DOE/ID/13331-4

DILUTE OXYGEN COMBUSTION

Phase 4 Report: Optimized Reheat Furnace Design

April 2003

Work Performed Under Cooperative Agreement DE-FC36-95ID13331

FOR:
U.S. Department of Energy
Assistant Secretary for
Energy Efficiency and Renewable Energy
Washington, DC

BY:
Praxair, Inc.
Praxair Metals Technologies
Indianapolis, IN
Michael F. Riley, Ph.D., Principal Investigator

ACKNOWLEDGEMENTS

This work was conducted with the financial support of the U.S. Department of Energy, Office of Industrial Technologies, under Cooperative Agreement DE-FC36-95ID13331. In addition to this financial support, technical guidance was provided under the Cooperative Agreement by Joseph Keller, Idaho National Engineering & Environmental Laboratory, and Robert Gemmer, Walter Mings, and Gideon Varga, U.S. Department of Energy.

Funding was also provided by Praxair, Inc. The contributions of Sho Kobayashi of Praxair to the furnace design effort, the excellent work of Richard Semenza of Praxair in developing the apparatus for the oxide scaling studies, and the valuable assistance of Ron Daruwala of Praxair Metals Technologies in developing the net present value calculation are gratefully acknowledged.

The outstanding efforts and cooperation of the engineers and managers at Techint Technologies were instrumental in the successful development and analysis of the DOC furnace designs. Sincere appreciation is extended to William Barraclough and Steven O'Connor of Techint Technolgies.

Thanks are extended to John Deacon, Nucor Auburn Steel, for supplying the steel for the scaling studies.

TABLE OF CONTENTS

Abstract.......... vii

1. INTRODUCTION.......... 1

2. DOC FURNACE DESIGN STRATEGIES.......... 3
Baseline Furnace Designs.......... 3
DOC Furnace Designs.......... 3
Maintenance Issues and Costs.......... 5

3. EVALUATION PROCEDURE.......... 6

4. RESULTS.......... 7
Furnace Structure.......... 7
Energy Balance.......... 10
NOx Emissions.......... 10
Oxide Scaling.......... 13
Net Present Value Calculation.......... 15

5. CONCLUSIONS.......... 18

Appendix 1: Natural gas chemistry.......... 21

Appendix 2: Oxide scaling experimental program summary.......... 22
Classical scaling mechanism.......... 22
Deviations from classical mechanism.......... 23
Effects of atmosphere.......... 23
Summary of literature results.......... 24
Experimental Method.......... 25
Results.......... 29
Analysis.......... 31

Appendix 3: Furnace structural drawings.......... 33

Appendix 4: Energy balances.......... 47

Appendix 5: Furnace and steel heating curves.......... 62

References.......... 70

LIST OF FIGURES

Figure 1 – Schematic of DOC concept. 1

Figure 2 – Furnace longitudinal internal profiles. Dimensions in feet. 7

Figure 3 – Heat input comparison as designed. 10

Figure 4 – Heat output comparison as designed. 11

Figure 5 – Comparison of flue gas volume and temperature as designed.. 11

Figure 6 - Heat input comparison with furnace degradation. 12

Figure 7 - Heat output comparison with furnace degradation. 12

Figure 8 – Comparison of flue gas volume and temperature with furnace degradation. 13

Figure 9 – Comparison of NOx emissions at full firing capacity. 14

Figure 10 –Comparison of estimated oxide scale formation 15

Figure 11 – Comparison of total cost per ton of steel processed for each design relative to standard furnace. 16

Figure 12 – Comparison of total cost per ton of steel processed for each design with NOx ≤ 10 lb/hr relative to standard furnace with SCR. 16

Figure 13 – Incremental cost of DOC furnace designs per pound NOx eliminated, relative to standard furnace. 19

Figure A-1 - Summary of parabolic rate constant data from Sheasby et al. and Tada. 24

Figure A-2 – Experimental apparatus for scaling tests. 26

Figure A-3 - Measured furnace temperature in Auburn Steel reheat furnace. 26

Figure A-4 - Parabolic rate constant for air-fired tests 30

Figure A-5 - Parabolic rate constant for oxy-fuel fired tests 30

Figure A-6 - Parabolic rate constant as function of level of total oxidizing species in gas. 31

Figure A-7 – Parabolic rate constant for tests simulating air-fired entry zone and oxy-fuel fired heat and soak zones.. 32

LIST OF TABLES

Table I – Summary of Furnace Designs ... 4

Table II – Burner arrangement ... 8

Table III – Fan and other electrical requirements ... 8

Table IV – Water, compressed air, and reagent requirements ... 8

Table V – Flue and stack dimensions ... 9

Table VI – Capital costs ... 9

Table VII – NOx emissions estimates ... 14

Table VIII – Summary of 10-year net present value calculation ... 15

Table A-I – Composition of steel used in scaling tests ... 25

Table A-II – Burner type for each conversion level ... 27

Table A-III – Firing rate, temperature, and gas velocity for each zone and conversion level ... 28

Table A-IV – Time, temperature, and flow rates for each zone and conversion level ... 28

ABSTRACT

Novel furnace designs based on Dilute Oxygen Combustion (DOC) technology were developed under subcontract by Techint Technologies, Coraopolis, PA, to fully exploit the energy and environmental capabilities of DOC technology and to provide a competitive offering for new furnace construction opportunities. Capital cost, fuel, oxygen and utility costs, NOx emissions, oxide scaling performance, and maintenance requirements were compared for five DOC-based designs and three conventional air-fired designs using a 10-year net present value calculation.

A furnace fired completely with DOC burners offers low capital cost, low fuel rate, and minimal NOx emissions. However, these benefits do not offset the cost of oxygen, and a full DOC-fired furnace is projected to cost $1.30 per ton more to operate than a conventional air-fired furnace. The incremental cost of the improved NOx performance is roughly $6/lb NOx, compared with an estimated $3/lb NOx for equipping a conventional furnace with selective catalytic reduction (SCR) technology.

A furnace fired with DOC burners in the heating zone and ambient temperature (cold) air-fired burners in the soak zone offers low capital cost with less oxygen consumption. However, the improvement in fuel rate is not as great as the full DOC-fired design, and the DOC-cold soak design is also projected to cost $1.30 per ton more to operate than a conventional air-fired furnace. The NOx improvement with the DOC-cold soak design is also not as great as the full DOC-fired design, and the incremental cost of the improved NOx performance is nearly $9/lb NOx.

These results indicate that a DOC-based furnace design will not be generally competitive with conventional technology for new furnace construction under current market conditions. Fuel prices of $7/MMBtu or oxygen prices of $23/ton are needed to make the DOC furnace economics favorable. Niche applications may exist, particularly where access to capital is limited or floor space limitations are critical. DOC technology will continue to have a highly competitive role in retrofit applications requiring increases in furnace productivity.

1. INTRODUCTION

Controlling the generation of nitrogen oxides (NO_x) in industrial combustion processes is essential to mitigating acid rain, ground level ozone, and photochemical smog.[1,2] The primary mechanism for NO_x formation is the Zeldovich, or "thermal NO_x" mechanism, which is very sensitive to peak flame temperature, nitrogen level, and excess oxygen level.[1]

Dilute Oxygen Combustion (DOC) burners, patented by Praxair, Inc., provide very low levels of NO_x by controlling each of these sensitive parameters.[3,4] DOC burners inject fuel and oxygen *separately* into a furnace as high-velocity jets. As shown schematically in Figure 1, with DOC burners fuel and oxygen do not react directly. Instead, the high-velocity oxygen jet mixes rapidly into the furnace gas, and the fuel jet entrains and reacts with this high-temperature, dilute-oxygen furnace gas. This dilution leads to low peak flame temperatures. In addition, since DOC burners use oxygen rather than air for combustion, there is no nitrogen added to the combustion process. Lastly, the flow controls employed with oxy-fuel systems offer close control of excess oxygen. This combination of temperature control, nitrogen control, and excess oxygen control leads to very low NO_x generation by DOC burners.

In Phase 1 of this project, laboratory-scale DOC burners operated under controlled conditions were shown to produce NO_x levels as low as 0.0009 lb/MMBtu at 2300°F in low-nitrogen furnace atmospheres (equivalent to 0.8 ppm from an air burner system at 3% oxygen, dry basis) and 0.03 lb/MMBtu (30 ppm air equivalent) at 2300°F with 77% nitrogen in the furnace atmosphere.[5]

Commercial-scale DOC burners were developed and tested in Phase 2 of this project with similar results. In low-nitrogen atmospheres, DOC burners produced

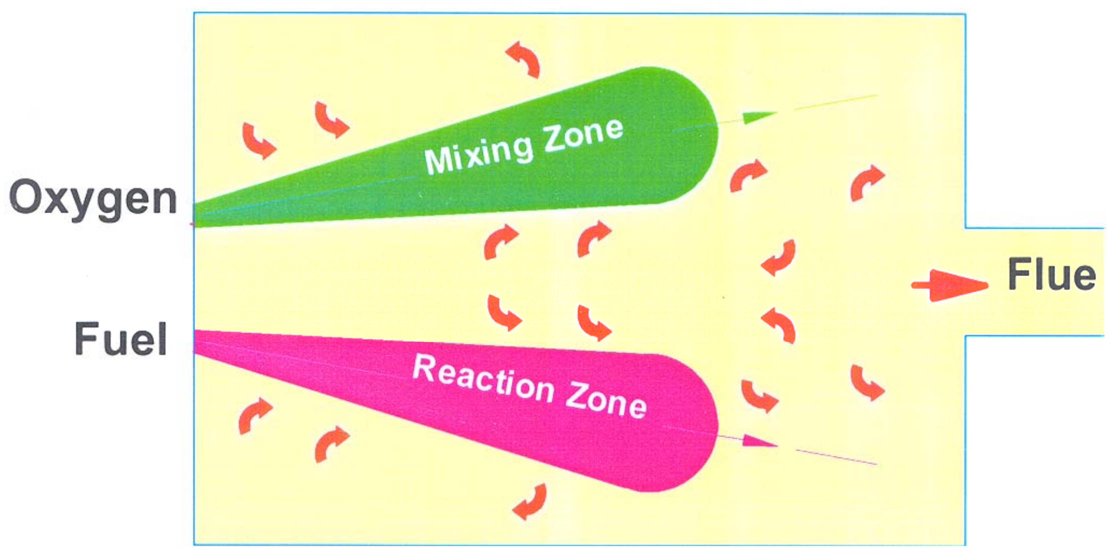


Figure 1 – Schematic of DOC concept.

0.001 lb/MMBtu at 2300°F at 5 MMBtu/hr firing rate while in a 75% nitrogen atmosphere DOC burners produced 0.035 lb/MMBtu at 2 MMBtu/hr.[6]

Under Phase 3 of this project, DOC burners were successfully installed and operated in the reheat furnace at Nucor Auburn Steel, Auburn, NY. Two new preheat zones were created employing a total of eight 6.5 MMBtu/hr burners. The preheat zones provided a 30 percent increase in maximum furnace production rate, from 75 tph to 100 tph. The fuel rate was essentially unchanged, with the fuel savings expected from oxy-fuel combustion being offset by higher flue gas temperatures. NOx performance of the DOC burners was higher than originally anticipated because of the high gas temperatures required for peak furnace productivity and because of the high nitrogen levels created by the combustion products of the original air-fired zones. When allowance was made for the high nitrogen level and high gas phase temperature in the furnace, measured NO_x emissions were in line with laboratory data on DOC burners developed in Phase 1 and Phase 2 of the project.[7]

The DOC system continues to be used as part of Nucor Auburn Steel's standard reheat furnace practice. Despite this success, it was clear that the full potential of DOC technology had not been reached on the commercial system. In addition, while DOC technology was demonstrated as a retrofit application, it remained unclear how DOC technology should be employed on newly constructed furnaces. Phase 4 of the DOC project was initiated to develop a reheat furnace design to fully exploit the capabilities of DOC technology and develop a competitive offering for new furnace construction opportunities.

A furnace designed around DOC technology would have many important commercial advantages. The principal advantage of a DOC furnace would be its low capital cost. Because oxy-fuel reheating is faster than air-fuel reheating, a DOC furnace can be much smaller. In addition, since oxy-fuel combustion gives high efficiency without heat recovery, furnace recuperators can be eliminated where oxy-fuel combustion is used. Finally, flue gas handling systems can be made much smaller since oxy-fuel combustion produces only ¼ the off-gas of air-fuel combustion. The low capital cost of a DOC furnace would make it very attractive to the domestic steel industry, where access to capital is increasingly difficult.

A DOC furnace would also offer lower environmental and permitting costs associated with lower NOx emissions and lower energy costs associated with a lower fuel rate. Countering these benefits are the increased operating costs associated with an oxygen supply system.

To find the optimum DOC furnace configuration, several design strategies were explored and evaluated for the lowest total cost, considering capital, operating, and maintenance expenses. The different designs were compared using a 10-year net present value (NPV) model.

2. DOC FURNACE DESIGN STRATEGIES

Baseline Furnace Designs

The baseline design for the study was a natural gas-fired walking-beam continuous reheat furnace providing 120-tons per hour of 6" square carbon steel billets at 2150°F average temperature with a maximum 50°F difference between the billet surface and billet core. (Assumed natural gas chemistry is listed in Appendix 1.) The furnace was equipped with a recuperative heat recovery system to capture energy from the flue gas and preheat combustion air to 900°F. The furnace was assumed to operate with an ambient temperature steel charge (70°F) and 1% oxygen (wet basis) in the flue gas.

Since a DOC furnace offers improved fuel and emissions performance, two cases employing conventional fuel reduction and emission control technologies were also examined. One is a standard furnace design with an extended preheat zone to extract more heat from the furnace gases before discharge to the flue. This design gives a lower fuel rate and slightly lower NOx emissions but requires slightly more capital. A consequence of extracting more heat from the gas within the furnace is that less heat is available for preheating air, and the long standard furnace design was assumed to operate with combustion air at 850°F.

The other baseline case is a standard furnace equipped with a selective catalytic reduction (SCR) unit to destroy NOx downstream of the reheat furnace.[8] This case offers lower NOx but requires higher capital and operating costs. There are also concerns about the difficulties of integrating an SCR unit with a steel reheating furnace.[9,10] While SCR eliminates >70% of NOx in boiler applications, a lower average efficiency is expected for steel reheating furnaces, and a 60% NOx removal efficiency was assumed for the SCR unit. A long furnace-SCR combination was not considered because of the difficulty in operating SCR with lower temperature flue gases.

These three cases using conventional technology provide the baseline for evaluation of a DOC furnace design.

DOC Furnace Designs

The optimal DOC furnace design must balance several operating parameters: fuel rate, oxide scaling rate, and NOx performance.

To obtain maximum fuel efficiency and lowest NOx performance, the entire reheat furnace should be fired with DOC burners. However, the need to control oxide scale formation on the steel being reheated may prohibit using DOC burners in the soak zone. Because nitrogen is eliminated from the oxidant, oxy-fuel combustion produces high concentrations of oxidizing gases (CO_2 and H_2O).

Table I – Summary of Furnace Designs

Furnace	Features					Key advantage	Key limitation
	Heat zone[a]	Soak zone[a]	Heat recovery[b]	Soak flue[c]	SCR[c]		
Full DOC	D	D	N	N	N	capital cost	scaling
Hot Soak	D	HA	S	N	N	no scaling	
Cold Soak	D	CA	N	N	N	no scaling	
Hot – 2nd flue	D	HA	S	Y	N	emissions	
Cold – 2nd flue	D	CA	N	Y	N	emissions	
Standard	HA	HA	L	N	N		
Std. long	HA	HA	L	N	N	operating cost	
Std. SCR	HA	HA	L	N	Y	emissions	capital cost

[a] D – DOC, HA – hot air, CA – cold air
[b] N – none, S – small unit, L – large unit
[c] Y – yes, N – no

In the heating zones, this is not a problem since the steel surface is generally below 2000°F, and scale formation kinetics are slow. However, in the soak zone scale forms quickly on the hot steel surface. Here the more oxidizing oxy-fuel atmosphere could lead to increased scale formation. A literature review and experimental program, described in Appendix 2, were conducted to provide more insight into the effect of oxy-fuel atmospheres on scaling rates. Those results suggest that if DOC furnace processing time is fast enough, the shorter contact time could offset the increased scaling rate, giving acceptable amounts of scale with a full DOC furnace design. Accordingly, two basic designs need to be considered, full-DOC and DOC with an air soak zone.

From the standpoint of minimizing fuel consumption, an air soak zone should use preheated air. This would require a small recuperator, raising the capital cost of the furnace. In contrast, using a cold air soak zone would eliminate the need for any heat recovery system, but this design will have higher operating costs since more fuel will be required. Therefore, two air soak zone cases need to be evaluated, a 900°F preheated (hot) air soak zone and an ambient (cold) air soak zone.

While air soak zones may minimize excess scale formation, they can lead to higher NOx generation in the DOC zones. This will occur if the high-nitrogen combusted gas from the air soak zone must pass through the DOC zones to reach the furnace flue as in conventional furnace designs. A second, separate flue for the soak zone would prevent mixing of the air zone and DOC zone gases, generating much less NOx in the DOC zones. However, these designs will require higher capital and operating costs. Therefore, two additional air soak zone cases need to be evaluated, hot air soak with separate flue and cold air soak with separate flue.

In summary, these competing capital, operating, and environmental considerations produce five DOC furnace cases with advantages and disadvantages summarized in Table I along with the three conventional technology cases.

Maintenance Issues and Costs

The primary difference in maintenance among the furnace designs in Table I is recuperator repair. The air-fired furnace designs will require considerable expense to maintain heat recovery performance of the large recuperator units. In contrast, the DOC-hot air designs will require less expense for the smaller recuperator while the other DOC designs will require no recuperator maintenance.

Recuperator maintenance is a major project and so it is generally done only after several years of operation. Between repairs, the performance of the recuperator gradually declines, leading to higher fuel rates.

In a similar fashion, the insulation covering the water-cooled components of the skids and walking beams in the furnace tends to degrade over time. These repairs are also made infrequently, leading to gradually increasing fuel rates.

To capture these effects in the analysis, the performance of each furnace design was evaluated under design conditions and under degraded conditions, assumed to be a 150°F drop in air preheat temperature and a 10% loss of skid insulation. The performance of each furnace was then assumed to decline linearly from design conditions to degraded conditions over a 5 year period. After 5 years, it was assumed that maintenance was performed on both the recuperator and skid insulation, restoring the furnace to design conditions. A second degradation and repair cycle was then assumed to occur, giving two complete cycles within the 10-year NPV calculation.

3. EVALUATION PROCEDURE

Detailed furnace design calculations were made for each case by Techint Technologies, Coraopolis, PA. Techint Technologies is a major reheat furnace manufacturer with over 150 reheat furnace customers in 35 countries.

Techint Technologies made capital cost calculations for each design, along with an estimate of maintenance costs specific to each design. NOx performance for air-fired zones was estimated by Techint Technologies based on commercial, low-NOx air burner performance data, and NOx performance for DOC-fired zones was estimated by Praxair from Phase 2 test results. Oxide scaling for each design was estimated by applying the equation developed in Appendix 2.

All costs were combined into a 10-year net present value calculation made according to the following assumptions:

- Capital costs are financed over a 10-year period at an overall average cost of capital of 12.5%.
- NOx emission reduction credits (ERCs) must be purchased at a new source offset ratio of 1.2 times the annual NOx emission rate at design firing capacity, consistent with a facility located in a “Serious” NAA non-attainment region.[11] The cost of NOx ERCs is $6,000/ton, representative of steelmaking state values.[12] These costs are paid “up front”, i.e., in year 0.
- The furnace operates for twenty, 8-hour turns per week, 50 weeks per year, with a 15% delay rate.
- Natural gas price in year 1 is $3.75/MMBtu. Natural gas price inflation is 3% per year.
- Oxygen price in year 1 is $32/ton. Oxygen price inflation is 1% per year.
- Electricity price in year 1 is $0.04/kWh and the cost of cooling water is $2.00 per 1000 gallons. Inflation for both utilities is 2% per year.
- The price of SCR reagent is $150/ton. Reagent price inflation is 2% per year.
- The cost of a large recuperator repair in year 1 is $300,000, and the cost of a small recuperator repair in year 1 is $40,000. Inflation for both costs is 2% per year. The cost of skid insulation repair is constant for all cases.
- Annual SCR maintenance cost in year 1 is $15,000. Inflation for SCR maintenance is 2% per year.
- The net present value of all costs beyond year 1 are discounted at a 12.5% discount rate.

4. RESULTS

Furnace Structure

Formal structural drawings for each design are found in Appendix 3. Simplified sketches comparing the longitudinal profile of each furnace interior are shown in Figure 2. The DOC furnace designs are 15% shorter in length and 15%-30% lower in height compared with the standard furnace. The long air-fired furnace, in contrast, is 23% longer and the same height as the standard furnace.

Table II shows the number and firing capacity of the burners for each furnace zone in each design. Table III shows the fan and other electrical requirements for each furnace design. Table IV shows the cooling water and compressed air requirements for each design. Table V compares the flue duct diameter and the required exhaust stack height and diameter for each design.

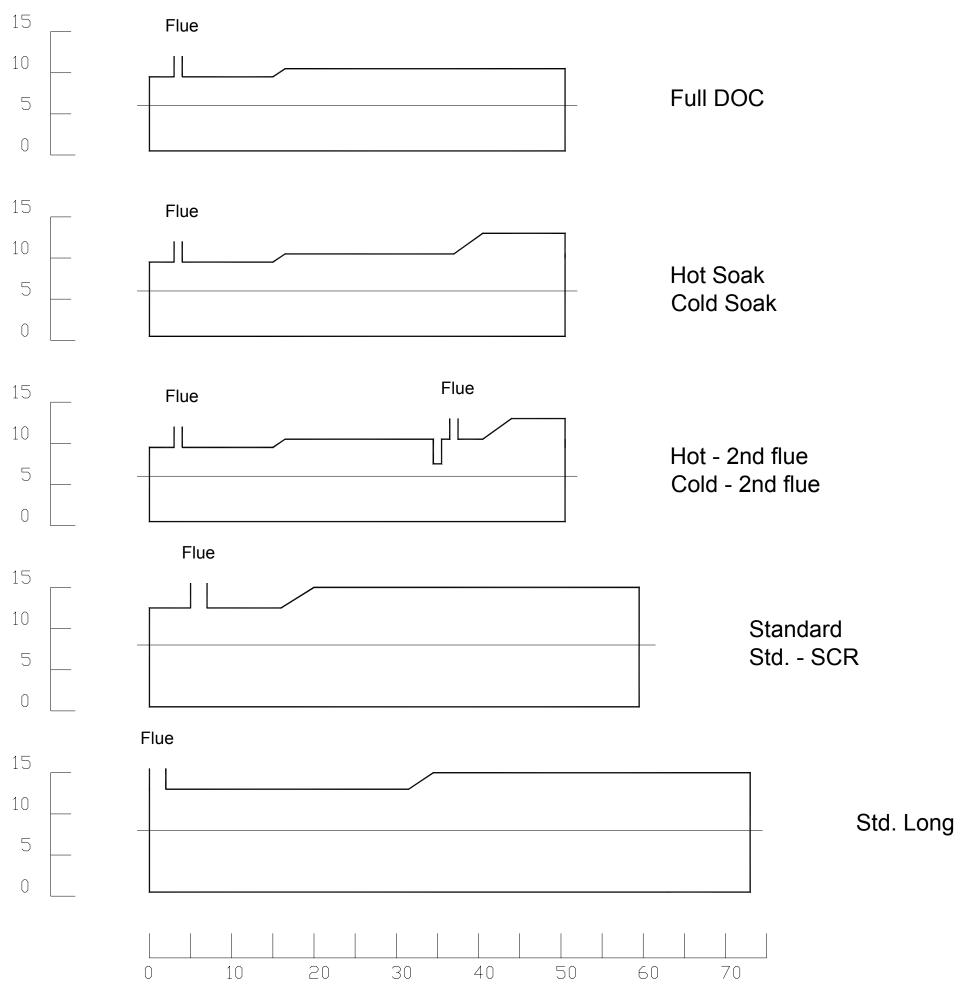


Figure 2 – Furnace longitudinal internal profiles. Dimensions in feet.

Table II – Burner arrangement

Furnace	Top Heat		Bottom Heat		Top Soak		Bottom Soak	
	Burners	Input, MMBtu/hr	Burners	Input, MMBtu/hr	Burners	Input, MMBtu/hr	Burners	Input, MMBtu/hr
Full DOC	6	51	6	51	8	16	8	20
Hot Soak	6	54	6	54	8	24	8	24
Cold Soak	6	48	6	48	8	28	8	36
Hot – 2nd flue	6	54	6	54	8	24	8	24
Cold – 2nd flue	6	54	6	54	8	32	8	42
Standard	8	54	6	58	8	24	8	28
Std. long	8	48	6	54	8	24	8	28
Std. SCR	8	54	6	58	8	24	8	28

Table III – Fan and other electrical requirements

Furnace	Combustion Air Fan, HP	Dilution Air Fan, HP	Peripheral, HP	Total, HP	SCR, kW	Electrical Usage, kWh/ton
Full DOC	0	0	300	300	0	1.7
Hot Soak	125	5	300	430	0	2.4
Cold Soak	100	0	300	400	0	2.2
Hot – 2nd flue	125	5	300	430	0	2.4
Cold – 2nd flue	100	0	300	400	0	2.2
Standard	350	15	350	715	0	4.0
Std. long	350	15	350	715	0	4.0
Std. SCR	350	15	350	715	150	5.3

Table IV – Water, compressed air, and reagent requirements

Furnace	Contact Water, GPM	Non-contact Water, GPM	Total Water, gal/ton	Compressed Air, scfm	SCR reagent, lb/ton
Full DOC	32	1500	766	150	0
Hot Soak	32	1500	766	150	0
Cold Soak	32	1500	766	150	0
Hot – 2nd flue	32	1500	766	150	0
Cold – 2nd flue	32	1500	766	150	0
Standard	37	1700	869	150	0
Std. long	45	1925	985	150	0
Std. SCR	37	1700	869	150	1.7

Table V – Flue and stack dimensions

Furnace	Flue ID, ft	Stack Height, ft	Stack ID, ft
Full DOC	3.0	50	3.0
Hot Soak	4.5	100	4.0
Cold Soak	5.0	50	5.0
Hot – 2nd flue	2.5 p	50 p	2.5 p
	3.8 s	100 s	3.0 s
Cold – 2nd flue	2.5 p	50 p	2.5 p
	4.7 s	50 s	4.7 s
Standard	8.0	150	6.5
Std. long	6.5	150	5.2
Std. SCR	8.0	150	6.5

p – primary flue
s – soak zone flue

Table VI – Capital costs

Furnace	Engineering	Equipment and Materials	Foundations	Installation and Commissioning	Total
Full DOC	1,271,000	2,598,000	295,000	2,019,000	$6,183,000
Hot Soak	1,279,000	2,558,000	308,000	2,025,000	$6,170,000
Cold Soak	1,259,000	2,461,000	295,000	1,958,000	$5,973,000
Hot – 2nd flue	1,304,000	2,634,000	314,000	2,090,000	$6,342,000
Cold – 2nd flue	1,284,000	2,508,000	302,000	1,986,000	$6,080,000
Standard	1,278,000	3,123,000	350,000	2,450,000	$7,021,000
Std. long	1,305,000	3,305,000	405,000	2,622,000	$7,637,000
Std. SCR	1,350,000	4,128,000	363,000	2,499,000	$8,340,000

Table VI compares the capital cost requirements for each design. These costs are broken down into engineering, equipment and materials, foundations, and installation and commissioning. Engineering includes all design engineering, drafting, project administration, procurement, expediting, shop inspections, and control software development and programming. Equipment and materials includes all steel fabrications, refractories, piping, mechanical product handling equipment inside the furnace, burners, combustion system, access platforms, flue, recuperator and stack, electric motors, motor controls, PLC for product handling control, and process control system including all instrumentation. Foundations include all civil work, excavation, back fill, concrete installation, drains and sewers, and embedded steel and anchor bolts. Installation and commissioning includes installation supervision and labor, unloading and storage at the job-site, tools, cranes, temporary electrical power, checkout, start-up, and commissioning.

Energy Balance

Detailed energy balances for each design are found in Appendix 4. Heating curves for the furnace and the steel for each design are found in Appendix 5. Figure 3 summarizes graphically the energy inputs for each design, and Figure 4 summarizes the energy outputs for each design. The primary difference in energy output is the heat carried off by the flue gas. The flue gas volume and temperature for each design are compared in Figure 5.

Figures 6 and 7 summarize the effect of furnace degradation (skid insulation loss and recuperator wear) on the energy inputs and outputs, respectively, of each design. Figure 8 compares the flue gas volume and temperature for each design under these conditions.

NOx Emissions

NOx emissions estimates for each design are given in Table VII and summarized graphically in Figure 9. Based on the heating curves given in Appendix 4, gas temperature in the heating zone was assumed to be 2490°F in the heating zone and 2350°F in the soak zone for all designs. In DOC zones, the furnace nitrogen

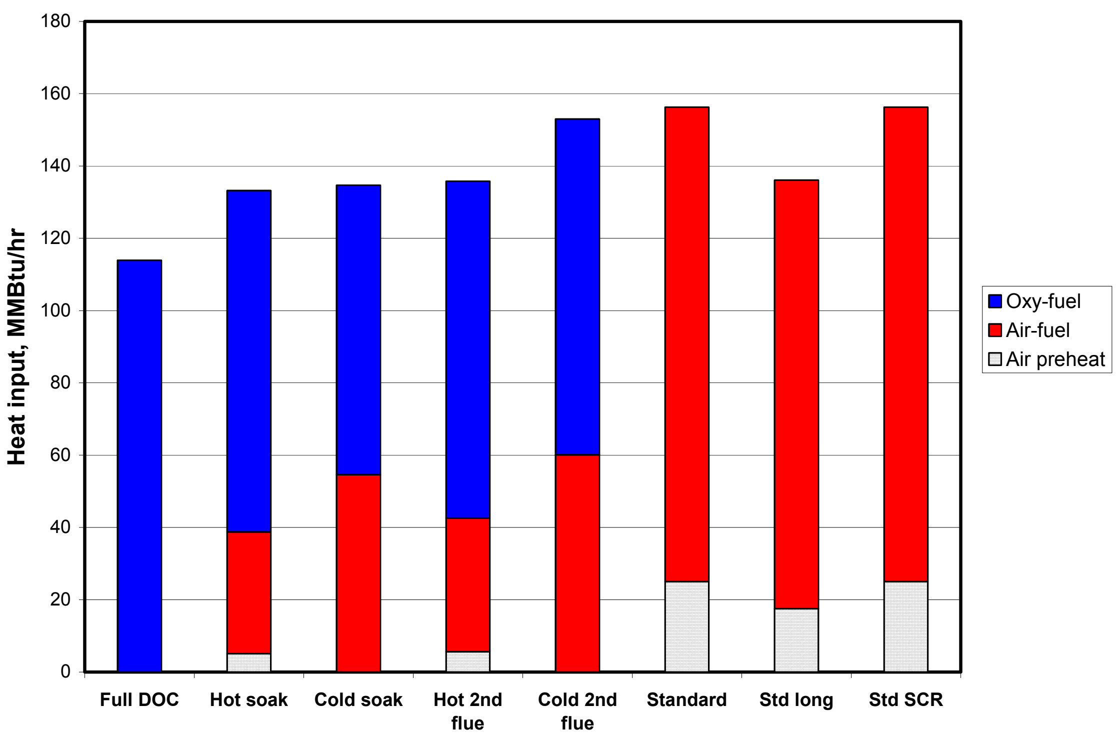


Figure 3 – Heat input comparison as designed.

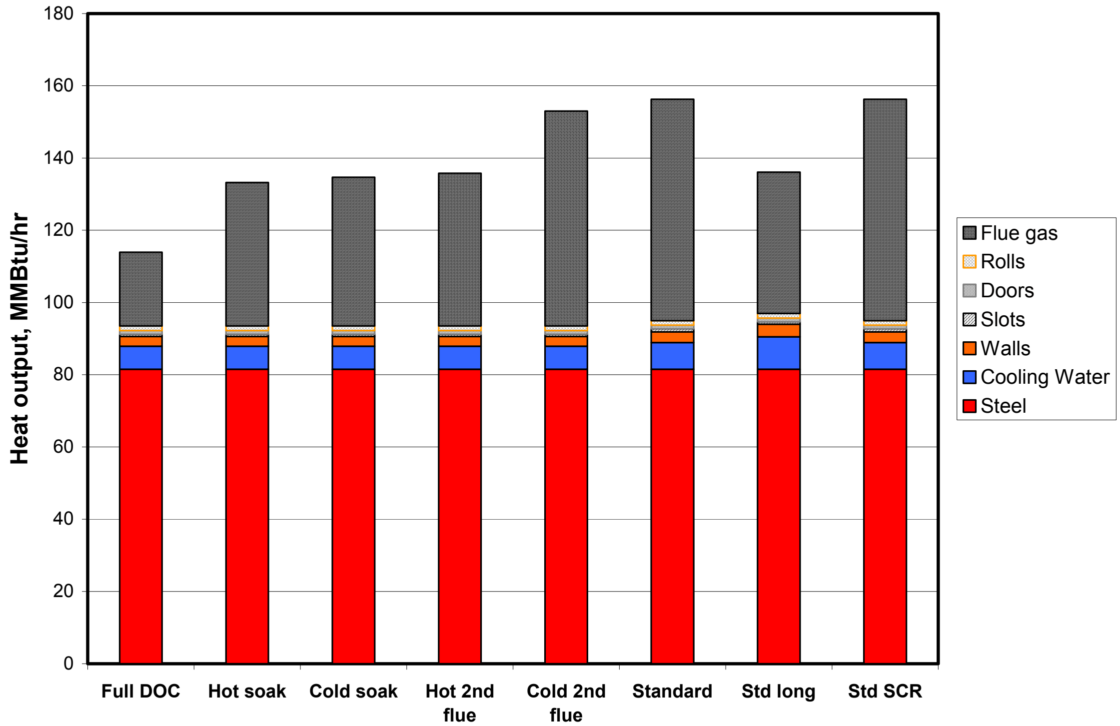


Figure 4 – Heat output comparison as designed.

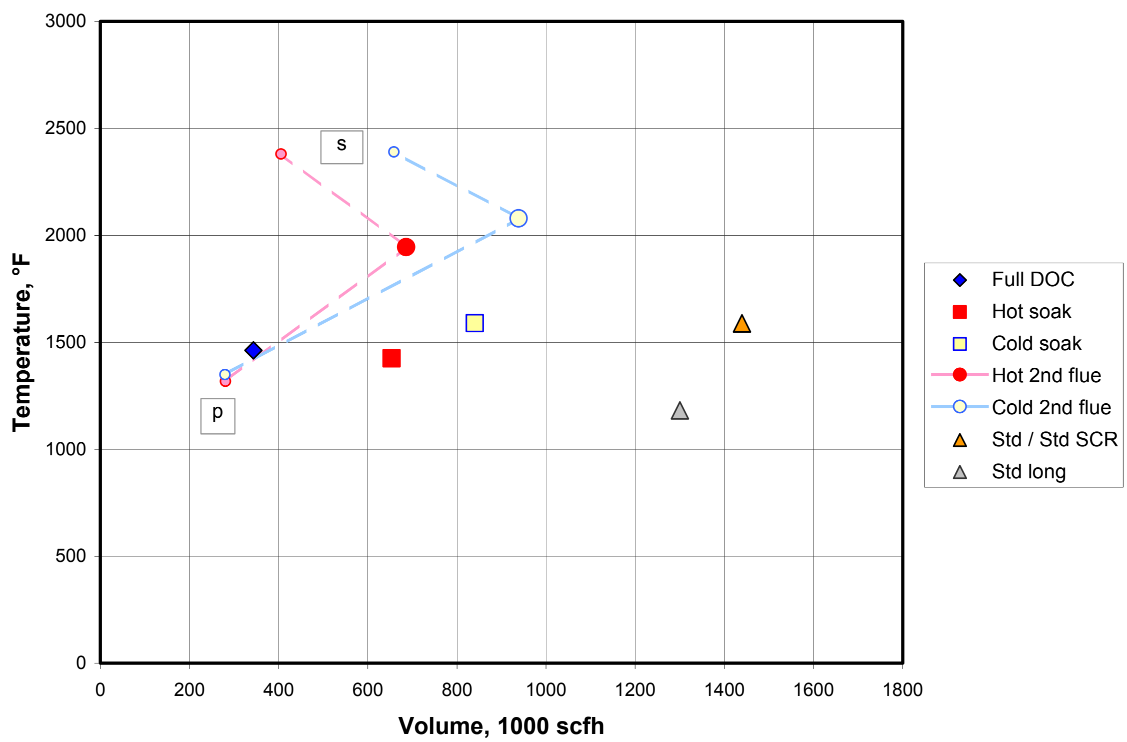


Figure 5 – Comparison of flue gas volume and temperature as designed.
Second flue cases show contributions from primary flue (p) and soak zone flue (s).

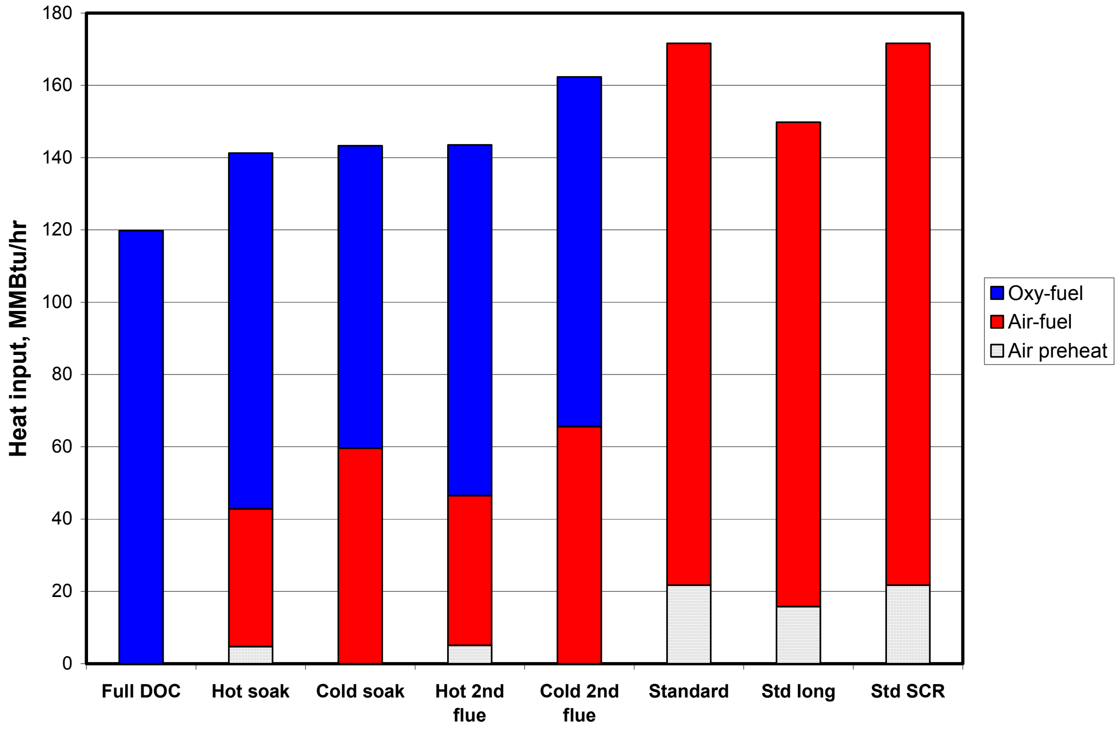


Figure 6 - Heat input comparison with furnace degradation.

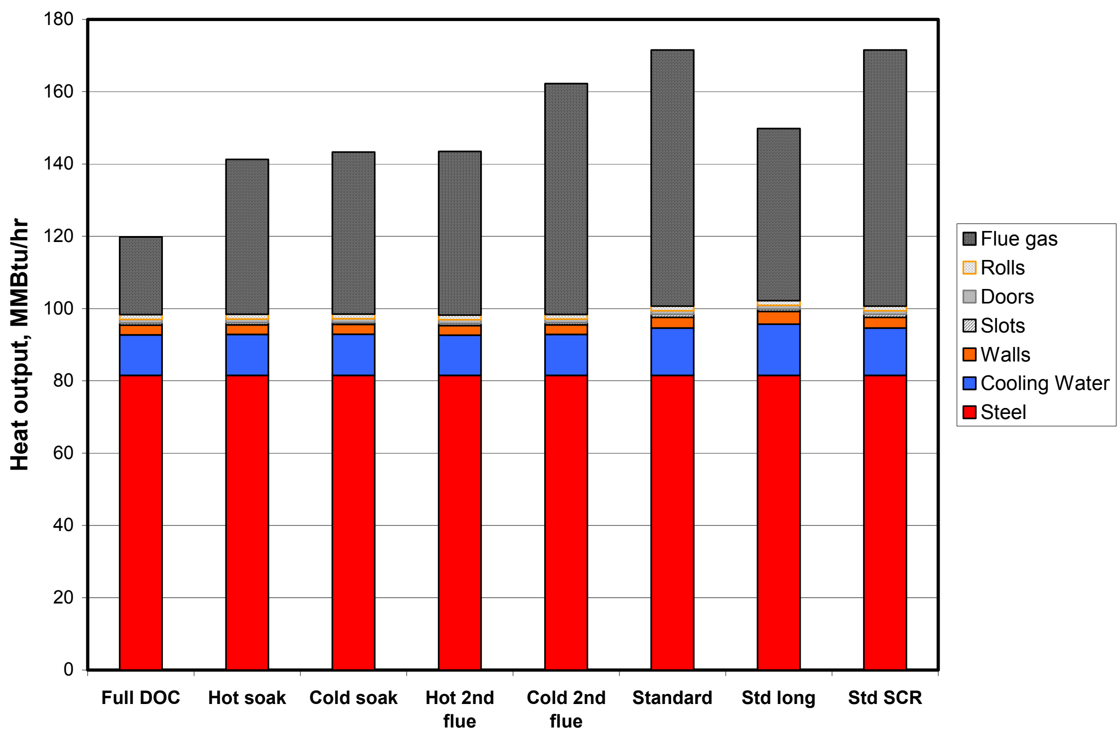


Figure 7 - Heat output comparison with furnace degradation.

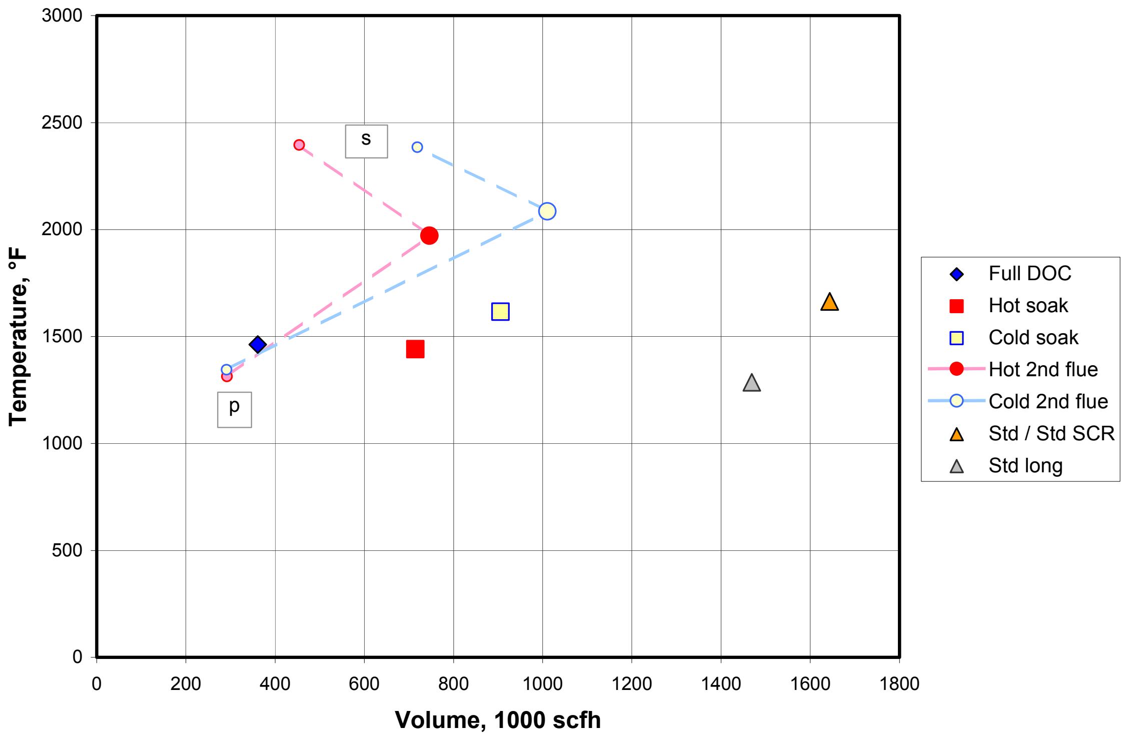


Figure 8 – Comparison of flue gas volume and temperature with furnace degradation. Second flue cases show contributions from primary flue (p) and soak zone flue (s).

level was calculated by mixing the products of DOC combustion with the combustion products from soak zone air burners. Since DOC zones are designed with three pairs of burners (see drawings, Appendix 3), mixing in the DOC zones was done in three stages. In the full DOC and separate flue cases, a conservative value of 20% (wet) furnace nitrogen was assumed from nitrogen in the fuel and air leakage.

Oxide Scaling

Oxide scaling estimates for each design are summarized in Figure 10. The steel top surface heating curves given in Appendix 4 and the furnace atmosphere profiles developed in the NOx emission calculation were used to define the oxidation conditions during each 1 minute interval in a billet's reheating cycle. The incremental scale formed during each interval was calculated using the parabolic rate equation developed in Appendix 2. The total scale formed was calculated as the square root of the sum of squares of the incremental weights, consistent with the parabolic model.

Table VII – NOx emissions estimates

Furnace	Air zones: NOx rate lb/MMBtu	Air zones: Firing Capacity MMBtu/hr	DOC Zones: Furnace Nitrogen pct	DOC Zones: Average NOx rate lb/MMBtu	DOC Zones: Firing Capacity, MMBtu/hr	Emission Rate lb/hr
Full DOC	--	--	20.0	0.006	138	0.83
Hot Soak	0.106	48	63.1 / 56.9 / 52.2	0.035	108	8.87
Cold Soak	0.045	64	65.7 / 60.8 / 56.9	0.042	96	6.91
Hot – 2nd flue	0.106	48	20.0	0.006	108	5.74
Cold – 2nd flue	0.047	74	20.0	0.006	108	4.13
Standard	0.106	164	--	--	--	17.38
Std. long	0.096	154	--	--	--	14.78
Std. SCR	0.042	164	--	--	--	6.95

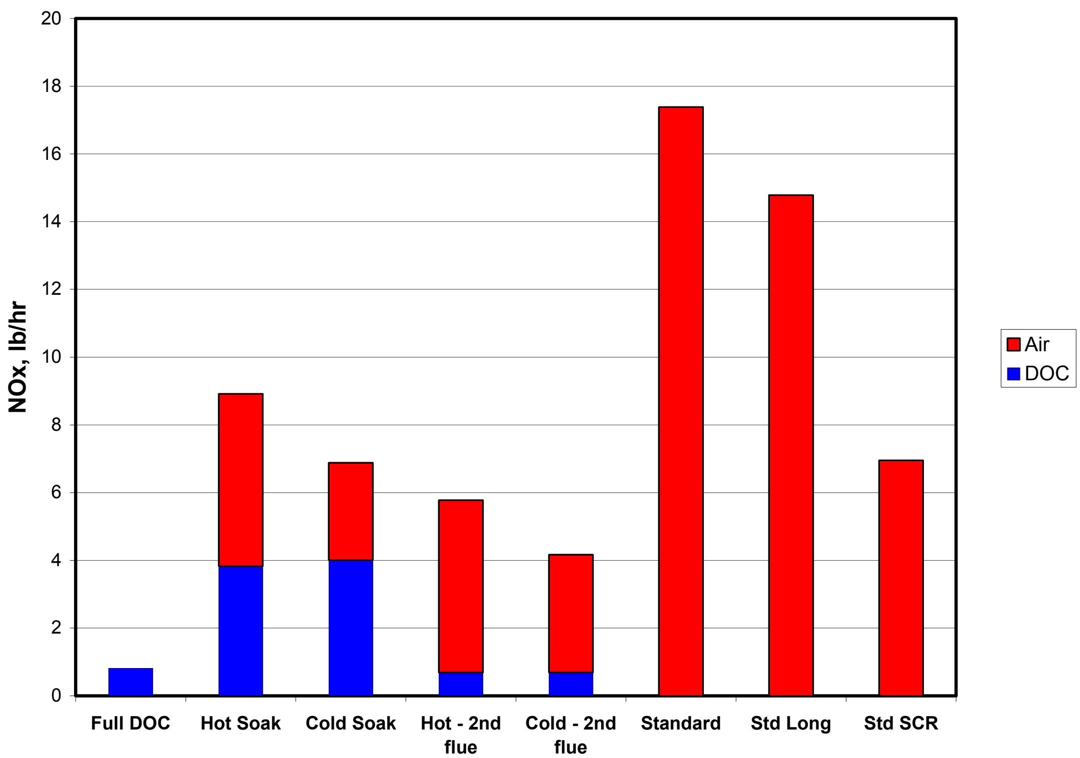


Figure 9 – Comparison of NOx emissions at full firing capacity.

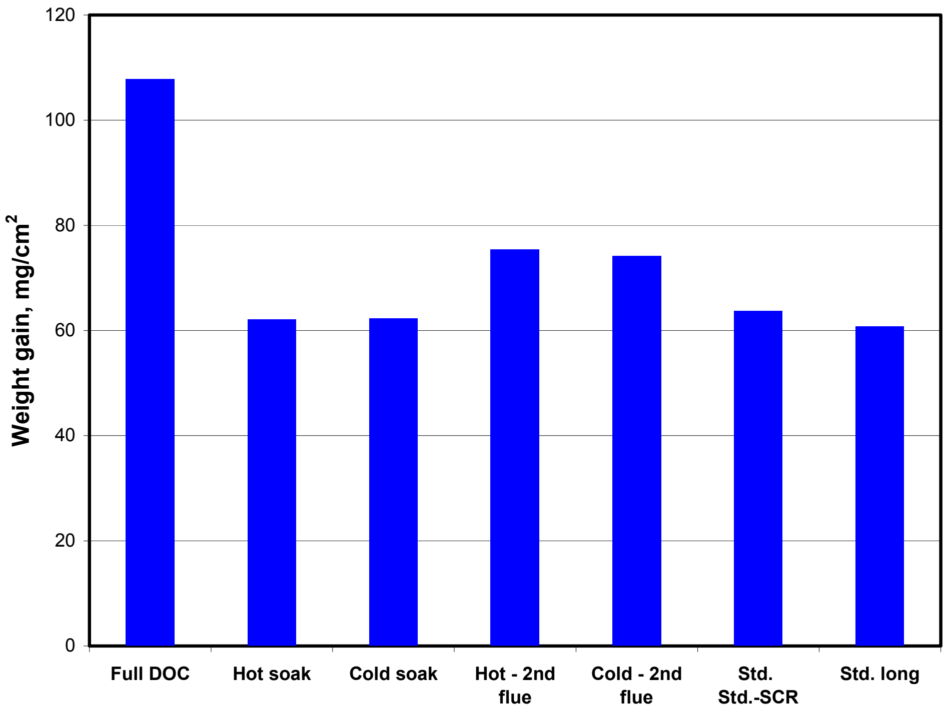


Figure 10 –Comparison of estimated oxide scale formation.

Net Present Value Calculation

Table VIII summarizes the 10-year net present value calculation, showing the value in year 1 dollars of all furnace expenses through year 10. Capital includes the cost of principal and financing costs, while Utilities include electrical, water, and reagent costs.

Table VIII – Summary of 10-year net present value calculation

	Millions of dollars						
Furnace	Capital	Emissions	Fuel	Oxygen	Utilities	Maintenance	Total
Full DOC	6.95	0.03	20.66	13.28	8.74	--	49.66
Hot Soak	6.94	0.30	23.40	11.06	8.90	0.04	50.64
Cold Soak	6.72	0.24	24.47	9.37	8.84	--	49.64
Hot – 2nd flue	7.13	0.22	23.83	10.92	8.90	0.04	51.04
Cold – 2nd flue	6.84	0.13	27.75	10.87	8.85	--	54.44
Standard	8.10	0.62	24.70	--	10.37	0.33	44.12
Std. long	8.59	0.52	22.29	--	11.63	0.33	43.36
Std. SCR	9.38	0.35	24.70	--	11.36	0.43	46.22

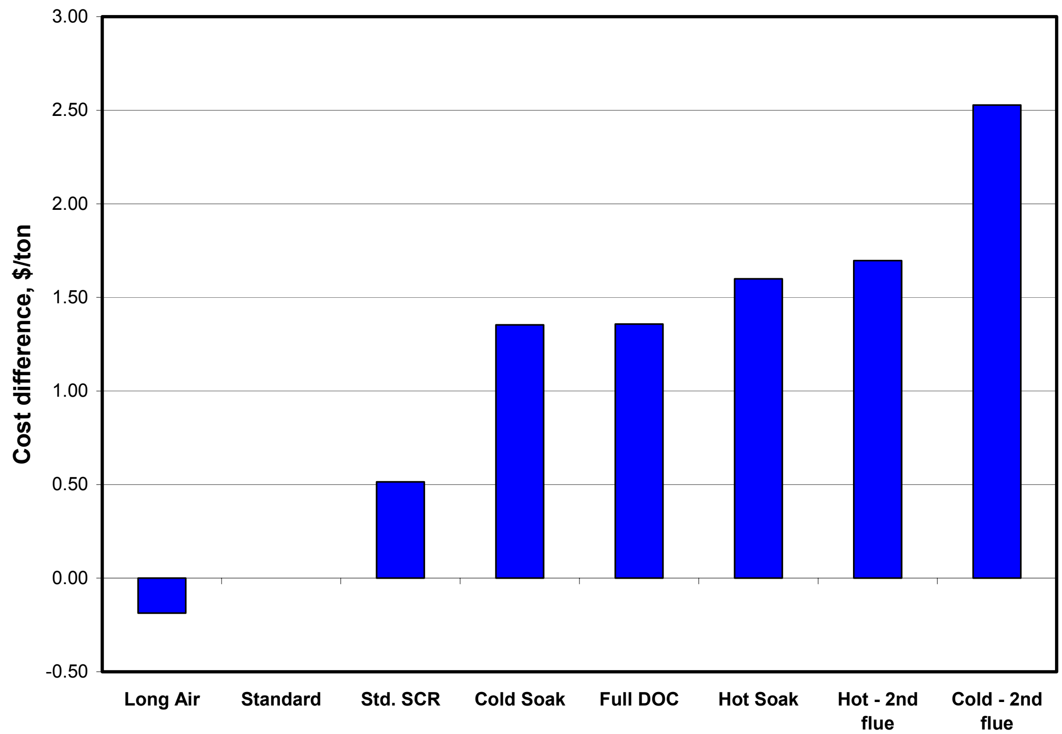


Figure 11 – Comparison of total cost per ton of steel processed for each design relative to standard furnace.

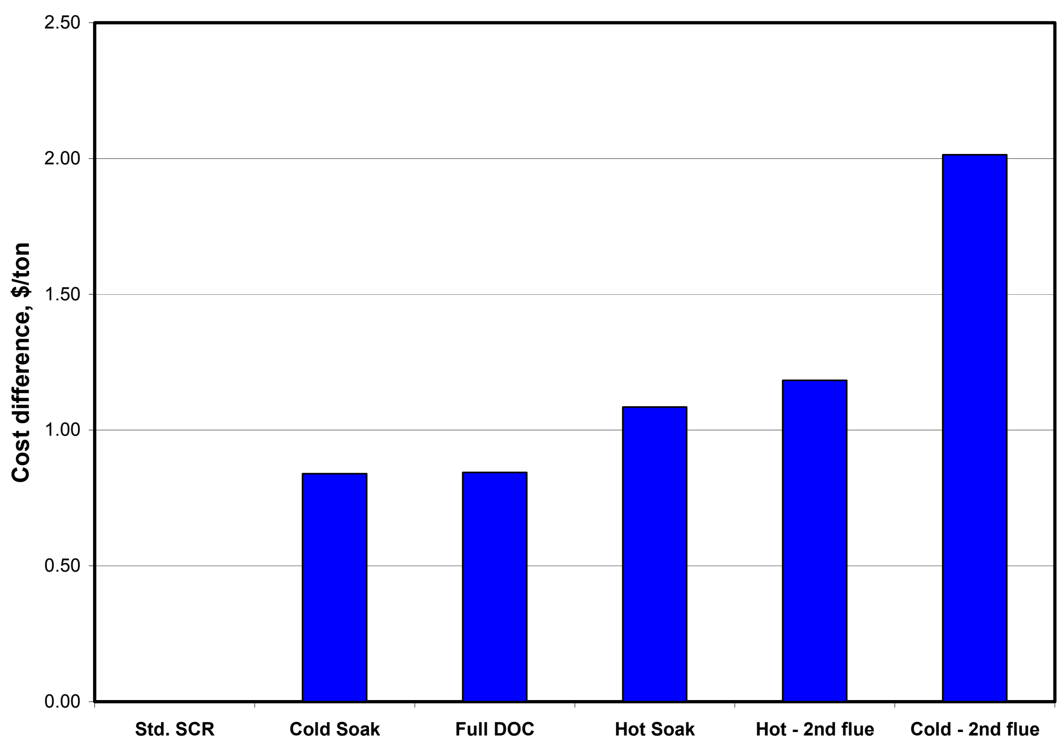


Figure 12 – Comparison of total cost per ton of steel processed for each design with NOx ≤ 10 lb/hr relative to standard furnace with SCR.

Figure 11 compares the cost difference in dollars per ton of steel processed for all designs relative to the standard design. Figure 12 compares the cost difference relative to the standard-SCR furnace for all designs with NOx emissions rates $\leq$ 10 lb/hr.

5. CONCLUSIONS

The data in Table VII show that the DOC furnace designs provide significantly lower costs for capital, fuel, utilities, and maintenance compared with the conventional furnace designs. These advantages, however, are not sufficient to offset the cost of oxygen. Figure 11 shows that, in the absence of strict NOx requirements, only the long conventional furnace design has a cost advantage over the standard design. Both the full DOC design and the cold soak design have a cost disadvantage of $1.30/ton compared with the standard design and $1.50/ton compared with the long standard design. Figure 12 shows that, with NOx requirements of 10 lb/hr, a standard furnace with SCR has the lowest overall cost. Reheating in a full DOC furnace or a DOC-cold air furnace costs nearly $1/ton more than the standard-SCR design.

The clear implication of these results is that DOC-based furnace designs will not compete with conventional designs under the conditions assumed in the NPV calculation. Factors which would improve the competitiveness of DOC furnace designs are:

- <u>Increase in fuel price</u> – A sensitivity analysis of the NPV calculation shows that the year 1 fuel price would have to be $7/MMBtu for the full DOC furnace design to have the same overall cost as the standard-SCR design.

- <u>Decrease in oxygen price</u> – A sensitivity analysis shows that the year 1 oxygen price would have to be $23/ton for the full DOC furnace design to have the same overall cost as the standard-SCR design.

- <u>Tightened NOx requirements</u> – Establishing NOx requirements below the capability of the standard-SCR design would make the added cost of a DOC furnace design moot.

- <u>Value not in the NPV model</u> – DOC furnace features which are not included in the NPV calculation that an operator would value at $1.00-$1.50/ton would give the DOC-based design a lower overall cost.

The required change in fuel price or oxygen price is highly unlikely for the foreseeable future. Tightened NOx requirements are possible, however, if regulators determine that improved technology is technically and economically feasible. One factor to consider in this determination is the incremental cost of the technology relative to the NOx improvement achieved. Figure 13 shows the incremental cost of each low-NOx furnace design per pound of NOx eliminated, relative to the standard design. The incremental cost of SCR is about $3.00/lb NOx eliminated. The full DOC design, with higher cost and greater NOx improvement, has an incremental cost of about $6.00/lb NOx, and the DOC-cold soak design, with intermediate cost and NOx improvement, has an incremental cost of about $9.00/lb NOx.

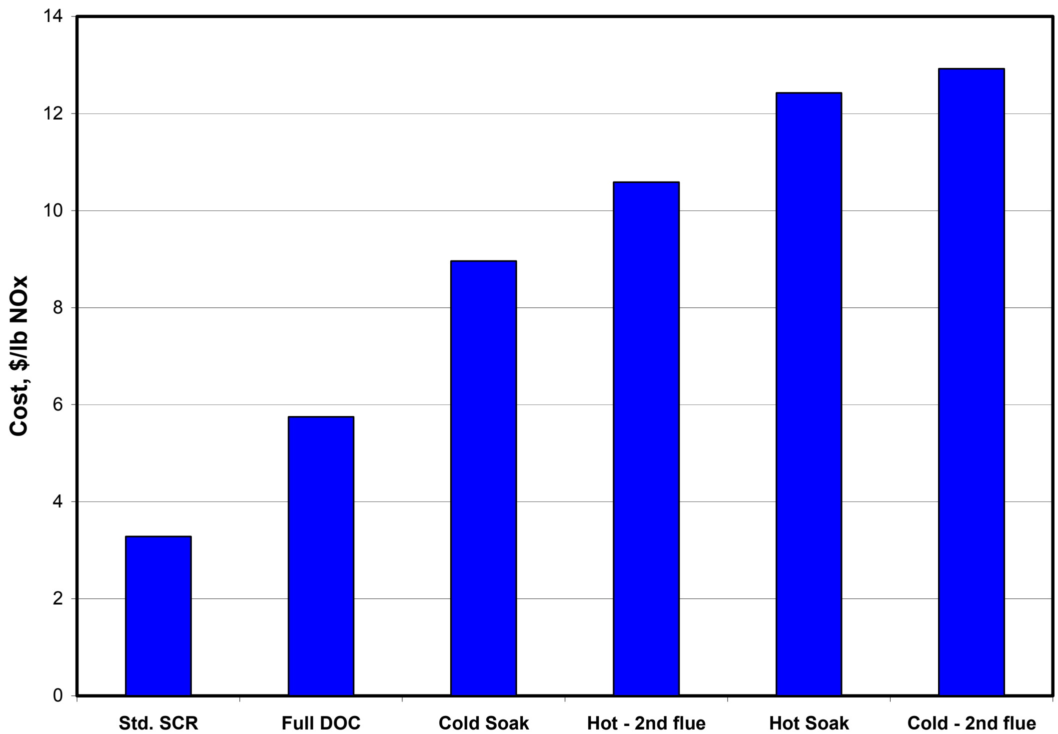


Figure 13 – Incremental cost of DOC furnace designs per pound NOx eliminated, relative to standard furnace.

While NOx regulatory history is mixed, recent actions suggest that incremental costs in the range of $2.00-$4.00/lb NOx are considered economically viable, while costs above $5.00/lb NOx are not.[13,14]

DOC furnace features not included in the model may provide the additional $1.00-$1.50/ton benefit needed for economic competitiveness in certain niches. For example, companies with very limited access to capital may require the lowest initial cost available. As another example, companies with floor space restrictions may place a premium on the small footprint of a DOC furnace.

DOC technology continues to be an attractive option for retrofit applications where higher furnace productivity is needed, such as at Nucor Auburn Steel in phase 3.

Appendix 1: Natural gas chemistry

Natural gas composition		
Component	Formula	Volume percent
Methane	CH_4	94.15
Ethane	C_2H_6	3.01
Propane	C_3H_8	0.42
Butane	C_4H_{10}	0.28
Nitrogen	N_2	1.41
Carbon dioxide	CO_2	0.71
Oxygen	O_2	0.01
Hydrogen	H_2	0.01

Combustion properties	Unit	Value
High heating value	Btu/scf	1034.9
Oxygen-fuel ratio	scf/scf	2.03
Air-fuel ratio	scf/scf	9.70

Appendix 2: Oxide scaling experimental program summary

A literature review and experimental program were conducted to provide more insight into the effect of oxy-fuel atmospheres on scaling rates. In continuous reheat furnaces oxy-fuel typically is used only in the relatively cold entry zones as was done at Nucor Auburn Steel during the phase 3 demonstration. Scaling kinetics are slow in these zones, and since the flue is located near the charge end, the oxy-fuel atmosphere is highly diluted by combustion products from the air-fired zones, minimizing the impact of oxy-fuel on scale formation. Converting only these entry zones to oxy-fuel limits market penetration and inhibits fuel savings and NO_x reductions. However, to convince mill management to convert higher-temperature zones, the ability to predict and control scaling in these zones under oxy-fuel atmospheres is needed.

Classical scaling mechanism

Oxidation of a clean metal surface begins with the adsorption of atomic oxygen on the metal surface from the dissociation of an oxidizing gas species. The metal and atomic oxygen then react to form oxide islands which grow into a continuous, adherent oxide film. This film thickens into a scale layer either by diffusion of metal ions to the gas/oxide interface or by diffusion of oxygen ions to the oxide/metal interface, depending on the defect structure of the oxide.[15] Because of the slow diffusion rates of ions through the scale layer, oxidation is then controlled by solid state diffusion.

Pettit and Wagner developed a predictive equation for the transition to diffusion controlled scaling.[16] For iron, the transition occurs at about 10-100 μm scale thickness for temperatures between 1300°F-2000°F. Using the average densities values given by Sheasby,[17] this corresponds to a relatively small weight gain of only about 1-10 mg/cm^2.

Accordingly, the classical kinetic mechanism for oxide scale formation assumes the instantaneous formation of the oxide film on the clean metal surface. Chemical equilibrium is assumed to exist at both the gas/oxide and oxide/metal interfaces, providing a constant driving force for diffusion. Under these conditions, Fick's law predicts that the thickness of the scale layer will grow parabolically with time, that is

$$x^2 = k_p\, t \qquad (1)$$

where x is the scale thickness, t is time, and k_p is the parabolic rate constant. Wagner derived an expression for k_p in terms of the diffusivities of metal and oxygen ions and the chemical potential gradients across the scale layer.[15]

Scaling of iron is more complicated since there are three stable oxides at elevated temperatures. Wustite forms closest to the metal, followed by magnetite, and then by hematite closest to the gas. Wustite and magnetite are metal-deficit (p-type) semiconductors, and so iron diffuses outward through these layers. Hematite is a metal-excess (n-type) semiconductor, and oxygen diffuses inward through this layer. Reaction occurs at the hematite/magnetite interface.[18,19]

The diffusivity of iron in wustite is considerably higher than in magnetite, and still higher than the diffusivity of oxygen in hematite. This means that at steady state the wustite layer must dominate the thickness of the scale, providing a shallower chemical potential gradient across the wustite. Accordingly, the rate of scale growth is controlled by the diffusion of iron through wustite.[19]

Deviations from classical mechanism

While Wagner's theory gives good agreement with experimental data for many metals, most data deviates from the classical theory because one or more of the assumptions of the theory do not apply in actual scale formation. Sachs and Tuck[19] reviewed experimental data on scaling of iron and steel and outlined 12 scale-growth schemes. For carbon steel, the main deviations from the classical theory are caused by:

- Additional oxide layers formed by oxidation of deoxidizing elements such as silicon or aluminum. As little as 0.25 percent Si may cause fayalite (Fe_2SiO_4) to form, retarding oxidation below the wustite-fayalite eutectic at 2150°F. At low oxygen potentials, silca can form by internal oxidation.

- Pores or cracks in the scale layer which may accelerate or retard scaling. Cracks through the scale provide shorter paths for diffusion and result in scaling rates higher than predicted by the classical mechanism. Cracks parallel to the metal/oxide interface provide an additional diffusive barrier and result in scaling rates lower than predicted.

Although scaling kinetics may not be controlled by the classical parabolic mechanism, the rate is usually described in terms of the parabolic rate constant.

Effects of atmosphere

According to the classical theory, atmosphere should have no effect on scaling rate. This is because an ample supply of oxidizing gas is implicit in the classical theory assumption of chemical equilibrium at the interfaces. Experimentally, the atmosphere has a significant effect on scaling.

In stagnant or in dilute oxidizing atmospheres, the supply of oxygen from the gas phase may be limited, and gas phase transport or surface dissociation reactions may control scaling. Dilute oxidizing atmospheres are typically encountered in reheat furnaces where the products of combustion may be 70% nitrogen.[19]

Solid state diffusivities of iron and oxygen can be affected by gas composition, particularly by the concentrations of CO_2 and H_2O.[18] The effects are believed to be related to the formation of vacancies and other atomic level defects.

The atmosphere also can have a considerable effect in the formation and behavior of cracks in the scale. For example, cracks in carbon steel scale form more readily in air than in oxygen. This would be consistent with crack formation through the escape of carbon-bearing gas during scaling of carbon steel followed by stabilization of the cracks by nitrogen from air or air combustion, preventing healing of the cracks. In contrast, water vapor appears to inhibit the formation of cracks along the interface, helping to retain scale-metal contact and increase the scaling rate. It is believed that water vapor is slightly soluble in the scale and that its presence improves the creep resistance of the scale.[17,19]

Summary of literature results

Sheasby et al.[17] compared the experimental parabolic rate constants for isothermal iron oxidation in air and oxygen from six published investigations. Figure A-1 shows the weighted average value calculated by Sheasby et al., represented by the equation

$$\log_{10} k_p = -\frac{8868}{T} + 6.977 \qquad (2)$$

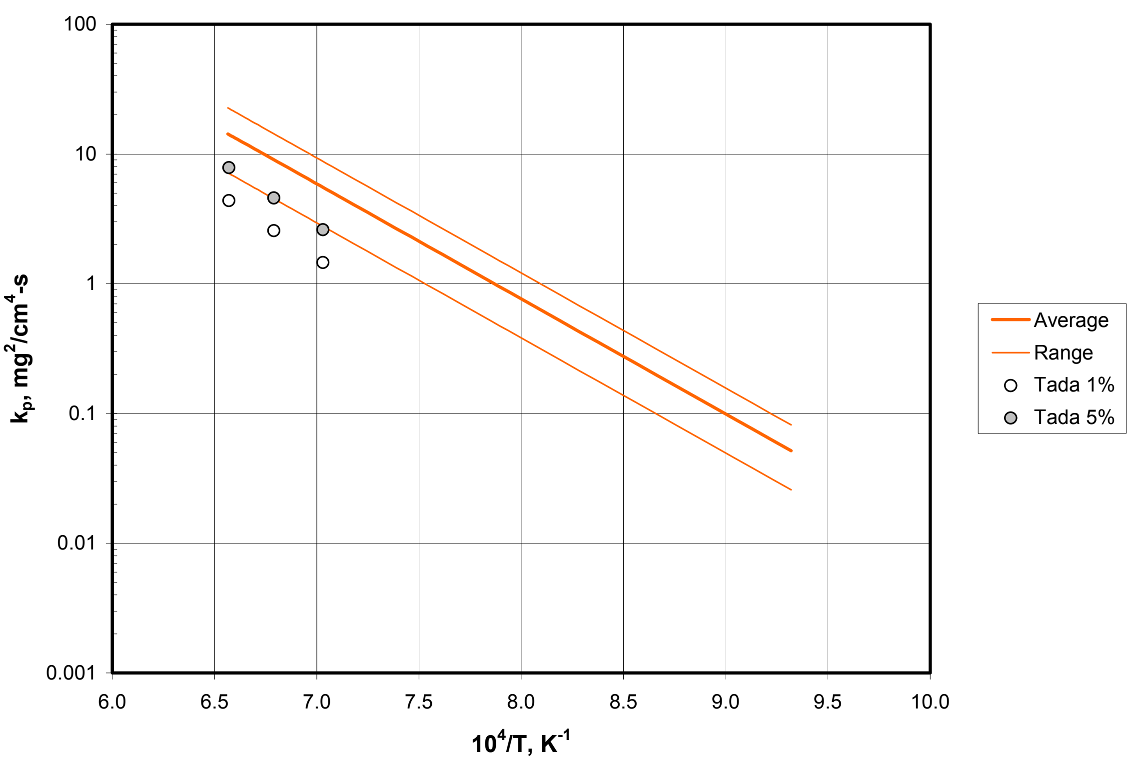


Figure A-1 - Summary of parabolic rate constant data from Sheasby et al. and Tada. Tada values shown for 250 min exposure time at 1% and 5% excess oxygen.

where k_p is the parabolic rate constant in mg^2/cm^4-s and T is temperature in Kelvins. This result is consistent with the results of Wagner's theoretical equation.[17] The range of values of the rate constant among the six papers is also shown in Figure A-1. The range extends to roughly ± 50 percent of the average value, so that k_p varies by a factor of 3 among the different investigations. This variation reflects the effect of the various deviations from the classical mechanism. Also shown in Figure A-1 are the results of the more recent laboratory investigation by Tada et al.,[20,21] on oxidation under simulated reheat furnace flue gas. Tada's data are in good agreement with the low end of the other data.

Experimental Method

The current tests were proposed to evaluate the effects of oxy-fuel conversion of a reheat furnace on scaling. The tests were designed to simulate sequential conversion to oxy-fuel of the zones of the phase 3 demonstration furnace at Nucor Auburn Steel. The key features of the simulation were:

- use of an actual as-cast surface for the scaling test;
- simulation of the heating and soaking time-temperature profiles of the Nucor Auburn furnace;
- simulation of the furnace gas composition for each furnace zone.

Nucor Auburn Steel supplied a section of 6" square ASTM A36 billet with chemistry shown in Table A-I. Test samples roughly ½" thick were cut from this billet with a ¾" x ¾" square face from the as-cast surface. The sample was cast into a MgO block so that only the as-cast face was exposed. The castable refractory protected the cut surfaces of the sample from oxidation and also prevented heat flux into the sample from the cut surfaces. In this way, the temperature profile in the sample more closely resembled that of the actual billet.

The reheating process was simulated using the apparatus shown in Figure A-2. A Lindberg horizontal tube furnace with silicon carbide heating elements was used to simulate the temperature profile created in the reheating furnace while a

Table A-I – Composition of steel used in scaling tests

Element	Percent
C	0.19
Mn	0.68
P	0.025
S	0.040
Si	0.20
Ni	0.12

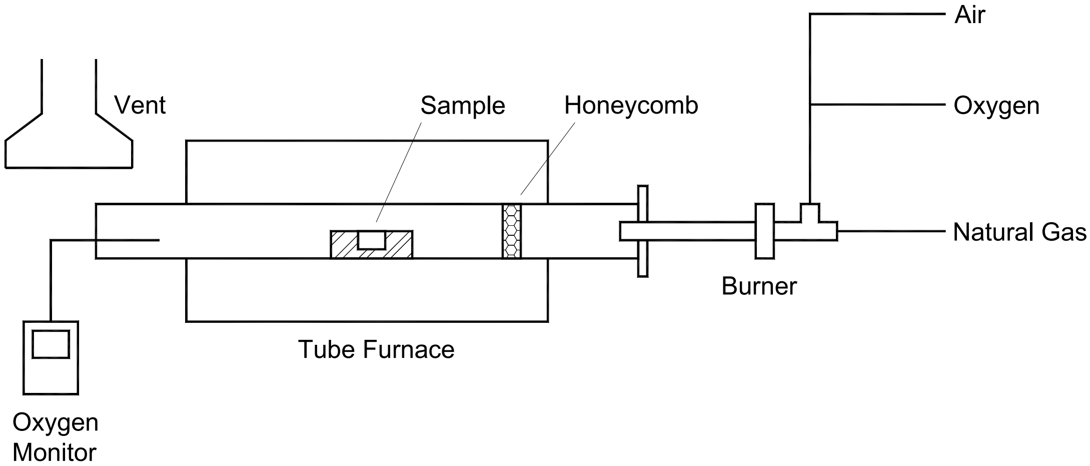


Figure A-2 – Experimental apparatus for scaling tests.

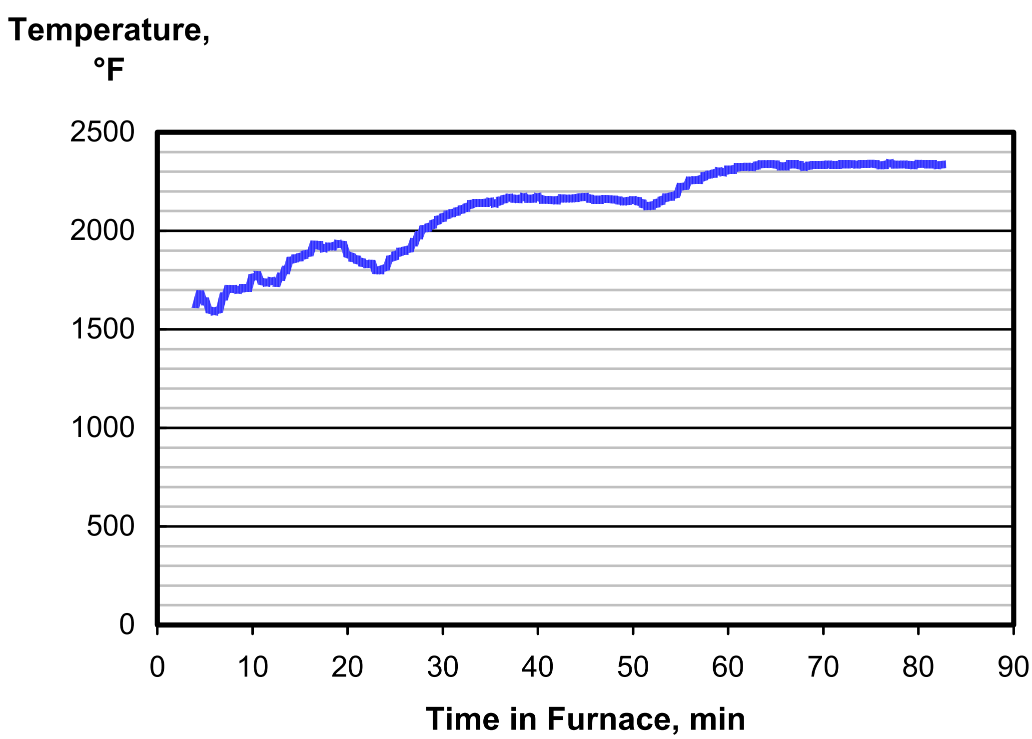


Figure A-3 - Measured furnace temperature in Auburn Steel reheat furnace.

simulated furnace atmosphere was generated by a small burner fitted to the end of the furnace tube.

The heating profile was determined from data collected at Nucor Auburn Steel during the phase 3 demonstration tests.[7] That data, reproduced in Figure A-3, showed that the furnace wall at the charge end of the furnace was approximately 1600°F and at a production rate of 100 tph, the temperature increased by 12°F/min. The steel then entered the 2300°F soak zone and remained there for 25 min at the 100 tph production rate. Because the sample was considerably thinner than the actual 6" billet, the sample surface temperature approached the furnace temperature more rapidly than the actual billet would. This results in the test sample being in the range of 1650°F to 1950°F for about 30 min longer than a billet. The effect of this on scaling behavior is expected to be small since the scaling rate is very low at these temperatures.

The relative flow rates of natural gas, air, and oxygen for the burner were determined from typical furnace zone firing rates under various assumed levels of oxy-fuel conversion assuming 2% excess oxygen on a wet basis. The furnace gas composition in a given zone reflected the combustion in that zone and the carryover of furnace gas moving from higher temperature zones to the flue. The total flow rate was selected to provide a realistic gas velocity over the steel to mimic actual transport conditions. A ceramic honeycomb was placed between the burner and the sample to provide uniform gas velocity across the sample and to prevent direct impingement of the burner flame on the sample.

Four conversion levels were evaluated as shown in Table A-II. The typical firing rates and gas temperatures of each zone in the Nucor Auburn Steel furnace and the calculated superficial velocity of the furnace gas in each zone for each conversion level are shown in Table A-III. To simplify adjustment of gas flows during the tests, a constant total flow rate was selected for each conversion level. For the total conversion case, the total flow rate was adjusted to provide 5 fps velocity over the sample at 2500°F. For all other levels of conversion, the flow rate was adjusted to provide 10 fps over the sample at 2500°F. (In comparison, Tuck and Down[22] observed no increase in scaling rate of En8 steel above a "critical speed" of 5 fps for combustion atmospheres with 20% H_2O and >0.8% O_2.) Table A-IV shows the flow rates of natural gas, oxygen, and air used for each zone at level of conversion. The table also lists the sample residence time under each atmosphere and the furnace temperature at the end of each test period. An additional case was tested for conversion level 1 with 6% excess oxygen (wet).

Table A-II – Burner type for each conversion level

Zone	Burner Type			
	Conversion Level 0 (air fire)	Conversion Level 1 (phase 3 demo)	Conversion Level 2	Conversion Level 3
Entry	None	None	None	None
Preheat	None	Oxy-fuel	Oxy-fuel	Oxy-fuel
Heat	Air-fuel	Air-fuel	Oxy-fuel	Oxy-fuel
Soak	Air-fuel	Air-fuel	Air-fuel	Oxy-fuel

Table A-III – Firing rate, temperature, and gas velocity for each zone and conversion level

Zone	Furnace Firing Rate MMBtu/hr	Zone Gas Temperature, °F	Gas velocity, fps			
			Conversion Level 0	Conversion Level 1	Conversion Level 2	Conversion Level 3
Entry	0	2000	15	19	8	6
Preheat	25	2500	18	23	10	7
Heat	75	2500	10	11	4	3
Soak	17	2500	4	4	4	1

Table A-IV – Time, temperature, and flow rates for each zone and conversion level

Zone	Time into Heating Cycle, min	Temperature at Zone Exit, °F	Flow rates, natural gas / oxygen / air, scfh			
			Conversion Level 0	Conversion Level 1	Conversion Level 2	Conversion Level 3
Entry	0-15	1760	6.1 0 65.6	7.3 3.2 61.2	16.6 29.3 25.8	11.7 24.2 0
Preheat	15-30	1950	6.1 0 65.6	7.3 3.2 61.2	16.6 29.3 25.8	11.7 24.2 0
Heat	30-50	2200	6.1 0 65.6	6.1 0 65.6	15.4 25.9 30.4	11.7 24.2 0
Soak	50-75	2200	6.1 0 65.6	6.1 0 65.6	6.1 0 65.6	11.7 24.2 0

The experimental procedure involved heating the furnace to 1600°F, igniting the burner, and putting the sample in the furnace through the open tube end once the gas composition was stabilized. Excess oxygen levels at the open end of the tube were monitored by a North American 8108-O oxygen analyzer. The temperature profile was controlled automatically by the furnace controller, and gas composition changes reflecting movement to the next furnace zone were made manually at the appropriate time. At the conclusion of the cycle, the sample was removed from the furnace, quenched, and the scale removed mechanically and weighed. (The average weight of caster scale was measured by mechanically descaling several unheated samples, and this weight was subtracted from the weight of scale removed from the heated samples.) Truncated tests were also conducted where the sample was removed from the furnace partway through the heating cycle and scale was removed and weighed. These tests provided a profile of the scaling rate in each zone at each level of conversion. The corresponding apparent parabolic rate constant was calculated from this scaling rate data.

Results

Figure A-4 shows the calculated parabolic rate constant for air-fuel fired zones as a function of a average inverse test temperature. Figure A-4 includes the data from conversion level 0 and the air-fired zones of the higher conversion cases. The data is compared in Figure A-4 with the range of data compiled by Sheasby et al. At higher temperatures, the rate constant is in good agreement with the bottom of the Sheasby et al. range, in agreement with the data of Tada[20] taken under simulated flue gas atmospheres.

Parabolic rate constants of this magnitude suggest that the scale is detaching from the metal under these conditions, and, in fact, the scale was quite easily removed from these samples. At lower temperatures, the rate is lower than the Sheasby et al. range. Since the lower temperature tests represent early time in the reheat process, the scale is relatively thin and surface reactions may actually control at this point. Competition with the decarburization reaction for oxidizing species may also play a role. Oxygen level alone does not seem to affect the scaling rate.

Figure A-5 shows the parabolic rate constant calculated similarly for oxy-fuel fired zones. These include data where the furnace gas was a mixture of oxy-fuel combustion products and air-fuel combustion products from higher-temperature zones. These data fall along the top of the Sheasby et al. range. This suggests better scale attachment consistent with the literature reports of better attachment at higher water vapor levels in the furnace gas. There is considerable scatter at low temperatures, where lower rate constants are associated with lower levels of conversion. Taken with the low-temperature air-fuel data in Figure A-4, this suggests that the availability of oxidizing species controls scaling early in the cycle when the scale is thin and diffusion rates are relatively high. Again, oxygen level alone does not have an effect.

The data of Figures A-4 and A-5 are plotted as a function of the level of oxidizing gas species (%CO_2 + %H_2O + %O_2) in Figure A-6. Also shown are the rate constants taken from the bottom of the Sheasby et al. range. The curves shown in Figure A-6 are power-law functions with exponents of approximately 1, suggesting a roughly linear increase in scaling with the level of oxidizing gas species at all but the lowest temperatures.

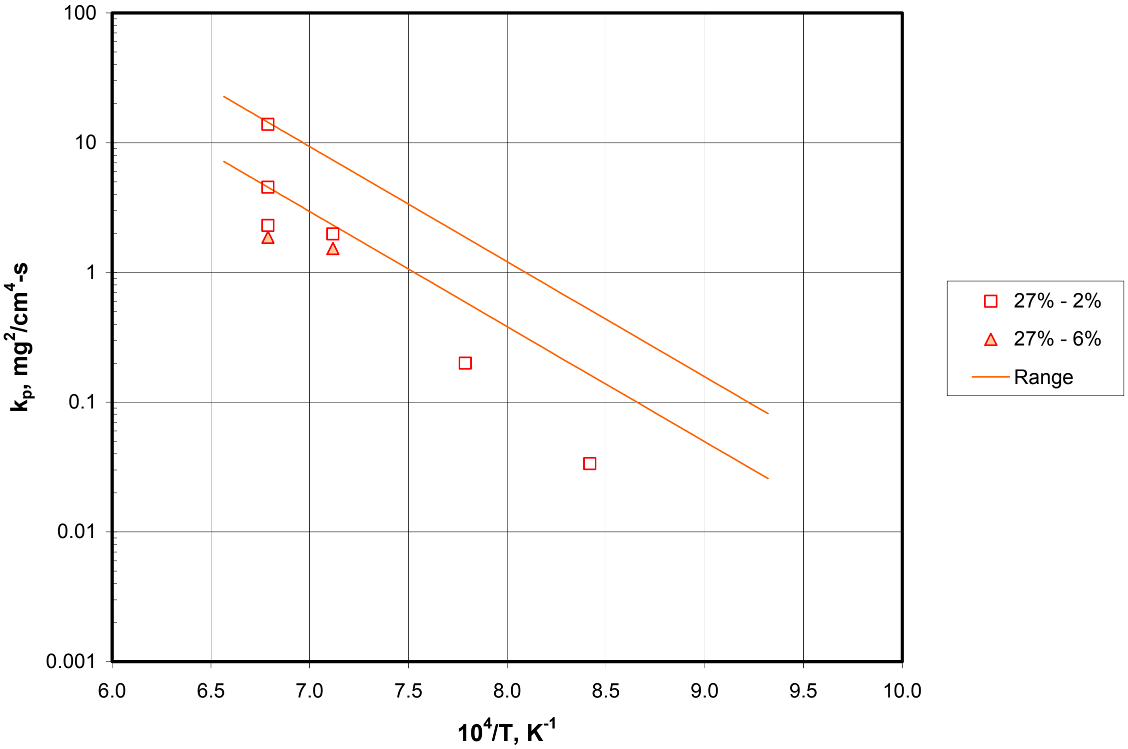


Figure A-4 - Parabolic rate constant for air-fired tests.
Legend indicates concentration of CO_2+H_2O and concentration of O_2.

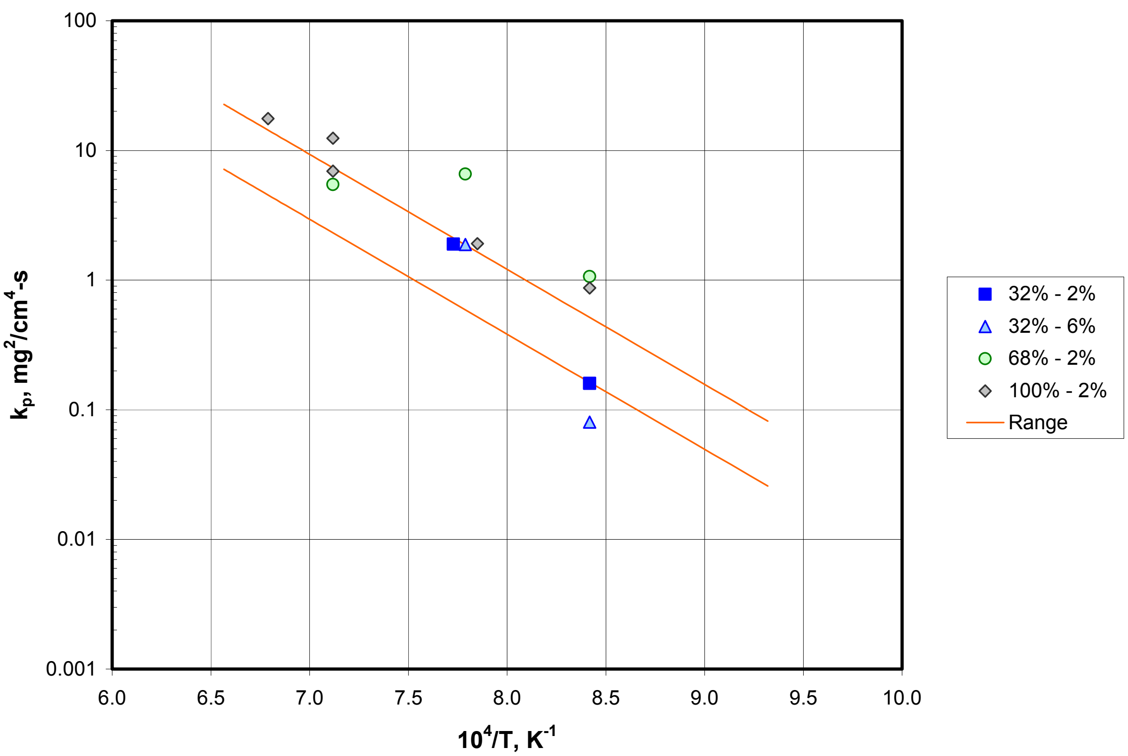


Figure A-5 - Parabolic rate constant for oxy-fuel fired tests.
Legend indicates concentration of CO_2+H_2O and concentration of O_2.

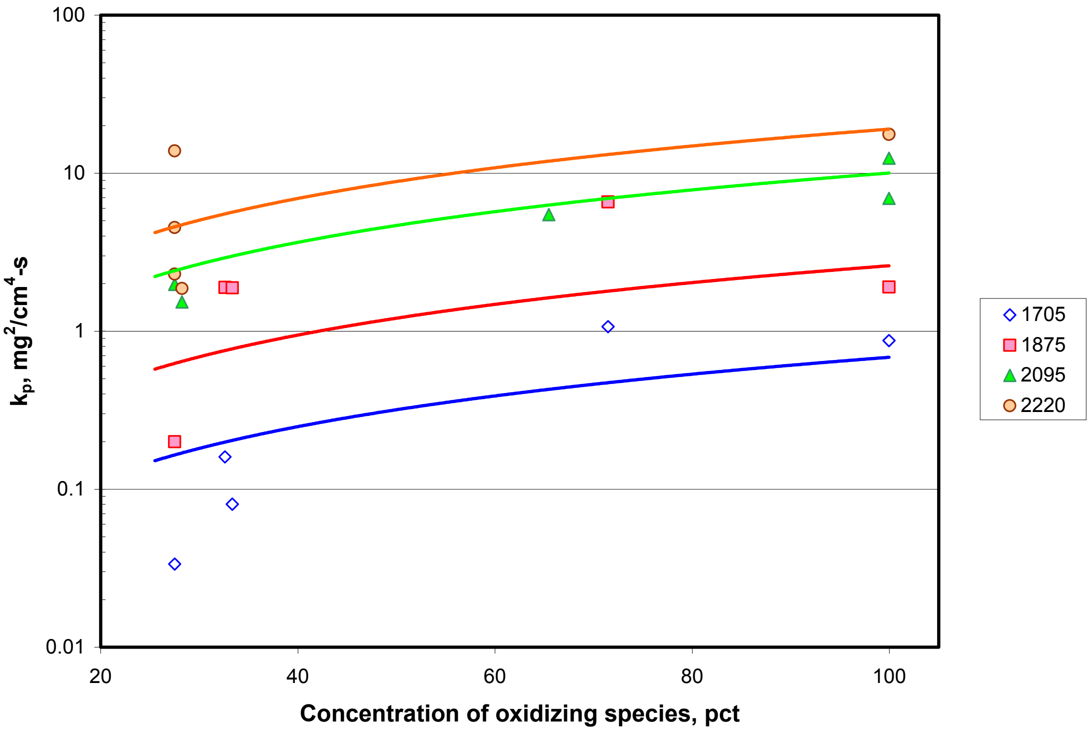


Figure A-6 - Parabolic rate constant as function of level of total oxidizing species in gas. Legend indicates average temperature, °F.

The data of Figure A-6 can be summarized in an equation relating temperature and gas composition to the parabolic rate constant. The equation represents the rate constant for an air-fuel atmosphere as the low end of the Sheasby et al. range. The effect of furnace atmosphere is described as a linear increase with the concentration of oxidizing species above the air-fuel level. Taking a best-fit value for the slope of the furnace atmosphere effect, the overall equation becomes:

$$\log_{10} k_p = \frac{-8868}{T} + 6.677 + \log_{10}(0.0436C - 0.2) \qquad (3)$$

where C is the concentration of oxidizing gas species.

Analysis

Although the scaling rate constant increases with conversion to oxy-fuel, total scale formation does not necessarily increase. This is because of production rate increases that may accompany oxy-fuel conversion. For example, the present data suggest that in the phase 3 demonstration (conversion level 1) the

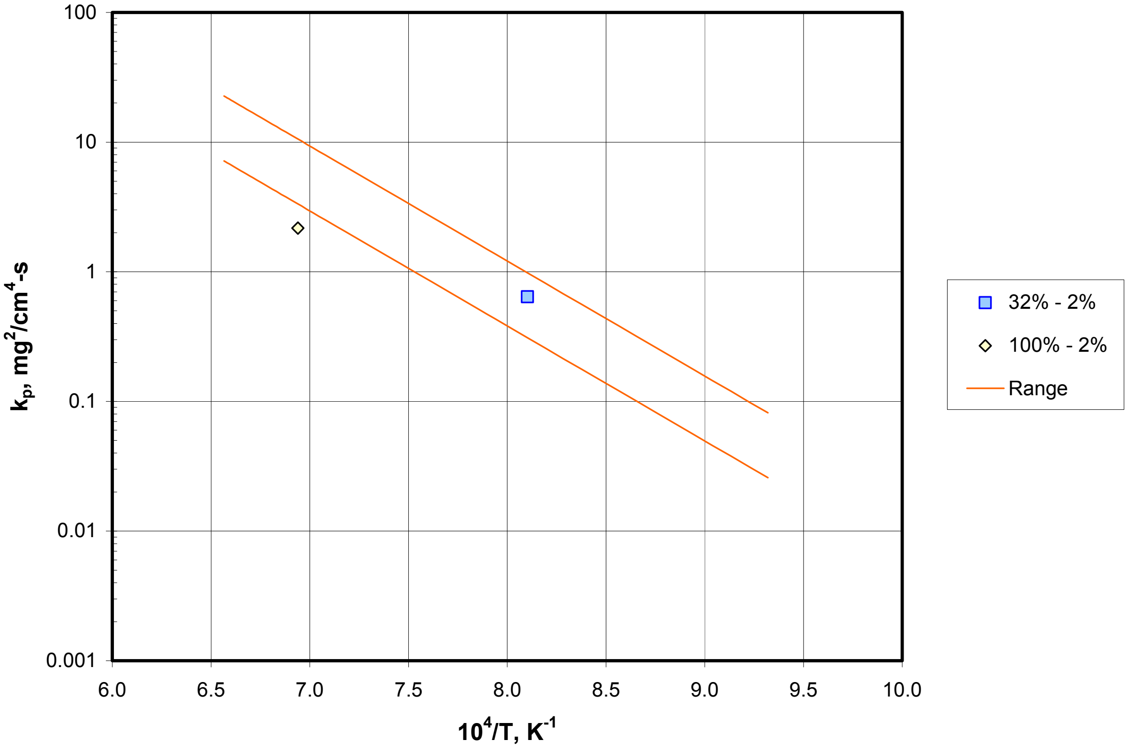


Figure A-7 – Parabolic rate constant for tests simulating air-fired entry zone and oxy-fuel fired heat and soak zones. Legend indicates concentration of CO_2+H_2O and concentration of O_2.

scaling rate constant increased by 20% over the baseline operation (conversion level 0). However, because the production rate increases from 75 tph to 100 tph, billet residence time falls by 25%, leading to a net decrease in total scale formation of about 10%. However, at full conversion and 100 tph production, the rate constant would increase by a factor of about 3, giving 40% more scale than the baseline.

In these cases, scale mitigation strategies may be needed. One possibility would be to generate a detached scale early in the reheat cycle in an attempt to inhibit the scaling rate later in the cycle. For example, it appears that for the ASTM A36 steel tested here, a predominantly air-fuel atmosphere leads to a detached scale. If the firing in the preheat zone was primarily air-fuel and a detached scale was formed, oxy-fuel might be used in the rest of the furnace without excessive scale formation.

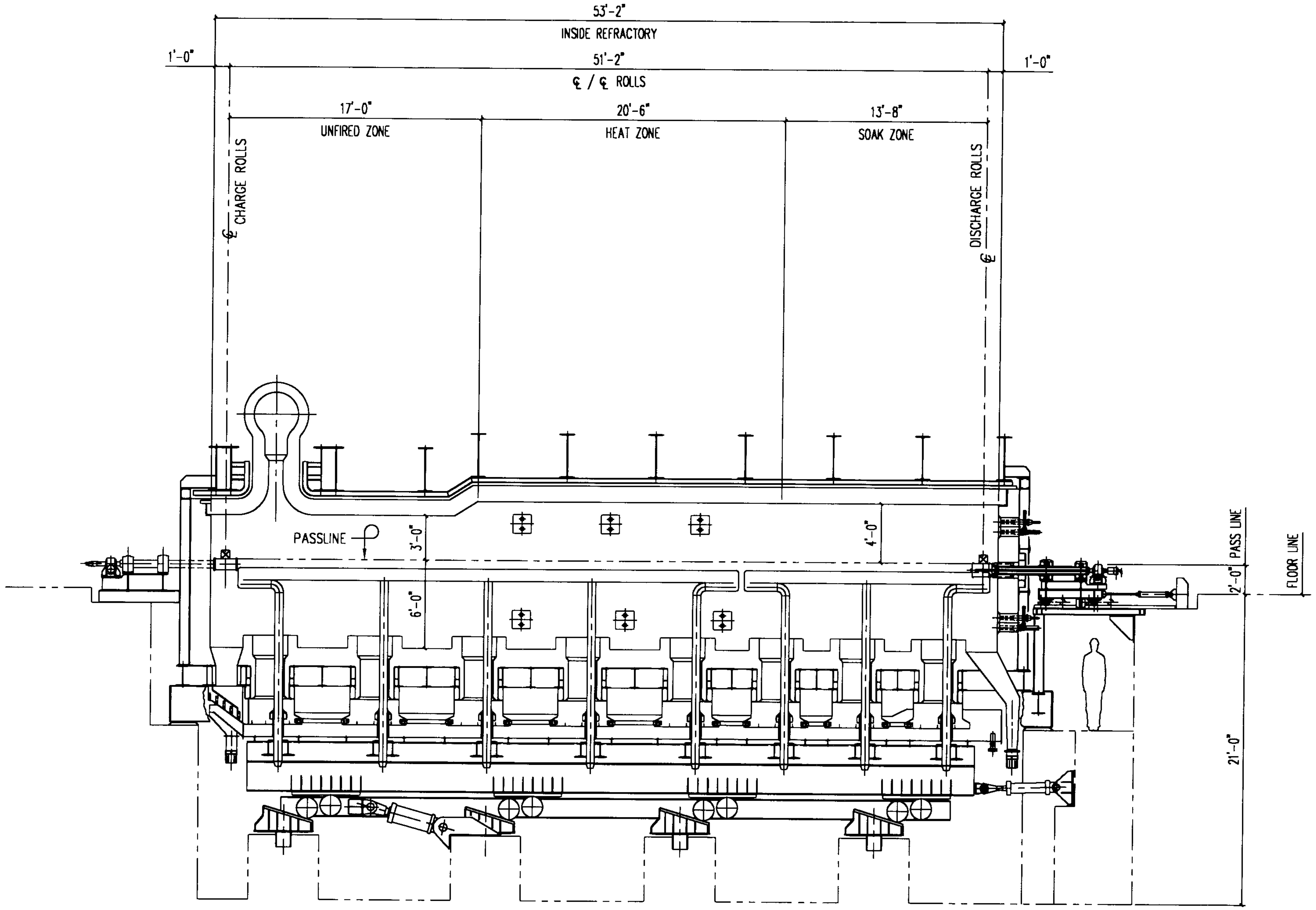
This idea was tested by additional tests with air-fuel firing in the preheat zone and oxy-fuel in the heat and soak zones. The calculated parabolic rate constants for the oxy-fuel zones are shown in Figure A-7. These high-temperature oxy-fuel values are closer to the air-fuel data, indicating that initial scale formation under predominantly air-fuel atmospheres can mitigate scale formation by full oxy-fuel atmospheres at higher temperatures.

Appendix 3

Furnace structural drawings

Longitudinal section drawings

DWG. NO. C-1167-001-07 REV.



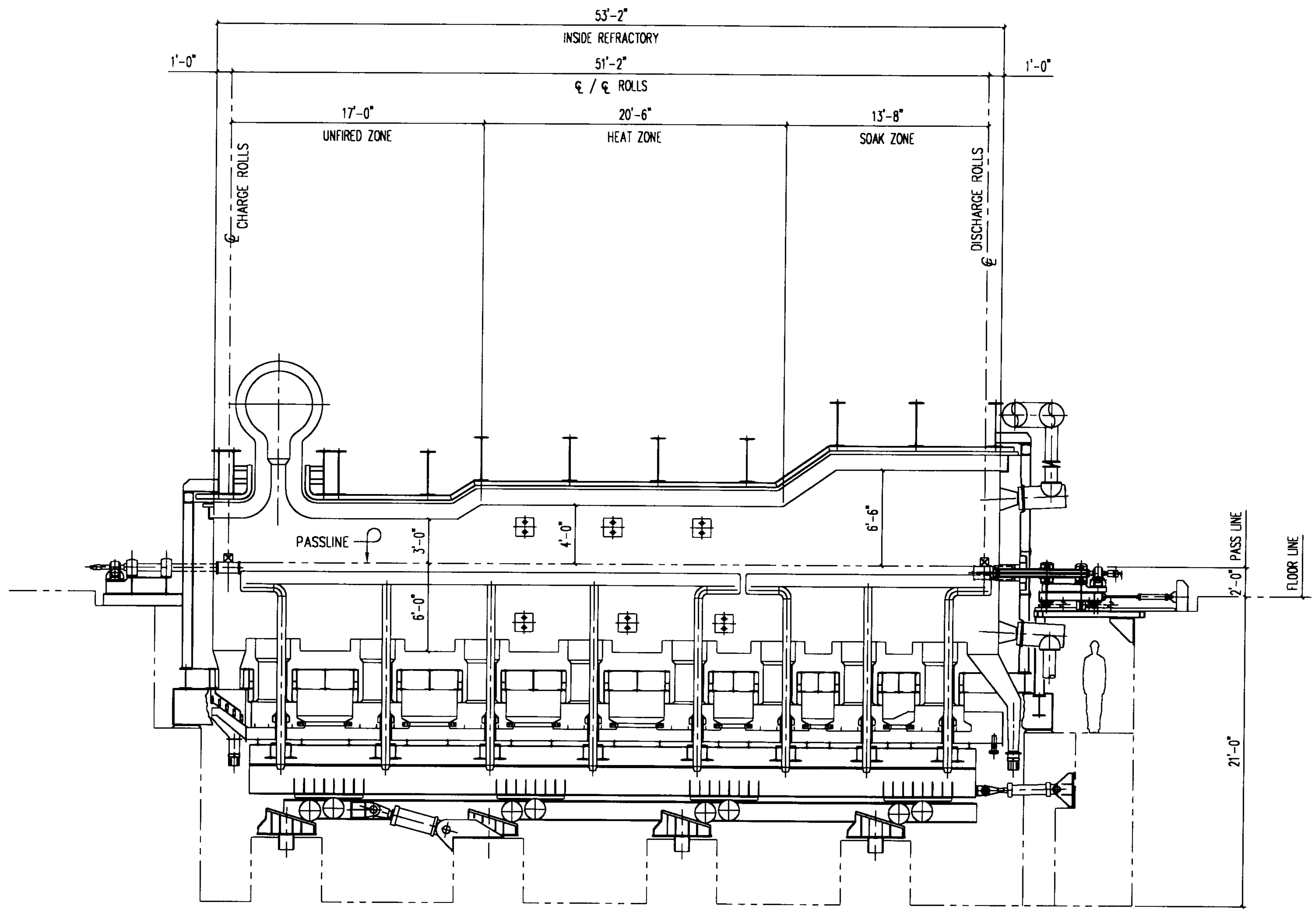
TECHINT TECHNOLOGIES

Furnace Division

TECHINT

PRAXAIR – ALL DOC FIRING
WALKING BEAM type REHEAT FURNACE
LONGITUDINAL SECTION

	NAME	DATE	SCALE	DWG. NO.	REV.
DRAWN	JW	11/21/02	1/4"=1'-0"	C-1167-001-07	
CHECKED					
APPROVED					



COMMON FLUE CONCEPT

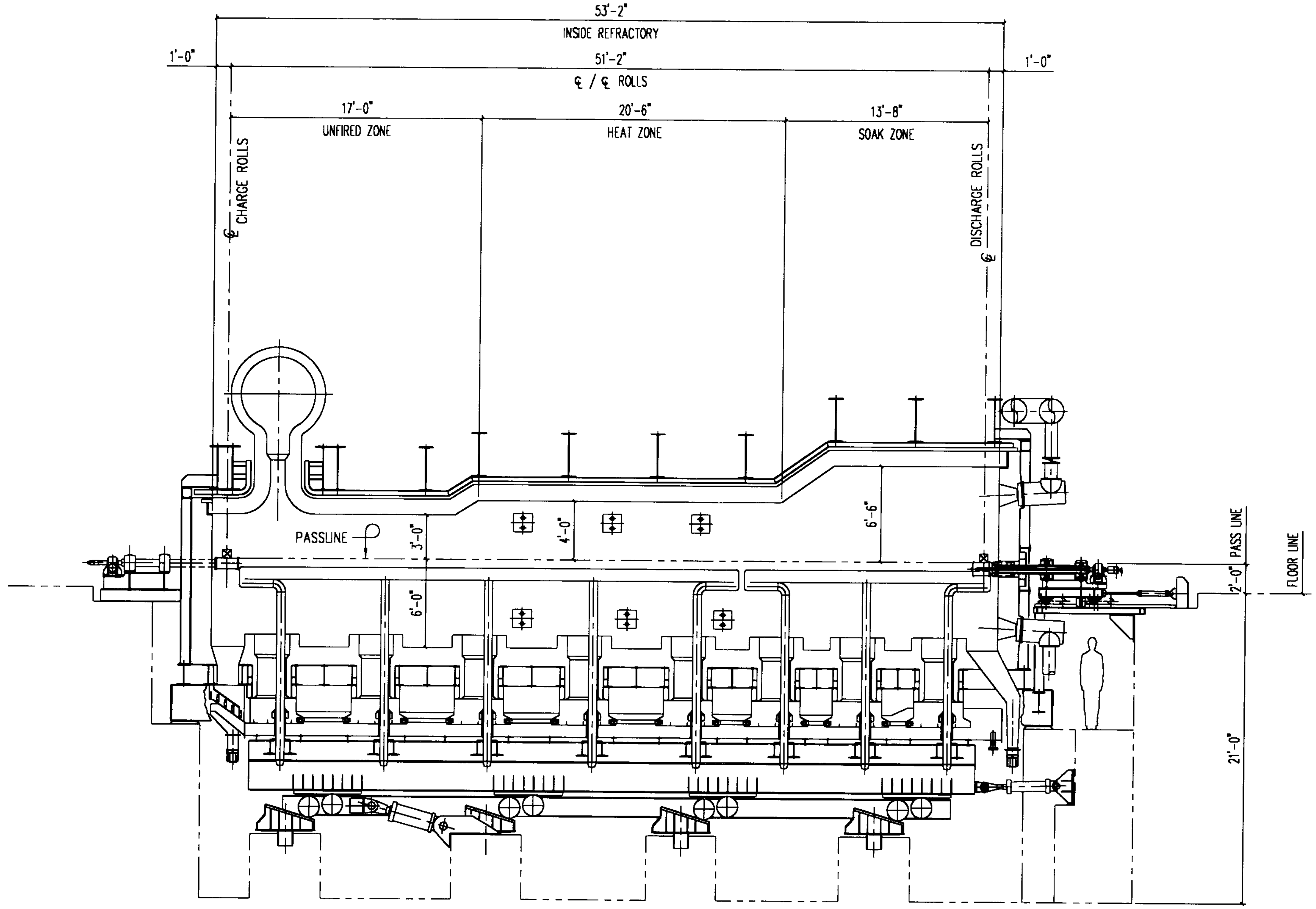
TECHINT TECHNOLOGIES
Furnace Division

PRAXAIR – DOC & HOT AIR FIRING
WALKING BEAM type REHEAT FURNACE
LONGITUDINAL SECTION

	NAME	DATE	SCALE	DWG. NO.	REV.
DRAWN	JFW	11/21/02	1/4"=1'-0"	C-1167-001-12	
CHECKED					
APPROVED					

TECHINT

DWG. NO. C-1167-001-22 REV.



COMMON FLUE CONCEPT

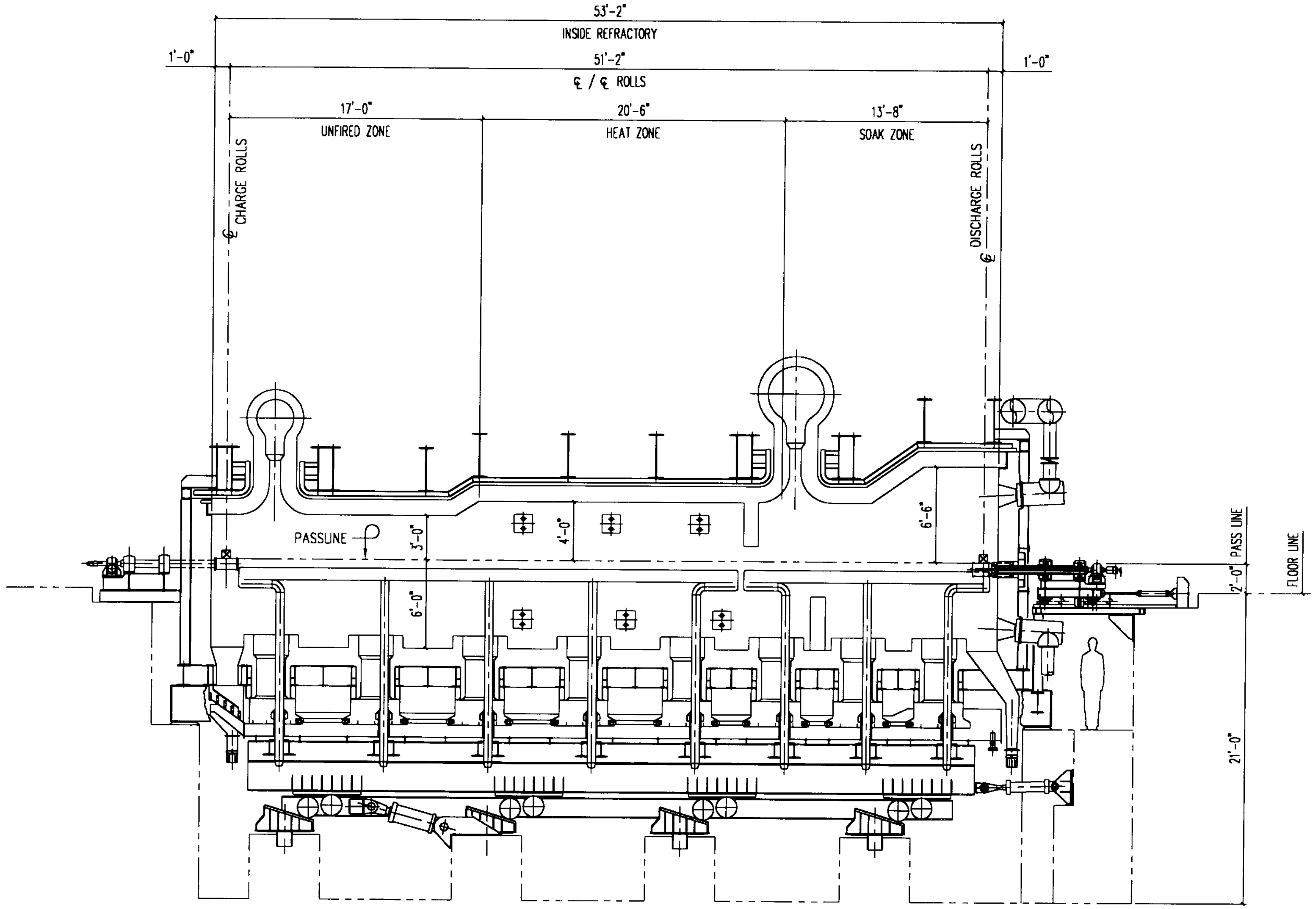
TECHINT TECHNOLOGIES
Furnace Division

PRAXAIR – DOC & COLD AIR FIRING
WALKING BEAM type REHEAT FURNACE
LONGITUDINAL SECTION

	NAME	DATE	SCALE	DWG. NO.	REV.
DRAWN	JFW	11/21/02	1/4"=1'-0"	C-1167-001-22	
CHECKED					
APPROVED					

TECHINT

DWG. NO. C-1167-001-17 REV.



SEPARATE FLUE CONCEPT

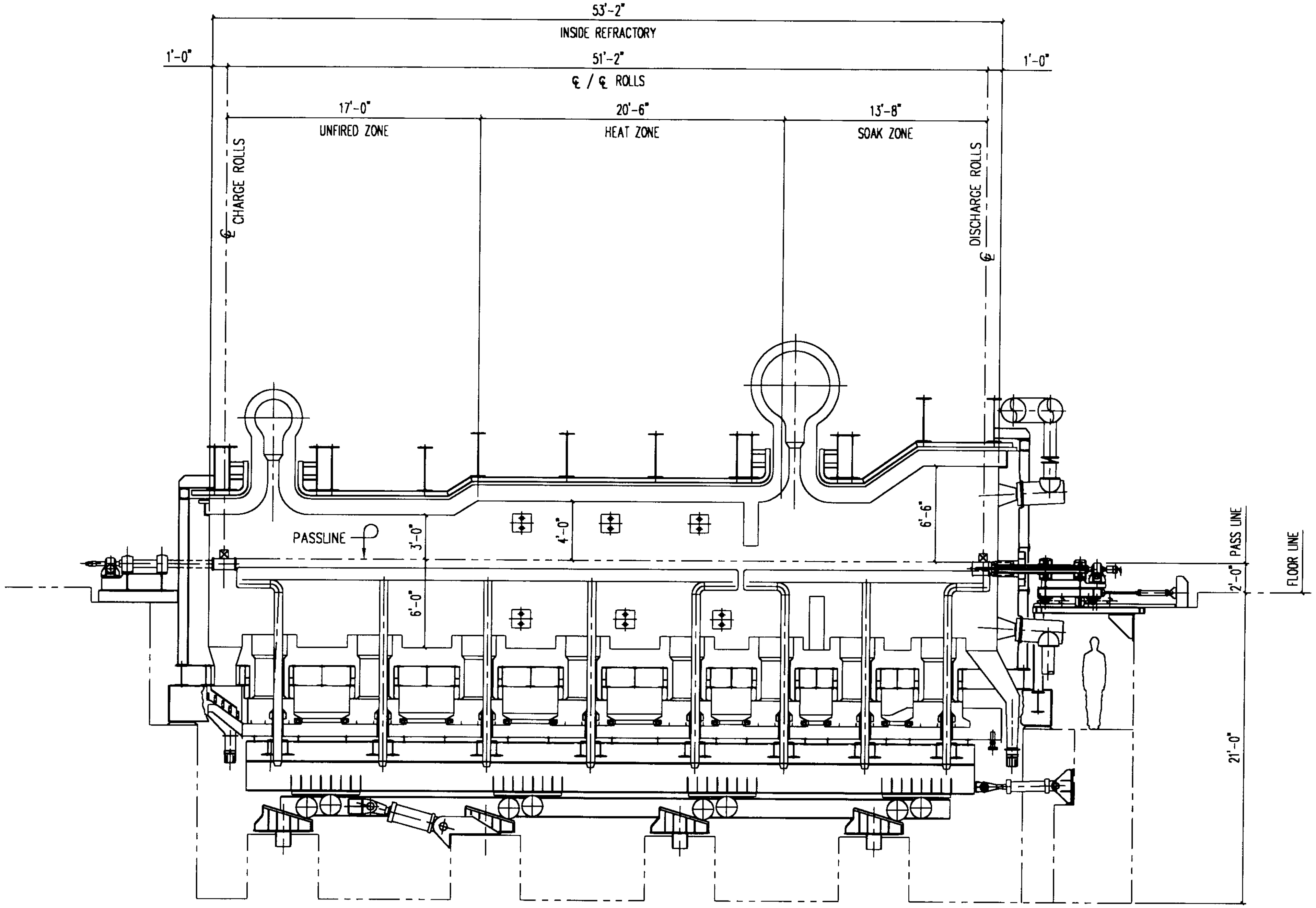
TECHINT TECHNOLOGIES

Furnace Division

TECHINT

PRAXAIR – DOC & HOT AIR FIRING
WALKING BEAM type REHEAT FURNACE
LONGITUDINAL SECTION

	NAME	DATE	SCALE	DWG. NO.	REV.
DRAWN	JFW	11/21/02	1/4"=1'-0"	C-1167-001-17	
CHECKED					
APPROVED					



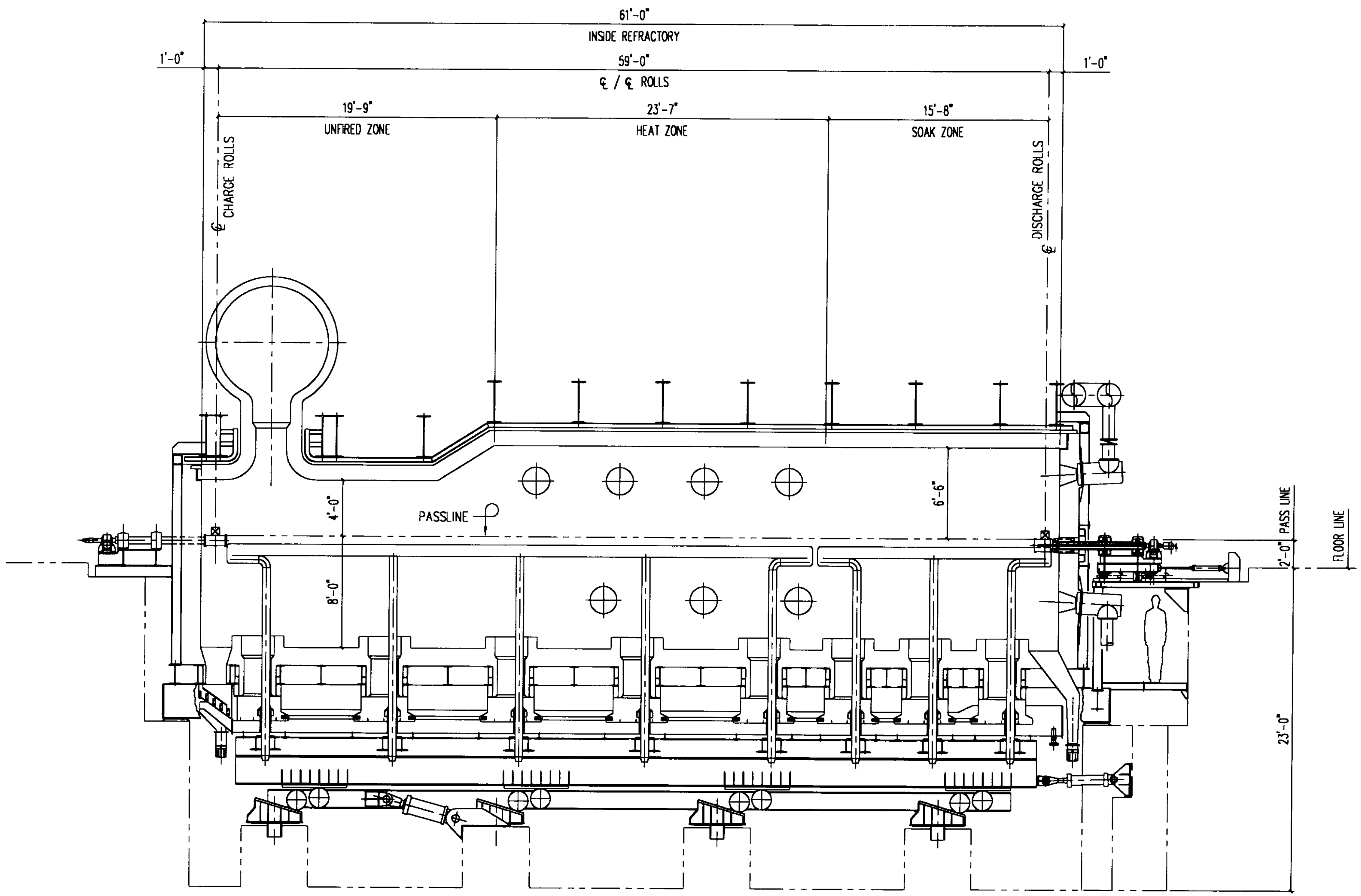
SEPARATE FLUE CONCEPT

TECHINT TECHNOLOGIES
Furnace Division

PRAXAIR – DOC & COLD AIR FIRING
WALKING BEAM type REHEAT FURNACE
LONGITUDINAL SECTION

	NAME	DATE	SCALE	DWG. NO.	REV.
DRAWN	JFW	11/21/02	1/4"=1'-0"	C-1167-001-27	
CHECKED					
APPROVED					

DWG. NO. C-1167-001-27 REV.

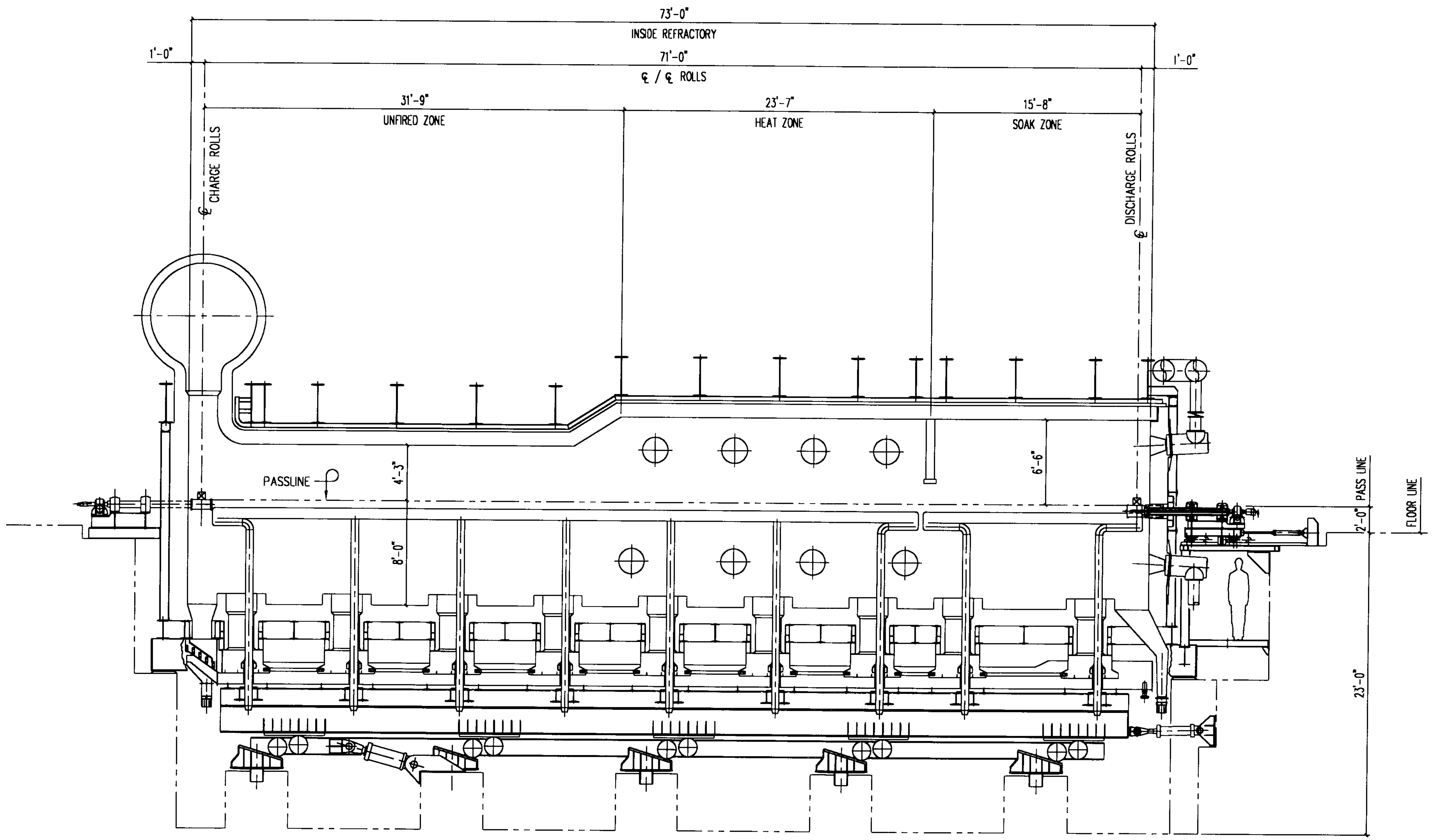


TECHINT TECHNOLOGIES

Furnace Division

PRAXAIR – ALL HOT AIR FIRING
WALKING BEAM type REHEAT FURNACE
LONGITUDINAL SECTION

	NAME	DATE	SCALE	DWG. NO.	REV.
DRAWN	JFW	11/21/02	1/4"=1'-0"	C-1167-001-02	
CHECKED					
APPROVED					



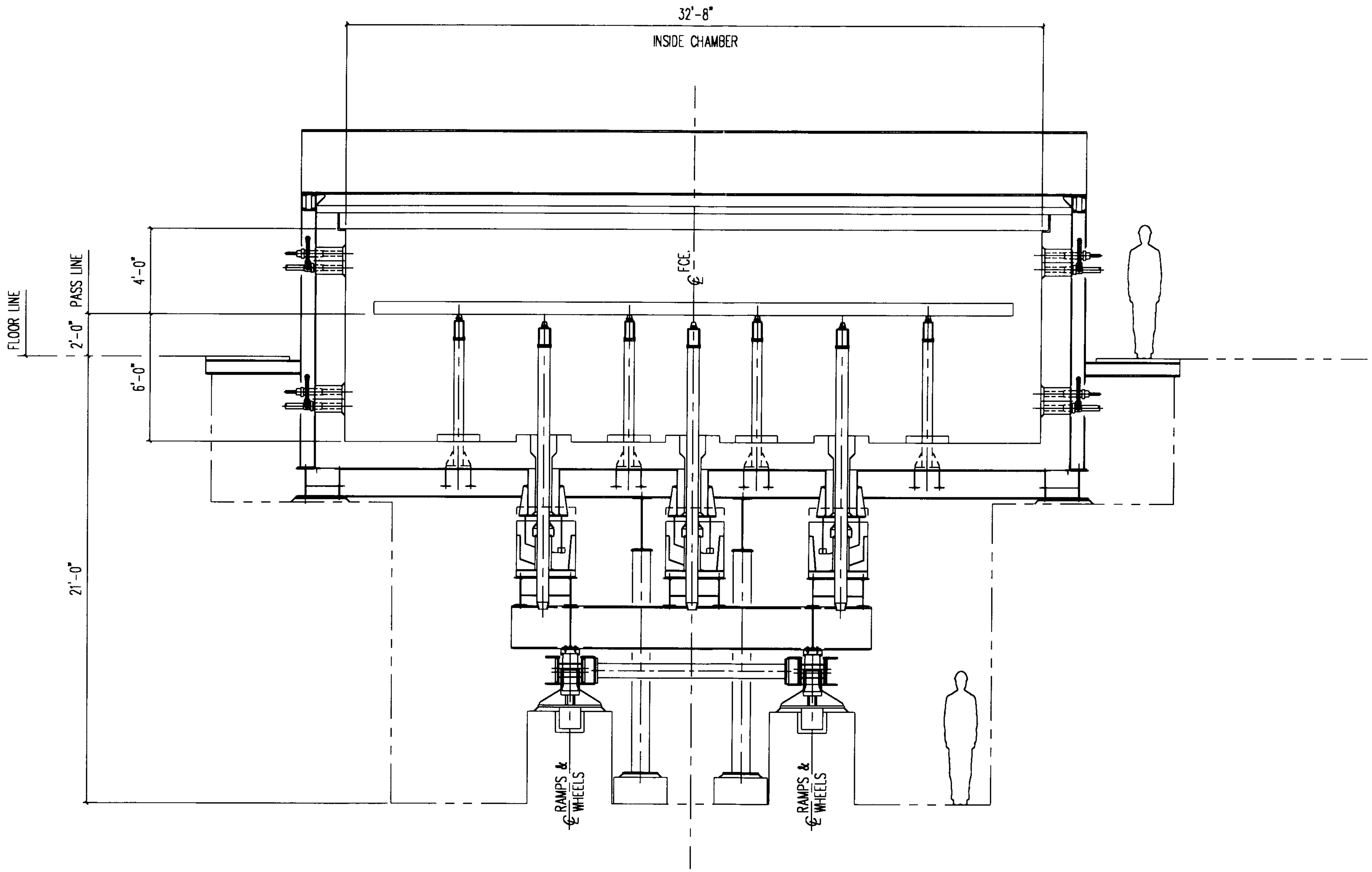
TECHINT TECHNOLOGIES

Furnace Division

PRAXAIR – ALL AIR FIRED LOW FUEL WALKING BEAM type REHEAT FURNACE LONGITUDINAL SECTION

	NAME	DATE	SCALE	DWG. NO.	REV.
DRAWN	JFW	11/21/02	1/4"=1'-0"	C-1167-001-32	
CHECKED					
APPROVED					

Transverse sectional drawings



TECHINT TECHNOLOGIES

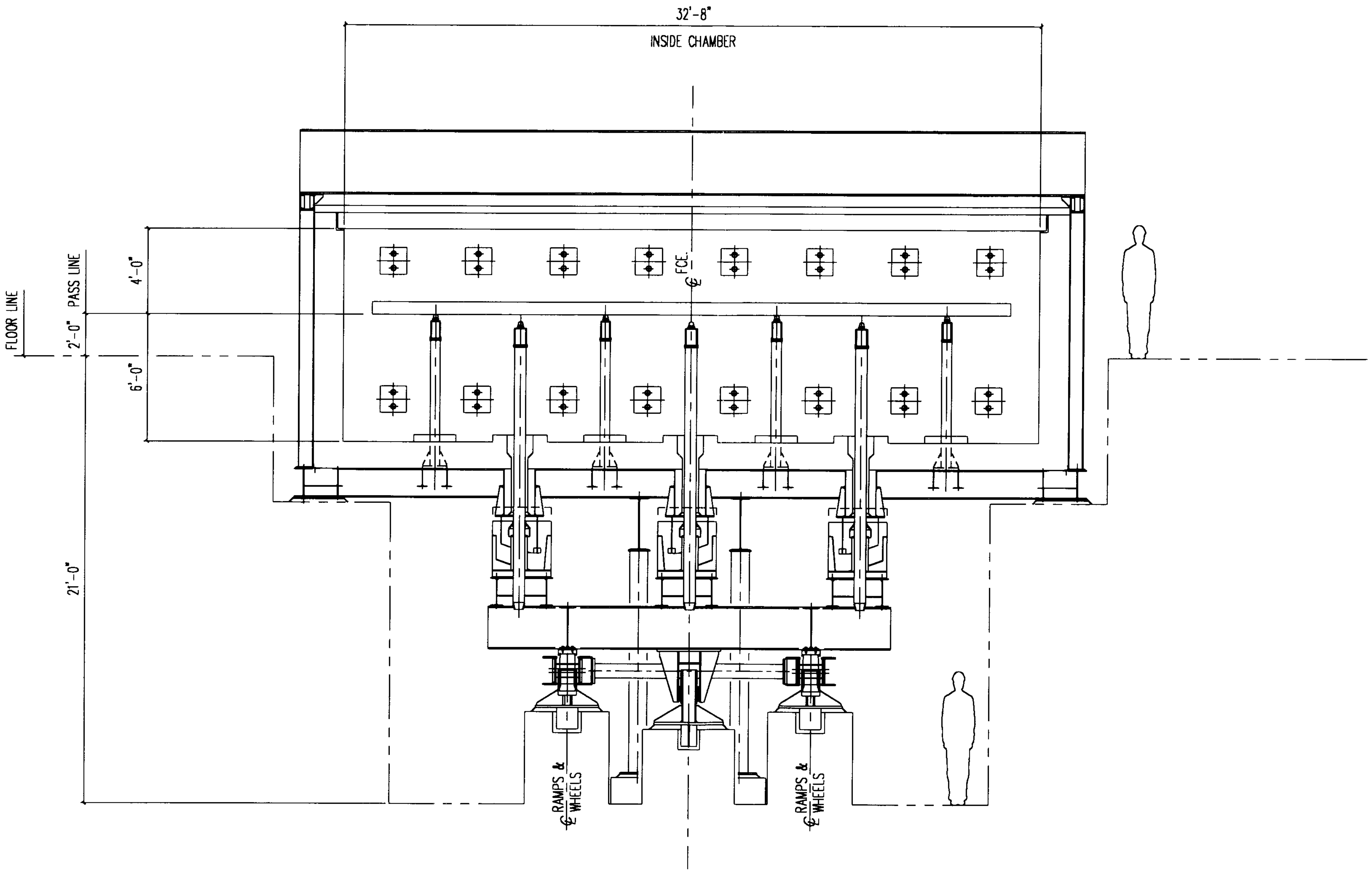
Furnace Division

PRAXAIR – ALL DOC FIRING
WALKING BEAM type REHEAT FURNACE
CROSS SECTION thru HEAT ZONE

	NAME	DATE	SCALE	DWG. NO.	REV.
DRAWN	JFW	11/21/02	3/8"=1'-0"	C-1167-001-08	
CHECKED					
APPROVED					

TECHINT

DWG. NO. C-1167-001-08 REV.



TECHINT TECHNOLOGIES

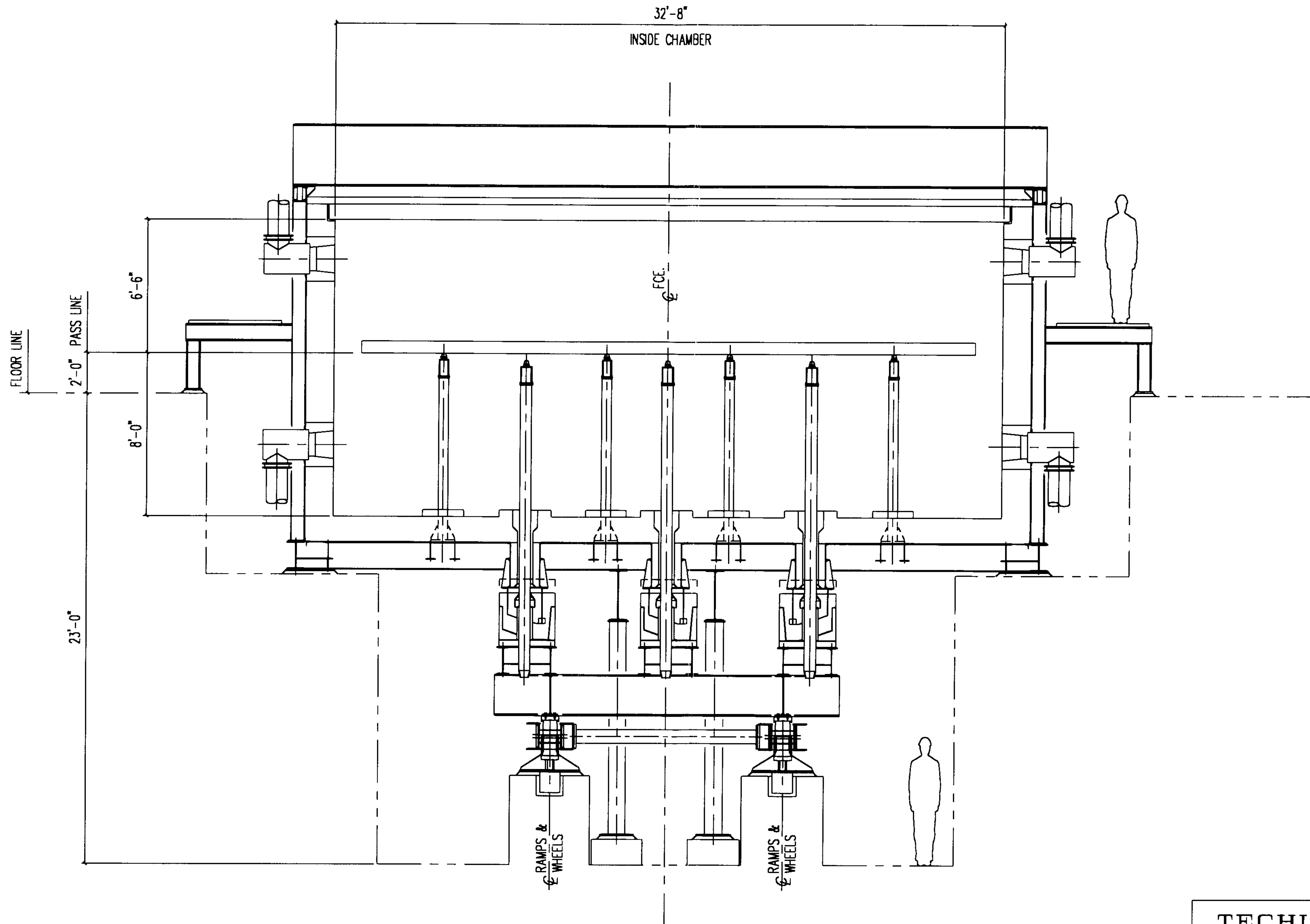
Furnace Division

PRAXAIR – ALL DOC FIRING
WALKING BEAM type REHEAT FURNACE
CROSS SECTION thru SOAK ZONE

TECHINT

	NAME	DATE	SCALE	DWG. NO.	REV.
DRAWN	JFW	11/21/02	3/8"=1'-0"	C-1167-001-09	
CHECKED					
APPROVED					

DWG. NO. C-1167-001-03 REV.



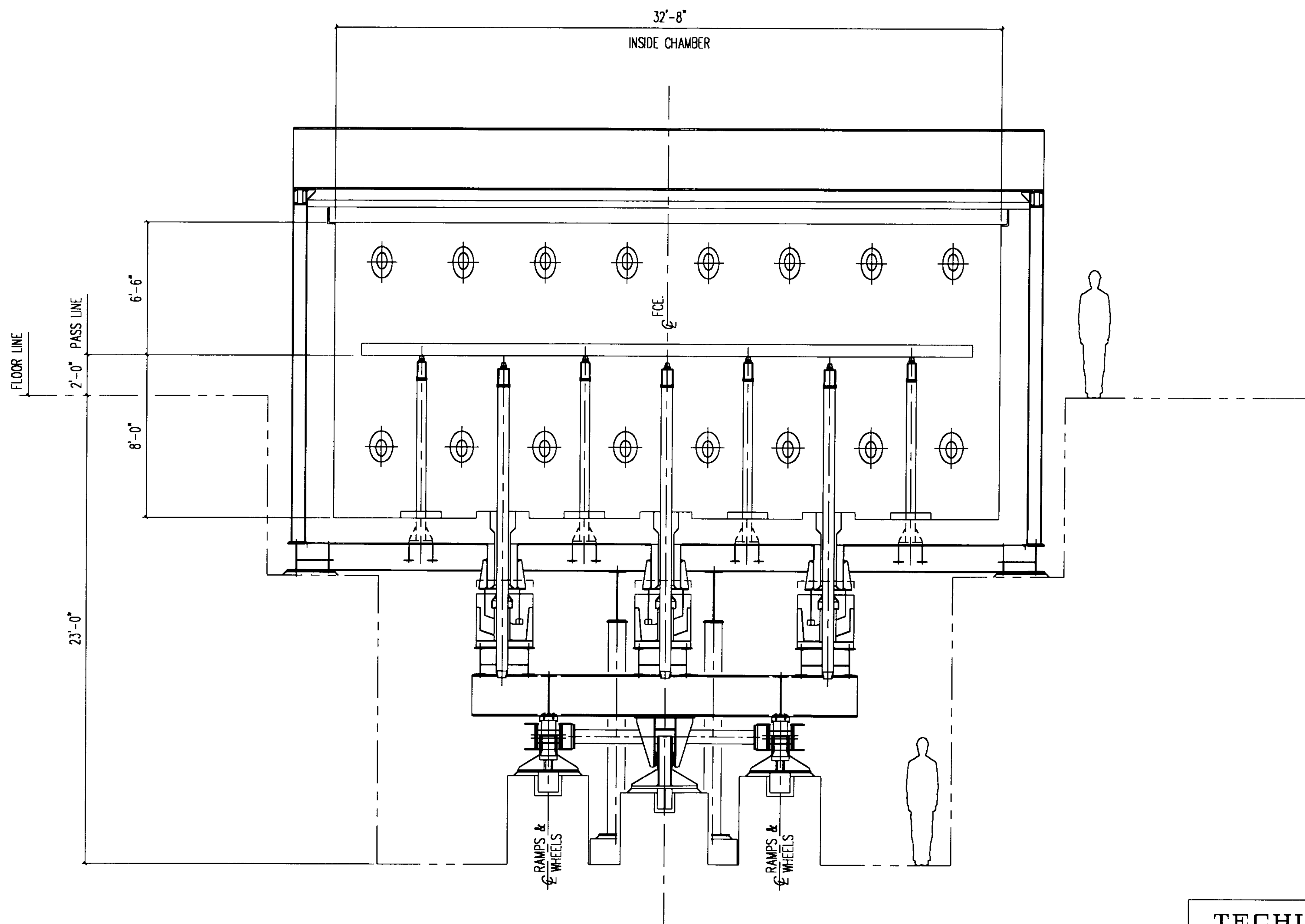
TECHINT TECHNOLOGIES

Furnace Division

TECHINT

PRAXAIR – ALL HOT AIR FIRING
WALKING BEAM type REHEAT FURNACE
CROSS SECTION thru HEAT ZONE

	NAME	DATE	SCALE	DWG. NO.	REV.
DRAWN	JFW	11/21/02	3/8"=1'-0"	C-1167-001-03	
CHECKED					
APPROVED					



TECHINT TECHNOLOGIES

Furnace Division

TECHINT

PRAXAIR – ALL HOT AIR FIRING
WALKING BEAM type REHEAT FURNACE
CROSS SECTION thru SOAK ZONE

	NAME	DATE	SCALE	DWG. NO.	REV.
DRAWN	JFW	11/21/02	3/8"=1'-0"	C-1167-001-04	
CHECKED					
APPROVED					

DWG. NO. C-1167-001-04 REV.

Appendix 4

Energy balances

HEAT BALANCE
03/18/02

ALL OXY FUEL FIRING

TTI CONTRACT
C 1167

EFFECTIVE LENGTH:	51 FT	FUEL:	1027 BTU/SCF HHV
INSIDE WIDTH:	33 FT	AIR PREHEAT TEMP	60 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1463 F
THROUGHPUT:	120 TPH	AIR RATIO:	1.5 % EXCESS O2
CHARGE TEMP:	69 F	DISCHARGE TEMP.:	2150 F
FUEL RATE:	0.950 MMBTU/TON (HHV)	HEATING TIME:	56.500 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	113.944	100.00	HEAT TO STEEL	81.501	71.53
HEAT FROM HOT AIR	0.000	0.00	HEAT TO WATER	6.416	5.63
			HEAT TO INSULATION	2.660	2.33
			HEAT TO SLOTS	0.637	0.56
			HEAT TO DOORS	1	0.88
			ROLLS	1.273	1.12
			WASTE GAS LOSSES	9.142	8.02
			LATENT HEAT OF WATER VAPOR	11.317	9.93
TOTAL	113.944	100.000	TOTAL	113.944	100.000

HEAT BALANCE
05/07/02

ALL OXY FUEL FIRING
10% SKID INSULATION LOSS

TTI CONTRACT
C 1167

EFFECTIVE LENGTH:	51 FT	FUEL:	1027 BTU/SCF HHV
INSIDE WIDTH:	33 FT	AIR PREHEAT TEMP	60 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1463 F
THROUGHPUT:	120 TPH	AIR RATIO:	1.5 % EXCESS O2
CHARGE TEMP:	69 F	DISCHARGE TEMP.:	2150 F
FUEL RATE:	0.998 MMBTU/TON (HHV)	HEATING TIME:	56.500 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	119.772	100.00	HEAT TO STEEL	81.501	68.05
HEAT FROM HOT AIR	0.000	0.00	HEAT TO WATER	11.207	9.36
			HEAT TO INSULATION	2.660	2.22
			HEAT TO SLOTS	0.637	0.53
			HEAT TO DOORS	1	0.83
			ROLLS	1.273	1.06
			WASTE GAS LOSSES	9.599	8.01
			LATENT HEAT OF WATER VAPOR	11.896	9.93
TOTAL	119.772	100.000	TOTAL	119.772	100.000

HEAT BALANCE
05/08/02

OXY FUEL FIRING
HOT AIR SOAK ZONES

TTI CONTRACT
C 1167

EFFECTIVE LENGTH:	51 FT	FUEL:	1027 BTU/SCF HHV
INSIDE WIDTH:	33 FT	AIR PREHEAT TEMP	900 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1425 F
THROUGHPUT:	120 TPH	AIR RATIO:	1.5 % EXCESS O2
CHARGE TEMP:	69 F	DISCHARGE TEMP.:	2150 F
FUEL RATE:	1.068 MMBTU/TON (HHV)	HEATING TIME:	56.500 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	128.148	96.15	HEAT TO STEEL	81.501	61.15
HEAT FROM HOT AIR	5.127	3.85	HEAT TO WATER	6.416	4.81
			HEAT TO INSULATION	2.660	2.00
			HEAT TO SLOTS	0.647	0.49
			HEAT TO DOORS	1	0.75
			CHARGE & EXTRACT	1.273	0.96
			WASTE GAS LOSSES	27.051	20.30
			LATENT HEAT OF WATER VAPOR	12.727	9.55
TOTAL	133.275	100.000	TOTAL	133.275	100.000

HEAT BALANCE
05/08/02

OXY FUEL FIRING
HOT AIR SOAK ZONES
BOTH SKID AND RECUPERATOR LOSSES

TTI CONTRACT
C 1167

EFFECTIVE LENGTH:	51 FT	FUEL:	1027 BTU/SCF HHV
INSIDE WIDTH:	33 FT	AIR PREHEAT TEMP	900 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1441 F
THROUGHPUT:	120 TPH	AIR RATIO:	1.5 % EXCESS O2
CHARGE TEMP:	69 F	DISCHARGE TEMP.:	2150 F
FUEL RATE:	1.138 MMBTU/TON (HHV)	HEATING TIME:	56.500 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	136.574	96.66	HEAT TO STEEL	81.501	57.68
HEAT FROM HOT AIR	4.713	3.34	HEAT TO WATER	11.294	7.99
			HEAT TO INSULATION	2.660	1.88
			HEAT TO SLOTS	0.647	0.46
			HEAT TO DOORS	1	0.71
			CHARGE & EXTRACT	1.273	0.90
			WASTE GAS LOSSES	29.349	20.77
			LATENT HEAT OF WATER VAPOR	13.564	9.60
TOTAL	141.287	100.000	TOTAL	141.287	100.000

HEAT BALANCE
05/07/02

OXY FUEL FIRING
COLD AIR SOAK ZONES

TTI CONTRACT
C 1167

EFFECTIVE LENGTH:	51 FT	FUEL:	1027 BTU/SCF HHV
INSIDE WIDTH:	33 FT	AIR PREHEAT TEMP	60 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1589 F
THROUGHPUT:	120 TPH	AIR RATIO:	1.5 % EXCESS O2
CHARGE TEMP:	69 F	DISCHARGE TEMP.:	2150 F
FUEL RATE:	1.122 MMBTU/TON (HHV)	HEATING TIME:	56.500 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	134.676	100.00	HEAT TO STEEL	81.501	60.52
HEAT FROM HOT AIR	0.000	0.00	HEAT TO WATER	6.416	4.76
			HEAT TO INSULATION	2.660	1.98
			HEAT TO SLOTS	0.663	0.49
			HEAT TO DOORS	1	0.74
			HEAT TO ROLLS	1.273	0.95
			WASTE GAS LOSSES	27.788	20.63
			LATENT HEAT OF WATER VAPOR	13.376	9.93
TOTAL	134.676	100.000	TOTAL	134.676	100.000

HEAT BALANCE	OXY FUEL FIRING	TTI CONTRACT
05/07/02	COLD AIR SOAK ZONES	C 1167
	10% SKID INSULATION LOSS	

EFFECTIVE LENGTH:	51 FT	FUEL:	1027 BTU/SCF HHV
INSIDE WIDTH:	33 FT	AIR PREHEAT TEMP	60 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1616 F
THROUGHPUT:	120 TPH	AIR RATIO:	1.5 % EXCESS O2
CHARGE TEMP:	69 F	DISCHARGE TEMP.:	2150 F
FUEL RATE:	1.194 MMBTU/TON (HHV)	HEATING TIME:	56.500 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	143.336	100.00	HEAT TO STEEL	81.501	56.86
HEAT FROM HOT AIR	0.000	0.00	HEAT TO WATER	11.435	7.98
			HEAT TO INSULATION	2.660	1.86
			HEAT TO SLOTS	0.663	0.46
			HEAT TO DOORS	1	0.70
			HEAT TO ROLLS	1.273	0.89
			WASTE GAS LOSSES	30.568	21.33
			LATENT HEAT OF WATER VAPOR	14.236	9.93
TOTAL	143.336	100.000	TOTAL	143.336	100.000

HEAT BALANCE
05/07/02

OXY FUEL FIRING
HOT AIR SOAK ZONES
SECOND FLUE

TTI PROPOSAL
P 1167

EFFECTIVE LENGTH:	51 FT		FUEL:	1027 BTU/SCF HHV
INSIDE WIDTH:	33 FT		AIR PREHEAT TEMP	900 F
PIECE SIZE:	6"X6"X30'		WASTE GAS TEMP.:	1318 F
THROUGHPUT:	120 TPH		(SECONDARY)	2380 F
CHARGE TEMP:	69 F		AIR RATIO:	1.5 % EXCESS O2
FUEL RATE:	1.085 MMBTU/TON (HHV)		DISCHARGE TEMP.:	2150 F
			HEATING TIME:	56.500 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	130.223	95.86	HEAT TO STEEL	81.501	60.00
HEAT FROM HOT AIR	5.621	4.14	HEAT TO WATER	6.416	4.72
			HEAT TO INSULATION	2.660	1.96
			HEAT TO SLOTS	0.630	0.46
			HEAT TO DOORS	1	0.74
			CHARGE & EXTRACT	1.273	0.94
			WASTE GAS LOSSES	29.432	21.67
			LATENT HEAT OF WATER VAPOR	12.934	9.52
TOTAL	135.845	100.000	TOTAL	135.845	100.000

HEAT BALANCE | OXY FUEL FIRING | TTI CONTRACT
05/07/02 | HOT AIR SOAK ZONES | C 1167
SECOND FLUE
BOTH SKID AND RECUPERATOR LOSSES

EFFECTIVE LENGTH:	51 FT	FUEL:	1027 BTU/SCF HHV
INSIDE WIDTH:	33 FT	AIR PREHEAT TEMP	750 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1313 F
THROUGHPUT:	120 TPH	(SECONDARY)	2395 F
CHARGE TEMP:	69 F	AIR RATIO:	1.5 % EXCESS O2
FUEL RATE:	1.153 MMBTU/TON (HHV)	DISCHARGE TEMP.:	2150 F
		HEATING TIME:	56.500 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	138.364	96.44	HEAT TO STEEL	81.501	56.81
HEAT FROM HOT AIR	5.103	3.56	HEAT TO WATER	11.149	7.77
			HEAT TO INSULATION	2.660	1.85
			HEAT TO SLOTS	0.630	0.44
			HEAT TO DOORS	1	0.70
			CHARGE & EXTRACT	1.273	0.89
			WASTE GAS LOSSES	31.513	21.97
			LATENT HEAT OF WATER VAPOR	13.742	9.58
TOTAL	143.467	100.000	TOTAL	143.467	100.000

HEAT BALANCE
05/07/02

OXY FUEL FIRING
COLD AIR SOAK ZONES
SECOND FLUE

TTI PROPOSAL
C 1167

EFFECTIVE LENGTH:	51 FT	FUEL:	1027 BTU/SCF HHV
INSIDE WIDTH:	33 FT	AIR PREHEAT TEMP	60 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1349 F
THROUGHPUT:	120 TPH	(SECONDARY)	2390 F
CHARGE TEMP:	69 F	AIR RATIO:	1.5 % EXCESS O2
FUEL RATE:	1.275 MMBTU/TON (HHV)	DISCHARGE TEMP.:	2150 F
		HEATING TIME:	56.500 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	153.022	100.00	HEAT TO STEEL	81.501	53.26
HEAT FROM HOT AIR	0.000	0.00	HEAT TO WATER	6.416	4.19
			HEAT TO INSULATION	2.660	1.74
			HEAT TO SLOTS	0.647	0.42
			HEAT TO DOORS	1	0.65
			ROLL LOSSES	1.273	0.83
			WASTE GAS LOSSES	44.328	28.97
			LATENT HEAT OF WATER VAPOR	15.198	9.93
TOTAL	153.022	100.000	TOTAL	153.022	100.000

HEAT BALANCE
05/07/02

OXY FUEL FIRING
COLD AIR SOAK ZONES
SECOND FLUE
10% SKID INSULATION LOSS

TTI CONTRACT
C 1167

EFFECTIVE LENGTH:	51 FT	FUEL:	1027 BTU/SCF HHV
INSIDE WIDTH:	33 FT	AIR PREHEAT TEMP	60 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1344 F
THROUGHPUT:	120 TPH	(SECONDARY)	2385 F
CHARGE TEMP:	69 F	AIR RATIO:	1.5 % EXCESS O2
FUEL RATE:	1.353 MMBTU/TON (HHV)	DISCHARGE TEMP.:	2150 F
		HEATING TIME:	56.500 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	162.340	100.00	HEAT TO STEEL	81.501	50.20
HEAT FROM HOT AIR	0.000	0.00	HEAT TO WATER	11.296	6.96
			HEAT TO INSULATION	2.660	1.64
			HEAT TO SLOTS	0.647	0.40
			HEAT TO DOORS	1	0.62
			ROLL LOSSES	1.273	0.78
			WASTE GAS LOSSES	47.840	29.47
			LATENT HEAT OF WATER VAPOR	16.123	9.93
TOTAL	162.340	100.000	TOTAL	162.340	100.000

HEAT BALANCE
3/19/02

ALL AIR FIRING

TTI CONTRACT
C 1167

EFFECTIVE LENGTH:	59 FT	FUEL:	1027 BTU/SCF (HHV)
INSIDE WIDTH:	33 FT	AIR PREHEAT TEMP.:	900 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1588 F
THROUGHPUT:	120 TPH	AIR RATIO:	5 % EXCESS AIR
CHARGE TEMP:	69 F	DISCHARGE TEMP.:	2150 F
FUEL RATE:	1.094 MMBTU/TON	HEATING TIME:	65.000 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	131.325	84.02	HEAT TO STEEL	81.501	52.14
HEAT FROM HOT AIR	24.972	15.98	HEAT TO WATER	7.381	4.72
			HEAT TO INSULATION	2.968	1.90
			HEAT TO SLOTS	0.752	0.48
			HEAT TO DOORS	1.000	0.64
			ROLLS	1.273	0.81
			WASTE GAS LOSSES	48.379	30.95
			LATENT HEAT OF WATER VAPOR	13.043	8.34
TOTAL	156.297	100.000	TOTAL	156.297	100.000

HEAT BALANCE
5/7/02

ALL AIR FIRING
COMBINED SKID AND RECUPERATOR LOSSES

TTI CONTRACT
C 1167

EFFECTIVE LENGTH:	59 FT	FUEL:	1027 BTU/SCF (HHV)
INSIDE WIDTH:	33 FT	AIR PREHEAT TEMP.:	750 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1664 F
THROUGHPUT:	120 TPH	AIR RATIO:	5 % EXCESS AIR
CHARGE TEMP:	69 F	DISCHARGE TEMP.:	2150 F
FUEL RATE:	1.249 MMBTU/TON	HEATING TIME:	65.000 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	149.891	87.36	HEAT TO STEEL	81.501	47.50
HEAT FROM HOT AIR	21.696	12.64	HEAT TO WATER	13.059	7.61
			HEAT TO INSULATION	2.968	1.73
			HEAT TO SLOTS	0.752	0.44
			HEAT TO DOORS	1.000	0.58
			ROLLS	1.273	0.74
			WASTE GAS LOSSES	56.147	32.72
			LATENT HEAT OF WATER VAPOR	14.887	8.68
TOTAL	171.587	100.000	TOTAL	171.587	100.000

HEAT BALANCE
3/19/02

ALL AIR FIRING
LONGER FURNACE

TTI CONTRACT
C 1167

EFFECTIVE LENGTH:	71 FT	FUEL:	1027 BTU/SCF (HHV)
INSIDE WIDTH:	32.5 FT	AIR PREHEAT TEMP.:	850 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1182 F
THROUGHPUT:	120 TPH	AIR RATIO:	5 % EXCESS AIR
CHARGE TEMP:	69 F	DISCHARGE TEMP.:	2150 F
FUEL RATE:	0.988 MMBTU/TON	HEATING TIME:	78.333 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	118.578	87.16	HEAT TO STEEL	81.501	59.91
HEAT FROM HOT AIR	17.461	12.84	HEAT TO WATER	8.895	6.54
			HEAT TO INSULATION	3.491	2.57
			HEAT TO SLOTS	0.727	0.53
			HEAT TO DOORS	1.000	0.74
			ROLLS	1.273	0.94
			WASTE GAS LOSSES	27.375	20.12
			LATENT HEAT OF WATER VAPOR	11.777	8.66
TOTAL	136.038	100.000	TOTAL	136.038	100.000

HEAT BALANCE
5/7/02

ALL AIR FIRING
LONGER FURNACE
COMBINED SKID AND RECUPERATOR LOSSES

TTI CONTRACT
C 1167

EFFECTIVE LENGTH:	71 FT	FUEL:	1027 BTU/SCF (HHV)
INSIDE WIDTH:	32.5 FT	AIR PREHEAT TEMP.:	700 F
PIECE SIZE:	6"X6"X30'	WASTE GAS TEMP.:	1286 F
THROUGHPUT:	120 TPH	AIR RATIO:	5 % EXCESS AIR
CHARGE TEMP:	69 F	DISCHARGE TEMP.:	2150 F
FUEL RATE:	1.117 MMBTU/TON	HEATING TIME:	78.333 MIN.

INPUT	MMBTU/HR	%	OUTPUT	MMBTU/HR	%
TOTAL GROSS FUEL	134.048	89.43	HEAT TO STEEL	81.501	54.37
HEAT FROM HOT AIR	15.845	10.57	HEAT TO WATER	14.207	9.48
			HEAT TO INSULATION	3.491	2.33
			HEAT TO SLOTS	0.727	0.48
			HEAT TO DOORS	1.000	0.67
			ROLLS	1.273	0.85
			WASTE GAS LOSSES	34.380	22.94
			LATENT HEAT OF WATER VAPOR	13.313	8.88
TOTAL	149.892	100.000	TOTAL	149.892	100.000

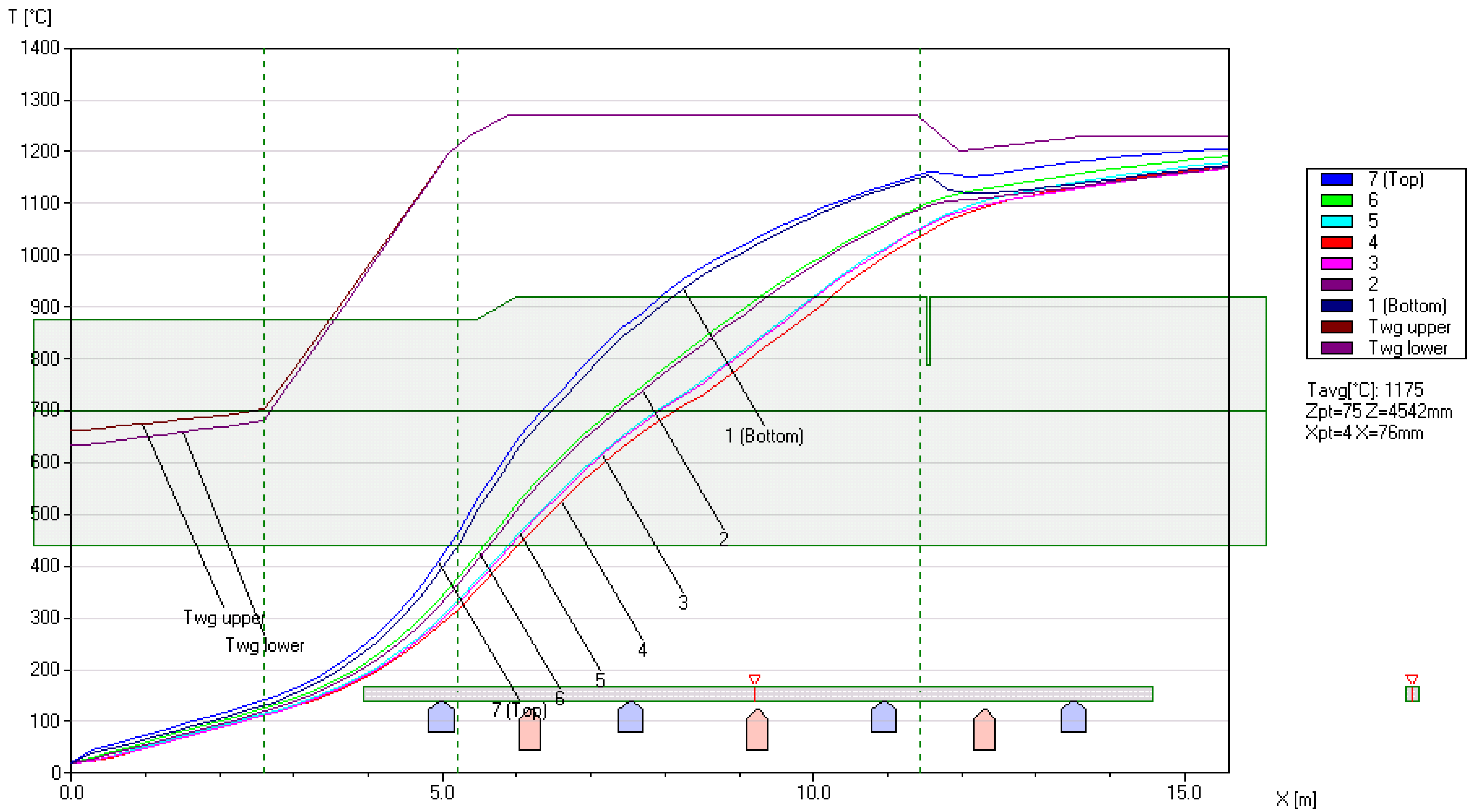
<u>Appendix 5</u>

Furnace and steel heating curves

HEATING CURVE: WALKING BEAM FURNACE

120 TPH: 6”X6”X30’ BILLETS

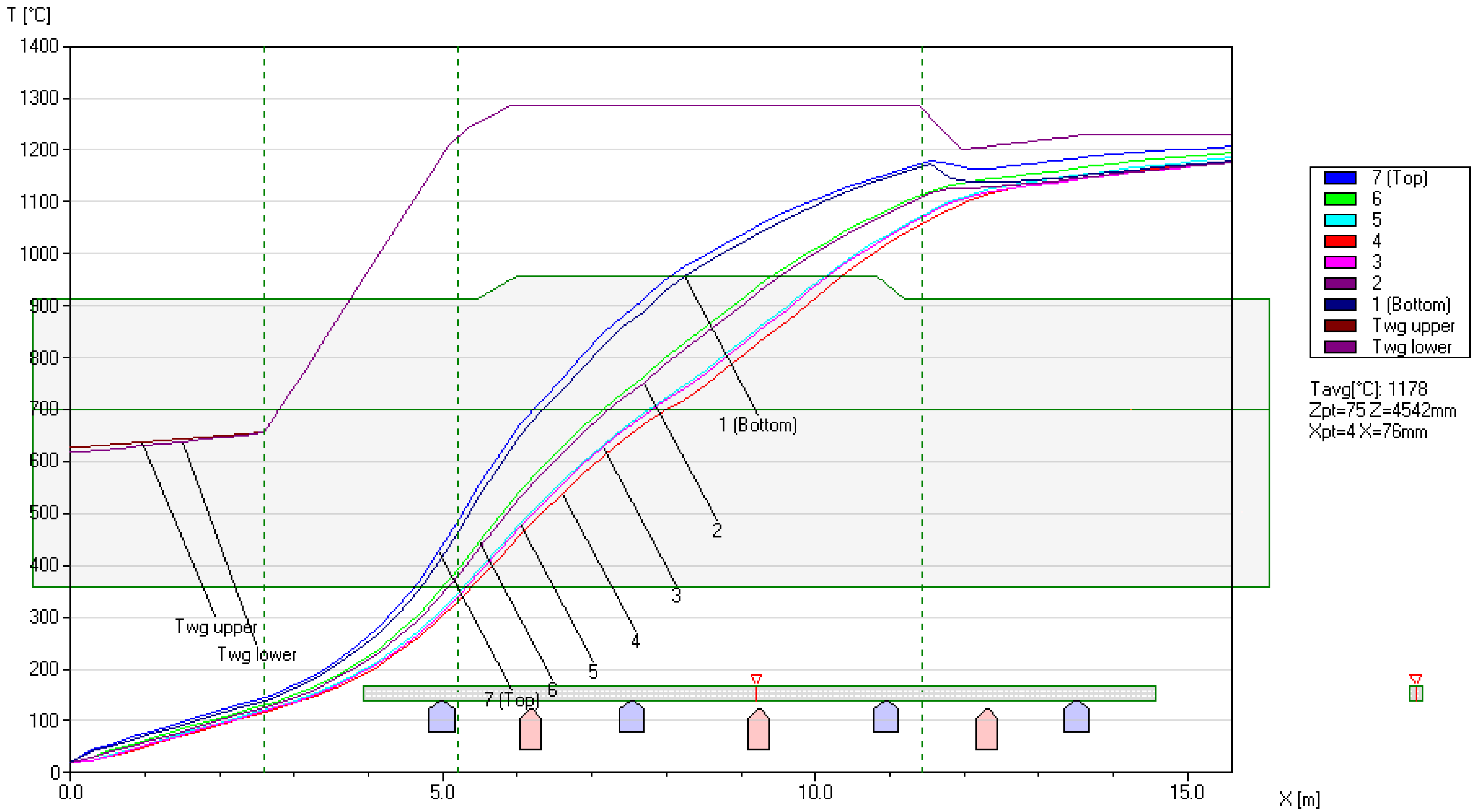
ALL DILUTE OXYGEN COMBUSTION



HEATING CURVE: WALKING BEAM FURNACE

120 TPH: 6”X6”X30’ BILLETS

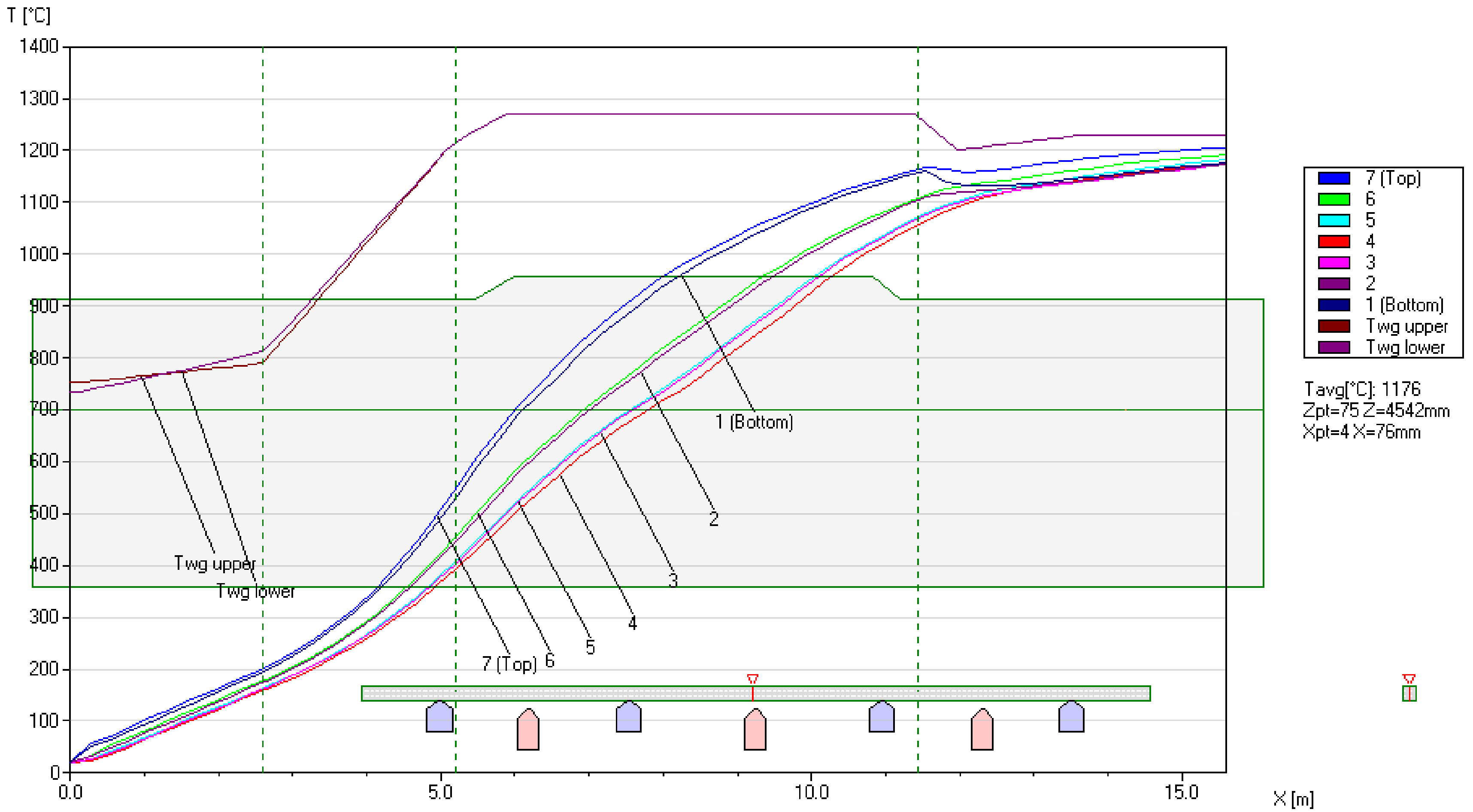
HOT AIR SOAK ZONE - CONVENTIONAL FLUE



HEATING CURVE: WALKING BEAM FURNACE

120 TPH: 6”X6”X30’ BILLETS

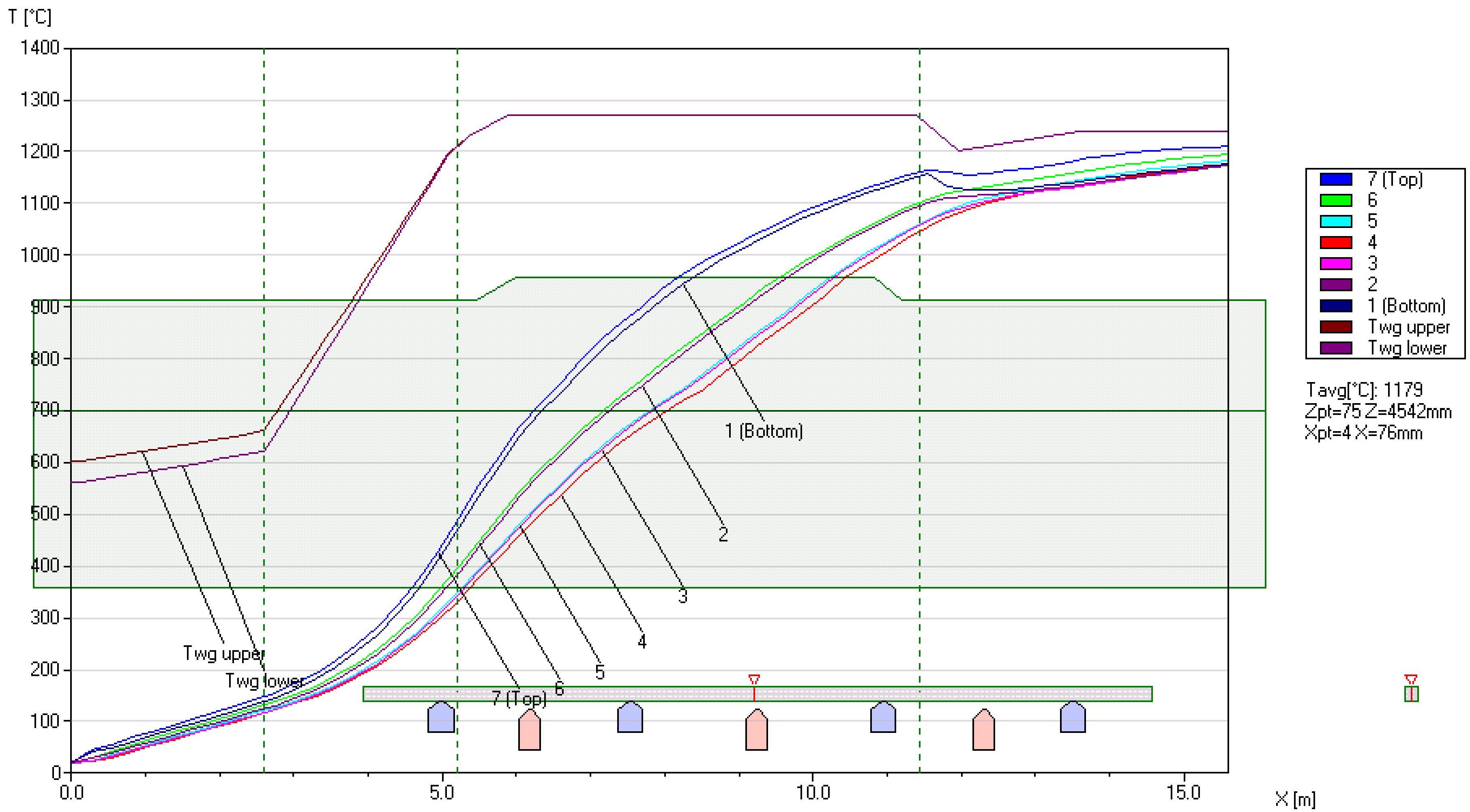
COLD AIR SOAK ZONE - CONVENTIONAL FLUE



HEATING CURVE: WALKING BEAM FURNACE

120 TPH: 6”X6”X30’ BILLETS

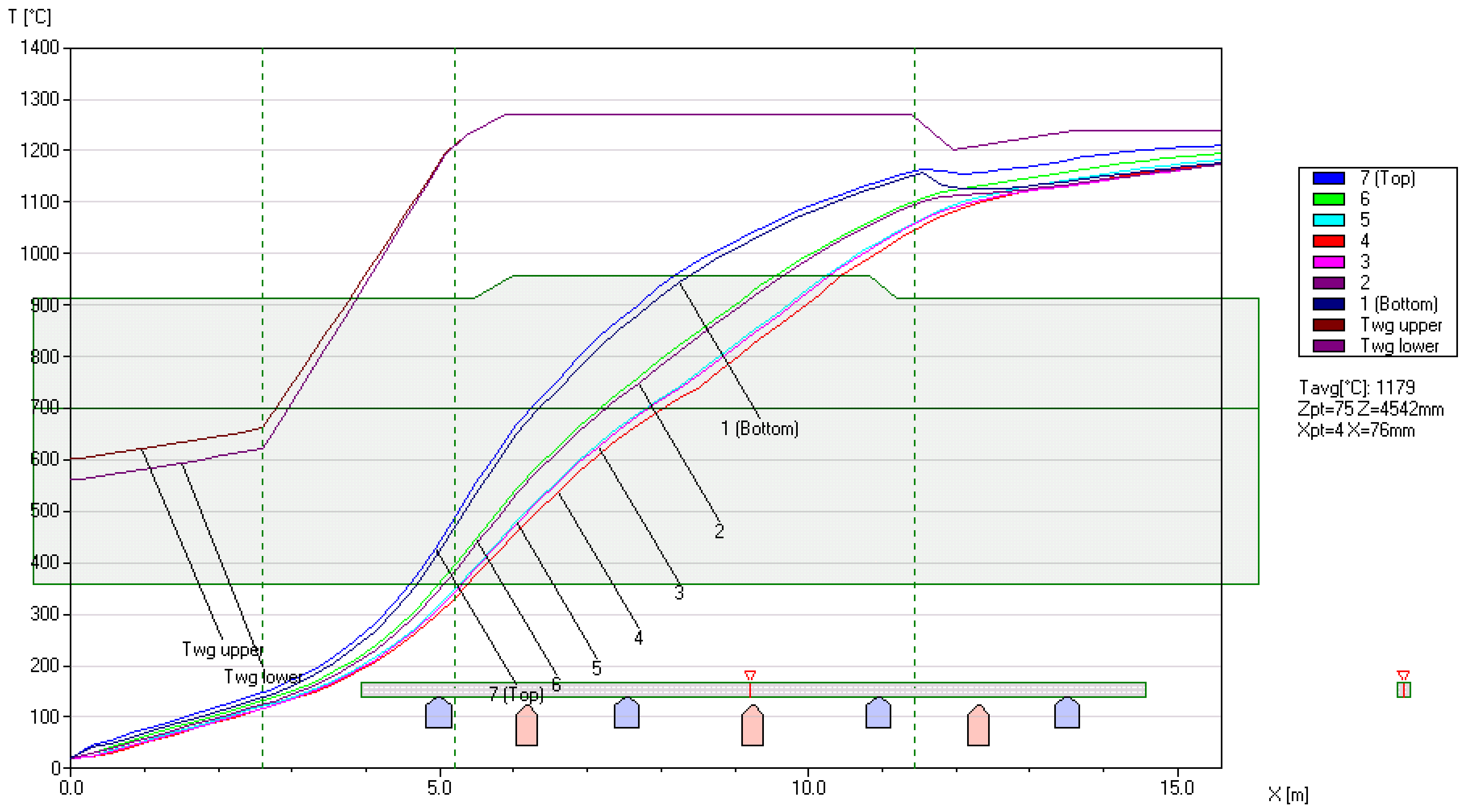
HOT SOAK - SEPARATE FLUE



HEATING CURVE: WALKING BEAM FURNACE

120 TPH: 6”X6”X30’ BILLETS

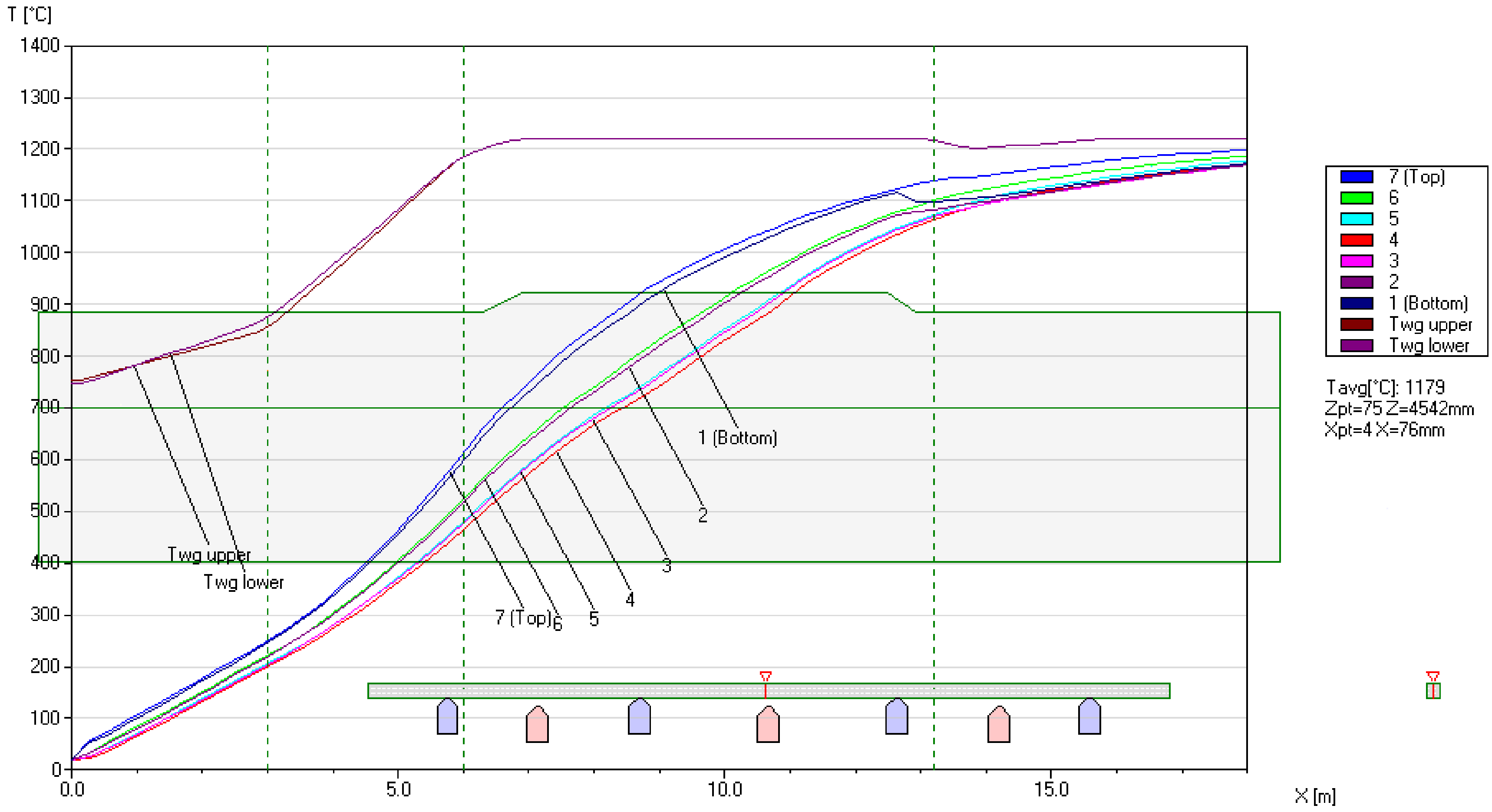
COLD SOAK - SEPARATE FLUE



HEATING CURVE: WALKING BEAM FURNACE

120 TPH: 6”X6”X30’ BILLETS

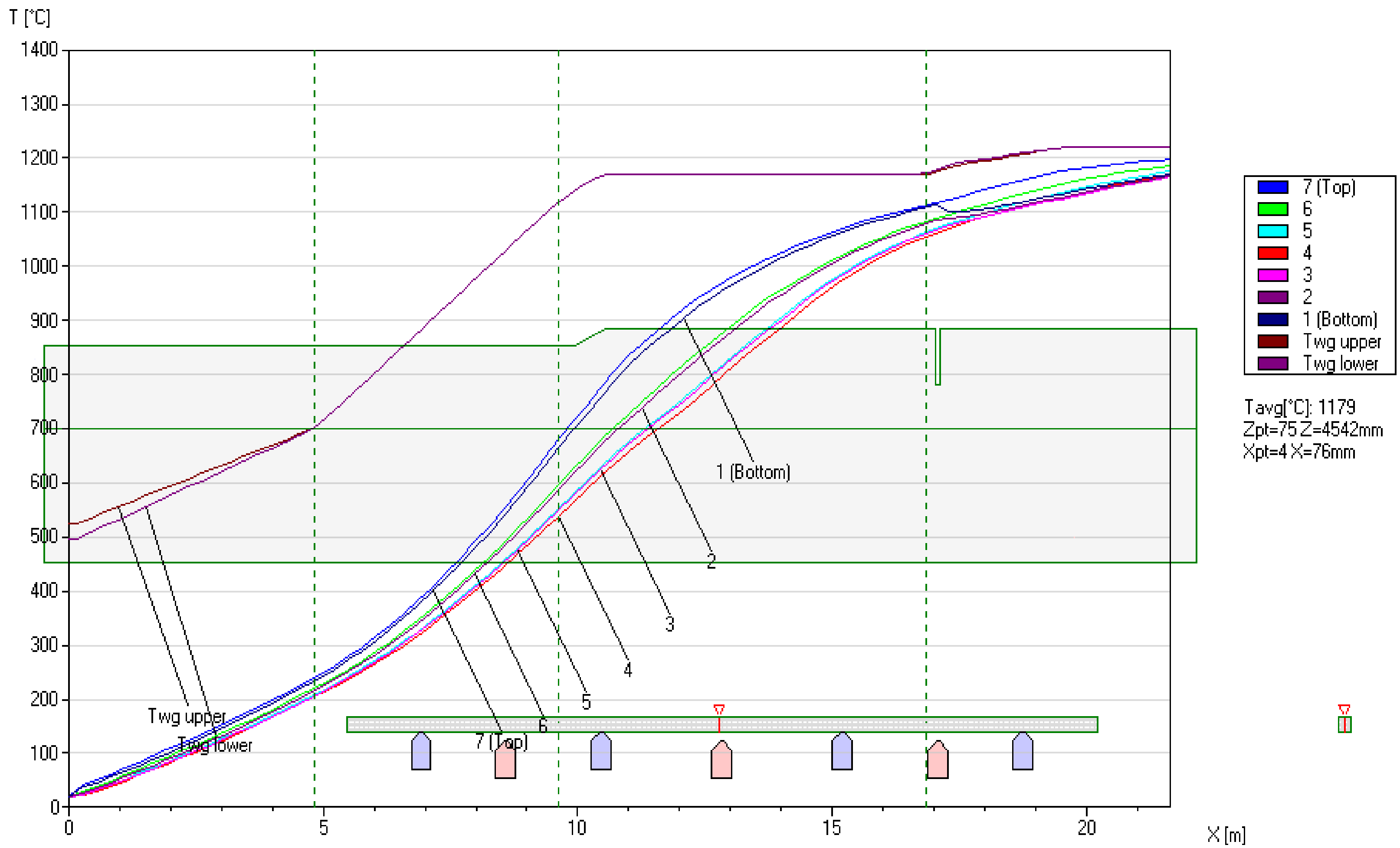
ALL CONVENTIONAL FIRING



HEATING CURVE: WALKING BEAM FURNACE

120 TPH: 6”X6”X30’ BILLETS

LONG CONVENTIONAL FIRING



References

1. J. Chomiak, *Combustion: A Study in Theory, Fact and Application*, Gordon and Breach Science Publishers, New York, 1990, pp. 304-309.

2. *Steel Technology Roadmap*, American Iron and Steel Institute, Washington DC, 1997, pp. 105-107.

3. H. Kobayashi, "Segregated Zoning Combustion", *U.S. Patent 5,076,779*, December 31, 1991.

4. H.M. Ryan III, et al., "Low NOx Combustion Process", *U.S. Patent 6,007,326*, December 28, 1999.

5. "Dilute Oxygen Combustion – Phase 1 Report", Report DOE/ID-13331-1, U.S. Department of Energy, Washington DC, October 1997, pp. 62-72, <http://www.osti.gov/dublincore/gpo/servlets/purl/565440-ryVauY/webviewable>.

6. "Dilute Oxygen Combustion – Phase 2 Report", U.S. Department of Energy, Washington DC, in press.

7. "Dilute Oxygen Combustion – Phase 3 Report", Report DOE/ID-13331-2, U.S. Department of Energy, Washington DC, May 2000, pp. 24-37, <http://www.osti.gov/dublincore/gpo/servlets/purl/805679-uNDvhA/native>.

8. E.J. Duckett, "NOx Controls for Steel Industry Sources", *AISE Steel Technology*, vol. 79, no. 4, April 2002, pp. 43-52.

9. P.D. Debski, "Cost and Design Implications of SCR Applied to Reheat Furnaces", *2001 Conference on Selective Catalytic Reduction and Selective Non-Catalytic Reduction for NOx Control*, National Energy Technology Laboratory, U.S. Department of Energy, 2002, <http://www.netl.doe.gov/publications/proceedings/01/scr/scr01.html-Innovat>.

10. U.S. Environmental Protection Agency (P. Blakeley), permit correspondence to Indiana Department of Environmental Management (P. Dubenetzky), April 30, 1999, <http://yosemite.epa.gov/r5/ardcorre.nsf/>.

11. "New Source Offset Markets and Permanent Emissions Reductions Credits", Natsource, 2002, <http://209.25.242.106/markets/index.asp?s=68>.

12. "Market Price Index", Cantor Fitzgerald Environmental Brokerage Services, <http://www.emissionstrading.com/index_mpi.htm>.

13. *In re* Steel Dynamics, Inc., PSD Appeal no. 01-03, *Order Denying Review*, Environmental Appeals Board, U.S. Environmental Protection Agency, April

23, 2001, pp. 23-29, <http://www.epa.gov.boarddec/disk11/steeldyn2.pdf>.

14. *U.S. et al. v. Nucor Corp.*, Civ. Act. No. 4-00:3945-24, Dist Court S.C., *Consent Decree*, December 19, 2000, §III.6.a, <http://www.usdoj.gov.enrd/nucorcd.htm>.

15. "Corrosion at Elevated Temperatures", *Heat-Resistant Materials*, J.R. Davis, ed., ASM International, Metals Park OH, 1997, pp. 36-44.

16. F.S. Pettit and J.B. Wagner, "Transition from the Linear to the Parabolic Rate Law during the Oxidation of Iron to Wustite in CO-CO_2 Mixtures", *Acta Met.*, vol. 12, January 1964, pp. 35.

17. J.S. Sheasby et al., "Scale Growth on Steels at 1200°C: Rationale of Rate and Morphology", *Metal Science*, vol. 18, March 1984, pp. 127-136.

18. F. Ajersch, "Scale Formation in Steel Processing Operations", *34th Mechanical Working and Steel Processing Conference Proceedings*, Iron and Steel Society, Warrendale PA, 1993, pp. 419-427.

19. K. Sachs and C.W. Tuck, "Surface Oxidation of Steel in Industrial Furnaces", publication no. 111, Iron and Steel Institute, London, 1968.

20. T. Tada, "Investigation of Steel Oxidation in Reheating Furnace", *CAMP-ISIJ*, vol. 4, 1991, p. 1483.

21. M.M. Wolf, "Scale Formation and Descaling in Continuous Casting and Hot Rolling", *Iron & Steelmaker*, July 2000, pp. 63-64.

22. C.W. Tuck and D.W. Down, "Effect of Gas Speed on Oxidation Rate", *Journal of the Iron and Steel Institute*, September 1967, p. 972.