OXYGEN ENRICHMENT

IN

BILLET REHEAT FURNACES

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BILLET REHEAT FURNACES

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SUMMARY

An important factor in the production of finished steel products is that virtually all steel is hot-rolled. This requires the steel to be heated to high temperatures in reheat furnaces. Considering the volume of steel produced, the fuel savings and the increase in productivity due to oxygen enrichment, will have a significant impact on the steel industry.

The purpose of this study was to determine the feasibility and economic viability of oxygen enrichment in reheat furnaces for plain-carbon steel billets. The study was concerned with two main aspects of oxygen enrichment:

1) the technical aspects
2) the economic aspects.

A series of trials was conducted to compare the fuel consumption and production rates with oxygen enrichment to those without oxygen enrichment. The final comparisons were made on the basis that the tests conducted with oxygen enrichment and those without oxygen enrichment were at steady state production levels and that all factors other than oxygen were similar. The major factors involved in the comparison were: fuel consumption per ton of steel heated, production rate, billet size, and billet exiting temperature.

The results of the tests conducted in this study indicate that oxygen enrichment is advisable under certain conditions. The first condition is that the ratio of oxygen cost per unit volume to the fuel cost per unit volume is sufficiently low. This ratio is the most important factor in determining the economic feasibility of oxygen enrichment. If the ratio is too high, oxygen enrichment is not recommended, since it is uneconomical even at highest production levels. The second condition is that the furnace is unable to produce the thermal output required without extensive redesign of the combustion system.

For a 2% enrichment level, a decrease of 9.6% in the specific fuel consumption rate and an increase of 14% in the production rate was observed. No problems were observed concerning the use of oxygen.

CHAPTER I

INTRODUCTION

Rapidly rising fuel costs and the possibility of fuel shortages in industry, created interest in the investigation of oxygen enrichment in Atlantic Steel Company's billet reheat furnaces. The study was conducted in their steel mill, on their 13" Mill Reheat Furnace. This furnace was chosen for the study because it contained the best instrumentation, and occasional production peaks caused the rolling operations to exceed the heating capacity of the furnace.

The primary goals of this study were:

1) a reduction of the specific fuel consumption (fuel required per ton of steel heated),

2) an increase in the production rate.

The result of an increase in the production rate would be a decrease in the fixed costs per ton of steel processed. The scope of the project included an examination of the effects of oxygen enrichment on: specific fuel consumption, production rate, billet temperature, scaling, refractory wear, burner problems, and refractory roof temperature.

Previous Work

At the start of this study, the author knew of no previous work done in this area. A comprehensive literature search was conducted at the Price Gilbert Memorial Library, located on the campus of the Georgia Institute of Technology. This search back to 1950, succeeded in locating only three papers dealing specifically with oxygen enrichment in reheat furnaces.[1,2,3] Only the papers by C. Moore and A. Gurson[1,2] dealing specifically with billet reheating furnaces for the rolling mills at Sheffield Rolling Mills in Great Britain, proved useful.

The work presented by Moore and Gurson was very limited in the extent of the work conducted. There was only one trial with fuel oil at an enrichment level of 4% and one trial with natural gas at an enrichment level of 2.6%. Since there was no mention of comparison tests without oxygen enrichment, the validity of the results was in question. Therefore, further study with a greater number of trials and with the necessary background data for comparison was indicated before the implementation of an oxygen enrichment system for production at Atlantic Steel Company's facilities.

The furnace at Sheffield was a walking-beam type furnace being used as a preheating furnace for two rapid heating furnaces. This furnace supplied a portion of the heat required by the billets, the remainder of the heat load was supplied by the rapid heating furnaces. Two methods of adding oxygen to the combustion air were attempted. The first method was jetting - the injection of a stream of pure oxygen into the underside of the flame. This method produced a locally higher flame temperature, but can cause extremely high local temperatures. The second method was the bulk premixing of oxygen in the combustion air. Bulk premixing avoided the extremely high flame temperatures, which may cause the surface of the steel to melt. The furnace had no recuperator system and used either natural gas or fuel oil as the fuel. The first trial took place in 1971, while the furnace was oil-fired. A nominal enrichment level of 4% was used for only one period of eight hours. This trial resulted in a 28% reduction in the fuel consumed per ton of steel heated.

In 1972, the furnace was converted to natural gas and another trial of oxygen enrichment was conducted. The second trial was only a four hour test at 2.6% oxygen enrichment, using the bulk enrichment method. It showed a 24% increase in the heating rate.

During these two trials there was no significant change in the roof temperature or refractory wear. No effect was observed on the scaling or decarburization of the steel due to oxygen enrichment. By careful adjustment of the air-to-fuel ratio, taking into account the increased oxygen content of the combustion air, little change in the oxygen content of the exhaust gases was observed. It was suggested that oxygen enrichment should be used only when the furnace was at full fire and could not maintain the heat in the steel.

Theory

The benefits of enriching the combustion air with oxygen are derived from the reduction in the volume of combustion gases. By supplying a portion of the oxygen required for combustion from oxygen enrichment, instead of air, less nitrogen must be heated.[3] By using an oxygen enrichment level of 2%, i.e. increasing the oxygen content of the combustion air from 21% to 23% oxygen; there is a reduction of 11% in the quantity of nitrogen which must be heated. The effects of the reduction in combustion gases are twofold[3]:

1) less heat is lost out the stack for a specified exhaust temperature,
2) higher flame temperatures are obtainable.

An oxygen enrichment level of 2%, results in a 7.9% reduction in the total volume of exhaust gases leaving the furnace. Accounting for the slightly different heat capacities of the two different gas mixtures[4] (0% and 2% oxygen enrichment); this results in a 7.1% reduction in the heat lost through the stack. A tabulation of the heat losses which I calculated for several levels of oxygen enrichment is found in Table 1. A sample calculation of the gas volumes and heat losses is found in Figure 1.

The reduction in the volume of combustion gases also results in a higher flame temperature. The effect of a higher flame temperature on the rate of heat transfer to the steel can be seen from an examination of radiant heat transfer. At high temperatures, such as those involved in heating steel for hot rolling, the major portion of the heat is transferred by thermal radiation(5) from the flame. The heat transfer rate, q, is proportional to the difference between the source temperature (flame temperature) raised to the fourth power and the sink temperature (steel temperature) raised to the fourth power. The heat transfer rate can be estimated by an equation developed by Hottel(5):

$$q = k(T^4_{source} - T^4_{sink})$$

This equation was developed for gray bodies and the proportionality constant, k, includes such factors as the emissivity (the ratio of the emissive power of an actual body to that of a black body), view factor (fraction of the radiation emitted from the source which is intercepted directly by the sink), area for heat transfer, and the Stefan-Boltzmann constant(5). The temperatures used in this equation must be absolute temperatures. Since the only variable which will change significantly due to oxygen enrichment is the source temperature, the factor k, can be assumed to remain constant and does not have to be evaluated since the interest lies in a comparison of q's and not their absolute values.

Using the results of the theoretical flame temperature calculation for natural gas shown below, a 2% oxygen enrichment level produces a 100 degree Fahrenheit increase in the source temperature, compared to air. This increase in temperature will produce a 9.9% increase in the heat transfer rate to the steel, when 1060°F is chosen as the sink temperature. This heat transfer rate can be translated into an increase in the production rate.

Prior to the start of experimental work on the furnace, an evaluation of the effect of oxygen enrichment on the flame temperature was conducted. The evaluation was performed on a theoretical basis by calculation of the adiabatic flame temperature[4], rather than by experimental methods.

To accomplish this calculation, a computer program was written to calculate the theoretical flame temperature for either natural gas or fuel oil. This program accounted for the effects of preheating the combustion air, as well as the dissociation of carbon dioxide and water vapor[6]. By first neglecting the dissociation of the combustion gases, an initial flame temperature was calculated by a series of mass and energy balances. A dissociation calculation for carbon dioxide and water vapor was then performed at the previously calculated flame temperature. The mass and energy balances were then adjusted taking the dissociation into account, and a new flame temperature was calculated. This procedure was repeated until the calculated temperatures converged. The resulting temperature was the theoretical adiabatic flame temperature. A diagram of the reaction path for the calculation is given in Figure 2. The reaction path for the calculation consisted of an adiabatic process in which the reactants were lowered to 25 degrees Centigrade (ΔH_1), the combustion reactions carried out ($\Delta H_{reaction}$), and the reactants raised to the adiabatic flame temperature (ΔH_2). Figure 3 provides a flowchart of the mechanics of the adiabatic flame temperature calculation. A list of calculated flame temperatures for natural gas and fuel oil is shown in Table 2.

CHAPTER II

EQUIPMENT AND INSTRUMENTATION

Furnace

The furnace used in this study was a pusher-type furnace manufactured by the Rust Engineering Company. The furnace has a 31 foot width with an effective packing length of 54 feet. It is divided into two zones, a heating zone and a soaking zone, each with a separate combustion system. The furnace has a maximum holding capacity of 132 tons and a maximum rated production capacity of 70 tons per hour. Figure 4 contains a drawing of the furance.

The combustion system consists of two banks of burners manufactured by North American, which can burn either natural gas or fuel oil. Both banks of furners fire toward the rear of the furance, parallel to the surface of the steel. The heating zone consists of 12 burners having a total maximum consumption rate of 120,000 cubic feet of natural gas per hour. The total maximum consumption for the soaking zones 16 burners is 30,000 cubic feet per hour. Both zones receive their combustion air from a single recuperator system. The recuperator is a heat exchanger which heats the combustion air with the hot exhaust gases. The combustion air was normally heated to 400 degrees Fahrenheit. After the recuperator, the combustion air is divided between the heating zone and the soaking zone. The combustion air is supplied by a constant speed fan and controlled by a system of dampers to control the air supply to each furnace zone.

The heating zone composes approximately 80% of the furnace length, and supplies the majority of the energy necessary to heat the steel. The cold steel billets are pushed into thefurnace at the beginning of the heating zone. At this time, hot exhaust gases pass over the top of the steel and then under a section of cold billets before being exhausted through the stack; this provides the most heat transfer possible. The billets then proceed down the furnance where they come under the horizontally directed flames of the heating zone burners. It is in this area, that most of the steel's heat is absorbed. The billets then pass under the heating zone burners into the soaking zone.

The soaking zone comprises the remainder of the furnace and supplies the heat necessary to provide a uniform heat distribution in the billets. This zone is relatively short and the flames often extend the entire length of this section. At the end of the soaking zone, the billets are pushed out the mill side of the furnace and fed to the rolling mill.

The refractories in the furnace consisted of silicon carbide brick for the hearth, Dietrick brick (refractory brick) for the roof, and 2500°F RAM(plastic brick) for the walls. The 2500°F RAM set a maximum temperature limit of

2500 degrees Fahrenheit. Initially this raised the concern that the increased flame temperature might cause refractory damage. Previous work conducted in this area indicated that there was no significant change in roof temperatures due to oxygen enrichment.

Furnace Instrumentation

The furnace control panel monitored or controlled the following operating parameters:

1) fuel and air flow rates for the heating and soaking zones
2) furnace temperature in each furnace zone
3) fuel-to-air ratios in each furnace zone
4) total fuel used
5) combustion air and exhaust gas temperature, before and after the recuperator
6) furnace pressure.

The quantity of steel heated was determined by the dimensions of the billets and the billet count. The temperature of the billets leaving the furnace was determined by the use of a Leeds and Northrup optical pyrometer. The soaking time was considered sufficient to bring the entire billet to a uniform temperature.

Oxygen Enrichment Apparatus

The equipment used in this study for the oxygen enrichment was specially designed. The control system consisted of: an orifice meter, regulator, regulator control valve, safety solenoid shut-off valve and switch. The enrichment level was controlled by monitoring the fuel flow rate and manually adjusting the flow of oxygen to maintain a constant enrichment level. Figure 5 contains a diagram of the oxygen control system used.

In order to obtain a uniformly distributed oxygen-air mixture, a sparger was made. A sparger is a device which is used to uniformly distribute a gas or liquid. The sparger was simple in design and was constructed of a section of two inch schedule 40 steel pipe. One end of the pipe was capped and 1/4 inch diameter holes were drilled in the pape, 90 degrees apart, sixteen per side. This arrangement provided equal cross-sectional areas for gas flow both through the main section of the pipe and the total number of small holes. The holes were deburred and the pipe was cleaned to prevent accidental ignition with the oxygen. A drawing of the oxygen injection device is given in Figure 6.

CHAPTER III

MATERIALS AND PROCEDURES

The finished products of the rolling mill include several sizes of reinforcing bars, rounds, squares, angles, and flats. Due to this variety of finished products and production rates for these different products, extreme care had to be taken to collect data which would exhibit validity. In order to collect valid data to evaluate the effects of oxygen enrichment, it was necessary to make certain that all variables other than oxygen enrichment were maintained constant. Comparisons between oxygen enrichment trials and "background," non-enriched trials were conducted on the same day and for the same product and billet sizes. To establish a background for the oxygen enrichment tests, the non-enriched tests were conducted first. This prevented the results of the oxygen enrichment tests from being diminished due to any residual effects from oxygen enrichment. In all cases, a steady state production level was required for a valid comparison.

During the trials, the following data was recorded:

1) fuel, air, and oxygen flow rates
2) temperature and air-to-fuel rates
3) exhaust gas temperatures, before and after the recuperator

4) preheated combustion air

5) furnace pressure

6) product and billet sizes

7) total fuel and billet comsumption during the period

8) significant delays.

Important factors for a valid comparison of the effects of oxygen enrichment are constant billet size and constant production levels during the background and oxygen enrichment trials.

In the trials, the data was recorded at fifteen minute intervals, while the furnace was operating under production conditions. The trial was started and data was recorded at intervals to determine that steady state conditions had been attained. After steady state operation was achieved, additional data was recorded to provide a basis for comparison. Steady state operation was assumed to exist when all the steel in the furnace at the start of the trial had been rolled; and the production rate remained constant, with no significant delays since the start of the trial. The oxygen was then turned on and manually regulated to provide a constant level of enrichment in the combustion air. Data was again collected under the same conditions as the background data, the new data was not considered valid until a new steady state condition existed. Comparisons were then made with regard to specific fuel consumption and production rates.

The major difficulty in the acquisition of valid data was the maintenance of steady state conditions. Any interruption of production for a period of more than fifteen consecutive minutes resulted in the steel becoming soaked, while it was still in the heating zone of the furnace. When the steel became soaked in this zone, it destroyed the steady state conditions and invalidated further data.

Although the furnace could burn either natural gas or fuel oil; all the tests were conducted with natural gas, using oxygen enrichment only in the heating zone. Oxygen enrichment was not used in the soaking zone because heating capacity was sufficient and oxidation problems might occur.

Method of Analysis

The data for both the oxygen enrichment trials and the background trials were carefully examined to determine if the necessary conditions for a valid comparison were present. If the test data did not meet the steady state or constant production conditions, the trial data was discarded.

All production data was converted to tons of steel heated per hour, and fuel and oxygen consumption were converted to cubic feet per ton of steel heated for easy comparison. Time periods, in the oxygen enrichment tests and background tests were chosen for comparison. During these periods, production was required to be at steady state and similar periods of delay were required.

Economic Analysis

The economics of oxygen enrichment are a significant part of evaluating the benefits of the process. If the oxygen costs are so high that they outweigh all savings, then oxygen enrichment is not an eceonomically viable process.

The first step in determining the economics of oxygen enrichment is to establish the fuel and oxygen required per ton of steel heated. Once these quantities are established for production using air and production using oxygen enrichment, the economics can be evaluated.

Letting Q_F represent the quantity of fuel required per ton of steel without oxygen enrichment; Q_{FO} represent the fuel required per ton of steel with oxygen enrichment; and Q_O represent the oxygen required per ton of steel. The heating costs attributable to fuel and oxygen are:

(3-1) Cost without $O_2 = Q_F$ x fuel price

(3-2) Cost with $O_2 = Q_{FO}$ x fuel price + Q_O x oxygen price

The savings in heating costs using oxygen enrichment will be:

$$\text{Savings} = (Q_F - Q_{FO}) \times \text{fuel price} + Q_O \times \text{oxygen price}$$

This equation or one of its variations may be plotted at several oxygen prices for variable fuel prices. This plot will show when oxygen enrichment will produce a reduction in heating costs.

In addition to the reduction in fuel costs per ton, the increase in production due to oxygen enrichment will produce a reduction in labor and in fixed costs per ton of steel rolled. This reduction will be proportional to the increase in the production rate and should be included in the economics of oxygen enrichment.

CHAPTER IV

RESULTS AND DISCUSSION

The results of this study were obtained under the steady state conditions previously described. Therefore, the summary data presented in this section and the raw data presented in the appendix were both taken after steady state production was achieved.

A summary of the results is shown in Table 3. This table gives a comparison of the results with 2% oxygen enrichment to those results without oxygen enrichment of the combustion air. The comparison was made using the overall results, rather than the results of a single test. The fuel consumption per ton without oxygen enrichment was calculated by dividing the total fuel used in all the background trials by the total tonnage produced in these trials. This method of calculation was also used in the oxygen enrichment trials to determine fuel and oxygen consumption per ton. The results of these calculations were then used to evaluate the effects of oxygen enrichment. An average of 9.6% reduction in the specific fuel consumption (fuel per ton of steel) was obtained with a 2% oxygen enrichment level, even though an average of 5% more heat was delivered to the steel billets. In addition, this level of oxygen enrichment gave an average increase of

14% in production rate for the furnace.

The effects of fuel and oxygen costs on the heating costs for the steel is shown in Figure 7. This figure is a plot of the heating costs per ton due to fuel and oxygen consumption. The curve representing no oxygen enrichment (background trials) is a plot of equations 3-1. The other curves on the plot represent equation 3-2 for various oxygen prices. The heating cost without oxygen enrichment can be determined by locating the present fuel price on the background curve, and reading off the heating cost. The curve corresponding to the present oxygen price is selected, and the fuel price is used to locate the heating cost on this curve. The reduction in the heating cost is the difference between the cost without oxygen enrichment, and the cost with oxygen enrichment. The costs given by this figure are specifically for this study, but the ratio of heating cost with oxygen enrichment to the heating cost without oxygen enrichment should apply generally.

The following two factors might have had some effect on the results of this study. The first factor is that the soaking zone, which did not have oxygen enrichment, experienced a deficiency of combustion air during the trials. Since this deficiency occurred during both the background and oxygen enrichment trials, it should not have a significant effect on the results. The second factor is that the steel left the furnace at a higher temperature during the oxygen enrichment trials than during the background trials. If the furnace temperature had been lowered to maintain the same billet temperature, the specific fuel consumption would have been lowered an additional 5% with the use of oxygen.

The roof temperature could be controlled and no noticeable change in refractory wear was observed during the study. Also, no effects on the scaling of the steel were observed.

A comparison of the findings of this study with those predicted by theory shows that they are in good agreement. Based on the assumption that the combustion air for both the heating and soaking zones was oxygen enriched and using the average temperature of the exhaust gases leaving the furnace, the predicted reduction in fuel consumption was 11.9% per ton. The actual reduction in fuel consumption was 9.6% per ton. In the study by Moore and Gurson, the reduction in fuel consumption was reported as 24.6% for a 2.6% oxygen enrichment level. The increase in production was 14% during this study, in comparison to the 9.9% predicted by a simplified version of radiant heat transfer theory (neglecting the change in the emissivity of the flame) and the 32.3% concluded by Moore and Gurson for 2.6% oxygen enrichment. There are two probable explanations for the difference between the results of this study and those of Moore and Gurson. The first reason is that the steel in Moore and Gurson's oxygen enrichment tests might have left the furnace at a lower temperature than the steel from normal production. No billet temperatures were reported and this could account for the differences in production rates and fuel reduction. The second reason is that they conducted only one test. Therefore, their results may not be truly representative.

CHAPTER V

CONCLUSION

The results of this study indicate that the use of oxygen enrichment in billet reheating furnaces is advisable under either one of the following conditions:

1) the ratio of oxygen cost per volume to the fuel cost per volume is sufficiently low (see Figure 7),
2) the production is limited solely by the thermal output of the furnace.

If the ratio of oxygen cost per volume of the fuel cost per volume is low enough, oxygen enrichment will be economical under all conditions. This will be the case, if the plant produces its own oxygen. Although the increase in production may not be required, there will be a reduction in heating costs due to reduced fuel consumption.

The second condition of operation requires a more careful examination. If the price of oxygen is low enough to be profitable even neglecting the increase in production, then a detailed examination is not required. A careful examination should be made, when it is found that oxygen enrichment would not be profitable, considering fuel savings. The increased production due to oxygen enrichment will produce a proportional reduction in labor and fixed costs per ton of steel rolled. The reduction in overall costs must be evaluated and compared to the increased heating costs, due to a high oxygen price. A break even point, above which the oxygen price to fuel price ratio makes oxygen enrichment unprofitable, must be determined. This determination will allow the proper evaluation of the economics of oxygen enrichment for a given set of operation conditions.

CHAPTER VI

RECOMMENDATIONS

Before an oxygen enrichment system is implemented, an evaluated of the ratio of oxygen cost per volume to the fuel cost per volume should be conducted. With oxygen produced cheaply on the plant site, the ratio should be favorable for oxygen enrichment, unless the fuel price is very low. If the oxygen is purchased in small quantities at existing high prices, the reduction in fuel costs will most likely not outweigh the increase in overall heating costs.

If oxygen enrichment appears favorable after an economic evaluation using the results from this thesis, implementation of an oxygen enrichment system should be carried out. For example, if the fuel price were $2.00 per thousand cubic feet of natural gas and the oxygen price were $.50 per thousand cubic feet, the fuel savings would be $.25 per ton of steel heated. Further trials at higher oxygen enrichment levels should be made to determine an optimum enrichment level for production. It must be emphasized, that higher temperatures are obtained with higher oxygen enrichment levels; therefore, it is recommended that care should be exercised to avoid burner or refractory damage at high enrichment levels.

APPENDIX

Table 1. Reduction in Heat Losses from Exhaust Gases

% Enrichment	Volume Reduction	Heat Loss Reduction*
0.0	0.0%	0.0%
2.0	7.9%	7.1%
4.0	14.5%	13.0%
6.0	20.1%	18.1%

*Note: Reduction in heat losses are based on calculated reduction in exhaust gas volumes and heat capacities.

Table 2. Theoretical Flame Temperature

% Enrichment	Natural Gas*	Heat Transfer Increase**	Fuel Oil	Heat Transfer Increase**
0.0	3810°F	0.0%	3732°F	0.0%
2.0	3910°F	9.9%	3842°F	11.1%
4.0	4005°F	19.9%	3927°F	20.3%
6.0	4091°F	29.5%	4011°F	29.9%

*Note: Flame temperatures were calculated with 400°F preheated combustion air.

**Heat transfer increase is the calculated increase in the heat transfer rate, compared to no oxygen enrichment (T_{sink} = 1060°F)

Table 3. Summary of Results

Date	7/07/77	7/26/77	8/11/77	8/25/77
Background Tests				
Billets	80	72	26	38
Tons	53.6	48.2	30.9	36.1
Fuel (KCF)	58.9	43.4	47.8	49.5
Duration (min.)	40	45	30	30
Tons/Hr.	80.3	64.3	59.7	72.2
Fuel/Ton	1.10	.90	1.55	1.37
Billet Temperature	2050°F	2060°F	2050°F	2060°F
Enrichment Tests				
Billets	89	80	33	42
Tons	59.6	53.6	39.2	39.9
Fuel (KCF)	54.2	42.9	60.1	48.3
Oxygen (KCF)	11.3	9.6	9.4	10.0
Duration (min.)	45	40	30	30
Tons/Hr.	79.4	78.4	78.3	79.8
Fuel/Ton	.91	.80	1.53	1.21
Oxygen/Ton	.19	.18	.24	.25
Billet Temperature	2140°F	2150°F	2150°F	2160°F

Average 5% more heat delivered to steel billet

Average 14% greater production rate

Average 9.6% reduction in specific fuel consumption (fuel/ton)

Table 4a. Raw Data from Trials - 7/07/77, 7/26/77

Date -	7/07/77	7/07/77	7/26/77	7/26/77
Soaking Zone				
Temperature (°F)	2230	2270	2235	2240
Gas (KCFH)	22.4	15.9	20.6	28.5
Air (KCFH)	180.0	155.0	202.5	232.5
Ratio (% Dev.)	+10	+8.3	+5	+15
Heating Zone				
Temperature (°F)	2230	2290	2155	2140
Gas (KCFH)	96.0	78.8	65.5	58.3
Air (KCFH)	875.0	695.0	645.0	562.5
Ratio (% Dev.)	0	-10	0	-10
Furance Pressure	+.048	+.047	+.036	+.033
Recuperator temperatures (°F)				
exhaust after 3)	635	545	710	675
air after 2)	390	375	439	423
exhaust before 1)	1009	950	1143	1073
Product size	# 11 rebar		#8 rebar	
Billet size	3-5/8"x3-5/8"x30'		3-5/8"x3-5/8"x30'	
Gas total (KCF)	58.9	54.2	43.4	42.9
% oxygen	none	2.0	none	2.0
Oxygen (KCFH)	none	11.3	none	9.6
Billet total	80	89	72	80
Billet temperature	2050°F	2140°F	2060°F	2150°F

Table 4b. Raw Data from Trials - 8/11/77, 8/25/77

Date	8/11/77	8/11/77	8/25/77	8/25/77
Soaking Zone				
Temperature (°F)	2323	2337	2370	2360
Gas (KCFH)	31.0	31.0	20.0	21.7
Air (KCFH)	173.0	202.0	178.0	183.0
Ratio (% Dev.)	+10	+10	+10	+10
Heating Zone				
Temperature (°F)	2390	2438	2380	2403
Gas (KCFH)	100.0	82.7	97.5	81.3
Air (KCFH)	920.0	780.0	850.0	760.0
Ratio (% Dev.)	0	-10	0	-10
Furnace Pressure	+.050	+.053	+.052	+.050
Recuperator temperatures (°F)				
exhaust after 3)	880	863	843	790
air after 2)	553	547	530	493
exhaust before 1)	1477	1463	1425	1370
Product size	3/8"x8" flats		3/8'x6" flats	
Billet size	3.5"x8.5"x23.5'		3.5"x7"x22'10"	
Gas total (KCF)	47.8	60.1	49.5	48.3
% oxygen	none	2.0	none	2.0
Oxygen (KCFH)	none	9.4	none	10.0
Billet total	26	33	38	42
Billet temperature	2050°F	2150°F	2060°F	2160°F

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

Nitrogen heated = $(100 - \%O_2)/\%O_2 \times 2$

<u>Exhaust Gas Composition (gm-moles)</u>

	CO_2	H_2O	N_2	Total
0% Enrichment	1.000	2.000	7.524	10.524
2% Enrichment	1.000	2.000	6.696	9.696

Reduction in gas volume = (10.524 - 9.696)/10.524 = 7.9%

<u>Reduction in Heat Losses</u>

$$C_p = a + bT + cT^2 \quad (T = °K)$$

	<u>a</u>	<u>b</u>	<u>c</u>
CO_2	6.393	1.01×10^{-2}	$-.3405 \times 10^{-5}$
H_2O	6.97	$.3464 \times 10^{-2}$	$-.0483 \times 10^{-5}$
N_2	6.529	$.1488 \times 10^{-2}$	$-.0227 \times 10^{-5}$

$$\Delta H = n_{CO_2}\int C_{p_{CO_2}}\,dT + n_{H_2O}\int C_{p_{H_2O}}\,dT + n_{N_2}\int C_{p_{N_2}}\,dT$$

$\Delta H_{0\%}$ = -84,702 calories $\qquad T_1 = 1000°F$

$\Delta H_{2\%}$ = -78,720 calories $\qquad T_2 = 70°F$

Reduction in heat losses = (84,702 - 78,720)/84,702 = 7.1%

Figure 1. Sample Calculation of Heat Losses.

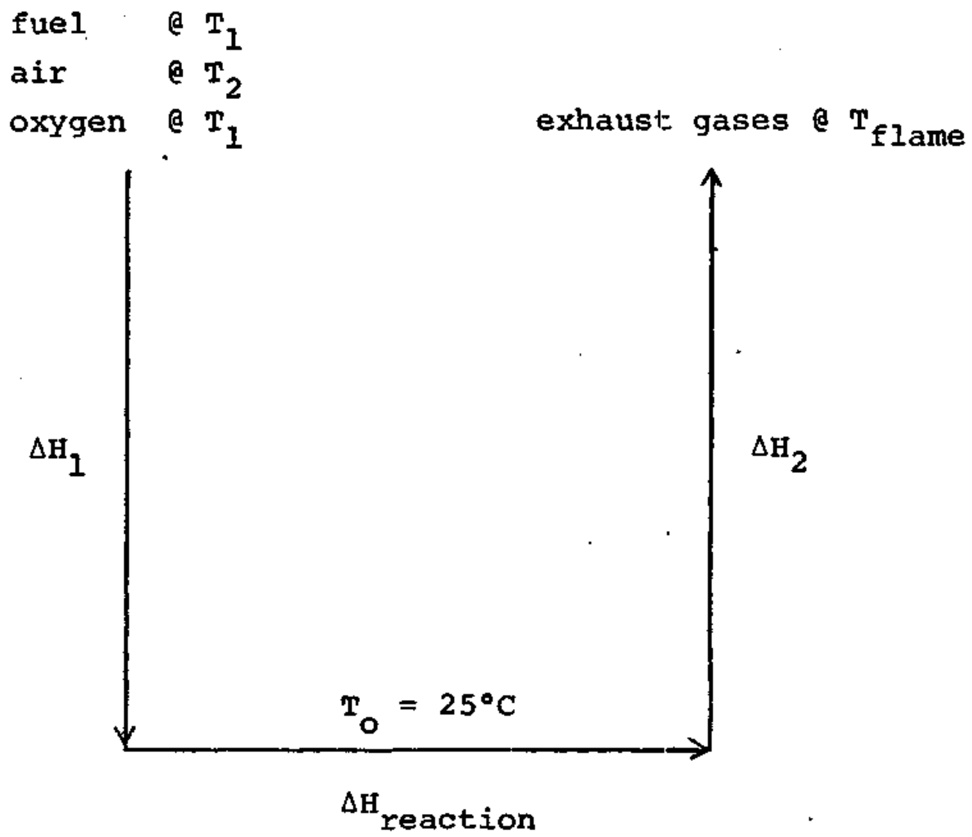


Figure 2. Reaction Path.

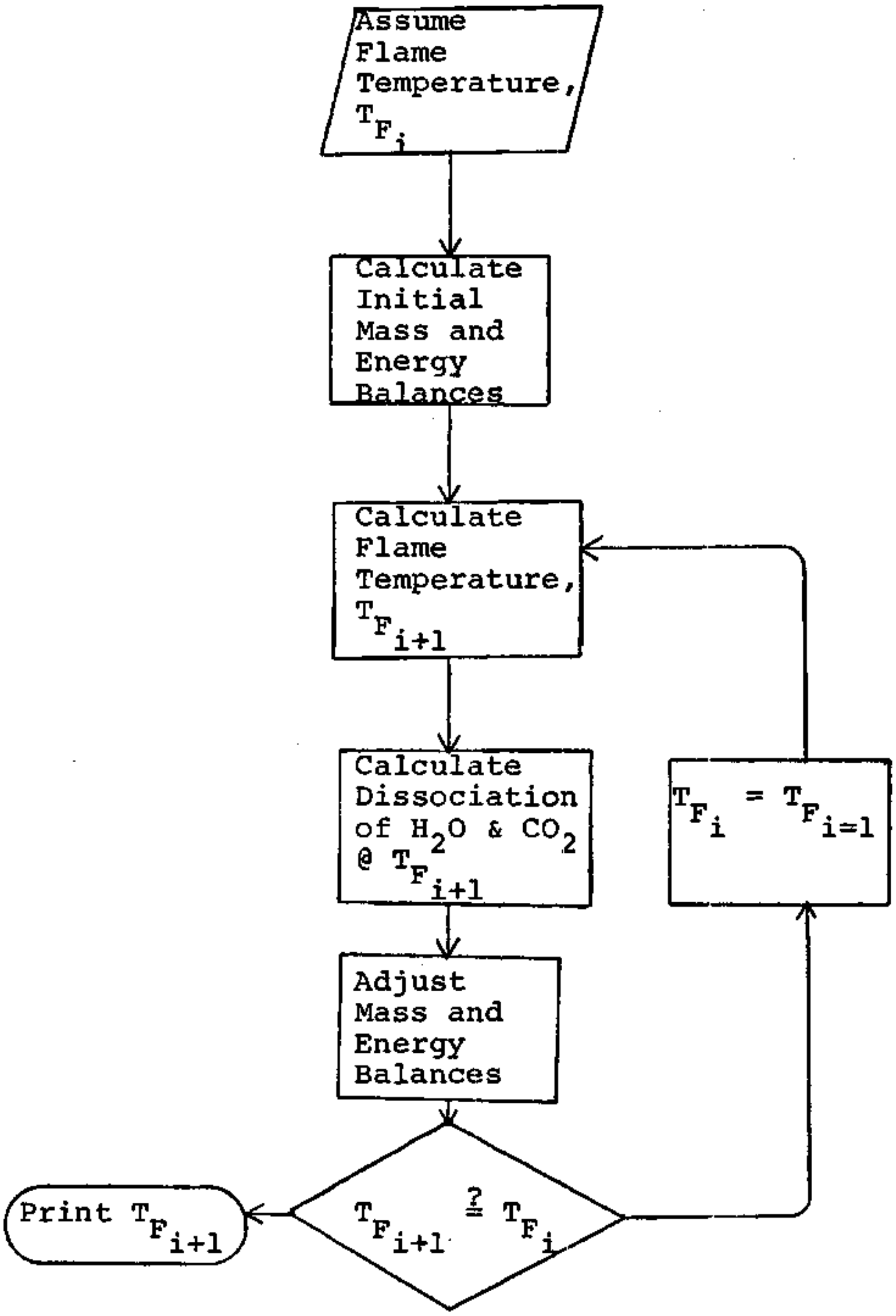
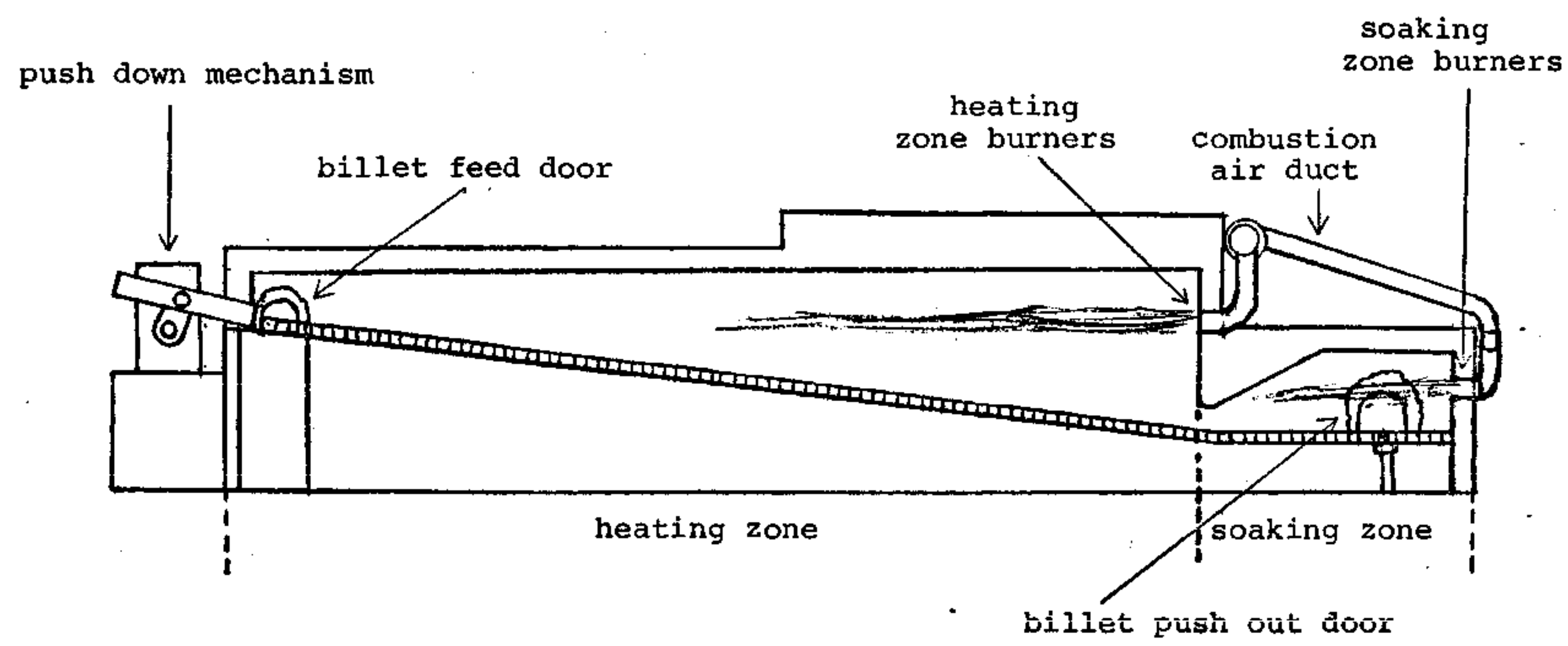


Figure 3. Flame Temperature Calculation Flowsheet.



(Scale: 1 inch = 8 feet)

Figure 4. Diagram of Furnace.

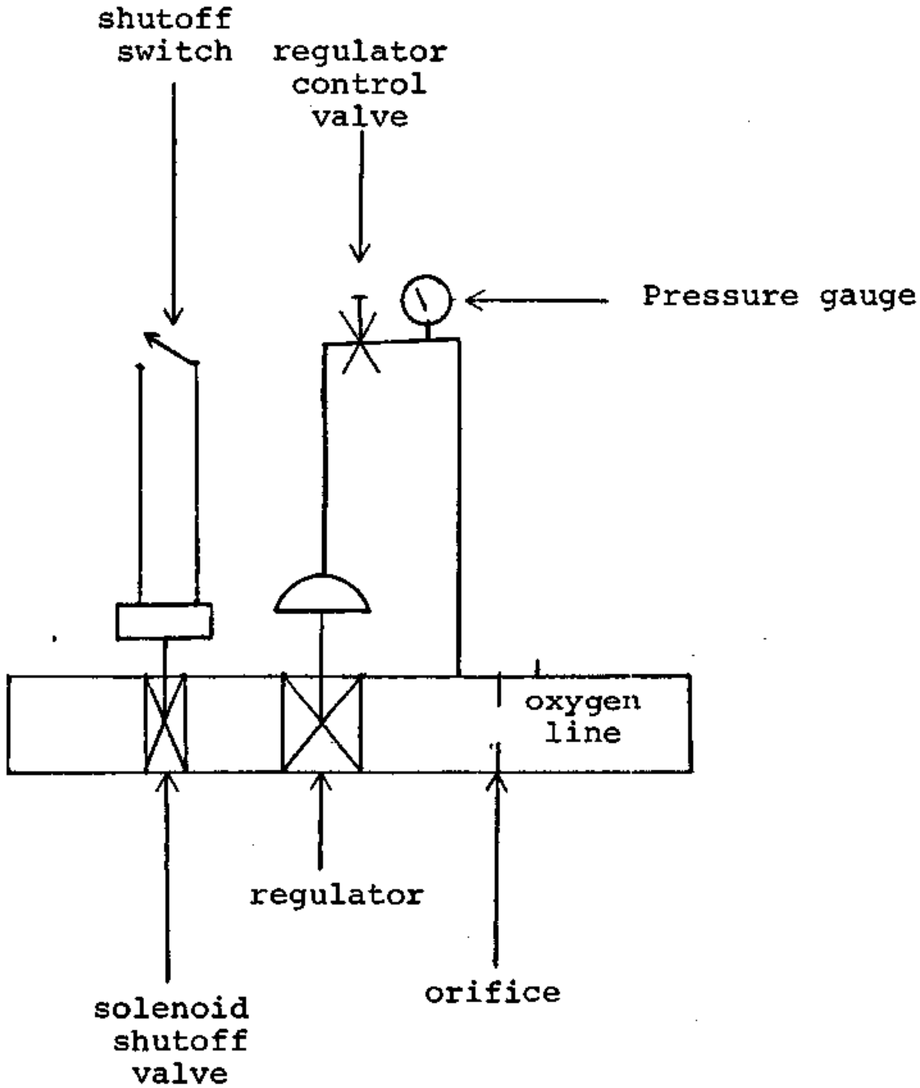


Figure 5. Oxygen Enrichment Control System.

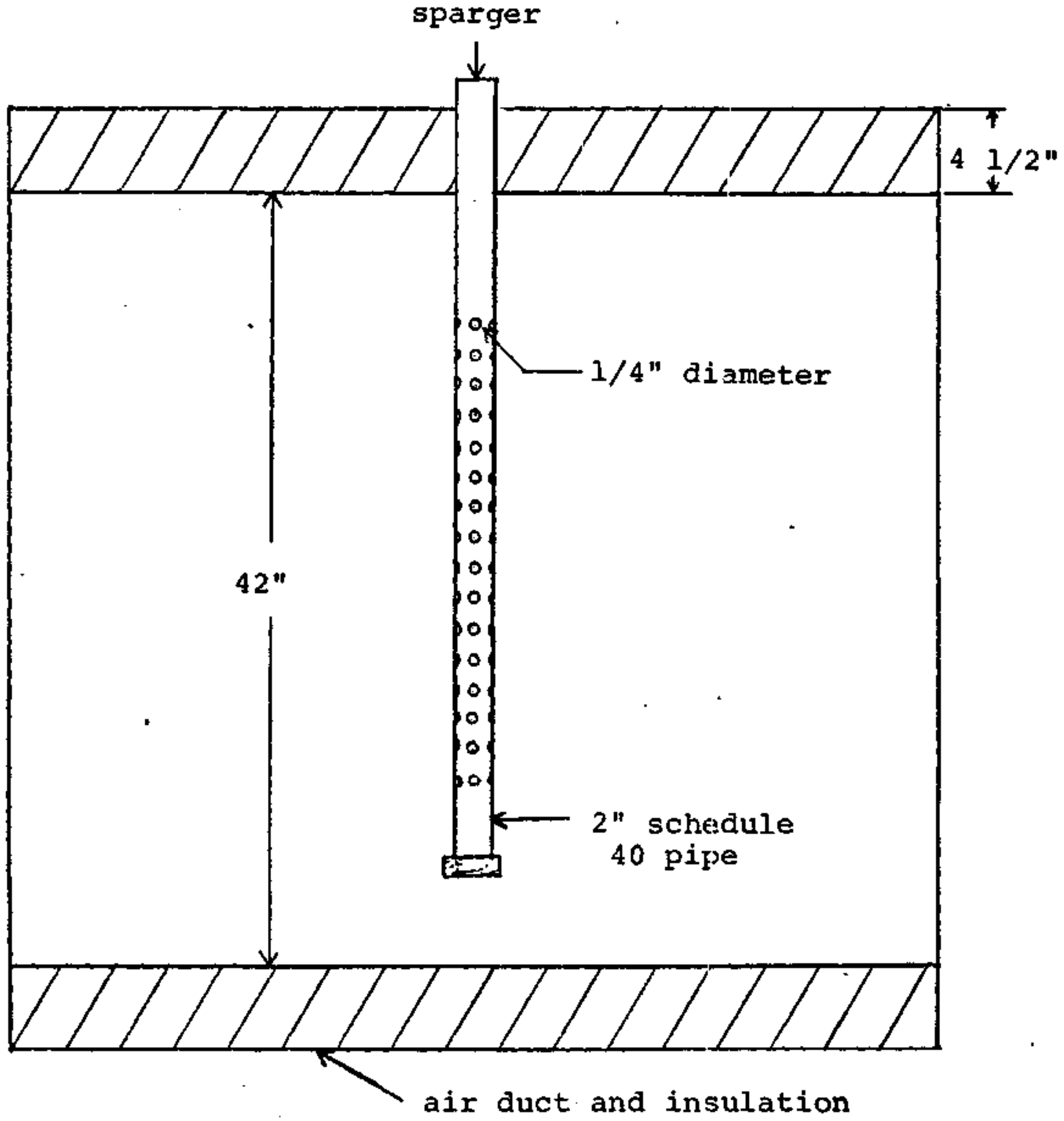


Figure 6. Oxygen Enrichment Apparatus.

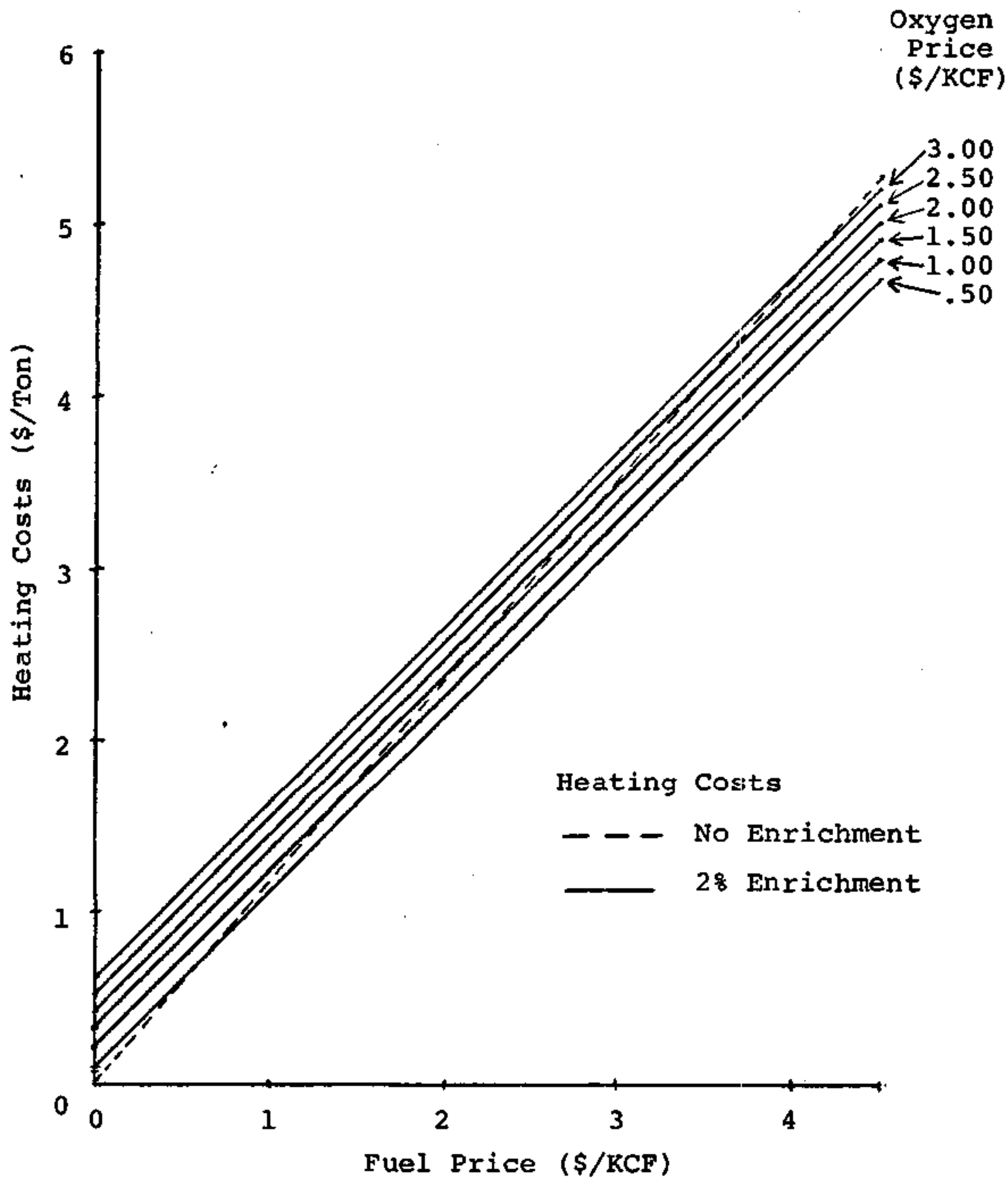


Figure 7. Fuel - Oxygen Heating Costs

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