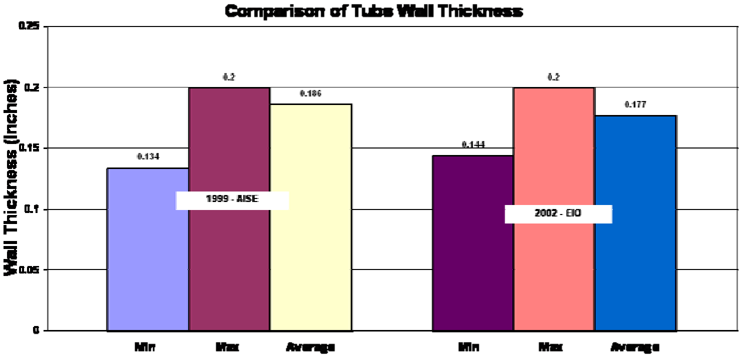


Figure 6

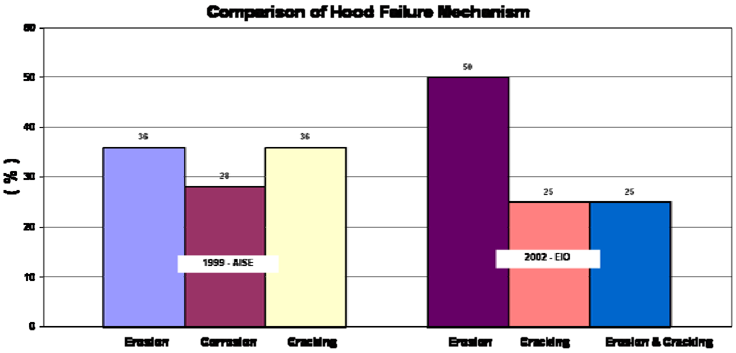
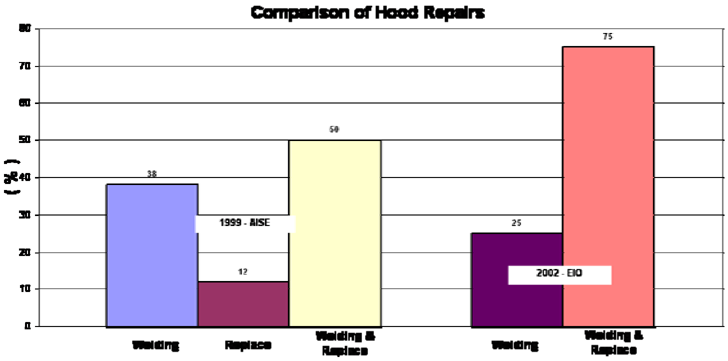


Figure 7



The results of the EIO survey were fairly comparable to the AISE 1999 survey. In particular, the results indicated that carbon steel and low alloy steels were the preferred materials of construction for BOF/EAF hoods, roofs and side vents (Figure 4) with tubing wall thicknesses averaging between 0.177 and 0.186 inches (Figure 5). In addition these surveys indicated that erosion, corrosion and thermal stress cracking were the mechanisms responsible for equipment failures and repairs (Figure 6) with weld repairs and replacement being the preferred methods of repair Figure 7). In addition to these surveys, individual plant visits were scheduled to more thoroughly investigate the issues surrounding the operations of BOF and EAF furnaces. Reports on each of these trips are attached in the Appendices.

Additional information obtained from published articles, such as a Betz Dearborn Technical Report entitled “A Review of Common Failure Mechanisms in BOF Hoods” (1999) and an article from Welding Services Inc. entitled “BOF Hood Life Cycle Cost Improvement Program” (Iron and Steel Technology Jan. 2004) indicated continuing problems with BOF Hoods. The final conclusion from this portion of the project confirmed that there was an urgent need for technically sound and economically feasible solutions to address root causes of failures associated with the operation of BOF and EAF hoods, roofs and side vents.

ALTERNATIVE MATERIAL EVALUATION AND SELECTION

The original project proposal envisioned three possible approaches to addressing the issues associated with the operation of BOF/EAF hoods, roofs and side vents – new materials of construction for the equipment, improved and less expensive weld overlay materials and innovative coatings. In prioritizing the work, company participants indicated that they felt that investigations in to coatings and coatings technologies should be addressed as a last resort even though coatings might be applied at significantly lower costs than weld overlays. The feeling was that the operating rigors in these applications (temperatures, temperature excursions, splashing slag, mechanical damage, etc.) would quickly breach the coating barrier and defeat any advantages gained.

Similarly, most of the participating companies had already evaluated or were cognizant of weld overlay materials (Inconel 625, the weld overlay of choice for this application). Weld overlays were considered overly expensive (discussions with Welding Services indicated that Inconel 625 overlays were estimated to cost in excess of $200 per square foot.) and difficult to repair once cracks developed. Those companies experienced with weld overlays indicated that they withstood process-side erosion and corrosion better but were still susceptible to thermal stress cracking (perhaps even slightly more susceptible due to increased wall thicknesses), and continued to suffer from failures in those portions of the tubing that were not overlayed.

As a result, the project focused on identifying alternate materials of construction for the tubing used to construct this equipment. The major criterion for this selection was a material that was commercially available in tubing form and, therefore, readily amenable to fabrication into the equipment in question. Two newer alloys were identified as possible replacements for carbon steel and low alloy steel in these applications – a patented iron-based alloy developed by Oak Ridge National Laboratory (Fe-3Cr-W-V), which was essentially an improvement on the low alloy Cr Mo steels currently used in these furnaces, and a second patented alloy in the aluminum bronze family (having a nominal composition of approximately 90.25% Copper 6.5% Al, 2.5% Fe, 0.25% Sn, and 0.5% max Other).

The chart shown below indicates the materials that were considered in detail during this phase of the project. Copper (Alloy 1) Chrome-Moly Steel (Alloy 2) and two versions of carbon steel (Alloy 3 and 4) were characterized to provide a basis for characterizing their performance and evaluating the potential performance of the newer alloys.

Table 1. Chemical Composition of Materials Evaluated for Use in EAF/BOF Applications.

Element (wt%)	**Alloy #1 Copper Alloy**	**Alloy #2 Cr1Mo Steel**	**Alloy #3 Carbon Steel (0.17C)**	**Alloy #4 Carbon Steel (0.16C)**	Fe-3Cr-W-V #18716 Alloy 6	Al Br **Alloy #5**
C	____	0.11	0.17	0.16	0.099	____
Mn	<0.01	0.49	0.68	0.81	0.37	0.01
P	____	0.013	0.008	0.009	0.007	____
S	____	0.002	0.005	0.011	0.005	____
Si	<0.01	0.23	0.22	0.24	0.20	<0.01
Ni	0.01	0.04	0.11	0.10	1.00	0.01
Cr	<0.01	2.21	0.16	0.11	2.98	<0.01
Mo	____	0.93	0.05	0.04	0.74	____
V	____	0.003	<0.001	<0.001	0.23	____
Cb	____	0.001	<0.001	<0.001	0.003	____
Ti	____	0.004	0.003	0.004	0.003	____
Co	____	0.007	0.01	0.008	0.008	____
Cu	Balance	0.04	0.21	0.21	0.01	Balance
Al	____	0.014	0.015	0.024	0.002	6.51
B	____	<0.001	<0.001	<0.001	<0.001	____
W	____	<0.01	<0.01	<0.01	1.51	____
As	____	0.007	0.004	0.002	0.002	____
Sn	<0.01	0.001	0.012	0.011	0.002	0.27
Zr	____	<0.001	<0.001	<0.001	<0.001	____
N	0.01	0.008	0.006	0.008	<0.001	____
O	____	0.001	0.001	0.001	0.003	____
Zn	<0.01	____	____	____	____	<0.01
Fe	0.02	Balance	Balance	Balance	Balance	2.44
Pb	<0.01	____	____	____	____	<0.01
Hardness(HV)						
Transverse	105	195	155	144	371 (N)	140
					342 (N/T)	
Longitudinal	99	198	150	142	367 (N)	139
					336 (N/T)	

Extensive data on these alloys were developed by ORNL over temperature ranges from 72°F (25°C) to 1112°F (600°C) except for the Coefficient of Thermal Expansion which was measured over the range of 200°F (93°C) to 1200°F (649°C). The values measured included Coefficient of Thermal Expansion (CTE); Thermal Conductivity (TC); Yield Strength (YS); Ultimate Tensile Strength (UTS); Total Elongation (TE) and

Reduction of Area (RA). The values for each of these properties are not included in this report but form the basis of evaluating these materials directly and through modeling to determine which might provide the best alternative to carbon steel in EAF/BOF applications with respect to the three major root causes of failures that were identified earlier – Thermal Fatigue, Process-side Corrosion, and Cooling Water-side Corrosion.

HEAT TRANSFER AND STRESS MODELING

Two types of modeling were conducted to illustrate the differences between the alloys with respect to various aspects of the thermal response of the selected alloys – Heat Transfer Modeling and Stress Modeling. Calculations were also performed to quantify thermal fatigue.

Heat Transfer Modeling – Simple heat transfer model calculations were done to examine the difference in heat removal performance between various alloys. Heat transfer model set-up conditions were established as follows:

- A simple heat transfer analysis was performed.
    - Gas and Water Velocities were not considered
- Patran and Procast Software was used
- Tube Diameters Considered
    - Case 1: 1.64 in. OD x 1.27 in. ID
    - Case 2: Actual Tube Dimensions
- Gas Temperature 3000ºF
- Inlet water Temperature
    - Case 1: 208ºF
    - Case 2: 112ºF

The model output is graphically shown in Figure 8 which displays steady state thermal gradients for each alloy on the left and the time-temperature plots for each alloy on the right for Case 1 conditions shown above. The results for both cases are presented in Table 2. These plots and the results in Table 2 show the effectiveness of heat transfer of Al-Bronze (alloy #5) as compared to the iron based alloys under consideration. The temperature difference between tube OD and ID for carbon steel and Fe-Cr-Mo and Fe-Cr-W alloys is calculated to be nearly 2 to 3 times as large as the temperature difference calculated between tube OD and ID for aluminum bronze.

Table 2: Comparative Results from Heat Transfer Model

	Water Inlet Temperature = 98°C			Water Inlet Temperature = 50°C		
	OD = 1.64	ID = 1.27	Same Dimensions	Actual tube dimensions		
Alloys	T_{OD}	T_{ID}	$\Delta T = T_{OD} - T_{ID}$	T_{OD}	T_{ID}	$\Delta T = T_{OD} - T_{ID}$
Alloy #2	167	155	12	132	115	17
Alloy #4	166	155	11	130	115	15
Alloy #5	163	156	87	118	110	8
33V (N)	171	155	16	138	115	23
33V (N/T)	173	155	18	140	115	25

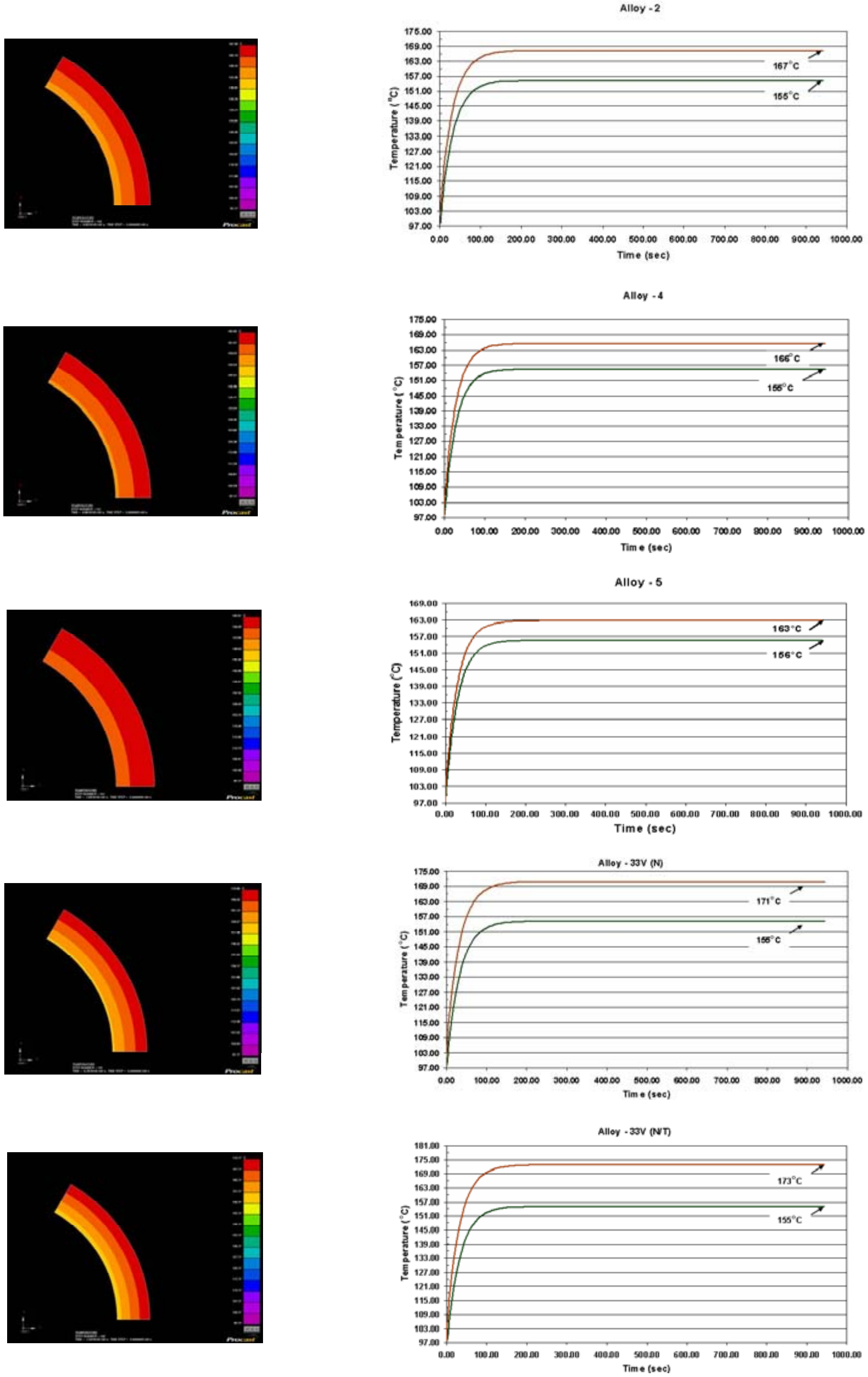


Figure 8. Heat Transfer and Time Temperature Simulations – Selected Alloys. Inlet 98°C

These results clearly suggest that Al-Bronze has superior heat transfer characteristics and should perform better than iron based alloys in EAF/BOF service since this alloy will operate at lower tubing temperatures at any given set of heat transfer conditions.

Stress Modeling – Stress modeling was also performed which evaluated 0.16 C steel (selected as a representative material for iron-based alloys since necessary mechanical parameter data was available for this alloy) as compared to copper (selected to represent the Al-Bronze material for the same reasons). Modeling was conducted for two typical work situations: transient and steady state heat transfer through the tube walls.

In the case of transient heat transfer, representing the beginning of the steel making process when tubing is being heated, average tube temperature is lower but the thermal gradients in are higher. In the steady state case tubing temperatures do not change with time and, as a result, average tube temperatures are higher but thermal gradients are lower. The end result is that displacements are smaller and stresses higher in case of transient heat transfer. The results of the transient modeling, showing displacements and stress tensors are shown in Figures 9 and 10.

In both modeling regimes, the stresses for Copper are less than those for a similarly sized steel tube even though the deviations from the initial position, i.e. deformations, are smaller for steel tube at the same thermal conditions. In spite of this, from thermo-mechanical point of view one can conclude that copper-based alloys should be more suitable for EAF/BOF applications than iron based alloy tubes.

THERMAL FATIGUE

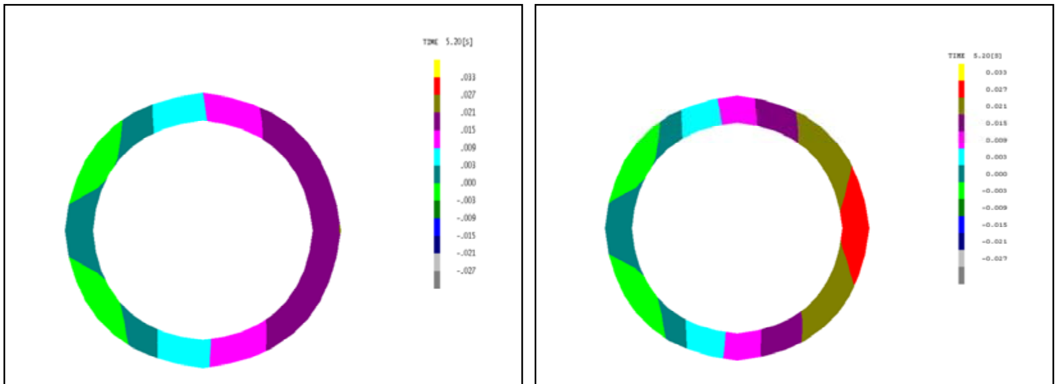
The thermal fatigue resistance factor for metallic materials is given by the equation shown below:

$$M = k(ys)(1 - \nu)/\alpha E$$

where:

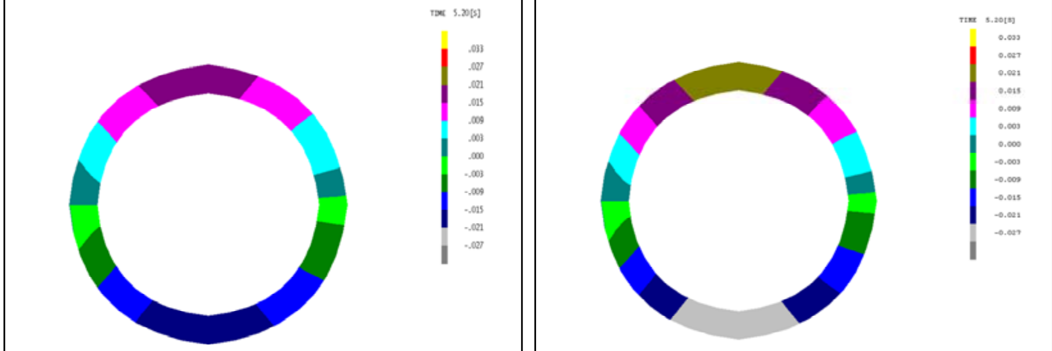
k = thermal conductivity,
ys = yield strength,
ν = Poisson's ratio,
E = modulus,
α = thermal expansion coefficient.

Data generated at ORNL on selected alloys were used to calculate their thermal fatigue resistance factor *M* (see Table 3). Values were calculated at room temperature (RT) and 400ºF. RT thermal fatigue resistance of Fe-2.25Cr-1Mo and Fe-3Cr-W steels is much higher than carbon steel and Al-Bronze. However, at 400ºF, *M* factor for iron-based alloys decreased, whereas it increased ~ 20% for Al-Bronze as a result of this alloy’s increase in thermal conductivity with temperature. At 600ºF, Al-Bronze *M* value will be even higher.



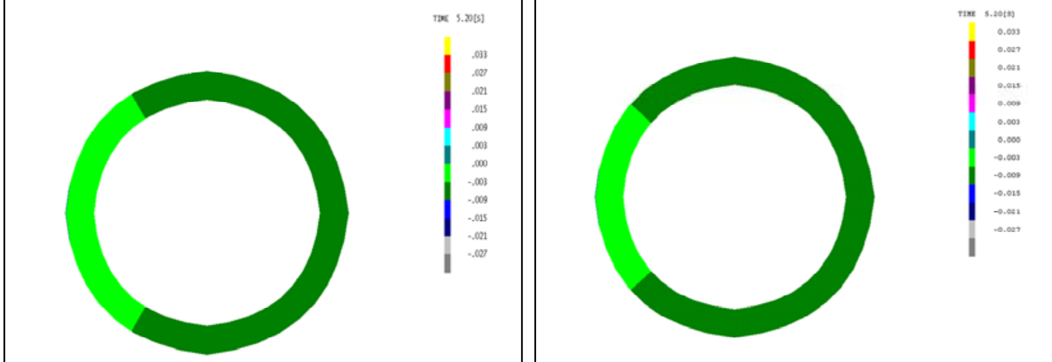
a) Field of the displacements in x direction [cm]

a) Field of the displacements in x direction [cm]



b) Field of the displacements in y direction [cm]

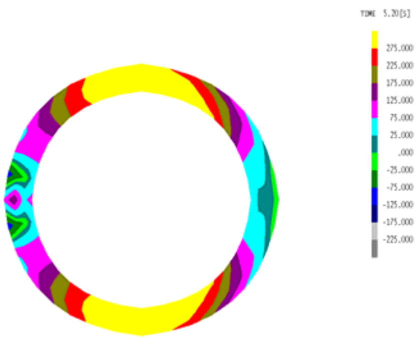
b) Field of the displacements in y direction [cm]



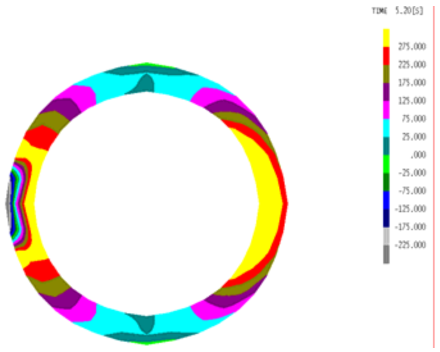
c) Field of the displacements in z direction [cm]

c) Field of the displacements in z direction [cm]

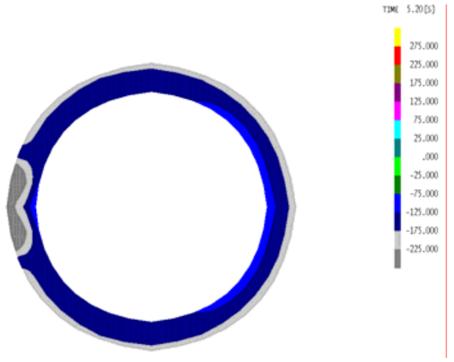
Figure 9. Modeled Displacement, 0.16 C Steel (left) and Copper (right) under Transient Conditions



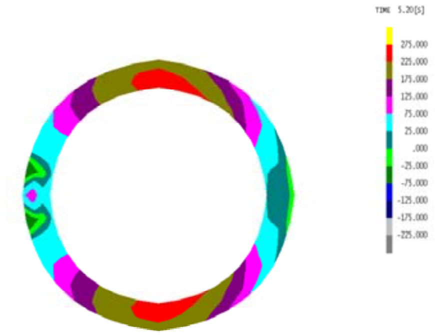
a) Stress tensor component σ_{xx} [MPa]



b) Stress tensor component σ_{yy} [MPa]



c) Stress tensor component σ_{zz} [MPa]



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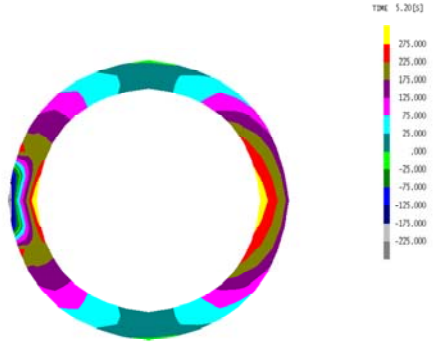
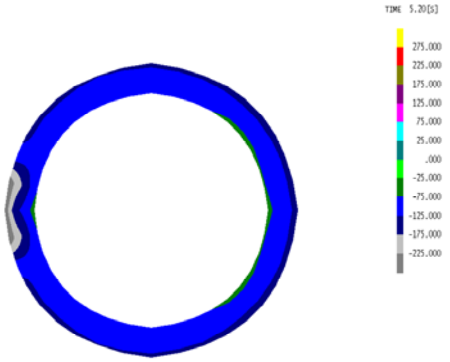


b) Stress tensor component σ_{yy} [MPa]



c) Stress tensor component σ_{zz} [MPa]

Figure 10. Modeled Stress Tensors, 0.16 C Steel (left) and Copper (right) under Transient Conditions

Table 3. Thermal Fatigue. Alloys of Interest

Alloy Designation	Composition Identifier	*M* Value (w/m)	
		Room Temperature	400ºF
2	2.25Cr-1Mo	5110	4849
3	Carbon Steel	4013	3397
4	Carbon Steel	4481	4160
5	Al-Bronze	4122	4877
6	3Cr-W (ORNL Alloy)	6227	5889

Based on calculations at 400ºF in Table 3, only the newly developed Fe-Cr-W type of steel showed superior thermal fatigue resistance as compared to Al-Bronze although Fe-Cr-Mo alloy was superior at low temperatures and equal at elevated temperatures.

These conclusions hold true, in the strictest sense, only for tubing with clean internal and external surfaces. Build-up of solid deposits or slag on the external surfaces of the tube as well as metal losses through corrosion or erosion would dramatically increase the thermal stress within the tubing. These deposits would serve as insulation and would allow “cold” spots to develop beneath the deposit. Copper-based alloys would be affected far less than steels since their significantly higher heat transfer properties would tend to minimize the resulting temperature difference. Similarly, water-side deposits would insulate the tubing from the cooling side, resulting in the development of “Hot” spots. Again, for a given sized deposit, copper’s greater heat transfer capability would minimize the impact of the resulting temperature increase on thermal fatigue.

PROCESS SIDE CORROSION MODELING

The reason for chemical corrosion of metals and alloys is the thermodynamic instability displayed by these materials under specific environmental conditions. One criterion that demonstrates the propensity for corrosion processes to occur is change in Gibbs Free Energy of the system, ∆G. For the oxidation, most common corrosion process at high temperatures, the following equation governs:

$$\Delta G = RT\ln\frac{1}{P_{O_2}^{mn/4}} - RT\ln K_p$$

where pressure P and temperature T are constant. The metal oxidation is possible only if oxygen partial pressure is higher than the dissociation pressure of metal oxide at the given temperature:

$$P_{O_2} > (P_{O_2})_P$$

Analogous relationships can be written for all components of a gas mixture which might cause corrosion.

Using ∆G, one can calculate thermodynamic favorability for reactions between gas components and the material of construction in a BOF hood. Negative changes in Free

Energy indicate a favorable reaction path. The more negative the change, the more favored the reaction. For this purpose it is important to know the composition of the gas entering the hood. Estimation or measurement of the quantity of these components is in general difficult problem. Hargrave in “Common failure mechanisms in BOF hoods” *(Iron and Steel Engineer*, Nov., 1996, pp.22-28) put forth the following conditions: 50-90% CO, 10-40% CO_2 , till 3% N_2, up to 5% O_2 and some quantity SO_2, H_2, H_2O. Gas temperatures usually vary between 1400 and 1800°C.

The alloys under consideration are all predominantly iron or copper. As a result, 16C steel and copper were used to approximate the corrosion tendencies of the various alloys, although it is recognized that the quantitative values obtained may vary considerably from those experienced by each individual alloy. Taking into account the main gas components in a BOF system as shown above, the following interactions are of interest for steel:

- $Fe+2CO_2 = CO+FeCO_3$
- $Fe+CO_2 = CO+FeO$
- $2Fe+3CO_2 = 3CO+Fe_2O_3$
- $3Fe+4CO_2 = 4CO+Fe_3O_4$
- $CO_2+FeO = FeCO_3$
- $CO+ CO_2+Fe_2O_3 = 2FeCO_3$
- $CO+2CO_2+Fe_3O_4 = 3FeCO_3$
- $2FeO+ CO_2 =CO+Fe_2O_3$
- $3FeO+ CO_2 = CO+Fe_3O_4$
- $1,5\ Fe_2O_3+0,5CO = 0,5CO_2+Fe_3O_4$
- $4Fe+3O_2=2Fe_2O_3$
- $2Fe+O_2=2FeO$
- $3Fe+2O_2=Fe_3O_4$

The reactions were developed by examining the phase stability diagrams for the system Fe-C-O. Calculated Gibbs energy changes for these reactions are shown below.

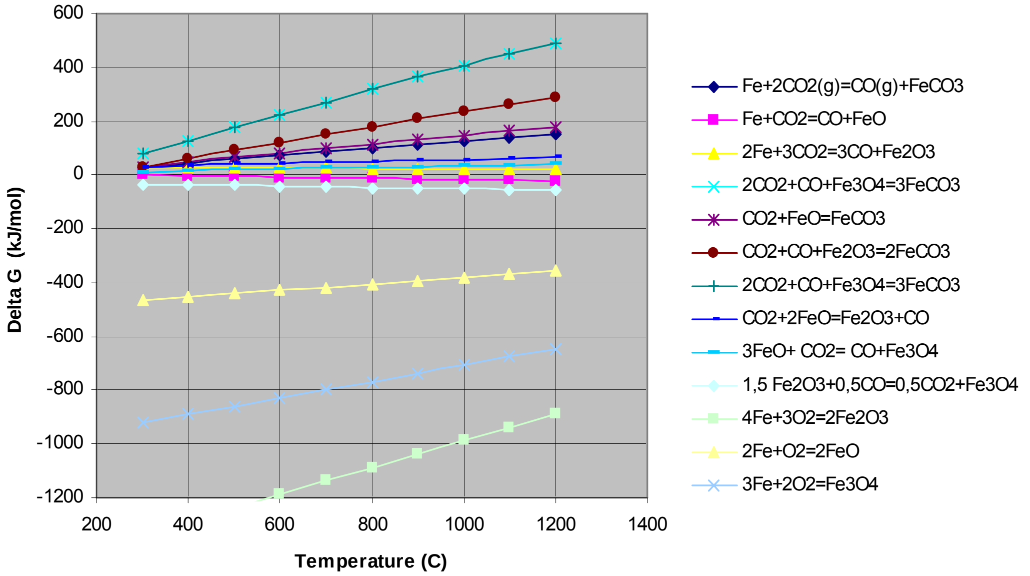


Figure 11. Gibbs Free Energy Changes; Fe – C – O System

The probability for each of these reactions to occur is function of Gibbs energy change for the case considered. Figure 11 suggests that, in the temperature interval considered, only the interactions between Fe and O_2 are likely to occur (see lowest 3 lines on the above plot). The stability areas of Fe containing species in this gas environment as a function of CO_2 and CO partial pressure and temperature are shown on Figure 12. While the positions of the phase boundaries change with temperature, thermodynamically, the FeO phase remains stable throughout the entire temperature interval. It is well recognized that FeO possesses extremely low protective properties for the base metal and does not hinder subsequent corrosion processes.

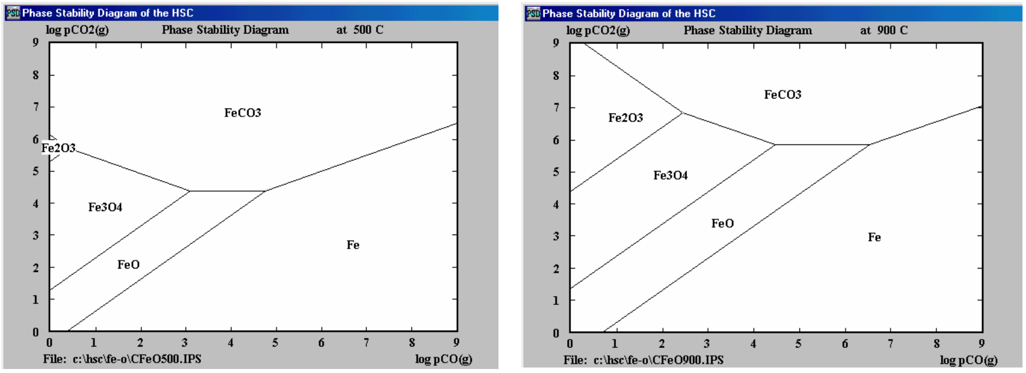


Figure. 12. Phase Stability Diagram; Fe – C – O System; at 500°C (left) and 900°C (right)

In case of copper tubes the following interactions are possible:

- $Cu+2CO_2=CO+CuCO_3$
- $Cu+CO_2=CO+CuO$
- $2Cu+CO_2=CO+Cu_2O$
- $CO_2+CuO = CuCO_3$
- $3CO_2+Cu_2O = 2CuCO_3+CO$
- $2CuO+CO = CO_2+Cu_2O$
- $2Cu+1/2O_2 = Cu_2O$
- $Cu+1/2O_2 = CuO$

Calculated Gibbs Free Energy changes in above reactions are shown in Figure 13. Again, Figure 13 suggests that, for the temperature interval under consideration, only the interactions between Cu and O_2 are possible (see lowest 3 lines on Figure 13). Comparing this Figure with that for the Fe-C-O systems shows that the values for ΔG in the copper system are significantly less negative than those in the iron system suggesting that, thermodynamically, Cu oxidation is significantly less than that of iron.

The areas of Cu-containing compounds stability as function of partial pressures of CO_2 and CO are shown in Figure 14. Generally, the areas of stability for copper oxides enlarge with temperature growth but under BOF hood conditions (relatively low partial pressures) the Cu phase is the only phase present.

On the basis of the above results it can be concluded that from thermodynamic point of view Cu-alloy tubes should possess much better corrosion resistance than steel tubes because they exhibit an oxidation driving force that is many times lower and, under BOF hood conditions, the Cu phase is stable whereas, for steel tubes, the stable phases are oxides which have poor mechanical characteristics and do not protect the tube from continuing corrosion.

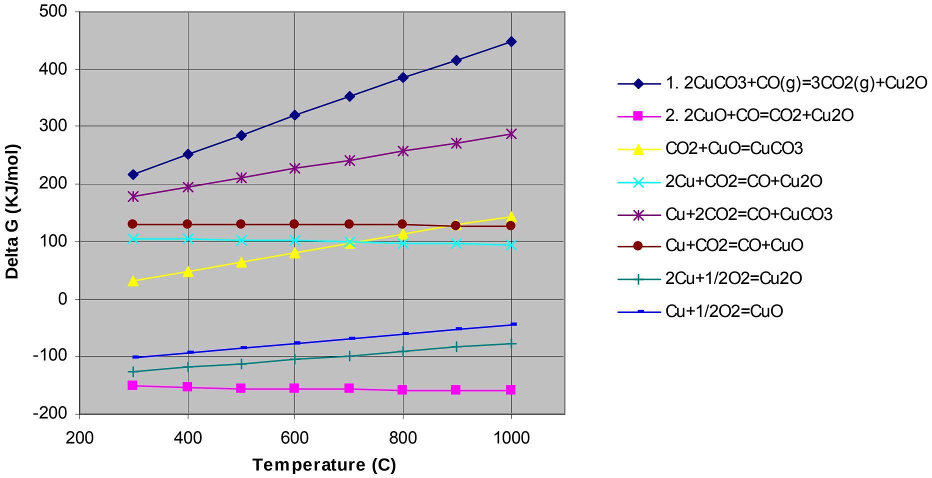


Figure 13. The Gibbs Free Energy Changes; Cu – C – O System

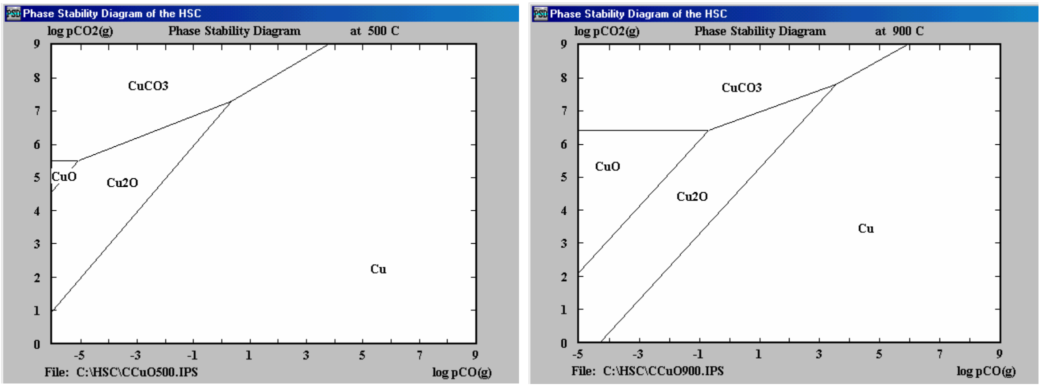


Figure 14. Phase Stability Diagram; Cu – C – O System; at 500°C (right) and 900°C (left)
(Note: x-axis represents significantly lower CO levels than Fe system diagrams)

WATER-SIDE CORROSION

Water-side corrosion issues revolve around two specific issues – water treatment practices and the nature of the system exposed to the cooling water. Systems comprised of steel components (including low alloys) tend to have simpler water treatment practices than systems comprised of copper heat exchange equipment embedded in carbon steel piping systems. Treatment regimes must avoid general corrosion, localized pitting, and stress corrosion cracking as well as the build up of cooling water deposits that can coat internal surfaces, impede heat transfer and aggregate the effects of thermal fatigue.

In general, cooling water systems should deliver water with little to no suspended or dissolved solids. Water pH should be around 12 for steel systems with appropriate surface active additives to minimize iron corrosion. Mixed copper / steel systems have been studied extensively in the electric power generation industry since most plants are built around mixed cooling water systems. The Manager of Water Quality at AEP commented on these systems to the effect that the only option available was to maintain a pH of 9.0 and an ORP potential as close to -350 ma as possible. While cooling water quality is an issue at many facilities, proper attention to the matter should remove it as a major factor in EAF/BOF processing equipment.

Materials Selection and Field Testing

Based on the results from the material testing discussed earlier, Fe-3Cr-W-V or Al-Bronze appeared to offer the best chance for improvements in the service life of EAF/BOF water-cooled equipment. Of these two materials, Al-Bronze was considered a superior choice for three reasons. First, the aqueous corrosion resistance of Fe-3Cr-W-V is poorer than Al-Bronze since this alloy is primarily iron-based. This could result in cooling side corrosion and leaks from inside the tube. Secondly, the oxidation resistance of Fe-3Cr-W-V is poorer than Al-Bronze again owing to the differences between iron-based and copper based alloys increasing the possibility that the Fe-3Cr-W-V alloy could experience significant metal loss from the external surface of the tube through corrosion and removal of the loosely adherent FeO layer. Third, the differences in thermal fatigue resistance between Fe-3Cr-W-V and Al-Bronze, particularly at temperature, were not sufficiently large to offset the disadvantages inherent in Al-Bronze.

Having identified the two primary candidates for further examination and testing, Al-Bronze and Fe-3Cr-W-V, the project began to consider the most appropriate manner of evaluation one or both of these materials. At this point, representatives from Republic Engineered Products (REP) indicated that they would be replacing one of their BOF skirts shortly and volunteered to conduct a full-scale test of one of the alloys. Since the Al-Bronze was readily available in tubing form, plans were made to proceed with this testing as the best method of evaluating the performance of this alloy and, by extension, validating the procedures undertaken to select this alloy in the first place.

The exposure location selected by REP was one of the most demanding in their hood system. The skirt is part of the suppressed combustion hood system in use at REP. As a result, the skirt is located immediately above the furnace and is exposed to the highest temperatures during normal operations. This location also exposes the skirt to contact with molten slag during the slag splashing operations undertaken to prolong the life of the refractory in the furnace. All-in-all, this location was considered ideal for evaluating the performance of the Al-Bronze alloy.

The Al-Bronze chosen for this study was a patented alloy supplied by AmeriFab, Inc. A literature search was carried out on Al-Bronzes (see Table 4). Based on data in this table, Al-Bronze supplied by AmeriFab appears to fit into the C61300 grade of aluminum bronzes. Literature data also showed that Al-Bronzes are used in rod; bar; sheet; plate; seamless tubing and pipe; welded pipe; fasteners; tube-sheets; heat exchanger tubes; acid resistant piping; and corrosion resistant vessels. Tensile properties of Al-Bronze supplied by AmeriFab were also compared with the published data on standard grade C61300/C61400.

The welded joint of AmeriFab Al-Bronze was also investigated for its microstructure and tensile properties. The weld microstructure is shown in Figure 15. Two observations from these figures are: (1) there is a notch at the weld root that was taken care of in component fabrication and (2) the weld structure is a coarse dendritic cast structure. Weld specimens that contain base metal and weld metal were tensile tested at RT, 200, 400, and 600ºC. Data on these specimens are compared in Figure 16. These figures show that: (1) yield strength of the welded joint is nearly the same as base metal, (2) the weld structure does not work harden in a manner similar to the similar to base metal (fine grain structure) and gives lower ultimate tensile strength values, and (3) the weld tends to have lower ductility at RT and 200ºC than base metal. These data suggest that welds might need careful attention during fabrication.

Table 4. Chemical Analysis of Standard Al-Bronzes with AmeriFab Al-Bronze Alloy #5

Element (wt %)	**C60600 95Cu-5Al**	**C60800 95Cu-5Al**	**C61000 92Cu-8Al**	**C61300 90Cu-7Al 2.7Fe-0.3Sn**	**C61400 91Cu-7Al-2Fe**	**AmeriFab Alloy 5**
Cu	92-96	92.5-94.8	Balance	88.5-91.5	88.5-92.5	Balance
Al	4-7	5.0-6.5	6.0-8.5	6.0-7.5	6.0-8.0	6.51
Fe	0.5 max	0.1 max	0.5 max	2.0-3.0	1.5-3.5	2.44
As	--	0.02-0.35	--	--	--	--
Pb	--	0.1 max	0.02 max	0.01 max	0.01 max	<0.01
Zn	--	--	0.2 max	0.05 max	0.2 max	--
Si	--	--	0.1 max	--	--	<0.01
Sn	--	--	--	0.02-0.5	--	0.27
Mn	--	--	--	0.1 max	1.0 max	0.01
Ni (+Co)	--	--	--	0.15 max	--	0.01
P	--	--	--	--	0.015 max	--
Cr	--	--	--	--	--	<0.01
Other Elements	0.5 max	--	0.5 max	0.05 max	0.5 max	--
CTE (µ in/in)	10	10	9.9	9.0	9.9	9.5
Thermal Conductivity (W/m*K)	79.5	79.5	69	56.5	56.5	59.9
Specific Heat (J/Kg)	375	380	375	375	375	--

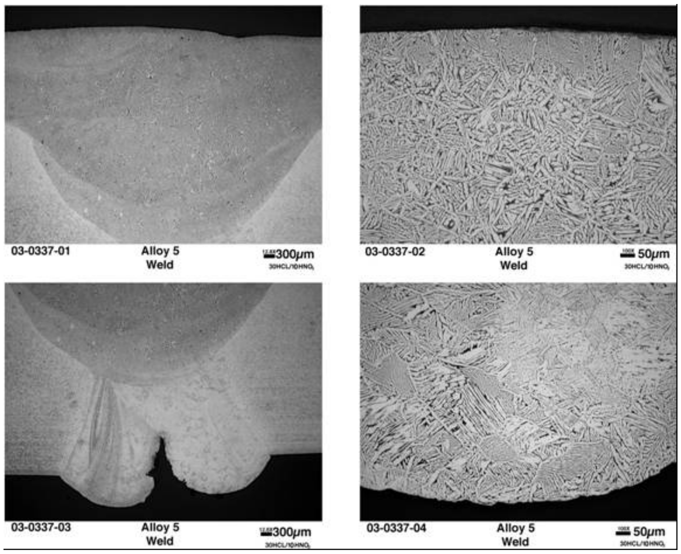


Figure 15. Microstructure of the Weld in Al-Bronze tube.

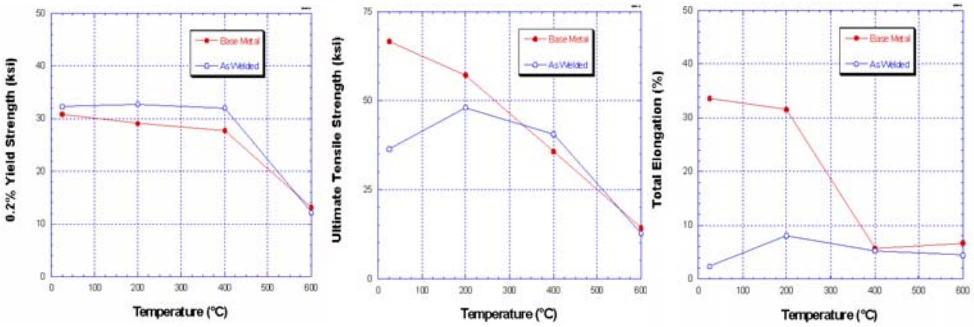


Figure 16. Mechanical Properties of AmeriFab Al-Bronze Base Metal and Welds; Yield Strength (right); Ultimate Tensile Strength (center); Total Elongation (right); 25 to 600°C.

Design and fabrication of the skirt and trough proceeded throughout the summer of 2004 with the equipment delivered to REP in late August 2004. The skirt that was produced had a water cooled section 40 5/16" tall with an upper diameter of 14'8" and a lower diameter of 17'4". The skirt was fabricated from 2.75" diameter extruded Al-Bronze tubing with a nominal wall thickness of 0.275" (+/- 0.03"). While the design required some minor changes in installation techniques and required ~ 250 gpm more cooling water, installation was fairly straightforward and the modifications to the cooling system minimal. Installation of the skirt and attendant water seal

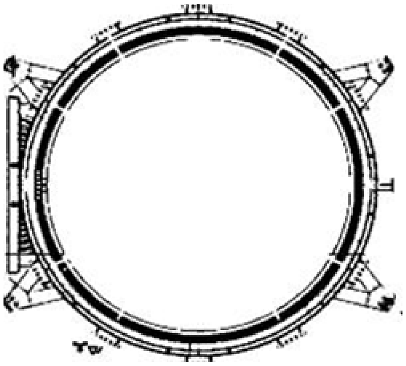


Figure 17. Top view. Al-Bronze Skirt

trough was completed on REP's "N Vessel" in October 2004 with the furnace placed in operation as REP's "back-up vessel" on November 4, 2004. Back-up vessel operation is intermittent. The "primary vessel" is normally in production with the back-up vessel only placed in service to provide production during times when the primary vessel is undergoing periodic maintenance. Back-up service was selected as the best alternative for the first portion of the testing in order to gain experience and confidence in the new alloy.

Back-up service was continued until August 2005 at which time the N Vessel was placed in primary service to allow maintenance on the L vessel. N vessel continued as the primary production vessel from that time until October 2006 at which time N vessel was taken out of service for maintenance.

Figure 18. Al-Bronze Skirt before Installation

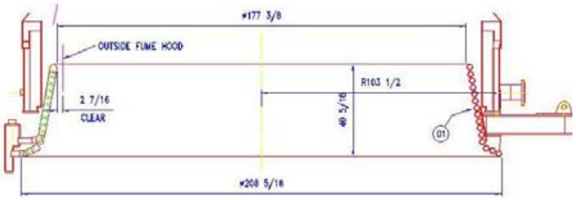


Figure 19. Skirt Cross Sectional Drawing

Performance of the Al-Bronze Skirt

An overview of the operating history of the Al-Bronze skirt is summarized in the following table:

Table 5. Summary of N Vessel Al-Bronze Skirt Operation

Time Period	Service	Number of Heats	Skirt Maintenance
11-2004 to 12-2004	Back-up	43	None
01-2005 to 07-2005	Back-up	247	None
08-2005 to 12-2005	Primary	1625	Once
01-2006 to 10-2006	Primary	2648	Once
End of October 2006	N Vessel taken down for Maintenance. Restart 01-2007		

While the exact product mix processed through N vessel varied from time to time throughout the year, on the average, the skirt was exposed to the following product mix:

- 61% Low Alloy Steels (Cr, Mo, Ni, High Si, etc.)
- 29% Plain Carbon Steels (10xx)
- 10% Resulfurized Steels (11xx, 12xx)

As indicated in Table 5, the Al-Bronze skirt required maintenance twice during its first two years of service. The first occasion resulted from a failure in the control system on the furnace. Normally, the skirt is raised to allow the furnace to rotate in order to tap off the completed heat. On this occasion, a failure in the furnace control system allowed the skirt to descend while the heat was being tapped and, as the furnace was rotated into operating position, it crashed into the lower portion of the skirt. The damage was extensive, necessitating the replacement of approximately 15 lineal feet of the lowest four courses of tubing (Figure 20.) AmeriFab was called in and repaired the damage in less than one week.

The second occurrence requiring maintenance on the skirt occurred approximately 3 months later. On this occasion one of the tubes in the upper portion of the skirt was creased and split when the skirt was lowered onto a slag skull that had formed on the stationary portion of the hood system. While this damage necessitated an immediate shutdown for repair, REP maintenance personnel were able to repair the tube in-house with the same techniques used to repair leaking carbon steel – patching and welding.

Figure 20. Skirt Damage, Collision with BOF Vessel.

This was the first of several unintended benefits from the use of Al-Bronze in BOF applications. Discussions with REP personnel after the collision with the furnace indicated that, in their opinion, had the same thing occurred with a carbon steel skirt after 2000 heats, the skirt would have had to have been replaced entirely. This opinion was based on two factors. First, a steel skirt would have suffered more damage than the Al-Bronze as a result of the higher yield strength and ultimate tensile strength of carbon steel. Secondly, the amount of metal loss generally experienced on the process side of carbon steel tubes would have made it questionable whether the skirt repair could have been accomplished in a manner that would have extended the life of the skirt. Thermal stresses normally experienced by a carbon steel skirt during operation would have been magnified by the extensive welding needed to repair the skirt. Aside from the stresses induced in the metal during welding, the wall thicknesses of the new tubing would have been significantly greater on the process side than those on the remaining skirt as a result of corrosion and metal removal during cleaning to achieve a weldable surface. This thickness variation would have provided significant stress points for rapid failures in the future. As it was, the damage was fairly localized in the Al-Bronze skirt and very little wall loss noted. This made a thorough repair relatively easy as evidenced by the more then 2600 heats subsequently processed without thermal or corrosion induced cracking.

Detailed Performance Evaluation

The 3-month scheduled down at the end of October provided a perfect opportunity to examine the skirt after over 4500 heats that was not possible after the furnace collision since that incident was an unplanned outage and restoring production as quickly as possible was critical. The current, planned shutdown allowed a thorough examination of the skirt that would not interfere with REP's production schedule. This examination included general observations, detailed ultrasonic thickness measurements of the process-side wall thickness, and microstructural examinations of tube sections that were removed as a result of the earlier evaluations.

Figure 21. Al-Bronze Skirt (Process-side looking south) after 4653 Heats.

General Observations – The general condition of the tubes in the process side of the skirt was very good (Figure 21). The tubes were generally covered uniformly by a thin, non-adherent coating typically less ~ 1/16" thick. This coating was easily removed, by hand with a wire brush. Several locations around the skirt did have a tightly adherent coating that was considerably thinner than the loose coating but these locations were localized and not extensive. Several other locations exhibited heavy coatings, ¼" in and thicker (See Figure 22. These areas were predominantly located around header portion of the skirt (See Figure 18) and are assumed to be the result of slag splashing and the physical arrangement of the piping in that area providing resistance to the free release of the coating. In all cases, these heavy coatings were not physically bound to the tubing and were easily removed with the bare hand revealing a surface with the thin coatings previously described.

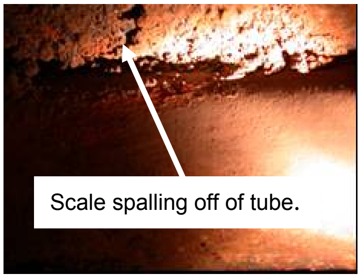


Figure 22. Thick Scale on Tubing.

This observation confirms a second unintended benefit of Al-Bronze in this application. REP personnel had reported earlier that, unlike carbon steel, slag that had splashed onto the skirt easily spalled off the skirt as it was moved into position for the next heat. This phenomenon was first noticed during periodic descaling operations when no evidence of scale was found on the skirt (although the remaining carbon steel portions of the hood did have scale build up and still requires periodic descaling) and confirmed by observing the scale falling into the furnace as the skirt was moved into position during future production operations.

The reasons for slag not adhering to the skirt are postulated to be the result of one or more of the following mechanisms – a minimal oxidation layer on the surface of the Al-

Bronze for adhesion; the lack of surface roughness form corrosion, pitting, etc. on Al-Bronze which removes the possibility of physically binding the slag to the surface; and a much cooler surface with much higher heat transfer characteristics that causes the slag to chill-off before an adherent bond can be formed and which causes the slag to spall away from the surface during the next heating cycle.

This observation holds considerable promise for future installations of Al-Bronze in BOF operations that have adopted slag splashing techniques to increase the life of furnace linings. The benefits of non-adherent slag (given the assumption that all slags would be non-adherent, an assumption that has yet to be demonstrated) have effects in several operational areas:

1. Periodic in-process descaling the skirt and hood, and the possibility of mechanical damage to the equipment would be minimized or eliminated. In process descaling has traditionally been accomplished by fitting a tool on the end of moving equipment similar to a back-hoe and, as gently as possible, scraping off the slag skull. Since this practice is performed on-the-fly, from 20 to 30 feet away, in an area with minimal visibility and poor lighting, damage to the skirt and hood system is, at times, unavoidable. Making in-process descaling unnecessary would eliminate this cause of equipment damage, downtime, energy loss and production interruption.
2. Significant skull build-ups on the skirt occasionally cause damage to the hydraulics that raise and lower the skirt by unbalancing the loads on the hydraulic system. REP has not experienced any such occurrences on N Vessel since the Al-Bronze skirt was installed.
3. On suppressed combustion hoods, such as the arrangement at REP, the ability to maintain good operation of the environmental control system and to avoid severe overheating in the hood system depends on properly positioning the skirt over the furnace. In the past, slag skulls have made proper positioning impossible, a condition noticed only after a batch has been charged to the furnace and, therefore, must be processed. REP again reports that this situation has not occurred on N Vessel since the installation of the Al-Bronze skirt.

The final observation made during the general inspection was of a number of areas where the tubing was “crushed” (a broad area where the tube was obviously flattened over a length) and “dinged” (a localized, deep distortion in the tube perhaps 0.5 to 0.75 inches in diameter and ~ 3/8” deep) were noted. This damage was localized to the lowest three tubing courses. The worst areas were observed on the bottom tube, including one such area of fairly severe crushing extending over 36 inches and reducing the tube from a cylinder 2.75 inches in diameter to a 3” x 1 11/16” oval. This damage could have been the result

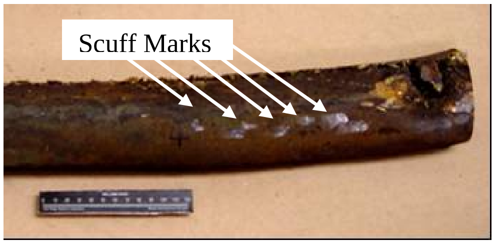


Figure 23. Scuff Marks on Damaged Tube.

either of the skirt contacting the seal ring (or slag skull) at the top of the furnace but the presence of “scuff marks” on portions of the tubing (Figure 23) indicates that the most likely cause is accidental damage during descaling operations.

None of these areas appears to have been leaking. However, since cooling water in the tubes is fed through common water headers, these crushed areas would increase the pressure drop through the affected tubes which result in reduced cooling water flow. REP decided to replace a six foot section of the bottom tube which showed the most severe damage This section included a length of undamaged tube at each end. It was sent to ORNL for microscopic examination.

Detailed Thickness Measurements – REP provided an ultrasonic thickness gage normally used for in-house measurements. A section of virgin aluminum bronze tube was used to calibrate the gage. Caliper measurements varied from 7.1 mm to 7.35 mm at the two points measured on the tubing. The UT gage calibration was adjusted such that the gage reading matched the caliper reading at those points.

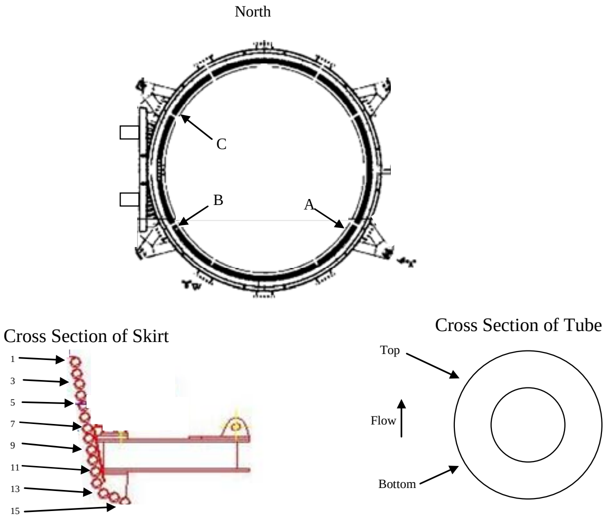


Figure 24. Ultrasonic Thickness Measurement Locations

Two measurements, one upstream and one downstream to the direction of flow were taken on every other tube at three points around the circumference of the skirt (See Figure 24). The loosely adherent scale at each point was removed by hand using a wire brush. Care was taken to make certain that the measurement recorded at each location was the minimum reading obtainable. Since the skirt was resting on the floor, readings on tube #15 in Figure 24 were difficult to obtain and multiple readings were not possible.

AmeriFab’s manufacturing specification for aluminum bronze tubes used in fabricating this type off equipment is:

Nominal tube thickness:	0.276” (7.01 mm)
Minimum tube thickness:	0.248” (6.30 mm)
Maximum tube thickness:	0.304” (7.72 mm)

The plots of the ultrasonic measurements appear in Figure 25 on the following page. Although it is recognized that some wear must have occurred on the tubing since its installation, the measurements suggest that there has been no significant metal loss on the tubes. All thickness measurements remain within standard manufacturing specifications as established by AmeriFab.

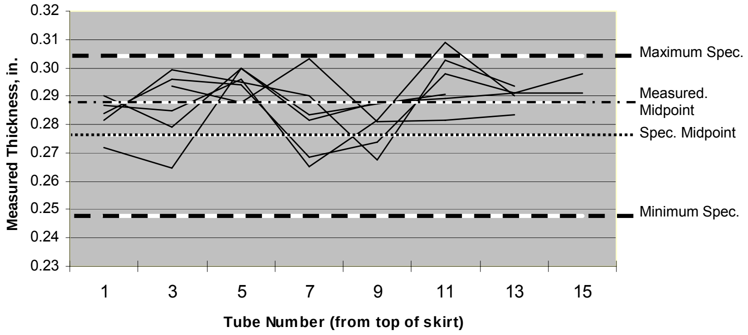


Figure 25. Ultrasonic Thickness Measurement, Al-Bronze

In addition to determining wear, two measurements were taken at each location, one upstream of the flow and one downstream, to determine whether there was increased wear on the upstream side resulting from direct impingement. A plot of the difference between these measurements (Downstream thickness – Upstream thickness) appears in Figure 26. No readily discernable pattern is evident and, while it may seem reasonable to assume that the tube face exposed to direct impingement would show more wear, this assumption is not supported by the data.

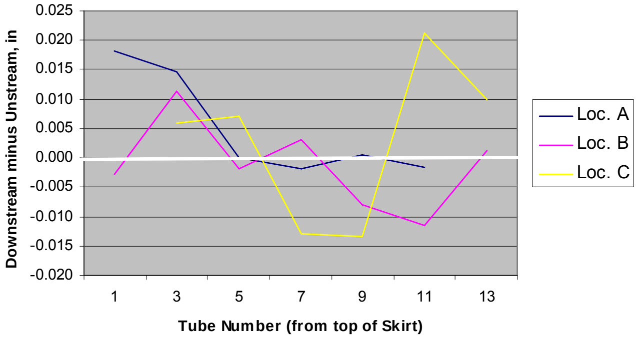
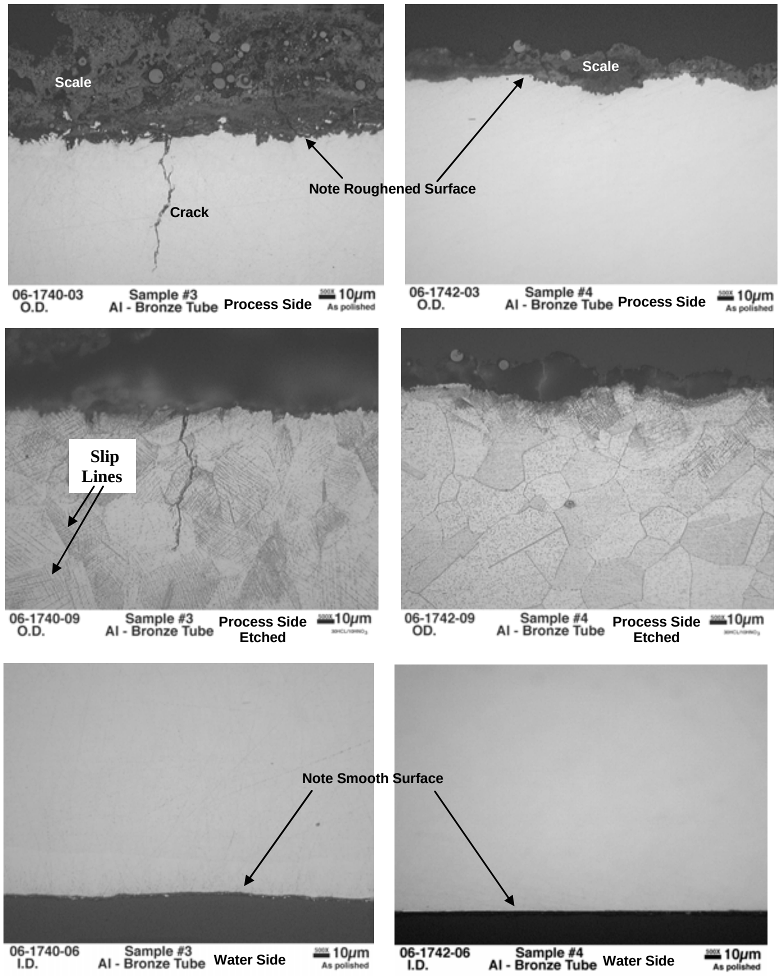


Figure 26. Ultrasonic Thickness Measurement Variations

Microstructural Analysis – Based on the recommendations from the initial inspection of the skirt, REP decided to replace a portion of the lowest tube on the portion of the skirt facing north. Approximately 7 feet of this tube was cut out of the unit including the portion that was severely collapsed and segments of unaffected tubing on each end. This tubing was sent to ORNL for detailed microstructural examination.

Figure 27 shows a series of micrographs taken from this tube. The micrographs on the left and the backscattered electron micrograph were taken from a sample from a section of the collapsed portion of the tube (labeled Tube 3). The micrographs on the right were taken from an unaffected section of the same tube (labeled Tube 4). Both Tube 3 and Tube 4 exhibit a roughened process-side surface, indicating some degree of metal loss during service. The Tube 3 sample exhibits cracking that goes through the grains of the alloy and slip lines in the grain that indicate some level of cold working. The crack in



Backscattered Electron Image. Process-Side (Tube 3).

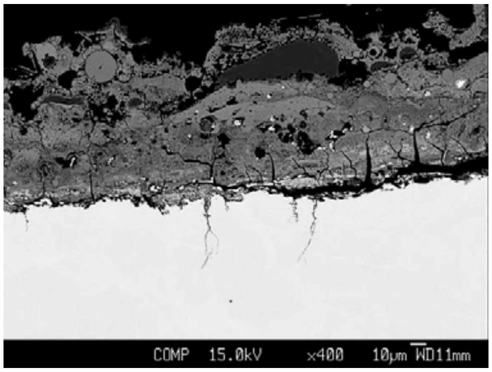


Figure 27. Micrographs of Al-Bronze Tube Removed at REP

Tube 3 is approximately 50 microns into the tube. The level of cracking in the Tube 3 sample is more easily appreciated by examining the backscattered electron picture.

The waterside surface of the tubes exhibit a smooth surface, smoother in Tube 4 than Tube 3 since Tube 4 had not been exposed to mechanical deformation, but each surface significantly smoother than the corresponding process-side surface. This result confirms the conclusion that some level of metal loss had occurred on the process-side of the tube and also indicates that the water treatment practices at REP have been sufficient to avoid any noticeable corrosion of the inner tube surface.

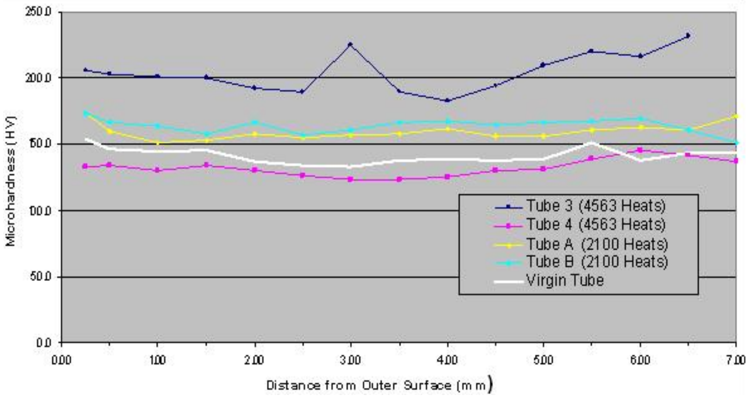


Figure 28. Aluminum Bronze Micro Hardness

The cause of the cracking exhibited in Tube 3 is of concern since experience has shown that physical cracking is a major cause of failures in tubing is BOF/EAF service. Figure 28 is a plot of micro hardness measurements across the tube wall of various samples of Al-Bronze taken from samples that had seen service at REP and also from a section of virgin tubing. Virgin tubes are extruded and later bent to the proper radius for fabrication into the skirt. As a result, each will exhibit some difference in hardness depending on the extrusion conditions experienced and the extent of bending required to arrive at the radius needed for each particular tube. However, since Tube 3 and Tube 4 are different sections of the same tube, stresses from extrusion and bending should be nearly identical.

Figure 28 suggests that tubes that have not undergone mechanical damage while in service do not vary considerably in micro hardness from a virgin tube either in the overall value of micro hardness or in the uniformity of the hardness from the exterior surface to the interior surface. The plot for Tube 3, however, exhibits dramatically higher overall micro hardness and significant variations in micro hardness across the wall thickness. This result suggests that the cracking exhibited in Tube 3 was probably the result of work hardening caused by mechanical deformation of the tubing rather than from process-related, thermally-induced fatigue.

The final examination of the tubes recovered from REP is the element map of the alloy and of the surface scale obtained through microprobe analysis (Figure 29.) Element enrichment levels are indicated by color scale on the right side of the maps. Note that the scale is predominantly iron oxide (see O and Fe maps) except for a thin layer at the scale alloy interface which shows increased levels of copper and aluminum perhaps from an interaction with chlorine. Mn-, Si-, and Ca-containing particles are also present in the oxide scale. The alloy element mapping shows relatively uniform composition in the bulk of the alloy. Again there are notable exceptions to this conclusion on the alloy surface (including the surface of the cracks), where there appears to be an enrichment of copper evidenced by the red areas identified in the Cu scan.

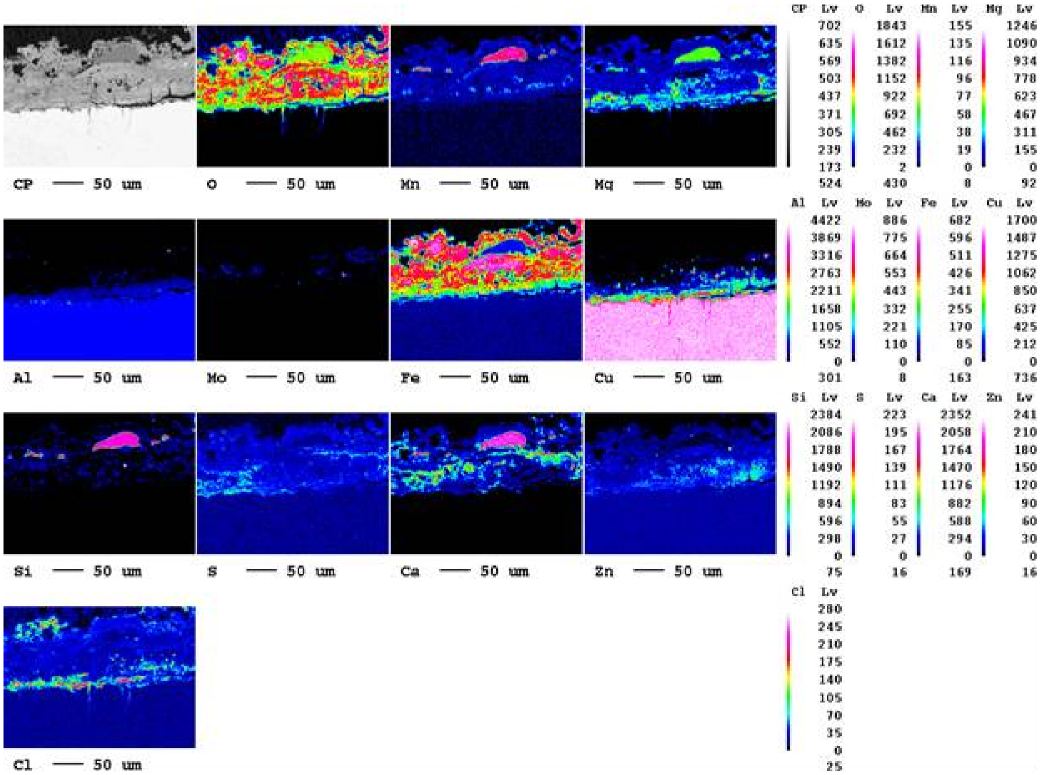


Figure 29. Element Mapping Using Microprobe Analysis.

ADDITIONAL REP ACTIONS

The success of the Al-Bronze material in the skirt application led REP to take additional steps to implement this alloy into other sections of their hood system. In early 2006 REP ordered new flux chutes for both BOF vessels fabricated out of Al-Bronze. The flux chute area was another major contributor to process downtime, generally requiring 24 repair shutdowns in an anticipated 1 year service life. Since installation, no maintenance for cracking or leaks has been necessary in approximately 6 months of service.

REP is currently soliciting quotations and considering the possibility of replacing the entire lower section of the hood system with Al-Bronze. This action could eliminate skull build-ups in the lower hood section and eliminate the need for periodic descaling, which is assumed to be the cause for mechanical damage to the skirt system, as well as provide an alloy with substantially longer life and far fewer shutdowns for maintenance and repair.

OVERALL EVALUATION, CONCLUSIONS, PROJECTIONS

Based on the performance and detailed analysis of sections of the skirt obtained during the two years of operation, evaluations at ORNL have projected that the Al-Bronze alloy may have as great as 5 times the service life of a comparable carbon steel skirt. The overall benefits of the project are summarized in the GPRA prepared for the project (See Appendices) by ORNL. The benefits summarized below are based on that document and input from REP representatives

Energy Savings – The GPRA calculations project a yearly energy savings of approximately 10.5 billion BTU for the single furnace installation at REP. The basis of these energy savings are found in the reduction of production shutdowns for the projected repairs of skirt, flux chute and lower hood components in the BOF hood system. Although each particular skirt, flux chute and lower hood section has its own maintenance history, detailed discussions with REP personnel placed the following estimates on the repairs required for each of these components:

Table 6. Typical Performance of Carbon Steel Skirts

Component	Nominal Service Life	Anticipated Repair Instances per year
Skirt	20 months	40
Flux Chute	6 months	24
Lower Hood	60 months	10
Total		74

During the preparation of the GPRA evaluation it was recognized that repair shutdowns probably would not deal with the maintenance needs of each component separately. As a result, the total number of shutdowns needed for hood repairs was taken at 52 per year, or one per week, a number considered reasonable to REP personnel. The duration of each particular shutdown again varies with the extent of the work needed to be undertaken. A reasonable assumption for repair duration per incident was placed at 8 hours, again a value that was considered reasonable by operating and maintenance personnel.

The use of Al-Bronze alloys applies not only to the BOF example addressed in detail during this project but equally as well to EAF applications. While conditions differ between these two steel making processes, the main operating envelope for process off-gases and causes for water-cooled equipment failure are essentially equivalent between the two steelmaking methods. ORNL estimated that, in the US, approximately 50 BOF furnaces and 260 EAF furnaces are used to produce the 100 million tons of steel that are manufactured each year. For calculation purposes, one BOF unit was considered to produce as much steel as 5 EAF units, yielding an "equivalent" number of total operating units of 102 (50 BOFs and 52 EAF "equivalent BOFs"). Assuming an 80% market penetration and a 2% adoption rate per year, the total equivalent energy savings was calculated to be 11.06 Trillion Btu's per year by the year 2025.

Environmental – The environmental benefits of the project fall into two categories – those calculated through GPRA based on the natural gas savings value of an equivalent Number of BTUs and the benefits gained through improved environmental practices. Based on the projected savings through GPRA of 10.77 billion cu feet of natural gas per year in 2025 the project is projected to reduce CO_2 emissions by approximately 657,000 tons per year.

Beyond this, the fact that slag skulls do not adhere to Al-Bronze in a manner similar to carbon steel allows the furnace operator to insure that the skirt is properly positioned for maximum containment and capture of all the effluents generated each heat of steel and avoids uncontrolled combustion in the hood system which causes the environmental control equipment to operate in a regime that does not allow for efficient contaminant removal. The scope of this project did not allow for a detailed examination of this situation and as a result detailed estimates of emission reductions are not possible.

Productivity – During the past year that N vessel was performing as the primary vessel, the lack of needed maintenance as a result of the performance of the skirt and flux chute allowed REP to increase their production in the BOF units to 21 heats per week from a previous 18 per week. REP valued this increase in production at over $11,000,000 per year. The GPRA estimates indicate a total economic benefit in 2025 of $241,000,000.

Governor's Award – In recognition of this project at REP, EIO and REP were awarded the 2006 Governor's Award for Excellence in Energy in a ceremony at the Ohio Statehouse on November 15, 2006. This award recognizes outstanding achievements in energy efficiency by organizations throughout the state of Ohio. Of the six award recipients in 2006, the Energy Industries of Ohio / Republic Engineered Products project was the only recipient in the industrial category.

Patents:	No applications have been made.
Publications and Presentations:	Presentation at the Ohio Steel Council – Scheduled Jan. 2007 Presentation at AISI BOF Committee – Requested for Feb. 2007 Invited Presentation at AISTech Conference in Indianapolis, IN – May, 2007 Technology Launch – Planned for June, 2007

Appendices

Company Visited: AK Steel Corporation.
1801 Crawford St.
Middletown, OH 45043-0001

Author: E.S. Robitz

Date: February 19, 2004

Contact: Stephen E. Palmer, Engineering Manager
Phone: (513) 425-3195
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Trip Report:

Overview:

The author visited with Mr. Stephen Palmer at his office on-site at the mill. Mr. Palmer has 15+ years of experience in steel making. Mr. Palmer also has a long history of involvement in hood-related issues, in fact, he sits on the AISE sub-committee for hood design, operation, and performance. Thus, his knowledge and willingness to be helpful were extremely valuable and are much appreciated.

Mr. Palmer gave a brief introduction to the mill. The history and background on the two BOF units currently in service were discussed. Mr. Palmer provided handouts with sketches depicting the hood design and gas flow path. He also briefly discussed his successful water treatment program, and recent attempts to weld overlay cold side regions of the lower hood and skirt to avoid external corrosion. Also discussed were hot side weld overlays that recently have been installed to minimize the effects of erosion at strategic locations within the hood.

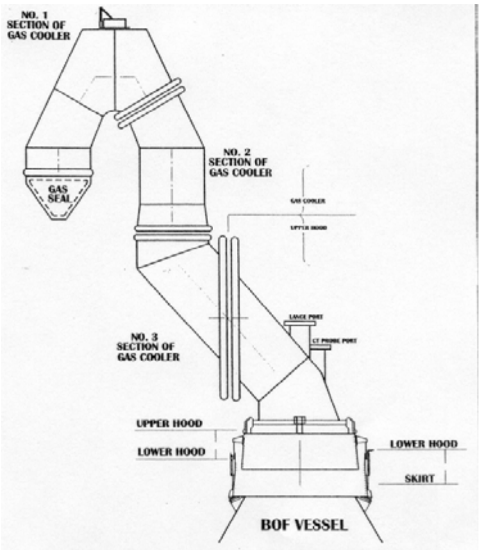
When discussions in the office were completed, Mr. Palmer accompanied the author to the Maintenance Department for further discussions with Mr. Kent Perdue, Section Manager, and with Mr. Paul Schoenberger, Maintenance Planner. Discussions here focused on the maintenance history of the BOF hoods, and future approaches to further extend hood life. A record of hood service life data also was provided as a handout.

When Maintenance Department discussions were completed, Mr. Schoenberger led the author on a tour that included a cursory examination of one of the hoods from bottom to top. He also accompanied the author to the yard to examine spare BOF hood sections and a few components that recently had been scrapped. Mr. Palmer joined us in the yard and offered to cut and ship samples for analysis of damage regions of the hood. In particular, one location on a scrapped skirt was identified as having suffered from the cold side corrosion that led to the need for a protective (cold side) weld overlay. No samples were available from the high-wear regions that caused the need for a protective hot side weld overlay. The visit concluded in Mr. Palmer's office where he provided the author with a metallurgical sample that the mill had prepared to characterize the cold side corrosion issue mentioned above.

History & Design:

- AK Steel Middletown has employed the basic oxygen process in steel making since 1969. Two 225 ton BOF units were installed at that time. These are designated as the No. 15 and No. 16 vessels. Today these units together are producing approximately 1,000 heats per month.

- Chemico designed and built the original hood systems for both furnaces, see figure below. Note that gas flows upward out of the BOF vessel, through the lower and upper hood then into a portion of the hood system that AK steel terms the "gas cooler". The gas continues upward until it reaches the top of Section 1 of the cooler where it is redirected downward and out into the gas cleaning system. After cleaning it is exhausted through a stack to the ambient environment.



- The original design involved a plate-type heat exchanger in the lower and upper hood sections. A tube-bar-tube construction was used in the "gas cooler" section of the hood. In this region the tube axes were parallel to the gas flow direction.

- In the early 80's, lower and upper hood sections were redesigned by Nagati Inc. Redesign was undertaken because of downtime associated with increased repair frequencies for the plate-type design. The Nagati design utilized tube-bar-tube construction, with tubes running in the flow direction for the upper hood and in a circumferential direction in the lower hood and skirt. This circumferential tube orientation was thus perpendicular to the gas flow direction.

- The current hood design was finalized in 1995 when modifications were made to reorient the tubes in the lower hood and skirt such that their axes were parallel to the flow direction.
- It should be noted that the original Chemico design has been maintained for the gas cooler section of the hood. So, the hood in use today is a hybrid between the Nagati and Chemico designs.

Maintenance:

- As one might anticipate, AK Steel has determined that the hood component life expectancy increases as one progresses in the direction of gas flow through the hood system and away from the mouth of the furnace. AK Steel has set target values for each component of the system, and recently has had good success in exceeding them. As a point of reference, the service life of the lower hood and skirt typically exceed 3 years. Other components in the system typically last longer.

- AK Steel only has one scheduled maintenance outage per year. Their plan is to continue in production until a problem is noted and then to address it if necessary. Otherwise they would plan to do a thorough inspection, including ultrasonic wall thickness measurements, during their annual outage. If refurbishment is indicated they can do a repair in situ. However, they might also remove the hood section of concern and replace it with a spare and/or refurbished hood section that they keep in covered storage in the yard. They noted that it takes about one week to replace a hood with its' spare.

- The above is not meant to imply that AK Steel does not have an on-going maintenance plan. Planned maintenance would included visual inspection three times per week, thermography (to look for hot spots indicative of a lack of flow) twice per month, and cleaning the skirt seal every five weeks.

- It should be noted that the maintenance techniques used to clean the hood interior has led to one of their current tube damage problems. AK Steel employs a Gradall equipped with a pneumatic chipping tool to remove built-up skull from the internal surfaces of the hood. This tool occasionally leads to mechanical damage that must be repaired.

Water Treatment:

- At some point, in the mid-90's, it became apparent that the hoods were experiencing damage due to poor control of the cleanliness and quality of the water used to cool these units. The original Chemico design employed an "open" cooling water system that allowed foreign matter to be entrained in the system and deposited on the heat transfer surfaces within the hood. These internal deposits insulated regions of the tubes and led to hot spots that ultimate led to tube failures and the need for repair.

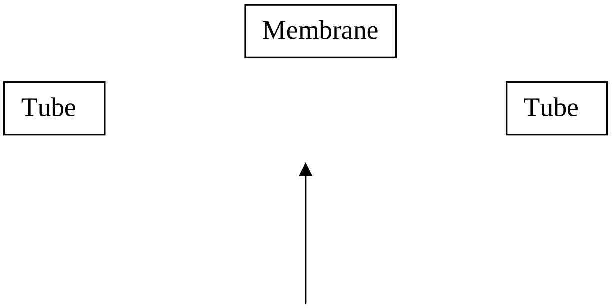
- When it became apparent that the water condition was reducing the life of these units, the mill undertook to work with Betz to design and install a "closed" system that does not allow for ingress of foreign matter. The redesigned system also controlled water flow rates in critical regions of the hood to ensure that boiling did not occur. This further ensured that the tubes would not overheat and thus prolonged their life.

- These water system modifications have led to the much improved life expectancy for hoods in service today. Now, the only water-related problems that AK Steel reports are due to an occasional metering nozzle plug up that would restrict the inflow of outside make-up water.

Weld Overlay Repairs:

- With the water treatment problem solved, AK Steel has turned their attention to other problem areas to further improve on the life expectancy of hood components. One area of particular concern is associated with the water trough-type configuration that allows the lower hood and skirt to seal to one another.

- The design of this seal region is such that some of the particulate matter that is expelled from the vessel becomes trapped and builds up in a relatively inaccessible region. This region, being continuously wet, gives rise to particularly corrosive conditions that cause the cold side of the skirt and lower hood to suffer from corrosion. The figure below shows a cross section through two adjacent tubes separated by a membrane. Inspection of this figure reveals that corrosion has affected both tubes. In fact, it has progressed through wall in one of them. The point of attack appears to be at the weld that is used to attach the tubes to the membrane. It should be noted that in this region, and throughout the hood, the tubes are seamless carbon steel boiler tubes that comply with ASTM A 192, Thus they are particularly susceptible to this form of corrosive attack.



- To address this problem, AK Steel has employed Monroe Inc. to protect these regions by cladding them with the very corrosion-resistant Inconel 625 weld metal. AK Steel does not have enough experience with this solution to be able to calculate an increase in life expectancy due to the cladding operation.

- AK Steel also has attempted to address an erosion problem that they have been experiencing in high-wear regions of the hood internals. Of particular concern was erosion near the “ #1 relief door “ that is located at the highest point in the gas cooler system. The solution once again was to clad these with Inconel 625 weld metal. AK Steel does not have sufficient experience to be able to calculate life expectancy improvements associated with this fix.

Solutions:

- Throughout the visit it was apparent that AK Steel has been employing a methodical and progressive approach toward continually improving the life of these hoods. Improvements began long ago with changes to the design of the hood system, and continued with improvements to water quality, and now finally, to employing weld cladding to impart corrosion and erosion resistance to critical regions of the hood.

- AK Steel indicated that they feel that it is very important to address water quality and water flow rate issues before attempting to address other issues. With this under control, then, one can focus on addressing environment, operating conditions and materials issues that affect hood life.

- AK Steel expressed an interest in considering other materials and design configurations that would further extend life, however, they also emphasized the need for good data based on service to minimize the risks associated with employing new alternatives. As an aside, discussions with other steel mills (and their reports of good success) led AK Steel to being willing to use the Inconel 625 cladding solution described above.

Summary:

1. The BOF hoods in service at the AK Steel Middletown plant, over the years, have gone through design iterations and changes to their operating and maintenance procedures that have led today to the good service life expectancies.

2. Nonetheless, AK Steel is continuing in their efforts to make further improvements in this regard.

3. AK Steel expressed the need for a matrix of solutions depending on the problem at hand. Such solutions might include alternative tube or cladding materials that address a specific need.

4. AK Steel indicated that ideally these “solutions” would be proven in service before they are broadly adopted.

Company Visited: ISG Cleveland, Inc.
3060 Eggers Avenue
Cleveland, OH 44105

Author: E.S. Robitz

Date: February 17, 2003

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Trip Report:

Overview:

The author visited with Mr. Jerry Lack at his work site within the mill. Mr. Lack has 25+ years of experience in steel making. Thus, his knowledge and willingness to be helpful were extremely valuable and are much appreciated.

Mr. Lack gave a brief introduction to the mill that included some background on the two BOF hoods currently in service. He then provided a guided tour that included an examination of one of the hoods from bottom to top. The hood design and operation were explained, then, Mr. Lack accompanied the author to the yard to examine BOF hoods that had been scrapped in the late 1990's. Lastly, Mr. Lack provided in-house drawings and sketches of the hood design.

History:

- There are two BOF furnaces in operation at ISG Cleveland. These are designated as Vessel No.1 and Vessel No. 2. Each furnace typically produces about17 heats per day, for a total of 32 to 34 heats per day.
- The original hood systems for both furnaces were built by American Air Filter (AAF) as a turn-key operation. ISG has been very happy with these uniquely designed hoods - for reasons that will become apparent later.
- The hood is comprised of a lower and upper system. The lower system has two sections (upper and lower) and a moveable skirt. The upper system (or "steaming hood") also has two sections (upper and lower). The units that currently are in service were installed on Vessel No. 1 in 1977, and on Vessel No.2 in 1976.
- The lower section of the lower hood system for both vessels was replaced in the late 1970's or early 1980's. When these replacement systems were installed, two additional lower hood systems (i.e. both lower and upper sections) were bought to be used as spares. One of these lower sections was used as a replacement on Vessel No. 1, then another spare was purchased.
- In 1999, both sections of the lower hood and the skirt were replaced on Vessel No. 2 using existing spares. ISG experimented on these sections using a nickel alloy weld overlay offered by Welding Services Inc. The experiment was not successful in the lower section of the lower hood, but was successful in the upper section.
- In 2000, both sections of the lower hood and the skirt were replaced on Vessel No. 1. These also were replaced from existing spares.

- Based on their history, and taking into consideration the mill's production and maintenances practices and costs, the mill's life expectancy for the lower hood sections of these units is a little over 20 years. It should be pointed out however, that Mr. Lack indicated that, after 15 to 18 years, ISG began having to perform emergency unscheduled maintenance on these hoods. The implications of these emergency repairs are that they are sufficiently severe that repair could not be delayed until the scheduled 3-week maintenance outage. Thus, the unit had to be shut down, and production time was lost. Normally, 12 hour outages are scheduled once every three weeks. This allows maintenance personnel to repair hood leaks concurrently with routine cleaning of the wet scrubbing system.
- It should be noted that it was only "a matter of weeks" before the first leaks were noted in the replacement hoods (i.e. the spare hoods). These typically were small leaks that were discovered and repaired during scheduled maintenance.
- In general, these are repaired using a weld pad build-up over a relatively small leakage hole. The weld build-up approach was used rather than to repair by removing sections and patching. It is understood that sections are only removed when the furnace is down for relining. Relining is scheduled once per vessel every 36 to 48 months.
- Mr. Lack provided an example from ISG's maintenance records to demonstrate their typical repair history. The ISG Cleveland Works had been off-line for some time but restarted operations in July 2002. The table below provides their repair records from July 2002 through February 2003.

Hood	Dates for Lower Hood Repairs	Dates for Upper Hood Repairs
1	10/16, 11/20, 1/6	---
2	9/23, 10/9, 12/9, 2/4	12/27, 1/8

- It should be noted that ISG monitors the temperature of the hood at various locations. They also monitor, at the outlet duct of the wet scrubbing system, the gas composition for the following constituents: oxygen, carbon dioxide, carbon monoxide and hydrogen. A shut-down alarm is sounded when a threshold high hydrogen level is reached because this reading is indicative of a significant leak in the hood. The leaks addressed in the table above were small enough that immediate shut down was not required.
- ISG believes that erosion is the most likely cause for the leaks that occurred over the service life of these hoods. However, they indicated thermal fatigue may have occurred in some instances. A cursory visual examination by the author of the scrapped hoods appeared to support the assumption that erosion was the major problem. However, a more detailed examination might indicate other contributing causes.
- Periodic repair of leaks is part of the planned maintenance for these units. ISG can live with small leaks for a short period of time. Ideally, these only would be repaired during scheduled maintenance, and not interrupt production.
- The maintenance history shows that, early in the life of the hoods, it was possible to repair them during the regularly scheduled hood internal cleaning outages that occur approximately every 3 weeks. The cleaning operation is unavoidable, so, since the cleaning and repairs are concurrent, little production time is lost associated with hood repair.
- As the hoods age, the frequency and severity of repairs increases. Ultimately this results in forced outages that are required to repair objectionably large leaks. Unfortunately, as the hood ages, these forced outages may no longer coincide with the 3 week maintenance interval. These outages, of course, are costly in terms of lost production time, and as costs mount, ultimately they lead to the need for hood replacement.
- As mentioned earlier, Welding Services, Inc. (WSI) convinced the ISG that the use of a nickel alloy weld overlay would extend the life of their hoods. The author believes this to be the Inconel

625 overlay that WSI has used at other sites (USS-Edgar Thompson Works and Weirton Steel-Weirton Works). Sections of the nickel alloy-clad hoods are currently stored on-site in the scrap area of the mill. Mr. Lack offered to cut sections from these for examination by the project. This would provide valuable information, confirming the failure mechanism(s), and perhaps giving guidance toward a solution.

Design:

- The AAF hood design involves a lower and an upper system. The lower system is a parallel plate heat exchanger. The upper system employs a tube-membrane-tube design.
- The lower system sits immediately above the BOF vessel, and is separated from it by an adjustable water cooled skirt (1600 gal/min.). The skirt can be positioned upwards and downwards to control the level of combustion within the furnace.
- The upper system of the hood (the upper section is also known as the "steaming hood") receives process exhaust gases from the lower section and directs the gases through an approximately 60 degree bend, first upwards then downwards, to the point where the gases are fed into a wet scrubber. The scrubber is used to remove particulates and other objectionable constituents from the gas stream. The gases then proceed through the remainder of system, then ultimately up the stack to the environment.
- The lower system of the hood is comprised of an upper and lower section (and a skirt). These are cooled by a high volume of water flow from continuous running pumps. Water, at 3900 gal/min., is used to cool the lower part of the lower hood. 3300 gal/min. are required to cool the upper part of the lower hood. Both sections are bottom fed with boiler feed quality water. A pump is used to start flow, then, natural circulation takes over. The water inlet temperature for the lower section is about 90 F. The outlet temperature for the lower section is 140 F.
- A closed loop system provides for water circulation to the upper "steaming hood" section of the hood. At the outlet, the temperature is 400 F at a pressure of 450 psi. The flow is through a steam drum which sits above the hood, then back through the system. Betz also provides water control for this system.
- The centerline of the lower section of the lower system of the hood coincides with the centerline of the BOF vessel. So, when it is in position, hot exhaust gases are able to flow directly upward through this region which experiences the highest service temperature, estimated to be about 3000 F. The centerline for the upper part of the lower hood is offset from that of the lower part by about 30 degrees. These taken together cause the lower hood to take on the shape of an elbow. The lower hood is roughly 15 ft. in diameter at its' inlet, and 11 ft. in diameter at its' outlet. Its' maximum height is about 13 ft.
- The elbow design implies that an upward moving process gas will impinge on the upper part of the lower hood at the point where the change in direction occurs. This is, in fact, one of the areas that experience a high degree of wear resulting in leaks that must be repaired.
- It should be pointed out that the AAF-supplied hoods in service at ISG are unique in that the lower system of the hood is essentially a parallel plate heat exchanger. It has concentric inner and outer plate walls, and channeling between them that directs the water flow to follow a helical path from bottom to top. The spacing between the inner and outer wall is about 3-1/2 inch. These are held in place by spring loaded stay bolts.
- The lower hood plate thickness is ½ inch. The original plate material was SA 515 gr. 70. The replacement plate material is SA 387, gr.11.
- The centerline of the first section of the upper "steaming" hood coincides with that of the top part of the lower hood. Thus, this steaming hood section is canted at 60 degrees relative to level. The total length of this section is about 55 ft. long. Considering the angle, this brings its' elevation above the lower hood to about 48 ft. At this point it connects to the second section of the steaming hood which directs steam flow downward. This change in direction within the steaming

hood provides another area of impingement; however, the degree of wear in this location is much reduced relative to that in the lower section of the hood.

- Both steaming hood sections are of membrane tube construction. The tubes are nominally 3-1/8 inch diameter by 0.200 inch wall. These are separated by ¼ inch membranes. The tube material is SA 178, gr A

Summary:

1. ISG uses a unique AAF-designed BOF hood that they feel has served them well. They favor this design to the extent that they recently installed replacement components to the same design even though they are knowledgeable and aware of other options.
2. ISG particularly likes the reliability and ease of maintenance that they associate with the parallel plate construction in the lower sections of their hoods. This is a critical area that is the focus of most maintenance repairs for these units.
3. The hoods were installed in the mid-1970's and served well for approximately 15 to 18 years. At that point, ISG was experiencing an increasing number of repairs. This led them to attempt to increase the life of the hoods by using an Inconel weld overlay approach proposed by WSI. This overlay was attempted in situ by WSI.
4. Overlay techniques were successful in extending the life of the upper section of the lower hood system for Vessel No.1.
5. Overlay techniques were also successful for extending the life of the upper section of the lower hood system for Vessel No. 2. The lower section of this hood also was coated but the overlay did not extend the life of this region of the hood.
6. ISG is willing to cut sections from their scrap hoods for the project to examine. The results of this examination could confirm the damage mechanism, and perhaps indicate a way to mitigate it. This thus would benefit both ISG and the project. This sampling will be arranged in the near future.

Company Visited: North Star BHP Steel Ltd
6767 County Road 9
Delta, Ohio 43515

Author: E.S. Robitz

Date: February 20, 2004

Contact: Paul Soltis, Melt Shop Mechanical Team Leader
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Trip Report:

Overview:

The author visited with Mr. Paul Soltis at his office on-site at the mill. Mr. Soltis has many years of experience in both EAF and BOF steel making operations. Thus, his knowledge and willingness to be helpful were extremely valuable and are much appreciated.

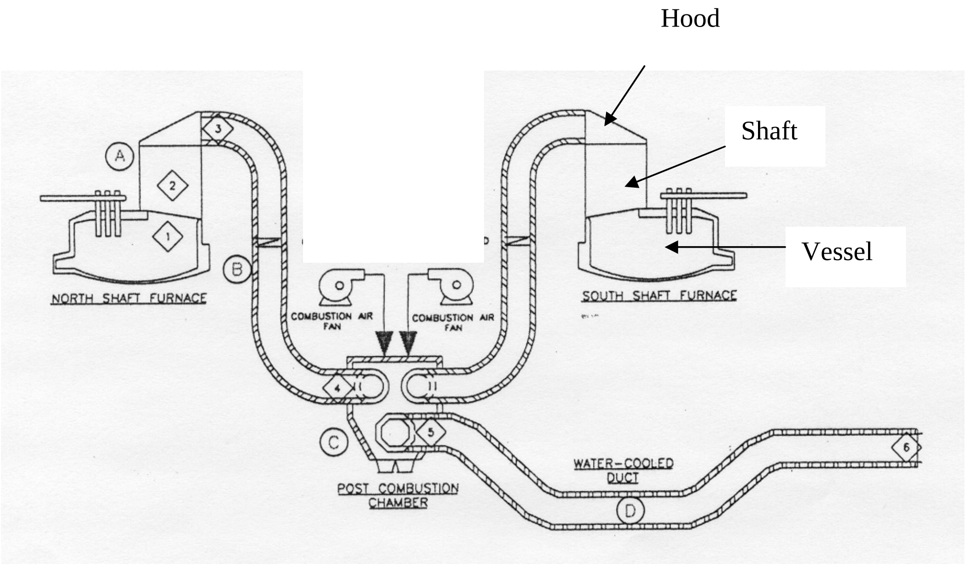
Mr. Soltis gave a brief introduction to this relatively new mini-mill which had been in operation for less than eight years. The mill employs two electric arc furnaces of identical design and manufacture. These furnaces both have hood exhaust systems that are used to contain and direct expelled gases and particulates through a system that ends in a bag house. Mr. Soltis described the design of the system and problems that North Star has experienced. This led to a brief discussion of some of the solutions that were being pursued by the EIO-led effort to address hood-related problems. Finally, Mr. Soltis provided a brief tour of the mill including the EAF shop floor.

History, Design & Maintenance:

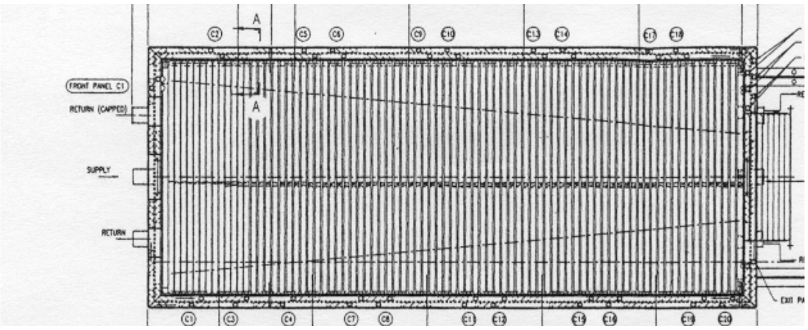
- North Star BHP has been in operation at the Delta, Ohio site since late 1996. The two EAF units in operation there together produce more than thirty 195 tons of liquid steel per day.
- The EAF vessel shell is approximately 25-feet in diameter. Cooling panels cover the roof and surround the perimeter of the shell. Three electrodes penetrate the roof of the vessel. The shell walls have penetrations for burners and oxygen jets. The shell sits on a rocker that allows it to be tilted to tap a heat and to drain off slag.
- Mr. Soltis indicated that cracking of the water-cooled plate material used to make up the structure of the roof and hood is one of his more significant problems. He also indicated a problem with arcing of copper tubing that is used to cool the roof panels.
- The EAF system design is unique in that it employs a water-cooled shaft that sits between the hood and the roof of the vessel. Thus the hood is somewhat separated from the more intense heat and erosion that it would experience if it were closer to the roof of the vessel.
- When the vessel is charged with the scrap that is used as make-up material for a heat, the hood is moved aside and the scrap is poured into the shaft. The shaft acts as a chute that directs the scrap into the body of the vessel.
- Mr. Soltis reported that, with time, movement of scrap through the shaft wears away at the wall thickness of the schedule 160 carbon steel tubing that comprises the walls in this region. This

wearing action is further exacerbated by erosion and heat flux issues as particulates and hot gases that are expelled up through the shaft when a heat of steel is produced.

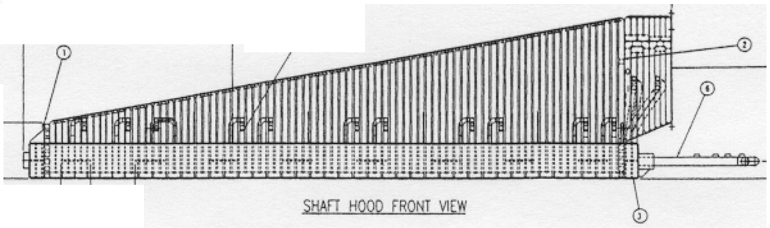
- Mr.Soltis indicated that shafts tend to require replacement due to excessive pipe leaks and warpage. This seems to imply that additional service life might be attained if a more wear-resistant material could be used in this area.
- It should also be noted that Mr. Soltis indicated that shaft tubing is also susceptible to a circumferential cracking phenomenon that progresses inward from the external hot side tube surface. While this hasn't been investigated fully, this cracking evidence suggests that tubes within the shaft experiencing thermal fatigue damage as well as the above mentioned erosion. Mr. Soltis indicated that these cracks are repaired using a carbon steel weld overlay (E7018).
- The figure below provides a schematic that depicts the two EAF units, their hoods and associated ductwork.



- The hood systems were designed by Fuchs / Voest-Alpine. These relatively large structures present a rectangular cross section (roughly 28-ft by 10-ft) to upward moving process gases and particulates.
- The hoods employ a water-cooled tubular structure manufactured from 2-1/2-inch diameter, Schedule 80, ASTM A106 pipe.
- <u>Both systems have been replaced twice</u> during the 7-1/2 years that the mill has been in operation. Mr. Soltis indicated that erosion leading to excessive leakage is the main reason that hoods need to be replaced. They maintain a spare hood on-site should this be required on short notice. It takes about six hours to change out a hood. The current system has been in operation since June 2003.
- The replacement units are "built-to-print" to the original design by a subcontractor. The figure below provides an indication of their configuration.



PLAN VIEW



SHAFT HOOD FRONT VIEW

- The mill used a “closed” loop water system for cooling the EAF system. City water is use for make-up. At some point it became apparent that the water used for cooling these units had an unacceptably high hardness. This became evident through a build-up of calcium on the tubing internals. In response to this problem the mill enhanced the treatment of the cooling water, and since then have had no water-related problems.
- Mr. Soltis indicated that they plan on installing an aluminum bronze “wedge style duct section” into the ducting system. He indicated that this component is expensive but relatively easy to replace. The mill historically has needed to replace this section of the ductwork about every six months, and that use of aluminum bonze is an experiment to see if the life here can be extended.
- The author mentioned that the program is in the process of evaluating the performance of an aluminum bronze skirt for a BOF hood application.

Summary:

1. The EAF system design at this North Star BHP mill is somewhat unique in that it employs a shaft to direct scrap steel into the shell. The shaft is suffering from damage due to a variety of mechanisms including: 1) wear due to movement of scrap down the shaft, 2) erosion due to upward moving gases and particulates, 3) thermal fatigue and warpage due to the high heat flux in this region. Further study would be required to recommend modifications that would increase the service life of this region. However, use of a more wear-resistant material might provide an immediate benefit in addressing the wear and erosion problems listed above.

It is speculated that improvements to the water cooling system may improve the resistance of the shaft materials to thermal fatigue. This would include both control of the water chemistry and flow rate. Further study would be required to substantiate this.

2. Further study would be required to better understand damage mechanisms on-going in the shell and roof of the vessel and in the hood. However, a cursory review suggests that the hood life expectancy might also be increased if a more wear resistant material (or cladding) were to be used in high-wear regions.

3. The mill is currently planning on experimenting with using an aluminum bronze component in their duct work.

Company Visited: Republic Engineered Products
1807 East 28th Street
Lorain, OH 44055-1883

Author: E.S. Robitz

Date: September 21, 2004

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Trip Report:

Overview:

The author was accompanied by Larry Boyd on a visit to Republic Engineered Products on September 21, 2004. Mr. Boyd works for Energy Industries of Ohio (EIO) and is the program manager on the BOF Hood Improvement project. The purpose of this visit to Republic was to discuss the design, operation, and maintenance of hoods for the two BOP units in service at their facility in Lorain, OH. Also, Republic had recently taken delivery on, and was preparing to install, a novel aluminum bronze hood skirt that was partially funded by EIO. Information gained in this visit was intended to provide a baseline reference to judge the relative benefit of this new skirt design. It also would be used to provide guidance for future hood improvement efforts.

Mr. Hagan was the primary Republic contact for this meeting. He assembled a team of individuals who were knowledgeable across the full range of relevant topics. Messrs Vogt and Buckley were present throughout the meeting. Also present were Mr. Dennis Proy, Maintenance Manager, and Mr. Ray Muharsky, Department Manager BOP. This team-approach permitted relevant topics to be quickly and clearly addressed. Republic also had gathered, in advance of the meeting, background information that was very helpful in understanding hood-related topics.

Mr. Hagan gave a brief introduction and described the operation of the two BOP vessels employed at the Lorain facility. These are termed the “L” and the “N” vessel. The “L” vessel is currently the only one in operation. It produces approximately 20 heats per day. Each heat represents approximately 220 short tons of steel. The aluminum bronze skirt is scheduled to be installed on the “N” vessel in late September and will begin operation at a rate of approximately 3 heats per day. If all goes well, the “N” vessel will be scheduled for 20 heats per day when the “L” vessel is taken down for maintenance , sometime in October. It is intended that the “N” vessel will continue to produce 20 heats per day until the “L” vessel can come back on line at that point. The “N” vessel will again run at a rate of 3 heats per day, while the

"L" vessel is returned to the full 20 heat per day production rate. This will bring the total production rate to approximately 23 heats per day.

After this introduction, Mr. Hagan went on to describe the design of the hood system using schematics. These schematics were included in a package, provided by Mr. Buckley, which also describes the maintenance and repair history for both the "L" and the "N" vessels. These packages are attached as appendices.

Mr. Hagan needed to depart the meeting due to an earlier commitment. At that point, the Republic team field questions for the remainder of the meeting. Republic suggested that we should schedule a follow-on visit to tour their facility after the "N" vessel was in operation with the aluminum-bronze skirt installed.

Hood Design Overview:

- Attachment 1 provides a schematic of the hood design. The lower hood is comprised of three sections and a skirt. Section 2 is a primarily a straight section having a canted end at the point where it intersects with Section 1. Section 2 is located immediately above the vessel. At this location, it also is adjacent to the skirt which can be raised or lowered to control combustion. Section 1 is next in the flow path for expelled gases and particulates, followed by Section 3.
- It is understood that, for most of its' length, the centerline for Section 2 is roughly parallel to the centerline for the vessel. From the schematic in Attachment 1, it can be seen that the centerlines for Sections 1 and 3 coincide, but are offset from that of Section 2 by approximately 30^o. Given this configuration, upwards moving gases and particulates would rise directly through Section 2, then be diverted to the side and upward by Section 1. This creates a situation where particulates can impact and erode the Sections 1 and 3 as they rise upward out of the vessel.
- The rising gases change direction once again at the point where Section 3 connects to the shaft section of the upper hood. This shaft is offset approximately 30^o in the opposite direction to allow gases and particulates to continue their flow directly upward. This change in direction provides another impact and erosion area.
- Examination of the schematic reveals other similar areas that may be susceptible to erosion as the gases change direction as they are being directed out of the hood and onward for further processing. It should be noted however that, the gases and particulates cool as they rise, and to some extent they loose momentum. So, as the gases progress downstream erosion becomes less of a problem.
- While it is not clear from the schematic, the hood is primarily of a tube-membrane-tube construction, with the axis of the tube oriented parallel to the flow direction for gases through the hood. This tube orientation helps to somewhat lessen the level of erosion for the both the lower and upper hood sections. However, it also should be noted that the skirt has tubes in a circumferential orientation, which would perhaps magnify any erosion problems in this area.
- Carbon steel tubes are used in constructing hood components. These generally are 1-inch I.D. by either 0.220-in. or 0.185-in. wall.

Cooling Water:

- Republic indicated that the current skirt design requires approximately 1,000 gal/min. of cooling water flow. Betz provides treatment (corrosion inhibition and pH) to the make-up water that is taken from the river and fed to the skirt. This source of water is not "closed", and in the past, Republic has had problems with internal tube sludging due to contamination from external sources.
- Republic indicated that they need to verify the flow rate required for their new aluminum-bronze skirt. They indicated that the system is able to deliver water at a flow rate of approximately 1,500

gal / min. It is believed, but needs to be confirmed, that AmeriFab recommends a flow rate of 1,300 gal / min.

- It is understood that the remainder of the hood (from Section 2 and beyond) is cooled by water that flows through the system at roughly 250 psi. This water is recirculated through a closed system that includes a heat exchanger. It is softened, treated, and inhibited.

Maintenance History:

- Appendix 2 provides a replacement history (through 1999) for each separate section of the hoods for both the “L” and “N” vessels, including the skirt. Also provided in these tables are the number of heats manufactured between replacements. From this it can be seen that during the period 1989 through 1998, the skirt on the “L” vessel was changed out six times, and the skirt on the “N” vessel was change out five times.
- For the “L” vessel, the number of heats between skirt replacements ranged from 2,738 to 14,330. For the “N” vessel, the number of heats between skirt replacements ranged from 3,450 to 8,998. It is difficult to know what can be inferred from this except that skirt life (and that of other hood components) was relatively short. Republic stated that, for a skirt, a two-year life is good, and a three-year life is great.
- Appendices 3 and 4 provide maps of each section of both hoods showing their replacement and repair histories.
- Republic considers that two factors are the primary causes of short hood component life, erosion and corrosion. Erosion was alluded to above, and inherent in the hood design. While some level of corrosion is also to be anticipated, it should be recognized that Republic uses these vessels to manufacture re-sulfurized steel. This involves adding sulfur-bearing compounds to the vessel as the heat is being produced. The net results is that the expelled gases are high in sulfur which is an aggressive corrodant, both at high and low temperatures.
- To address both of these problems, Republic has undertaken a program where the internal surfaces of hood are overlayed with a corrosion-resistant weld cladding of Inconel 625. This cladding was applied by Welding Services, Inc. Republic noted that this same cladding had been reported to have good results at the Edgar Thompson Steel Works in Pennsylvania.
- It should be noted that the weld overlay protective barrier has been applied in a progressive approach, starting in the lower hood sections and extending upward into the shaft. Appendices 3 and 4 provide maps of weld overlay and panel replacement for both hoods. For the “L” vessel hood, by August 2004, overlay had been applied to Sections 2, 1 and 3 and approximately 40% of the shaft. Republic anticipates that eventually cladding will be applied all the way to the relief section at the point where gases are directed downward.
- It should be noted that Republic does not clad skirts and has no plans to do so in the future. These generally are considered a “consumable” component of the system.
- Republic indicated that they have a scheduled outage approximately every five weeks. This outage is based on the need to re-line the vessel every 3,000 to 4,000 heats. It takes between 12 to 18 hours. During this time, they perform any weld repairs that are needed.
- Republic schedules an annual outage which takes approximately seven to ten days. Major repairs and refurbishment are undertaken during the annual outage. Republic indicated that it takes approximately four days to change out the lower hood and that all three sections typically are changed out together.
- Republic indicated that they perform ultrasonic test (UT) thickness measurements to decide whether repair or replacement is necessary. In many cases, they will either repair using a weld pad build-up, or replace individual tubes if necessary. Republic indicated that the main purpose of these is to prevent tube leakage, and that only a “pop can” metal thickness is required.

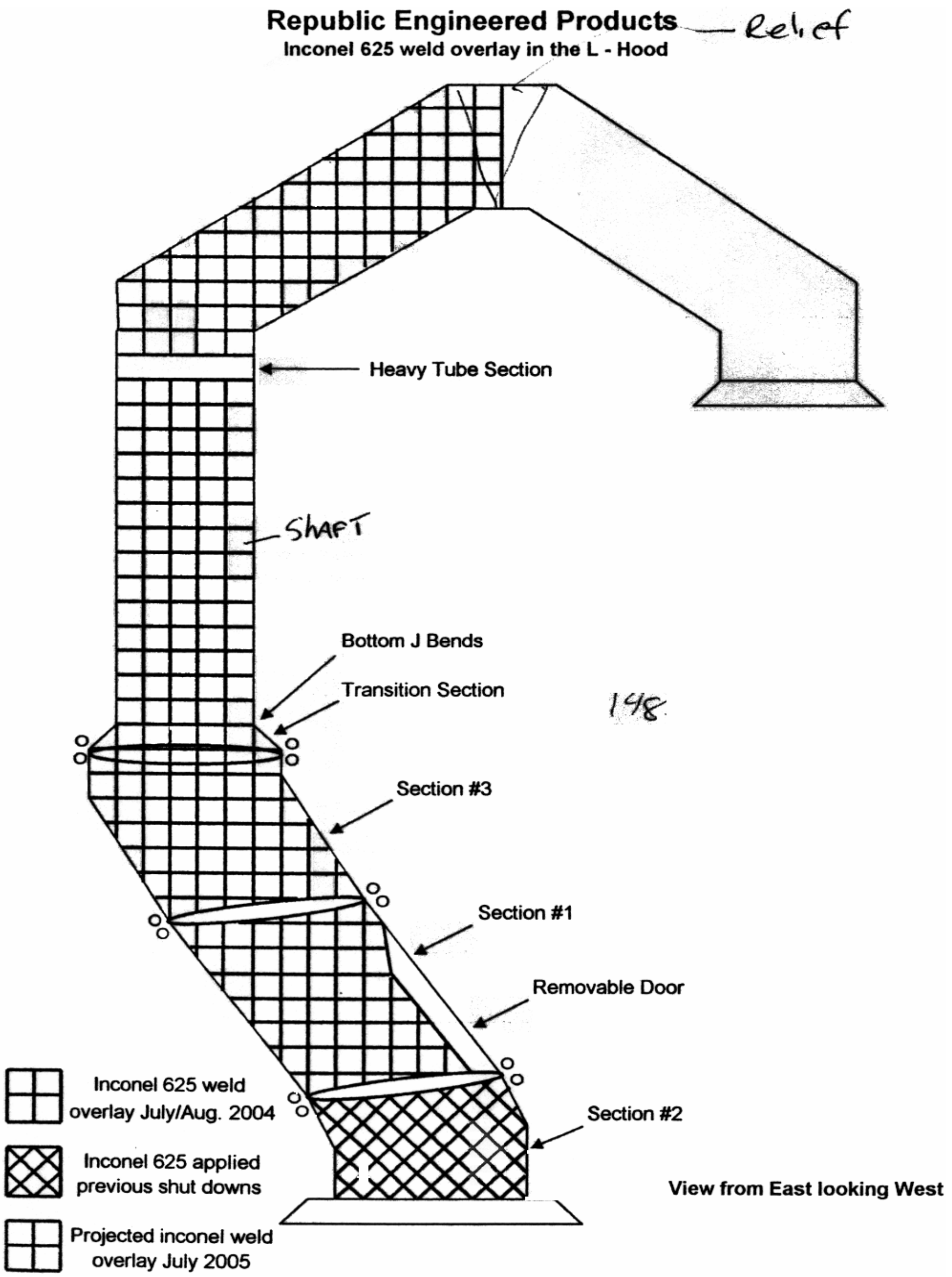
- For the record, Republic indicated that recent UT thickness measurements showed only minimal losses (if any) in weld overlayed areas of the hood. Results such as this have given impetus to their intentions to further extend this approach to ameliorate corrosion of hood internals.
- The major problem encountered with the overlayed areas is that they are subject to corrosion on the external surfaces of the hood, requiring the removal of both the overlayed surface once the external surface fails. They now are starting to consider how best to address corrosion on the external surfaces of the hood which also are undergoing corrosion due to the presence of sulfur in the environment (albeit at a lower temperature).
- Republic indicated that they have received, from AmeriFab, a written procedure for weld repair (SMAW and GMAW) of their new aluminum-bronze skirt. They indicated that have bought appropriate welding hoods and that their welders have received instruction from an AmeriFab representative.
- Republic reported that they have an outside vendor (MPW) perform chemical cleaning from time-to-time on these units. They stated that the “N” vessel hood “leaked everywhere” when an acid cleaning was applied in July 2004. It is understood that these leaks have been repaired and that the “N” vessel hood is ready for service on October 5th when this unit will be used while the “L” vessel is being refurbished.

Summary:

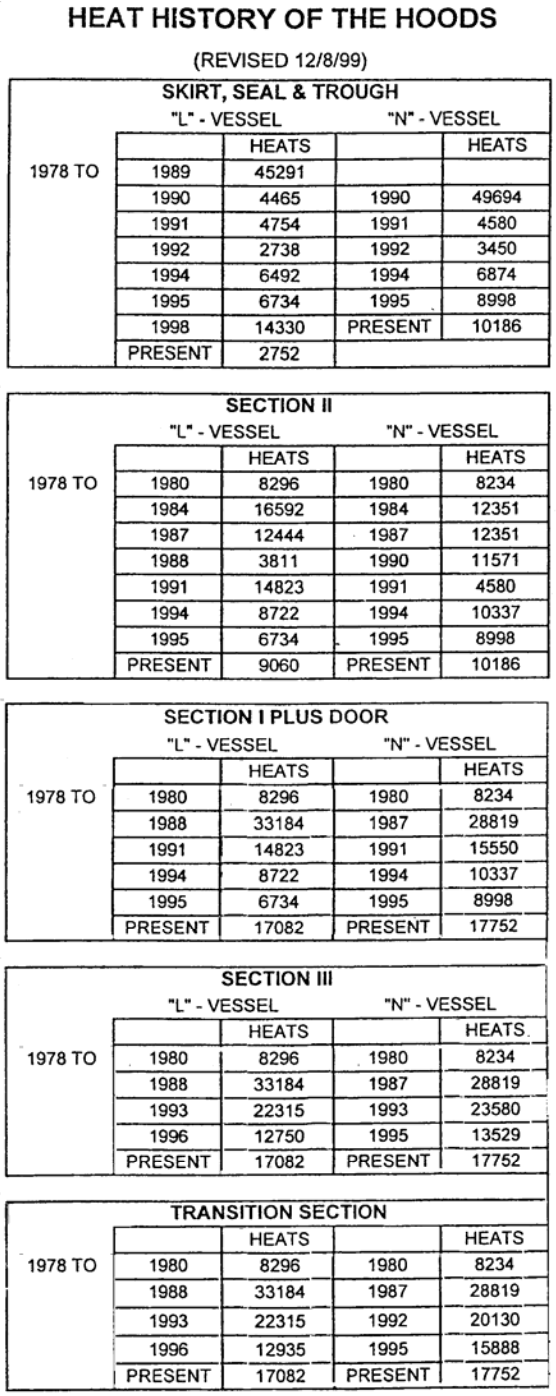
Formatted: Bullets and Numbering

5. Republic has had a long history and good experience in using BOP hoods under the very demanding conditions implied by production of re-sulfurized steel.
6. Based on this, and in an effort to improve, Republic has undertaken a progressive program to provide a corrosion-resistant weld overlay on the internal surface of critical hood components. This program has met with good success, and Republic is considering how it might be extended.
7. Republic has provided data that can be used to measure the benefits that will be derived from employing the aluminum- bronze skirt manufactured by AmeriFab.

Appendix 1: Schematic of BOP Hood in Service for Republic Engineered Products



Appendix 2: Heat History and Component Replacement for “L” Vessel and “N” Vessel Hoods



HEAT HISTORY OF THE HOODS

(REVISED 12/8/99)

SKIRT, SEAL & TROUGH

	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
1978 TO	1989	45291		
	1990	4465	1990	49694
	1991	4754	1991	4580
	1992	2738	1992	3450
	1994	6492	1994	6874
	1995	6734	1995	8998
	1998	14330	PRESENT	10186
	PRESENT	2752		

SECTION II

	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
1978 TO	1980	8296	1980	8234
	1984	16592	1984	12351
	1987	12444	1987	12351
	1988	3811	1990	11571
	1991	14823	1991	4580
	1994	8722	1994	10337
	1995	6734	1995	8998
	PRESENT	9060	PRESENT	10186

SECTION I PLUS DOOR

	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
1978 TO	1980	8296	1980	8234
	1988	33184	1987	28819
	1991	14823	1991	15550
	1994	8722	1994	10337
	1995	6734	1995	8998
	PRESENT	17082	PRESENT	17752

SECTION III

	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
1978 TO	1980	8296	1980	8234
	1988	33184	1987	28819
	1993	22315	1993	23580
	1996	12750	1995	13529
	PRESENT	17082	PRESENT	17752

TRANSITION SECTION

		HEATS		HEATS
1978 TO	1980	8296	1980	8234
	1988	33184	1987	28819
	1993	22315	1992	20130
	1996	12935	1995	15888
	PRESENT	17082	PRESENT	17752

BATCH FLOOR 15' UP SHAFT

	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
1978 TO	1988	41480	1980	8234
	1994	25561	1987	28819
	1966	12750	1993	23580
3-Sides	PRESENT	17082	1995	13529
Northside	PRESENT	6117	PRESENT	17752

LANCE FLOOR SHAFT AREA

	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
1978 TO	1991	54935	1990	49694
	1996	20702	1995	25061
	PRESENT	17082	PRESENT	17752

LANCE PLATFORM SHAFT AREA

	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
1978 TO	1994	65673	1993	61703
	PRESENT	21810	PRESENT	23715

201 LEVEL - BOTTOM

	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
South	PRESENT	94735	PRESENT	92362
East	PRESENT	91983		
West	PRESENT	91983		
North	PRESENT	656		

C-1 PANEL

	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
1978 TO	1993	62427	1992	58253
	1996	16035	1995	15888
	PRESENT	17082	PRESENT	17752

G-1 PANEL

	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
1978 TO	1993	62427	1993	61703
	1996	16035	1995	15888
	PRESENT	17082	PRESENT	17752

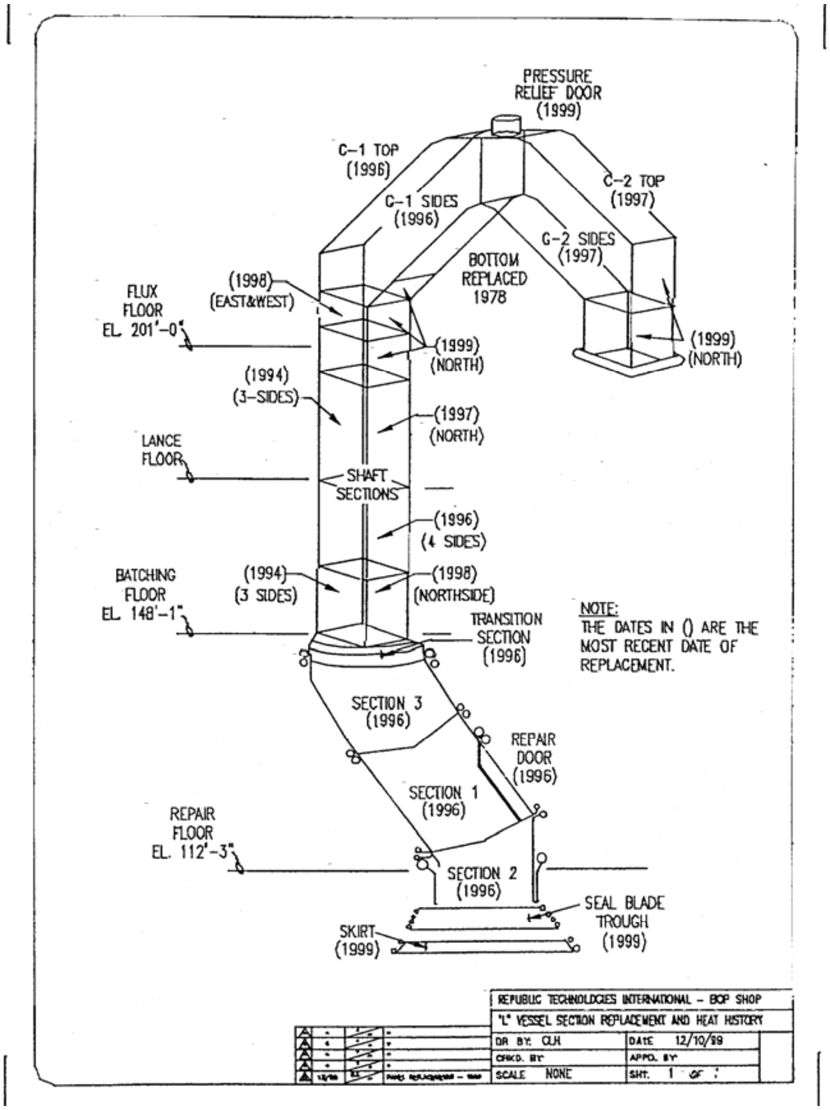
RELIEF DOOR AREA

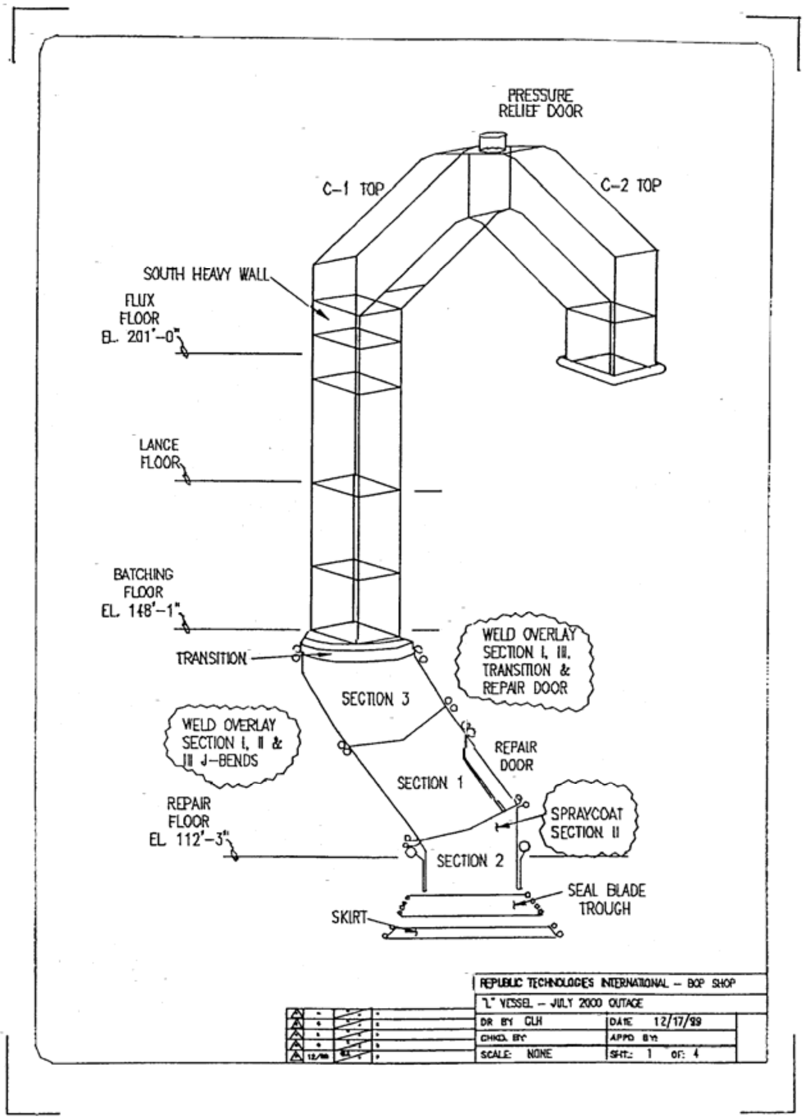
	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
1978 TO	1993	62427	1993	61703
	1996	16035	1995	13529
	1999	16426	PRESENT	17752
	PRESENT	656		

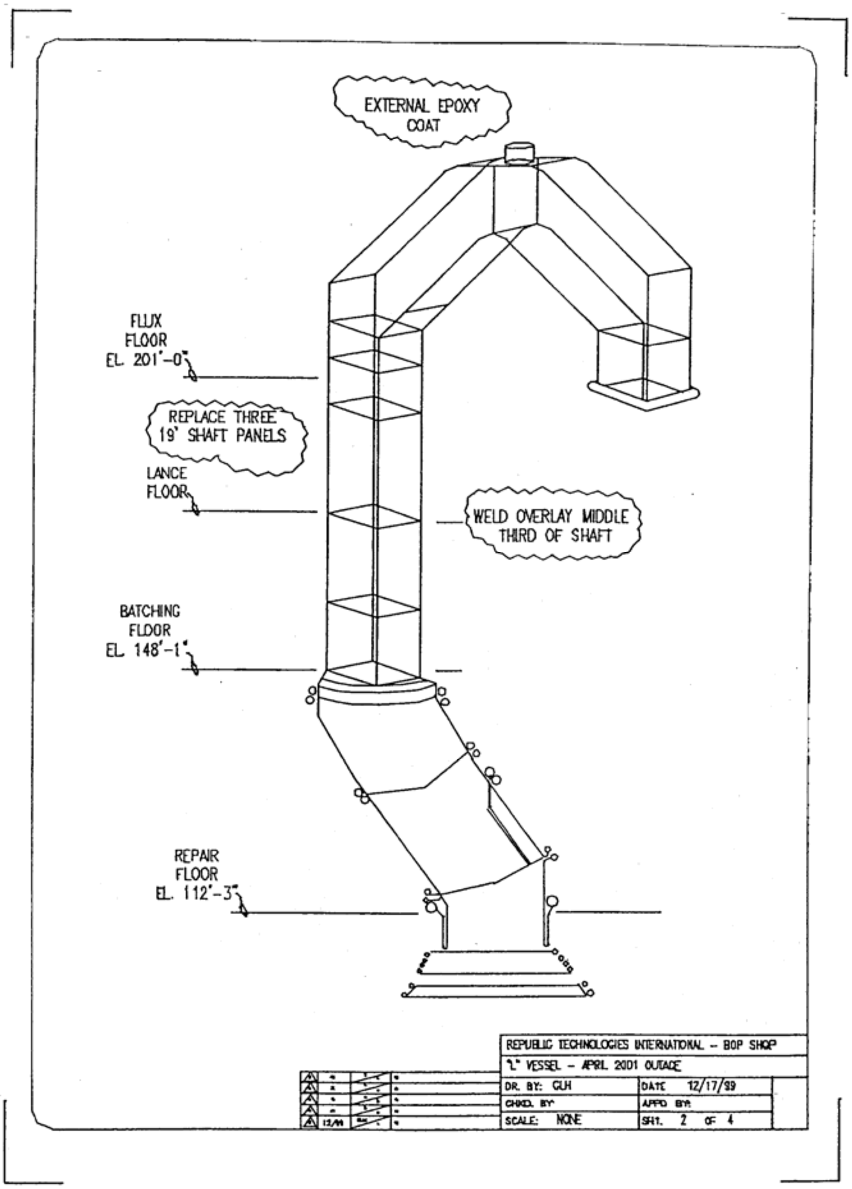
BOTTOM OF CROSS OVER

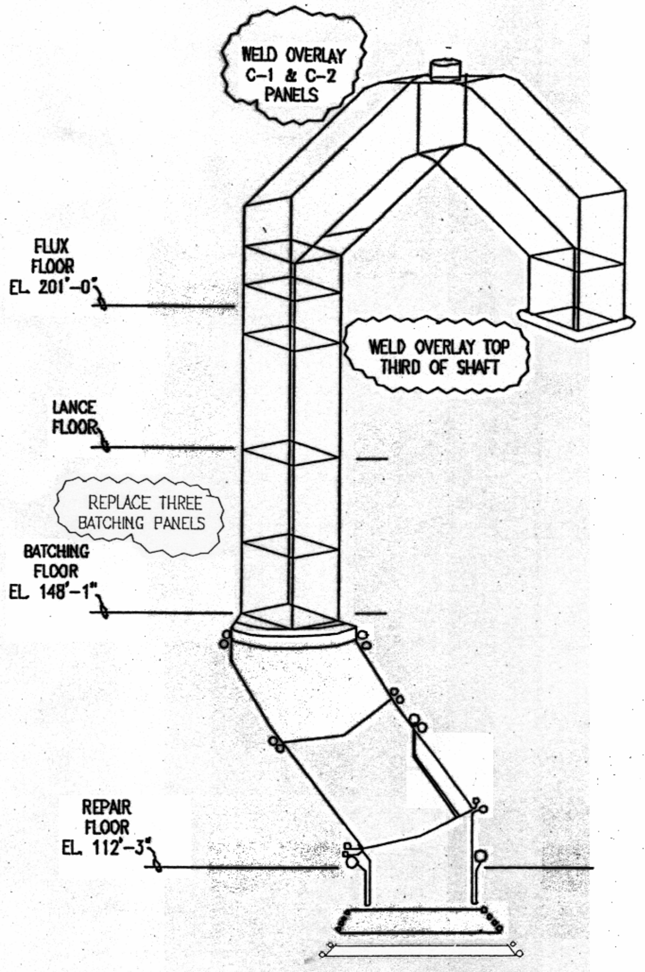
	"L" - VESSEL		"N" - VESSEL	
		HEATS		HEATS
1978 TO	PRESENT	86713	PRESENT	84340

Appendix 3: "L" Vessel Component Repair and Replacement History

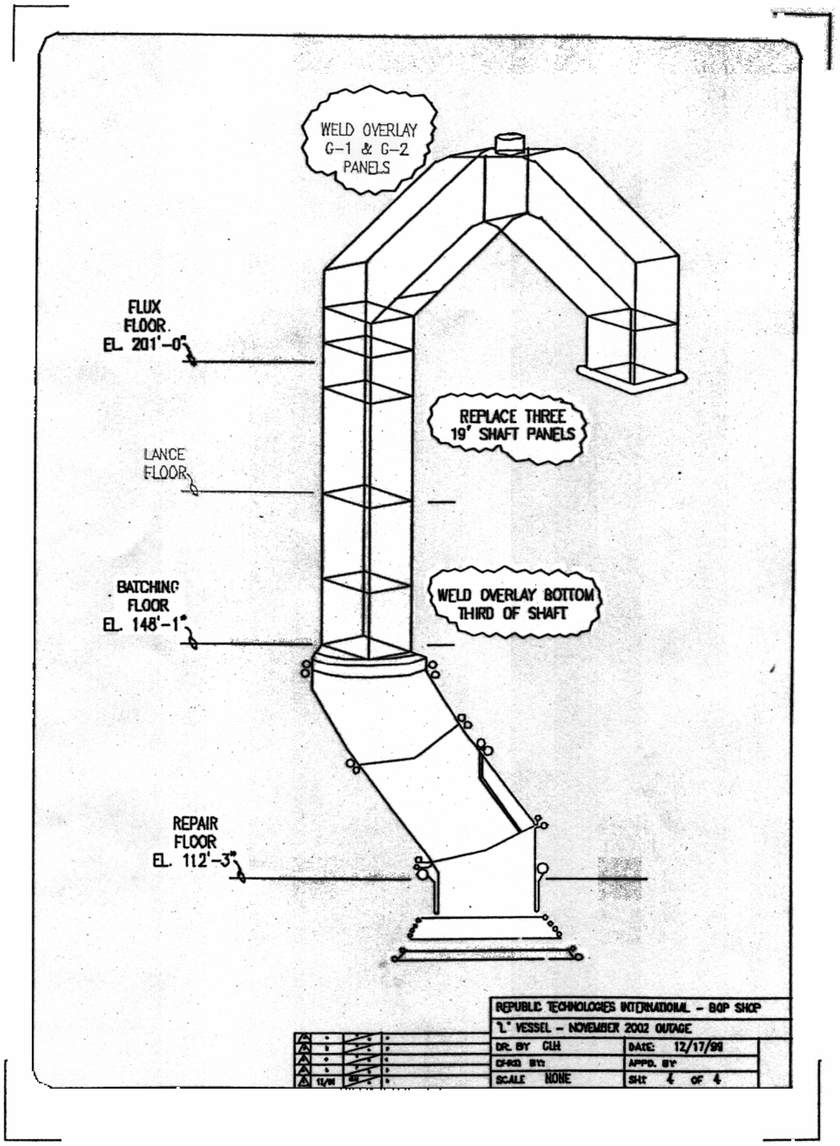



PRESSURE RELIEF DOOR
C-1 TOP
C-2 TOP
SOUTH HEAVY WALL
FLUX FLOOR EL. 201'-0"
LANCE FLOOR
BATCHING FLOOR EL. 148'-1"
TRANSITION
WELD OVERLAY SECTION I, III, TRANSITION & REPAIR DOOR
SECTION 3
WELD OVERLAY SECTION I, II & III J-BENDS
REPAIR DOOR
SECTION 1
REPAIR FLOOR EL 112'-3"
SPRAYCOAT SECTION II
SECTION 2
SEAL BLADE TROUGH
SKIRT
REPUBLIC TECHNOLOGIES INTERNATIONAL – BOP SHOP
"L" VESSEL – JULY 2000 OUTAGE
DR BY CLH
DATE 12/17/99
CHKD. BY:
APPD BY:
SCALE: NONE
SHT.: 1 OF: 4

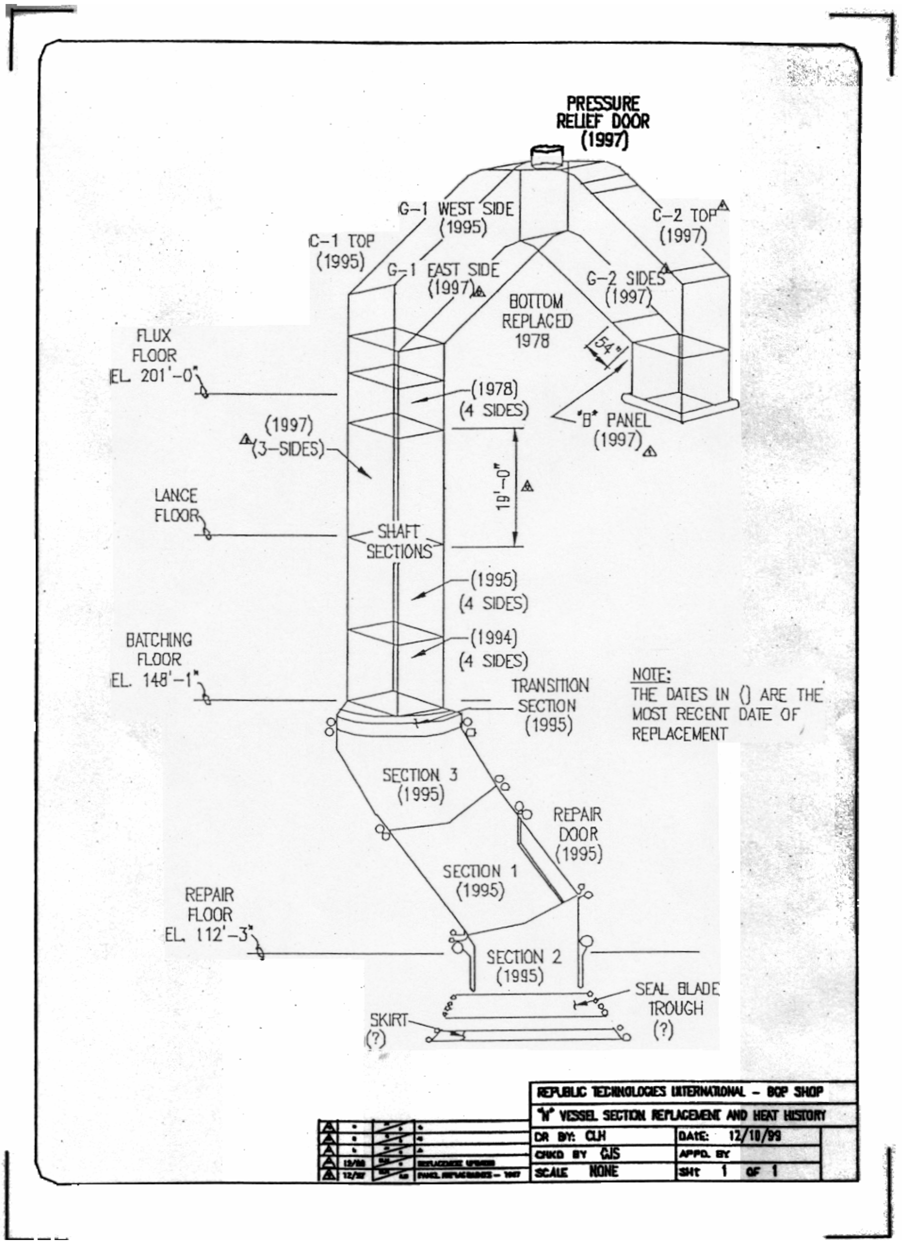

EXTERNAL EPOXY COAT
FLUX FLOOR EL. 201'-0"
REPLACE THREE 19' SHAFT PANELS
LANCE FLOOR
WELD OVERLAY MIDDLE THIRD OF SHAFT
BATCHING FLOOR EL. 148'-1"
REPAIR FLOOR EL. 112'-3"
REPUBLIC TECHNOLOGIES INTERNATIONAL – BOP SHOP
"L" VESSEL – APRL 2001 OUTAGE
DR. BY: GLH
DATE 12/17/99
CHKD. BY:
APPD BY:
SCALE: NONE
SHT. 2 OF 4



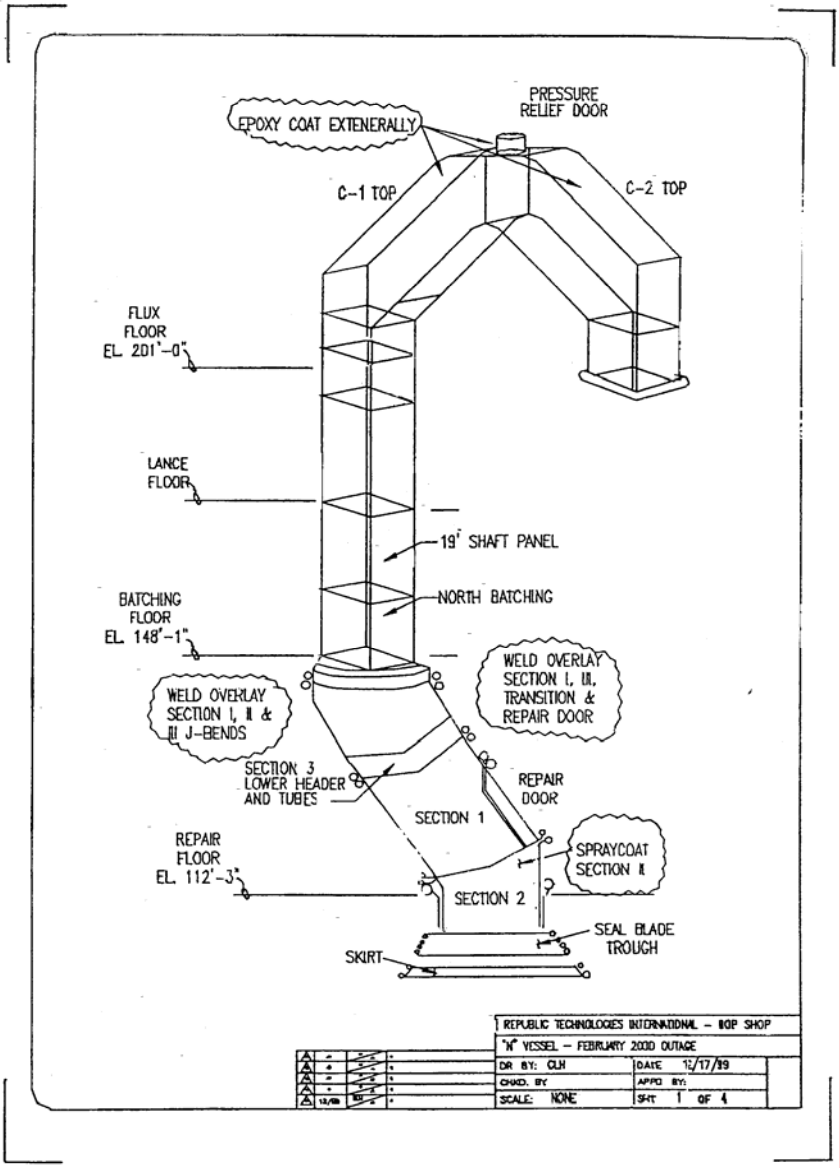
REPUBLIC TECHNOLOGIES INTERNATIONAL – BOP SHOP	
"L" VESSEL – JANUARY 2002 OUTAGE	
DR BY CLH	DATE 12/17/99
CHKD. BY	APPD. BY
SCALE: NONE	SHT.: 3 OF 4

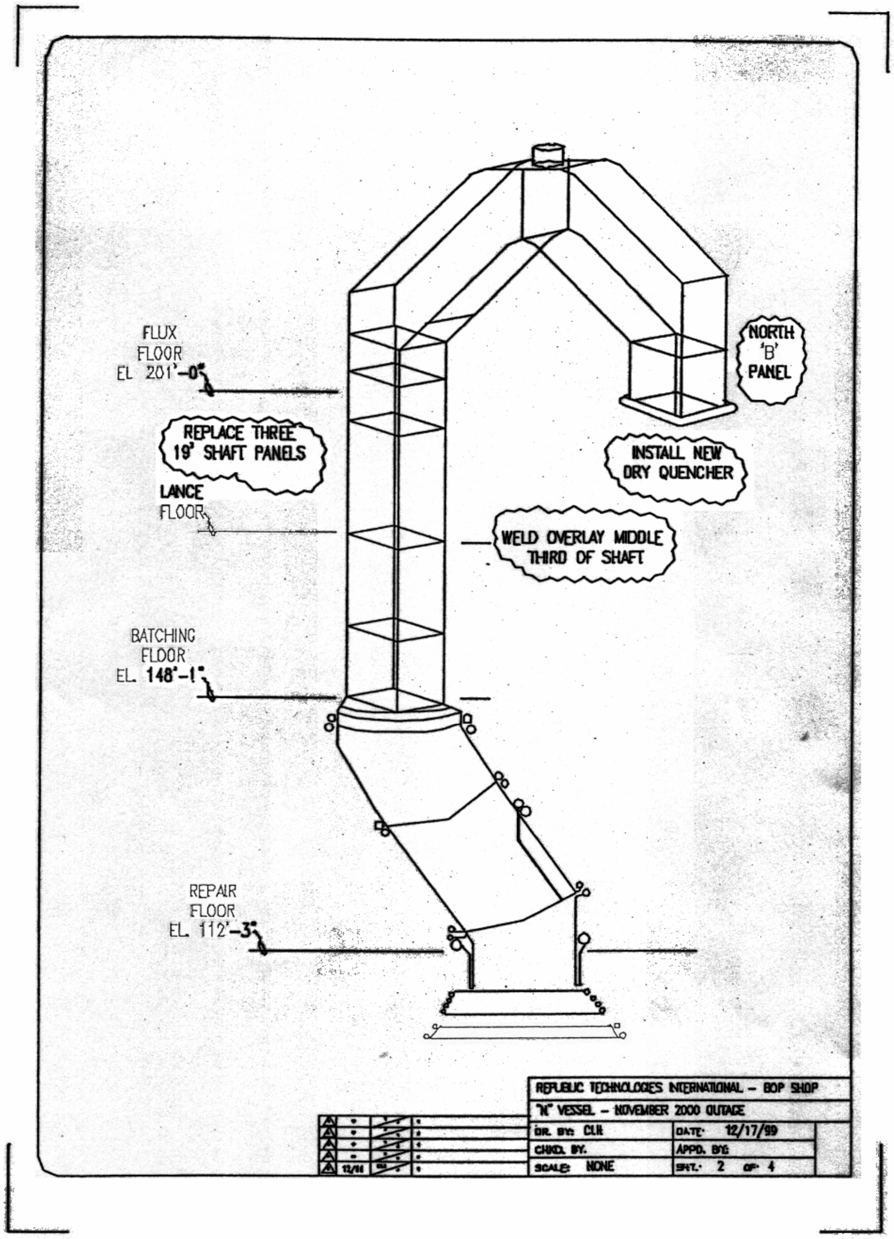

WELD OVERLAY
G-1 & G-2
PANELS
FLUX
FLOOR.
EL. 201'-0"
REPLACE THREE
19' SHAFT PANELS
LANCE
FLOOR
WELD OVERLAY BOTTOM
THIRD OF SHAFT
BATCHING
FLOOR
EL. 148'-1"
REPAIR
FLOOR
EL. 112'-3"
REPUBLIC TECHNOLOGIES INTERNATIONAL - BOP SHOP
"L" VESSEL - NOVEMBER 2002 OUTAGE
DR. BY CLH
DATE: 12/17/99
CHKD. BY:
APPD. BY:
SCALE NONE
SHT 4 OF 4
11/98

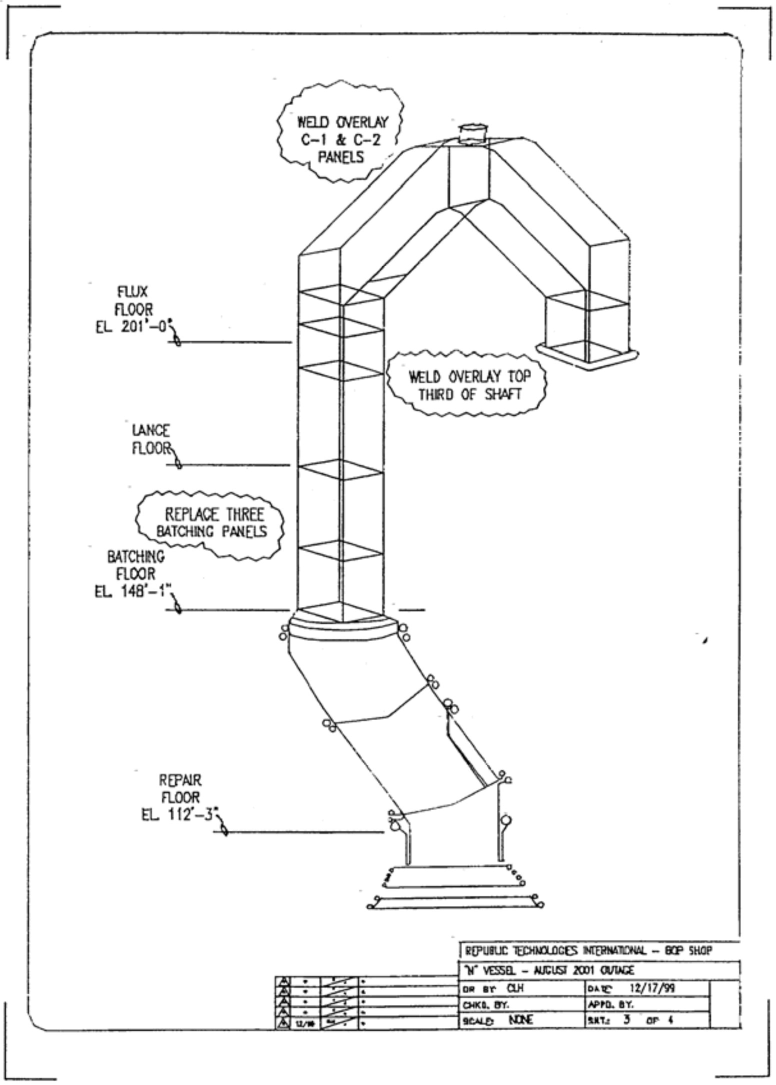
Appendix 4: “N” Vessel Component Repair and Replacement History

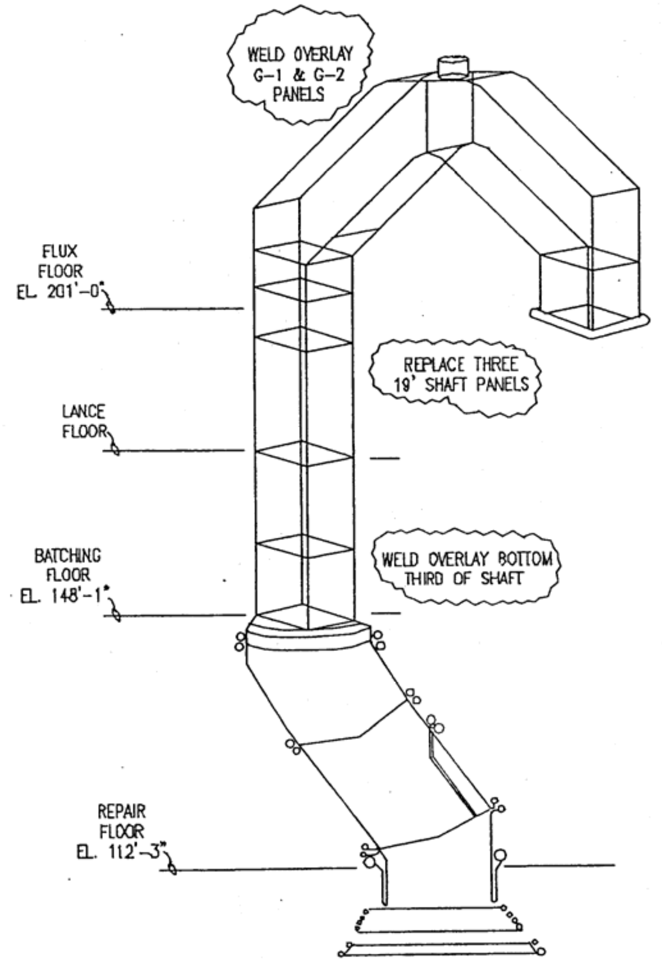


N vessel


PRESSURE RELIEF DOOR
EPOXY COAT EXTENERALLY
C-1 TOP
C-2 TOP
FLUX FLOOR EL. 201'-0"
LANCE FLOOR
19' SHAFT PANEL
NORTH BATCHING
BATCHING FLOOR EL. 148'-1"
WELD OVERLAY SECTION I, III, TRANSITION & REPAIR DOOR
WELD OVERLAY SECTION I, II & III J-BENDS
SECTION 3 LOWER HEADER AND TUBES
REPAIR DOOR
SECTION 1
REPAIR FLOOR EL. 112'-3"
SPRAYCOAT SECTION II
SECTION 2
SEAL BLADE TROUGH
SKIRT
REPUBLIC TECHNOLOGIES INTERNATIONAL – BOP SHOP
"N" VESSEL – FEBRUARY 2000 OUTAGE
DR BY: CLH
DATE 12/17/99
CHKD. BY
APPD BY:
SCALE: NONE
SHT 1 OF 4


FLUX FLOOR EL 201'-0"
NORTH 'B' PANEL
REPLACE THREE 19' SHAFT PANELS
INSTALL NEW DRY QUENCHER
LANCE FLOOR
WELD OVERLAY MIDDLE THIRD OF SHAFT
BATCHING FLOOR EL. 148'-1"
REPAIR FLOOR EL. 112'-3"
REPUBLIC TECHNOLOGIES INTERNATIONAL – BOP SHOP
"N" VESSEL – NOVEMBER 2000 OUTAGE
DR. BY: CLH
DATE: 12/17/99
CHKD. BY.
APPD. BY:
SCALE: NONE
SHT.: 2 OF: 4


WELD OVERLAY C-1 & C-2 PANELS
FLUX FLOOR EL 201'-0"
WELD OVERLAY TOP THIRD OF SHAFT
LANCE FLOOR
REPLACE THREE BATCHING PANELS
BATCHING FLOOR EL 148'-1"
REPAIR FLOOR EL 112'-3"
REPUBLIC TECHNOLOGIES INTERNATIONAL – BOP SHOP
"N" VESSEL – AUGUST 2001 OUTAGE
DR BY: CLH
DATE: 12/17/99
CHKD. BY.
APPD. BY.
SCALE: NONE
SHT.: 3 OF 4



REPUBLIC TECHNOLOGIES INTERNATIONAL - BOP SHOP

"N" VESSEL - JUNE 2002 OUTAGE

DR. BY GLH	DATE: 12/17/99
CHKD. BY:	APPD. BY
SCALE NONE	SHT 4 OF 4

GPRA Files

Project Name:	**Materials for BOF Hoods and EAF roofs**
OITIS Number (if an active DOE contract exists):	DE-FC36-02ID14345
Run File Name:	IMF FY 2006, GPRA
Preparer:	Vinod K Sikka (ORNL), and Larry Boyd (Energy Industries of Ohio)
OIT Program Manager:	Sara Dillich
OIT Planning Unit:	Industrial Materials for the Future
SIC:	Steel
National Lab Participant/Contact:	Oak Ridge National Laboratory / Dr.Vinod K. Sikka (865-574-5112)
Industrial Partner/Contact:	Larry Boyd EIO ((216- 518-0131
Data Source:	

Technology Description

Please provide a concise description (more than one-half page is unncessary) of the new technology you are proposing, addressing:
- Its function, and benefits to the industrial user of the technology
- The state-of-the art technology it replaces
- The target of the technology and potential limitations to its applications and barriers
- Plant modifications necessary to incorporate the new technology
- Competing technologies
- The definition of one technology unit-year

This project deals with use of an advanced material known as Aluminum Bronze for hoods and roofs of the basic open hearth (BOF) and electric arc furnaces (EAF) for steel production. The Al-Bronze gets used as tubular components with water going through them for the purpose of cooling the gases being emitted from the BOF furnace during steel production and for keeping the roofs and side walls of the EAF cooled from the heat that is generated from electric arc melting of the steel scrap in them. The major benefits to the industrial user of the technology include: longer uptime of the BOF and EAF furnaces, reduced maintenace time and cost, increased production, energy savings, cost savings from the saving in energy and reduced maintenace, and significant reduction in green house gas emmissions.The initial industrial user of the technology is Republic engineered products and the components using the technology include a skirt (this component connects the BOF furnace to the hood) and chutes (these are used to feed the scrap in to BOF.

The technology replaces the use of carbon and low alloy steel for the above mentioned components. These steels suffer form erosion caused by the oxide and slag particles that are emitted during the steel making process in the BOF. The tubes also leaks from their corrosion caused from the cooling water going through them. In addition to erosion the slag particles also stick to the tube outer diameter causing the poor heat transfer and a hot spot that further weakens the steel. The net result of these effects is the leaking of the new skirt within 6months of its installation, and requires continuous leak repair for the next six months before it needs replacement. The Al-bronze material of this project can extend the useful life of the skirt by several multiples and without requiring leak repair and it also prevents any slag sticking.

Technology is targetted for use in 50 BOF furnaces and 260 EAF furnaces. There are no technical limitations of the technology. Implementation requires 1) technology awareness, 2) committment from the user. The sucessful operation of the new technology at Republic Engineered Products serves as an excellent justification for other companies to try this technology.

No significant plant modifications are neccessary for implementing this technology.

There are no competeing technology of material replacement as is the case with this one. The alternate technology is a stop gap where some of the leaking systems can be weld overalyed by corrosion resistance materials. However, besides being expensive,such a process causes change in heat transfer properties and thus reduce the cooling effeciency of the components.

The 100 million tons of steel per year in the united states is produced by 50 BOF and 260 EAF furnaces. For the purpose of the enegy calculations it is noted that the steel produced in by one BOF is equivalent to 5 EAF furnaces. Thus a unit is a BOF and total equivalent units are 102 (50 BOF's and 52 BOF equivalents of 262 EAF's).

Unit Inputs

Industrial Materials for the Future: Materials for BOF Hoods and EAF roofs

Per Unit Impacts per year	New Technology	Current Technology	Net Impact
Energy Use			
Electricity (billion kWh)			0.00E+00
Natural Gas (billion cubic feet)	2.79E-05	1.06E-02	1.05E-02
Petroleum - Residual Fuel (million barrels)			0.00E+00
Petroleum - Distillate Fuel (million barrels)			0.00E+00
Petroleum - Liquefied Petroleum Gas (million barrels)			0.00E+00
Coal (million short tons)			0.00E+00
Feedstock (trillion Btu, please specify)			0.00E+00
Biomass (trillion Btu, please specify)			0.00E+00
Waste (trillion Btu, please specify)			0.00E+00
Other (please specify, trillion Btu)			0.00E+00
Environmental			
Non combustion related emissions			
Carbon Dioxide emissions (Metric TCE)			0.00E+00
Other greenhouse emissions (Metric TCE)			0.00E+00
SO2 (Metric tons)			0.00E+00
NOx (Metric tons)			0.00E+00
Particulates (Metric tons)			0.00E+00
VOCs (Metric tons)			0.00E+00
CO (Metric tons)			0.00E+00
Hydrocarbons (Metric tons)			0.00E+00
Solid Waste (Metric tons, please specify)			0.00E+00
Other environmental emissions (Metric tons)			0.00E+00
Combustion related emissions (using 2020 emission factors)			
Carbon Dioxide emissions (Metric TCE)	4.13E-01	1.56E+02	1.56E+02
Other greenhouse emissions (Metric TCE)	5.20E-05	1.97E-02	1.96E-02
SO2 (Metric tons)	1.09E+01	4.12E+03	4.11E+03
NOx (Metric tons)	3.04E+03	1.15E+06	1.15E+06
Particulates (Metric tons)	5.03E+00	1.90E+03	1.90E+03
VOCs (Metric tons)	8.45E+01	3.20E+04	3.19E+04
CO (Metric tons)	8.25E+02	3.12E+05	3.12E+05
Cost & Lifetime			
Capital Cost ($/unit)	5.23E+05	2.99E+05	-2.23E+05
O&M cost ($/unit/yr)			0.00E+00
Non-energy variable cost ($/unit/yr)	0.00E+00	0.00E+00	0.00E+00
Life of equipment (yrs)	5	1	-4
Annualized capital cost ($/unit/year)	104528	299280	194752

* TCE = Tons Carbon Equivalent

Comments

Capital cost and lifetime from project proposal. Non-energy variable cost calculations on background sheet.

No information needed on this sheet

Industrial Materials for the Future: Materials for BOF Hoods and EAF roofs

Other Greenhouse Gas Emissions Worksheet			
Name of Pollutant Gas	New Unit Emissions (Metric ton/yr)	Current Unit Emissions (Metric ton/yr)	Carbon Equivalent Factor (Metric ton carbon/Metric ton)
-			
-			
-			
-			
-			
-			
	0	0	

Market Inputs

Industrial Materials for the Future: Materials for BOF Hoods and EAF roofs

Total Market

x

# of installed units in US market
102
year for data above
2004
annual market growth rate (%)
2.0%

Comments

U.S. units = 102 BOFunits

Ultimate Potential Market Share

x

Ultimate Potential Accessible Market (%)
90%
Likely Technology Market Share (%)
80%
Savings Attributed to Program (%)
100%

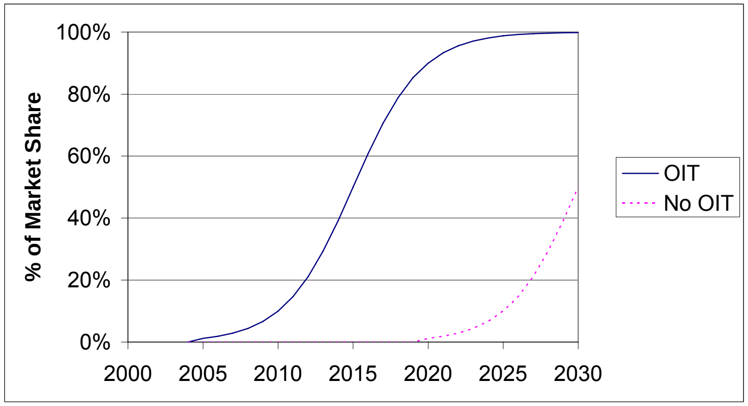
Comments

.

Market Penetration

	(10+ years)	(4-8 Years)			(2-3 Years)			
Case	Initial R&D Completed	Initial System Prototype	Refined Prototype	Commercial Prototype	Commercial Introduction	Years Accelerated	Technology Class	Years to Saturation
With OIT	▨	2003	2004	2004	2005	15	b	10
Without OIT	▨	▨	▨	▨	2020	▨	b	10

Comments



Expenditures Inputs

Industrial Materials for the Future: Materials for BOF Hoods and EAF roofs

Impact By Year	Before 2000	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
With OIT																	
Expenditures (millions nominal $)																	
EERE				0.200	0.200	0.200	0.100	0.100	0.000								
Other Government																	
Private Sector																	
Expenditures (millions 2000 $)																	
EERE	0.000	0.000	0.000	0.192	0.187	0.182	0.089	0.086	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other Government	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Private Sector	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Without OIT																	
Expenditures (millions nominal $)																	
EERE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other Government																	
Private Sector																	
Expenditures (millions 2000 $)																	
EERE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other Government	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Private Sector	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
GDP Implicit Price Deflators																	
(2000=1.000)	0.978	1.000	1.022	1.042	1.072	1.100	1.129	1.160	1.190	1.220	1.249	1.279	1.311	1.346	1.382	1.420	1.458

Impact By Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
With OIT															
Expenditures (millions nominal $)															
EERE															
Other Government															
Private Sector															
Expenditures (millions 2000 $)															
EERE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other Government	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Private Sector	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Without OIT															
Expenditures (millions nominal $)															
EERE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other Government															
Private Sector															
Expenditures (millions 2000 $)															
EERE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other Government	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Private Sector	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
GDP Implicit Price Deflators															
(2000=1.000)	1.499	1.542	1.592	1.646	1.706	1.756	1.808	1.860	1.915	1.971	2.028	2.088	2.149	2.211	2.276

Background Data & Calculations

Industrial Materials for the Future: Materials for BOF Hoods and EAF roofs

Total steel produced in USA in 2004 by BOF and EAF

BOF	52595000	Using avg of 239ton capacity and heats made every 2 h	BOF units	50.24264
EAF	57285000	Using avg of 50ton capacity and heats made every 2 h	EAF units	261.5753

Welding energy uses and savings

Saving of welding energy for Skirt fabrication

Welding energy used for AL bronze Hood Tube size 3X0.304

h	a	v	watth	KWh	btu
70	250	30	525000	525	**1791825**
					1.8 MBTU

Al Bronzr tube volume 23983.25 15 tube layers 0f 3-inx0.3 -n tube.

Density .3172lb/cuin

Tube weight/skirt 7607.487 lbs

		Welding Cost	2800	$40/h
3.803744	tons	**Cost of tubes/skirt**	30429.95	$4/lb
		Fab cost	3600	$30/h for 120
		shipping	1000	
		installation cost	2500	
			40329.95	

Energy for tube Production **38.03744** MBTU Assume that AL -bronze takes 2/3 energy of steel=10MBTU

Welding energy used for steel skirt Tube size 1.638X0.178

Welding per skirt assuming same enegy per weld as for Al bronze

Extra steel tubes 1.831502 welds 2x 1050 **3583650**

3.56 MBTU

Life extension

Assumed Al-bronze to last 5X longer

Welding energy will be 5X 17918250

Extra tube production for steel

Tube dia	tube wall	tube lengtl	height	
1.65	0.2	628.32	30 tube layers	Assuming an average skirt radius of 100-in (88-101)

Volume per tube 572.4397 (inch*3)

Weight per tube 162.0004 0.283lb/cuin

Weight of 30 layers 4860.013 pounds

Weight of 1 skirt	**2.430007**	tons	Steel skirt		
			Welding Cost	5600	$40/h
Energy/ Skirt	**36.6931**	MBTU	**Cost of tubes/skirt**	9720.027	$2/lb
			Fab cost	6000	$30/h for 200
Weight of 5 skirts	**12.15003**	tons	**shipping**	1000	
Energy to Produce extra tubes	**183.465**	**MBTU**	**installation cost**	2500	
				24820.03	
			Total for 5 over 10Y	**124100.1**	

Background Data and Calculations (Continued)

Steel Skirt performance

Year 1	Repair	0
Year 2	month 3	3
	month 5	10
	Month 4	17
	total	**30**

Energy to repair consists of weld energy and energy from down time of the furnace, which is discussed below.

Weld energy per repair			assume that each repair requires 1-2 welds	
about the same as new			Orinal fab requiring a total of 50 welds consumes (	**3583650 btus**
See assumptions	**3583650**			
	3.6	**MBTU**		

Furnace Shut downs

Due to skulling	12	in 2 years	Shut downs are due to slag sticking to steel tubes. No such sticking to Al bronze
Due to repair	30	in 2 years	Each shut down is 6-8 hrs. Normal process takes 150t of 2450F liquid + 50t Scrap at RT
Total	42		Sht down needs 165t of 2450F +35t at Rt. This means we need 15t of steel at 2450F.
Total tons needed @ 2450 in 2 years	630	tons	Energy used /ton of steel 14.2x106
Energy for that	**8946**	**MBTU**	

Hood Replacement shut down:

Replacement	40h down		It uses 5X more heat than 8 hr shut down
Energy used /40h shut	1065	MBTU	
Energy for 5 shut dov	**5325**	**MBTU**	10 years

New Skirt Technology

Skirt welding	1.8	MBTU	
Skirt tube production	38.04	MBTU	
	39.84	MBTU	10 Year life

Old technology

Tube welding	3.56		
Tube production	36.7		
Weld repair	3.56		
Furnace shut downs	8946		Repair and slag
Total	8989.82		For 2 years
Total for 10year servic	44949.1		10Year life will require 5 steel skirts
Replcaemant 10Year	5325		Skirt replacements will require 5 shut downs of 40 h
Grand Total of old Tech per 10year life of Al bronz skirt	**50274.1**	MBTU	10Year span

Background Data and Calculations (Continued)

Flux Chutes

Current material is Steel It has a life of 12 months with 3 months not requiring any repir
Next nine months it will need shut downs of 1,1,2,2,3,3,4,4,4 during 4,5,6,7,8,9,10,11 and 12th months

Total shut downs in a year 24 one year

Assuming
as
8hdown
Energy
saving **5112 MBTU** one year for 24 shut downs

For chute to yield a 5X life extension similar to that noted for the skirt, energy used for chutes in 5years will be **25560 MBTU** **Old Technology in 5 years**

New Chute Technology
Based on its structure it is estimated that it uses 2X number of tubes and welds as opposed to the Skirt.
Skirt used an energy of 39.84MBTU for its tubes and welding.
Chute energy 79.68 MBTU 5 Years

Lower section of the hood

Based on the location with respect to the Skirt, the lower portion of the hood has a life of 5 years vs 2 years for the steel skirt

It is assumed that the shut downs for the hood are proportional to its life and it may be only **10 shut downs**

Total shut downs for skirt, chute and lower hood are:
40+24+10=74

Some of the shut downs will be combined between different causes and thus we anticipate 52 shut downs instead of 74, which is one shut down a week, a very reasonable number.

Energy calculation for new and old technology for the lower portion of the hood

Lower hood life with current steel tubes is ~ 5 years.
Al bronze is expected to increase the hood life by 5X and thus will take it to 25 Years

Old technology calculations

As stated above only 10 furnace shut downs will occure for leaks in the lower hood over its life of 5years
for a 25 year life of the Al Bronze skirt shut downs will be 50.
Energy for 50 shut downs over 25 years **10650** MBTU

New Technology

Based on its structure, lower hood uses ~5X more tubes and welds than the skirt
Energy for its fabrication **199.2 MBTU**

Summary

	old/year	new/year	
Skirt	5027.41	3.984	MBTU
chute	5112	15.936	
lower hood	426	7.968	
Total	**10565.41**	**27.888**	**MBTU**
	3.095637	0.008171	kwh
	10.56541	0.027888	Mcuft

Output Used for GPRA Data Call

Industrial Materials for the Future: Materials for BOF Hoods and EAF roofs

Impact By Year	2004	2005	2006	2007	2008	2010	2015	2020	2025	2030
ANNUAL SAVINGS										
Energy Metrics										
Total primary energy displaced (trillion Btu)	0.00	0.01	0.02	0.02	0.04	0.09	0.49	0.97	1.07	0.66
Direct electricity displaced (billion kWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct natural gas displaced (bcf)	0.00	0.01	0.02	0.02	0.04	0.09	0.48	0.94	1.04	0.65
Direct petroleum displaced (million barrels)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct coal displaced (million short tons)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feedstock energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Financial Metrics										
Net Economic Benefit ($MM/yr)	-0.18	0.12	0.25	0.52	0.81	1.92	10.71	21.21	23.67	14.84
Energy-cost savings ($MM/yr)	0.00	0.03	0.05	0.08	0.13	0.31	1.82	3.78	4.43	2.91
Non-energy cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Consumer Investment ($MM/yr)	0.00	0.18	0.28	0.44	0.68	1.61	8.89	17.43	19.25	11.93
EERE Expenditures ($MM/yr)	-0.18	-0.09	-0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Government Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private Sector Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Environmental Metrics										
CO Displaced (Metric tonnes)	0.00	0.28	0.45	0.70	1.09	2.58	14.23	27.89	30.79	19.10
Carbon Dioxide emissions displaced (MM TCE)	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.01
Other greenhouse emissions displaced (MM TCE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2 displaced (Metric tonnes)	0.00	0.00	0.01	0.01	0.01	0.03	0.19	0.37	0.41	0.25
NOx displaced (Metric tonnes)	0.00	1.05	1.65	2.59	4.03	9.51	52.49	102.91	113.62	70.46
Particulates displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.01	0.02	0.09	0.17	0.19	0.12
VOCs displaced (Metric tonnes)	0.00	0.03	0.05	0.07	0.11	0.26	1.46	2.86	3.15	1.96
Hydrocarbons displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solid Waste (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other environmental benefits (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CUMULATIVE SAVINGS										
Energy Metrics										
Total primary energy displaced (trillion Btu)	0.00	0.01	0.03	0.05	0.09	0.24	1.72	5.77	11.06	15.43
Direct electricity displaced (billion kWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct natural gas displaced (bcf)	0.00	0.01	0.02	0.05	0.09	0.23	1.67	5.62	10.77	15.03
Direct petroleum displaced (million barrels)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct coal displaced (million short tons)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feedstock energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Financial Metrics										
Net Economic Benefit ($MM/yr)	-0.56	-0.44	-0.19	0.33	1.14	4.32	36.41	124.69	241.34	338.74
Energy-cost savings ($MM/yr)	0.00	0.03	0.08	0.17	0.29	0.81	6.20	21.65	43.05	61.75
Non-energy cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Consumer Investment ($MM/yr)	0.00	0.18	0.46	0.90	1.58	4.24	30.94	103.78	199.02	277.72
EERE Expenditures ($MM/yr)	-0.56	-0.65	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74
Other Government Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private Sector Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Environmental Metrics										
CO Displaced (Metric tonnes)	0.00	0.28	0.73	1.43	2.53	6.79	49.50	166.05	318.44	444.36
Carbon Dioxide emissions displaced (MM TCE)	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.08	0.16	0.22
Other greenhouse emissions displaced (MM TCE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2 displaced (Metric tonnes)	0.00	0.00	0.01	0.02	0.03	0.09	0.65	2.19	4.20	5.86
NOx displaced (Metric tonnes)	0.00	1.05	2.70	5.29	9.32	25.06	182.65	612.69	1174.98	1639.58
Particulates displaced (Metric tonnes)	0.00	0.00	0.00	0.01	0.02	0.04	0.30	1.01	1.94	2.71
VOCs displaced (Metric tonnes)	0.00	0.03	0.07	0.15	0.26	0.70	5.07	17.01	32.61	45.51
Hydrocarbons displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solid Waste (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other environmental benefits (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Output Used for GPRA Data Call (Continued)

LIFETIME SAVINGS										
Energy Metrics										
Total primary energy displaced (trillion Btu)	0.00	0.05	0.08	0.12	0.19	0.50	2.97	7.81	13.16	16.47
Direct electricity displaced (billion kWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct natural gas displaced (bcf)	0.00	0.05	0.08	0.12	0.18	0.48	2.89	7.60	12.81	16.04
Direct petroleum displaced (million barrels)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct coal displaced (million short tons)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feedstock energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Financial Metrics										
Net Economic Benefit ($MM/yr)	-0.74	0.32	0.92	1.86	3.31	9.91	63.35	168.96	286.80	360.61
Energy-cost savings ($MM/yr)	0.00	0.16	0.26	0.40	0.64	1.70	10.68	29.13	50.74	64.89
Non-energy cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Consumer Investment ($MM/yr)	0.00	0.89	1.40	2.19	3.41	8.94	53.40	140.56	236.79	296.46
EERE Expenditures ($MM/yr)	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74
Other Government Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private Sector Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Environmental Metrics										
CO Displaced (Metric tonnes)	0.00	1.42	2.24	3.51	5.46	14.31	85.44	224.90	378.86	474.34
Carbon Dioxide emissions displaced (MM TCE)	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.11	0.19	0.24
Other greenhouse emissions displaced (MM TCE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2 displaced (Metric tonnes)	0.00	0.02	0.03	0.05	0.07	0.19	1.13	2.96	4.99	6.25
NOx displaced (Metric tonnes)	0.00	5.25	8.26	12.94	20.16	52.80	315.27	829.82	1397.93	1750.22
Particulates displaced (Metric tonnes)	0.00	0.01	0.01	0.02	0.03	0.09	0.52	1.37	2.31	2.89
VOCs displaced (Metric tonnes)	0.00	0.15	0.23	0.36	0.56	1.47	8.75	23.03	38.80	48.58
Hydrocarbons displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solid Waste (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other environmental benefits (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Impacts: New Technology (With OIT) vs Current Technology

Industrial Materials for the Future: Materials for BOF Hoods and EAF roofs

Impact By Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cumulative Units installed	0	1	1	2	4	5	8	12	18	26	35	46
Annual New Units Installed	0	1	1	1	1	2	3	4	6	8	9	11
Annual Replacement Units Installed	0	0	0	0	0	0	1	1	1	1	2	4
Annual Installations Total	0	1	1	1	1	2	4	5	7	9	11	14
Market penetration	0%	1%	2%	3%	4%	7%	10%	15%	21%	29%	39%	50%
ANNUAL SAVINGS												
Energy Metrics												
Total primary energy displaced (trillion Btu)	0.00	0.01	0.02	0.02	0.04	0.06	0.09	0.13	0.20	0.28	0.38	0.49
Direct electricity displaced (billion kWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct natural gas displaced (bcf)	0.00	0.01	0.02	0.02	0.04	0.06	0.09	0.13	0.19	0.27	0.37	0.48
Direct petroleum displaced (million barrels)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct coal displaced (million short tons)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feedstock energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Financial Metrics												
Net Economic Benefit ($MM/yr)	-0.18	0.12	0.25	0.52	0.81	1.26	1.92	2.89	4.24	6.03	8.22	10.71
Energy-cost savings ($MM/yr)	0.00	0.03	0.05	0.08	0.13	0.20	0.31	0.47	0.70	1.01	1.39	1.82
Non-energy cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Consumer Investment ($MM/yr)	0.00	0.18	0.28	0.44	0.68	1.06	1.61	2.42	3.54	5.02	6.83	8.89
EERE Expenditures ($MM/yr)	-0.18	-0.09	-0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Government Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private Sector Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Simple Payback Period (years)	None	6.26	6.21	6.17	6.06	6.01	5.94	5.85	5.76	5.69	5.65	5.60
Environmental Metrics												
CO Displaced (Metric tonnes)	0.00	0.28	0.45	0.70	1.09	1.69	2.58	3.87	5.66	8.02	10.93	14.23
Carbon Dioxide emissions displaced (MM TCE)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Other greenhouse emissions displaced (MM TCE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2 displaced (Metric tonnes)	0.00	0.00	0.01	0.01	0.01	0.02	0.03	0.05	0.07	0.11	0.14	0.19
NOx displaced (Metric tonnes)	0.00	1.05	1.65	2.59	4.03	6.23	9.51	14.26	20.88	29.61	40.34	52.49
Particulates displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.05	0.07	0.09
VOCs displaced (Metric tonnes)	0.00	0.03	0.05	0.07	0.11	0.17	0.26	0.40	0.58	0.82	1.12	1.46
Hydrocarbons displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solid Waste (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other environmental benefits (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CUMULATIVE SAVINGS												
Energy Metrics												
Total primary energy displaced (trillion Btu)	0.00	0.01	0.03	0.05	0.09	0.15	0.24	0.37	0.57	0.85	1.22	1.72
Direct electricity displaced (billion kWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct natural gas displaced (bcf)	0.00	0.01	0.02	0.05	0.09	0.14	0.23	0.36	0.55	0.82	1.19	1.67
Direct petroleum displaced (million barrels)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct coal displaced (million short tons)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feedstock energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Financial Metrics												
Net Economic Benefit ($MM/yr)	-0.56	-0.44	-0.19	0.33	1.14	2.39	4.32	7.21	11.45	17.47	25.69	36.41
Energy-cost savings ($MM/yr)	0.00	0.03	0.08	0.17	0.29	0.50	0.81	1.28	1.99	3.00	4.38	6.20
Non-energy cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Consumer Investment ($MM/yr)	0.00	0.18	0.46	0.90	1.58	2.63	4.24	6.66	10.20	15.21	22.05	30.94
EERE Expenditures ($MM/yr)	-0.56	-0.65	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74
Other Government Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private Sector Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Environmental Metrics												
CO Displaced (Metric tonnes)	0.00	0.28	0.73	1.43	2.53	4.21	6.79	10.66	16.32	24.34	35.27	49.50
Carbon Dioxide emissions displaced (MM TCE)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.02
Other greenhouse emissions displaced (MM TCE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2 displaced (Metric tonnes)	0.00	0.00	0.01	0.02	0.03	0.06	0.09	0.14	0.22	0.32	0.46	0.65
NOx displaced (Metric tonnes)	0.00	1.05	2.70	5.29	9.32	15.55	25.06	39.32	60.21	89.82	130.15	182.65
Particulates displaced (Metric tonnes)	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.06	0.10	0.15	0.21	0.30
VOCs displaced (Metric tonnes)	0.00	0.03	0.07	0.15	0.26	0.43	0.70	1.09	1.67	2.49	3.61	5.07
Hydrocarbons displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solid Waste (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other environmental benefits (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Impacts (Continued)

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
57	67	76	84	91	96	100	104	107	110	113	115	118	120	123
11	10	9	8	6	5	4	4	3	3	3	3	3	2	2
5	7	9	11	14	16	17	18	19	21	21	21	22	22	24
16	17	18	19	21	21	21	22	22	24	24	24	24	25	26
61%	71%	79%	85%	90%	93%	96%	97%	98%	99%	99%	99%	100%	100%	100%
Annual Savings														
0.61	0.73	0.83	0.91	0.98	1.04	1.09	1.12	1.16	1.19	1.22	1.25	1.27	1.30	1.33
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.60	0.71	0.81	0.89	0.96	1.01	1.06	1.09	1.13	1.16	1.19	1.21	1.24	1.27	1.29
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13.31	15.80	18.03	19.93	21.50	22.79	23.86	24.78	25.59	26.34	27.04	27.72	28.39	29.06	29.73
2.28	2.73	3.14	3.51	3.83	4.10	4.34	4.55	4.74	4.92	5.10	5.28	5.46	5.64	5.83
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11.03	13.07	14.89	16.42	17.67	18.69	19.53	20.23	20.85	21.41	21.94	22.44	22.93	23.42	23.90
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.56	5.49	5.43	5.37	5.29	5.23	5.17	5.11	5.05	4.99	4.93	4.87	4.81	4.76	4.70
17.65	20.92	23.82	26.27	28.27	29.90	31.24	32.38	33.37	34.26	35.10	35.90	36.69	37.46	38.24
0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.23	0.28	0.31	0.35	0.37	0.39	0.41	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.50
65.12	77.18	87.90	96.93	104.32	110.33	115.28	119.46	123.11	126.42	129.51	132.47	135.37	138.24	141.11
0.11	0.13	0.15	0.16	0.17	0.18	0.19	0.20	0.20	0.21	0.21	0.22	0.22	0.23	0.23
1.81	2.14	2.44	2.69	2.90	3.06	3.20	3.32	3.42	3.51	3.59	3.68	3.76	3.84	3.92
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cumulative Savings														
2.33	3.06	3.89	4.80	5.78	6.82	7.90	9.03	10.19	11.38	12.60	13.84	15.12	16.42	17.75
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.27	2.98	3.78	4.67	5.63	6.64	7.70	8.79	9.92	11.08	12.26	13.48	14.72	15.99	17.28
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
49.72	65.52	83.55	103.48	124.98	147.77	171.63	196.41	222.01	248.35	275.39	303.11	331.50	360.56	390.29
8.48	11.21	14.36	17.86	21.70	25.80	30.13	34.68	39.42	44.35	49.45	54.73	60.20	65.84	71.67
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
41.97	55.04	69.93	86.35	104.02	122.71	142.23	162.47	183.32	204.74	226.67	249.11	272.04	295.46	319.36
-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
67.15	88.07	111.89	138.16	166.43	196.33	227.58	259.95	293.32	327.58	362.68	398.58	435.27	472.73	510.98
0.03	0.04	0.06	0.07	0.08	0.10	0.11	0.13	0.15	0.16	0.18	0.20	0.22	0.24	0.26
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.88	1.16	1.47	1.82	2.19	2.59	3.00	3.43	3.87	4.32	4.78	5.25	5.74	6.23	6.73
247.77	324.95	412.85	509.78	614.10	724.43	839.71	959.17	1082.29	1208.71	1338.22	1470.69	1606.06	1744.29	1885.40
0.41	0.54	0.68	0.84	1.01	1.20	1.39	1.58	1.79	2.00	2.21	2.43	2.65	2.88	3.11
6.88	9.02	11.46	14.15	17.04	20.11	23.31	26.62	30.04	33.55	37.14	40.82	44.58	48.41	52.33
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Impacts (Continued)	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
LIFETIME SAVINGS												
Energy Metrics												
Total primary energy displaced (trillion Btu)	0.00	0.05	0.08	0.12	0.19	0.29	0.50	0.75	1.10	1.58	2.19	2.97
Direct electricity displaced (billion kWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct natural gas displaced (bcf)	0.00	0.05	0.08	0.12	0.18	0.29	0.48	0.73	1.08	1.54	2.13	2.89
Direct petroleum displaced (million barrels)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct coal displaced (million short tons)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feedstock energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Financial Metrics												
Net Economic Benefit ($MM/yr)	-0.74	0.32	0.92	1.86	3.31	5.53	9.91	15.33	23.01	33.35	46.52	63.35
Energy-cost savings ($MM/yr)	0.00	0.16	0.26	0.40	0.64	0.99	1.70	2.59	3.86	5.60	7.82	10.68
Non-energy cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Consumer Investment ($MM/yr)	0.00	0.89	1.40	2.19	3.41	5.28	8.94	13.48	19.88	28.49	39.44	53.40
EERE Expenditures ($MM/yr)	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74
Other Government Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private Sector Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Environmental Metrics												
CO Displaced (Metric tonnes)	0.00	1.42	2.24	3.51	5.46	8.44	14.31	21.57	31.81	45.58	63.10	85.44
Carbon Dioxide emissions displaced (MM TCE)	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.04
Other greenhouse emissions displaced (MM TCE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2 displaced (Metric tonnes)	0.00	0.02	0.03	0.05	0.07	0.11	0.19	0.28	0.42	0.60	0.83	1.13
NOx displaced (Metric tonnes)	0.00	5.25	8.26	12.94	20.16	31.14	52.80	79.58	117.36	168.20	232.82	315.27
Particulates displaced (Metric tonnes)	0.00	0.01	0.01	0.02	0.03	0.05	0.09	0.13	0.19	0.28	0.38	0.52
VOCs displaced (Metric tonnes)	0.00	0.15	0.23	0.36	0.56	0.86	1.47	2.21	3.26	4.67	6.46	8.75
Hydrocarbons displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solid Waste (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other environmental benefits (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Impacts (Continued)	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lifetime Savings															
	3.81	4.74	5.72	6.75	7.88	9.01	10.16	11.34	12.55	13.83	15.10	16.40	17.71	19.05	20.47
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3.71	4.61	5.57	6.58	7.67	8.77	9.89	11.04	12.22	13.46	14.70	15.96	17.25	18.55	19.93
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	81.72	101.80	123.23	145.80	170.41	195.19	220.61	246.61	273.23	301.55	329.83	358.63	387.94	417.88	449.55
	13.83	17.29	21.03	25.00	29.39	33.85	38.47	43.24	48.17	53.47	58.80	64.29	69.93	75.74	81.95
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	68.63	85.25	102.93	121.53	141.76	162.08	182.88	204.10	225.80	248.82	271.76	295.07	318.75	342.87	368.33
	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	109.82	136.39	164.69	194.45	226.81	259.33	292.61	326.57	361.28	398.12	434.83	472.12	510.00	548.60	589.33
	0.05	0.07	0.08	0.10	0.11	0.13	0.15	0.16	0.18	0.20	0.22	0.24	0.26	0.27	0.29
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1.45	1.80	2.17	2.56	2.99	3.42	3.86	4.30	4.76	5.25	5.73	6.22	6.72	7.23	7.77
	405.20	503.26	607.68	717.47	836.89	956.87	1079.67	1204.97	1333.03	1468.99	1604.42	1742.02	1881.81	2024.22	2174.53
	0.67	0.83	1.00	1.18	1.38	1.58	1.78	1.99	2.20	2.43	2.65	2.88	3.11	3.34	3.59
	11.25	13.97	16.87	19.91	23.23	26.56	29.97	33.44	37.00	40.77	44.53	48.35	52.23	56.18	60.36
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Impacts: New Technology (Without OIT) vs Current Technology

Industrial Materials for the Future: Materials for BOF Hoods and EAF roofs

Impact By Year	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Cumulative Units installed	0	0	0	0	0	0	0	0	0	0	0	0
Annual New Units Installed	0	0	0	0	0	0	0	0	0	0	0	0
Annual Replacement Units Installed	0	0	0	0	0	0	0	0	0	0	0	0
Annual Installations Total	0	0	0	0	0	0	0	0	0	0	0	0
Market penetration	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
ANNUAL SAVINGS												
Energy Metrics												
Total primary energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct electricity displaced (billion kWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct natural gas displaced (bcf)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct petroleum displaced (million barrels)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct coal displaced (million short tons)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feedstock energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Financial Metrics												
Net Economic Benefit ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy-cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Non-energy cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Consumer Investment ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EERE Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Government Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private Sector Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Simple Payback Period (years)	None	None	None	None	None	None	None	None	None	None	None	None
Environmental Metrics												
CO Displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carbon Dioxide emissions displaced (MM TCE)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other greenhouse emissions displaced (MM TCE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2 displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particulates displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
VOCs displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrocarbons displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solid Waste (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other environmental benefits (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CUMULATIVE SAVINGS												
Energy Metrics												
Total primary energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct electricity displaced (billion kWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct natural gas displaced (bcf)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct petroleum displaced (million barrels)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct coal displaced (million short tons)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feedstock energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Financial Metrics												
Net Economic Benefit ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy-cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Non-energy cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Consumer Investment ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EERE Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Government Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private Sector Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Environmental Metrics												
CO Displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carbon Dioxide emissions displaced (MM TCE)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other greenhouse emissions displaced (MM TCE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2 displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particulates displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
VOCs displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrocarbons displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solid Waste (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other environmental benefits (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Impact by Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	0	0	0	0	1	2	3	5	7	11	17	24	35	47	61
	0	0	0	0	1	1	1	2	3	4	6	8	10	13	14
	0	0	0	0	0	0	0	0	0	1	1	1	2	3	5
	0	0	0	0	1	1	1	2	3	5	6	9	12	15	19
	0%	0%	0%	0%	1%	2%	3%	4%	7%	10%	15%	21%	29%	39%	50%
Annual Savings															
	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.05	0.08	0.12	0.18	0.26	0.38	0.51	0.66
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.05	0.08	0.12	0.18	0.26	0.37	0.50	0.65
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.29	0.46	0.72	1.13	1.74	2.67	4.01	5.88	8.36	11.41	14.89
	0.00	0.00	0.00	0.00	0.05	0.08	0.13	0.21	0.32	0.50	0.76	1.12	1.61	2.22	2.92
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.24	0.38	0.59	0.92	1.42	2.17	3.25	4.76	6.75	9.20	11.97
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	None	None	None	None	5.29	5.23	5.17	5.11	5.05	4.99	4.93	4.87	4.81	4.76	4.70
	0.00	0.00	0.00	0.00	0.38	0.60	0.94	1.47	2.27	3.47	5.20	7.62	10.80	14.71	19.15
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.03	0.05	0.07	0.10	0.14	0.19	0.25
	0.00	0.00	0.00	0.00	1.41	2.22	3.48	5.43	8.38	12.80	19.20	28.11	39.85	54.29	70.65
	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.03	0.05	0.07	0.09	0.12
	0.00	0.00	0.00	0.00	0.04	0.06	0.10	0.15	0.23	0.36	0.53	0.78	1.11	1.51	1.96
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cumulative Savings															
	0.00	0.00	0.00	0.00	0.01	0.03	0.07	0.12	0.20	0.32	0.50	0.76	1.14	1.65	2.31
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.19	0.31	0.49	0.74	1.11	1.61	2.25
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.29	0.75	1.47	2.60	4.34	7.01	11.01	16.90	25.25	36.67	51.55
	0.00	0.00	0.00	0.00	0.05	0.13	0.27	0.47	0.79	1.29	2.05	3.17	4.78	7.00	9.91
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.24	0.62	1.21	2.12	3.54	5.71	8.96	13.73	20.48	29.67	41.64
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.38	0.99	1.93	3.40	5.67	9.14	14.34	21.96	32.76	47.47	66.62
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.03
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.04	0.07	0.12	0.19	0.29	0.43	0.63	0.88
	0.00	0.00	0.00	0.00	1.41	3.64	7.12	12.54	20.93	33.72	52.92	81.03	120.88	175.17	245.82
	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.06	0.09	0.13	0.20	0.29	0.41
	0.00	0.00	0.00	0.00	0.04	0.10	0.20	0.35	0.58	0.94	1.47	2.25	3.36	4.86	6.82
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Impacts (Continued)	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
LIFETIME SAVINGS																											
Energy Metrics																											
Total primary energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.10	0.16	0.26	0.39	0.67	1.01	1.49	2.13	2.95	3.99
Direct electricity displaced (billion kWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct natural gas displaced (bcf)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.10	0.16	0.25	0.38	0.65	0.98	1.45	2.07	2.87	3.89
Direct petroleum displaced (million barrels)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct coal displaced (million short tons)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feedstock energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Financial Metrics																											
Net Economic Benefit ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.46	2.29	3.60	5.61	8.69	14.76	22.28	32.92	47.27	65.56	88.94
Energy-cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.41	0.65	1.02	1.59	2.72	4.14	6.17	8.93	12.48	17.06
Non-energy cost savings ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Consumer Investment ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	1.88	2.95	4.59	7.10	12.04	18.14	26.75	38.34	53.08	71.87
EERE Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Government Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private Sector Expenditures ($MM/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Environmental Metrics																											
CO Displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.92	3.01	4.72	7.35	11.36	19.26	29.03	42.81	61.35	84.92	115.00
Carbon Dioxide emissions displaced (MM TCE)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.03	0.04	0.06
Other greenhouse emissions displaced (MM TCE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2 displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.04	0.06	0.10	0.15	0.25	0.38	0.56	0.81	1.12	1.52
NOx displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.07	11.11	17.41	27.13	41.92	71.06	107.11	157.95	226.37	313.35	424.31
Particulates displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.07	0.12	0.18	0.26	0.37	0.52	0.70
VOCs displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.31	0.48	0.75	1.16	1.97	2.97	4.38	6.28	8.70	11.78
Hydrocarbons displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solid Waste (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other environmental benefits (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Energy Prices by Source (2000 Dollars per Million Btu, Unless Otherwise Noted)

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Industrial 4/	5.70	5.73	5.73	5.78	5.82	5.89	5.97	6.04	6.10	6.15	6.21	6.27
Primary Energy	4.45	4.49	4.52	4.57	4.61	4.68	4.76	4.81	4.88	4.92	4.99	5.05
Petroleum Products 2/	6.36	6.36	6.39	6.47	6.48	6.59	6.69	6.74	6.83	6.87	6.97	7.08
Distillate Fuel	5.52	5.54	5.54	5.62	5.60	5.78	5.89	5.91	5.98	6.15	6.34	6.52
Liquefied Petroleum Gas	8.36	8.28	8.30	8.38	8.40	8.43	8.60	8.64	8.84	8.83	8.87	8.98
Residual Fuel	3.56	3.57	3.59	3.60	3.62	3.64	3.65	3.66	3.68	3.71	3.73	3.74
Natural Gas 5/	3.21	3.30	3.32	3.35	3.41	3.43	3.47	3.53	3.58	3.62	3.65	3.69
Metallurgical Coal	1.61	1.60	1.59	1.58	1.57	1.57	1.56	1.55	1.55	1.54	1.52	1.52
Steam Coal	1.36	1.35	1.34	1.33	1.32	1.31	1.30	1.30	1.29	1.28	1.27	1.26
Electricity	12.82	12.72	12.50	12.43	12.44	12.44	12.54	12.62	12.58	12.63	12.61	12.62
Feedstock	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Renewable	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

2/ This quantity is the weighted average for all petroleum products, not just those listed below.
4/ Includes cogenerators.
5/ Excludes uses for lease and plant fuel.
Source: GPRA2004 Data Call

Energy Prices on Physical Unit Basis

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Industrial												
Primary Energy												
Petroleum Products												
Distillate Fuel (million $ / million barre	32.18	32.26	32.26	32.72	32.61	33.67	34.29	34.40	34.84	35.81	36.95	37.99
Liquefied Petroleum Gas (million $ / n	30.13	29.82	29.90	30.18	30.25	30.38	30.97	31.13	31.85	31.80	31.97	32.37
Residual Fuel (million $ / million barre	22.37	22.45	22.56	22.63	22.74	22.86	22.97	23.00	23.12	23.30	23.42	23.54
Natural Gas (million $ / bcf)	3.29	3.39	3.41	3.44	3.50	3.53	3.57	3.63	3.68	3.72	3.75	3.79
Metallurgical Coal (million $/ million sho	36.23	36.03	35.82	35.62	35.30	35.21	35.12	34.91	34.78	34.62	34.27	34.16
Steam Coal (million $ / million short tor	30.63	30.38	30.20	29.97	29.73	29.44	29.29	29.20	28.98	28.76	28.62	28.40
Electricity-site (million $ / billion kWh)	43.73	43.39	42.65	42.40	42.46	42.46	42.77	43.05	42.94	43.10	43.02	43.07
Feedstock	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Renewable	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Energy Prices by Source (Continued)

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	After 2030
6.31	6.33	6.38	6.43	6.49	6.54	6.59	6.65	6.70	6.76	6.81	6.87	6.93	6.98	7.04	7.04
5.08	5.07	5.10	5.15	5.19	5.23	5.28	5.33	5.37	5.42	5.47	5.52	5.56	5.61	5.66	5.66
7.10	7.06	7.06	7.11	7.13	7.17	7.22	7.26	7.31	7.35	7.40	7.45	7.49	7.54	7.59	7.59
6.58	6.59	6.60	6.68	6.70	6.79	6.88	6.97	7.06	7.15	7.25	7.34	7.44	7.53	7.63	7.63
9.00	9.02	9.03	9.08	9.11	9.16	9.22	9.27	9.32	9.38	9.43	9.49	9.54	9.60	9.66	9.66
3.77	3.79	3.81	3.84	3.86	3.89	3.91	3.93	3.95	3.97	4.00	4.02	4.04	4.06	4.09	4.09
3.72	3.76	3.80	3.85	3.90	3.95	4.00	4.04	4.09	4.14	4.19	4.24	4.29	4.34	4.39	4.39
1.51	1.50	1.49	1.48	1.46	1.45	1.44	1.43	1.43	1.42	1.41	1.40	1.39	1.38	1.37	1.37
1.26	1.25	1.23	1.22	1.21	1.21	1.20	1.19	1.18	1.17	1.16	1.16	1.15	1.14	1.13	1.13
12.71	12.81	12.92	12.97	13.04	13.10	13.15	13.20	13.25	13.31	13.36	13.41	13.46	13.52	13.57	13.57
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Energy Prices on a Physical Unit Basis

38.33	38.41	38.44	38.90	39.05	39.56	40.08	40.60	41.13	41.67	42.21	42.76	43.32	43.89	44.46	44.46
32.44	32.49	32.55	32.70	32.82	33.02	33.21	33.40	33.60	33.79	33.99	34.19	34.39	34.59	34.79	34.79
23.67	23.80	23.94	24.14	24.30	24.43	24.57	24.71	24.85	24.99	25.13	25.27	25.41	25.56	25.70	25.70
3.82	3.86	3.90	3.95	4.01	4.06	4.10	4.15	4.20	4.25	4.30	4.35	4.40	4.45	4.51	4.51
34.03	33.69	33.56	33.24	32.91	32.69	32.48	32.27	32.06	31.85	31.65	31.44	31.24	31.03	30.83	30.83
28.25	28.00	27.75	27.51	27.31	27.12	26.93	26.74	26.55	26.37	26.18	26.00	25.82	25.64	25.46	25.46
43.36	43.72	44.08	44.25	44.51	44.68	44.86	45.04	45.22	45.40	45.58	45.76	45.94	46.12	46.31	46.31
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Heat Rates

Energy Content of Fuel

Coal production	21.070	million Btu per short ton
Coal consumption	20.753	million Btu per short ton
Coke Plants	27.426	million Btu per short ton
Industrial	22.489	million Btu per short ton
Residential and Commercial	23.880	million Btu per short ton
Electric Utilities	20.401	million Btu per short ton
Crude oil production	5.800	million Btu per barrel
Oil products consumption	5.336	million Btu per barrel
Motor gasoline	5.204	million Btu per barrel
Jet fuel (kerosene)	5.670	million Btu per barrel
Distillate fuel oil	5.825	million Btu per barrel
Residual fuel oil	6.287	million Btu per barrel
Liquefied petroleum gas	3.603	million Btu per barrel
Kerosene	5.670	million Btu per barrel
Petrochemical feedstocks	5.545	million Btu per barrel
Unfinished oils	5.825	million Btu per barrel
Natural gas production	1,027	Btu per cubic foot
Natural gas consumption	1,027	Btu per cubic foot
Natural gas consumption from electric utilities	1,019	Btu per cubic foot

Source: GPRA2004 Data Call

Projected Electricity Heat Rates Using Marginal Fuel Mix

	2004	**2005**	**2006**	**2007**	**2008**	**2010**	**2015**	**2020**	**2025**	**2030**	**After 2030**
Fuel Mix											
Natural Gas	62.9%	58.8%	54.9%	47.7%	47.7%	51.9%	60.3%	63.2%	63.2%	63.2%	63.2%
Oil	9.2%	5.3%	5.4%	4.7%	4.7%	1.2%	1.3%	1.8%	1.8%	1.8%	1.8%
Coal	27.8%	35.9%	39.7%	47.7%	47.7%	46.9%	38.5%	35.0%	35.0%	35.0%	35.0%
Non-Fossil	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Heat Rates (Btu/kWh)											
Natural Gas	10,787	10,573	9,736	9,624	9,624	7,754	6,866	6,705	6,705	6,705	6,705
Oil	10,494	10,767	10,724	10,354	10,354	10,354	10,043	9,658	9,658	9,658	9,658
Coal	10,616	10,601	10,583	10,556	10,556	10,387	10,402	9,942	9,942	9,942	9,942
Non-Fossil	0	0	0	0	0	0	0	0	0	0	0
GPRA Heat Rates											
Electricity (Btu per kWh)	**10,713**	**10,593**	**10,126**	**10,102**	**10,102**	**9,019**	**8,266**	**7,891**	**7,891**	**7,891**	**7,891**
Natural Gas Electricity (Btu per kWh)	6,789	6,218	5,345	4,589	4,589	4,027	4,139	4,239	4,239	4,239	4,239
Oil Electricity (Btu per kWh)	967	568	580	482	482	126	126	171	171	171	171
Coal Electricity (Btu per kWh)	2,956	3,807	4,201	5,032	5,032	4,867	4,001	3,480	3,480	3,480	3,480
Non-Fossil (Btu per kWh)	0	0	0	0	0	0	0	0	0	0	0

Source: GPRA2004 Data Call

Emission Factors

	2004	2005	2006	2007	2008	2010	2015	2020	2025	2030	After 2030
Emission Factors on Physical Unit Basis											
Carbon Coefficient											
Electricity (MMTCE per billion kWh)	0.194	0.199	0.196	0.205	0.205	0.185	0.164	0.153	0.153	0.153	0.153
Natural Gas (MMTCE tonnes per bcf)	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
Petroleum - Residual Fuel (MMTCE per million b	0.134	0.134	0.134	0.134	0.134	0.134	0.134	0.134	0.134	0.134	0.134
Petroleum - Distillate Fuel (MMTCE per million b	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.115
Petroleum - LPG (MMTCE per million barrels)	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062
Coal (MMTCE per million short tons)	0.571	0.571	0.571	0.571	0.571	0.571	0.571	0.571	0.571	0.571	0.571
Feedstock (MMTCE per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biomass (MMTCE per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Waste (MMTCE per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other (MMTCE per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NOx Coefficients											
Electricity (Metric tonnes per billion kWh)	1608	1708	1717	1834	1834	1682	1474	1359	1359	1359	1359
Natural Gas (Metric tonnes per bcf)	109	109	109	109	109	109	109	109	109	109	109
Petroleum (Metric tonnes per million barrels)	878	878	878	878	878	878	878	878	878	878	878
Coal (Metric tonnes per million short tons)	5716	5716	5716	5716	5716	5716	5716	5716	5716	5716	5716
Feedstock (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biomass (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Waste (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SO2 Coefficients											
Electricity (Metric tonnes per billion kWh)	2193	2465	2695	3116	3116	2834	2342	2070	2070	2070	2070
Natural Gas (Metric tonnes per bcf)	0.390	0.390	0.390	0.390	0.390	0.390	0.390	0.390	0.390	0.390	0.390
Petroleum (Metric tonnes per million barrels)	3315	3315	3315	3315	3315	3315	3315	3315	3315	3315	3315
Coal (Metric tonnes per million short tons)	12781	12781	12781	12781	12781	12781	12781	12781	12781	12781	12781
Feedstock (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biomass (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Waste (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
VOCs Coefficients											
Electricity (Metric tonnes per billion kWh)	27	25	23	22	22	19	18	18	18	18	18
Natural Gas (Metric tonnes per bcf)	3.029	3.029	3.029	3.029	3.029	3.029	3.029	3.029	3.029	3.029	3.029
Petroleum (Metric tonnes per million barrels)	23	23	23	23	23	23	23	23	23	23	23
Coal (Metric tonnes per million short tons)	30	30	30	30	30	30	30	30	30	30	30
Feedstock (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biomass (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Waste (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO Coefficients											
Electricity (Metric tonnes per billion kWh)	242	230	210	196	196	174	167	164	164	164	164
Natural Gas (Metric tonnes per bcf)	29.572	29.572	29.572	29.572	29.572	29.572	29.572	29.572	29.572	29.572	29.572
Petroleum (Metric tonnes per million barrels)	84	84	84	84	84	84	84	84	84	84	84
Coal (Metric tonnes per million short tons)	259	259	259	259	259	259	259	259	259	259	259
Feedstock (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biomass (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Waste (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PM10 Coefficients											
Electricity (Metric tonnes per billion kWh)	43	51	56	65	65	61	50	44	44	44	44
Natural Gas (Metric tonnes per bcf)	0.180	0.180	0.180	0.180	0.180	0.180	0.180	0.180	0.180	0.180	0.180
Petroleum (Metric tonnes per million barrels)	41	41	41	41	41	41	41	41	41	41	41
Coal (Metric tonnes per million short tons)	273	273	273	273	273	273	273	273	273	273	273
Feedstock (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biomass (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Waste (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other (Metric tonnes per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other GHG Coefficients											
Electricity (MMTCE per billion kWh)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Natural Gas (MMTCE tonnes per bcf)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Petroleum (MMTCE per million barrels)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Coal (MMTCE per million short tons)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Feedstock (MMTCE per trillion Btu)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000