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PROCESS MODELING OF PELLET INDURATION FURNACES

COLERAINE MINERALS RESEARCH LABORATORY

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Executive Summary

Section 1 Description of Minntac Line 6 and Meters

Section 2 Medusa: Material and Energy Balance Calculation

Section 3 Model Validation and Process Analysis

Section 4 Figures

Section 5 Appendices

The authors wish to acknowledge **Mr. Raymond Potts** for his contribution to this project. Ray was responsible for coordinating installation and calibration of the mass flow sensors, scheduling plant tests and collection of plant data. He also helped answer numerous questions regarding the cooler design as well as locating necessary information.

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Executive Summary:

This report completes a two-year collaborative effort between Minntac, NRRI Coleraine Minerals Laboratory and UMD Chemical Engineering, aimed at modeling the Minntac Line 6 Grate-Kiln induration system. The goals of this research were twofold:

1. Develop numerical models of existing taconite induration operations.
2. Demonstrate application of these models for process analysis leading to improved process efficiency defined by increased productivity and reduced fuel costs.

We have shown through the combination of an overall mass and energy balance model (MEDUSA) with a computational fluid dynamics model (CFD Cooler), that induration furnace performance can be predicted. Furthermore, a range of cooler operating conditions has been simulated and used to predict optimum furnace performance. Furnace productivity is dependent on primary and secondary cooling fan flow settings, and we have defined an operating window that demonstrates this effect. Within this window, grate feed rate can vary by as much as 30 WLTPH depending on fan flows. Additionally it may be possible to increase Line 6 production by as much as 94,500 LTPY with the installation of a wall in the Line 6 cooler, if certain operating conditions can be met. This represents a 3% maximum production increase on an annual basis.

The techniques developed during this study can be used to evaluate a wide range of process variables, such as additional recoup ducts, increased fan capacities, cooler wall locations, installation of a ported kiln, and furnace firing cycles. With additional research, it may even be possible to adapt the operating window concept for prediction of product quality parameters. An extensive effort has been made to validate the models against a range of plant operating conditions. The synergism of combining the models provides a powerful tool for evaluating proposed furnace modifications.

This study demonstrates how the models can be used to evaluate the installation of an overbed dividing wall in the cooler. An overbed dividing wall will break the interaction between the 3A and 3B fans. This will permit the 3B fan to be placed under automatic control, allowing the cooler to operate consistently near its optimum. Currently, the 3B is operated in manual control to avoid interfering with 3A fan performance; under these conditions cooler flow may or may not be optimized in a consistent manner. Cooler performance should not be hindered by installation of the wall if waste gas fan flow is maximized. This requires a review of the current control philosophy. Plant production could increase by as much as 94,500 LTPY, if the wall is installed, waste gas fan maximized, and 3B fan placed under automatic control. The actual production increase depends on how far annual plant production, currently under manual control, deviates from the predicted optimum. This deviation has not been determined in this study, however, plant personnel should be able to estimate it from historical cooler fan operation.

The plant data collected for model validation was also analyzed on individual (test by test) and collective (test composite) basis. Several important observations emerged from the plant data:

1. The Line 6 process fans exhibited frequent, but not periodic, cycling throughout the test period. The frequency of the oscillations was sufficient to prevent the machine from achieving steady state conditions. If the furnace behavior exhibited during the 15 day test period was typical of plant operation, this line is seldom under stable operating conditions.

A direct consequence of this type of operation is lost production and higher than necessary fuel consumption. Product quality is most likely also affected, but these affects are more difficult to predict. The factors responsible for these oscillations need to be identified and corrected.

2. The Line 6 waste gas fan does not appear capable of keeping up with the preheat fans once they open up beyond 45% fan damper. When this condition occurs, the waste gas fan is operating at 100% fan damper, but drying zone overbed pressure increases above the set point. Under these conditions, the waste gas fan cannot exhaust air fast enough and productivity is limited as a result.

3. The control strategy for the waste gas fan should also be evaluated. There were periods of time when the waste gas fan operated between 60 and 80% damper and maintained the overbed pressure set point (approximately -0.6 inH_2O). Because recoup flow is directly proportional to pressure drop between the furnace and cooler, these periods of lower fan flow represent lost energy recovery through the recoup system, which in turn limits productivity. Recoup flow should be maximized with maximum waste gas fan flow. An extended test (5-10 days) was recommended. In this test, the waste gas fan should be held at 90-100% damper, to determine the impact on Line 6 operation.

A summary of the steps required to accomplish the project goals follows. Four objectives were carried out to complete this project. They were:

1. Install mass flow meters on Minntac Line 6 and collect operating data to validate the models.
2. Develop and validate an overall material and energy balance model called MEDUSA.
3. Develop and validate a Computational Fluid Dynamics (CFD) model of the Line 6 cooler.
4. Perform an analysis of Line 6 using these models, and, if possible, propose operating changes.

The MEDUSA model is an overall mass and energy balance type model and is used to evaluate process changes in terms of the whole process. The MEDUSA model can be used independently of the CFD Cooler model, but it requires accurate estimates of process airflow. The Line 6 cooler as it now exists has no overbed dividing wall, which makes the estimation of cooler flow splits between the parallel flow duct (kiln), the recoup ducts, and the vent stack very difficult without extensive in-plant air flow surveys.

The CFD Cooler model is ideally suited to providing the individual duct flow information required by MEDUSA. Through the use of an experimental design, a series of cooler operating conditions were simulated, and then used to define predictive linear equations for gas flow and temperature in the cooler outlets. Four control variables were used to define these operating conditions. They were pellet ferrous iron content entering the cooler, pellet production rate, primary cooling (3A) fan mass flow, and secondary cooling (3B) fan mass flow. A cooler parametric series (27 simulations) was performed for each physical modification to the cooler.

Initially, a number of physical modifications were to be evaluated. They included a comparison of recoup B duct location between Line 6 and Line 7, a comparison of the current cooler (no overbed dividing wall) with a cooler including an overbed dividing wall (two locations evaluated), and the addition of a third recoup duct. Most of these comparisons were dropped when it became apparent that a separate series of simulations would be required for each option. Two complete series were performed simulating the current plant cooler and the cooler with an overbed dividing wall offset one wind box into the primary cooling zone.

Before the cooler simulation series could be performed, both models were validated. A series of plant tests was performed and used to tune the models over a wide range of plant operating conditions. The goal was to make sure both models successfully predicted trends in the plant data. An exact numerical value match was not required between plant and model.

When the validation phase was completed, two CFD Cooler parametric series were performed. The results were analyzed using statistical software. Information from the parametric series was correlated with linear equations that predict cooler flow and temperature responses to changes in operating conditions. Operating windows were defined to show acceptable 3A and 3B fan flow ranges. The windows were bounded on the low flow side by a maximum vent stack temperature and bounded on the high flow side by a maximum primary cooling overbed pressure, which can be related to firing hood pressure. The linear equations for cooler outlet conditions, specifically kiln secondary air flow and total recoup flow, were embedded in MEDUSA, to give it predictive cooler capability. This model is referred to as the hybrid MEDUSA/CFD.

A series of fan flow combinations was taken from the window and analyzed using the MEDUSA/CFD hybrid. This model was also modified to find the optimum feed rate based on the input cooling fan combinations and target preheat fan gas and kiln solids discharge temperatures. Fuel flow rate was held constant, but fuel consumption on BTU/LT basis varied with the optimized feed rate. The simulation results showed that plant productivity and fuel consumption were affected by cooler fan performance. For the current cooler, it was shown that feed to the grate could vary by as much as 30 WLTPH depending on the combination of fan flows. The operating window showed that there was an optimum combination of fan flows for maximum production and minimum fuel consumption.

A series of plant tests was conducted in February and March 2000, using the operating window defined by computer simulation as a guide to specify fan flows. The test conditions were intended to run the plant through the range of flows found in the window. Plant data was logged for each test and analyzed. A total of nine tests were conducted. These tests were composited into a single database, from which two plant data models were derived. One model used the same control variable criteria (feed rate, and cooling fan mass flows) as the CFD model, with the exception of pellet ferrous iron content, which was not measured in the plant. The second model used the MEDUSA/CFD control response criteria (3A and 3B mass flow). The plant models were then compared against the appropriate computer model, using a variety of response variables for comparison. In general, the trends exhibited in the plant data models agreed with the corresponding trends in the simulation based models.

1 Description of Minntac Line 6 and Meters

Page No	Text Heading
1.1	1.1 Line 6
1.1	1.2 Meters and Probes
1.2	1.2.1 Thermal Sensing Meter
1.3	1.2.2 Pressure Differential Meter
1.4	1.3 Conclusions and Recommendations

1.1 Line 6

Seven indurating lines have been constructed at Minntac for producing taconite pellets. Only five are operable at this time – lines 3 through 7. Line 6 was chosen for this modeling project because it is one of the two newest lines; construction was completed in 1978. All the lines at Minntac use Svedala grate-kiln systems for induration. The line 6 grate is 144 ft long and 15 ft wide. It is a two-pass, downdraft machine divided into three chambers above the grate and two windboxes beneath it. The sizes of the chambers are designated in eight ft long bays. The first section of the grate is the first stage downdraft drying section (DD1). It contains six active bays above the grate. The second section is the second stage of downdraft drying (DD2). It contains three active bays above the bed. There is a common windbox below the DD1 and DD2 furnaces consisting of nine bays total. The third section is the preheat section (PH). It contains seven active bays and has a dedicated windbox the same length. The kiln is 21 ft in diameter and 130 ft long. It can be fired with #2 fuel oil, coal or natural gas (preferred). Natural gas was used in all of the tests for this project. The cooler is an annular cooler with a mean diameter of 56 ft. Pallets are eight ft wide. The line has five process fans. There are two 900 HP cooling fans (labeled 3A and 3B), two 1500 HP preheat fans (labeled 1A and 1B), and one 3500 HP waste gas fan (labeled WG or #2 fan). A schematic of the furnace-kiln-cooler is shown in section 3, Figure 2.

Line 6 was originally constructed with a low temperature recoup system. In this system process gas was drawn from the second cooling stage of the cooler into the preheat fan cyclone system through two separate ducts – one for each preheat fan. Because of temperature restrictions on the preheat fans, the air had to be tempered with the addition of ambient air. It was later converted into a high temperature system by adding DD2. Process gas drawn from the cooler is now directed to the DD2 furnace without being tempered, permitting more efficient operation.

1.2 Meters and Probes

Mass flow meters were installed in seven process gas streams to provide real time process gas flow rate data. In addition, an extensive data logging system was developed that allowed up to 100 data points to be monitored during any time frame between 10 seconds and 24 hours. A maximum of 1500 readings could be collected. Data could be averaged within a selected time frame or an instantaneous value recorded. The data could be transferred to computer spreadsheets, such as Excel, for further manipulation.

All the meters used for this project utilized probes installed within the gas stream. They were installed in the following locations: The 3A fan inlet duct, the 3B fan outlet duct prior to the cooler, the cooler vent stack, the east (1B) recoup duct, the west (1A) recoup duct, the 1A fan inlet duct, the 1B fan inlet duct and the waste gas stack after the wet scrubber.

Originally, two different types of meters were used – thermal sensing (heat loss differential) and pressure differential. The thermal sensing meters were installed in all locations except for the recoup ducts where temperatures exceed the manufacturer's recommendations. Multiple-point pressure differential meters were installed in recoup ducts. Pressure differential meters require an air purge system to keep the probes clear of particulate buildup, which increases the cost of installation and operation of this type of meter relative to the thermal meters.

1.2.1 Thermal Sensing Meter

All probes in the thermal sensing meters were multi-point and self-averaging. All of them, including the one in the waste gas stack were constructed of 316 SS with a nickel braze. The manufacturer offered as an option, probes constructed of Hastelloy C. Consideration was given to purchasing this option for the waste gas meter because of the corrosive atmosphere within the stack. After reviewing the gas composition, it was believed the 316 SS would withstand the conditions within the stack and the decision was made to use it instead of the Hastelloy. After less than a month, the meter in the waste gas stack failed. The body of the probe was relatively undamaged and the failure occurred because thermal elements were badly corroded. It is unlikely the use of the Haselloy C would have prevented this. The waste gas meter was replaced with a single point pressure differential meter. The pressure differential meter was found to be accurate and did not drift but the flow in the stack was stratified making it necessary to apply a factor to output values. In addition, the Line 6 waste gas stack was equipped a CEM system that was not part of this project. That system included an ultra sonic mass flow meter. Experience with the ultra sonic meter will also be discussed relative to accuracy and dependability later in this section.

Within the first year of operation, there appeared to be considerable drift in the remaining thermal meters. Some of this may have been due to the temperatures of the streams measured. Generally this type of meter is recommended for gas streams below certain temperatures. This temperature varies somewhat by manufacturer. The manufacturer of the meters used on line 6 indicated they could be used in streams up to 850°F. It was later learned that other sources indicate they should not be used in streams over 550°F. The meters were originally calibrated against pitot traverses done across the various ducts. After a year of operation all the thermal meters except the one installed in the 3A fan inlet duct had drifted considerably and differed from pitot traverses (calibration checks) by as much as 30%. It is probably not coincidental that the 3A duct meter performed better that the others since this is one of the coolest and cleanest streams measured.

Overall operating experience with the thermal sensing meters was poor. This is the first time thermal sensing mass flow meters have been used in process gas streams within a taconite indurating facility. Because of this, there was no experience to draw upon in selecting the meters other than the manufacturer's recommendations. Three different manufacturers supplied meters for this project. All three asked for and were given as much information about the gas streams as was available. Two of the three suppliers appear to have overestimated the ability of their meters to withstand the conditions encountered.

All experience with the meters was not bad. Meter operating experience was obtained and, with the exception of the original waste gas meter, all the meters provided significant usable data. The thermal type meters performed well in the 3A and 3B ducts but not in the other applications where they had a tendency to drift. It was reported earlier that the 3B meter had drifted but a review of relevant data indicated it had been accurate for about 15 months before it started drifting. Good quality data was obtained during the entire project from the 3A meter. After it was determined that the 3B meter had drifted out of calibration, usable data was obtained by doing pitot traverses and applying factors to the meter's output. It appears thermal meters would work in other moderate to low temperature applications with routine calibration.

1.2.2 Pressure Differential Meter

The multi-point, pressure differential meters installed in the recoup ducts were very accurate but could not withstand the temperatures within the ducts. However, they remained very accurate up to the point when they failed and provided 15-18 months of accurate data.

The multi-point meters installed in the recoup ducts did not drift but failed because of the heat within the ducts. These meters were described by the manufacturer as "multi-point, self-averaging, Pitot Fechheimer airflow traverse probes with integral airflow direction correcting design". Two probes were installed in each duct – one vertically and one horizontally. They were constructed of Inconel 601 and were expected to withstand temperatures up to 1900°.

The output from the 1B recoup meter was lost after 15 months of operation. It was not possible to inspect the probes until the line was down for its annual repair several months after that. When the probes were inspected it was learned there was extensive heat damage (creep) to all four probes. No temperatures greater than 1750 °F were noted or recorded during the life of the probes within the 1B duct and temperatures were typically 200-300 degrees lower within the 1A duct. The CFD modeling indicated temperature stratification of about 200° within the ducts. Because of this, it is possible that temperatures greater than 1900° existed but were not detected in the 1B duct. However even with the 200° stratification, the temperature would not have exceeded 1650° in the 1A duct. It is most likely that the probes failed at temperatures that were within the expected range and less than 1900°. It should be noted that the manufacturer of these meters was different than the manufacturer of the thermal meters.

The single-point pressure differential meter installed in the waste gas stack was very dependable and did not drift. It was accurate at the measurement point but did not provide an accurate measurement for the entire gas stream because of stratification of the flow within the stack. The ultra sonic meter installed in the waste gas stack was also very dependable but subject to the same measurement problems as the pressure differential meter. Usable data was obtained from both meters by using multiple pitot traverses to develop factors to account for the stratification.

1.3 Conclusions and Recommendations

Future application of process gas measurement technology in this and other plants will benefit from the experience gained in this project. Because taconite processing plants like almost all plants are not built with measuring instrumentation in mind, obtaining the desired accuracy will always be a problem. Routine calibration will be necessary and frequent calibration will be necessary in some applications. In addition most of the gas streams are at elevated temperatures and contain abrasive taconite dust. Some streams also contain corrosive chemical species. Selection of meters for future projects must take these factors into account. Generally installation of probes within ducts should be avoided with two exceptions - cooling air which is cool and clean and in cases where accuracy is critical.

In selecting meters for future work, there are a number of viable options for the low temperature gas streams. Thermal meters would work well in clean ambient streams such as the cooling air but should be avoided for other applications (waste gas). Thermal meters are difficult to install (with probes placed within the stream) and depending upon location can be difficult to maintain. They also have a tendency to drift at intermediate temperatures. Single-point ultra sonic meters are not recommended for any application in taconite indurating facilities. However, ultra sonic meters can be purchased which will traverse entire ducts and this type would perform well in the low temperature streams. They would not be affected by the atmosphere (including the particulate material) within the stream and are easy to install. Multi-point pressure differential meters would also work on the low temperature streams. Because they do not drift like the thermal or ultra sonic type they are the most accurate but they are difficult to install and have slightly higher operating and installation costs.

For the intermediate temperature (400-1200^{o}) gas streams such as those in the preheat fan ducting and cooler vent stacks the multi-point pressure differential meters would be the instruments of choice. They are the most accurate by far since both the thermal and ultra sonic types have a tendency to drift in these temperature ranges. They have the disadvantages of being difficult to install and needing to be routinely back flushed with compressed air. The presence of particulate material in the intermediate temperature streams makes back flushing the meters necessary but the experience during this project relative to plugging – with back flushing- was very positive. During the 15-18 months the recoup meters were operable, there were no instances of plugging recorded despite the fact, the recoup ducts on Line 6 are known to contain significant amounts of particulate material.

The recoup streams are the most difficult to measure. This project indicated there are three options for measuring temperature and flow in recoup streams: 1) Install probes constructed of Inconell 601 and replace them every 1-2 years, 2) Find an alloy that will handle higher temperatures (may be cost prohibitive), 3) Calculate recoup flows using CFD modeling. Depending upon the cost of alloys for probes, this may be the most promising but it's only applicable if the meters are used in conjunction with CFD modeling.

Despite all the problems with the meters, enough usable data were obtained to allow the completion of the other parts of the project. In many instances, it was also informative to know if the mass flow of a stream changed relative to other streams. This could be done even when the meters were out of calibration. In addition to the other parts of the project a lot of knowledge gained relative to the mass flows of gas streams within the line and the nature of mass flow measurement in taconite indurating facilities. The ultimate value of all this has yet to be determined.

2 Medusa: Material and Energy Balance Calculations

Page No	Text Heading	Tables	Figures
2-1	2.1 Introduction		
2-2	2.2 Zones		2.1-2.2
2-3	2.3 Mass Transfer		
2-3	2.3.1 Drying		2.3
2-5	2.3.2 Flux Calcination		
2-5	2.3.3 Magnetite Oxidation		
2-7	2.4 Heat Transfer Model		
2-7	2.4.1 Traveling Grate/Cooler Model		2.2
2-9	2.4.2 Rotary Kiln Model		
2-10	2.4.3 CFD Cooler Model		
2-11	2.4.4 Model Calibration		
2-11	2.5 Model Implementation		
2-12	2.5.1 Medusa.for		2.4
2-12	2.5.2 Medusa.exe		
2-12	2.5.3 Medusa.ctl		
2-12	2.5.4 Name.dat		
2-12	2.5.5 Name.fld or Name.met		
2-13	2.5.6 Medusa.rst		
2-13	2.6 Graphical User Interface	2.1	
2-13	2.6.1 File Manager		2.5
2-14	2.6.2 Pellet Bed		2.6
2-14	2.6.3 Furnace Zones I & II		2.7-2.8
2-14	2.6.4 Rotary Kiln		2.9
2-15	2.6.5 Process Gas		2.10
2-15	2.6.6 Leakage		2.11
2-15	2.6.7 Gas Distribution		2.12
2-15	2.7 Results	2.2	2.13-2.15
2-16	2.8 Summary		
2-16	2.9 Nomenclature		
2-18	2.9 References		

2.1 Introduction

A mathematical model of heat and mass transfer in the grate-kiln induration furnace was developed to explore the effects of process changes on the overall performance of the machine. The model was implemented in a FORTRAN program entitled Medusa. The furnace model was developed as a series of zones arranged according to the solid flow and process gas distribution. In the model, solids move sequentially through the zones from the feed end of the machine where pellets are initially dried, to the cooler where fired pellets are cooled and thermal energy is recouped by the process gas. The mechanisms for heat transfer include: convection between the process gases and solid surfaces, such as pellets and walls; conduction within the pellet bed and walls; radiation exchange between gas and exposed solid surfaces; and fuel combustion, calcinations and magnetite oxidation heat generation or consumption. The net radiation method was used in the kiln. Mass transfer mechanisms included: evaporation and condensation of moisture in the pellets; flux decomposition and carbon dioxide evolution; and magnetite oxidation. The furnace model was built around the following assumptions:

1. Steady-state operation
2. Two dimensional profiles in bed length and depth; ignores changes in bed width.
3. Fueled by natural gas.
4. No solids mixing on grate or cooler.
5. First-order mixing of solids in rotary kiln zone.
6. Perfect gas phase mixing in each grate or cooler zone above and below the bed of solids.
7. No gas mixing within the bed of solids in grate or cooler zones.
8. Gas flow distribution is known a priori.
9. Individual pellets are isothermal.

2.2 Zones

A zone is defined as a section of the furnace model where the process gases are considered well mixed, or homogeneous in temperature and composition. A zone may be configured with any combination of process gas entering from other zones as well as air from outside the furnace or leakage.to the zone (no leakage is permitted from a zone to the surroundings). Leakage is also permitted between adjacent zones; above or below the bed on the grate. The process gas leaving a zone may be distributed to any other zone in the model. The furnace modeled for this project may be divided into seven zones in the following order, as illustrated in Figure 2.1: first and second drying stages, preheat stage, kiln, and three cooling stages. Air is used in the annular cooler to lower the pellet bed temperature. Air supplied to the first cooler zone leaves as secondary air to the kiln. The air from the second cooler zone is transferred to the second stage dryer where the thermal energy is recouped to drive the moisture from the green balls at the front end of the machine. Finally, the air from the third cooler zone is vented. The process gas leaving the preheat zone is routed to the second stage drying zone for additional heat recovery. The air leaving the two drying zones is vented as waste gas. Leakage to the zones was added above bed on the grate and below bed in the preheat zone.

The solid bed traveling on the grate or annular cooler is modeled as horizontal layers of well-mixed solids, as illustrated in Figure 2.2. The composition and temperature of a solid layer is considered to be locally uniform, changing only in the flow direction due to heat transfer and chemical reaction with the gas phase. It was determined by trial-and-error that 20 layers provided satisfactory results.

The Minntac cooler was difficult to model using the Medusa assumptions because there are no physical structures separating the three hypothetical cooler zones. The annular shape of the cooler was mapped to two-dimensional space by using an average bed diameter to calculate the average pellet residence time in the cooler. The length of each cooler zone was estimated by comparing the measured pressure drop across the bed to the predicted pressure drop using the Ergun equation for pressure drop in porous media:

$$\frac{\Delta P}{L_b} = \frac{1.75\rho_g u_g^2}{d_p}\left(\frac{1-\varepsilon_b}{\varepsilon_b^3}\right) + \frac{150\mu_g u_g (1-\varepsilon_b)^2}{d_p^2 \varepsilon_b^3} \tag{2.1}$$

where L_b is the bed depth, ρ_g is the gas density, u_g is the superficial gas velocity, d_p is the average pellet diameter, ε_b is the bed porosity, and μ_g is the gas viscosity. Given a pressure drop across the bed, gas volumetric flow rate, bed width, and bed depth, Equation (2.1) was solved for the length indirectly from the superficial gas velocity:

$$z_c = V_g / u_g w_c \tag{2.2}$$

where z_c is the length of the cooler zone, V_g is the volumetric flow rate of the gas through the cooler zone, and w_c is the width of the cooler zone.

This approach for estimating a cooler zone length provided reasonable results for the machine under a specific set of operating conditions. However, the relative lengths of each zone would need to be adjusted for each new set of flow conditions. A computational fluid dynamic (CFD) model of the cooler avoids this problem by allowing the gases to mix and distribute according to the operating conditions. A model of the cooler using CFD is discussed in under the section entitled, CFD Cooler Model.

2.3 Mass Transfer Models

The mathematical models for mass transfer and reaction in the pellet bed are described here. The models includes drying, flux decomposition, and magnetite oxidation. All of the models assume homogeneous, isothermal pellets. Only the magnetite oxidation model accounts for changes in the composition of magnetite in the radial coordinate direction of the pellet.

2.3.1 Drying

Green balls are dried by contact with heated air in the first two stages of the furnace. The model for drying includes a warming period, followed by a constant drying period. Chemically bound water is ignored in this model. During the warming period, the moist pellets are heated to the boiling temperature of water. The rate of evaporation was modeled in terms of convection mass transfer of water vapor from the pellet surface to the under-saturated air:

$$\frac{dX_w}{dz} = \frac{k_w a A_l M_w \left(C_{we} - C_{w,b}\right)}{m_{sl}} \tag{2.3}$$

where X_w is the mass fraction of water in the pellet, z is the length dimension in the direction of the traveling grate, C_{wb} is the bulk gas phase water concentration, and m_{sl} is the mass flow rate of the solids layer, A_l is the cross sectional area of the bed layer, M_w is the molecular weight of water, a is the pellet surface area per unit bed volume:

$$a = \frac{6\left(1-\varepsilon_b\right)}{d_p} \tag{2.4}$$

C_{we} is the equilibrium gas phase concentration of water, calculated assuming Raoult's law:

$$y_w = P_w^v / P_T \tag{2.5}$$

$$C_{we} = y_{we} P / R_g T \tag{2.6}$$

where y_w is the mole fraction of water in the gas phase, P_T is the total pressure of the gas phase (assumed 1 atm), and P_w^v is the vapor pressure of water. The vapor pressure was calculated from an Antoine correlation for pure water vapor pressure (Reid, et al, 1987). The mass transfer coefficient, k_g, was calculated from the dimensionless correlation for fluid in a packed bed of spheres (Seader and Henley, 1998):

$$\frac{k_g d_p}{D_g} = 2.0 + 1.1\left(\frac{u_g d_p}{\nu_g}\right)^{0.6}\left(\frac{\nu_g}{D_g}\right)^{1/3} \tag{2.7}$$

where d_p is the average pellet diameter, D_g is the diffusivity of water in the gas phase, u_g is the superficial gas velocity (calculated assuming a bed voidage of one), and ν_g is the kinematic viscosity of the gas. The viscosity was approximated from the Chapman-Enskogg theory for gas mixtures as described by Reid, et al (1987). The diffusivity of the water in air was correlated from the data in Mills (p. 947; 1999):

$$\begin{aligned} D_{w\text{-}air}/\left(m^2/s\right) &= 1.87\times10^{-10}\left(T/K\right)^{2.072};280 < T < 450K \\ D_{w\text{-}air}/\left(m^2/s\right) &= 2.75\times10^{-9}\left(T/K\right)^{1.632};450 < T < 1070K \end{aligned} \tag{2.8}$$

During the constant rate period, the rate of moisture evaporation from a pellet was modeled in terms of the rate of heat transfer to the pellet:

$$\frac{dX_w}{dz} = -\frac{q_s'}{\lambda_w m_{sl}} \tag{2.9}$$

where q_s' is the heat transfer rate to the solid bed per unit length and λ_w is the latent heat of water vaporization. The same equations apply under conditions of condensation. The heat consumed by evaporation was calculated as

$$q_v' = \lambda_w m_{sl} \frac{dX_w}{dz} \tag{2.10}$$

A flow chart for the drying algorithm is shown in Figure 2.3.

2.3.2 Flux Calcination

The flux was assumed to be a mixture of calcium carbonate (75 wt%) and magnesium carbonate (25 wt%). The flux decomposition reaction was assumed to be irreversible. The reaction expression is

$$CaCO_3 \cdot MgCO_3 \rightarrow CaO + MgO + 2CO_2 \tag{2.11}$$

The kinetics of flux calcination was modeled assuming homogeneous, isothermal pellets. The rate of flux decomposition is first order with respect to the mass fraction of flux:

$$\frac{dX_f}{dz} = \frac{-k_f X_f}{u_s} \tag{2.12}$$

where X_f is the mass fraction of flux in the solid bed, u_s is the linear bed velocity, and k_f is the flux decomposition reaction rate constant. The reaction rate constants for flux decomposition are as follows (Thurlby, 1988):

$$k_{Mg}/s^{-1} = 2.50 \times 10^5 \exp\left(-\frac{1.12 \times 10^4}{T/K}\right) \tag{2.13}$$

$$k_{Ca}/s^{-1} = 8.30 \times 10^6 \exp\left(-\frac{1.83 \times 10^4}{T/K}\right) \tag{2.14}$$

Since the activation energy for magnesium carbonate is smaller, this compound is consumed first, followed by the decomposition of calcium carbonate.

The rate of carbon dioxide production was used in the gas phase material balance:

$$F_{CO_2} = \frac{2m_{sl}}{M_f} \frac{dX_f}{dz} \tag{2.15}$$

where M_f is the molecular weight of flux. The calcination reaction is endothermic. The rate of heat consumption by this reaction is

$$q_f' = \Delta H_f m_{sl} \frac{dX_f}{dz} \tag{2.16}$$

where ΔH_f is the endothermic heat of flux decomposition.

2.3.3 Magnetite Oxidation

The magnetite oxidation reaction expression is

$$4Fe_3O_4 + O_2 = 6Fe_2O_3 \tag{2.17}$$

The shrinking core model (SCM) was used to adequately describe the kinetics of magnetite oxidation. SCM assumes that the reaction proceeds topochemically from the outside in along a sharp reaction front to the center of the pellet. The model also assumes homogeneous, isothermal pellets. The overall rate of reaction is a function of convective mass transfer of oxygen from the bulk air to the pellet surface, diffusion through an ash layer of hematite surrounding the unreacted magnetite core, and surface reaction at the interface between the ash layer and core.

$$\frac{dr_c}{dz} = \frac{-4\left(C_{O_2b} - C_{O_2e}\right)}{u_s\rho_c\left[\frac{1}{k_{ox}} + \frac{r_c}{D_e}\left(1 - \frac{r_c}{r_p}\right) + \frac{1}{k_g}\left(\frac{r_c}{r_p}\right)^2\right]} \tag{2.18}$$

where r_c is the unreacted core radius, r_p is the pellet radius, C_{O2b} is the bulk gas oxygen concentration, r_c is the molar density of the magnetite core, C_{O2e} is the equilibrium gas oxygen concentration, and kg is the convective mass transfer coefficient, calculated from the dimensionless correlation in Equation (2.7) for O_2 in air. The equilibrium partial pressure of oxygen with magnetite and hematite is calculated from the following expression for the change in the free energy of the reaction (Gaskell, D.R., 1981):

$$\Delta G^o/(J/mol) = -RT\ln\left[\frac{1}{\left(P_{O_2}/atm\right)}\right] = -472900 + 272.68(T/K) \tag{2.19}$$

where P_{O_2} is the partial pressure of O_2 in the gas. Rearrangement of Equation (2.19) for P_{O_2} gives

$$P_{O_2e}/atm = \exp\left[32.794 - \frac{56873}{T/K}\right] \tag{2.20}$$

The equilibrium concentration was calculated assuming ideal gas behavior:

$$C_{O_2e} = P_{O_2e}/R_gT \tag{2.21}$$

The Arrhenius expression for the forward reaction rate constant, k_{ox}, for magnetite oxidation used in this work is (Thurlby, 1988):

$$k_{ox}/(m/s) = 1.16\times10^8(T/K)\exp\left(-\frac{1.983\times10^4}{T/K}\right) \tag{2.22}$$

The diffusivity of oxygen in air was correlated from the data in Mills (1999):

$$D_{O_2}/\left(m^2/s\right) = 1.535\times10^{-9}(T/K)^{1.665} \tag{2.23}$$

The effective diffusivity was calculated as follows.

$$D_e = D_{O_2}\varepsilon_p/\tau_p \tag{2.24}$$

where ε_p is the porosity of the pellet and τ_p is the tortuosity of the pore structure of the pellet. The tortuosity was correlated from the data of Papanastassiou and Bitsianes (1973):

$$\tau_p = 1 + 0.2538\left(\frac{1-\varepsilon_p}{\varepsilon_p}\right) + 0.2213\left(\frac{1-\varepsilon_p}{\varepsilon_p}\right)^2 \tag{2.25}$$

This correlation has the features that $\tau \to 1$ as $\varepsilon_p \to 1$ and $\tau \to \infty$ as $\varepsilon_p \to 0$. Also, for randomly packed uniform spheres, $\varepsilon_p \cong 0.38$, $\tau \cong 2.0$.

The mass fraction of magnetite was related to the core radius as follows.

$$\frac{dX_m}{dz} = \frac{3X_{mi}}{r_p}\left(\frac{r_c}{r_p}\right)^2 \frac{dr_c}{dz} \tag{2.26}$$

where X_m is the mass fraction of magnetite in the green ball and X_{mi} is the initial mass fraction of magnetite. The conversion of magnetite was calculated as follows.

$$x_m = 1 - \left(\frac{r_c}{r_p}\right)^3 \tag{2.27}$$

The rate of oxygen consumption by reaction with magnetite was used in the material balance for the gas phase:

$$F_{O_2} = \frac{m_{sl}}{4M_m}\frac{dX_m}{dz} \tag{2.28}$$

where M_m is the molecular weight of magnetite. The oxidation reaction is exothermic. The heat generation rate per unit length is a function of the change in the magnetite core radius:

$$q'_{ox} = \frac{m_{sl}\Delta H_{ox}}{4M_m}\frac{dX_m}{dz} \tag{2.29}$$

where ΔH_{ox} is the heat of oxidation reaction per mole of O_2 reacted.

2.4 Heat Transfer Model

The mathematical models for heat transfer on the grate, in the kiln, and cooler are described here. Pellets are assumed to be isothermal. The grate and cooler models are identical. The results from the CFD simulations were incorporated into the overall Medusa model by replacing the original calls to the grate code with least-squares regressions of the CFD data for cooler gas flow and temperature as functions of the kiln solids discharge conditions and the gas feed to the cooler.

2.4.1 Traveling Grate/Cooler Model

The bed of solid pellets traveling on the grate or cooler was modeled as a system of discrete layers as illustrated in Figure 2.2. The temperature of the solids was assumed to be locally uniform in each layer. These assumptions permit the change in the gas temperature calculation:

$$T_{go} = T_s + \left(T_{gi} - T_s\right)\exp\left(\frac{-haA_l}{F_g^{'}\bar{c}_{pg}}\right) \tag{2.30}$$

where T_{go} is the temperature of the gas exiting the bed layer, T_{gi} is the temperature of the gas entering the bed layer, T_s is the average temperature of the solids layer $F_g^{'}$ is the molar flow rate of gas per unit length, and $\bar{c}_{pg}$ is the average heat capacity of the gas in the solid layer. The heat transfer coefficient is calculated from the dimensionless correlation:

$$\frac{hd_p}{\kappa_g} = 2.0 + 1.1\left(\frac{u_g d_p}{\nu_g}\right)^{0.6}\left(\frac{\nu_g \bar{c}_{pg}}{\kappa_g}\right)^{1/3} \tag{2.31}$$

where κ_g is the gas thermal conductivity. Correlations of the thermal conductivity of the process gases available from Reid, et al (1987) are used in Medusa.

The heat transfer rate per unit length between the gas and solids is calculated from an energy balance:

$$q_{gs}^{'} = F_g^{'}\bar{c}_{pg}\left(T_{gi} - T_{go}\right) \tag{2.32}$$

The energy balance for the solids in each layer is

$$m_{sl}c_{ps}\frac{dT_s}{dz} = q_{gs}^{'} + q_v^{'} + q_f^{'} + q_{ox}^{'} \tag{2.33}$$

where q' is the heat transfer rate per unit length. The subscripts gs, v, f, ox refer to heat transfer between the gas and solids, heat of vaporization, heat of flux decomposition, and heat of magnetite oxidation, respectively. The model of the rectangular bed consists of an equation similar to Equation (2.33) for each layer of the bed. The model for the solids flow resulted in a system of 20 coupled non-linear, first-order, ordinary differential equations for each bed layer in each grate/cooler type zone.

The specific heat of the solids was calculated as a weighted average of the composition:

$$c_{ps}/\left(J/kg\cdot K\right) = \frac{X_c c_{pc}}{M_c} + \frac{X_f c_{pf}}{M_f} + \frac{X_h c_{ph}}{M_h} + \frac{X_m c_{pm}}{M_m} + \frac{X_w c_{pw}}{M_w} + \frac{X_i c_{pi}}{M_i} \tag{2.34}$$

The heat capacity of each species was correlated for temperature (TAPP, 1991):

The grate models only two dimensions: length and depth. The annular cooler was modeled like the grate by calculating an average length based on the average radius of the cooler bed:

$$z_c = \frac{\pi\left(d_i + d_o\right)}{2} \tag{2.35}$$

where d_i is the inner diameter and d_o is the outer diameter.

2.4.2 Rotary Kiln Model

The model for the rotary kiln is based on a first order mixing rule for the pellets and the net radiation method for heat transfer. The bed of pellets in the kiln was modeled as two regions: a mantle surrounding a core. Mixing between the mantle and core is assumed to follow a simple first order mixing rule:

$$\frac{dT_m}{dt} = (T_a - T_s) \tag{2.36}$$

$$\frac{dT_c}{dt} = (T_a - T_c) \tag{2.37}$$

where the average temperature of the solids was the weighted average of the core and mantle temperatures:

$$T_a = \frac{f_c c_{pc} T_c + (1 - f_c) c_{ps} T_s}{f_c c_{pc} + (1 - f_c) c_{ps}} \tag{2.38}$$

An energy balance around the mantle includes radiation heat transfer exchange between the solids and the wall and flame as well as convection with the secondary air. The net-radiation model of Thornton and Batterham (1982) is used to calculate the radiation heat exchange between the exposed wall of the kiln, the surface of the bed of solids and the flame. Radiation exchange with the secondary air was found to be insignificant in the kiln. The models of Tscheng and Watkinson (1979) for convective and conductive heat transfer in rotary kilns are also used in the model for heat transfer other than radiation between the gases, wall, and solids.

A tanks-in-series model of the kiln was used to perform the local material and energy balances. This approach is a departure from the differential approach used for the grate/cooler material and energy balances. The tanks-in-series model results in a system of non-linear algebraic equations.

The kiln was divided into a sequence of small divisions. It was found by trial-and-error that 100 divisions was satisfactory. The mantle and core were assumed to be perfectly mixed within each division. The energy balance for the solids in each kiln division was

$$mc_p (T_{in} - T_{out}) + q_{rs} + q_{gs} + q_{ws} + q_{ox} - q_c = 0 \tag{2.39}$$

The energy balance for the flame and secondary air streams in each kiln division were calculated according to the tanks-in-series model:

$$\left(\sum F_i H_i\right)_{in} - \left(\sum F_i H_i\right)_{out} + q_{gs} + q_{gw} + q_r = 0 \tag{2.40}$$

where F_i and H_i are the molar flow rate and enthalpy of species i in the gas stream, q_{gs} and q_{gw} are the convective heat transfer rates between the gas, solids and wall, and q_r is the net heat transfer rate to the gas stream. The enthalpy of each species was calculated in terms of the average heat capacity:

$$H = H^o + \bar{c}_p (T - T_r) \tag{2.41}$$

where H^o is the heat of formation and T_r is the reference temperature of formation.

The convective heat transfer rate between the gas and solids, and gas and wall is described by the following equation:

$$q_{gs} = A_s h(T_{sa} - T_s); q_{gw} = A_w h(T_{sa} - T_w) \tag{2.42}$$

where A_s and A_w are the surface areas of exposed solids and wall, respectively, in the kiln division.

The temperature of the wall was calculated from a steady-state energy balance through the wall. The net heat transfer rate to the wall was equated with the composite heat transfer rate through the wall:

$$\sum q_w = U_{wo} z_k (T_w - T_\infty) \tag{2.43}$$

where zk is the length of a kiln division, T_w and T_∞ are the inside wall surface temperature and ambient outside air temperature, respectively, and U_{wo} is the overall heat transfer coefficient for the outside wall area:

$$U_{wo} = \frac{2\pi}{\frac{1}{\kappa_{kr}}\ln\left(\frac{r_k}{r_{ki}}\right) + \frac{1}{\kappa_{ks}}\ln\left(\frac{r_{ki}}{r_{ko}}\right) + \frac{1}{h_o r_{ko}}} \tag{2.44}$$

where κ is the thermal conductivity of the kiln refractory or steel skin and r is the radius of the kiln refractory, inside skin or outside skin, respectively.

The combustion model assumes mixed-is-burned according to the methane combustion reaction:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{2.45}$$

The model assumes the fuel (natural gas) is methane. The surface areas of the flame and secondary air streams were calculated proportional to the relative temperature and mass flow rate each stream:

$$A_f = \frac{F_f T_f \left(\pi r_k^2 - A_b\right)}{F_f T_f + F_{sa} T_{sa}}; A_{sa} = \pi r_k^2 - A_b - A_f \tag{2.46}$$

where A, F, T are the cross sectional area, molar flow rate, and temperature of the flame and secondary air streams respectively, A_b is the solids bed cross sectional area, and r_k is the internal kiln radius.

The model equations for the rotary kiln were solved by relaxation on ordinary iteration. The wall temperature was particularly difficult to converge due to the highly non-linear radiation terms involved. The kiln zone model is solved in an inner loop before the overall solution procedure is completed.

2.4.3 CFD Cooler Model

CFD is not constrained by the limiting assumptions used to develop Medusa. The splits of the air flows to the kiln, recoup and vent are not required a priori; they are determined by the model. The other advantage of CFD is three dimensional modeling. Using CFD to model the cooler overcomes the limitation of Medusa's two dimensions. A parametric study of the effects of production rate, magnetite concentration entering the cooler, and cooling air rates was performed on the CFD cooler model. The results were correlated by multivariable linear regressions. Regressed equations for secondary air flow and temperature and recoup flow and temperature were substituted into Medusa for the cooler model.

$$F_{rcp}/(kmol/s) = 1.78 - 0.145X_m - 1.31\times10^{-3}\left[m_s/(kg/s)\right] \tag{2.47}$$

$$T_{rcp}/K = 1.49\times10^3 + 4.81\times10^2 X_m + 6.70\left[m_s/(kg/s)\right] \tag{2.48}$$

$$F_{sa}/(kmol/s) = 1.42 + 5.49\times10^{-2} X_m + 1.33\times10^{-3}\left[m_s/(kg/s)\right] \tag{2.49}$$

$$T_{sa}/K = 1.67\times10^3 + 2.82\times10^2 X_m + 1.47\left[m_s/(kg/s)\right] \tag{2.50}$$

Equations (2.47) through (2.50) were programmed directly into the FORTRAN program for Medusa. Modifying Medusa at the program level should be done with caution. Users are encouraged to consult with Richard Davis before attempting to change the original code.

2.4.4 Model Calibration

The model was calibrated to the plant data by adjusting the leakage of ambient air on the grate and cooler. The leakage to a zone was assumed to be proportional to the length of the zone and the square root of the pressure drop across the leak into the zone, according to the Bernoulli equation:

$$F_{leak} \propto L_b\sqrt{\Delta P_{leak}} \tag{2.51}$$

The temperature of the solids exiting the kiln and the temperature of the gas leaving the preheat zone were used as the target temperatures. The leakage was adjusted until the difference between the model predictions for the target temperatures and the plant data for these temperatures was minimized. The minimization function was the least squares expression:

$$f = \sum\left(T_p - T_m\right)^2 \tag{2.52}$$

where T_m was the measured temperature in the plant and T_p was the model predicted temperature. Powell's "dog leg" optimization method was used to search for the minimum (Press, et al, 1987). It was assumed for the conditions of the simulation that there was a unique global minimum within the plant operating conditions. Repeating the search for the minimum at different starting conditions validated this assumption; the same solution for the minimum was reached.

2.5 Model Implementation

The mathematical model equations were solved using standard numerical algorithms for solving systems of differential/algebraic equations. The algorithms were coded into computer programs and a graphical user interface was developed to make the code generic, independent of any particular machine. Hence, the models and their implementation may be used for any grate-kiln system, independent of the dimensions or configuration. All of the files are available at the Medusa web site

http://www.d.umn.edu/~rdavis/research/medusa/medusa.htm

2.5.1 Medusa.for

The model equations were solved numerically using standard FORTRAN algorithms. The program is designed to pass information between subroutines using common statements. The differential equations used to model the grate or cooler were solved by a variable-step second-order Runge-Kutta method. The main program initializes the variables using typical target values for taconite pellet induration furnaces. Initialization subroutines are located at the end of the program. SI (metric) units were used in the model solutions for convenience in the calculations. Field (English) units are an option in the user interface described below. The solution is iterative due to the nonlinear nature of the radiation and chemical reaction models. The solids temperature trajectories were calculated based on the initial guesses for the zone gas temperatures and flow rates. The zone gas temperatures and flow rates are upgraded from the solids temperatures. This cycle is repeated until the zone gas and solids temperatures converge. A block diagram of the solution algorithm is shown in Figure 2.4.

2.5.2 Medusa.exe

A compiled version of the FORTRAN program MEDUSA.EXE executes the calculations. MEDUSA.EXE is called from a graphical user interface (GUI) described in the next section. The required operating parameters are read from a data file. The GUI is also used to control the duration of the calculations or stop the calculations premature to convergence.

2.5.3 Medusa.ctl

The GUI creates a control file named Medusa.ctl. This file contains the name of the data and results files and the maximum number of overall convergence iterations. Upon execution, Medusa.exe first reads Medusa.ctl to get the name of the data file. This file is also read before each overall solution iteration. The GUI controls the iterations by changing the maximum iteration number while the program is executing.

2.5.4 Name.dat

The GUI is used to create a data file that is read by Medusa.exe. The user provides the name of the file in the GUI. The GUI adds the identifying extension .DAT. The data file contains all of the required input parameters for solving the Medusa model equations for a particular case. Experienced users may find it convenient to modify the .DAT file instead of using the GUI. Use caution when modifying the .DAT file without the aid of the GUI. Errors in input are difficult to trace.

2.5.5 Name.fld or Name.met

The results from the model solution are written to the output file. The user provides the name of the output file in the GUI. The extension .FLD indicates FIELD (English) units. SI (Metric) units are indicated by a .MET extension. The output file first lists the input data for identification purposes. The results for residence time, average temperature and average composition are tabulated for each zone. The profiles through the bed are given for the end of a zone. The zone gas flows are also tabulated. A material balance for the gas phase is included at the end of the output file that includes the zone gas compositions.

2.5.6 Medusa.rst

The converged temperatures and flow rates of the process gas in each zone are written to the file Medusa.rst. The process gas temperatures and flow rates are used to initialize the model solution. When the restart feature is selected, the data in Medusa.rst are read into Medusa.exe as the initial guesses for the unknown gas characteristics. This file only used after the first implementation of the model to speed up convergence. Medusa.rst is generally not available for the first run.

2.6 Graphical User Interface

A graphical user interface was developed to provide a convenient tool for creating the data files needed by the executable Medusa model. The interface was created with Microsoft Excel using Visual Basic for Applications. The interface requires MS Excel 97 or higher. The interface is organized as an Excel workbook with seven sheets. Examples of each sheet are presented in Figures 2.5 through 2.12. The model calculates on the SI unit basis. The GUI accepts both SI and Field (English) units. Common unit conversions are listed in Table 2.1.

2.6.1 File Manager

The File Manager Sheet, shown in Figure 2.5, is used to create the data, results, and control files. The data and results files are named by the user in the box entitled: Results File Name. The results file lists the date and title supplied by the user. It is important to select the system of units before entering numerical data: Field (English) or SI (metric). The selection of units changes the headings for required units of all dimensional parameters in the other sheets. It is important to note that changing the type of units does not automatically convert the numbers in the sheets into the new dimensions; only the headings change. If the user decides to change the unit designator on the File Manager sheet, it is the responsibility of the user to supply the corresponding numerical values that match the new unit set. Table 2.1 lists several common unit conversions for this system. The program gives the data file name an extension .DAT. The model results file name is given an extension corresponding to the type of units selected: .FLD for Field units, of .MET for metric units. In addition, there are two other control files that are generated. The executable program to manage the input and output file names and control the number of overall solution iterations uses the file MEDUSA.CTL. MEDUSA.CTL is also used to stop the executable program before convergence using the GUI to generate the results file containing the model results from the last iteration. The other file is MEDUSA.RST. This file is generated at the end of the model calculations and contains a new set of initial guesses for the model. Using restart calls this file for the initial guesses for the next execution of MEDUSA.EXE. Generally, restart speeds up the convergence. This file is not available the first time MEDUSA.EXE is executed.

The What-if feature on the File Manager allows the user to run the model for a range of Fuel or Solids feed rates. This feature allows the user to explore the affects of changing either solids or fuel rates on the model without creating a new data file for each change. Up to ten runs may be selected for any range of the what-if variable. The base case is defined by the parameters supplied to the other sheets in the GUI.

The other features of the File Manager sheet are described next. The Maximum Medusa Cycles is used to limit the number of overall solution iterations to stop the program is reasonable convergence times are not achieved. The Optimization radio button should only be checked if the user has a modified version of MEDUSA.EXE that uses the inherent optimization algorithm. A WWW site is maintained that has current versions of the programs and a help file for using Medusa.

The three buttons located in the lower right corner are used to generate the data file after all the required parameters are supplied, launch the executable version of Medusa, and prematurely stop the program execution.

2.6.2 Pellet Bed

The Pellet Bed sheet, shown in Figure 2.6, lists all of the parameters required by Medusa to define the characteristics of the solids feed and pellet bed. The sheet is divided into sections for pellet chemistry, pellet characteristics, green ball feed conditions, and bed characteristics. Recommended values are given for some parameters based on experience with the model. The recommendations are only intended to serve as a guide. The user should consider using alternative values to adjust the model solutions to match plant data where appropriate. The heat transfer resistance and Convection Enhancement Factors are useful for adjusting the rates of heat transfer between the process gases and the bed of pellets.

2.6.3 Furnace Zones I & II

The Furnace Zone GUIs are shown in Figures 2.7 and 2.8. The first spreadsheet for furnace zones is used define the machine type: grate-kiln or straight-grate. The principal firing zone is also identified. The firing zone is used by the what-if calculations described under File Manager. Furnace Zones I is used to name the zones and provide the physical dimensions of each zone. In the case of a straight grate machine, the depth of the hearth layer is also listed. The hearth layer depth should be set to zero for grate-kiln machines. However, the hearth layer may be used in grate-kiln models to artificially model additional heat transfer with the traveling grate.

The second sheet for furnace zones permits the user to specify a different bed porosity (voidage) in each zone. The porosity is used in the GUI to calculate a bed depth given a linear bed velocity, or a linear bed velocity given a bed depth. The bed density is based on the pellet chemistry defined in the Pellet Bed sheet.

2.6.4 Rotary Kiln

The Rotary Kiln data sheet is shown in Figure 2.9. The rotary kiln zone is unique to the grate-kiln model. The straight-grate model ignores the parameters supplied to this sheet. The required parameters for the kiln are self-explanatory. A ported kiln model is available, though untested. To use the ported kiln feature, the user must decide on the length and location of a single section of the kiln that is ported. The model assumes that the gas is evenly distributed along the length of the ported kiln section. The kiln is divided into 100 sections, starting at the pellet feed end of the kiln. The location of the ported section is defined relative to the lower section number and the length of the kiln. For example, consider a 150 ft long kiln with a 50 ft long ported section that starts at 50 ft from the feed end. The length of a section is 1.5 ft/section. The location of the start section is at (50 ft)/(1.5 ft/section) = 33.33 sections. The location of the end of the ported section is at (50 + 50 ft)/(1.5 ft/section) = 66.67. To ensure that the modeled ports encompass the entire length of the ported section, the start location is rounded down to the lowest integer value of 33, while the end location is rounded up to the next highest integer value of 67. Thus, the start and end divisions are at 33 and 67, respectively.

2.6.5 Process Gas

The ambient gas temperature, fuel, primary air, and secondary air feed rates to the zones are set in the Process Gas sheet, shown in Figure 2.10. The ability to fix the temperatures of the secondary air independently builds flexibility into the model set-up. This feature may be useful when using Medusa to model a portion of the entire furnace. For example, the user may model the grate alone, fixing the temperatures and flow rates of the recoup air to the second drying stage and the secondary air from the kiln. The direction of flow through the bed on the grate or cooler is set here for each zone. The user may explore the effects of updraft versus downdraft flow in each zone independently. The outside air temperature and humidity are also set on this sheet.

2.6.6 Leakage

The Leakage GUI is shown in Figure 2.11. The Medusa model includes capabilities of accounting for leakage into the machine as well as leakage between zones, either above or below the bed. The model does not allow for leakage from the machine. In the case of interzone leakage, the model permits the leakage to occur in one of two directions. Leakage to and from adjacent zones is a feature that may be useful to model mixing in the gas phase where there are no physical separations between the zones, such as the Minntac cooler. The temperature of the air leaking into the machine is also set on this sheet.

2.6.7 Gas Distribution

The Medusa model requires that the distribution of process gases be set for each zone. The Gas Distribution sheet, shown in Figure 2.12, is arranged for the user to set-up the gas distribution in terms of the volume percent of the gas leaving a zone being distributed to the other zones. The gas is leaving the zone in the left column and distributed to a zone listed along the top row. For example, the user may set-up the model for 30% of the preheat zone gas directed to the first drying stage and 70% of the preheat exit gas directed to the second drying stage.

2.7 Results

The Medusa model was solved for the parameters as shown in the GUI. Sample results from the program are listed in Table 2.2. Temperature and composition profiles for the drying, preheat, and kiln zones are plotted in Figures 2.13 through 2.15. The average solids temperature is plotted in Figure 2.13 as a function of position. When compared to the average solids temperature profile plotted with residence time in Figure 2.14, it is clear that the zone with the largest residence time is the rotary kiln. The composition of flux, magnetite, and water are plotted in terms of mass fraction in Figure 2.15. Figure 2.15 shows that the model predicts that the pellets are completely dry before the preheater, and that most of the flux decomposes in the preheater before the solids enter the kiln. The model also predicts that oxidation starts slowly in the dryers, increases in the preheater, then slows in the kiln. This is probably due to the poor mixing of air with the solids in the kiln.

Plots of the data generated by Medusa are readily created in Excel. The procedure involves copying the rows of data of interest and pasting into Excel. The data are pasted into a single column. Parsing the data using that intrinsic feature of Excel that creates columns separates the individual data columns. Once the data are available in the spreadsheet, they are easily manipulated according to the needs of the user.

2.8 Summary

The Medusa model is designed for overall material and energy balances around grate-kiln induration furnaces. The model assumes that gases are well mixed and requires the process gas flow distribution. The mathematical model consists of a system of nonlinear, algebraic and first-order ordinary differential equations. The solution of the coupled system of equations requires iteration on the unknown variables. The solution method consists of standard numerical methods programmed in FORTRAN. A graphical user interface was created with Excel to allow users to operate the model without knowledge of FORTRAN. An optimization routine is available in the FOTRAN code that is not accessible through the Excel graphical user interface. Modification of the FORTRAN code requires experience in FORTRAN programming. It is recommended that users consult the authors before attempting to change the FORTRAN code. The model gives average temperature and composition profiles in the furnace, kiln, and cooler. The model may also be modified to include correlated equations that represent the cooler, or other unit operations.

2.9 Nomenclature

a	area per unit volume
A	cross sectional area
C	concentration
c	heat capacity
d	diameter
D	diffusivity
f	fraction or function
F	gas molar flow rate
G	free energy
H	enthalpy
h	local heat transfer coefficient
k	mass transfer coefficient or reaction rate constant
L	length (depth)
m	mass flow rate
M	molecular weight
P	gas pressure
q	heat transfer rate
R	ideal gas constant

r	pellet radius
T	temperature
U	overall heat transfer coefficient
u	velocity
V	volume
w	width
X	mass fraction
y	gas phase mole fraction
z	length coordinate

Greek Symbols

ε	porosity
κ	thermal conductivity
λ	latent heat
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
τ	tortuosity

Subscripts/Superscripts

b	bed of solids or bulk gas phase
c	cooler zone or calcined flux
c	magnetite pellet core
Ca	calcium carbonate
e	effective
e	equilibrium
f	flux or flame
g	gas
h	hematite
i	in, inside, or inert
k	kiln
l	bed layer of solids
m	magnetite or mantle or measured
Mg	magnesium carbonate
o	out or outside
ox	oxidation
p	pellet
p	predicted
'	per unit length
r	radiation
rcp	recoup
s	solids
sa	secondary air
v	vaporization
w	water or wall

2.10 References

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Table 2.1. Unit Conversions for Medusa and CFD

To Convert From:	To:	Multiply By:
in	m	0.0240
ft	m	0.3048
scfm	kmol/s	2.1056×10^{-5}
LT/hr	kg/s	0.28222
Lb_m/min	kg/s	7.56×10^{-3}
MBTU/hr	Kmol/s	3.5×10^{-4}

Table 2.2 Medusa Output File

```
*******************************************************
  MEDUSA: TACONITE PELLET INDURATION MODELER
          FOR STRAIGHT-GRATE & GRATE-KILN SYSTEMS

  BY: RICHARD DAVIS, UMD CHEMICAL ENGINEERING DEPARTMENT
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                      ALL RIGHTS RESERVED.

  DISCLAIMER: USE THIS PROGRAM AT YOUR OWN RISK!
              NO WARRANTIES ARE EXPRESSED OR IMPLIED,
              THAT THIS PROGRAM IS FREE OF ERROR, OR
              WILL MEET YOUR REQUIREMENTS FOR ANY
              PARTICULAR APPLICATION. THE AUTHOR
              DISCLAIMS ALL LIABILITY FOR DIRECT OR
              CONSEQUENTIAL DAMAGES RESULTING FROM YOUR
              USE OF THIS PROGRAM.

*******************************************************
 GRATE-KILN MODEL RESULTS
 FIELD UNITS

 TITLE: test
 RUN DATE: 5/18/00
 RESULTS FILE NAME: test.fld
 WHAT-IF VARIABLE: FUEL RATE
 Restart? False
 Minimum what-if %:     100.0
 Maximum what-if %:     100.0
 Number of what-if:  1

 *** RUN FILE DATA ***

 SOLIDS FEED RATE (LT/hr):
    Green ball   =    472.00
    Hearth layer =    .00000

 Pellet diameter (in) =    .43700

 SOLIDS FEED TEMPERATURE (deg F):
```

```
   Green ball   =    62.300
   Hearth layer =    62.300

FEED MASS FRACTION:
   Magnetite =    .75800
   Hematite  =    .41000E-01
   Inert     =    .44000E-01
   Flux      =    .69000E-01
   Water     =    .88000E-01

Pellet porosity =    .25000

Heat conduction resistance factor =    .00000

Solids emmisity =    .60000

AIR TEMPERATURES (deg F):
   Outside air =    37.000
   Leakage air =    62.300

Number of zones =  4

Machine type (1 = SG; 2 = GK) = 2
Kiln zone =  4
Fire zone =  4

ZONE NAMES:
 1  DD1
 2  DD2
 3  PH
 4  KILN

FLOW DIRECTIONS (1 = DOWN-DRAFT; -1 = UP-DRAFT):
 1   1
 2   1
 3   1
 4   1

AIR FLOW RATE TO ZONE (SCFM):
 1      .00000
 2      70099.
 3      .00000
 4      85486.

TEMPERATURE OF AIR TO ZONE (deg F):
 1      62.300
 2      1686.0
 3      62.300
 4      2316.0

LEAKAGE INTO BED-GAS FEED SIDE (SCFM):
 1      66428.
 2      35536.
 3      59171.
 4      .00000

LEAKAGE INTO BED-GAS EXIT SIDE (SCFM):
```

```
 1      .00000
 2      .00000
 3      10923.
 4      .00000

FUEL TO ZONE (SCFM):
 1      .00000
 2      .00000
 3      1083.0
 4      2850.0

PRIMARY AIR TO ZONE (SCFM):
 1      .00000
 2      .00000
 3      1168.0
 4      3078.0

ZONE LENGTH (ft):
 1      49.200
 2      23.000
 3      55.800
 4      131.00

ZONE WIDTH (ft):
 1      15.700
 2      15.700
 3      15.700
 4      19.700

ZONE HIGHT (ft):
 1      10.800
 2      10.800
 3      10.800
 4      10.800

ZONE REFRACTORY THICKNESS (in):
 1      5.5000
 2      5.5000
 3      5.5000
 4      5.5000

ZONE BED DEPTH (in):
 1      5.1000
 2      5.1000
 3      5.1000
 4      5.1000

ZONE HEARTH LAYER DEPTH (in):
 1      .00000
 2      .00000
 3      .00000
 4      .00000

ZONE BED POROSITY:
 1      .30000
 2      .30000
 3      .30000
```

```
 4      .35000

ZONE BED SPEED (in/min)
 1      270.73
 2      270.73
 3      270.73
 4      232.36

KILN PARAMETERS:
   Length (ft)             =    131.00
   Inside diameter (ft)    =    20.000
   Outside diameter (ft)   =    21.300
   Rotation speed (rpm)    =    1.1400
   Pitch angle (deg)       =    3.0000

UP-STREAM LEAKAGE-GAS FEED SIDE (SCFM):
 1      .00000
 2      .00000
 3      .00000
 4      .00000

DOWN-STREAM LEAKAGE-GAS FEED SIDE (SCFM):
 1      .00000
 2      .00000
 3      .00000
 4      .00000

UP-STREAM LEAKAGE-GAS EXIT SIDE (SCFM):
 1      .00000
 2      .00000
 3      .00000
 4      .00000

DOWN-STREAM LEAKAGE-GAS EXIT SIDE (SCFM):
 1      .00000
 2      .00000
 3      .00000
 4      .00000

TO VENT (SCFM):
 1      47492.
 2      47492.
 3      .00000
 4      .00000

FRACTION OF GAS FLOW FROM ZONE J TO ZONE I:
 1   1     .00000
 2   1     .00000
 3   1     1.0000
 4   1     .00000

 1   2     .00000
 2   2     .00000
 3   2     .00000
 4   2     .00000

 1   3     .00000
```

2 3 .00000
3 3 .00000
4 3 1.0000

1 4 .00000
2 4 .00000
3 4 .00000
4 4 .00000

Percent Humidity = 50.0

*** END RUN FILE DATA ***

What-if % = 100.00

*** MACHINE-LENGTH PROFILES ***

ZONE: DD1
SOLIDS LINEAR VELOCITY/ (in/min) = 270.73

Z/ ft	t/ min	T-Bed/ F (Ave)	T-Layer/ F (Out)	T-Air/ F (Out)	X-Flux (Ave)	X-Fe3O4 (Ave)	X-H2O (Ave)	Solids/ LT/hr	C-Fe3O4 % cnvrsn
.0	.00	62.3	62.3	62.3	.0690	.7580	.0880	472.00	.00
1.0	.04	74.7	63.4	72.8	.0690	.7580	.0882	472.11	.00
2.0	.09	87.7	65.6	78.4	.0690	.7580	.0884	472.21	.00
3.0	.13	100.6	70.0	87.4	.0690	.7580	.0885	472.25	.00
3.9	.17	113.0	77.9	100.3	.0690	.7580	.0884	472.20	.00
4.9	.22	124.1	89.6	116.0	.0690	.7580	.0880	471.99	.00
5.9	.26	133.2	105.5	131.4	.0690	.7580	.0870	471.53	.00
6.9	.31	140.0	121.1	143.0	.0690	.7580	.0854	470.78	.00
7.9	.35	144.2	133.3	151.5	.0690	.7580	.0832	469.73	.00
8.9	.39	146.7	140.5	154.4	.0690	.7580	.0805	468.48	.00
9.8	.44	148.7	142.7	154.7	.0690	.7580	.0777	467.16	.00
10.8	.48	151.2	143.2	154.5	.0690	.7580	.0750	465.86	.00
11.8	.52	154.3	142.3	153.3	.0690	.7580	.0724	464.63	.00
12.8	.57	158.2	141.2	152.8	.0690	.7580	.0699	463.45	.00
13.8	.61	162.8	140.1	151.9	.0690	.7580	.0675	462.32	.00
14.8	.65	168.3	138.8	151.3	.0690	.7580	.0652	461.25	.00
15.7	.70	174.2	138.1	151.3	.0690	.7580	.0630	460.21	.00
16.7	.74	180.7	137.1	150.9	.0690	.7580	.0609	459.21	.00
17.7	.79	187.8	136.4	151.2	.0690	.7580	.0589	458.24	.00
18.7	.83	195.1	136.0	151.4	.0690	.7579	.0568	457.29	.01
19.7	.87	203.0	135.1	151.5	.0689	.7578	.0549	456.37	.02
20.7	.92	211.3	134.7	152.6	.0689	.7577	.0530	455.47	.04
21.6	.96	219.9	134.4	152.9	.0688	.7574	.0511	454.57	.08
22.6	1.00	229.0	133.8	153.6	.0688	.7570	.0493	453.70	.14
23.6	1.05	238.6	133.7	155.0	.0687	.7563	.0475	452.84	.23
24.6	1.09	248.7	133.4	155.6	.0685	.7552	.0457	451.98	.37
25.6	1.13	259.3	132.9	157.0	.0683	.7538	.0440	451.15	.55
26.6	1.18	270.1	133.1	159.1	.0681	.7522	.0422	450.30	.77
27.6	1.22	281.1	132.7	159.6	.0678	.7504	.0405	449.46	1.01
28.5	1.26	293.0	132.4	161.0	.0676	.7483	.0389	448.66	1.28
29.5	1.31	305.1	132.7	163.3	.0674	.7459	.0372	447.84	1.59
30.5	1.35	317.5	132.3	164.9	.0671	.7434	.0356	447.06	1.92
31.5	1.40	330.2	132.0	167.0	.0668	.7407	.0340	446.28	2.28
32.5	1.44	343.5	132.5	169.6	.0666	.7378	.0323	445.51	2.67
33.5	1.48	357.2	132.0	171.7	.0664	.7346	.0307	444.76	3.08
34.4	1.53	370.9	132.1	175.4	.0661	.7313	.0292	444.02	3.52
35.4	1.57	384.7	132.4	177.6	.0658	.7278	.0276	443.26	3.98
36.4	1.61	399.4	131.9	180.6	.0656	.7241	.0261	442.56	4.47
37.4	1.66	414.0	132.2	185.1	.0653	.7202	.0246	441.85	4.99
38.4	1.70	428.5	132.3	188.1	.0649	.7161	.0231	441.12	5.53
39.4	1.74	443.7	131.9	192.2	.0647	.7118	.0216	440.45	6.10
40.3	1.79	458.9	132.4	197.5	.0644	.7073	.0202	439.77	6.68
41.3	1.83	474.1	132.3	200.8	.0640	.7027	.0187	439.09	7.30
42.3	1.88	489.5	132.0	206.6	.0637	.6979	.0174	438.44	7.93
43.3	1.92	505.1	132.8	213.2	.0633	.6929	.0160	437.79	8.59
44.3	1.96	520.7	132.3	217.4	.0630	.6877	.0146	437.16	9.27
45.3	2.01	537.0	132.2	225.1	.0627	.6824	.0134	436.59	9.97
46.2	2.05	552.9	133.3	232.7	.0624	.6769	.0120	435.97	10.69
47.2	2.09	568.8	132.4	239.0	.0620	.6713	.0108	435.41	11.44
48.2	2.14	585.2	132.6	247.9	.0617	.6655	.0097	434.89	12.20
49.2	2.18	601.1	133.9	256.5	.0613	.6596	.0084	434.32	12.99

ZONE: DD2
SOLIDS LINEAR VELOCITY/ (in/min) = 270.73

Z/ ft	t/ min	T-Bed/ F (Ave)	T-Layer/ F (Out)	T-Air/ F (Out)	X-Flux (Ave)	X-Fe3O4 (Ave)	X-H2O (Ave)	Solids/ LT/hr	C-Fe3O4 % cnvrsn
49.7	2.20	613.2	130.9	263.0	.0612	.6557	.0078	434.05	13.49
50.1	2.22	625.5	129.0	267.4	.0610	.6519	.0072	433.80	14.00
50.6	2.24	637.9	127.9	272.7	.0609	.6480	.0066	433.56	14.51
51.0	2.26	650.3	127.7	279.1	.0607	.6441	.0061	433.32	15.03
51.5	2.28	662.5	127.9	285.4	.0604	.6400	.0055	433.06	15.56
52.0	2.30	674.9	126.7	290.0	.0602	.6360	.0050	432.85	16.10
52.4	2.32	687.3	125.9	297.6	.0601	.6319	.0046	432.68	16.64
52.9	2.34	699.7	125.9	306.2	.0599	.6278	.0042	432.49	17.18
53.3	2.36	711.9	126.4	314.6	.0597	.6236	.0037	432.30	17.73
53.8	2.38	724.1	127.3	322.4	.0594	.6193	.0032	432.10	18.29
54.3	2.41	736.4	127.4	329.4	.0592	.6150	.0028	431.92	18.86
54.7	2.43	748.4	126.1	340.0	.0591	.6108	.0025	431.79	19.42
55.2	2.45	760.4	126.0	350.7	.0588	.6064	.0021	431.65	20.00
55.6	2.47	772.2	126.8	361.9	.0586	.6020	.0018	431.50	20.58
56.1	2.49	784.0	127.8	371.9	.0583	.5976	.0014	431.36	21.16
56.6	2.51	795.9	129.1	382.7	.0581	.5931	.0011	431.21	21.75
57.0	2.53	807.2	126.9	395.3	.0579	.5887	.0009	431.14	22.34
57.5	2.55	818.4	126.7	409.7	.0576	.5841	.0007	431.06	22.94
57.9	2.57	829.6	127.6	423.5	.0574	.5795	.0005	430.99	23.55
58.4	2.59	839.3	128.8	438.8	.0571	.5749	.0003	430.90	24.16
58.9	2.61	850.2	130.3	451.5	.0568	.5703	.0001	430.81	24.76
59.3	2.63	859.5	149.9	469.2	.0565	.5656	.0000	430.79	25.38
59.8	2.65	868.5	178.5	489.1	.0562	.5609	.0000	430.79	26.00
60.2	2.67	877.7	205.9	507.4	.0559	.5562	.0000	430.80	26.63
60.7	2.69	886.9	232.4	526.5	.0556	.5514	.0000	430.82	27.26
61.2	2.71	895.9	258.0	545.0	.0553	.5466	.0000	430.83	27.88
61.6	2.73	905.7	283.0	563.2	.0550	.5418	.0000	430.83	28.52
62.1	2.75	914.5	307.2	580.5	.0547	.5369	.0000	430.84	29.16
62.5	2.77	923.1	330.9	599.7	.0543	.5320	.0000	430.84	29.81
63.0	2.79	932.2	354.1	615.6	.0538	.5271	.0000	430.82	30.46
63.5	2.81	940.5	376.7	633.1	.0535	.5223	.0000	430.82	31.10
63.9	2.83	949.5	398.9	650.1	.0531	.5173	.0000	430.81	31.76
64.4	2.85	958.4	420.5	666.3	.0527	.5122	.0000	430.81	32.42
64.8	2.87	966.5	441.7	683.6	.0524	.5072	.0000	430.81	33.09
65.3	2.89	975.1	462.5	700.1	.0520	.5022	.0000	430.81	33.75
65.8	2.91	983.2	482.9	716.3	.0516	.4972	.0000	430.79	34.41
66.2	2.94	990.6	502.9	732.4	.0511	.4920	.0000	430.77	35.09
66.7	2.96	998.6	522.5	747.8	.0506	.4869	.0000	430.75	35.77
67.1	2.98	1006.4	541.8	764.3	.0502	.4817	.0000	430.75	36.45
67.6	3.00	1013.6	560.7	779.9	.0498	.4766	.0000	430.73	37.12
68.1	3.02	1020.8	579.3	795.2	.0493	.4714	.0000	430.70	37.81
68.5	3.04	1028.1	597.5	810.1	.0488	.4661	.0000	430.69	38.51
69.0	3.06	1035.0	615.6	827.4	.0483	.4608	.0000	430.65	39.20
69.4	3.08	1041.3	633.5	840.3	.0477	.4556	.0000	430.60	39.90
69.9	3.10	1048.0	651.3	855.3	.0472	.4503	.0000	430.57	40.59
70.4	3.12	1054.4	669.3	870.2	.0466	.4450	.0000	430.53	41.29
70.8	3.14	1060.8	688.0	884.6	.0461	.4396	.0000	430.51	42.01
71.3	3.16	1067.2	707.9	901.1	.0456	.4342	.0000	430.49	42.72
71.7	3.18	1073.3	729.9	915.8	.0451	.4288	.0000	430.46	43.43
72.2	3.20	1079.1	754.7	930.1	.0445	.4234	.0000	430.42	44.14

ZONE: PH
SOLIDS LINEAR VELOCITY/ (in/min) = 270.73

Z/ ft	t/ min	T-Bed/ F (Ave)	T-Layer/ F (Out)	T-Air/ F (Out)	X-Flux (Ave)	X-Fe3O4 (Ave)	X-H2O (Ave)	Solids/ LT/hr	C-Fe3O4 % cnvrsn
73.3	3.25	1090.7	790.9	924.9	.0432	.4145	.0000	430.26	45.32
74.4	3.30	1102.0	819.3	949.6	.0419	.4059	.0000	430.11	46.45
75.5	3.35	1113.3	850.5	966.9	.0407	.3979	.0000	429.96	47.51
76.7	3.40	1123.8	882.6	989.7	.0395	.3902	.0000	429.81	48.52
77.8	3.45	1133.9	914.1	1010.5	.0382	.3830	.0000	429.65	49.48
78.9	3.50	1143.9	941.6	1027.8	.0369	.3760	.0000	429.47	50.40
80.0	3.55	1153.0	966.0	1043.8	.0356	.3693	.0000	429.27	51.28
81.1	3.60	1161.8	988.0	1058.2	.0341	.3628	.0000	429.06	52.14
82.2	3.65	1170.8	1007.7	1071.4	.0327	.3565	.0000	428.84	52.97
83.4	3.69	1179.0	1025.6	1083.8	.0313	.3504	.0000	428.61	53.77
84.5	3.74	1187.9	1041.8	1094.9	.0298	.3445	.0000	428.38	54.56
85.6	3.79	1195.8	1056.6	1105.8	.0283	.3387	.0000	428.14	55.32
86.7	3.84	1204.6	1071.2	1115.5	.0269	.3330	.0000	427.91	56.06
87.8	3.89	1212.3	1085.4	1124.8	.0255	.3275	.0000	427.68	56.79
88.9	3.94	1219.9	1098.1	1133.5	.0241	.3221	.0000	427.45	57.50
90.1	3.99	1227.5	1109.5	1141.4	.0227	.3168	.0000	427.23	58.20
91.2	4.04	1235.0	1119.7	1148.6	.0214	.3117	.0000	427.01	58.88
92.3	4.09	1242.5	1128.9	1155.3	.0201	.3066	.0000	426.81	59.55
93.4	4.14	1250.0	1137.1	1161.5	.0188	.3016	.0000	426.61	60.21
94.5	4.19	1257.6	1144.5	1167.2	.0176	.2967	.0000	426.42	60.85
95.6	4.24	1265.1	1151.2	1172.7	.0165	.2919	.0000	426.24	61.49
96.8	4.29	1272.7	1157.3	1177.8	.0154	.2872	.0000	426.06	62.11
97.9	4.34	1280.3	1162.9	1182.7	.0143	.2826	.0000	425.90	62.72
99.0	4.39	1288.0	1168.1	1187.5	.0133	.2780	.0000	425.74	63.32
100.1	4.44	1295.7	1173.0	1192.2	.0123	.2736	.0000	425.59	63.91
101.2	4.49	1303.5	1177.6	1196.8	.0113	.2691	.0000	425.45	64.49
102.3	4.54	1311.3	1182.0	1201.5	.0105	.2648	.0000	425.32	65.07
103.4	4.59	1319.2	1186.3	1206.1	.0096	.2605	.0000	425.20	65.63
104.6	4.63	1327.2	1190.5	1210.8	.0088	.2563	.0000	425.08	66.18
105.7	4.68	1335.2	1194.7	1215.6	.0080	.2522	.0000	424.98	66.73
106.8	4.73	1343.2	1198.9	1220.6	.0073	.2481	.0000	424.88	67.27
107.9	4.78	1351.3	1203.1	1225.6	.0066	.2441	.0000	424.79	67.80
109.0	4.83	1359.5	1207.5	1230.9	.0060	.2401	.0000	424.71	68.32
110.1	4.88	1367.6	1211.9	1236.3	.0054	.2362	.0000	424.64	68.84
111.3	4.93	1375.9	1216.5	1242.0	.0048	.2324	.0000	424.58	69.35
112.4	4.98	1384.1	1221.2	1247.9	.0043	.2286	.0000	424.52	69.85
113.5	5.03	1392.4	1226.2	1254.1	.0038	.2248	.0000	424.47	70.34
114.6	5.08	1400.6	1231.3	1260.5	.0033	.2211	.0000	424.43	70.83
115.7	5.13	1409.0	1236.7	1267.2	.0029	.2175	.0000	424.39	71.31
116.8	5.18	1417.2	1242.4	1274.2	.0025	.2139	.0000	424.37	71.79
118.0	5.23	1425.6	1248.3	1281.6	.0022	.2103	.0000	424.35	72.25
119.1	5.28	1433.8	1254.6	1289.2	.0019	.2068	.0000	424.33	72.72
120.2	5.33	1442.1	1261.2	1297.2	.0016	.2034	.0000	424.33	73.17
121.3	5.38	1450.3	1268.2	1305.5	.0013	.2000	.0000	424.32	73.62
122.4	5.43	1458.4	1275.6	1314.2	.0011	.1966	.0000	424.33	74.06
123.5	5.48	1466.4	1283.4	1323.1	.0009	.1933	.0000	424.34	74.50
124.7	5.53	1474.3	1291.6	1332.5	.0007	.1900	.0000	424.35	74.94
125.8	5.57	1482.0	1300.2	1342.0	.0006	.1868	.0000	424.37	75.36
126.9	5.62	1489.7	1309.2	1352.0	.0005	.1836	.0000	424.39	75.78
128.0	5.67	1497.2	1318.6	1362.0	.0004	.1804	.0000	424.42	76.20

ZONE: KILN
SOLIDS LINEAR VELOCITY/ (in/min) = 70.154

Z/ ft	t/ min	T-Bed/ F (Ave)	T-Layer/ F (Core)	T-Air/ F (Free)	X-Flux (Ave)	X-Fe3O4 (Ave)	X-H2O (Ave)	Solids/ LT/hr	C-Fe3O4 % cnvrsn
130.6	6.12	1499.5	1496.1	2150.0	.0000	.1800	.0000	424.35	76.25
133.2	6.57	1503.2	1496.3	2161.0	.0000	.1796	.0000	424.36	76.31
135.9	7.02	1506.9	1496.7	2172.1	.0000	.1792	.0000	424.36	76.36
138.5	7.47	1510.8	1497.3	2183.2	.0000	.1788	.0000	424.37	76.42
141.1	7.91	1514.8	1498.0	2194.5	.0000	.1783	.0000	424.38	76.47
143.7	8.36	1519.0	1498.9	2205.8	.0000	.1779	.0000	424.38	76.53
146.3	8.81	1523.2	1499.9	2217.2	.0000	.1775	.0000	424.39	76.58
149.0	9.26	1527.6	1501.1	2228.7	.0000	.1771	.0000	424.40	76.64
151.6	9.71	1532.2	1502.4	2240.1	.0000	.1767	.0000	424.41	76.69
154.2	10.16	1536.9	1503.9	2251.6	.0000	.1762	.0000	424.41	76.75
156.8	10.60	1541.8	1505.5	2263.0	.0000	.1758	.0000	424.42	76.81
159.4	11.05	1546.9	1507.2	2274.3	.0000	.1754	.0000	424.43	76.86
162.1	11.50	1552.2	1509.1	2285.5	.0000	.1750	.0000	424.43	76.92
164.7	11.95	1557.8	1511.2	2296.5	.0000	.1745	.0000	424.44	76.98
167.3	12.40	1563.7	1513.4	2307.3	.0000	.1741	.0000	424.45	77.03
169.9	12.84	1569.8	1515.9	2317.8	.0000	.1737	.0000	424.45	77.09
172.5	13.29	1576.4	1518.4	2328.0	.0000	.1732	.0000	424.46	77.15
175.2	13.74	1583.3	1521.2	2337.6	.0000	.1728	.0000	424.47	77.21
177.8	14.19	1590.7	1524.2	2346.7	.0000	.1723	.0000	424.48	77.27
180.4	14.64	1598.7	1527.3	2355.1	.0000	.1719	.0000	424.48	77.33
183.0	15.08	1607.3	1530.8	2362.6	.0000	.1714	.0000	424.49	77.39
185.6	15.53	1616.7	1534.4	2369.0	.0000	.1709	.0000	424.50	77.45
188.3	15.98	1627.1	1538.4	2374.0	.0000	.1705	.0000	424.51	77.51
190.9	16.43	1638.7	1542.6	2377.4	.0000	.1700	.0000	424.51	77.57
193.5	16.88	1651.8	1547.3	2378.7	.0000	.1695	.0000	424.52	77.64
196.1	17.33	1666.8	1552.4	2377.4	.0000	.1690	.0000	424.53	77.70
198.7	17.77	1684.2	1557.9	2372.8	.0000	.1685	.0000	424.54	77.76
201.4	18.22	1705.1	1564.1	2363.9	.0000	.1680	.0000	424.55	77.83
204.0	18.67	1730.6	1571.1	2349.6	.0000	.1675	.0000	424.55	77.90
206.6	19.12	1763.0	1579.1	2327.9	.0000	.1670	.0000	424.56	77.96
209.2	19.57	1802.8	1588.5	2296.2	.0000	.1665	.0000	424.57	78.03
211.8	20.01	1841.8	1599.1	2297.2	.0000	.1660	.0000	424.58	78.10
214.5	20.46	1879.8	1610.9	2298.0	.0000	.1655	.0000	424.59	78.17
217.1	20.91	1916.5	1623.8	2298.6	.0000	.1650	.0000	424.60	78.23
219.7	21.36	1952.1	1637.6	2299.1	.0000	.1645	.0000	424.60	78.29
222.3	21.81	1986.3	1652.3	2299.4	.0000	.1641	.0000	424.61	78.36
224.9	22.26	2019.3	1667.8	2299.6	.0000	.1636	.0000	424.62	78.42
227.6	22.70	2050.8	1684.0	2299.6	.0000	.1632	.0000	424.63	78.48
230.2	23.15	2080.8	1700.8	2299.6	.0000	.1627	.0000	424.63	78.53
232.8	23.60	2109.3	1718.1	2299.4	.0000	.1623	.0000	424.64	78.59
235.4	24.05	2136.1	1735.8	2299.2	.0000	.1619	.0000	424.65	78.64
238.0	24.50	2161.0	1753.8	2298.9	.0000	.1615	.0000	424.65	78.69
240.7	24.94	2183.6	1772.1	2298.5	.0000	.1612	.0000	424.66	78.74
243.3	25.39	2203.5	1790.5	2298.1	.0000	.1608	.0000	424.66	78.78
245.9	25.84	2219.9	1808.8	2297.7	.0000	.1605	.0000	424.67	78.82
248.5	26.29	2232.2	1826.9	2297.3	.0000	.1602	.0000	424.67	78.86
251.1	26.74	2239.4	1844.6	2296.8	.0000	.1599	.0000	424.68	78.90
253.8	27.19	2241.3	1861.7	2296.5	.0000	.1597	.0000	424.68	78.94
256.4	27.63	2238.3	1878.0	2296.2	.0000	.1593	.0000	424.69	78.98
259.0	28.08	2231.8	1893.3	2296.0	.0000	.1590	.0000	424.69	79.02

*** KILN TEMPERATURE PROFILES ***

Z/ ft	Time/ min	T-Flame/ F	T-Air/ F	T-Bed/ F (Ave)	T-Mantle/ F	T-Core/ F	T-Wall/ F
2.6	.45	1865.3	2150.0	1499.5	1501.2	1496.1	1619.8
5.2	.90	1874.4	2161.0	1503.2	1506.6	1496.3	1628.3
7.9	1.34	1883.9	2172.1	1506.9	1512.1	1496.7	1637.0
10.5	1.79	1893.7	2183.2	1510.8	1517.6	1497.3	1646.1
13.1	2.24	1904.1	2194.5	1514.8	1523.3	1498.0	1655.6
15.7	2.69	1914.9	2205.8	1519.0	1529.1	1498.9	1665.5
18.3	3.14	1926.3	2217.2	1523.2	1535.0	1499.9	1675.9
21.0	3.59	1938.3	2228.7	1527.6	1541.0	1501.1	1686.8
23.6	4.03	1951.1	2240.1	1532.2	1547.2	1502.4	1698.3
26.2	4.48	1964.6	2251.6	1536.9	1553.6	1503.9	1710.5
28.8	4.93	1979.1	2263.0	1541.8	1560.2	1505.5	1723.5
31.4	5.38	1994.6	2274.3	1546.9	1567.0	1507.2	1737.4
34.1	5.83	2011.3	2285.5	1552.2	1574.1	1509.1	1752.4
36.7	6.27	2029.4	2296.5	1557.8	1581.4	1511.2	1768.5
39.3	6.72	2049.1	2307.3	1563.7	1589.1	1513.4	1786.1
41.9	7.17	2070.7	2317.8	1569.8	1597.2	1515.9	1805.3
44.5	7.62	2094.4	2328.0	1576.4	1605.8	1518.4	1826.4
47.2	8.07	2120.7	2337.6	1583.3	1614.8	1521.2	1849.9
49.8	8.51	2150.0	2346.7	1590.7	1624.5	1524.2	1876.1
52.4	8.96	2182.9	2355.1	1598.7	1634.9	1527.3	1905.7
55.0	9.41	2220.0	2362.6	1607.3	1646.2	1530.8	1939.3
57.6	9.86	2262.4	2369.0	1616.7	1658.5	1534.4	1977.7
60.3	10.31	2310.7	2374.0	1627.1	1672.2	1538.4	2022.0
62.9	10.76	2366.3	2377.4	1638.7	1687.5	1542.6	2073.4
65.5	11.20	2430.9	2378.7	1651.8	1704.8	1547.3	2133.9
68.1	11.65	2506.7	2377.4	1666.8	1724.8	1552.4	2205.9
70.7	12.10	2596.6	2372.8	1684.2	1748.2	1557.9	2292.7
73.4	12.55	2704.9	2363.9	1705.1	1776.3	1564.1	2399.3
76.0	13.00	2837.5	2349.6	1730.6	1811.0	1571.1	2532.7
78.6	13.44	3003.9	2327.9	1763.0	1855.4	1579.1	2704.6
81.2	13.89	3219.5	2296.2	1802.8	1909.9	1588.5	2820.2
83.8	14.34	3229.9	2297.2	1841.8	1962.4	1599.1	2820.9
86.5	14.79	3229.6	2298.0	1879.8	2012.5	1610.9	2821.5
89.1	15.24	3229.1	2298.6	1916.5	2060.2	1623.8	2822.0
91.7	15.69	3228.2	2299.1	1952.1	2105.6	1637.6	2822.3
94.3	16.13	3226.8	2299.4	1986.3	2148.6	1652.3	2822.0
96.9	16.58	3224.7	2299.6	2019.3	2189.2	1667.8	2821.0
99.6	17.03	3221.4	2299.6	2050.8	2227.6	1684.0	2818.8
102.2	17.48	3216.6	2299.6	2080.8	2263.5	1700.8	2815.1
104.8	17.93	3209.5	2299.4	2109.3	2297.0	1718.1	2809.1
107.4	18.37	3198.7	2299.2	2136.1	2327.9	1735.8	2799.5
110.0	18.82	3182.4	2298.9	2161.0	2356.0	1753.8	2784.6
112.7	19.27	3157.3	2298.5	2183.6	2380.7	1772.1	2761.7
115.3	19.72	3118.0	2298.1	2203.5	2401.4	1790.5	2726.5
117.9	20.17	3056.3	2297.7	2219.9	2417.1	1808.8	2673.6
120.5	20.62	2959.9	2297.3	2232.2	2426.8	1826.9	2596.6
123.1	21.06	2813.0	2296.8	2239.4	2429.2	1844.6	2492.4
125.8	21.51	2600.1	2296.5	2241.3	2423.9	1861.7	2367.4
128.4	21.96	2313.5	2296.2	2238.3	2411.8	1878.0	2242.0
131.0	22.41	1958.2	2296.0	2231.8	2395.1	1893.3	2141.5

*** BED-LAYER PROFILES:
TOP LAYER i=1 ; BOTTOM LAYER i=20 ***

END-ZONE: DD1

i	T-Air/ F	T-Layer/ F	X-Flux/ lb/lb	X-Fe3O4/ lb/lb	X-H2O/ lb/lb
1	840.1	884.1	.0505	.4186	.0000
2	853.9	898.2	.0512	.4422	.0000
3	867.3	909.6	.0514	.4680	.0000
4	878.7	914.7	.0510	.4950	.0000
5	886.1	909.7	.0493	.5245	.0000
6	888.7	896.6	.0515	.5575	.0000
7	882.7	864.1	.0512	.5971	.0000
8	865.2	809.8	.0529	.6477	.0000
9	837.6	750.1	.0624	.7126	.0000
10	800.3	681.2	.0666	.7491	.0000
11	757.9	621.6	.0682	.7567	.0000
12	710.5	555.9	.0688	.7579	.0000
13	656.6	478.6	.0690	.7580	.0000
14	594.7	386.6	.0690	.7580	.0000
15	522.8	276.7	.0690	.7580	.0000
16	437.9	139.4	.0690	.7580	.0000
17	372.7	135.3	.0690	.7580	.0210
18	323.6	134.8	.0690	.7580	.0373
19	285.9	134.3	.0690	.7580	.0500
20	256.5	133.9	.0690	.7580	.0600

END-ZONE: DD2

i	T-Air/ F	T-Layer/ F	X-Flux/ lb/lb	X-Fe3O4/ lb/lb	X-H2O/ lb/lb
1	1172.3	1164.3	.0350	.2623	.0000
2	1169.5	1161.0	.0366	.2753	.0000
3	1166.6	1157.8	.0375	.2886	.0000
4	1163.8	1155.2	.0379	.3016	.0000
5	1161.2	1153.3	.0372	.3145	.0000
6	1158.6	1150.7	.0395	.3275	.0000
7	1156.2	1148.7	.0400	.3408	.0000
8	1153.8	1146.5	.0406	.3547	.0000
9	1151.3	1143.5	.0423	.3689	.0000
10	1148.4	1139.5	.0435	.3844	.0000
11	1144.8	1133.7	.0448	.4015	.0000
12	1139.9	1125.1	.0450	.4201	.0000
13	1133.1	1112.0	.0475	.4406	.0000
14	1123.2	1092.7	.0461	.4632	.0000
15	1109.4	1067.1	.0501	.4885	.0000
16	1090.8	1033.5	.0494	.5174	.0000
17	1064.6	983.2	.0471	.5514	.0000
18	1031.0	926.6	.0509	.5930	.0000
19	986.3	845.7	.0549	.6491	.0000
20	930.1	754.7	.0651	.7244	.0000

END-ZONE: PH

i	T-Air/ F	T-Layer/ F	X-Flux/ lb/lb	X-Fe3O4/ lb/lb	X-H2O/ lb/lb
1	1592.7	1602.5	.0000	.1060	.0000
2	1596.6	1604.5	.0000	.1131	.0000
3	1599.3	1604.8	.0000	.1204	.0000
4	1600.5	1602.9	.0000	.1274	.0000
5	1599.8	1598.4	.0000	.1345	.0000
6	1596.9	1591.0	.0000	.1414	.0000
7	1591.7	1580.9	.0000	.1486	.0000
8	1584.0	1568.1	.0000	.1558	.0000
9	1573.8	1552.7	.0000	.1631	.0000
10	1561.1	1535.0	.0000	.1709	.0000
11	1546.2	1515.4	.0000	.1791	.0000
12	1529.4	1494.5	.0000	.1876	.0000
13	1510.8	1472.3	.0000	.1966	.0000
14	1490.9	1449.6	.0000	.2060	.0000
15	1469.9	1425.9	.0001	.2157	.0000
16	1448.2	1402.7	.0002	.2260	.0000
17	1426.4	1380.4	.0005	.2367	.0000
18	1404.1	1357.1	.0011	.2479	.0000
19	1382.4	1336.2	.0020	.2598	.0000
20	1362.0	1318.6	.0031	.2717	.0000

END-ZONE: KILN * NOT APPLICABLE *

*** GAS FLOW AND TEMPERATURE SUMMARY ***

TO BED	Volume Flow/ SCFM	Mass Flow/ lb/min	T/F
DD1	222133.9	17799.6	826.1
DD2	110478.1	8865.3	1181.8
PH	143414.7	11369.4	1588.2
KILN	76041.2	6101.9	2295.9

FROM ZONE	Volume Flow/ SCFM	Mass Flow/ lb/min	T/F
DD1	249930.5	19206.1	164.1
DD2	112973.7	9011.1	553.2
PH	155710.2	12469.6	1109.4
KILN	81992.8	6479.1	2038.0

*** OVERALL GAS PHASE MATERIAL BALANCE (SCFM) ***

	Secondary Air	.151E+06
+	Fuel/Prim Air	.818E+04
+	Net Leakage	.172E+06
+	CO2 (LOI)	.473E+04
+	H2O (Drying)	.309E+05
-	O2 (Oxidation)	.409E+04

TOTAL NET GAS IN = .363E+06

TOTAL NET GAS OUT = .363E+06

*** GAS COMPOSITION (%) ***

ZONE		CO2	H2O	O2	N2	CH4
DD1	(To Bed)	3.1	3.9	16.1	76.8	.0
	(From Zone)	3.0	14.6	14.1	68.3	.0
DD2	(To Bed)	.0	.4	20.9	78.7	.0
	(From Zone)	1.0	3.0	19.0	77.0	.0
PH	(To Bed)	2.8	5.8	14.9	76.5	.0
	(From Zone)	4.5	5.4	14.1	76.0	.0
KILN	(To Bed)	.0	.4	20.9	78.7	.0
	(From Zone)	3.5	7.3	13.2	76.0	.0

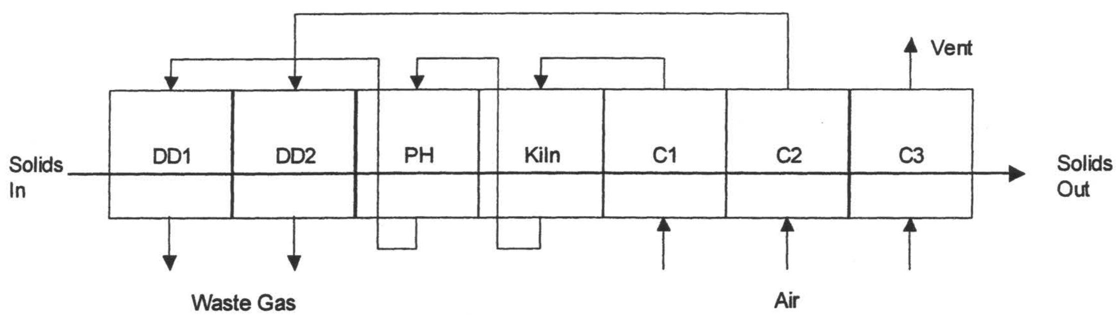


Figure 2.1. Block diagram of zone and gas distribution.

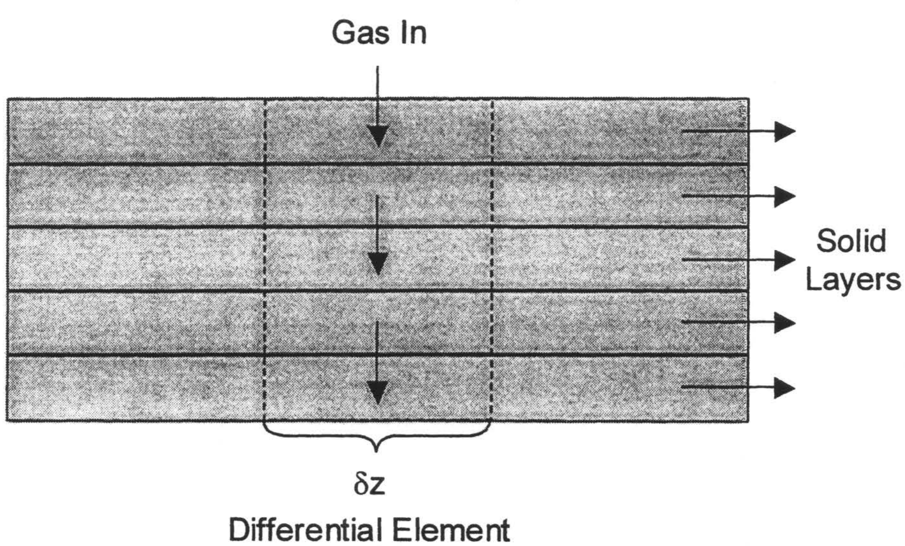


Figure 2.2. Diagram of solid layers in model of pellet bed.

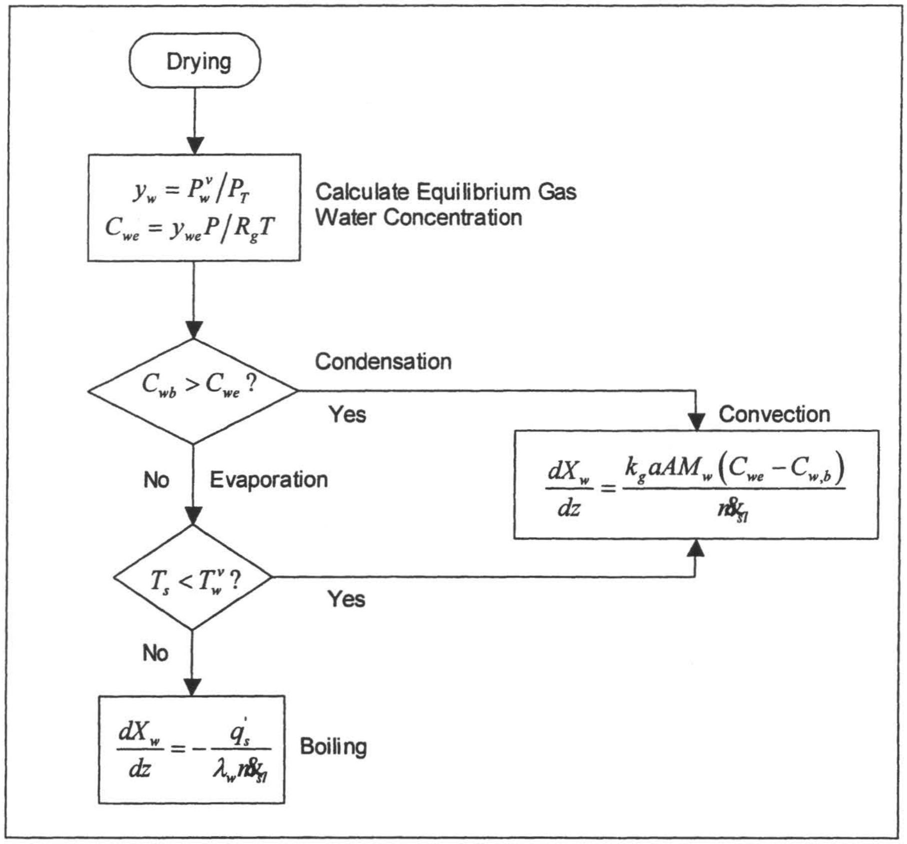


Figure 2.3. Drying algorithm

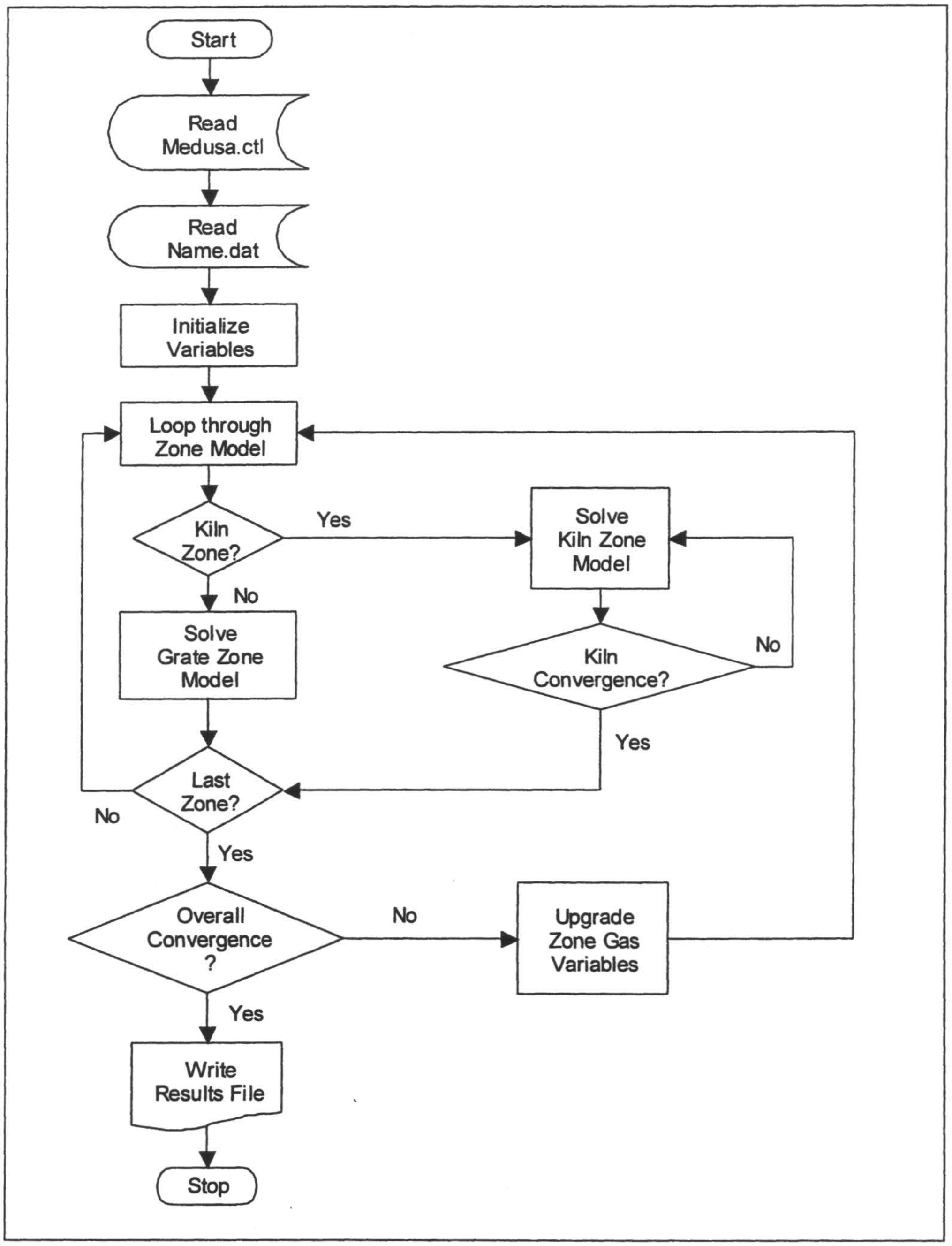


Figure 2.4. Medusa model solution algorithm.

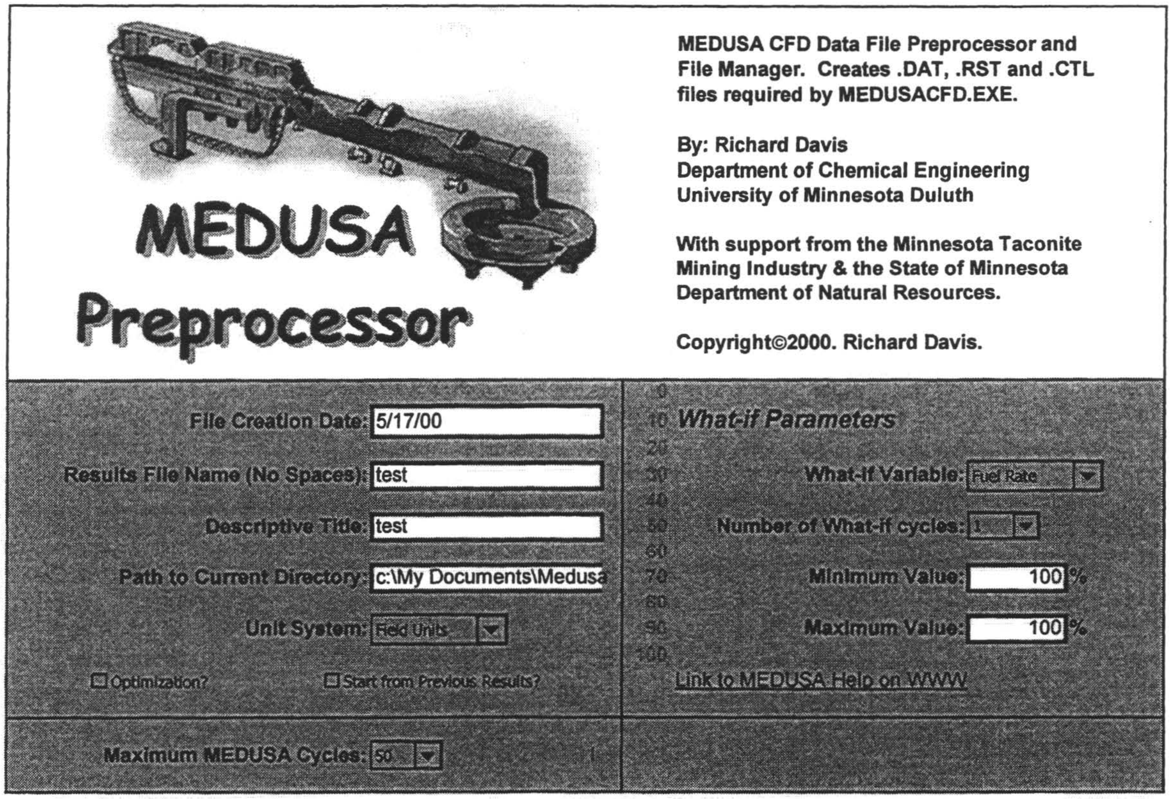


Figure 2.5. Graphical User Interface for Medusa: File Manager.

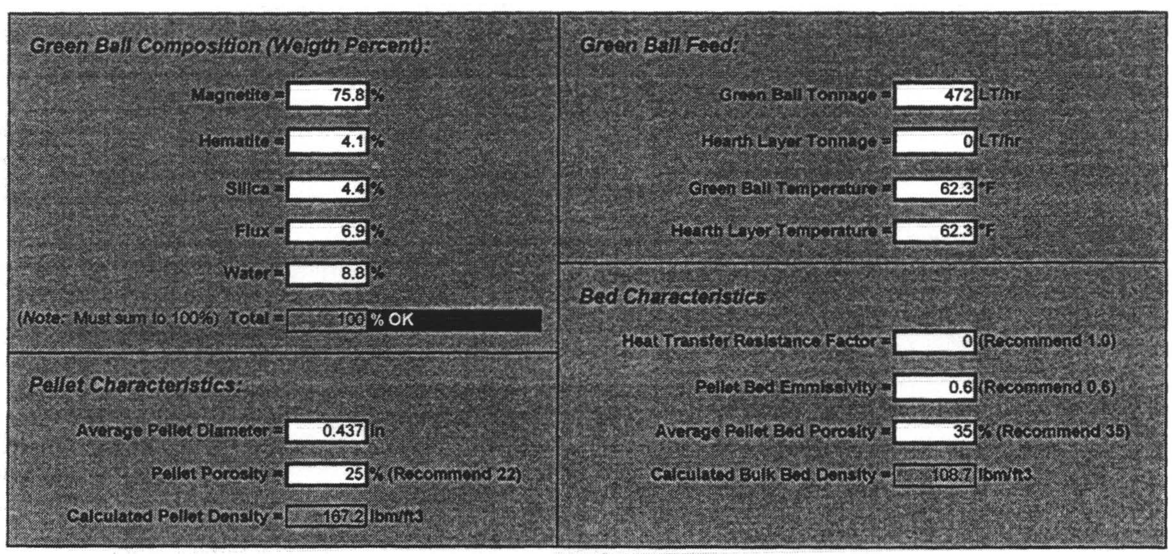


Figure 2.6. Graphical User Interface for Medusa: Pellet Bed.

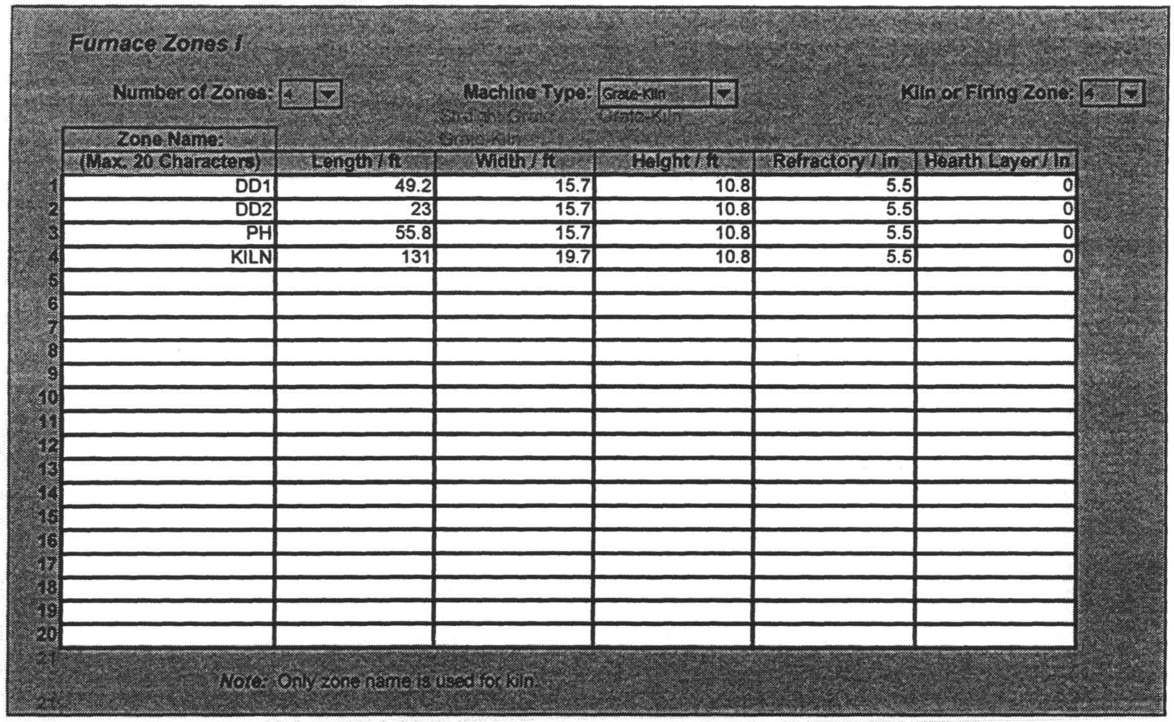


Figure 2.7. Graphical User Interface: Furnace Zones I.

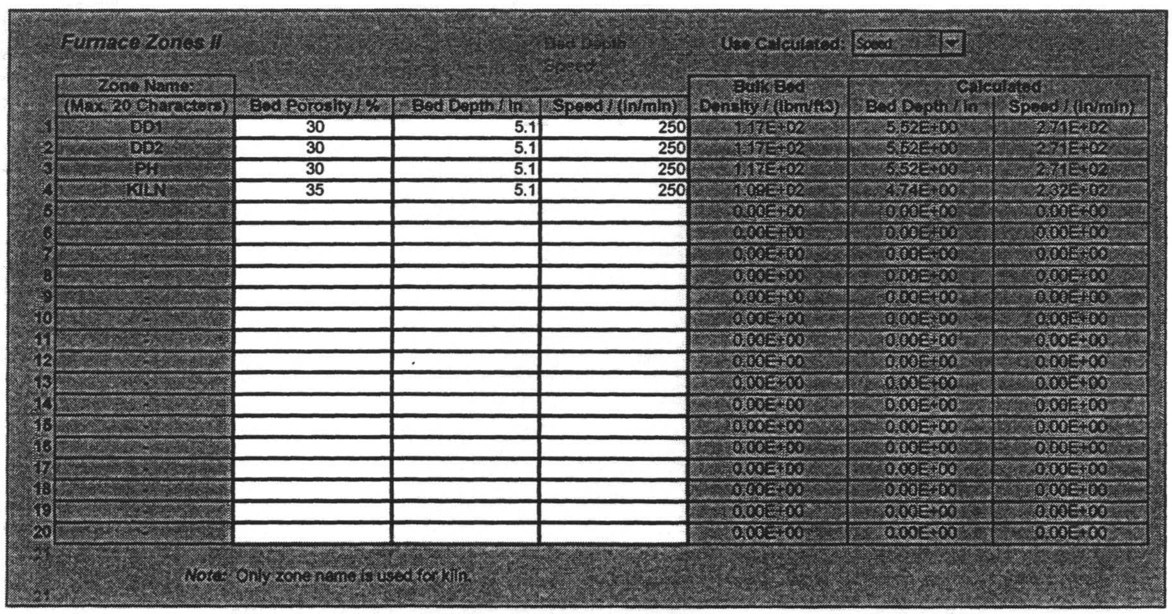


Figure 2.8. Graphical User Interface: Furnace Zones II.

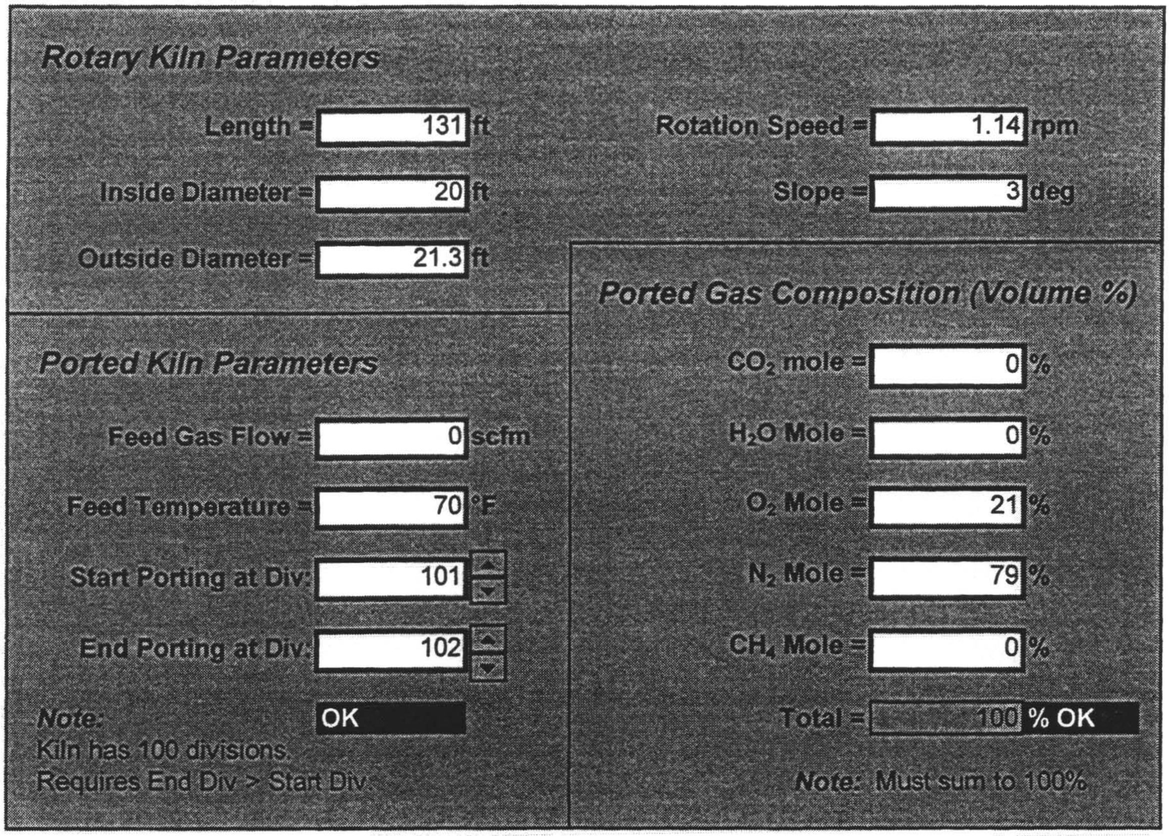


Figure 2.9. Graphical User Interface for Medusa: Rotary Kiln.

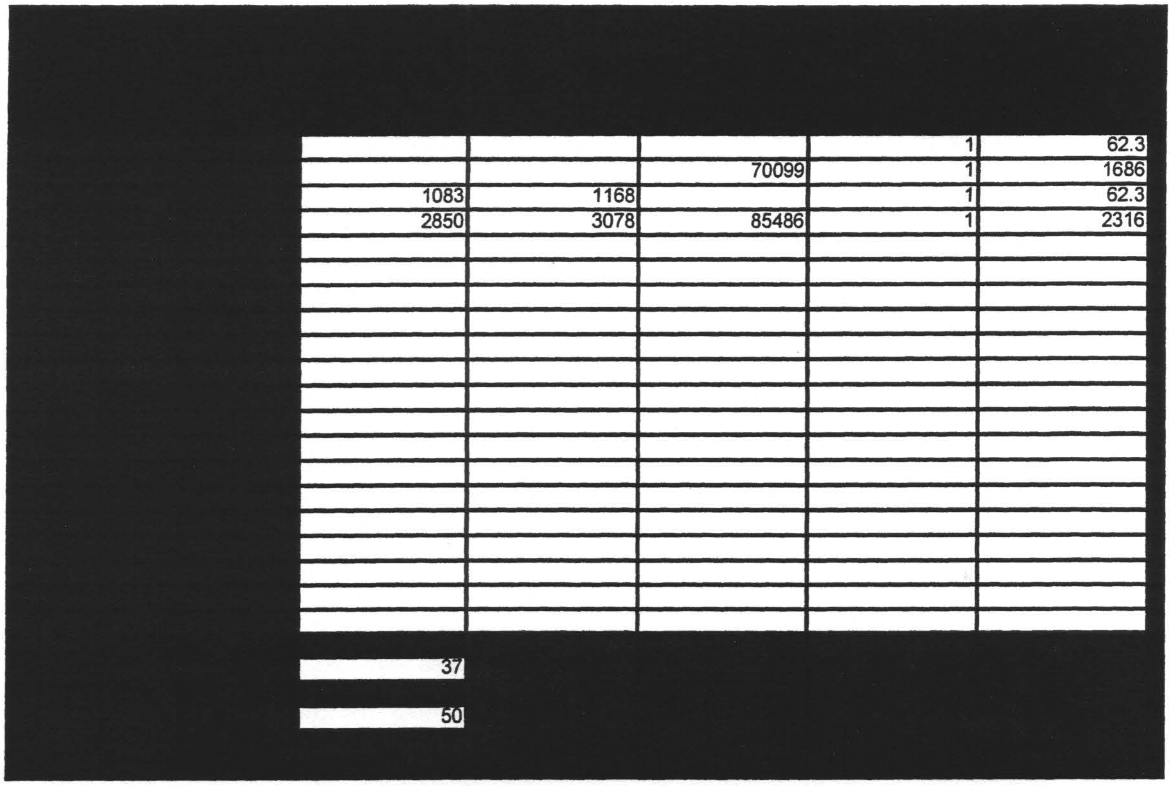


Figure 2.10. Graphical User Interface for Medusa: Process Gas.

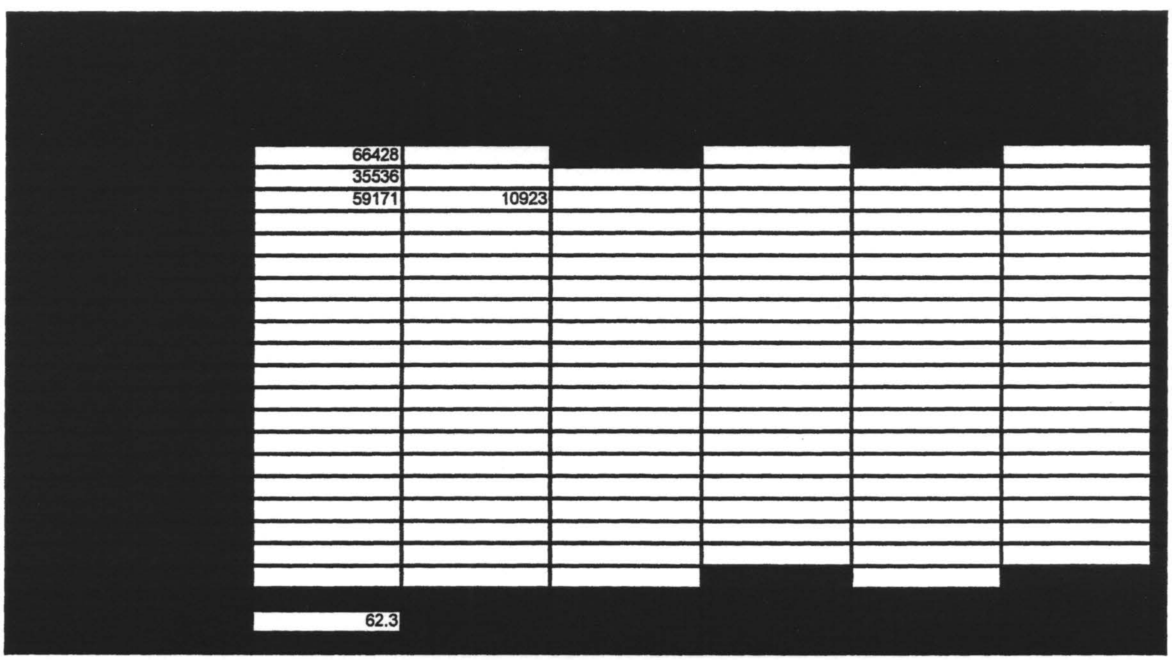


Figure 2.11. Graphical User Interface for Medusa: Leakage.

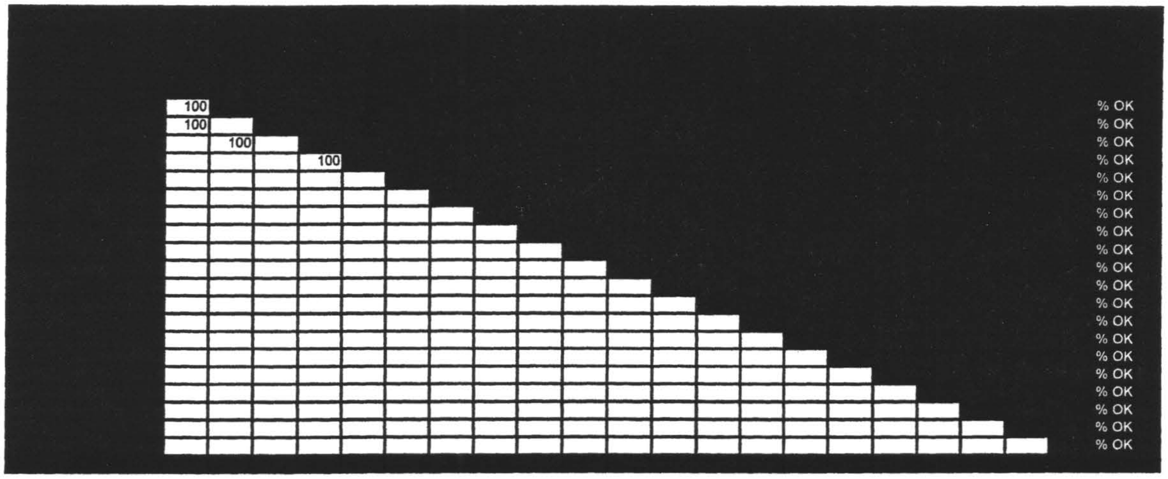


Figure 2.12. Graphical User Interface for Medusa: Gas Distribution.

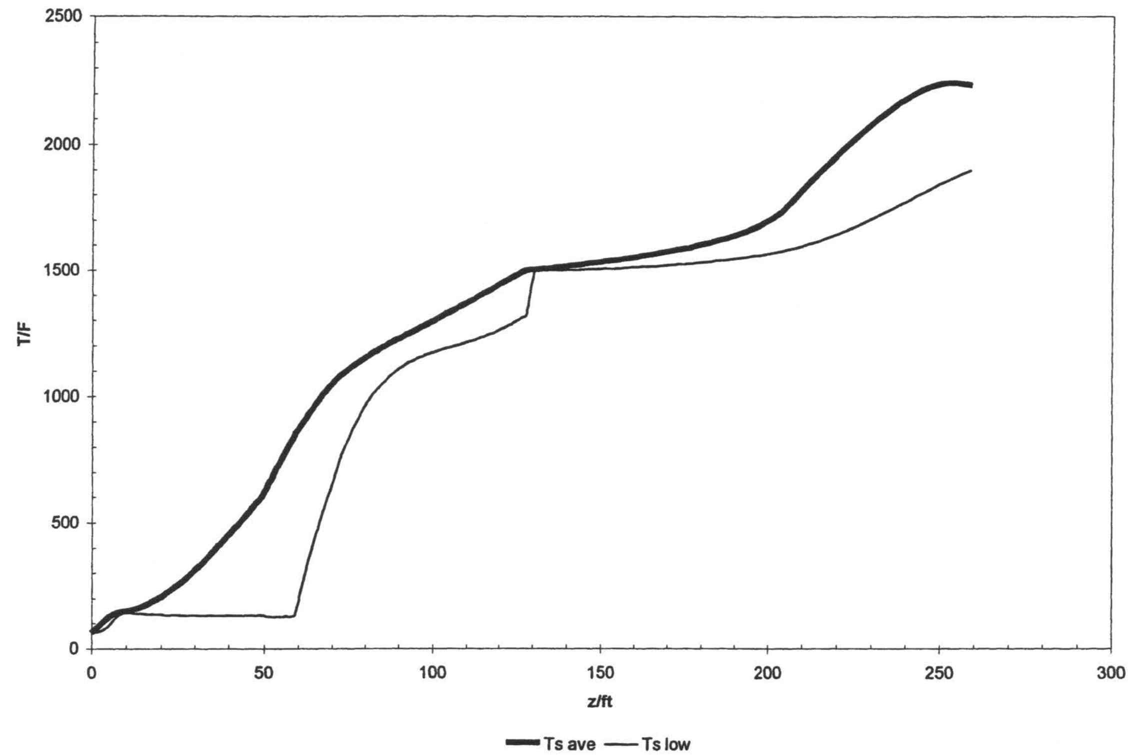
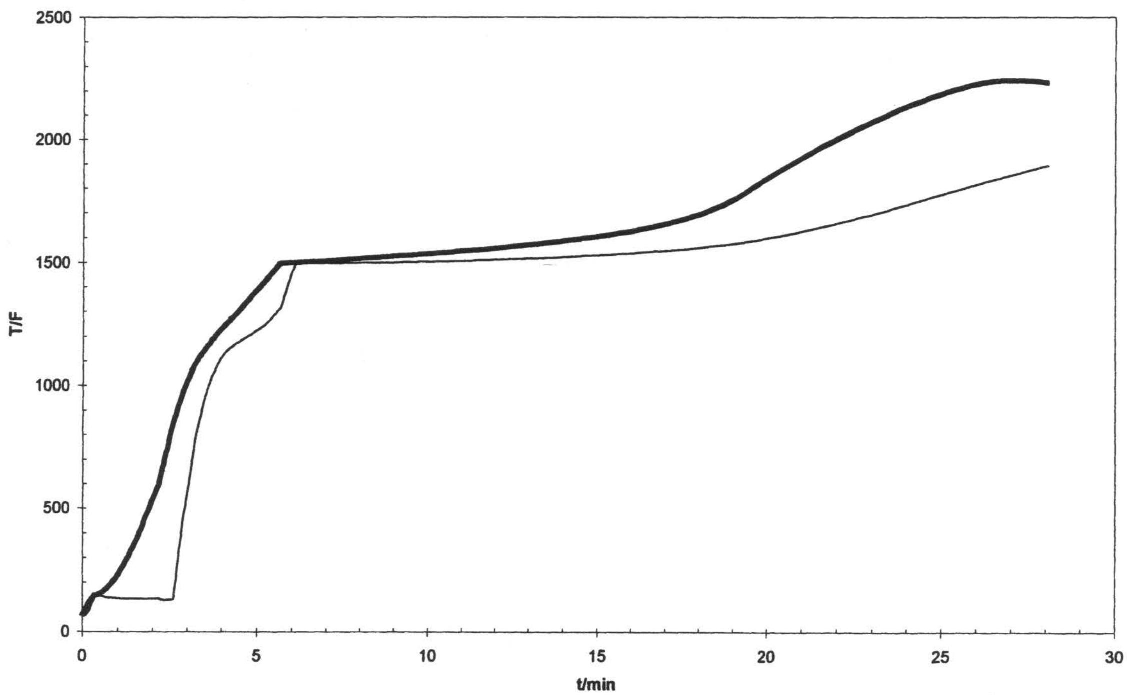


Figure 2.13. Solids temperature-position profiles.



[redacted]

Figure 2.14. Solids temperature-residence time profiles.

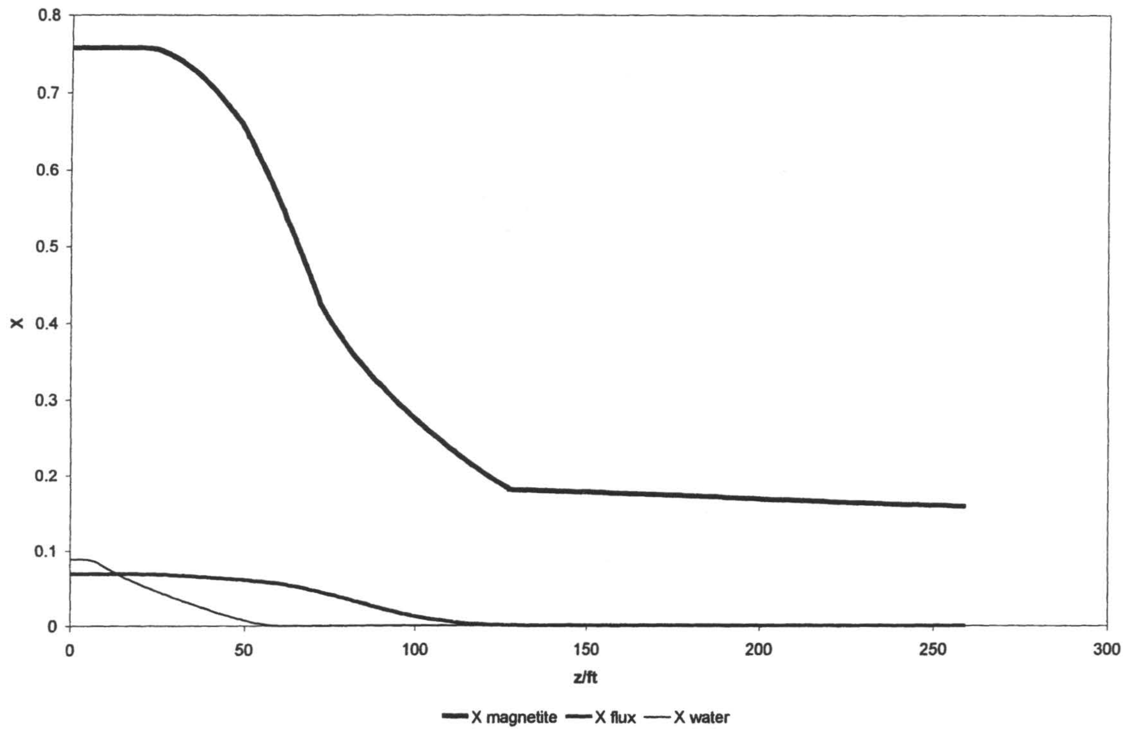


Figure 2.15. Average pellet composition profiles.

3 Model Validation and Process Analysis

Page No	Text Headings	Tables	Figures	Appendix
3-7	3.1 Introduction			
	3.1.1 Objectives			
3-8	3.1.2 Model Description			
	3.1.2.1 Simulation Units			I
	3.1.2.2 MEDUSA			
	3.1.2.3 CFD Cooler		1	
	3.1.2.3.1 Boundary Conditions			
3-9	3.1.2.3.2 Bed Pressure Drop Resistance		2, 3	
	3.1.2.4 MEDUSA/CFD Hybrid			
	3.1.2.5 Cooler Schematic			
3-10	3.2 Model Validation			
	3.2.1 Plant Tests		1	I
	3.2.1.1 Estimating Feed Rate		1	
	3.2.1.2 Thermocouples vs CFD Averages		2	
	3.2.1.3 Feed Variability			
3-11	3.2.1.4 Simulation Tuning - Variable Description		3	
	3.2.1.4.1 Magnetite Entering Cooler			
	3.2.1.4.2 Pellet Feed Rate to Cooler			
	3.2.1.4.3 Kiln Solids Discharge Temperature			
	3.2.1.4.4 Cooler Wind Box Leakage			
	3.2.1.4.5 Wind Box Damper			
	3.2.2 MEDUSA File Input/Output			
3-12	3.2.3 Section Summary			
	3.2.4 CFD Cooler Model Validation - Test by Test Comparison			
	3.2.4.1 Cooler Feed Rate		4	
	3.2.4.2 Kiln Discharge Solids Temperature		5	
3-13	3.2.4.3 Primary Cooling Overbed Pressure		6, 7	
	3.2.4.4 Primary Cooling Wind Box Pressure		8	
	3.2.4.5 Kiln Secondary Air Temperature	6	9, 10	
	3.2.4.6 Secondary Cooling Overbed Pressure		11	
3-14	3.2.4.7 Secondary Cooling Wind Box Pressure		12	

3 Model Validation and Process Analysis

Page No	Text Headings	Tables	Figures	Appendix
	3.2.4.8 Recoup Duct Temperatures	2	13-18	
	3.2.4.8.1 Recoup A Duct Thermocouple Traverse	7	17	
	3.2.4.8.2 Averaged Recoup Temperature vs DD2 Overbed		18	
3-15	3.2.4.9 Recoup Duct Flows		19, 20	
	3.2.4.10 Cooler Vent Stack Flow and Temperature		21, 22	
	3.2.5 CFD Cooler Model Validation - Common Test Trends			
	3.2.5.1 Cooler Fan Inlet Flows		23, 24	
	3.2.5.2 Cooler Vent Stack Flow		25	
3-16	3.2.5.3 Kiln Secondary Air Temperature		26	
	3.2.5.4 Recoup Temperature vs Primary Cooling Fan Flow		27, 28	
	3.2.5.5 Recoup Temperature vs Secondary Cooling Fan Flow		29-31	
	3.2.5.6 Cooler Overbed Pressure vs Cooler Fan Flow		32, 33	
	3.2.5.7 Preheat Overbed Pressure vs Primary Cooling Overbed Pressure		34	
3-17	3.2.5.8 Kiln Flow vs Primary Cooling Fan Flow		35	
	3.2.5.9 Section Summary			
	3.2.6 MEDUSA Validation	4		
	3.2.6.1 Convergence Criteria	5		
3-18	3.2.6.1.1 Target Temperatures		36-39	
	3.2.6.1.2 Feed Rate Comparison		40	
	3.2.6.2 Section Summary			
3-19	3.3 CFD Cooler Model - Parametric Series	8,9	41	
	3.3.1 Cooler Variables and Experimental Design			
	3.3.2 Cooler Fan Flow Series	10	42-48	
3-20	3.3.3 First Parametric Series - Mixed Cooler Physical Layouts	10		
	3.3.4 Second Parametric Series - Current Cooler Baseline	11		
	3.3.4.1 Linear Regression - Variable Abbreviations		49	

3 Model Validation and Process Analysis

Page No	Text Headings	Tables	Figures	Appendix
3-21	3.3.4.2 Linear Regression - Prediction Profiles		49,79	
3-22	3.3.4.3 Current Cooler Operating Window			
3-23	3.3.4.3.1 Vent Stack Temperature vs Pellet Exit Temperature		50	
	3.3.4.3.2 Operating Variable Constraints		51	
	3.3.4.3.3 Effect of Feed Rate on Operating Window		52	
3-24	3.3.6 Third Parametric Series - Cooler with Overbed Dividing Wall	12	53	
	3.3.6.1 Vent Stack Temperature vs Pellet Exit Temperature		54	
	3.3.6.2 Operating Variable Constraints		55	
	3.3.6.3 Effect of Feed Rate		56	
	3.3.7 Section Summary			
3-25	3.4 MEDUSA/CFD Hybrid Simulations			
	3.4.1 Target Constraints			
	3.4.2 Flow Conditions	13,14		
	3.4.3 Target Temperature vs Simulation Results Temperature		57-59	
	3.4.4 Feed Rate and Fuel Consumption Response Surfaces	13,14	60-63	
3-26	3.4.5 Current Cooler vs Cooler with Wall Comparison		60,61	
	3.4.5.1 Cooler Flow vs System Feed Rate and Fuel Consumption		60-63	
	3.4.5.2 Preheat and Recoup Flow vs System Feed Rate and Fuel Consumption		62,63	
3-27	3.4.5.3 Least Squares Model Fitting Analysis		64-69	II
	3.4.6 Section Summary			
3-28	3.5 Plant Validation Tests			
	3.5.1 Project Review - Test Criteria			
	3.5.2 Test Data Manipulation		70-77	
	3.5.3 Plant Cooler Flow vs Operating Window		78-80	
3-29	3.5.4 Unedited Data Observations		81-86	
	3.5.4.1 Process Fan Damper Position		87-92	
3-30	3.5.4.2 Process Fan Power vs Fan Damper Position		93,94	

3 Model Validation and Process Analysis

Page No	Text Headings	Tables	Figures	Appendix
	3.5.4.3 Process Fan Power vs Recoup Flow		95-100	
	3.5.4.4 Recoup A Flow vs Average Recoup Temperature		101-106	
3-31	3.5.4.5 Cooler Outlet Stream Temperature Oscillations		107-112	
	3.5.5 Section Summary			
	3.6 Edited Plant Data			
	3.6.1 General Statistics			
	3.6.1.1 Estimated Feed Rate		113	
3-32	3.6.1.2 DD1 and DD2 Overbed Temperatures		114	
	3.6.1.3 DD1 and DD2 Overbed Pressures		115	
	3.6.1.4 Preheat Fan - Damper Control Thermocouples		116	
	3.6.1.5 Recoup A Duct Flow and Temperature		117	
	3.6.1.6 Average Recoup Temperature		118	
	3.6.1.7 Waste Gas Fan and Primary Cooling Fan Flows		119	
3-33	3.6.1.8 Secondary Cooling Fan Correction Factor and Cooling Fan Inlet Temperatures		120	
	3.6.1.8.1 Secondary Cooling Fan - Indicated Flow and Corrected Flow		121	
	3.6.1.9 Process Fan Power		122-123	
	3.6.1.10 Cooler Vent Stack Flow and Temperature		124	
	3.6.2 Data Trends - XY Format			
3-34	3.6.2.1 Waste Gas Fan Power vs Waste Gas Fan Damper Waste Gas Fan Power vs Average Preheat Fan Power		125,126	
	3.6.2.2 DD1 Wind Box Pressure vs Waste Gas Fan Damper DD1 Wind Box Pressure vs Waste Gas Fan Power		127	
	3.6.2.3 DD1 Overbed Temperature vs Preheat Fan Inlet Temperature DD2 Overbed Temperature vs Average Recoup Temperature		128	
	3.6.2.4 DD1 Overbed Pressure vs Waste Gas Fan Power DD1 Overbed Pressure vs Average Preheat Fan Power		129,130	
	3.6.2.5 Recoup A Duct Flow vs Recoup A Duct Temperature Recoup A Duct Flow vs Average Preheat Fan Power		131	

3 Model Validation and Process Analysis

Page No	Text Headings	Tables	Figures	Appendix
3-35	3.6.2.6 Average Preheat Fan Power vs Preheat Fan Damper Total Preheat Fan Flow vs Preheat Fan Power		132	
	3.6.2.7 Preheat Overbed Pressure vs Average Preheat Fan Damper Preheat Overbed Pressure vs Average Preheat Fan Power		133-135	
	3.6.2.8 Primary Cooling Fan Flow vs Average Preheat Fan Power Primary Cooling Fan Flow vs Firing Hood Pressure		136,137	
	3.6.2.9 Kiln Exit Gas Temperature vs Cooler Flow to Kiln Kiln Discharge Solids Temperature vs Calculated Flow to Cooler		138	
3-36	3.6.2.10 Primary Cooling Fan Flow vs Primary Cooling Fan Power Secondary Cooling Fan Flow vs Secondary Cooling Fan Power		139,140	
	3.6.2.11 Recoup A Duct Flow vs Total Cooler Inlet Flow Recoup A Duct Temperature vs Total Cooler Inlet Flow		141,142	
	3.6.3 Section Summary			
	3.7 Plant Data Models			
	3.7.1 Description			
	3.7.2 Linear Regression - CFD Model Criteria		143-146	
3-37	3.7.2.1 Correlation Fit			
	3.7.2.2 Operating Window		80,147,148	
	3.7.3 Linear Regression - MEDUSA/CFD Hybrid			
3-38	3.7.3.1 Feed Rate and Fuel Consumption Response Surfaces		149	
	3.8 Comparison of Plant Data Model with CFD or MEDUSA/CFD Models			
	3.8.1 Description			
	3.8.2 Desirability Criteria			
	3.8.3 Secondary Cooling Overbed Pressure Correlations		78	
3-39	3.8.3.1 Secondary Cooling Overbed Pressure - CFD Current Cooler Series		49,150	
	3.8.3.2 Secondary Cooling Overbed Pressure - CFD Cooler with Wall Series		151	
	3.8.3.3 Secondary Cooling Overbed Pressure - Plant Data		152-154	

3 Model Validation and Process Analysis

Page No	Text Headings	Tables	Figures	Appendix
	3.8.4 Statistics and Prediction Profiles - Plant Data		155,156	
3-40	3.8.5 Statistics and Prediction Profiles - CFD Current Cooler Series		157,158	
	3.8.6 Statistics and Prediction Profiles - CFD Cooler with Wall Series		159,160	
3-41	3.8.7 Waste Gas Fan Operating Issues			
3-42	3.8.8 Comparison of Plant Model to CFD and Hybrid Models			
	3.8.8.1 Comparison with CFD Models			
	3.8.8.1.1 Primary Cooling Overbed Pressure vs Total Cooler Flow		161	
	3.8.8.1.2 Kiln Secondary Air Temperature vs Total Cooler Flow		162	
	3.8.8.1.3 Calculated Flow to Kiln vs Total Cooler Flow		163	
3-43	3.8.8.1.4 Total Recoup Flow vs Total Cooler Flow		164	
	3.8.8.1.5 Averaged Recoup Temperature vs Total Cooler Flow		165	
	3.8.8.1.6 Vent Stack Temperature vs Total Cooler Flow		166	
	3.8.8.1.7 Section Summary			
3-44	3.8.8.2 Comparison with Hybrid Model			
	3.8.8.2.1 Estimated Feed Rate vs Total Cooler Flow		167	
	3.8.8.2.2 Calculated Flow to Kiln vs Total Cooler Flow		168	
	3.8.8.2.3 Fuel Consumption vs Total Cooler Flow		169	
	3.8.8.2.4 Section Summary			
3-45	3.9 Conclusions			
	3.9.1 General			
	3.9.2 Specific to Minntac Line 6			
3-46	3.10 Recommendations			
	3.10.1 General			
	3.10.2 Specific to Minntac Line 6			

3.1 Introduction

3.1.1 Objectives: This report documents the work of a two-year collaborative effort between USX-Minntac, UMD-Chemical Engineering and NRRI-CMRL. The goals of this research were twofold:

1. Develop numerical models of existing taconite induration operations.
2. Demonstrate the use of these models for process analysis and optimization.

There were four main objectives to be accomplished in successfully completing this project:

1. Install mass flow meters on Minntac Line 6 and collect operating data to validate the models.
2. Develop and validate an overall material and energy balance model called MEDUSA.
3. Develop and validate a Computational Fluid Dynamics (CFD) model of the Line 6 cooler.
4. Perform an analysis of Line 6 using these models and, if possible, propose operating changes.

This section of the report documents:

1. Initial validation of the MEDUSA and CFD models.
2. The method of analysis using the models.
3. A comparison of model predictions with plant data.
4. Trends found in the plant data collected.
5. Conclusions from the analysis.
6. Recommendations for process improvements to Minntac Line 6.

The CFD model of the cooler provided air flow and temperature information for the MEDUSA model. Ultimately, the CFD results were quantified as linear equations capable of predicting cooler outflows to the kiln, recoup duct and vent stack, based on cooler fan inlet flows. These equations were subsequently inserted into MEDUSA, allowing the user to specify only cooler fan flows, thus avoiding the task of estimating air flow splits in the cooler.

3.1.2 Model Descriptions:

3.1.2.1 Simulation Units: The reader will find both SI and English units used in this report. CFD simulations are always carried out using SI units; appropriate conversions were made to English units for comparison with plant operating data. The earlier versions of MEDUSA required SI units for direct file input, and, as a result, the tables summarizing that work appear in original format.

3.1.2.2 MEDUSA: See section two for a description of this model.

3.1.2.3 CFD Cooler: AEA Technologies Tascflow software was used to construct the model. The model is illustrated in Figure 1. It includes the kiln secondary air duct, the double vent stack system and approximately one-third of the double recoup duct assembly. The model contains 358,000 cells and requires 11-14 hours to converge, using an SGI 320 workstation, with dual P-III 500 Mhz chips and 1 GB of memory. The simulations are performed serially, but this workstation is equipped to run one simulation on each processor. Tascflow allows attachment of grids at specified interfaces, eliminating the requirement of multi-block propagation across these interfaces. The main grid consists of the cooler assembly. The attached fan inlet ducts, recoup ducts, vent stacks and kiln secondary air duct, also referred to as the parallel flow duct, are then attached to this grid. One advantage of Tascflow software is the relative ease with which grid attachments can be detached, moved and reattached. This allows ducts to be moved and evaluated, without having to re-block the grid.

3.1.2.3.1 Boundary Conditions: The boundary conditions specified for the cooler model consisted of:

3A fan mass flow	10,000 - 17,000 lbs/min
3B fan mass flow	10,000 - 17,000 lbs/min
Cooler fan inlet temperature	5 - 40°F
Cooler bed depth	28 inches
Cooler bed porosity	35% voids
Cooler bed bulk density	125.3 lbs/ft^3
Incoming magnetite in pellets	16-28%wt (Fe^{++} = 4.6 - 6.9%)
Incoming pellet temperature	2268°F
Incoming pellet rate (based on feed to grate)	450 - 520 WLTPH grate feed
A total green ball magnetite content	87%wt

Pressures were specified at cooler outlets based on plant measurements. They were:

Kiln firing hood opening	-0.73 in.H_2O (not measured)
Kiln secondary air outlet to kiln	-0.40 in.H_2O (not measured)

Recoup A Duct	-0.9 to -1.1 in.H_2O
Recoup B Duct	-1.0 to -1.3 in.H_2O

This model incorporates heat transfer and magnetite oxidation routines similar to those in the MEDUSA model to simulate heat transfer and oxidation in the cooler, based on actual fired pellet properties. Cooler speed is determined based on volumetric flow and density, and incorporated into the heat transfer equations, to simulate the effect of changes in production rate that occur in the plant. The CFD model was intended to function in a way similar to the plant cooler.

3.1.2.3.2 Bed Pressure Drop Resistance: A resistance term was determined empirically in the model to match bed pressure drop in the model with values measured in the plant during the initial validation tests. This method compared primary and secondary cooling pressures above and below the bed with CFD simulation values at corresponding locations in the grid. The factor value used was 545. Constant values as low as 480 or as high as 575 yielded pressures within the plant operating range. Once established, this factor was not changed. It represents a best fit between actual flow and estimated system leakages, production rate and bed permeability. Figure 2 shows the furnace-kiln-cooler layout, with flow and pressure sensor locations; Figure 3 provides additional cooler layout information.

It is recognized that pressures at cooler outlets vary depending on flow conditions in the process. For our purposes these pressures were maintained constant throughout the simulations, once acceptable values were established. The underlying assumption is that process fans (preheat and waste gas) will maintain these pressures. The study of outlet pressure as a variable is left as a subject for future research. The approach was to accept the mass flow measurements in the plant data as accurate and to base validation simulations on these values. Wind box leakage was determined by attempts to match the overall cooler outlet flows and temperatures. For this cooler, these leakages ranged 10 to 13% of the total input to the cooler; they were attributed to poor wind box seals. Location of the leakage was across the width of the cooler at the beginning of the primary cooling zone. In reality, this leakage occurs throughout the cooler. In an effort to keep the model analysis manageable, we did not want to test a large number of leakage variations, although this could be done at a later time.

3.1.2.4 MEDUSA/CFD Hybrid: In time, it became apparent that we could describe the CFD model results as linear equations derived from a parametric series of runs. These equations could predict the cooler outlet flows based on cooler boundary conditions. These equations were embedded into MEDUSA, so that cooler responses reflected the effects of magnetite content and feed rate, as they were optimized during the simulation. This procedure is described in detail in the MEDUSA report.

3.1.2.5 Cooler Schematic: Figure 41 shows the cooler grid with wind box numbers. Note that in the plant, numbering begins at location "A" in the figure, which is the kiln discharge point. Since this zone was not part of the model grid, numbering began at the first wind box in the model. Ducts, thermocouples and pressure sensors are also labeled. Figure 2 shows the overall furnace, kiln and cooler system, with flow sensor locations, and Figure 3 provides some additional information on the cooler layout.

3.2 Model Validation:

3.2.1 Plant Tests: Plant tests were performed on November 19, 1998; February 11, 1999; February 17, 1999; and April 19, 1999. These tests were of relatively short duration, ranging from 1 to 6 hours in length. The primary goal was to generate varied cooler operating conditions by changing 3A and 3B fan flows. Minntac personnel developed a computer program to log 91 control room readouts throughout the furnace, kiln and cooler. A list of these parameters is given in Appendix I. Table 1 briefly summarizes the dates, test times, production rates and fan settings. The data was collected and tabulated in spreadsheet form, from which averaged test conditions were generated. The actual plant data has not been provided in this report. Table 2 serves as a summary of the plant conditions and CFD simulations. It is organized chronologically.

Ideally, the plant tests should have spanned longer periods. We were continually plagued by daily upsets. These tests represent stable but short periods of operation. The long-term impact on furnace operation is clouded by the changes made to the cooler fans over these relatively short test periods. Since the first goal was to validate the cooler model, we opted to make changes in the fan flow and record the immediate results, hence the sequential times for the tests. Additional tests were conducted in February and March 2000 that spanned 24-48 hour periods of time. If feed rate remained relatively constant, we felt this approach was acceptable, since the changes in cooler airflow and temperature were essentially immediate.

3.2.1.1 Estimating Feed Rate: Estimating feed rate to the grate and ultimately the cooler is perhaps the largest single source of error. Feed rate continually cycles, and there are fluctuations in green ball moisture and pellet flux addition as well. Table 1 describes two methods used to fix feed rate for the simulations. Method one simply multiplies green ball production rate by a plant factor (0.77) to estimate production rate or feed to the cooler. Method two calculates a modified production factor by making the assumption that moisture, flux addition, and magnetite content are relatively constant and that fines removed at the grate roller feeder are variable. Method two produced plant production factor variations from 0.72 to 0.79, which appeared to yield a better fit in the simulation results than did method one.

3.2.1.2 Thermocouples vs CFD Averages: Another source for error between plant and simulation results from thermocouple readouts. The plant values given in Table 2 represent temperature at the thermocouple location. While CFD simulations can provide a corresponding point source value, averaged values at the duct outlets are reported, since these are needed in the MEDUSA runs. In Table 2, plant temperatures are provided on one row and CFD averages on the row below it in the simulation result column. For the November 19 simulations, a range of temperatures at the thermocouple location in the grid was also reported, as a check. This number was dropped from later simulations, as we found good correlation between the CFD averaged value and the plant thermocouple value.

3.2.1.3 Feed Variability: Finally, there are the fluctuations in pellet moisture, flux addition and pellet size distribution that are not recorded on-line. Our approach with these variables was to work with constant values for moisture (9.5%wt) and flux addition (8.0%wt) and let the deviations fall where they would. Bed permeability also remained constant, although if we had the means to estimate it from plant operation, we could have varied it as well.

3.2.1.4 Simulation Tuning - Variable Description: Table 3 provides a link between the results given in Table 2 and plotted in Figures 4-35. It provides the reader with an index of exploratory boundary conditions that were varied as we tuned the CFD model. The CFD boundary conditions given in Table 2 evolved with time. Some conditions were only used once, while others were repeated for several tests. We were faced with a large number of variable combinations that could be used to alter the CFD results. Because there were limitations in the plant data collected, changing these parameters became somewhat subjective. The goal was to introduce as few variations as possible before evaluating the fit with plant tests. The conditions that were varied included:

3.2.1.4.1 Magnetite Entering Cooler: The pellet ferrous iron content was not measured for the plant tests. The range in ferrous iron was provided by Minntac, from plant sampling performed by Svedala in December, 1998. Ferrous iron ranged from 4.56 to 6.94%wt (18.9 to 28.8% wt magnetite). The CFD series ranged from 16 to 28% wt magnetite.

3.2.1.4.2 Pellet Feed Rate to Cooler: As previously mentioned, two methods of calculating feed rate to the cooler were evaluated. The first multiplied green ball production by a constant plant factor. The second modified this factor for variable plant recycle. Method two provided a better fit between the CFD simulations and the plant conditions.

3.2.1.4.3 Kiln Solids Discharge Temperature: Plant instrumentation provided a pellet surface temperature on the bed, about 15 feet upstream from the discharge point. This temperature ranged from 2252 to 2284°F. Two temperatures (2200 and 2250°F) were evaluated in the simulations; 2250°F was chosen as it was closer to the plant value.

3.2.1.4.4 Cooler Wind Box Leakage: A one-inch gap across the width of the cooler was initially used to allow wind box leakage out of the cooler in the primary cooling zone. As the simulations progressed, it was clear that down stream outlet temperatures were cold relative to the plant data, and that the primary cooling wind box pressure was too high in the simulations. This gap was ultimately increased to 3.6 inches. This leakage was taken as a point source in these simulations, however, it is more likely that it accumulates throughout the cooler.

3.2.1.4.5 Wind Box Damper: Line 6 has a movable damper installed in the wind box separating primary cooling flow from secondary cooling flow. Only one plant test was performed with the damper open, after which Minntac personnel decided to keep it closed. In the CFD model we also simulated leakage around the damper. Initially we used a 4.7-inch effective gap (across the wind box width), which was subsequently decreased to 1.7 inches. The criteria for estimating this gap was a comparison of both wind box pressures with the CFD results. The magnitude of this dimension is also influenced by bed pressure drop, and wind box leakage. It was meant to be a relative number and not absolute.

3.2.2 MEDUSA File Input/Output: Table 4 is organized in MEDUSA direct data input format; all units are SI. This table presents the base data conditions for each of the simulations.

The range in feed rate based on both methods of calculation is shown at the top. The bottom half of the table splits into two columns for each test by relative wind box leakage (low or high), which refers to the wind box gap given in Table 3 (1" or 3.6"). Target temperatures refer to the plant data for each test. Cooler inlet flows are taken from CFD simulations. Plant pressures are also presented for the furnace zones; leakages in MEDUSA were initially calculated using these pressures. Using the data as presented in Table 4, we continually adjusted leakages to hit target temperatures at the given feed rates, varying leakages from run to run. We eventually opted to follow a constant leakage basis, letting MEDUSA find the feed rate that balanced the target temperatures. Simulation results are not presented from Table 4.

Table 5 presents the final form for MEDUSA simulations. The basic inputs and target temperatures remain unchanged from Table 4. The production rates given on the last line of Table 5 are the end result of several attempts to hit target temperatures at each set of conditions. Furnace leakages remain constant for the runs given in Table 5. The reader is referred to the MEDUSA report for a detailed explanation of their calculation.

3.2.3 Validation Criteria Summary: We standardized boundary conditions when possible to keep the number of simulations manageable, without compromising simulation sensitivity or accuracy. The above parameters were used to develop a feel for the model in this phase. Leakages can be incorporated wherever they occur, but are variable, changing with maintenance policies and machine wear. The leakages remained constant in location and opening area once established. Magnetite content and feed rate were varied throughout the anticipated range to quantify their effects. In the April 1999 tests, pitot tube sampling of the recoup ducts indicated a difference in static pressure of 0.2 in.H_2O at the thermocouple locations between the two ducts. The recoup B duct averaged about 0.2 in.H_2O more negative than the recoup A duct. The April CFD simulations and the adjusted feed rate simulations take this difference into account, as do all the subsequent runs.

3.2.4 CFD Cooler Model Validation - Test by Test Comparison: The previous section provided general background regarding our validation phase and the criteria used to achieve it. We were faced with the task of limiting the number of possible variable combinations existing in the plant data. The discussion that follows will refer to plots generated from the data in Table 2. The reader is referred to Table 3 for a complete description of the variable levels used for each plotting symbol.

3.2.4.1 Cooler Feed Rate: Figure 4 compares feed rate calculation methods one and two. It can be seen that method two yields wider fluctuations in the cooler feed rate, and also shows more deviation in the April test series. If the plant scales are good indicators, then method two is more likely a better reflection of the feed entering the cooler. This method was used exclusively once the initial validation was completed.

3.2.4.2 Kiln Discharge Solids Temperature: Figure 5 shows the variation in temperature measured at the pellet surface approximately 15 feet from the kiln discharge. Two temperatures were tested in the simulations, 2200 and 2250°F. It was initially thought that the average pellet temperature within the bed would be lower, cooling as it neared the end of the kiln (basis for 2200). As the testing progressed, and down stream cooler temperatures appeared too cold, this temperature was raised to 2250°F. If we had not been faced with so many runs in our parametric series, we would have made this another boundary condition variable and evaluated a range of three temperatures: 2215, 2250, and 2285°F.

3.2.4.3 Primary Cooling Overbed Pressure: Figures 6 and 7 compare plant overbed pressures. In Figure 6 overbed pressures tended to compare slightly better for the simulations with lower wind box out leakage, although the simulations as a whole followed the pressure trends reasonably well. The feed rate, kiln discharge pellet temperature, magnetite content and wind box leakage all affected pressure, raising the pressure as solids temperature in the bed increased.

Figure 7 plots plant primary cooling overbed pressure vs itself on the y axis, and the CFD predicted value on the y axis vs the actual plant value on the x-axis. The comparison shows that the CFD predictions are approximately 0.07 in.H_2O more negative than the plant measurement. This is mentioned now for reference and is discussed again in section 3.3.4.3. The implication is that the pressure offset must be taken into account so that plant operation under predicted CFD conditions is possible.

3.2.4.4 Primary Cooling Wind Box Pressure: Figure 8 plots wind box pressure. The fit was adjusted by varying the cross zone leakage at the wind box damper and changing the effective size of the opening for out leakage. The subtle effects of temperature variation show up as increased pressures. For the April tests there is some deviation, which may be due to an increase in bed permeability. The CFD wind box pressures were higher and the overbed pressures lower for these tests, which may be an indication that permeability in the plant bed improved, generating a smaller pressure drop relative to the previous tests.

3.2.4.5 Kiln Secondary Air Temperature: Figure 9 compares plant secondary air temperature with simulated results. The CFD values were consistently hotter and showed significantly more variation with test conditions. This comparison is perhaps the worst of all parameters compared. However, this temperature is measured by a single thermocouple extending approximately 18 inches beyond refractory in a duct location that is approximately fifteen feet across. The CFD simulations showed significant temperature variation across this duct. The simulated value reported is a mass weighted average temperature in the duct outlet; the plant value is based on the thermocouple. Initially we considered point to point comparisons of temperature, but decided to compare the CFD cross section average with the plant data. The average duct outlet temperature was considered more reliable than a localized point value. Figure 10 illustrates the temperature variation in duct cross-section at this location; the thermocouple is shown at relative scale. Table 6 shows the results of a plant test of the Line 7 parallel flow duct, which is identical to Line 6. The maximum deviation was 36°F at 38 inches from the refractory wall. This temperature range is comparable to the variation near the thermocouple location shown in Figure 10.

3.2.4.6 Secondary Cooling Overbed Pressure: This data is plotted in Figure 11. All of the variations in simulation conditions gave good correlation with the plant data for this sensor, although the simulations using the adjusted feed rate were the best. Overall, the trends in the plant data were reflected in the simulations.

3.2.4.7 Secondary Cooling Wind Box Pressure: For this sensor, the simulations matched the overall trends, see Figure 12. The fit, however, was affected by the wind box leakage and damper cross zone leakage conditions. The primary cooling wind box pressure was usually greater than secondary cooling, thus the direction of leakage across the damper was usually into secondary cooling, which contributed to the secondary cooling zone pressure variations.

3.2.4.8 Recoup Duct Temperatures: Figures 13-18 compare averaged simulated recoup duct temperatures with plant thermocouple values. The reason for increased wind box out leakage and higher kiln solids discharge temperatures can be seen in Figures 13 and 14. At low wind box leakage levels, too much air appeared to be moving through the bed, resulting in low recoup temperatures. Temperatures were raised by increasing the amount of air leaking out of the primary cooling wind box. However, in the April tests, the simulated values greatly exceeded the plant values. When the feed rates were adjusted by method two, the recoup temperatures more closely matched the plant values.

Figures 15 and 16 illustrate the variation in temperature at the thermocouple location for CFD run 1_20_0800 (Nov. 1998 Run 1). The variation near the thermocouple (box region) is compared with the plant value in Table 2. In the A duct, this range is 1290 to 1390°F, vs 1348°F plant. In the B duct, the range is 1600 to 1625°F vs 1607°F plant. When the range in temperature near the thermocouple (box area) is compared to the duct cross section average, the A duct local thermocouple region was 10 to 110°F hotter (1290-1390 vs 1280 avg), while in the B duct, the local value was 20 to 50°F colder (1600-1625 vs 1650 avg). This implies that the A duct plant thermocouple reads a temperature hotter than the true average, while the B duct thermocouple reads a temperature actually colder than the true average.

3.2.4.8.1 Recoup A Duct Thermocouple Traverse: On February 5, Minntac personnel conducted a thermocouple traverse of the Recoup A duct; they were unable to get the probe into the B duct. The results of this traverse are found in Table 7. The temperatures range from 1195°F to 1285°F, the hottest region occurring near the middle of the duct. Figure 17 is from a simulation performed as part of the parametric series. Velocity vectors show the movement of gas in the plane of the traverse, and the hot spot in this run has rotated from a 2 o'clock position in Figure 15 to a 1 o'clock position in Figure 17. It is likely that the hot spot moves with operating conditions, given the rotation in the gas stream. Experience has shown that small changes in turbulence can affect the location at which the hot spot will occur. Thus, simulations and the plant correlate on the magnitude of the temperature gradient, but the exact locations can appear slightly different.

3.2.4.8.2 Averaged Recoup Temperature vs DD2 Overbed Temperature: Figure 18 plots the average recoup temperature vs the furnace DD2 overbed temperature. For the plant data, average recoup temperature is the numerical average of the two ducts, while the CFD average is a mass weighted average of the individual duct averages. There is a clear correlation between the plant recoup average and the plant DD2 zone value, although there is an approximate drop of 300°F in these tests. The CFD averages track very closely with the plant recoup average and follow the same trend with the DD2 zone value. The intent was to make sure that recoup temperatures tracked with furnace temperatures, which would be important when running MEDUSA.

3.2.4.9 Recoup Duct Flows: The recoup duct flow sensors were the last to be installed, and became operational for the April plant tests. The simulations indicated flow rates approximately 10 to 20% higher than reported by the instrumentation as shown in Figures 19 and 20. Several attempts were made to solicit information regarding the accuracy of these meters given the temperature gradients across them (100 - 300^{o}F). This information was never attained. However, the simulations did seem to pick up the trends in the tests. The accuracy and reliability of these sensors further degraded with time. The reader is referred to the Minntac report section for details.

3.2.4.10 Cooler Vent Stack Flow and Temperature: Figure 21 compares plant flow with the CFD simulations. The simulations tended to be more erratic than the plant sensor. Minntac personnel monitored this meter from time to time with pitot tube traverses; they consistently reported flows 20 to 30% lower than the sensor was indicating. Their flows were comparable to the simulated data. Figure 22 plots vent stack temperature vs averaged simulated temperature. While the sensitivity seems to vary in the simulations, they appear to track with the plant trends. Changing bed permeability may be a factor in some of these variations.

3.2.5 CFD Cooler Model Validation - Common Test Trends: In the last section, simulations and plant conditions were compared by test date. The following figures and comparisons use the same data (Table 2), but present the results in relation to another process variable. In these plots, the first test (Nov. 1998 Run 1 Open Damper) was excluded, since it represents a completely different operating condition. The CFD results are classified by the damper gap (cross zone leakage 4.7" [BC-3 & 4] vs 1.7"[BC-5]), and the simulations adjusted for roll feed recycle using method 2 [BC-6] are shown separately. A linear fit was applied to the adjusted feed points, since they represent the closest fit to the plant results.

3.2.5.1 Cooler Fan Inlet Flows: Figures 23 and 24 plot wind box pressure as a function of fan flow for the two cooling zones. The simulations and the plant measurements compare favorably. In Figure 23 (3A - Primary Cooling), the CFD results appear biased, indicating slightly higher pressures at the same flow. This can be attributed to the combination of empirically determined leakage and bed resistance. In Figure 24 (3B - Secondary Cooling) the comparison is also close, however, the CFD pressures are slightly higher at lower flows, and then starting at 13,000 lbs/min, become slightly lower relative to the plant values.

3.2.5.2 Cooler Vent Stack Flow: The cooler vent stack is located near the end of the secondary cooling zone. At this stage of the investigation, it was thought that the 3B fan should have a strong influence on stack flow. Figure 25 shows an erratic relation between stack and fan in the plant data, while the CFD simulations show an increasing stack flow with increasing 3B fan flow. It will be shown in sections 3.8.3.1 and 3.8.3.3 that both fans exert an influence on stack flow in this cooler, because there is no overbed dividing wall to isolate fan flow above the pellet bed.

3.2.5.3 Kiln Secondary Air Temperature: Plant personnel indicated they typically saw an increase in kiln secondary air temperature as 3A fan flow increased. The plant data in Figure 26 does show a slight increase of 20°F over the flow range. However the CFD data indicates a significant drop in temperature, approximately 170°F over the same range. It is believed that the plant measurement is not representative of the true average temperature in the duct, and that the simulated average indicates a truer response with increasing flow. There was some discussion with Minntac to install additional thermocouples in this duct, to verify the simulations, but at this time there are no plans to do so.

3.2.5.4 Recoup Temperature vs Primary Cooling Fan Flow: Recoup A duct temperature is plotted as a function of 3A fan flow in Figure 27, while Recoup B duct temperature is plotted in Figure 28. Both figures show a decrease in temperature as 3A fan flow increases; this was expected, since more cooling is taking place upstream from the recoup outlets. In both figures, the CFD simulations demonstrated a stronger relationship (steeper slope) with flow, but the trends are similar to the plant data. The statements made earlier indicated the A duct thermocouple should read hotter than the true gas average. If the CFD value is taken as true average, then this statement is true with 3A flows greater than 13,500 lbs/min. At flows less than 13,500, the thermocouple appears to read colder than the true average. The Recoup B duct thermocouple was stated to read colder than the true gas average. Again comparing to the CFD average this statement appears to be accurate at flows up to 15,000 lbs/min on the 3A fan.

3.2.5.5 Recoup Temperature vs Secondary Cooling Fan Flow: Figures 29 and 30 are analogous to 27 and 28, showing recoup temperature as a function of 3B flow. In both ducts, plant data trends upward (increasing temperature) with increasing flow. This effect is more pronounced in the B duct (Figure 30) than in the A duct (Figure 29). The CFD simulations yield the same trends but with steeper slopes. The reader is cautioned at this point. Because of the interdependence in the cooler fans, the effects shown in these plots are not independent of each other. As the 3B fan flow increases, there is usually a corresponding decrease in 3A fan flow, because the 3A fan is controlled by pressure, and the 3B is operated in manual, and will raise pressure at the 3A control point causing the 3A to cut back. Thus, as 3B flow increases, 3A cooling has diminished, shifting more heat toward secondary cooling. Figure 31 illustrates this relation between the 3A and 3B fan flow in the plant data.

3.2.5.6 Cooler Overbed Pressure vs Cooler Fan Flow: Figure 32 plots primary cooling overbed pressure vs 3A fan flow, and Figure 33 plots secondary cooling overbed pressure vs 3B fan flow. While both fans have a combined impact, these two figures illustrate that plant data and CFD simulations follow the same trends.

3.2.5.7 Preheat Overbed Pressure vs Primary Cooling Overbed Pressure: The preheat overbed and primary cooling overbed zones are linked by the kiln and firing hood. Since the 3A fan is set to maintain a kiln firing hood pressure, Figure 34 plots the relation between preheat and primary cooling overbed pressure sensors. The plant data shows a slight trend for primary cooling overbed pressure to decrease with increasing (more positive) pressure in the preheat zone. Plotting the CFD data against the plant preheat pressure yielded the same relation. The trend is marginal, but is consistent between the CFD and plant data.

3.2.5.8 Kiln Flow vs Primary Cooling Fan Flow: Preheat fan flow was plotted as a function of 3A fan flow for the plant data in Figure 35. For the CFD simulations, the total kiln flow is plotted against the secondary y-axis (on left) as CFD Kiln Flow. This total consists of the parallel duct flow (kiln secondary air) and firing hood flow. Both data sets show close correlation, although in this case the plant slope appears slightly steeper.

3.2.5.9 Section Summary: At this point we felt confident that the CFD cooler model was tracking with the plant validation tests. The model probably could have been tuned further with regard to bed pressure drop (resistance factor) and cooler wind box leakages, but we lacked credible data on which to base further modifications. The decision was made to move on to validating MEDUSA using the information we gained from the cooler simulations.

3.2.6 MEDUSA Validation: Table 4 summarizes the data file inputs for the thirteen plant validation tests. The table is organized for direct input into MEDUSA FORTRAN files. The units are SI. Feed rates based on both methods of calculation are included. Although we favored the higher level of primary cooling wind box leakage, we also tested the lower level for the first seven plant tests. The reader will thus find two sets of air flow inputs to the cooler. These values were computed from the appropriate CFD simulations given in Table 2; the data file heading is provided in Table 4 as well.

The target variables were our criteria for evaluating the MEDUSA runs. Plant overbed pressures are tabulated for comparison purposes, because they were used to establish leakages in the system. Given below the pressures are the plant fuel rates for these tests. Fuel is shown for the kiln burner and the preheat burners. Line 6 also has a burner in the DD2 zone; we chose to ignore the burner because the fuel input was less than 7% of the total. In hindsight it is not recommended that this burner be ignored, although its impact is small. Feed composition was kept constant, as was green ball moisture. There was a lack of reliable information to justify changing composition from run to run.

We found ourselves continually adjusting the combination of furnace leakages, green ball moisture and flux addition to hit target temperatures. With this many variables, the number of combinations became unmanageable, and as a result, the fit of MEDUSA with plant conditions became subject to the user's experience. This approach has always presented a dilemma for the user, because even relatively small errors in measurement of moisture, composition, feed rate and leakage assessment can affect the mass and energy balance simulations. For this reason the results of the runs performed using the data of Table 4 have not been included..

3.2.6.1 Convergence Criteria: A constant set of leakages was determined, based on zone area and pressure. The reader is referred to the MEDUSA report for the details. Feed moisture and composition were held constant. MEDUSA was given a set of target temperatures such as preheat fan inlet and kiln solids discharge, a constant fuel flow (SMCFH), and the specified cooler outlet flows and temperatures. MEDUSA, using an optimization routine, found the feed rate that balanced the target temperatures and cooler flows. The focus was on attaining a good overall match between the simulations and a range of plant operating conditions. The specific effects of moisture, composition, and feed rate fluctuations could then be studied individually or in combination by the user, under steady feed rate or fuel input conditions.

This method was tested manually, making several runs at each set of plant conditions, adjusting the feed rate up or down according the desired change to match target temperatures. Table 5 presents the results of this method. The data input information is copied from Table 4 for convenience. Since the plant was now operating with the wind box damper closed, the first test was dropped from this series. For the results given in Table 5, we used DD1, DD2, and preheat fan inlet temperatures as targets. The optimized production rate is given on the last line of Table 5.

3.2.6.1.1 Target Temperatures: Figures 36-39 illustrate the results of manually adjusting feed rates to hit each test target temperature. The criteria were arbitrarily chosen as simulation temperatures falling within approximately 10°K of the specific target. This strategy worked well for DD1 overbed and preheat fan inlet temperatures shown in Figures 36 and 38. It did not yield similar fits with DD2 overbed and kiln solids exit temperatures, see Figures 37 and 39.

Discussion with Minntac personnel helped resolve the target choices. Since DD1 and preheat fan temps were closely related in the plant, usually within 25-50°F of each other, DD1 was eliminated as a target, in favor of the preheat fan temperature. The DD2 overbed temperature is not considered an accurate measurement because of the thermocouple location and turbulence in this zone. Thus the DD2 temperature was also eliminated as a target, with a relatively accurate estimate of the recoup temperature from the CFD model. The plant controls kiln firing based on the kiln solids discharge temperature, so this became the second target. MEDUSA now optimized feed rate under constant moisture, composition, and leakage conditions, using preheat fan inlet temperature and kiln solids discharge temperature as the operating constraints.

3.2.6.1.2 Feed Rate Comparison: Plant measured feed rate is compared with the optimized feed rates for the tests presented in Table 5 in Figure 40. These are the manually adjusted results by the user to hit the target temperatures discussed in the section above. We considered the fit to be very good, as the deviation between the plant indicated rate, and the optimized rate was less than 4% for all runs, and under 3% for 9 of the 12 tests.

3.2.6.2 Section Summary: Summarizing the MEDUSA validation, we matched the simulations over a range of plant conditions. We did so by eliminating the moisture, composition and leakage variations from the data input, fixing preheat fan and kiln solids discharge temperatures, and letting the model find the feed rate that yielded these targets. Fuel flow changed in each of these runs as reported by plant data. Fuel flow could be fixed or kept as a variable, depending on the investigation objective. The traditional approach has been to calibrate the model to one set of data at a time, which then leads to a continual tweaking as the model is calibrated against each new set of data. It is felt that the method outlined will lead to more consistent results, so long as the user does not expect an exact numerical match between simulated results and plant data.

3.3 CFD Cooler Model - Parametric Series:

3.3.1 Cooler Variables and Experimental Design: We were now ready to begin developing a predictive model of the cooler. In total, four experimental series were performed. Table 8 describes the control variables and levels tested for these series. Magnetite, feed rate, and fan flow levels were determined by anticipated minimum, mean, and maximum plant levels. In the case of the First Parametric Series, we initially tried to structure the 3A flow to meet firing hood pressure constraints as well as making physical changes to the cooler. This method required an additional 5 tests (varied 3A flows) to complete the series. Experimental designs for these series are given in Table 9.

A fan flow series was performed to determine basic cooler behavior under constant feed conditions. This information was used to determine the 3A fan flows in the first parametric series of Table 8. Figure 41 shows the cooler layout and wind box numbers as used in this report. In the plant, there is an additional wind box where pellets are discharged from the kiln; this zone is considered "dead" in terms of air flow, and, because the bed is not uniform (upstream of the screed wall), it is not included in the CFD model.

Upon completion of the first series, we revised our method because mixing the physical modifications (walls, duct moves) tended to produce a set of linear equations that averaged all effects. Thus wall effects were mixed with no wall effects, yielding a relation that was not true to either of the physical conditions simulated.

Once we realized this, the series was repeated dropping out one wall location, and the recoup B duct move. The two-position evaluation of recoup B duct was to provide some insight for comparison to Minntac Line 7, which has the B recoup duct attached to the cooler in wind box 5. The second series modeled the Line 6 cooler as it existed at the time of this study. The third series in design was the same as the second, but now a wall was installed between wind boxes 6 and 7. The second and third series are partial factorial designs, 27 combinations out of 81 total were simulated.

Tables 10-12: These tables summarize the CFD simulations for the four experimental series. The fan flow series and the first parametric series are given in Table 10. Individually the results in Table 10 are acceptable, statistically they cannot be combined into a predictive model. Table 11 summarizes the second parametric series and Table 12 the third.

3.3.2 Cooler Fan Flow Series: This series of simulations investigated the response of the cooler under constant production, constant ferrous iron conditions for a series of fan flows. Fan flows consisted of a minimum flow (10,000 lbs/min) a mean flow (13,500 lbs/min) and a maximum flow (17,000 lbs/min) for both the 3A and 3B fans. The results demonstrated that cooler response was linear, in most cases, and for those responses where it was non-linear, a linear regression yielded a reasonable approximation.

Figure 42 shows effect of flow on primary overbed pressure and pellet exit temperature for each level of 3A fan flow. Pressure response is linear, pellet exit temperature displays some non-linearity. Pellet exit temperature is defined at a point location (single cell) about 2 inches down from the top of the bed, centered on grate width, in the last cell of the cooler. Figure 43 shows pellet exit temperature as a function of total cooler flow. Figure 44 shows primary overbed pressure as a function of total flow. Figure 45 plots average recoup gas temperature for each 3A series as a function of the 3B fan flow; the data is plotted vs total flow in Figure 46. Recoup flow is plotted in Figure 47 for each 3A fan series as a function of the 3B flow and in Figure 48 as a function of total flow. We concluded on the basis of this series that a linear regression model of cooler behavior should give a good approximation of the cooler behavior.

3.3.3 First Parametric Series - Mixed Cooler Physical Layouts: This series consisted of a number of physical modifications as well as operating variations. The full factorial design required 162 simulations; a partial design consisting of 18 simulations was carried out (see Tables 9 and 10). As mentioned, no regression analysis was utilized from this series because of the mixed physical changes to the cooler. However, the individual tests may be of interest to the reader.

In this series, we intended to compare Minntac Lines 6 and 7 recoup duct arrangements. Line 7 is identical to Line 6 except that the recoup B duct is attached to the cooler in wind box 5 on the roof. On Line 6, this duct is attached to the outside wall in wind box 9. A third recoup duct arrangement was also to be evaluated (wind boxes 5, 9, 10), as well as two overbed dividing wall locations, between wind boxes 5 and 6, and between wind boxes 7 and 8.

Budget constraints restricted the subsequent series to the current cooler, and the cooler with a wall installed at one location. The recoup B duct relocation and addition of third recoup duct were dropped from the investigation. The results of this series were useful in determining the wall location for the third series. It was apparent from the simulations of a wall in the original location (wind box 7/8) that 3A fan flow was severely limited, and with the two wind box offset (wind box 5/6) that the 3A fan would run at maximum flow, because of plant control attempting to maintain a neutral firing hood pressure. The third series evaluated the location between these two extremes with one wind box offset (wind box 6/7).

3.3.4 Second Parametric Series - Current Cooler Baseline: The full factorial design called for 81 simulations; we carried out a partial factorial of 27, which at this time appears sufficient. Table 9 details the conditions, and Table 11 presents the results. At two simulations per day, 14 days were required to complete each series. JMP statistical software was used for the statistical analysis and linear model regression.

3.3.4.1 Linear Regression - Variable Abbreviations: The results of the linear regression are presented in Figure 49. The equation parameters are given in the box at the top of the page. Response variables run across the top of the table, control variables are listed vertically on the left. Variable names are abbreviated as much as possible to conserve space, given below is a complete listing of all variables presented in these plots:

Full Name	Abbreviation
Response Variables	
3A Overbed Pressure, in. H_2O	3A OB PRS in.H_2O
Total Kiln Flow, lbs/min	T Kiln Lbs/Min
Average Kiln Gas Temperature, ^oF	A Kiln Temp F
Total Recoup Flow, lbs/min	T Rec Lbs/Min
Average Recoup Gas Temperature, ^oF	A Rec Temp F
Pellet Exit Temperature, (top cent) ^oF	Pell Ext Tmp F
Average Vent Stack Temperature, ^oF	Vent Stk Tmp F
Control Variables	
% Magnetite in Pellets Entering Cooler, % wt	% Mag
Furnace Grate Feed, WLTPH	Feed LTPH
3A Fan Flow, lbs/min	3A Lbs/Min
3B Fan Flow, lbs/min	3B Lbs/min

3.3.4.2 Linear Regression - Prediction Profiles: In Figure 49, the box entitled Prediction Profile provides matrix of responses for each control variable. This chart shows the effect of each control variable on each response. Vertical center lines in each plot show the current control variable level, for example:

% Mag is at 22%, Feed at 485 WLTPH, 3A Fan at 13,500 lbs/min, 3B Fan at 13,500 lbs/min

On a computer screen, these vertical lines are active and can be dragged to any level within the variable range. The response level is shown centered on each vertical scale; this value changes with changes in the control variable settings, for example, the above settings result in:

Vent stack temp = 613.9^oF, Ave Rec Temp = 1430^oF, Total kiln flow = 7879.9 lbs/min ....

The slope of these lines provides a visual comparison of control variable effects. For example, examining 3A overbed pressure, one can see that changes in magnetite content or feed rate have little impact on pressure. But both fans have significant effects on pressure, and comparing the fans, the 3A fan has the most significant effect. This would be expected, since 3A fan flow is closest to the overbed sensor. The impact of the 3B fan is attributed to the fact that there is no overbed wall in this cooler. Taking this analysis one step further, if the 3A fan is held constant, and the 3B fan flow is increased, it is possible, (depending on how much 3A air is supplied), for the overbed pressure to become positive. If primary cooling overbed pressure exceeds +0.05 in.H2O, firing hood pressure will become positive (see plant data relation between firing hood pressure and primary cooling overbed pressure in Figure 79). If a positive firing hood pressure results in the plant, the 3A fan cuts back to maintain a negative firing hood pressure. In normal plant operation, the 3A fan is maintained in automatic control, flow determined by a firing hood pressure, and the 3B is set in manual mode to a level that achieves the desired final cooling for the current production rate.

This analysis can be extended to all the response variables in similar manner. In general, magnetite content and feed rate have no direct effect on cooler outlet flows, which is expected. They do affect temperatures in the process, and if temperatures become too hot, cooler inlet flows are increased to achieve desired cooling. Magnetite content has the largest impact on kiln gas temperature, and its effects on recoup and vent stack gases diminish. This is expected because the magnetite oxidation is readily completed upstream of the recoup and stack outlets, and the bulk of this heat is carried back into the kiln. Feed rate, however, affects temperatures throughout the cooler.

As process fan inlet flows increase, there are corresponding increases in the outlet flows, while temperatures in these streams decrease. It is clear that increasing 3B flow will also drive up flow through the kiln, as is observed in the plant. However, the 3B affect on kiln flow is less than the 3A effect for a similar increase. Looking at the kiln gas temperature, the 3A fan has the more pronounced affect. The effect of both fans on recoup flow is about the same slope. One can then use these linear equations to evaluate relative changes in fan flow by comparing the response variable parameter constants. For example, the 3A constant for average recoup temperature is -0.1098 vs -0.0429 for the 3B fan; thus a 1 lb/min loss in flow by the 3A fan requires a 2.38 lb/min gain in flow by the 3B fan to maintain constant temperature, all other control variables remaining constant.

Pellet plants do not measure a pellet exit temperature. However, they do measure vent stack temperature, and, with enough data, we think a correlation could be made relating vent stack temperatures to hot product. This relationship will have an impact on the development of a cooler operating window, which is defined section 3.3.4.3. With this relationship, MEDUSA/CFD models can avoid analysis of operating regimes where hot product may result, or at least could warn the user that his choice of operating conditions may cause problems in the plant.

The analysis of this parametric series is not complete. Due to the magnitude of this project, we limited our analysis to the variables that directly influence material and energy balance calculations in MEDUSA. More detailed studies could be carried out evaluating leakage effects, pellet bed temperature profiles, pressure profiles relative to sensor locations, and evaluation of sensor locations for better temperature and pressure measurement. Control variables could also be included for kiln discharge solids temperature, bed depth, and pressure fluctuations at the cooler outlets. The cost is in the additional simulations required by the experimental design, given the current computation limitations.

3.3.4.3 Current Cooler Operating Window: This step defines an operating window of possible 3A/3B fan flows. The window is bounded on the high flow side by a maximum 3A overbed pressure and on the low flow side by a simulated maximum pellet exit temperature or maximum vent stack temperature. Because the CFD simulation pressure value trended slightly more negative than the plant, a limit of -0.05 in.H_2O was initially selected. In the plant this corresponded to pressure values between 0.0 and 0.075 in.H_2O. The pellet exit temperature is a direct indicator, but it is not measured in the plant. However, vent stack temperature is, and vent stack temperature tracks with pellet exit temperature.

3.3.4.3.1 Vent Stack Temperature vs Pellet Exit Temperature: Figure 50 plots vent stack temperature as a function of pellet exit temperature. It is believed that using the CFD simulations, a soft sensor for pellet exit temperature could be developed. This involves running CFD simulations for enough operating conditions to completely quantify a pellet temperature in the bed. From these simulations, a model of pellet exit temperature vs cooler operating conditions could be developed. This model could then be linked through a data base to plant instrumentation, from which the model would calculate a pellet exit temperature. This temperature could then be compared against the operating times when the cooler is discharging hot product, to develop a relation between hot product and pellet exit temperature. This model could run in the background several times a shift and be used to alert operators to cooler conditions where hot product is a likely result. Alternatively, a more direct method would track cooler operating conditions and relate vent stack temperature to those conditions where hot product results. If vent stack temperature exceeds this limit, operators would be alerted to possible problems.

3.3.4.3.2 Operating Variable Constraints: Figure 51 shows the operating window; 3A fan flow is plotted on the x-axis, 3B flow on the y-axis. This window is based on 485 WLTPH to the grate. The upper limit on combined flow is determined by 3A overbed pressure set at -0.05 in.H_2O in this window. Any combination of flows that moves across the limit (moving right into dark area) will generate pressures exceeding plant control limits. Similarly, a 500°F pellet exit temperature limit bounds the low flow conditions, and any combination of flows that crosses this line (moving left into dark area) will result in excessively hot pellets. The vent stack limit is also shown; it has slightly different slope but the principle is the same. On the left side of this limit, conditions are too hot in the cooler. Any combination of flows that remains in the white region should yield acceptable operating conditions, based on firing hood pressure and hot product. It will be demonstrated in section 3.4.4 that productivity and fuel consumption change depending on the location in this window.

3.3.4.3.3 Effect of Feed Rate on Operating Window: The effect of feed rate on the size of this window can be seen in Figure 52, which shows how the operating window shrinks at 520 WLTPH. The model simulations and comparisons with plant data were based on the 485 LTPH window. Since the higher feed rate appeared to be a subset of lower tonnage flow combinations, the 485 rate was used as the baseline. Further plant validation work could be carried out comparing various operating windows (defined by tonnage) with plant conditions, if the feed rate in the plant could be correspondingly controlled. This would be a difficult set of tests, requiring operators to maintain both production as well as specific fan flows. The approach taken uses a lower tonnage window (485) and requires operators to control fan flows, allowing feed rates to vary according to normal plant guidelines.

The models used to constrain the operating window were based on two variables, primary cooling overbed pressure, and vent stack or pellet exit temperature. The software package allows any number of variables. Thus, if additional parameters were desired, such as maximum recoup gas temperature or maximum secondary cooling overbed pressure, they could be incorporated as well. The goal was to keep the model as simple as possible using only these two constraints, until the plant validation tests could be completed.

3.3.6 Third Parametric Series - Cooler with Overbed Dividing Wall: Figure 53 shows the linear model parameters and prediction profiles for the third parametric series, simulating the installation of a wall off-set one wind box into the primary cooling zone. The most important changes from the wall are the diminished effect of the 3B fan on kiln gas flow and temperature. The wall effectively isolates the 3A and 3B fans, preventing the 3B fan from overriding the 3A fan, and it also diverts some of the 3A fan flow to the secondary cooling zone. There is still some 3B effect due to cross wind box leakage below the bed and leakage between the bottom of the dividing wall and the pellet bed (6" clearance). One can also compare the values of the response variables at the same control variable levels, (22 % Mag, 485 WLTPH, 3A 13500, 3B 13500) to see that installation of a wall results in:

a very slight decrease in overbed pressure, in H_2O	-0.0805 to -0.0918
a decrease in kiln gas flow, lbs/min	7879 to 7720
a very slight increase in kiln gas temperature, ^oF	2242 to 2243
an increase in total recoup flow, lbs/min	6142 to 6212
an increase in average recoup temperature, ^oF	1430 to 1447
a very slight increase in pellet exit temperature, ^oF	394 to 395
a slight increase in vent stack temperature, ^oF	614 to 620

One can also compare the relative ratios of the parameter estimates. For example, using 3A overbed pressure the ratio of 3A:3B flow for the no wall case is 2.59, and increases to 8.76 with the wall in place, indicating a significant reduction in the influence of the 3B fan on primary cooling overbed pressure.

3.3.6.1 Vent Stack Temperature vs Pellet Exit Temperature: Figure 54 plots the relation between vent stack temperature and pellet exit temperature for this cooler layout. For all practical purposes the relation is identical to the one shown for the baseline cooler in Figure 50.

3.3.6.2 Operating Variable Constraints: Figure 55 shows the operating window as defined at 485 WLTPH; note that the window has shifted to the right. Because some of the 3A fan flow is now diverted away from the kiln, the 3A overbed pressure becomes more negative at low 3A fan flows. If a minimum hood pressure is to be maintained, the 3A fan must now operate at slightly higher flow levels. Pellet exit and vent stack limits also cut off some of the operating window at lower 3B fan flows. Correspondingly, the window has shifted to the right, allowing higher 3A fan flows with high 3B flows before the maximum overbed pressure is reached. This is a positive benefit because the window has shifted in the region where optimum productivity and fuel consumption exist. Thus, installation of the wall should make it possible to operate at higher levels of productivity and lower levels of fuel consumption.

3.3.6.3 Effect of Feed Rate: Figure 56 illustrates the corresponding window at 520 WLTPH. Again, the window is shifted, relative to the window of the current cooler.

3.3.7 Section Summary: The CFD cooler model simulations permitted the definition of a plant operating window for the 3A and 3B fans, constrained by a maximum overbed pressure and a maximum pellet exit temperature or vent stack gas temperature, for each cooler configuration.

The size of this window is dependent on operating conditions. Increasing feed rates will shrink the size of the window; 3A overbed pressure can be related to firing hood pressure (see Figure 79), and a model of pellet exit temperature based on cooler operating conditions could be developed with sufficient CFD simulations.

3.4 MEDUSA/CFD Hybrid Simulations:

In this step, the linear equations defining kiln secondary air temperature and flow, and total recoup flow and temperature, were embedded into the MEDUSA model, defining the MEDUSA/CFD hybrid version. This model was used to evaluate various cooler fan flow combinations extracted from the operating windows shown in Figures 51 and 55. The goal was to establish response surfaces for feed to the grate and fuel consumption.

3.4.1 Target Constraints: These simulations were performed under the following constraints:

Preheat fan temperature, °F	680
Kiln solids discharge temperature, °F	2268
Kiln Fuel Flow, SMCFH	179
Preheat Fuel Flow, SMCFH	68.3

3.4.2 Flow Conditions: Various combinations of 3A and 3B fan flows were extracted from each operating window and plugged into the hybrid model. The hybrid model used the respective equations that define kiln gas and recoup gas temperature and flow in terms of production rate, ferrous iron content, 3A fan flow and 3B fan flow. The user specified 3A/3B flow combinations, and, as the simulator adjusted production rate to hit the target temperatures, the cooler responses were adjusted accordingly. Twenty-four simulations were performed within each window. Tables 13-14 list the results. The actual values for preheat fan and kiln solids discharge temperature are provided for comparison to the target. The DD2 Zone flow and temperature reflect perfect mixing with furnace leakages. The recoup flows and temperature at cooler were generated from the linear equations themselves, since the MEDUSA output did not provide these values at the time.

3.4.3 Target Temperature vs Simulation Results: Figure 57 shows the preheat fan temperature calculated vs the optimized feed rate for both cooler series. The optimization routine appears to converge on the target temperature with increasing production rates. Figure 58 compares kiln discharge temperature in a similar manner, and, again, the optimization appears better at higher tonnages. Figure 59 plots simulation deviation from the target as a percent of the target value ((simulation value-target)/target)*100 for both targets. Preheat fan temperature showed a maximum deviation of about 4.8% at 446 WLTPH, while kiln discharge solids temperature had a maximum deviation of about 1.2% at 445 WLTPH. The cooler series with an overbed dividing wall appeared to have a slightly better match between target and actual values.

3.4.4 Feed Rate and Fuel Consumption Response Surfaces: JMP software was then used to generate surface responses of feed rate and fuel consumption for 3A and 3B fan flows in both cooler operating windows. The linear models were determined using the data contained in

Tables 13 and 14; 3A and 3B fan flow were the control variables, and feed rate and fuel consumption were the responses. Figures 60 and 61 summarize the results. Two plots are shown for feed rate and fuel consumption respectively. The approximate location of the operating window limits are drawn on the surface responses for reference.

The best feed rate (highest level 470-480 WLTPH) and the lowest fuel consumption (570-590,000 BTU/LT) fall in the same region of both windows. This region occurs where the 3B fan is maximized between 16,000 and 17,000 lbs/min and 3A fan is operating between 12,500 and 13,500 lbs/min. The prediction profiles for fuel and feed rate from these simulations are shown in Figures 62 A and 63 A. Production rate increased with increasing fan flows, and fuel consumption decreased with increasing fan flows. Figures 62 B and 62 B present a second model, showing that production and fuel are more significantly affected by changes in recoup flow than preheat fan flow. Again, increasing recoup flow increases feed rate and decreases fuel consumption. These effects will be discussed further in sections 3.4.5.1 – 3.4.5.3.

3.4.5 Current Cooler vs Cooler with Wall Comparison: Referring to Figures 60 and 61, several comparisons can be made. First, the shape of the operating window changes with the installation of the wall, the slope of the pressure and temperature limits becoming steeper with the wall in place. Second, the window is shifted to the right in the higher 3B region, indicating that higher 3A flow can now be achieved before the maximum overbed pressure is reached. Correspondingly, the lower pressure limit also shifts to the right with the wall, meaning that the 3A fan will operate at slightly higher flows to maintain the minimum overbed pressure, unless control set points are changed. Third, the slope of the iso feed and fuel levels have increased with the wall. Again the implication is that for the same level of 3A fan increase, the cooler with the wall should result in more significant increases in production and decreases in fuel consumption. This can be seen in comparing the ratio of 3A parameter constants. Without the wall, the constant is 0.00579; with the wall the constant increases to 0.0081. Thus, the same increase in 3A fan flow with the wall will generate a 39% increase in grate feed rate, and a 49% decrease in fuel, with respect to the cooler without the wall. However, since the production and fuel levels start out at slightly lower levels with the wall, the benefits begin appearing at higher flow conditions. This is discussed in more detail in sections 3.8.4 – 3.8.6.

3.4.5.1 Cooler Flow vs System Feed Rate and Fuel Consumption: Figures 62 and 63 present additional information about the cooler behaviors. In 62 and 63 A, production and fuel trends are shown as functions of cooler fan performance. The significance of these trends is given by the t Ratio statistic contained in the parameter estimates box in Figures 60 and 61. The variable increases in significance as the absolute value of the t Ratio increases from 2. At values below 2 the variable is considered insignificant. A more detailed definition is given in Appendix II. For both coolers, the t Ratio (absolute value) is greater than 18 for both cooler fans, indicating significant effects from both.

3.4.5.2 Preheat and Recoup Flow vs Feed Rate and Fuel Consumption: In Figures 62 and 63 B, the analysis goes one step further. In these plots, fuel and productivity are compared to preheat flow and total recoup flow in the MEDUSA/CFD results. For the current cooler, the t statistic is low for preheat fan flow 2.4 and 2.28 (feed rate and fuel respectively), but relatively high for recoup flow, indicating a poorer correlation with the preheat fan flow, relative to the recoup flow variable. But with the cooler containing a wall, the preheat fan t statistic increases to 18.9 for feed rate and 17.5 for fuel. Thus, installing the wall appears to improve the correlation of furnace performance with preheat fan flow. This may be one more reason why it is so difficult to correlate plant data with the current cooler configuration.

3.4.5.3 Least Squares Model Fitting Analysis: The JMP software provides additional insight, by using least squares model fitting. Leverage plots are shown for each proposed model, these plots contain confidence curves. The plots indicate whether the test is significant at the 5% level by showing a confidence region for the line of fit. If the confidence region between the curves contains the horizontal line, the effect is not significant. If the curves cross the line, the effect is significant. A more detailed explanation is found in Appendix II.

Figure 64 compares the models for fuel consumption response using 3A and 3B fan flow as control variables. The plots show that 3A and 3B flow is significant in both coolers. Figure 65 shows a similar comparison for feed to the grate as a function of 3A and 3B flow, and again, both fan flows are significant in both coolers. Figure 66 compares fuel to preheat and recoup flow. In this Figure preheat flow is shown to have a marginal effect for the current cooler, while it has a significant effect in the cooler containing a wall. Figure 67 shows the same effects for productivity. If one compares relative size of the parameter constants for preheat and recoup flow in the cooler with a wall, one sees that pound for pound recoup flow has a more significant effect on production and fuel consumption, about 61% greater. Figure 68 shows leverage plots for a model predicting preheat flow from 3A fan flow for both coolers. The effect of the wall is clear. The correlation is considerably stronger for the cooler with wall, t ratio 27.3 vs 6.6 without wall, and can be seen visually by the scatter in the leverage plots. Figure 69 demonstrates that if 3B flow is accounted for, the correlation between preheat flow and cooler flow is significantly improved. In the plant, such a correlation would be difficult to sort out without some knowledge of how flows develop in the cooler outlet streams.

3.4.6 Section Summary: The simulations using the hybrid MEDUSA/CFD model predicted an optimum fuel and production region in the operating window as defined by the CFD cooler model. This optimum region occurred in the same location for both production and fuel, and required a maximized 3B fan flow. However, to maximize the 3B fan on a continuous basis it should be under automatic control. This cannot be done in the current cooler without affecting the 3A fan performance. The simulations indicated that recoup flow has a significant affect on production and fuel relative to the preheat fan, so recoup flow should be maximized as well for the best plant performance, but this implies adequate waste gas fan capacity to move recoup air. In terms of fuel consumption and production levels, the current cooler appears to yield slightly better numbers at lower fan flows. But installation of a wall increases the slopes of these responses and increases the potential 3A flow at maximized 3B levels, such that marginal gains in fuel and productivity would be expected. Since these simulations were constrained by primary cooling overbed pressure in the operating window, they should all be attainable under normal operating conditions.

One key assumption must be pointed out regarding pressure at the recoup duct outlet in the CFD model. For these simulations it is assumed that the pressure drop between furnace and secondary cooling can be maintained, which means that the waste gas fan must be capable of *increasing the differential if the recoup flow is to increase as shown. This issue was not investigated in this study, but as will be shown in sections 3.5.4 and 3.6.2.4, the capacity of the waste gas fan may have limits on line 6, which prevent attaining the higher levels of recoup flow. One other point to make is that Line 6 operators maintain the 3B fan in manual control, which means that as operating conditions change, this fan may not be at its best flow rate for overall plant performance all of the time.*

3.5 Plant Validation Tests:

3.5.1 Minntac Project Review - Test Criteria: A presentation was made to Minntac personnel in December 1999, showing the operating window for the current cooler and the effects of 3A and 3B fan flow on production and fuel consumption. In February and March, two series of plant tests were conducted to test the predictions of the MEDUSA/CFD model. The operating window was divided into five regions comprising a flow range for both cooler fans. Operators were instructed to hold the fans within these ranges, while fuel and production were allowed to fluctuate according to normal operating procedures. Six tests were conducted in February, one for each flow region, and a duplicate of the one most preferred by operators. These tests lasted 48 hours each. Three additional tests were conducted in March, intending to duplicate test regions, I,II, and V. Data was logged automatically using ten-minute averages. Pitot tube traverses were carried out on the 3B cooler fan flow meter, but the 3A was inaccessible on a regular basis and no checks were performed. By this time the recoup B meter had failed, although the recoup A meter appeared to be giving reliable information. Meter drift is suspected in the waste gas and preheat meters, but these flows were not rechecked during these tests. As it turned out, the 3A meter readings coincided with the target ranges. The 3B flows, when corrected by a factor determined by the pitot tube traverses, compared reasonably well to the test targets.

3.5.2 Test Data Manipulation: The plant data is referred to as "unedited" or "edited". Unedited data is chronologically complete consisting of all data points logged, including plant upsets. Edited data represents a single pass to remove data based solely on plant production upsets. This procedure was somewhat subjective, in that only the points lying outside (>50 tons/hr) of the mean were eliminated. No attempt was made to edit the data for furnace residence time effects. Thus, the first point average back at acceptable feed rate was included, even though the effects of the upset were still within the furnace. The edited data was used in the construction of plant models for comparison with the simulation models. Ideally, additional duplicate tests were desired to confirm the results presented. Figures 70-77 show statistics on feed rate to the grate before and after editing. The goal was to remove most or all of the statistical outliers in a single pass. Tests 7 and 8 were sufficiently stable, so no editing was performed. Test 5 was the least stable and required the most editing.

3.5.3 Plant Cooler Flow vs Operating Window: Figure 78 shows the test regions, test number designations, and the edited data points. The approximate location of the predicted operating window is also included. One can see a significant number of points lying outside of the -0.05 pressure contour. A second pressure contour limit is included for 0.01 in.H_2O. At this level virtually all data points are included.

As mentioned earlier, the CFD 3A overbed pressure prediction corresponds to a more positive plant value, (plant = CFD value + 0.07). For the plant tests, the mean maximum 3A overbed pressure was +0.02 in.H_2O, which would correspond with the simulated contour at -0.05. However, to include all of the plant data in the window, a simulated value of +0.01 is required, which corresponds to a plant value of approximately +0.08, thus there is a small level of error in the initial tuning. Figure 79 relates the primary overbed pressure to firing hood pressure. Figure 80 plots the mean and standard deviations for primary cooling overbed pressure. Note that multiple data points at the same value plot as a single point on the vertical axis.

In reference to the JMP plots that will follow, note that the software limits marker types to 8. Each test series was given a label, and where symbols are the same, a different color is used, which may or may not appear in the report reproductions. JMP is also limited at times in displaying grids. This is apparent in the operating windows in Figures 51, 52, 55 and 56. Finally, JMP does not permit easy resizing of grids so that figure size varies slightly from plot to plot.

3.5.4 Unedited Data Observations: As the data was analyzed, it was apparent that there were significant fluctuations in the process fan operating conditions. These trends show up in both the edited and unedited data. However, illustrating the trends with edited data destroys the time sequence. For this reason, a number of plots are presented to illustrate the variability in the plant data. The data was normalized in order to plot the variable responses on a single y-axis, with JMP. A 70-minute running average was then computed to smooth the curves in these plots. The normalization was done as follows:

(variable value - variable mean)/std dev variable

The normalized value is referred to as the "Relative Deviation from the Mean, (RDM)" in units of the standard deviation. Tests 1-5 and 7 were selected to illustrate this unsteady nature. Figures 81-86 show relevant statistics for Tests 1-5 and 7; these figures give the number of data points, mean and standard deviations for the fan amps, recoup A duct flow, kiln secondary air temperature, average recoup air temperature, and vent stack temperature. These variables were selected because they highlight the process instability during these tests. The reader is referred to Figures 81-86 for the standard deviation values when evaluating the trend plots that will follow.

3.5.4.1 Process Fan Damper Position: Figures 87-92 plot the averaged damper % open for the preheat (1A/B), furnace waste gas (2A), and cooler fans (3A/B). In these six tests, there is considerable fluctuation in the damper settings. In typical operation, the preheat fans, waste gas fan and 3A fan are all under automatic control. The preheat fans are controlled off wind box thermocouples, and the waste gas is controlled to maintain a DD1 overbed pressure and the 3A fan by firing hood pressure.

In all these plots, it appears that the preheat fans are at the center of the fluctuations. When they open up or close down, the waste gas fan follows according to DD1 overbed pressure, and the 3A fan, according to the effect of preheat fan on firing hood pressure. The 3B is relatively stable because it is normally in manual mode. Based on these tests, Line 6 demonstrated an unstable mode of operation. The cycles do not appear at regular intervals, and as a result, the reasons for them are uncertain. However, changes in bed permeability, flux addition, pellet size distribution and green ball moisture are all suspected as having some influence on these cycles. Also, it appears that the waste gas fan keeps up with preheat fans, until they reach about 45 to 55 % open, at which time the waste gas fan damper reaches its maximum at 100 % open, even though the preheat fans can continue to open further. The 3A fan appears to keep up with the preheats throughout the operating ranges.

3.5.4.2 Process Fan Power vs Fan Damper Position: Figure 93 illustrates plots of fan amps vs fan damper for Test 1. This plot will be constructed later as a composite for all the tests. The point to note is that the preheat fans operate on the linear part of their fan curve; the 3A fan operates over the range of the curve, but does not appear to reach a maximum. The 2A fan, on the other hand, does reach its maximum, which may be an indication that this fan is undersized for the demands being placed upon it, or that there is some other restriction between the fan and the wind box. Figure 94 plots the normalized (70 minute average RDM values) fan amps, and again, the cycles are very prominent. The cyclical curve for the 3B fan tracks with outside air temperature variations between night and day.

3.5.4.3 Process Fan Power vs Recoup Flow: Figures 95-100 relate fan power to recoup flow. This was accomplished by defining a parameter called "net fan power," based on fan power "relative deviations from the mean" for each fan. The relationship was defined as follows:

Net AMP RDM = 2A AMPS RDM - 1A/B AMPS RDM + 3A AMPS RDM + 3B AMPS RDM

where RDM = Relative Deviation from Mean

This relation is based on the fact that waste gas fan flow is limited and is comprised of recoup flow and preheat fan flow, and that at constant waste gas fan damper position, increases in preheat power draw or flow will displace recoup air. Increases in 3A and 3B power indicate more air entering the cooler, being made available to the process. For example, if the waste gas fan power is constant, preheat power is increasing, 3A and 3B are constant, there should be a decrease in recoup flow, having been displaced by preheat fan flow. Thus, if the Net AMP RDM is increasing in value (more positive), recoup flow should likewise be increasing, and conversely, if the Net AMP is decreasing in value, recoup flow should be decreasing. These trends show up clearly in Figures 95-100. The reader can judge the significance of changes in recoup flow by multiplying the standard deviation of flow by the deviation value. For example, in Test 1 a two sigma deviation in Recoup A flow equates to 2*104=208 lbs/min change in flow. Note that because the recoup B flow sensor had malfunctioned by this time, there is no corresponding B flow data. Tests when both recoup sensors were working indicated approximately equal flows in both ducts. So, not only were the process fans cycling, but their affects were also seen in the recoup system.

3.5.4.4 Recoup A Flow vs Average Recoup Temperature: Figures 101-106 relate recoup A flow to average recoup temperature. Temperature data was available for both ducts, and was averaged (numerically). For reference the reader is referred to Figure 49, which shows the cooler fan impacts on the mass weighted average recoup temperature and flow. In general, as recoup flow increased (Figure 49), average recoup temperature decreased. And since both recoup ducts share a common plenum, increases in flow to one duct must also occur in the other. Thus recoup A flow in the plant is indicative of the change in flow in recoup B duct. In Figures 101-106, it is obvious that this trend shows up in the plant; increases in A duct flow coincide with decreases in the averaged recoup temperature, with the exception of a few times where other upsets were clearly involved. Thus the cycles in process fan flow and recoup flow also generated cycles in the recoup temperatures in the system.

3.5.4.5 Cooler Outlet Stream Temperature Oscillations: Figures 107-112 plot deviations in kiln secondary air, average recoup temperature, and vent stack temperature. The purpose of these plots is again to demonstrate the cyclical instabilities in Line 6.

3.5.5 Section Summary: Based on the tests carried out in this study, Line 6 appears to be operating in a highly unstable mode, and while this plant data will be correlated with simulations in section 3.8.0, it would prove worthwhile to repeat the tests at a later time. From a process point of view, these cycles must have an impact on line productivity, quality and fuel consumption. Eliminating these cycles would certainly have a positive effect on process efficiency. As already mentioned, the periods of production upsets were removed from the data, and a composite data file of all tests was generated, in order to continue the validation process.

3.6 Edited Plant Data:

3.6.1 General Statistics: Figures 113 -124 provide mean and standard deviation comparisons for the composite test data by variable. The JMP software plots the means and standard deviation limits on these figures. Some tests contain significant amounts of data scatter, which also show up in the plots. No attempt was made to remove these points because the process of editing the data then becomes too subjective. It was thought that the relative number of data points provided a reasonable weighting to the overall test averages. In all these plots, temperature is ^{o}F, pressure is in.H_2O, and flow is lbs/min. Because of heading limitations, the units do not always appear in the figures.

3.6.1.1 Estimated Feed Rate: Figure 113 shows the estimated feed to the grate (WLTPH) which is calculated as the green ball production rate minus the pro-rated roll feeder recycle rate. When these tests were conducted, Lines 6 and 7 shared a belt scale for roll feeder fines return. For tests 1 – 5, Line 7 was down and the recycle material is 100% attributable to Line 6. For tests 6 - 9 the return rate was calculated as:

Line 6 returns = Tot Returns* (Line 6 Grn Ball Prod/(Line 6 + Line 7 Grn Ball Prod))

Note that while green ball production remained relatively constant, the amount of fines steadily decreased by 33 % based on Test 1. Test 1 produced 73.9 WLTPH recycle as compared to Test 9 at 49.8 WLTPH. The standard deviation in feed to the grate ranged from 4.8 in Test 7 to 10.9

in Test 5, while the grate feed rate ranged from 469 to 504 WLTPH. By comparison, the CFD model simulations were based on a grate feed range of 450 to 520 WLTPH.

3.6.1.2 DD1 and DD2 Overbed Temperatures: Figure 114 plots the DD1 and DD2 overbed temperatures. DD1 mean temperatures ranged from 646 in Test 1 to 692 in Test 5. Tests 4 and 5 exhibited the largest standard deviations in DD1 temperature at 23.4 and 21.9°F, respectively, while the remaining tests ranged between 4 and 8°F. DD2 overbed temperature is a combination of the two recoup ducts and a single burner input. Plant personnel suspect that the location of this thermocouple prevents an accurate reading, being out of the gas streams entering the zone. However, it does trend well with recoup temperatures measured at the cooler, which are discussed in section 3.6.2.3. DD2 overbed mean temperature steadily increased over the course of these tests from 963 to 1224°F. The standard deviation in these tests ranged from 26.3 (Test 4) to 88.4 (Test 5). Most of the tests exhibited standard deviations between 26 and 32°F.

3.6.1.3 DD1 and DD2 Overbed Pressures: Figure 115 plots DD1 and DD2 overbed pressures. In DD1, pressure is limited to -0.6 in.H_2O by waste gas fan damper control. If pressure becomes more negative, the fan damper closes down. With the exception of Test 4 at -0.13 in.H_2O, all the remaining tests ranged between -0.51 and -0.62 in.H_2O. Standard deviations were mostly below 0.2 in.H_2O, with the exception of Test 4 at 0.42 in.H_2O. DD2 overbed pressure was also relatively stable, ranging between -1.2 and -1.5 in.H_2O, while the standard deviations were less than 0.13 in.H_2O.

3.6.1.4 Preheat Fan - Damper Control Thermocouples: Figure 116 plots preheat wind box thermocouples designated as 1A WBOX 3A and 1B WBOX 3B. These temperatures are used for control of the 1A and 1B preheat fans, respectively. These values are provided for reference. In general, the B side tends to run slightly hotter. Mean temperatures fell between 949 and 980°F, while standard deviations ranged between 13 and 20°F.

3.6.1.5 Recoup A Duct Flow and Temperature: Figure 117 plots Recoup A duct flow and temperature, the flow sensor was located about midway between the furnace and the cooler, while the thermocouple is relatively close to the cooler (see Figure 2). Flow ranged from 2297 (Test 4) to 2842 (Test 5) lbs/min. Standard deviations ranged from 65 to 110 lbs/min. The mean recoup temperature ranged from 1226°F (Test 6) to 1474°F (Test 9), and standard deviations fell between 44°F and 60°F with the exception of Test 5 at 173°F.

3.6.1.6 Average Recoup Temperature: Figure 118 displays average recoup temperature, (A+B)/2, and the total preheat flow rate. Plant personnel estimate the error in the preheat flow sensors at 20 -30%, although this was not checked during the tests, so no correction factor is applied to the data. Average recoup temperature mean values ranged from 1309°F to 1570°F, and standard deviations fell between 38°F and 54°F, with the exception of Test 5 at 157°F. Preheat fan flow means ranged from 18,425 to 19,447 with standard deviations falling between 293 lbs/min and 530 lbs/min.

3.6.1.7 Waste Gas Fan and Primary Cooling Fan Flows: Figure 119 displays waste gas fan 2A flow and primary cooling fan 3A flow. Plant personnel estimate there may be 15-25% error in the waste gas fan flow measurement. At this time it is thought that the 3A fan is relatively accurate, but this has not been verified, because it is difficult to access this sensor. Mean waste gas fan flow ranged from 24,810 to 26,100 lbs/min, and standard deviations fell between 1435 and 1997 lbs/min. Primary cooling fan flow means ranged from 11,620 to 14,045 lbs/min, while the standard deviations ranged between 203 and 843 lbs/min.

3.6.1.8 Secondary Cooling Fan Correction Factor and Cooling Fan Inlet Temperatures: Figure 120 shows the secondary cooling fan 3B correction factor as determined by comparison with pitot tube traverses performed during the tests, and the inlet cooling fan air temperatures. The range in temperature for each test reflects the changes between night and day during the test. For these tests, the means ranged from 3°F to 48°F.

3.6.1.8.1 Secondary Cooling Fan - Indicated Flow and Corrected Flow: Figure 121 plots secondary cooling fan flow as measured and as corrected by the factors shown in Figure 120. The corrected flow values are used in the plots that follow, as well as the model development. In general, the relative changes in flow were reflected after the correction was applied, except for Tests 7 and 8, which show little or no decrease in flow relative to Test 6, after the correction. For the uncorrected flow, the means ranged from 8,480 to 12,512 lbs/min, with standard deviations ranging from 163 to 352 lbs/min. In the corrected flows, the means ranged from 10,092 to 15,515 lbs/min, and the standard deviations ranged from 203 to 458 lbs/min.

3.6.1.9 Process Fan Power: Figures 122 and 123 display process fan power draw in amps. The preheat fan power draw is the numerical average of both fans; total preheat fan power is double this value. For the waste gas fan, means ranged from 344 to 380 amps, with standard deviations ranging from 6 to 16 amps. The preheat fan means ranged from 139 to 147 amps, with standard deviations of 2 to 7 amps. In Figure 123, primary cooling fan power means ranged from 110 to 127 amps, with standard deviations 0.5 to 3.9 amps. The secondary cooling fan power means ranged from 109 to 128 amps, with standard deviations of 0.5 to 2.8 amps.

3.6.1.10 Cooler Vent Stack Flow and Temperature: Figure 124 shows cooler vent stack flow and temperature. These measurements are made down stream of the junction between the two stacks, so they represent the total flow in the stack system. Plant personnel estimate the error in this sensor around 25-30%, but this was not checked during the tests. Stack mean flows ranged from 8,710 to 12,179 lbs/min, with standard deviations of 366 to 1,051 lbs/min. Stack mean temperatures ranged from 605 to 765°F, with standard deviations between 29 and 99°F.

3.6.2 Data Trends - XY Format: Figures 125-142 are X-Y plots of selected variables to illustrate various trends, or lack thereof, in the data. Summary of fit, and parameter estimates are also given. When possible, the line fit is kept linear, and polynomial degree 2 curves are used when there is a significant improvement in the R-square term. For some reason, the minus signs in the parameters show up as Û symbol in the regression equation. Individual data points in the test composite data file are plotted. Each test series is plotted as a different symbol, or color if using the same symbol, but given the number of points, it is difficult to distinguish between them.

3.6.2.1 Waste Gas Fan Power vs Waste Gas Fan Damper
Waste Gas Fan Power vs Average Preheat Fan Power

Figure 125 displays waste gas fan power as functions of waste gas fan damper % open, or preheat fan power (average of two fans). Waste gas fan power appears to reach a maximum between 80 and 90 % damper or at an average preheat fan power of 150 amps. The correlation with fan damper is $R^2 = 0.92$, while the correlation with preheat fan power is $R^2 = 0.56$. Figure 126 plots waste gas fan flow as a function of waste gas fan damper position and waste gas fan power. A linear fit is displayed, but the fit is poor; $R^2 < 0.2$ in both plots due to the scatter in the flow readings.

3.6.2.2 DD1 Wind Box Pressure vs Waste Gas Fan Damper
DD1 Wind Box Pressure vs Waste Gas Fan Power

Figure 127 shows DD1 wind box pressure as functions of waste gas fan damper position or waste gas fan power. The correlation R^2 terms are 0.72 and 0.66 respectively. Wind box pressure appears to stop decreasing around 80% damper.

3.6.2.3 DD1 Overbed Temperature vs Preheat Fan Inlet Temperature
DD2 Overbed Temperature vs Average Recoup Temperature

Figure 128 plots DD1 overbed temperature as a function of the averaged preheat fan inlet temperature, and DD2 overbed temperature as a function of the averaged recoup duct temperatures. The R^2 terms are 0.95 and 0.81 respectively. In general, the DD1 overbed temperature is about 15°F less than the average preheat fan inlet temperature, and the strong correlation supports our decision to use preheat fan temperature as the target in the MEDUSA simulations. In the DD2 zone there is some question as to the accuracy of this thermocouple due to its location. It does pick up the trends in recoup temperature very well, even though the absolute value may be off 200-300°F.

3.6.2.4 DD1 Overbed Pressure vs Waste Gas Fan Power
DD1 Overbed Pressure vs Average Preheat Fan Power

Figure 129 plots DD1 overbed pressure as functions of waste gas fan power and preheat fan power. The R^2 for fan power is 0.16, but the plant control philosophy is clear; overbed pressure is maintained constant, out to the point where the preheat fans appear to overpower the waste gas fan, thereby increasing the DD1 overbed pressure. This point occurs where under bed pressure stops increasing as indicated in Figure 127. The correlation is better with preheat fan power, $R^2 = 0.74$. Note that relatively small increases in preheat fan power rapidly raise DD1 overbed pressure. Figure 130 plots DD1 and DD2 overbed pressure as functions of wind box pressure. The R^2 terms are 0.42 and 0.22, respectively. In these plots, the waste gas fan maintains overbed pressure with wind box pressures down to -10 in.H_2O, after which DD1 overbed pressure begins to rise. The correlation with DD2 overbed pressure is less certain.

3.6.2.5 Recoup A Duct Flow vs Recoup A Duct Temperature
Recoup A Duct Flow vs Average Preheat Fan Power

Figure 131 plots Recoup A duct flow as a function of Recoup A temperature and preheat fan average power. The R^2 terms are < 0.15 in both plots. The trends as indicated by the linear fits show flow decreasing with increasing gas temperature, and increasing preheat fan power, although data scatter is so great that these relations need further investigation.

3.6.2.6 Average Preheat Fan Power vs Preheat Fan Damper
Total Preheat Fan Flow vs Preheat Fan Power

Figure 132 plots average preheat fan power as a function of average preheat fan damper position, and total preheat fan flow as a function of preheat fan power. Fan power vs damper position has an $R^2 = 0.72$, while flow vs fan power exhibits an R^2 of 0.46. The increase in fan power draw and flow show no signs of reaching a maximum, indicating the preheat fans are capable of supplying more air than the waste gas fan can exhaust from the DD1 zone.

3.6.2.7 Preheat Overbed Pressure vs Average Preheat Fan Damper
Preheat Overbed Pressure vs Average Preheat Fan Power

Figure 133 plots preheat zone overbed pressure as a function of average damper position and average fan power. These fans appear capable of developing significant negative overbed pressure. The R^2 values are 0.58 and 0.44 respectively. Figure 134 plots preheat overbed pressure vs wind box pressure, and preheat wind box pressure vs average preheat fan power. Again, it appears that the preheat fans have more than adequate capacity to move air through this zone; the R^2 terms are 0.39 and 0.74 respectively. Figure 135 plots total preheat fan flow as a function of wind box pressure; the increase in flow is linear throughout the operating conditions tested. Also shown in Figure 135 is a plot of kiln firing hood pressure vs preheat overbed pressure, showing that firing hood pressure decreases with corresponding decreases in preheat overbed pressure. Since the 3A fan control is tied to firing hood pressure, this fan will open up or close down in accordance with the preheat fans. The R^2 values are 0.55 and 0.72 respectively.

3.6.2.8 Primary Cooling Fan Flow vs Average Preheat Fan Power
Primary Cooling Fan Flow vs Firing Hood Pressure

Figure 136 displays primary cooling 3A fan flow as functions of preheat average fan power and firing hood pressure. The correlations are poor in these plots, with R^2 values < 0.24. In an attempt to improve the fit, a Net Flow to the Kiln was calculated as follows:

Net Flow to Kiln = (3A Flow + 3B Corr Flow)-(Total Recoup Flow + Vent Stack Flow)

Where total recoup flow is based on the CFD model relation between total recoup and recoup A duct flow.

Total Recoup Flow = 627 + 1.848 * Recoup A Flow

In Figure 137, net flow to the kiln is plotted vs firing hood pressure and preheat fan power. The correlations are not much better than in Figure 136. Sensor drift may be partly to blame for the lack of correlation in this data.

3.6.2.9 Kiln Exit Gas Temperature vs Cooler Flow to Kiln
Kiln Discharge Solids Temperature vs Calculated Flow to Cooler

Figure 138 looked for correlations between kiln exit gas temperature and net gas flow to kiln, and kiln solids discharge temperature and net gas flow to kiln. The correlations again were poor, with R^2 values < 0.16.

3.6.2.10 Primary Cooling Fan Flow vs Primary Cooling Fan Power
Secondary Cooling Fan Flow vs Secondary Cooling Fan Power

Figure 139 plots 3A flow and 3B flow as functions of their respective fan amps. In these plots, the 3B flow is the uncorrected sensor output. There is some scatter in the 3A flow vs amps relation ($R^2 = 0.64$), while the 3B correlation is considerably better ($R^2 = 0.93$). Figure 140 plots the 3B correction factor and corrected 3B flow vs fan amps. At this time it is not clear why at low fan amps the correction factor was also low at 1.2 and then suddenly jumps to 1.33 and then decreases with increasing fan power draw. The R^2 term for the corrected 3B flow is slightly worse than the uncorrected fit ($R^2 = 0.89$), but is still very good.

3.6.2.11 Recoup A Duct Flow vs Total Cooler Inlet Flow
Recoup A Duct Temperature vs Total Cooler Inlet Flow

Figure 141 plots recoup A duct flow and temperature as functions of the total cooler inlet flow. Recoup flow appears to increase with increasing cooler flow ($R^2 = 0.48$), but the correlation of temperature with total cooler flow is poor ($R^2 = 0.1$). In Figure 142, averaged recoup temperature is plotted vs total cooler flow, and, again, the correlation is poor ($R^2 = 0.08$). Also shown in Figure 142 is vent stack temperature vs vent stack flow where the fit is better ($R^2 = 0.52$).

3.6.3 Section Summary: Nine plant tests were performed, data collected, and analyzed. Trends in the plant data indicated an unsteady state of operation, with frequent upsets, and a waste gas fan that is undersized for the demands placed on it. It appears that the waste gas fan cannot keep up with the preheat fans as they increase in flow beyond about 50% damper. A number of correlations were plotted, looking for trends in the plant data. For those plots in which the fit is poor, it may be due to the influence of more than one variable, sensor drift or other undetected changes in operating conditions.

3.7 Plant Data Models:

3.7.1 Description: Two models were generated from the plant data. The first model was patterned after the CFD cooler model, using grate feed rate, 3A fan flow, and 3B fan flow as control variables to predict selected response variables. The only difference between the plant and CFD models was the absence of a ferrous iron content at the kiln discharge point. The second model was patterned after the hybrid MEDUSA/CFD model, in which only the 3A and 3B flows serve as control variables to predict grate feed rate and fuel consumption.

3.7.2 Linear Regression - CFD Model Criteria: Figures 143-145 give the linear regression results for the plant data model using CFD criteria. The Prediction Profiles are contained in Figures 145 and 146, respectively. For comparison, the corresponding CFD simulation profiles are found in Figure 49, along with a Table of parameter estimates.

Two pressures are reported in the plant profiles. The 3A overbed pressure corresponds to the 3A overbed value in the CFD model; this is not the pressure that controls the 3A fan, but it is measured in the plant cooler. The firing hood pressure controls the 3A fan operation, but was not part of the CFD cooler model. The relation between these two measurements in the plant data is found in Figure 79.

As already mentioned, there is no direct measurement of cooler flow to the kiln, so it must be inferred from a mass balance between cooler input and cooler output measured at the stack and in the recoup ducts. Further, since the recoup B duct sensor had malfunctioned, total plant recoup flow was estimated using the CFD model relation between recoup A flow and total recoup flow, this was described in detail in section 3.6.2.8.

Kiln secondary air temperature is a direct measurement whose accuracy is questioned. Based on CFD simulations (see Figure 10), the temperature in this duct is not uniform, and the largest deviations appear on the side opposite the thermocouple. In the plant data, actual recoup A duct flow and temperature, as well as the estimated total recoup flow and average temperature are included. The total recoup flow and averaged recoup temperature are used for comparison with the CFD model. Keep in mind that the CFD average is mass weighted, and the plant average is numerically averaged from single point sources. Vent stack temperature is provided, as it is felt that this could serve as an indicator of potentially hot product in the system. Vent stack flow was omitted since this flow exits the system.

3.7.2.1 Correlation Fit: Overall, the data fit with the predictions is not too bad, given the variability in the data. The R^2 terms are listed below for the plant model:

3A Overbed pressure	0.37
Firing Hood Pressure	0.59
Net Flow to Kiln	0.66
Kiln Sec Air Temperature	0.48
Recoup A Duct flow	0.58
Recoup A Duct Temperature	0.60
Recoup Total Flow	0.58
Average Recoup Temperature	0.66
Vent Stack Temperature	0.41

With the exception of Kiln secondary air temperature trends, the model based solely on plant data gives the same general trends as does the CFD model. Relative slopes may vary, but given the limited number of CFD runs and operating parameters tested, the overall comparison is acceptable. The predictions from both of these models are compared in the next section.

3.7.2.2 Operating Window: An operating window can be constructed in the same manner as was done with the CFD model. This window is shown in Figure 147. The 3A overbed pressure high limit of 0.01 in.H_2O is specified based on the maximum mean values listed in Figure 80. This window with its vent stack temperature and maximum 3A overbed pressure constraints is superimposed on a plot of 3B corrected flow vs 3A flow in Figure 148. Figure 148 shows that the operating window predicted by the plant data is similar in shape and location to the CFD base window, and that it encompasses most of the operating data.

3.7.3 Linear Regression - MEDUSA/CFD Hybrid: The second plant model is developed using only 3A flow and 3B flow control variables and is used to predict the feed rate and fuel consumption as responses. This allows comparison to the hybrid MEDUSA/CFD simulations.

3.7.3.1 Feed Rate and Fuel Consumption Response Surfaces: Figure 149, displays the linear regression results and the surface plots for the plant data. The R^2 values are relatively low at 0.24 for feed rate and 0.18 for fuel consumption, but the trends predicted match with the computer simulations. The highest production rate and lowest fuel consumption values fall in the same region of the operating window as they do in the computer simulations, indicating the best efficiency at highest 3B flow, and moderate 3A flow levels. The question of how much improvement in the R^2 could be expected if the plant had been operating under more stable conditions remains unanswered at this time.

3.8 Comparison of Plant Data Model with CFD or MEDUSA/CFD Models

3.8.1 Description: The final step in the analysis compares the predictions of the computer models with a model developed solely from plant data using the same criteria. The plant model can be compared with the CFD model or MEDUSA/CFD model. The same plant data is used for both comparisons, and the differences between the two models are the control variables used to predict the responses in the plant data. There is also the question of choosing the conditions under which the comparison should be performed. The JMP software once again provides a means by which this task can be accomplished.

Within the prediction profile menu is an option entitled "desirability functions". These functions allow the user to give a weighted desirability to each response variable in the profile. The desirability factor runs from zero to one, zero being the least desirable, one being the most desirable. These factors are then attached to minimum, mid-range, and maximum response levels by the user. These functions are set for each response variable. The JMP software then finds the combination of control variables that maximize the total desirability of all functions.

3.8.2 Desirability Criteria: The desirability criteria were established to approximate plant operating conditions. Note that there is a range of values that could be selected, and these yield reasonable results.

	Levels			Desirability		
	Minimum	Mid-Range	Maximum	Min.	Mid.	Max
3A Overbed pressure	-0.30	-0.10	+0.05	0	1.0	0
3B Overbed pressure	-0.40	-0.25	-0.10	0	1.0	0
Feed Rate to Grate	450	485	525	0	0.5	1.0
Fuel Consumption	550,000	595,000	640,000	1.0	0.5	0

3.8.3 Secondary Cooling Overbed Pressure Correlations: Before we can complete this discussion, one more response variable must be discussed. This is the 3B overbed pressure. In the current Line 6 cooler, the 3B fan is maintained in manual mode, to avoid overriding the 3A. Also the 3B fan flow cannot be set so high that a positive overbed pressure in secondary cooling results. From experience, the operators know approximately how much 3B fan can be tolerated to maximize cooling without affecting the 3A fan. Remember, from Figure 78, that Region II is the preferred fan configuration, 14,000 - 16,000 lbs/min 3B flow and 12,000 - 14,000 3A flow.

3.8.3.1 Secondary Cooling Overbed Pressure - CFD Current Cooler Series: The relation of 3B overbed pressure to the four control variables (% Mag, WLTPH, 3A Flow, 3B Flow) is shown for the current cooler in Figure 150, with 3A overbed pressure also included for reference. These profiles are from the same database used to generate the profiles shown in Figure 49. The point to note is that the 3B fan affects 3A overbed pressure, and the 3A fan has a slight affect on 3B overbed pressure. This is because there is no wall separating the two zones.

3.8.3.2 Secondary Cooling Overbed Pressure - CFD Cooler with Wall Series: In Figure 151, the corresponding plot for the cooler with an overbed wall, we see that the affect of 3B fan flow on 3A overbed pressure is significantly reduced, and the affect of 3A fan on 3B overbed pressure is reversed, although the impact can be considered minimal at best. The 3A fan still has a small impact on 3B overbed pressure because there is one wind box of primary cooling entering the secondary cooling zone. Thus, installation of a wall breaks the cross zone interaction of the 3B fan on the 3A fan, allowing the 3B fan to operate in automatic control. This cannot be done in the current cooler.

3.8.3.3 Secondary Cooling Overbed Pressure - Plant Data: Figure 152 plots these same interactions in the plant data. We see that the cross zone interactions on pressure sensors are considerably more pronounced than in the CFD simulations. In the prediction profiles, the 3A fan appears to have a large affect on the 3B overbed pressure sensor. Under these conditions it is impossible to have both fans in automatic control based on overbed pressures. This control state is unstable, and is the reason that the 3B is now in manual mode. Figures 153 and 154 tabulate mean and standard deviations in the plant data by test, for reference to the following discussion. Firing hood pressure means range from -0.31 to 0.00 in.H_2O; 3A overbed pressure means range from -0.06 to +0.02 in.H_2O; and 3B overbed pressure means range from -0.61 to -0.35 in.H_2O.

3.8.4 Statistics and Prediction Profiles - Plant Data: Figures 155-156 present the summary of fit, with parameter estimates and prediction profiles for the plant data model constructed using 3A and 3B fan flow as the control variables. This is the format used to compare to the MEDUSA/CFD simulations. The desirability functions in the JMP software optimize the plant data model (maximum desirability) and show that optimum 3B fan flow is 15,960 lbs/min and the 3A fan flow is 13,960 lbs/min. This is expected since this flow combination falls in the region where plant production is highest and fuel consumption is lowest.

The desirability values are also printed on the plots shown in Figure 156. The highest desirability for the overbed pressures is placed mid-range so that the optimization will find values close to the means in the plant data. Feed rate is desired as high as possible, so desirability increases to a maximum at maximum feed rate. Similarly, low levels of fuel consumption are desirable, so maximum desirability occurs at lowest fuel consumption per ton. The variable levels were chosen to fit the levels occurring in all three data sets, (two CFD parametric series, and the plant data series).

At the optimum, the predicted feed rate to the grate is 495.2 WLTPH, at 581,800 BTU/LT. The middle plot shows what happens if 3B flow is reduced by 2,000 lbs/min, which can occur if an operator is not running at peak 3B fan flow. In this case, feed rate drops to 485.8

WLTPH and fuel increases to 595,800 BTU/LT. Conversely, if the 3B fan is normally operated below the predicted optimum, cooler and furnace conditions will prevent achieving the highest possible production level. Using 330 operating days per year (24 hrs/day, $2.50/MMBTU, and a production factor of 0.77), this amounts to 57,325 LTPY of lost production on Line 6. Comparing total fuel costs based on these two feed rates, there is a fuel penalty of about $20,000 per year at the lower production level. This is based on:

495.2*0.77*330*24*(581,800/1,000,000)*2.5 vs 485.8 *0.77*330*24*(595,800/1,000,000)*2.5

Thus, not only are fewer tons produced, but fuel costs are slightly higher.

Another aspect to consider is NO_x generation. These comparisons were carried out at constant fuel flow. Total tons produced with this fuel flow varies. Thus, using this example, as much as 57,325 LTPY might be produced or lost at the same NO_x rate. This loss or gain in production depends on how close to the optimum operators run the plant. The process fan cycles must certainly work against them in this goal. The third plot in Figure 156 shows that if the 3A fan flow increases to fill the void left by the 3B fan, there is small gain in productivity from 485.8 to 487.8 WLTPH, but the full optimum is not achieved.

3.8.5 Statistics and Prediction Profiles - CFD Current Cooler Series: Figures 157 and 158 follow the same format as 155 and 156, using the MEDUSA/CFD simulations for the current cooler design. In the first plot of Figure 158, the fully optimized conditions occur for a 3A fan flow of 12,750 lbs/min and a 3B fan flow of 15,275 lbs/min; again, these conditions are found in the same general region of the operating window. In this case the optimum production rate is 469.9 WLTPH, as compared to 495.2 WLTPH from the plant data. This absolute difference is not important. What is important is the effect on production if the 3B flow is reduced from optimum. This condition is shown in the second plot where 3B flow is decreased by 1000 lbs/min. Feed rate to the grate is reduced from 469.9 to 463.0 WLTPH. This equates to 42,080 LTPY loss in production if the 3B optimum is missed by this averaged amount over the year. On the other hand, if the 3B is operated at 900 lbs/min above the optimum, yearly production increases by 22,560 LTPY, (473.6 WLTPH). However, under these conditions, the 3B overbed pressure is becoming more positive. Obviously, the plant will deviate on both sides of the optimum. What is not known is whether the deviations cancel or whether they are weighted to one side or the other. Common sense says they are weighted to the side that yields the least maintenance problems and highest operating margin of safety. Minntac personnel could determine this point if interested.

3.8.6 Statistics and Prediction Profiles - CFD Cooler with Wall Series: Figures 159 and 160 extend the analysis to the cooler with wall series of MEDUSA/CFD simulations. Now the comparison changes slightly, because with a wall in the cooler, the 3B fan can be placed back under automatic control, and continuously operated near optimum. The optimum flow occurs with 3A fan at 15,000 lbs/min and 3B fan at 13,550 lbs/min. Feed rate is essentially the same under these conditions at 469.88 WLTPH. This is shown in the first plot of Figure 160. This feed rate can be used again to judge the relative deviations explained in section 3.8.5, when the plant is not at full optimum. In this case, the additional control of the 3B fan should maintain the plant at optimum most of the time. The additional tonnage possible by installation of a wall can be computed under several scenarios:

Scenario One: Operators using manual mode maintain plant at optimum with the current cooler vs the cooler with wall that has automatic control installed on 3B fan; 3B overbed desirability limits are the same in both coolers:

Cooler without wall	469.9 WLTPH
Cooler with wall	469.9 WLTPH

No benefit with wall.

Scenario Two: Operators using manual mode maintain plant at a yearly averaged feed rate equivalent to 463.0 WLTPH (3B flow 1000 lbs/min < optimum) vs cooler with wall and automatic 3B control:

Cooler without wall	463.0 WLTPH
Cooler with wall	469.9 WLTPH

42,080 LTPY benefit with the wall installed.

Scenario Three: If the 3B overbed high pressure limit can be tightened using automatic control, raising the set point levels on 3B overbed pressure to:

low level	-0.25	in.H_2O
mid range	-0.15	in.H_2O
high limit	-0.05	in.H_2O

a) Cooler without wall, 3B flow at optimum	469.9 WLTPH
b) Cooler without wall, 3B flow below optimum	463.0 WLTPH
vs	
Cooler with wall, 3B flow continually at new optimum	478.5 WLTPH

a) 52,450 LTPY benefit with wall installed
b) 94,525 LTPH benefit with wall installed

3.8.7 Waste Gas Fan Operating Issues: Installation of a wall accomplishes three things:

1. Allows both cooler fans to operate in automatic control.
2. Dampens out the air flow oscillations moving through the kiln, preheat and DD1 zones, which are in part caused by 1A/B fans.
3. Results in more air available to the heat recoup system, possibly at slightly hotter temperatures.

The waste gas fan, however, must be operated differently from the present mode, where it is allowed to float with the preheat fan oscillations. If the full advantage of the wall is to be achieved, the waste gas fan must be run at maximum flow all the time. This will ensure moving the most recoup flow possible under any given operating conditions. If the waste gas fan continues to cycle with the preheats, the advantage of increased recoup heat recovery is lost, and this heat is vented up the stack. In addition, by not moving the maximum recoup flow, secondary cooling overbed pressure will increase slightly, which may limit the 3B flow under certain operating conditions.

3.8.8 Comparison of Plant Model to CFD and Hybrid Models:

The last set of figures compares the CFD and MEDUSA/CFD predictions with similar models generated from the plant data. These plots do not reflect cooler operation under optimum conditions, but rather operation through a range of conditions. The range chosen is patterned after current operation, where the 3A fan cycles through a range of flow, while the 3B fan is held constant in manual mode. Variable responses are plotted as a function of total cooler flow, where the 3A fan flow ranges from 10,000 to 17,000 lbs/min and the 3B flow is fixed at 13,500 lbs/min.

3.8.8.1 Comparison with CFD Models: Figures 161-166 compare the predictions of the plant data model with the CFD cooler model. Control variables in the plant data are feed rate, 3A flow and 3B flow. Control variables in the CFD model also include the ferrous iron content at the kiln discharge point.

3.8.8.1.1 Primary Cooling Overbed Pressure vs Total Cooler Flow: In Figure 161, overbed pressure is plotted for primary cooling zone in the plant and CFD models. Plant firing hood pressure is also included for reference. From about 26,000 lbs/min up to the maximum of 30,500 lbs/min, the plant and CFD predictions fall within 0.1 in.H_2O of each other. The installation of a wall offset one wind box does not significantly affect the primary cooling overbed pressure; it is essentially the same as the current cooler. Three simulations with a wall offset two wind boxes show that overbed pressure is decreased about -0.1 in.H_2O relative to the current cooler. This is because substantially more flow is diverted to secondary cooling. It is presumed that the firing hood pressure would be correspondingly lower, which implies that the 3A fan would operate at a higher level of flow if the same pressure control scheme is in place. Moving the wall one additional wind box would also increase the effect of 3A flow on 3B overbed pressure. This aspect has not been investigated in this study.

3.8.8.1.2 Kiln Secondary Air Temperature vs Total Cooler Flow: Figure 162 plots the kiln secondary air temperature as a function of cooler flow. The plant data shows relatively no change in temperature, while the CFD models predict a significant drop in temperature over the flow range (2350 to 2140°F). The presence of a wall offset one wind box does not significantly affect secondary air temperature. But if the wall is offset two wind boxes temperature is increased by 50 to 75°F by diverting the coolest portion of these gases to secondary cooling. Remember, the walls are being moved into the primary cooling zone, so that the zone size is reduced with each wind box of offset.

3.8.8.1.3 Calculated Flow to Kiln vs Total Cooler Flow: Figure 163 compares mass flow to the kiln. For the plant data, this is calculated as the difference between total flow into the cooler and that going out through the recoup and stack. Recoup flow is estimated using the CFD relationship between total flow and recoup A flow, since only the recoup A flow sensor was working during these tests. The plant data shows steeper slope over the flow range, doubling in mass flow (7,000 to 14000 lbs/min) as the 3A fan flow increases from 10,000 to 17,000 lbs/min. The CFD data tracks in the same direction, with flow ranging from 6,300 to 8,800 lbs/min. Placement of a wall with one wind box offset, again shows little impact on cooler flow. This is because the location chosen is near the natural break point (between flow reporting to kiln and flow reporting to recoup) in the cooler without a wall. However, shifting the wall another wind box (2 wind box offset) drops 1,000 to 1,500 lbs/min out of the kiln flow.

3.8.8.1.4 Total Recoup Flow vs Total Cooler Flow: Figure 164 displays predicted total recoup flow. In this figure, the plant and CFD models exhibit approximately the same slope, and the CFD prediction is approximately 1,000 lbs higher for both ducts. The effect of the wall shows slight deviations in flow, indicating slightly more flow at low 3A fan , and slightly less flow at high 3A fan, because with low 3A fan flow, the natural tendency is for 3A air entering through the last few wind boxes of primary cooling to move toward the kiln. Placement of a wall prevents this and keeps the air in the secondary cooling zone. At high 3A fan flow, the tendency is for 3A air in this same region to now move toward the secondary cooling zone, and the wall in this case prevents air from migrating to the recoup ducts. In moving the wall an additional wind box, there is a significant increase in recoup flow, because the wall is located upstream from the natural break point, and now diverts more 3A air to the secondary cooling zone. In the flow range tested, the wall at two wind box offset increases recoup flow approximately 200-400 lbs/min.

3.8.8.1.5 Averaged Recoup Temperature vs Total Cooler Flow: Figure 165 shows how the averaged recoup temperature for the total flow is affected by cooler flow. In this plot, the plant and CFD models track within 100°F or less over the flow range. The plant average is numerical, while the CFD values are mass weighted. The CFD values are slightly hotter on the low flow range and slightly cooler on the high flow range. The effect of the wall at one wind box offset further raises temperature at low flows (30-60°F) and very slightly decreases temperature under the high flow conditions (10-30°F). Moving the wall an additional wind box significantly raises the temperature by 100-150 °F. This was expected, since more primary cooling gas was diverted to secondary cooling.

3.8.8.1.6 Vent Stack Temperature vs Total Cooler Flow: Figure166 plots vent stack temperature vs total cooler flow. The plant and CFD models start out the same at low flow, and then diverge at maximum flow, the plant temperature remaining approximately 150°F hotter. The effect of the wall with one wind box offset is minimal, but with a two wind box offset the vent stack temperature is increased approximately 50°F.

3.8.8.1.7 Section Summary: The trends predicted by the CFD cooler simulations are reflected in the plant data, when analyzed in a similar manner. In some cases, the comparison is quite close to actual values, but in other instances the actual values vary significantly. However, both models demonstrate similar trends, which is most important. The weakest comparison occurs for kiln secondary air temperature. An additional validation test could be performed by obtaining a temperature profile across this duct for comparison to the

CFD simulations. If this gradient exists, it might be useful to monitor temperature at several locations across the duct and average the temperatures in this process stream.

3.8.8.2 Comparison with Hybrid Model: The last three figures are based on the same cooler flow conditions, just discussed, but now the plant model is compared on the same basis as the MEDUSA/CFD models. The interest is in predicting overall impact on furnace productivity and fuel consumption. The predictions were carried out over a flow range; they do not necessarily represent attainable operating conditions, which are limited by firing hood pressure, cooler overbed pressures and pellet exit temperatures from the cooler.

3.8.8.2.1 Estimated Feed Rate vs Total Cooler Flow: Figure 167 shows predicted feed rate to the grate as a function of cooler flow. Remember this is wet feed, and actual production must be adjusted for moisture and dust losses, and net LOI or GOI for magnetite and flux additions. The plant model consistently predicted a higher feed rate than MEDUSA/CFD, but the slopes of the two simulations are nearly equal, indicating that MEDUSA/CFD predicted a similar increase in production over the cooler flow range. This amounted to about a 35 WLTPH increase in the plant model, as compared to a 45 WLTPH increase in the computer model. The impact of a wall offset one wind box is also shown. The wall results in a loss of about 10 LTPH under low flow conditions, and an increase in flow of about 4 LTPH under the high 3A flow conditions.

3.8.8.2.2 Calculated Flow to Kiln vs Total Cooler Flow: Figure 168 is a second comparison of flow to the kiln. The flows are slightly different from those shown in figure 163, but the trends are essentially the same.

3.8.8.2.3 Fuel Consumption vs Total Cooler Flow: Figure 169 plots fuel consumption as a function of cooler flow. Fuel consumption decreases as cooler flow increases. The plant model has a steeper slope, intersecting the computer simulation at about 28,000 lbs/min. Under low flow conditions, the computer model predicted about 30,000 BTU/LT lower fuel than the plant model. Under the high flow conditions, the computer prediction was about 30,000 BTU/LT higher. The effect of the wall in the MEDUSA/CFD simulations resulted in a 20,000 BTU/LT increase in fuel consumption under low flow conditions and a 10,000 BTU/LT decrease under high flow conditions, relative to the simulations without a wall.

3.8.8.2.4 Section Summary: The plant data model yielded trends similar to those in the MEDUSA/CFD simulations. Feed rate predictions were offset about 25 WLTPH, but the slopes in the trends were nearly the same. For fuel consumption, the slope in the plant data was steeper over the flow range, indicating a greater sensitivity to cooler conditions. Improvement in model fit might also be attained by performing the full factorial design, instead of the one third used in this study, and by including the kiln solids discharge temperature as a variable in the CFD model design. MEDUSA calculates the kiln solids discharge temperature, and the greater the deviation between the MEDUSA value and the assumed CFD value, the greater the error in cooler heat flows. However, adding another variable to the CFD cooler design increases the full factorial simulations from 81 to 243, and the one third design from 27 to 81. Computer resources would have to at least double to keep the analysis on a reasonable time frame, or if a long range plan to model the current cooler in significantly more detail were approved, such an experimental design could be achieved over a three to six month time frame.

3.9 Conclusions:

3.9.1 General:

3.9.1.1 A three dimensional CFD cooler model was developed , validated and used to predict cooler performance over a range of plant operating conditions.

3.9.1.2 The MEDUSA mass and energy balance model has been validated against an operating Grate-Kiln induration line and proven capable of predicting plant performance with regard to changes in feed rate and fuel consumption.

3.9.1.3 An analytical method was developed using the CFD and MEDUSA models to optimize a Grate-Kiln induration line.

3.9.2 Specific to Minntac Line 6:

3.9.2.1 The waste gas fan appears undersized on Line 6 and probably limits furnace performance. The cooler does not appear to present any limitations under the conditions tested.

3.9.2.2 The computer simulations predicted an optimum cooler fan flow combination for maximum production and minimum fuel consumption. The plant tests duplicated this optimum, and indicated that the plant operates in this region most of the time.

3.9.2.3 Impact of a Cooler Wall:

3.9.2.3.1 Without a wall, the 3A and 3B fans are interdependent, and as a result, the 3B fan must be operated in manual to avoid affecting 3A fan operation.

3.9.2.3.2 A wall placed in the original location, aligned with the under bed damper, will restrict 3A fan flow to about 50% of its operating range, using firing hood pressure as an operating constraint.

3.9.2.3.3 A wall offset by one wind box from the original location, moving into the primary cooling zone, has the potential to increase production up to 94,500 LTPY. The production benefit is dependent on cooler fan operation, and on waste gas fan operation. The 3B cooler fan must be placed under automatic control, and the waste gas fan flow must be maximized at all times. If the waste gas fan is not maximized, 3B fan flow may be restricted, and cooling efficiency lost.

3.10 Recommendations:

3.10.1 General:

3.10.1.1 A complete factorial CFD model series should be completed and compared against the one third design used in this study, to test for non-linearity and overall accuracy.

3.10.1.2 A database model should be developed from the CFD simulations, for prediction of cooler responses to operating conditions. The list of control variables should also include kiln solids discharge temperature, cooler fan inlet air temperature, recoup duct outlet pressure, parallel flow duct outlet pressure, bed depth, bed permeability and pellet bulk density.

3.10.1.3 CMRL should purchase additional workstations to improve cooler simulation turn around time.

3.10.1.4 The cooler model should be used to study changes in cooler operating conditions under the Svedala Ported Kiln concept.

3.10.1.5 A more detailed analysis of pressure drop across the bed as function of air flow and bed characteristics should be performed.

3.10.2 Specific to Minntac Line 6:

3.10.2.1 A comprehensive study should be performed to isolate the causes of the oscillations in the Line 6 process fans, looking at filter, balling line, and roller screen operation.

3.10.2.2 Waste gas fan performance should be fully investigated, to determine if modifications can be made that would increase fan capacity.

3.10.2.3 A waste gas fan test should be conducted with this fan in manual at 90 to 100 % open damper, to test maximized recoup flow conditions in the plant. This test should last 5-10 days minimum.

3.10.2.4 A study of waste gas fan capacity could be conducted to define process productivity as a function of waste gas fan capacity. This study could also evaluate the relative sizes of the DD1 and DD2 drying zones, and substitution of hydrate lime for limestone on firing cycle.

3.10.2.5 An overbed dividing wall should be installed in the Line 6 cooler, offset one wind box from the under bed damper moving into the primary cooling zone (wind boxes 6/7 see Figure 34). A simulation series evaluating the two wind box offset, could also be completed for comparison to aid in determining the final wall location.

TABLE 1
MINNTAC COOLER INITIAL VALIDATION TEST SUMMARY

TEST DESCRIPTION			GREEN BALL RATE	PRORATED	PRODUCTION FACTOR		COOLER FEED RATE		3A FAN		3B FAN	
DATE	TIMES	ID	WLTLPH	RECYCLE	METH. 1	METH. 2	METH. 1	METH. 2	AMPS	LBS/MIN	AMPS	LBS/MIN
NOV 19, 1998	12:30-13:31	RUN 1	537.46	38.36	0.77	0.789	413.84	424.06	104.0	10,366	141.0	15,968
NOV 19, 1998	15:47-16:58	RUN 3	536.61	47.51	0.77	0.771	413.19	413.73	117.0	14,074	119.0	12,554
FEB 11, 1999	13:34-14:40	RUN 1	545.89	36.56	0.77	0.793	420.34	432.89	114.8	12,985	137.3	14,822
FEB 11, 1999	14:32-16:38	RUN 2	545.51	39.13	0.77	0.788	420.04	429.86	117.1	13,402	130.6	13,721
FEB 17, 1999	08:40-14:02	RUN 1	540.06	61.60	0.77	0.746	415.85	402.88	117.6	13,408	136.2	14,259
FEB 17, 1999	14:04-18:00	RUN 2	543.6	59.68	0.77	0.750	418.57	407.70	122.2	14,473	126.7	13,019
FEB 17, 1999	18:02-22:02	RUN 3	545.5	60.51	0.77	0.749	420.04	408.58	125.8	15,411	120.1	11,321
FEB 17, 1999	22:04-06:00	RUN 4	543.12	59.56	0.77	0.750	418.20	407.34	119.6	14,090	136.5	14,438
APR 19, 1999	13:22-17:04	RUN 1	549.05	67.76	0.77	0.737	422.77	404.65	115.3	13,823	116.2	12,105
APR 19, 1999	17:06-21:02	RUN 2	535.01	76.87	0.77	0.716	411.96	383.07	104.6	11,333	125.9	13,621
APR 19, 1999	21:04-00:44	RUN 3	548.77	70.70	0.77	0.731	422.55	401.15	101.6	10,329	137.0	15,355
APR 19, 1999	02:14-07:12	RUN 4	546.56	72.67	0.77	0.727	420.85	397.35	106.3	11,731	127.1	13,854
APR 19, 1999	07:14-0:814	RUN 5	546.71	78.45	0.77	0.716	420.97	391.44	105.1	11,493	124.6	13,406

COOLER FEED RATE CALCULATION

METHOD 1 GREENBALL RATE X PRODUCTION FACTOR$_1$

METHOD 2 (GREEN BALL RATE - PRORATED LINE 6 FINES RECYCLE) X (PRODUCTION FACTOR$_2$)

METHOD 1 PRODUCTION FACTOR$_1$ = 0.77

METHOD 2 PRODUCTION FACTOR$_2$ = 1-(NET FURNACE LOSS)

NET FURNACE LOSS = MOISTURE+ CALCINATION - OXIDATION GAIN + DUST/SPILLAGE LOSS = 0.14

	%WT	% LOI/GOI		FACTOR	
AVE MOISTURE =	9.5	100.00		0.095	
AVE LIMESTONE =	8.0	44.00		0.035	
AVE MAGNETITE =	87.0	3.45		-0.020	65% ON GRATE
EST DUST LOSS =	2.9	100.00		0.029	
			TOTAL	0.140	

METHOD 2 PRODUCTION FACTOR$_2$ = 1-(.14+RECYCLE/FEED)

TABLE 2:
MINNTAC PLANT VALIDATION TESTS

NOVEMBER 19, 1998 TESTS

Parameter	Item	Units	USX RUN 1 11/19/98	CFD 1_20_0800	CFD 1_21_0705	USX RUN 3 11/19/98	CFD RUN 3_1 1_22_0735	RUN 18 3_16_0830
GREENBALL FEED RATE		LTPH	537.46	NA	NA	536.61	NA	NA
PRODUCTION FACTOR METHOD 1			0.77	NA	NA	0.77	NA	NA
RECYCLE PRORATED PROD FACT. METHOD 2			0.79			0.77		
PELLET FEED TO COOLER METH. 1		LTPH	413.84	413.79	413.79	413.19	413.79	413.79
PRORATED FEED TO COOLER METH. 2			423.86			413.67		
GREENBALL MAGNETITE %WT			NA	87.00	87.00	NA	87.00	87.00
FE++ IN COOLER FEED			4.56-6.94	3.86	6.75	NA	6.75	5.31
FE3O4 IN COOLER FEED (FE3O4=FE++/.2412)		%WT	18.9 -28.8	16.00	28.00	NA	28.00	22
PELL. TEMP 15' FROM KILN DISCHG		DEGF	2,262	NA	NA	2,284	NA	NA
AVG PELLET TEMP ENTERING COOLER		DEGF	NA	2,199	2,199	NA	2,199	2,250
COOLER SPEED		IN/MIN	122	91	91	116	91	
COOLER BED DEPTH		IN	28	28	28	28	28	
PRI. COOLING ZONE 3A FAN	FLOW	LBS/MIN	10,366	10,366	10,884	14,074	14,074	14,074
	G/S		0.6551			0.9113		
	POWER	AMPS	104	NA	NA	117	NA	NA
	INLET	DEGF	19	19.4	19.4	16	19.4	19.4
	O'BED	IN.H2O	-0.119	-0.105	-0.059	0.030	0.022	-0.037
	U'BED	IN.H2O	14.385	14.140	14.920	15.686	17.450	16.86
	KFACT		NA	545	545	NA	545	545
KILN SECONDARY AIR	PLANT	DEGF	2,047	NA	NA	2,051	NA	NA
	AVG	DEGF	NA	2,194	2,265	NA	2,166	2,219
		LBS/MIN	NA	4,740	5,027	NA	5,582	5,139
	OUTLET	INH2O	NA	-0.40	-0.40	NA	-0.40	-0.40
FURNACE PHEAT O'BED		INH2O	-0.584	NA	NA	-0.506	NA	NA
		LBS/MIN	23,199	NA	NA	22,951	NA	NA
		G/S	1.4661			1.4861		
FIRING HOOD AIR		DEGF	NA	2,216	2,245	NA	2,235	2,297
		LBS/MIN	NA	2,747	2,834	NA	3,055	2,851
	OUTLET	INH2O	NA	-0.73	-0.73	NA	-0.73	-0.73
WINDBOX LEAKAGE		LBS/MIN	NA	861	887	NA	974	3,306
GAP HEIGHT		INCHES	NA	1	1	NA	1	3.62
WINDBOX DAMPER POSITION			OPEN	OPEN	OPEN	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER		INCHES	NA	NA	NA		4.7	1.67
SEC. COOLING ZONE 3B FAN	FLOW	LBS/MIN	15,968	15,969	16,767	12,554	12,554	12,554
	G/S		1.0091			0.8129		
	POWER	AMPS	141	NA	NA	119	NA	NA
	INLET	DEGF	19	19.4	19.4	16	19.4	19.4
	O'BED	IN.H2O	-0.113	-0.088	-0.015	-0.169	-0.175	-0.2457
	U'BED	IN.H2O	14.493	14.030	14.810	10.449	11.600	10.52
RECOUP B SIDE (WB 9)	PLANT	DEGF	1,607	1600-1625	1652-1668	1,558	1350-1370	
	AVG	DEGF	NA	1,647	1,684	NA	1,423	1,547
		LBS/MIN	NA	2,862	2,946	NA	2,921	2,728
	OUTLET	INH2O	NA	-1.00	-1.00	NA	-1.00	-1.00
FURNACE DD2 O'BED		INH2O	-1.007	NA	NA	-0.979	NA	NA
		DEGF	1,171	NA	NA	1,156	NA	NA
RECOUP A SIDE (WB10)	PLANT	DEGF	1,348	1297-1398	1296-1409	1,282	1140-1220	
	AVG	DEGF	NA	1,279	1,285	NA	1,121	1,265
		LBS/MIN	NA	3,314	3,441	NA	3,321	3,059
	OUTLET	INH2O	NA	-1.00	-1.00	NA	-1.00	-1.00
COOLER VENT STACK	PLANT	DEGF	727	NA	NA	687	NA	NA
	AVG	DEGF	NA	508	483	NA	527	584
		LBS/MIN	13,131	11,296	11,978	12,176	10,339	9,511
	OUTLET	INH2O	NA	-0.88	-0.88	NA	-0.88	-0.88
VENT STACK SEPARATION WALL			YES	YES	YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER		DEGF						
WINDBOX LEAKAGE		LBS/MIN	NA	581	594	NA	537	153
GAP HEIGHT		INCHES	NA	1	1	NA	1.0	1.0
O'BED LEAKAGE		LBS/MIN	NA	(68)	(58)	NA	(101)	(119)
GAP HEIGHT		INCHES	NA	1	1	NA	1	1
TOTAL AIR IN		LBS/MIN		26,403	27,710		26,729	26,747
TOTAL AIR OUT		LBS/MIN		26,401	27,708		26,729	26,746

NOTES:

1. RECOUP B SIDE TC LOCATION IN CFD IS 20-70 F COLDER THAN AVE. OUT
2. RECOUP A SIDE TC LOCATION IN CFD IS 20-120 F HOTTER THAN AVE. OUT
3. GAP ON VENT STACK SEPARATION WALL IS 8"
4. CFD PRESSURES CORRESPOND TO APPROX PLANT SENSOR LOCATIONS

TABLE 2:

MINNTAC PLANT VALIDATION TESTS

FEBRUARY 11, 1999 TESTS

				USX RUN 1 2/11/99	CFD RUN_4 2_17_99_0800	CFD RUN 17 3_15_0800	USX RUN 2 02/11/99	CFD RUN 5 2_18_2202	CFD RUN 16 3_12_0855
GREENBALL FEED RATE			LTPH	545.89	NA	NA	545.51	NA	NA
PRODUCTION FACTOR METHOD 1				0.77	NA	NA	0.77	NA	NA
RECYCLE PRORATED PROD FACT. METHOD 2				0.79			0.79		
PELLET FEED TO COOLER METH. 1			LTPH	420.34	420.33	420.33	420.04	420.33	420.33
PRORATED FEED TO COOLER METH. 2				432.88			430.03		
GREENBALL MAGNETITE %WT				NA	87.00	87.00	NA	87.00	87.00
FE++ IN COOLER FEED				NA	5.31	5.31	NA	5.31	5.31
FE3O4 IN COOLER FEED (FE3O4=FE++/.2412)			%WT	NA	22	22	NA	22	22
PELL. TEMP 15' FROM KILN DISCHG			DEGF	2,272	NA	NA	2,270	NA	NA
AVG PELLET TEMP ENTERING COOLER			DEGF	NA	2,199	2,250	NA	2,199	2,250
COOLER SPEED			IN/MIN	119.3	92		119.1		
COOLER BED DEPTH			IN	28	28		28		
PRI. COOLING ZONE	3A FAN	FLOW	LBS/MIN	12,985	12,985	12,985	13,403	13,402	13,402
		G/S		0.8035			0.8348		
		POWER	AMPS	114.83	NA	NA	117.05	NA	NA
		INLET	DEGF	13	12.2	12.2	12.6	12.2	12.2
		O'BED	IN.H2O	0.05	0.024	-0.042	0.0415	0.022	-0.0436
		U'BED	IN.H2O	16.16	16.990	16.17	16.2	17.18	16.45
		KFACT		NA	545	545	NA	545	545
	KILN SECONDARY AIR	PLANT	DEGF	2,057	NA	NA	2,055	NA	NA
		AVG	DEGF	NA	2,146	2,249	NA	2,142	2,243
			LBS/MIN	NA	5,652	5,115	NA	5,619	5,095
		OUTLET	INH2O	NA	-0.40	-0.40	NA	-0.40	-0.40
	FURNACE PHEAT O'BED		INH2O	-0.55	NA	NA	-0.56	NA	NA
			LBS/MIN	23,501	NA	NA	23,336	NA	NA
			G/S	1.4542			1.4536		
	FIRING HOOD AIR		DEGF	NA	2,222	2,297	NA	2,221	2,297
			LBS/MIN	NA	3,020	2,819	NA	3,026	2,826
		OUTLET	INH2O	NA	-0.73	-0.73	NA	-0.73	-0.73
	WINDBOX LEAKAGE		LBS/MIN	NA	952	3,215	NA	960	3,249
	GAP HEIGHT		INCHES	NA	1	3.62	NA	1	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES		4.7	1.67		4.7	1.67
SEC. COOLING ZONE	3B FAN	FLOW	LBS/MIN	14,822	14,818	14,818	13,721	13,720	13,720
		G/S		0.9172			0.8547		
		POWER	AMPS	137.31	NA	NA	130.62	NA	NA
		INLET	DEGF	13	12.2	12.2	13	12.2	12.2
		O'BED	IN.H2O	-0.15	-0.104	-0.145	-0.175	-0.147	-0.191
		U'BED	IN.H2O	14.07	12.5	12.22	12.5	11.91	11.49
	RECOUP B SIDE (WB 9)	PLANT	DEGF	1526			1522		
		AVG	DEGF	NA	1,422	1,622	NA	1,416	1,609
			LBS/MIN	NA	3,032	2,825	NA	2,973	2,765
		OUTLET	INH2O	NA	-1.00	-1.00	NA	-1.00	-1.00
	FURNACE DD2 O'BED		INH2O	-1.04	NA	NA	-1.06	NA	NA
			DEGF	1,151	NA	NA	1,153	NA	NA
	RECOUP A SIDE (WB10)	PLANT	DEGF	1,293			1,308		
		AVG	DEGF	NA	1,102	1,290	NA	1,111	1,303
			LBS/MIN	NA	3,481	3,218	NA	3,390	3,125
		OUTLET	INH2O	NA	-1.00	-1.00	NA	-1.00	-1.00
	COOLER VENT STACK	PLANT	DEGF	687	NA	NA	690	NA	NA
		AVG	DEGF	NA	471	541	NA	498	574
			LBS/MIN	12,500	11,197	10,543	12,274	10,704	10,007
		OUTLET	INH2O	NA	-0.88	-0.88	NA	-0.88	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF		258.8	291.2		284	320
	WINDBOX LEAKAGE		LBS/MIN	NA	556	158	NA	545	156
	GAP HEIGHT		INCHES	NA	1.0	1.0	NA	1.0	1.0
	O'BED LEAKAGE		LBS/MIN	NA	(83)	(89)	NA	(93)	(101)
	GAP HEIGHT		INCHES	NA	1	1	NA	1	1
	TOTAL AIR IN		LBS/MIN		27,886	27,891		27,214	27,223
	TOTAL AIR OUT		LBS/MIN		27,890	27,892		27,217	27,223

NOTES:

1. RECOUP B SIDE TC LOCATION IN CFD IS 20-70 F COLDER THAN AVE. OUT
2. RECOUP A SIDE TC LOCATION IN CFD IS 20-120 F HOTTER THAN AVE. OUT
3. GAP ON VENT STACK SEPARATION WALL IS 8"
4. CFD PRESSURES CORRESPOND TO APPROX PLANT SENSOR LOCATIONS

TABLE 2:
MINNTAC PLANT VALIDATION TESTS

FEBRUARY 17, 1999 TESTS

			USX	CFD		USX	CFD	CFD
			RUN 1	RUN 6	RUN 15	RUN 2	RUN 7	RUN 14
			2/17/99	2_24_0740	3_11_0735	2/17/99	2_25_0720	3_10_0930
GREENBALL FEED RATE		LTPH	540.06	NA	NA	543.6	NA	NA
PRODUCTION FACTOR METHOD 1			0.77	NA	NA	0.77	NA	NA
RECYCLE PRORATED PROD FACT. METHOD 2			0.75			0.75		
PELLET FEED TO COOLER METH. 1		LTPH	415.85	415.85	415.85	418.57	418.57	418.57
PRORATED FEED TO COOLER METH. 2			402.89			407.80		
GREENBALL MAGNETITE %WT			NA	87.00	87.00	NA	87.00	87.00
FE++ IN COOLER FEED			NA	5.31	5.31	NA	5.31	5.31
FE3O4 IN COOLER FEED (FE3O4=FE++/.2412)		%WT	NA	22	22	NA	22	22
PELL. TEMP 15' FROM KILN DISCHG		DEGF	2,259	NA	NA	2269	NA	NA
AVG PELLET TEMP ENTERING COOLER		DEGF	NA	2,199	2,250	NA	2,199	2,250
COOLER SPEED		IN/MIN	116.2			117.6	92	92
COOLER BED DEPTH		IN	28			28		
PRI. COOLING ZONE 3A FAN	FLOW	LBS/MIN	13,408	13,407	13,407	14,473	14,472	14,472
	G/S		0.8914			0.9506		
	POWER	AMPS	117.66	NA	NA	122.17	NA	NA
	INLET	DEGF	4.5	3.2	3.2	13	12.2	12.2
	O'BED	IN.H2O	0.025	0.0278	-0.0364	0.0266	0.0578	-0.0072
	U'BED	IN.H2O	16.125	17.11	16.4	17.45	17.85	17.26
	KFACT		NA	545	545	NA	545	545
KILN SECONDARY AIR	PLANT	DEGF	2,036	NA	NA	2,036		
	AVG	DEGF	NA	2,130	2,233	NA	2,101	2,202
		LBS/MIN	NA	5,682	5,161	NA	5,875	5,363
	OUTLET	INH2O	NA	-0.40	-0.40	NA	-0.40	-0.40
FURNACE PHEAT O'BED		INH2O	-0.495	NA	NA	-0.544	NA	NA
		LBS/MIN	23,328	NA	NA	23,846	NA	NA
		G/S	1.5509			1.5663		
FIRING HOOD AIR		DEGF	NA	2,221	2,296	NA	2,218	2,295
		LBS/MIN	NA	3,034	2,838	NA	3,114	2,913
	OUTLET	INH2O	NA	-0.73	-0.73	NA	-0.73	-0.73
WINDBOX LEAKAGE		LBS/MIN	NA	957	3,239	NA	984	3,346
GAP HEIGHT		INCHES	NA	1	3.62	NA	1	3.62
WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER		INCHES		4.7	1.67		4.7	1.67
SEC. COOLING ZONE 3B FAN	FLOW	LBS/MIN	14,259	14,259	14,259	13,019	13,020	13,020
	G/S		0.9480			0.8551		
	POWER	AMPS	136.17	NA	NA	126.72	NA	NA
	INLET	DEGF	4.5	3.2	3.2	13	12.2	12.2
	O'BED	IN.H2O	-0.188	-0.1307	-0.1745	-0.22	-0.167	-0.2185
	U'BED	IN.H2O	13.26	11.99	11.6	11.649	11.33	10.68
RECOUP B SIDE (WB 9)	PLANT	DEGF	1,507			1,483		
	AVG	DEGF	NA	1,377	1,570	NA	1,326	1,505
		LBS/MIN	NA	3,032	2,821	NA	3,028	2,810
	OUTLET	INH2O	NA	-1.00	-1.00	NA	-1.00	-1.00
FURNACE DD2 O'BED		INH2O	-1.000	NA	NA	-0.988	NA	NA
		DEGF	1,111	NA	NA	1,113	NA	NA
RECOUP A SIDE (WB10)	PLANT	DEGF	1,285			1,286		
	AVG	DEGF	NA	1,065	1,255	NA	1,035	1,220
		LBS/MIN	NA	3,474	3,202	NA	3,438	3,158
	OUTLET	INH2O	NA	-1.00	-1.00	NA	-1.00	-1.00
COOLER VENT STACK	PLANT	DEGF	625	NA	NA	676	NA	NA
	AVG	DEGF		459	530		478	551
		LBS/MIN	13,596	11,032	10,350	13,610	10,620	9,862
	OUTLET	INH2O	NA	-0.88	-0.88	NA	-0.88	-0.88
VENT STACK SEPARATION WALL			YES	YES	YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER		DEGF		251.6	284		276.8	309.2
WINDBOX LEAKAGE		LBS/MIN	NA	544	155	NA	533	152
GAP HEIGHT		INCHES	NA	1.0	1.0	NA	1.0	1.0
O'BED LEAKAGE		LBS/MIN	NA	(89)	(97)	NA	(102)	(113)
GAP HEIGHT		INCHES	NA	1	1	NA	1	1
TOTAL AIR IN		LBS/MIN		27,756	27,763		27,593	27,605
TOTAL AIR OUT		LBS/MIN		27,755	27,764		27,594	27,604

NOTES:

1. RECOUP B SIDE TC LOCATION IN CFD IS 20-70 F COLDER THAN AVE. OUT
2. RECOUP A SIDE TC LOCATION IN CFD IS 20-120 F HOTTER THAN AVE. OUT
3. GAP ON VENT STACK SEPARATION WALL IS 8"
4. CFD PRESSURES CORRESPOND TO APPROX PLANT SENSOR LOCATIONS

TABLE 2:

MINNTAC PLANT VALIDATION TESTS

FEBRUARY 17, 1999 TESTS

Parameter		Item	Units	USX RUN 3 2/17/99	CFD RUN 8 2_26_0725	CFD RUN 13 3_09_	USX RUN 4 2/17/99	CFD RUN 9 3_1_0725	CFD RUN 10 3_2_0900
GREENBALL FEED RATE			LTPH	545.5	NA	NA	543.1	NA	NA
PRODUCTION FACTOR METHOD 1				0.77	NA	NA	0.77	NA	NA
RECYCLE PRORATED PROD FACT. METHOD 2				0.75			0.75		
PELLET FEED TO COOLER METH. 1			LTPH	420.04	418.57	418.57	418.19	418.57	418.57
PRORATED FEED TO COOLER METH. 2				408.63			407.57		
GREENBALL MAGNETITE %WT				NA	87.00	87.00	NA	87.00	87.00
FE++ IN COOLER FEED				NA	5.31	5.31	NA	5.31	5.31
FE3O4 IN COOLER FEED (FE3O4=FE++/.2412)			%WT	NA	22	22	NA	22	22
PELL. TEMP 15' FROM KILN DISCHG			DEGF	2268	NA	NA	2268	NA	NA
AVG PELLET TEMP ENTERING COOLER			DEGF	NA	2,199	2,250	NA	2,199	2,250
COOLER SPEED			IN/MIN	119.4	92	92	118.6	92	92
COOLER BED DEPTH			IN	28			28		
PRI. COOLING ZONE	3A FAN	FLOW	LBS/MIN	15,411	15,412	15,412	14,091	14,091	14,091
		G/S		1.0102			0.9261		
		POWER	AMPS	125.84	NA	NA	119.64	NA	NA
		INLET	DEGF	5.5	5	5	1.3	1.4	1.4
		O'BED	IN.H2O	-0.028	0.0671	0.0042	0.0652	0.0665	0.123
		U'BED	IN.H2O	17.69	18.3	17.86	16.765	17.65	19.02
		KFACT		NA	545	545	NA	545	545
	KILN SECONDARY AIR	PLANT	DEGF	2,027			2,029		
		AVG	DEGF	NA	2,085	2,182	NA	2,101	2,122
			LBS/MIN	NA	5,915	5,431	NA	5,957	6,274
		OUTLET	INH2O	NA	-0.40	-0.40	NA	-0.40	-0.40
	FURNACE PHEAT O'BED		INH2O	-0.625	NA	NA	-0.516	NA	NA
			LBS/MIN	24,094	NA	NA	23,910	NA	NA
			G/S	1.5794			1.5714		
	FIRING HOOD AIR		DEGF	NA	2,215	2,291	NA	2,219	2,261
			LBS/MIN	NA	3,159	2,961	NA	3,116	3,210
		OUTLET	INH2O	NA	-0.73	-0.73	NA	-0.73	-0.73
	WINDBOX LEAKAGE		LBS/MIN	NA	1,000	3,415	NA	974	1,006
	GAP HEIGHT		INCHES	NA	1	3.62	NA	1	1
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES		4.7	1.67		4.7	1.67
SEC. COOLING ZONE	3B FAN	FLOW	LBS/MIN	11,321	11,321	11,321	14,438	14,438	14,438
		G/S		0.7421			0.9489		
		POWER	AMPS	120.06	NA	NA	136.54	NA	NA
		INLET	DEGF	5.5	5	5	1.3	1.4	1.4
		O'BED	IN.H2O	-0.342	-0.231	-0.289	-0.136	-0.1125	-0.157
		U'BED	IN.H2O	8.711	10.26	9.39	13.389	11.97	10.53
	RECOUP B SIDE (WB 9)	PLANT	DEGF	1,433			1,476		
		AVG	DEGF	NA	1,296	1,466	NA	1,314	1,288
			LBS/MIN	NA	2,965	2,743	NA	3,128	3,136
		OUTLET	INH2O	NA	-1.00	-1.00	NA	-1.00	-1.00
	FURNACE DD2 O'BED		INH2O	-1.083	NA	NA	-0.945	NA	NA
			DEGF	1,098	NA	NA	1,108	NA	NA
	RECOUP A SIDE (WB10)	PLANT	DEGF	1,303			1,268		
		AVG	DEGF	NA	1,015	1,201	NA	1,007	1,011
			LBS/MIN	NA	3,334	3,044	NA	3,584	3,532
		OUTLET	INH2O	NA	-1.00	-1.00	NA	-1.00	-1.00
	COOLER VENT STACK	PLANT	DEGF	707	NA	NA	635	NA	NA
		AVG	DEGF		501	583		432	420
			LBS/MIN	13,503	9,973	9,137	13,683	11,314	10,964
		OUTLET	INH2O	NA	-0.88	-0.88	NA	-0.88	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF		303.8	339.8		235.4	
	WINDBOX LEAKAGE		LBS/MIN	NA	511	147	NA	542	
	GAP HEIGHT		INCHES	NA	1.0	0.5	NA	1.0	1.0
	O'BED LEAKAGE		LBS/MIN	NA	(123)	(142)	NA	(88)	(103)
	GAP HEIGHT		INCHES	NA	1	1	NA	1	1
		TOTAL AIR IN	LBS/MIN		26,856	26,875		28,617	28,632
		TOTAL AIR OUT	LBS/MIN		26,857	26,876		28,616	28,121

NOTES:

1. RECOUP B SIDE TC LOCATION IN CFD IS 20-70 F COLDER THAN AVE. OUT
2. RECOUP A SIDE TC LOCATION IN CFD IS 20-120 F HOTTER THAN AVE. OUT
3. GAP ON VENT STACK SEPARATION WALL IS 8"
4. CFD PRESSURES CORRESPOND TO APPROX PLANT SENSOR LOCATIONS

TABLE 2:

MINNTAC PLANT VALIDATION TESTS

						APRIL 19, 1999 TESTS			
				CFD	CFD	USX	CFD	USX	CFD
				RUN 11	RUN 12	RUN 1	RUN 19	RUN 2	RUN 20
				3_5_0730	3_8_1240	4/19/99	4_22_0715	4/19/99	4_23_0725
GREENBALL FEED RATE			LTPH	NA	NA	549.05	NA	535.01	NA
PRODUCTION FACTOR METHOD 1				NA	NA	0.77	NA	0.77	NA
RECYCLE PRORATED PROD FACT. METHOD 2						0.74		0.72	
PELLET FEED TO COOLER METH. 1			LTPH	418.57	418.57	422.77	422.76	411.96	411.95
PRORATED FEED TO COOLER METH. 2						404.43		383.20	
GREENBALL MAGNETITE %WT				87.00	87.00	NA	87.00	NA	87.00
FE++ IN COOLER FEED				5.31	5.31	NA	5.31	NA	5.31
FE3O4 IN COOLER FEED (FE3O4=FE++/.2412)			%WT	22	22	NA	22	NA	22
PELL. TEMP 15' FROM KILN DISCHG			DEGF	NA	NA	2273	NA	2255	NA
AVG PELLET TEMP ENTERING COOLER			DEGF	2,250	2,250	NA	2,250	NA	2,250
COOLER SPEED			IN/MIN	92	92	114.7	93	109.5	91
COOLER BED DEPTH			IN			28		28	
PRI. COOLING ZONE	3A FAN	FLOW	LBS/MIN	14,091	14,091	13,823	13,823	11,333	11,333
		G/S				0.9155		0.7922	
		POWER	AMPS	NA	NA	115.26	NA	104.6	
		INLET	DEGF	1.4	1.4	42.3	42.26	47.5	47.66
		O'BED	IN.H2O	0.0619	0.0001	-0.008	-0.069	-0.018	-0.138
		U'BED	IN.H2O	18.02	17	15.46	16.81	12.66	14.61
		KFACT		545	545	NA	545	NA	545
	KILN SECONDARY AIR	PLANT	DEGF			2,028		2,031	
		AVG	DEGF	2,163	2,204	NA	2,252	NA	2,315
			LBS/MIN	5,870	5,439	NA	4,857	NA	4,339
		OUTLET	INH2O	-0.40	-0.40	NA	-0.40	NA	-0.40
	FURNACE PHEAT O'BED		INH2O	NA	NA	-0.475	NA	-0.356	NA
			LBS/MIN	NA	NA	22,379	NA	21,075	NA
			G/S			1.4822		1.4731	
	FIRING HOOD AIR		DEGF	2,284	2,294	NA	2,296	NA	2,308
			LBS/MIN	3,059	2,917	NA	2,797	NA	2,606
		OUTLET	INH2O	-0.73	-0.73	NA	-0.73	NA	-0.73
	WINDBOX LEAKAGE		LBS/MIN	2,204	3,306	NA	3,313	NA	3,055
	GAP HEIGHT		INCHES	2.24	3.62	NA	3.62	NA	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67		1.67		1.67
SEC. COOLING ZONE	3B FAN	FLOW	LBS/MIN	14,438	14,438	12,105	12,104	13,621	13,622
		G/S				0.8017		0.9521	
		POWER	AMPS	NA	NA	116.15	NA	125.89	NA
		INLET	DEGF	1.4	1.4	42.3	42.26	47.5	47.66
		O'BED	IN.H2O	-0.15	-0.16	-0.331	-0.303	-0.279	-0.214
		U'BED	IN.H2O	11.08	11.48	9.58	10.7	11.78	12.38
	RECOUP B SIDE (WB 9)	PLANT	DEGF			1,526		1,622	
		AVG	DEGF	1,386	1,496	NA	1,626	NA	1,816
			LBS/MIN	3,035	2,909	2635	3,026	2450	2,736
		OUTLET	INH2O	-1.00	-1.00	-1.3	-1.30		-1.10
	FURNACE DD2 O'BED		INH2O	NA	NA	-1.23	NA	-1.07	NA
			DEGF	NA	NA	1,104	NA	1,202	NA
	RECOUP A SIDE (WB10)	PLANT	DEGF			1,291		1,358	
		AVG	DEGF	1,091	1,187	NA	1,343	NA	1,487
			LBS/MIN	3,437	3,302	2,308	3,039	2,171	2,713
		OUTLET	INH2O	-1.00	-1.00	-1.1	-1.10		-0.90
	COOLER VENT STACK	PLANT	DEGF	NA	NA	697	NA	685	NA
		AVG	DEGF	450	497		650		691
			LBS/MIN	10,874	10,600	11,963	8,865	11,818	9,437
		OUTLET	INH2O	-0.88	-0.88	NA	-0.88	NA	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF		262.4		406.4		413.6
	WINDBOX LEAKAGE		LBS/MIN	149	153	NA	157	NA	166
	GAP HEIGHT		INCHES	0.5	0.5	NA	0.5	NA	0.5
	O'BED LEAKAGE		LBS/MIN	(99)	(96)	NA	(125)	NA	(97)
	GAP HEIGHT		INCHES	1	1	NA	1	NA	1
	TOTAL AIR IN		LBS/MIN	28,628	28,625		26,052		25,052
	TOTAL AIR OUT		LBS/MIN	28,628	28,626		26,054		25,053

NOTES:

1. RECOUP B SIDE TC LOCATION IN CFD IS 20-70 F COLDER THAN AVE. OUT
2. RECOUP A SIDE TC LOCATION IN CFD IS 20-120 F HOTTER THAN AVE. OUT
3. GAP ON VENT STACK SEPARATION WALL IS 8"
4. CFD PRESSURES CORRESPOND TO APPROX PLANT SENSOR LOCATIONS

TABLE 2:
MINNTAC PLANT VALIDATION TESTS

APRIL 19 1999

				USX RUN 3 4/19/99	CFD RUN 21 4_26_0720	USX RUN 4 4/19/99	CFD RUN 22 4_27_0745	USX RUN 5 4/19/99	CFD RUN 23 4_28_0710
GREENBALL FEED RATE			LTPH	548.77	NA	546.56	NA	546.71	NA
PRODUCTION FACTOR METHOD 1				0.77	NA	0.77	NA	0.77	NA
RECYCLE PRORATED PROD FACT. METHOD 2				0.73		0.73		0.72	
PELLET FEED TO COOLER METH. 1			LTPH	422.55	422.48	420.85	420.87	420.97	420.87
PRORATED FEED TO COOLER METH. 2				401.27		397.38		391.76	
GREENBALL MAGNETITE %WT				NA	87.00	NA	87.00	NA	87.00
FE++ IN COOLER FEED				NA	5.31	NA	5.31	NA	5.31
FE3O4 IN COOLER FEED (FE3O4=FE++/.2412)			%WT	NA	22	NA	22	NA	22
PELL. TEMP 15' FROM KILN DISCHG			DEGF	2256	NA	2252	NA	2266	NA
AVG PELLET TEMP ENTERING COOLER			DEGF	NA	2,250	NA	2,250	NA	2,250
COOLER SPEED			IN/MIN	116	93	113.4	93	111.98	92
COOLER BED DEPTH			IN	28		28		28	
PRI. COOLING ZONE	3A FAN	FLOW	LBS/MIN	10,329	10,331	11,731	11,731	11,493	11,498
		G/S		0.6895		0.7907		0.7858	
		POWER	AMPS	101.6	NA	106.3	NA	105.13	NA
		INLET	DEGF	40	40.46	35.7	35.6	37	37.4
		O'BED	IN.H2O	-0.048	-0.152	-0.025	-0.124	-0.055	-0.141
		U'BED	IN.H2O	12.11	14.05	13.15	15.06	12.47	14.81
		KFACT		NA	545	NA	545	NA	545
	KILN SECONDARY AIR	PLANT	DEGF	2,017		2,037		2,003	
		AVG	DEGF	NA	2,347	NA	2,311	NA	2,323
			LBS/MIN	NA	4,232	NA	4,449	NA	4,293
		OUTLET	INH2O	NA	-0.40	NA	-0.40	NA	-0.40
	FURNACE PHEAT O'BED		INH2O	-0.494	NA	-0.439	NA	-0.457	NA
			LBS/MIN	21,876	NA	21,653	NA	21,779	NA
			G/S	1.4603		1.4595		1.4891	
	FIRING HOOD AIR		DEGF	NA	2,308	NA	2,304	NA	2,305
			LBS/MIN	NA	2,569	NA	2,645	NA	2,606
		OUTLET	INH2O	NA	-0.73	NA	-0.73	NA	-0.73
	WINDBOX LEAKAGE		LBS/MIN	NA	2,971	NA	3,098	NA	3,071
	GAP HEIGHT		INCHES	NA	3.62	NA	3.62	NA	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES		1.67		1.67		1.67
SEC. COOLING ZONE	3B FAN	FLOW	LBS/MIN	15,355	15,353	13,854	13,854	13,406	13,405
		G/S		1.0250		0.9338		0.9166	
		POWER	AMPS	137	NA	127.09	NA	124.6	NA
		INLET	DEGF	40	40.46	35.7	35.6	37	37.4
		O'BED	IN.H2O	-0.279	-0.166	-0.297	-0.216	-0.348	-0.239
		U'BED	IN.H2O	13.73	13.79	11.77	12.42	11.547	12.3
	RECOUP B SIDE (WB 9)	PLANT	DEGF	1,664		1,651		1,641	
		AVG	DEGF	NA	1,906	NA	1,799	NA	1,859
			LBS/MIN	2517	2,870	2525	2,881	2573	2,822
		OUTLET	INH2O		-1.21		-1.21		-1.21
	FURNACE DD2 O'BED		INH2O	-1.19	NA	-1.205	NA	-1.266	NA
			DEGF	1,223	NA	1,231	NA	1,186	NA
	RECOUP A SIDE (WB10)	PLANT	DEGF	1,344		1,356		1,359	
		AVG	DEGF	NA	1,509	NA	1,464	NA	1,514
			LBS/MIN	2,286	2,950	2,255	2,913	2,256	2,834
		OUTLET	INH2O		-1.01		-1.01		-1.01
	COOLER VENT STACK	PLANT	DEGF	717	NA	692	NA	727	NA
		AVG	DEGF		671		667		710
			LBS/MIN	11,887	10,001	11,515	9,530	11,784	9,211
		OUTLET	INH2O	NA	-0.88	NA	-0.88	NA	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF		401		399.2		435.2
	WINDBOX LEAKAGE		LBS/MIN	NA	170	NA	165	NA	166
	GAP HEIGHT		INCHES	NA	0.5	NA	0.5	NA	0.5
	O'BED LEAKAGE		LBS/MIN	NA	(79)	NA	(96)	NA	(97)
	GAP HEIGHT		INCHES	NA	1	NA	1	NA	1
		TOTAL AIR IN	LBS/MIN		25,763		25,681		24,999
		TOTAL AIR OUT	LBS/MIN		25,764		25,682		25,003

NOTES:
1. RECOUP B SIDE TC LOCATION IN CFD IS 20-70 F COLDER THAN AVE. OUT
2. RECOUP A SIDE TC LOCATION IN CFD IS 20-120 F HOTTER THAN AVE. OUT
3. GAP ON VENT STACK SEPARATION WALL IS 8"
4. CFD PRESSURES CORRESPOND TO APPROX PLANT SENSOR LOCATIONS

TABLE 2:

MINNTAC PLANT VALIDATION TESTS

				ADJUSTED TONNAGE RUNS					
				4/19-R5	2/17-R4	2/11-R1	4/19-R2	2/17-R3	4/19-R3
				RUN 24	RUN 25	RUN 26	RUN 27	RUN 28	RUN 29
				4_30_0710	5_3_0805	5_4_0930	5_5_0755	5_6_0800	5_7_1410
GREENBALL FEED RATE			LTPH	NA	NA	NA	NA	NA	NA
PRODUCTION FACTOR METHOD 1				NA	NA	NA	NA	NA	NA
RECYCLE PRORATED PROD FACT. METHOD 2									
PELLET FEED TO COOLER METH. 1			LTPH						
PRORATED FEED TO COOLER METH. 2				391.34	407.53	432.88	383.27	408.66	401.18
GREENBALL MAGNETITE %WT				87.00	87.00	87.00	87.00	87.00	87.00
FE++ IN COOLER FEED				5.31	5.31	5.31	5.31	5.31	5.31
FE3O4 IN COOLER FEED (FE3O4=FE++/.2412)			%WT	22	22	22	22	22	22
PELL. TEMP 15' FROM KILN DISCHG			DEGF	NA	NA	NA	NA	NA	NA
AVG PELLET TEMP ENTERING COOLER			DEGF	2,250	2,250	2,250	2,250	2,250	2,250
COOLER SPEED			IN/MIN	86	90	95	84	90	88
COOLER BED DEPTH			IN						
PRI. COOLING ZONE	3A FAN	FLOW	LBS/MIN	11,498	14,091	12,985	11,333	15,412	10,331
		G/S							
		POWER	AMPS	NA	NA	NA	NA	NA	NA
		INLET	DEGF	37.4	1.4	12.2	47.66	5	40.46
		O'BED	IN.H2O	-0.154	0.0047	-0.0253	-0.1509	-0.0017	-0.1587
		U'BED	IN.H2O	14.45	16.84	16.36	14.26	17.69	13.76
		KFACT		545	545	545	545	545	545
	KILN SECONDARY AIR	PLANT	DEGF						
		AVG	DEGF	2,300	2,182	2,256	2,289	2,169	2,336
			LBS/MIN	4,195	5,494	5,243	4,243	5,403	4,177
		OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40
	FURNACE PHEAT O'BED		INH2O	NA	NA	NA	NA	NA	NA
			LBS/MIN	NA	NA	NA	NA	NA	NA
			G/S						
	FIRING HOOD AIR		DEGF	2,310	2,296	2,296	2,311	2,293	2,310
			LBS/MIN	2,572	2,919	2,854	2,573	2,946	2,499
		OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73	-0.73	-0.73
	WINDBOX LEAKAGE		LBS/MIN	3,035	3,292	3,232	3,019	3,400	2,944
	GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62	3.62	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67	1.67	1.67
SEC. COOLING ZONE	3B FAN	FLOW	LBS/MIN	13,405	14,438	14,818	13,622	11,321	15,353
		G/S							
		POWER	AMPS	NA	NA	NA	NA	NA	NA
		INLET	DEGF	37.4	1.4	12.2	47.66	5	40.46
		O'BED	IN.H2O	-0.273	-0.1472	-0.0999	-0.2486	-0.2992	-0.1887
		U'BED	IN.H2O	11.57	11.25	12.55	11.66	9.19	13.27
	RECOUP B SIDE (WB 9)	PLANT	DEGF						
		AVG	DEGF	1,730	1,430	1,654	1,705	1,411	1,842
			LBS/MIN	2,847	3,011	2,893	2,758	2,961	2,883
		OUTLET	INH2O	-1.21	-1.00	-1.00	-1.10	-1.10	-1.21
	FURNACE DD2 O'BED		INH2O	NA	NA	NA	NA	NA	NA
			DEGF	NA	NA	NA	NA	NA	NA
	RECOUP A SIDE (WB10)	PLANT	DEGF						
		AVG	DEGF	1,392	1,138	1,340	1,366	1,156	1,432
			LBS/MIN	2,866	2,975	2,880	2,737	2,846	2,974
		OUTLET	INH2O	-1.01	-0.80	-0.80	-0.90	-0.90	-1.01
	COOLER VENT STACK	PLANT	DEGF	NA	NA	NA	NA	NA	NA
		AVG	DEGF	608	472	586	590	553	599
			LBS/MIN	9,334	10,785	10,624	9,569	9,176	10,125
		OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88	-0.88	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF	348.8	240.8	321.8	332.6	314.6	338
	WINDBOX LEAKAGE		LBS/MIN	159	151	161	159	144	166
	GAP HEIGHT		INCHES	0.5	0.5	0.5	0.5	0.5	0.5
	O'BED LEAKAGE		LBS/MIN	(107)	(97)	(84)	(104)	(145)	(83)
	GAP HEIGHT		INCHES	1	1	1	1	1	1
	TOTAL AIR IN		LBS/MIN	25,010	28,626	27,887	25,059	26,877	25,767
	TOTAL AIR OUT		LBS/MIN	25,008	28,627	27,887	25,059	26,877	25,767

NOTES:

1. RECOUP B SIDE TC LOCATION IN CFD IS 20-70 F COLDER THAN AVE. OUT
2. RECOUP A SIDE TC LOCATION IN CFD IS 20-120 F HOTTER THAN AVE. OUT
3. GAP ON VENT STACK SEPARATION WALL IS 8"
4. CFD PRESSURES CORRESPOND TO APPROX PLANT SENSOR LOCATIONS

TABLE 3
INITIAL VALIDATION TESTS - PLOTTING SYMBOL INDEX

Legend Label	BC-1	BC-2	BC-3	BC-4	BC-5	BC-6
	□	△	▲	╳	⧗	⊠
Simulations						
11/19_R1	X	X	—	—	—	—
11/19_R3	—	—	X	—	X	—
2/11_R1	—	—	—	X	X	X
2/11_R2	—	—	—	X	X	—
2/17_R1	—	—	—	X	X	—
2/17_R2	—	—	—	X	X	—
2/17_R3	—	—	—	X	X	X
2/17_R4	—	—	—	X	X	X
4/19_R1	—	—	—	—	X	—
4/19_R2	—	—	—	—	X	X
4/19_R3	—	—	—	—	X	X
4/19_R4	—	—	—	—	X	—
4/19_R5	—	—	—	—	X	X
Variable Parameters						
% Magnetite	16	28	28	22	22	22
Pellet Feed to Cooler	Method 1	Method 1	Method 1	Method 1	Method 1	Method 2
Pellet Discharge Temp Deg	2200	2200	2200	2200	2250	2250
Primary Cooling Zone Leakage	LOW LEAKAGE RATE				HIGH LEAKAGE RATE	
Under Bed Gap	1	1	1	1	3.6	3.6
Damper Gap	Open	Open	Closed - 4.7"	Closed - 4.7"	Closed - 1.7"	Closed - 1.7"
3A Fan Flow	Plant	Plant+5%	Plant	Plant	Plant	Plant
3B Fan Flow	Plant	Plant+5%	Plant	Plant	Plant	Plant
Recoup Outlet Pressures	A = B	A = B	A = B	A = B	A = B for Nov & Feb A is 0.2 > B for Apr	A is 0.2 > B

TABLE 4

MINNTAC MEDUSA VALIDATION SUMMARY:
FEED RATES CALC. FROM PLANT DATA

	Test		Nov19 Run 1	Nov19 Run 3		Feb 11 Run 1	
CFD DATA FILE:			1_20_0800	1_22_0735	3_16_0830	2_17_0800	3_15_0800
Medusa Data Format			EQUAL OUTLET PRESSURES ON RECOUP DUCTS				
3A/3B DAMPER POSITION			open	closed		closed	
GREEN BALLS	kg/s	2	140.84	137.94		143.73	
		1	135.77	135.77		137.92	
HEARTH LAYER	kg/s		0	0		0	
PELLET DIAMETER	M		0.0111	0.0111		0.0111	
GREEN BALLS TEMPERATURE	K		290	290		290	
HEARTH LAYER TEMPERATURE	K		290	290		290	
MAGNETITE FRACTION	Xm		0.7582	0.7582		0.7582	
HEARTH LAYER FRACTION	Xh		0	0		0	
INERT FRACTION			0.04380	0.04380		0.04380	
FLUX FRACTION			0.06934	0.06934		0.06934	
MOISTURE FRACTION			0.08759	0.08759		0.08759	
PELLET POROSITY			0.25	0.25		0.25	
SOLIDS EMMISSITIVITY			0.60	0.60		0.60	
OUTSIDE AIR TEMPERATURE	K		266	264		262	
LEAKAGE AIR TEMPERATURE	K		290	290		290	
NUMBER OF ZONES			7	7		7	
MACHINE TYPE			1	1		1	
KILN ZONE #			4	4		4	
FIRING ZONE			4	4		4	
AIR IN, KMOLS/S				Low Outleak	High Outleak	Low Outleak	High Outleak
	DD1	1	0	0		0	
	DD2	2	0	0		0	
	PH	3	0	0		0	
	KILN	4	0	0		0	
	C1	5	1.9536	2.2537	2.0849	2.2629	2.0703
	C2	6	1.6116	1.6288	1.5100	1.6995	1.5768
	C3	7	2.9476	2.6978	2.4818	2.9217	2.7511
TEMPS K	C1		1479	1472	1503	1462	1514
	C2		1061	957	1032	950	1058
TARGET VARIALBLES							
DD1 OBED	K		621	625		632	
PH FAN -1A	K		616	624		622	
PH FAN -1B	K		633	635		654	
KILN SEC AIR	K		1392	1395		1397	
BURN ZONE (REFRAC)	K		1629	1626		1622	
KILN SOLIDS EXIT	K		1512	1524		1517	
PLANT OVER BED PRESSURES	DD1		-0.49	-0.48		-0.67	
	DD2		-1.01	-0.98		-1.04	
	PH		-0.58	-0.51		-0.55	
UNDER BED PRESSURE	PH		-9.63	-9.85		-4.89	
ESTIMATED LEAK KMOLS/S	DD1 OBED		0.53	0.52		0.61	
	DD2 OBED		0.35	0.38		0.39	
	PH OBED		0.81	0.75		0.79	
	PH UBED		1.19	1.20		0.85	
FUEL, KMOLS/S	DD2		0	0		0	
	PH	3	0.0288	0.0288		0.0288	
	KILN	4	0.0643	0.0533		0.0588	

MINNTAC MEDUSA VALIDATION SUMMARY:
FEED RATES CALC. FROM PLANT DATA

	Test			Feb 11 Run 2		Feb 17 Run 1		Feb 17 Run 2	
CFD DATA FILE:				2_18_2202 3_12_0855		2_24_0740 3_11_0735		2_25_0720 3_10_0930	
Medusa Data Format				EQUAL OUTLET PRESSURES ON RECOUP DUCTS					
3A/3B DAMPER POSITION				closed		closed		closed	
GREEN BALLS	kg/s		2	142.89		135.02		136.56	
			1	137.92		136.45		137.34	
HEARTH LAYER	kg/s			0		0		0	
PELLET DIAMETER	M			0.0111		0.0111		0.0111	
GREEN BALLS TEMPERATURE	K			290		290		290	
HEARTH LAYER TEMPERATURE	K			290		290		290	
MAGNETITE FRACTION	Xm			0.7582		0.7582		0.7582	
HEARTH LAYER FRACTION	Xh			0		0		0	
INERT FRACTION				0.04380		0.04380		0.04380	
FLUX FRACTION				0.06934		0.06934		0.06934	
MOISTURE FRACTION				0.08759		0.08759		0.08759	
PELLET POROSITY				0.25		0.25		0.25	
SOLIDS EMMISSITIVITY				0.60		0.60		0.60	
OUTSIDE AIR TEMPERATURE	K			262		257		262	
LEAKAGE AIR TEMPERATURE	K			290		290		290	
NUMBER OF ZONES				7		7		7	
MACHINE TYPE				1		1		1	
KILN ZONE #				4		4		4	
FIRING ZONE				4		4		4	
				Low Outleak	High Outleak	Low Outleak	High Outleak	Low Outleak	High Outleak
AIR IN, KMOLS/S	1	DD1		0		0		0	
	2	DD2		0		0		0	
	3	PH		0		0		0	
	4	KILN		0		0		0	
	5	C1		2.2558	2.0669	2.2743	2.0872	2.3456	2.1595
	6	C2		1.6603	1.5369	1.6977	1.5716	1.6872	1.5573
	7	C3		2.7931	2.7511	2.8787	2.7007	2.7712	2.5734
TEMPS K		C1		1461	1512	1456	1508	1445	1497
		C2		952	1059	928	1034	906	1008
TARGET VARIALBLES									
DD1 OBED		K		631		627		631	
PH FAN -1A		K		624		624		626	
PH FAN -1B		K		652		645		647	
KILN SEC AIR		K		1397		1386		1386	
BURN ZONE (REFRAC)		K		1620		1619		1623	
KILN SOLIDS EXIT		K		1516		1510		1516	
PLANT OVER BED PRESSURES		DD1		-0.64		-0.58		-0.30	
		DD2		-1.06		-1.00		-0.99	
		PH		-0.56		-0.50		-0.54	
UNDER BED PRESSURE		PH		-5.04		-5.90		-6.21	
ESTIMATED LEAK KMOLS/S		DD1	OBED	0.60		0.57		0.41	
		DD2	OBED	0.39		0.38		0.38	
		PH	OBED	0.79		0.74		0.78	
		PH	UBED	0.86		0.93		0.95	
FUEL, KMOLS/S		DD2		0		0		0	
	3	PH		0.0288		0.0284		0.0288	
	4	KILN		0.0576		0.0584		0.0596	

MINNTAC MEDUSA VALIDATION SUMMARY
FEED RATES CALC. FROM PLANT DATA

	Test		Feb 17 Run 3		Feb 17 Run 4	
CFD DATA FILE:			2_26_0725	3_09_	3_1_0725	3_8_1240
Medusa Data Format						
3A/3B DAMPER POSITION			closed		closed	
GREEN BALLS	kg/s	2	136.86		136.45	
		1	137.34		137.34	
HEARTH LAYER	kg/s		0		0	
PELLET DIAMETER	M		0.0111		0.0111	
GREEN BALLS TEMPERATURE	K		290		290	
HEARTH LAYER TEMPERATURE	K		290		290	
MAGNETITE FRACTION	Xm		0.7582		0.7582	
HEARTH LAYER FRACTION	Xh		0		0	
INERT FRACTION			0.04380		0.04380	
FLUX FRACTION			0.06934		0.06934	
MOISTURE FRACTION			0.08759		0.08759	
PELLET POROSITY			0.25		0.25	
SOLIDS EMMISSITIVITY			0.60		0.60	
OUTSIDE AIR TEMPERATURE	K		258		256	
LEAKAGE AIR TEMPERATURE	K		290		290	
NUMBER OF ZONES			7		7	
MACHINE TYPE			1		1	
KILN ZONE #			4		4	
FIRING ZONE			4		4	
			Low Outleak	High Outleak	Low Outleak	High Outleak
AIR IN, KMOLS/S	1 DD1		0		0	
	2 DD2		0		0	
	3 PH		0		0	
	4 KILN		0		0	
	5 C1		2.3677	2.1898	2.3675	2.1804
	6 C2		1.6436	1.5100	1.7514	1.6207
	7 C3		2.6023	2.3842	2.9522	2.3842
TEMPS K	C1		1439	1489	1445	1497
	C2		893	992	894	995
TARGET VARIALBLES						
DD1 OBED	K		632		629	
PH FAN -1A	K		626		622	
PH FAN -1B	K		646		644	
KILN SEC AIR	K		1381		1382	
BURN ZONE (REFRAC)	K		1624		1620	
KILN SOLIDS EXIT	K		1515		1515	
PLANT OVER BED PRESSURES	DD1		-0.33		-0.25	
	DD2		-1.08		-0.95	
	PH		-0.63		-0.52	
UNDER BED PRESSURE	PH		-6.24		-6.22	
ESTIMATED LEAK KMOLS/S	DD1	OBED	0.43		0.37	
	DD2	OBED	0.40		0.37	
	PH	OBED	0.83		0.76	
	PH	UBED	0.96		0.95	
FUEL, KMOLS/S	DD2		0		0	
	3 PH		0.0288		0.0288	
	4 KILN		0.0614		0.0585	

MINNTAC MEDUSA VALIDATION SUMMARY
FEED RATES CALC. FROM PLANT DATA

	Test			APR 19 RUN 1	APR 19 RUN 2	APR 19 RUN 3	APR 19 RUN 4	APR 19 RUN 5
CFD DATA FILE:				4_22_0715	4_23_0725	4_26_0720	4_27_0745	4_28_0710
Medusa Data Format				RECOUP OUTLET PRESSURES PROPORTIONAL TO PLANT				
3A/3B DAMPER POSITION				closed	closed	closed	closed	closed
GREEN BALLS	kg/s		2	135.81	129.28	134.91	133.73	132.13
			1	138.72	135.17	138.63	138.10	138.10
HEARTH LAYER	kg/s			0	0	0	0	0
PELLET DIAMETER	M			0.0111	0.0111	0.0111	0.0111	0.0111
GREEN BALLS TEMPERATURE	K			290	290	290	290	290
HEARTH LAYER TEMPERATURE	K			290	290	290	290	290
MAGNETITE FRACTION	Xm			0.7582	0.7582	0.7582	0.7582	0.7582
HEARTH LAYER FRACTION	Xh			0	0	0	0	0
INERT FRACTION				0.04380	0.04380	0.04380	0.04380	0.04380
FLUX FRACTION				0.06934	0.06934	0.06934	0.06934	0.06934
MOISTURE FRACTION				0.08759	0.08759	0.08759	0.08759	0.08759
PELLET POROSITY				0.25	0.25	0.25	0.25	0.25
SOLIDS EMMISSITIVITY				0.60	0.60	0.60	0.60	0.60
OUTSIDE AIR TEMPERATURE	K			279	281	277	275	276
LEAKAGE AIR TEMPERATURE	K			290	290	290	290	290
NUMBER OF ZONES				7	7	7	7	7
MACHINE TYPE				1	1	1	1	1
KILN ZONE #				4	4	4	4	4
FIRING ZONE				4	4	4	4	4
AIR IN, KMOLS/S				High Outleak	High Outleak	High Outleak	High Outleak	High Outleak
	1 DD1			0	0	0	0	0
	2 DD2			0	0	0	0	0
	3 PH			0	0	0	0	0
	4 KILN			0	0	0	0	0
	5 C1			1.9972	1.8122	1.7746	1.8511	1.8002
	6 C2			1.5826	1.4218	1.5187	1.5119	1.4759
	7 C3			2.3132	2.4625	2.6096	2.4867	2.4035
TEMPS K	C1			1515	1540	1551	1538	1542
	C2			1080	1173	1202	1161	1192
TARGET VARIALBLES								
DD1 OBED	K			616	612	614	614	611
PH FAN -1A	K			620	618	617	617	614
PH FAN -1B	K			627	627	627	628	625
KILN SEC AIR	K			1381	1383	1375	1387	1368
BURN ZONE (REFRAC)	K			1622	1607	1617	1607	1617
KILN SOLIDS EXIT	K			1518	1508	1509	1506	1514
PLANT OVER BED PRESSURES	DD1			-0.67	-0.69	-0.69	-0.71	-0.72
	DD2			-1.23	-1.07	-1.19	-1.21	-1.27
	PH			-0.48	-0.36	-0.49	-0.44	-0.46
UNDER BED PRESSURE	PH			-5.61	-4.50	-5.23	-5.18	-5.74
ESTIMATED LEAK KMOLS/S	DD1	OBED		0.61	0.62	0.62	0.63	0.63
	DD2	OBED		0.42	0.39	0.42	0.42	0.43
	PH	OBED		0.73	0.63	0.74	0.70	0.71
	PH	UBED		0.91	0.81	0.87	0.87	0.92
FUEL, KMOLS/S	DD2			0	0	0	0	0
	3 PH			0.0288	0.0285	0.0288	0.0287	0.0228
	4 KILN			0.0542	0.0509	0.0582	0.0536	0.0600

MINNTAC MEDUSA VALIDATION SUMMARY: FEED RATES CALC. FROM PLANT DATA

TABLE 4 NOTES

Green ball rate method:
1. CFD Cooler value/0.86
2. Actual Feed to grate, adjusted for roll feeder return

Basis for Composition Calculation			
composition	dry basis	wet basis	%wet basis
magnetite	83.1	83.1	0.758212
hematite	4.5	4.5	0.041058
silica	4.8	4.8	0.043796
flux stone	7.6	7.6	0.069343
water		9.6	0.087591
	100	109.6	1
Actual moisture and flux vary , we assume constant values			

Outside Air Temp is temperature used for air entering CFD cooler zones

Basis for Cooler Inlet Flows
C1 = CFD Kiln Sec +Firing Hood outlet flow C2 = CFD Total Recoup Outlet flow C3 = Stack Outlet flow
CFD values are based on matching Plant 3A and 3B Sensor flows A Relatively large CFD outleakage is taken in 3A windbox assumes not all plant indicated flow passes through bed

TABLE 5
MINNTAC MEDUSA VALIDATION SUMMARY
FEED RATES OPTIMIZED BY MEDUSA

	1		2		3		4		5		6		7		8	9	10	11	12
	Nov19		Feb 11		Feb 11		Feb 17		Feb 17		Feb 17		Feb 17		APR 19	APR 19	APR 19	APR 19	APR 19
	Run 3		Run 1		Run 2		Run 1		Run 2		Run 3		Run 4		RUN 1	RUN 2	RUN 3	RUN 4	RUN 5
TARGETS																			
DD1-OBED DEGK	625		632		631		627		631		632		629		616	612	614	614	611
AVG PH FAN DEG K	629		638		638		634		636		636		633		624	622	622	623	619
DD2 OBED DEGK	897		895		896		872		874		865		871		869	923	935	939	914
KILN SEC AIR DEG K	1395		1397		1397		1386		1386		1381		1382		1381	1383	1375	1387	1368
KILN SOLIDS EXIT DEG K	1524		1517		1516		1510		1516		1515		1515		1518	1508	1509	1506	1514
GRATE FEED RATE KG/S	137.94		143.73		142.89		135.02		136.56		136.86		136.45		135.81	129.28	134.91	133.73	132.13
PLANT AVG % MOIST	9.6		9.6		9.6		9.6		9.6		9.6		9.6		9.6	9.6	9.6	9.6	9.6
WIND BOX LEAK LEVEL	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
DATA FILE VAULES																			
PROD RATE KG/S	135.40	133.50	140.50	139.70	140.70	138.70	138.70	137.00	140.60	138.90	141.10	139.50	141.10	139.70	136.80	129.40	135.20	134.30	132.9
DD1 OBED KMOL/S	0.2518	0.2518	0.2960	0.2960	0.2900	0.2900	0.2754	0.2754	0.1986	0.1986	0.2079	0.2079	0.1806	0.1806	0.2954	0.3011	0.3000	0.3045	0.3062
DD2 - OBED KMOL/S	0.3775	0.3775	0.3898	0.3898	0.3930	0.3930	0.3823	0.3823	0.3792	0.3792	0.3970	0.3970	0.3709	0.3709	0.4231	0.3946	0.4169	0.4188	0.4293
PHEAT OBED KMOL/S	0.7510	0.7510	0.7851	0.7851	0.7879	0.7879	0.7428	0.7428	0.7786	0.7786	0.8346	0.8346	0.7583	0.7583	0.7276	0.6299	0.7420	0.6995	0.7137
PHEAT UBED KMOL/S	1.5999	1.5999	1.1269	1.1269	1.1445	1.1445	1.2383	1.2383	1.2704	1.2704	1.2737	1.2737	1.2711	1.2711	1.2076	1.0817	1.1656	1.1597	1.2212
C1 KMOLS/S	2.2537	2.0849	2.2629	2.0703	2.2558	2.0669	2.2743	2.0872	2.3456	2.1595	2.3677	2.1898	2.3675	2.1804	1.9972	1.8122	1.7746	1.8511	1.8002
C1 DEG K	1452	1503	1462	1514	1461	1512	1456	1508	1445	1497	1439	1489	1445	1497	1515	1540	1551	1538	1542
C2 KMOL/S	1.6288	1.5100	1.6995	1.5768	1.6603	1.5369	1.6977	1.5716	1.6872	1.5573	1.6436	1.5100	1.7514	1.6207	1.5826	1.4218	1.5187	1.5119	1.4759
C2 DEG K	937	1032	950	1058	952	1059	928	1034	906	1008	893	992	894	995	1080	1173	1202	1161	1192
PH FUEL	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0284	0.0284	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0285	0.0288	0.0287	0.0228
KILN FUEL	0.0533	0.0533	0.0588	0.0588	0.0576	0.0576	0.0584	0.0584	0.0596	0.0596	0.0614	0.0614	0.0585	0.0585	0.0542	0.0509	0.0582	0.0536	0.0600
SIMULATION RESULTS:																			
DD1-OBED DEGK	620	616	627	624	626	625	624	622	629	625	630	626	625	621	610	601	603	602	599
PHEAT FAN INLET DEG K	636	633	648	645	646	645	643	641	643	639	643	640	637	634	630	624	625	623	621
DD2 - OBEDK	855	928	866	950	865	948	849	932	831	911	814	890	825	905	959	1031	1058	1021	1038
KILN SEC AIR DEG F	1452	1503	1462	1514	1461	1512	1456	1508	1445	1497	1439	1489	1445	1497	1515	1540	1551	1538	1542
KILN SOLIDS EXIT DEG K	1585	1616	1590	1621	1585	1617	1600	1632	1593	1624	1588	1618	1588	1618	1610	1641	1648	1626	1638
OPTIM. FEED RATE KG/S	135.40	133.50	140.50	139.70	140.70	138.70	138.70	137.00	140.60	138.90	141.10	139.50	141.10	139.70	136.80	129.40	135.20	134.30	132.90

TABLE 6
LINE 7 LINEAL AIR FLOW DUCT TEMPERATURE PROFILE
(SECONDARY AIR TEMPERATURE)

DATE: 5/13/99

DISCUSSION: A TEMPERATURE PROFILE WAS TAKEN AT THE LINE 7 LINEAL AIR FLOW DUCT THERMOCOUPLE LOCATION PORT. A SET OF TRAVERSES WERE TAKEN WITH A 4 FT HAND HELD THEMOCOUPLE WITH A FEED RATE OF 540 WLTPH AND THE LINE STABLE.

TRAVERSE POINT INCHES	TEMPERATURE DEG F	CONTROL SECONDARY AIR TEMP DEG F
2	1995	1974
6	2021	
8	2030	
14	2032	
18	2035	
22	2039	
26	2031	
30	2040	
34	2035	
38	2031	1988

TESTED BY: R. BRASKI
B. SCOTT

TABLE 7
TEMPERATURE PROFILE
LINE 6 RECOUP A DUCT
FEBRUARY 5, 1999

POINT	DISTANCE FROM INSIDE EDGE INCHES	TEMPERATURE DEG F
1	1	1195
2	6	1230
3	12	1238
4	18	1245
5	24	1253
6	30	1212
7	36	1248
8	42	1285
9	48	1272
10	54	1277
11	60	1257
12	66	1260
13	71	1228

TABLE 8
USX CFD COOLER OPTIMIZATION
INITIAL OPTIMIZATION PARAMETERS

				FAN FLOW SERIES			FIRST PARAMETRIC SERIES			SECOND PARAMETRIC SERIES			THIRD PARAMETRIC SERIES		
			AVERAGE OR	EXPERIMENTAL DESIGN LEVELS											
VARIABLE			EXISTING STATUS	1	2	3	1	2	3	1	2	3	1	2	3
PELLET MAGNETITE INTO COOLER	*1	%WT	22	22	-----	-----	16	22	28	16	22	28	16	22	28
GREENBALL FEED RATE		WLTPH	485	485	-----	-----	450	485	520	450	485	520	450	485	520
3A FAN FLOW	*2	LBS/MIN	13500	10000	13500	17000	DETERMINED BY 3B FLOW			10000	13500	17000	10000	13500	17000
3B FAN FLOW		LBS/MIN	13500	10000	13500	17000	10000	13500	17000	10000	13500	17000	10000	13500	17000
UNDERBED DAMPER	*3	LOCATION	7/8	7/8	-----	-----	7/8	-----	-----	7/8	-----	-----	7/8	-----	-----
		POSITION	CLOSED	CLOSED	-----	-----	CLOSED	-----	-----	CLOSED	-----	-----	CLOSED	-----	-----
OVERBED DIVIDING WALL (8" GAP)		LOCATION	NONE	NONE	-----	-----	NONE	5/6	7/8	NONE	-----	-----	6/7	-----	-----
RECOUP DUCT (B-SIDE)	*4	LOCATION	9	-----	-----	-----	5	9	-----	-----	-----	-----	-----	-----	-----
THREE RECOUP DUCTS (WB 5,9,10)	*5	LOCATION	NONE	-----	-----	-----	YES	-----	-----	-----	-----	-----			

NOTES:

PELLET MAGNETITE DETERMINED BY SVEDALA KILN DISCHARGE SAMPLES, FE++; %WT MAG.=FE++/0.2411: RANGE WAS 4.56 TO 6.94 % FE++

3A FAN FLOW WILL BE DETERMINED FROM MULTIPLE REGRESSION OF PELLET EXIT TEMP (TOP OF BED) AND PRIMARY OVER BED PRESSURE, WITH THE THREE LEVELS OF 3B FAN FLOW. (FIRST SERIES ONLY)

LOCATIONS REFER TO WINDBOX #'S 7/8 WOULD BE WALL BETWEEN WBOX 7 AND WBOX 8 ETC (WBOX 1 STARTS AT SCREED WALL)

RECOUP DUCT (B-SIDE) REFERS TO EITHER WIND BOX 5 OR 9

THREE RECOUP DUCTS (WB 5,9,10), REFERS TO ADDING A THIRD DUCT IN WBOX 5

TABLE 9
EXPERIMENTAL DESIGNS

FAN FLOW SERIES: 22% MAGNETITE, 485 WLTPH

3A FAN FLOW LBS/MIN	3A FAN FLOW LBS/MIN
10000	10000
10000	13500
10000	17000
13500	10000
13500	13500
13500	17000
17000	10000
17000	13500
17000	17000

> 3A FAN FLOW RATES AS DETERMINED BY OVER BED PRESSURE

FIRST PARAMETRIC SERIES

	RECOUP B DUCT LOCATION WIND BOX #	MAGNETITE % WT	GREEN BALL FEED WLTPH	3A FAN FLOW LBS/MIN	3B FAN FLOW LBS/MIN	OVER BED DIVIDING WALL WIND BOX #	3A FLOW LBS/MIN
1	6	16	450	BY 3A OVER BED PRESSURE	10000	NO WALL	14670
2	6	16	485		13500	7/8 WALL	11722
3	6	16	520		17000	5/6 WALL	14622
4	6	22	450		13500	5/6 WALL	15622
5	6	22	485		17000	NO WALL	11722
6	6	22	520		10000	7/8 WALL	16100
7	6	28	450		17000	7/8 WALL	11722
8	6	28	485		10000	5/6 WALL	16620
9	6	28	520		13500	NO WALL	13200
10	9	16	450		17000	5/6 WALL	14622
11	9	16	485		10000	NO WALL	14670
12	9	16	520		13500	7/8 WALL	11722
13	9	22	450		10000	7/8 WALL	11722
14	9	22	485		13500	5/6 WALL	12622
15	9	22	520		17000	NO WALL	11722
16	9	28	450		13500	NO WALL	13200
17	9	28	485		17000	7/8 WALL	12622
18	9	28	520		10000	5/6 WALL	16622

SECOND AND THIRD SERIES

						SECOND	THIRD
1	9	16	450	10000	10000	NO WALL	6/7 WALL
2	9	16	450	13500	17000	NO WALL	6/7 WALL
3	9	18	450	17000	13500	NO WALL	6/7 WALL
4	9	16	485	10000	17000	NO WALL	6/7 WALL
5	9	16	485	13500	13500	NO WALL	6/7 WALL
6	9	16	485	17000	10000	NO WALL	6/7 WALL
7	9	16	520	10000	13500	NO WALL	6/7 WALL
8	9	18	520	13500	10000	NO WALL	6/7 WALL
9	9	18	520	17000	17000	NO WALL	6/7 WALL
10	9	22	450	10000	17000	NO WALL	6/7 WALL
11	9	22	450	13500	13500	NO WALL	6/7 WALL
12	9	22	450	17000	10000	NO WALL	6/7 WALL
13	9	22	485	10000	13500	NO WALL	6/7 WALL
14	9	22	485	13500	10000	NO WALL	6/7 WALL
15	9	22	485	17000	17000	NO WALL	6/7 WALL
16	9	22	520	10000	10000	NO WALL	6/7 WALL
17	9	22	520	13500	17000	NO WALL	6/7 WALL
18	9	22	520	17000	13500	NO WALL	6/7 WALL
19	9	28	450	10000	13500	NO WALL	6/7 WALL
20	9	28	450	13500	10000	NO WALL	6/7 WALL
21	9	28	450	17000	17000	NO WALL	6/7 WALL
22	9	28	485	10000	10000	NO WALL	6/7 WALL
23	9	28	485	13500	17000	NO WALL	6/7 WALL
24	9	28	485	17000	13500	NO WALL	6/7 WALL
25	9	28	520	10000	17000	NO WALL	6/7 WALL
26	9	28	520	13500	13500	NO WALL	6/7 WALL
27	9	28	520	17000	10000	NO WALL	6/7 WALL

TABLE 10:

MINNTAC FIRST PARAMETRIC SERIES
VARIED COOLER MODIFICATIONS

RECOUP B IN WBOX 9 POSITION

3A/3B FAN FLOW SERIES

			OPT_1	OPT_2	OPT_3	OPT_4	OPT_5
			5_14_0800	5_18_0805	5_19_0735	5_20_0745	5_21_0715
FEED RATE (WET BALLS ON GRATE)		LTPH	485.00	485.00	485.00	485.00	485.00
PRODUCTION FACTOR			0.86	0.86	0.86	0.86	0.86
PELLET FEED TO COOLER		LTPH	417.10	417.10	417.10	417.10	417.10
GREENBALL MAGNETITE %WT			87.00	87.00	87.00	87.00	87.00
FE++ IN COOLER FEED			5.31	5.31	5.31	5.31	5.31
FE3O4 IN FEED (FE3O4=FE++/.2412)		%WT	22.00	22.00	22.00	22.00	22.00
AVG PELLET TEMP INTO COOLER		DEGF	2,250	2,250	2,250	2,250	2,250
COOLER SPEED		IN/MIN	92	92	92	92	92
COOLER BED DEPTH		IN	28	28	28	28	28
PRIMARY COOLING ZONE							
3A FAN	FLOW	LBS/MIN	10,000	10,000	10,000	13,500	13,500
G/S (THRU BED)		LBS/LB	0.4581	0.4556	0.4517	0.6551	0.6563
	INLET	DEGF	39.2	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.2467	-0.1868	-0.1213	0.0288	-0.0372
	U'BED	IN.H2O	13.040	13.450	14.080	16.810	16.570
	KFACT		545	545	545	545	545
KILN SECONDARY AIR	AVG	DEGF	2,388	2,366	2,334	2,196	2,235
		LBS/MIN	3,260	3,902	4,523	5,666	5,135
	G/S	LBS/MIN	0.2093	0.2506	0.2905	0.3639	0.3297
	OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40	-0.40
FIRING HOOD AIR		DEGF	2,309	2,309	2,306	2,297	2,299
		LBS/MIN	2,318	2,441	2,579	2,896	2,784
	G/S	LBS/LB	0.1489	0.1568	0.1656	0.1860	0.1788
	OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73	-0.73
WINDBOX LEAKAGE		LBS/MIN	2,867	2,905	2,966	3,300	3,280
GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62	3.62
WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67	1.67
OVERBED DIVIDING WALL							
LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE	NONE
GAP HEIGHT		INCHES	NA	NA	NA	NA	NA
FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA	NA
SECONDARY COOLING ZONE							
3B FAN	FLOW	LBS/MIN	10,000	13,500	17,001	17,001	13,500
G/S (THRU BED)		LBS/MIN	0.6311	0.8560	1.0809	1.0815	0.8568
	INLET	DEGF	39.2	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.3799	-0.2278	-0.0840	-0.0431	-0.1987
	U'BED	IN.H2O	10.950	12.917	14.450	13.253	11.480
RECOUP B SIDE (WB 6)	AVG	DEGF					
		LBS/MIN					
	OUTLET	INH2O					
RECOUP B SIDE (WB 9)	AVG	DEGF	2,098	1,986	1,840	1,475	1,585
		LBS/MIN	2,326	2,604	2,885	3,268	2,944
	OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11	-1.11
RECOUP A SIDE (WB10)	AVG	DEGF	1,877	1,649	1,405	1,115	1,280
		LBS/MIN	2,155	2,565	2,994	3,393	2,938
	OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90	-0.90
COOLER VENT STACK	AVG	DEGF	1,096	803	589	434	587
		LBS/MIN	7,054	9,007	10,950	11,887	9,881
	OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88	-0.88
VENT STACK SEPARATION WALL			YES	YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER		DEGF	795	507	338	226	340
WINDBOX LEAKAGE		LBS/MIN	172	171	169	159	158
GAP HEIGHT		INCHES	1	1	1	1	1.0
O'BED LEAKAGE		LBS/MIN	(153)	(96)	(66)	(71)	(103)
GAP HEIGHT		INCHES	1	1	1	1	1
TOTAL AIR IN			20,153	23,595	27,066	30,571	27,103
TOTAL AIR OUT			20,152	23,595	27,067	30,570	27,119

TABLE 10: 2 OF 6

MINNTAC FIRST PARAMETRIC SERIES
VARIED COOLER MODIFICATIONS

RECOUP B IN WBOX 9 POSITION

3A/3B FAN FLOW SERIES

			OPT_6	OPT_7	OPT_8	OPT_9
			5_26_0715	5_25_0955	5_27_0655	6_01_0715
FEED RATE (WET BALLS ON GRATE)		LTPH	485.00	485.00	485.00	485.00
PRODUCTION FACTOR			0.86	0.86	0.86	0.86
PELLET FEED TO COOLER		LTPH	417.10	417.10	417.10	417.10
GREENBALL MAGNETITE %WT			87.00	87.00	87.00	87.00
FE++ IN COOLER FEED			5.31	5.31	5.31	5.31
FE3O4 IN FEED (FE3O4=FE++/.2412)		%WT	22.00	22.00	22.00	22.00
AVG PELLET TEMP INTO COOLER		DEGF	2,250	2,250	2,250	2,250
COOLER SPEED		IN/MIN	92	92	92	92
COOLER BED DEPTH		IN	28	28	28	28
PRIMARY COOLING ZONE						
3A FAN	FLOW	LBS/MIN	13,500	17,001	17,001	17,001
G/S (THRU BED)		LBS/LB	0.6575	0.8616	0.8607	0.8598
	INLET	DEGF	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.1036	0.0649	0.1382	0.2115
	U'BED	IN.H2O	16.34	19.080	19.27	19.46
	KFACT		545	545	545	545
KILN SECONDARY AIR	AVG	DEGF	2,273	2,125	2,075	2,027
		LBS/MIN	4,571	5,826	6,382	6,917
	G/S	LBS/MIN	0.2935	0.3742	0.4099	0.4442
	OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
FIRING HOOD AIR		DEGF	2,297	2,288	2,289	2,290
		LBS/MIN	2,675	3,055	3,154	3,255
	G/S	LBS/LB	0.1718	0.1962	0.2025	0.2090
	OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
WINDBOX LEAKAGE		LBS/MIN	3,261	3,584	3,597	3,612
GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
OVERBED DIVIDING WALL						
LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
GAP HEIGHT		INCHES	NA	NA	NA	NA
FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE						
3B FAN	FLOW	LBS/MIN	10,000	10,000	13,500	17,001
G/S (THRU BED)		LBS/MIN	0.6322	0.6329	0.8574	1.0820
	INLET	DEGF	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.3533	-0.3339	-0.1785	-0.0206
	U'BED	IN.H2O	9.52	8.41	10.34	12.13
RECOUP B SIDE (WB 6)	AVG	DEGF				
		LBS/MIN				
	OUTLET	INH2O				
RECOUP B SIDE (WB 9)	AVG	DEGF	1,707	1,354	1,229	1,121
		LBS/MIN	2,627	2,998	3,346	3,712
	OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
RECOUP A SIDE (WB10)	AVG	DEGF	1,468	1,108	972	840
		LBS/MIN	2,465	2,825	3,317	3,826
	OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
COOLER VENT STACK	AVG	DEGF	798	585	440	334
		LBS/MIN	7,908	8,738	10,666	12,603
	OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
VENT STACK SEPARATION WALL			YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER		DEGF	527	358	243	171
WINDBOX LEAKAGE		LBS/MIN	156	144	148	151
GAP HEIGHT		INCHES	1.0	1.0	1.0	1.0
O'BED LEAKAGE		LBS/MIN	(162)	(171)	(111)	(76)
GAP HEIGHT		INCHES	1	1	1	1
TOTAL AIR IN			23,661	27,171	30,611	34,078
TOTAL AIR OUT			23,663	27,170	30,610	34,076

TABLE 10: MINNTAC FIRST PARAMETRIC SERIES VARIED COOLER MODIFICATIONS

3 OF 6

RECOUP B IN WBOX 9 POSITION

O'BED DIVIDING WALL BETWEEN WBOXES 7 & 8 (ALIGNED W

		3A FLOW SERIES			FACTORIAL POINTS	
		3A12622	3A11722	3A10822	3A11722	3A11722
		6_2_0800	6_3_0750	6_7_0700	6_9_0750	6_10_0000
FEED RATE (WET BALLS ON GRATE)	LTPH	485.00	485.00	485.00	520.00	450.00
PRODUCTION FACTOR		0.86	0.86	0.86	0.86	0.86
PELLET FEED TO COOLER	LTPH	417.10	417.10	417.10	447.20	387.00
GREENBALL MAGNETITE %WT		87.00	87.00	87.00	87.00	87.00
FE++ IN COOLER FEED		6.75	6.75	6.75	3.86	5.31
FE3O4 IN FEED (FE3O4=FE++/.2412)	%WT	28.00	28.00	28.00	16	22
AVG PELLET TEMP INTO COOLER	DEGF	2,250	2,250	2,250	2,250	2,250
COOLER SPEED	IN/MIN	92	92	92	98	85
COOLER BED DEPTH	IN	28	28	28	28	28
PRIMARY COOLING ZONE						
3A FAN FLOW	LBS/MIN	12,622	11,722	10,822	11,722	11,722
G/S (THRU BED)	LBS/LB	0.6028	0.5509	0.4989	0.5156	0.6006
INLET	DEGF	39.2	39.2	39.2	39.2	39.2
O'BED	IN.H2O	0.0466	-0.0158	-0.0689	-0.0469	-0.0781
U'BED	IN.H2O	16.31	15.53	14.79	15.19	14.46
KFACT		545	545	545	545	545
KILN SECONDARY AIR AVG	DEGF	2,252	2,305	2,348	2,253	2,243
	LBS/MIN	5,797	5,337	4,926	5,150	4,916
G/S	LBS/MIN	0.3723	0.3427	0.3163	0.3085	0.3403
OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40	-0.40
FIRING HOOD AIR	DEGF	2,308	2,314	2,318	2,283	2,306
	LBS/MIN	2,913	2,790	2,682	2,745	2,665
G/S	LBS/LB	0.1871	0.1792	0.1722	0.1644	0.1844
OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73	-0.73
WINDBOX LEAKAGE	LBS/MIN	3,236	3,143	3,053	3,114	3,044
GAP HEIGHT	INCHES	3.62	3.62	3.62	3.62	3.62
WINDBOX DAMPER POSITION		CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER	INCHES	1.67	1.67	1.67	1.67	1.67
OVERBED DIVIDING WALL						
LOCATION (BETWEEN WBOXES)		7/8	7/8	7/8	7/8	7/8
GAP HEIGHT	INCHES	8	8	8	8	8
FLOW (- = 3A TO 3B; + = 3B TO 3A)	LBS/MIN	-127.7	-81.2	-41.0	-160.7	-233.7
SECONDARY COOLING ZONE						
3B FAN FLOW	LBS/MIN	17,001	17,001	17,001	13,500	10,000
G/S (THRU BED)	LBS/MIN	1.0813	1.0811	1.0809	0.7985	0.6814
INLET	DEGF	39.2	39.2	39.2	39.2	39.2
O'BED	IN.H2O	-0.1124	-0.0934	-0.0837	-0.2761	-0.5229
U'BED	IN.H2O	13.7	14.11	11.99	12.66	9.45
RECOUP B SIDE (WB 6) AVG	DEGF					
	LBS/MIN					
OUTLET	INH2O					
RECOUP B SIDE (WB 9) AVG	DEGF	1,589	1,712	1,820	1,783	1,677
	LBS/MIN	3,031	2,966	2,901	2,627	2,244
OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11	-1.11
RECOUP A SIDE (WB10) AVG	DEGF	1,158	1,265	1,366	1,438	1,365
	LBS/MIN	3,178	3,105	3,030	2,593	2,048
OUTLET	INH2O	-0.90	-0.90	-0.90	-1.00	-1.00
COOLER VENT STACK AVG	DEGF	458	508	501	738	743
	LBS/MIN	11,375	11,283	11,126	8,924	6,828
OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88	-0.88
VENT STACK SEPARATION WALL		YES	YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER	DEGF	248	275	307.4	491	525.2
WINDBOX LEAKAGE	LBS/MIN	163	166	169	169	155
GAP HEIGHT	INCHES	1.0	1.0	1.0	1.0	1.0
O'BED LEAKAGE	LBS/MIN	(71)	(68)	(65)	(101)	(178)
GAP HEIGHT	INCHES	1	1	1	1	1
TOTAL AIR IN		29,694	28,790	27,888	25,323	21,900
TOTAL AIR OUT		29,693	28,790	27,887	25,323	21,900

TABLE 10:
MINNTAC FIRST PARAMETRIC SERIES
VARIED COOLER MODIFICATIONS

RECOUP B IN WBOX 9 POSITION

OBED DIVIDING WALL BETWEEN WBOXES 5 & 6

			3A FLOW SERIES			FACTORIAL POINTS	
			3A 12622	3A 13622	3A 14622	3A 16622	3A_14622
			6_11_0710	6_12_0800	6_13_0905	6_14_0715	6_15_0800
FEED RATE (WET BALLS ON GRATE)		LTPH	485.00	485.00	485.00	520.00	450.00
PRODUCTION FACTOR			0.86	0.86	0.86	0.86	0.86
PELLET FEED TO COOLER		LTPH	417.10	417.10	417.10	447.20	387.00
GREENBALL MAGNETITE %WT			87.00	87.00	87.00	87.00	87.00
FE++ IN COOLER FEED			5.31	5.31	5.31	6.75	3.86
FE3O4 IN FEED (FE3O4=FE++/.2412)		%WT	22	22	22	28	16
AVG PELLET TEMP INTO COOLER		DEGF	2,250	2,250	2,250	2,250	2,250
COOLER SPEED		IN/MIN	92	92	92	98	85
COOLER BED DEPTH		IN	28	28	28	28	28
PRIMARY COOLING ZONE							
3A FAN	FLOW	LBS/MIN	12,621	13,622	14,622	16,621	14,622
	G/S (THRU BED)	LBS/LB	0.6053	0.6630	0.7211	0.7786	0.7805
	INLET	DEGF	39.2	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.2376	-0.2022	-0.1648	-0.0827	-0.1674
	U'BED	IN.H2O	15.89	16.75	17.57	19.65	17.06
	KFACT		545	545	545	545	545
KILN SECONDARY AIR	AVG	DEGF	2,343	2,316	2,285	2,290	2,202
		LBS/MIN	3,490	3,817	4,144	4,698	4,246
	G/S	LBS/MIN	0.2241	0.2451	0.2661	0.2814	0.2938
	OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40	-0.40
FIRING HOOD AIR		DEGF	2,294	2,290	2,288	2,290	2,280
		LBS/MIN	2,459	2,559	2,659	2,880	2,651
	G/S	LBS/LB	0.1579	0.1643	0.1708	0.1725	0.1835
	OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73	-0.73
WINDBOX LEAKAGE		LBS/MIN	3,196	3,298	3,393	3,621	3,345
GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62	3.62
WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67	1.67
OVERBED DIVIDING WALL							
LOCATION (BETWEEN WBOXES)			5/6	5/6	5/6	5/6	5/6
GAP HEIGHT		INCHES	8	8	8	8	8
FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	246.4	244.6	243.3	182.8	302.5
SECONDARY COOLING ZONE							
3B FAN	FLOW	LBS/MIN	13,500	13,500	13,500	10,000	17,001
	G/S (THRU BED)	LBS/MIN	0.8565	0.8567	0.8569	0.5897	1.1662
	INLET	DEGF	39.2	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	0.0033	0.0086	0.0129	-0.1583	0.175
	U'BED	IN.H2O	12.04	11.65	11.29	9.34	12.31
RECOUP B SIDE (WB 6)	AVG	DEGF					
		LBS/MIN					
	OUTLET	INH2O					
RECOUP B SIDE (WB 9)	AVG	DEGF	1,835	1,736	1,640	1,704	1,380
		LBS/MIN	3,155	3,260	3,370	3,155	3,843
	OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11	-1.11
RECOUP A SIDE (WB10)	AVG	DEGF	1,561	1,452	1,346	1,419	1,059
		LBS/MIN	3,133	3,244	3,359	2,990	3,981
	OUTLET	INH2O	-1.00	-1.00	-1.00	-1.00	-1.00
COOLER VENT STACK	AVG	DEGF	708	650	598	773	385
		LBS/MIN	10,608	10,872	11,129	9,264	13,468
	OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88	-0.88
VENT STACK SEPARATION WALL			YES	YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER		DEGF	375.8	338	305.6	473	163.4
WINDBOX LEAKAGE		LBS/MIN	163	160	156	154	152
GAP HEIGHT		INCHES	1.0	1.0	1.0	1.0	1.0
O'BED LEAKAGE		LBS/MIN	(84)	(87)	(89)	(143)	(63)
GAP HEIGHT		INCHES	1	1	1	1	1
TOTAL AIR IN			26,206	27,208	28,211	26,764	31,686
TOTAL AIR OUT			26,205	27,210	28,211	26,762	31,685

TABLE 10:

MINNTAC FIRST PARAMETRIC SERIES
VARIED COOLER MODIFICATIONS

		RECOUP B IN WBOX 9 POSITION			RECOUP B IN WBOX 6 POSITION		
		NO OVER BED DIVIDING WALL			OBED DIV WALL WBOXES 5 & 6		
		FACTORIAL POINTS			FACTORIAL POINTS		
		3A 11722	3A_13200	3A_14670	3A 16620	3A 14622	3a 15622
		6_16_0725	6_17_0705	6_18_0700	6_25_0725	6_28_0810	6_29_0710
FEED RATE (WET BALLS ON GRATE)	LTPH	520.00	450.00	485.00	485.00	520.00	450.00
PRODUCTION FACTOR		0.86	0.86	0.86	0.86	0.86	0.86
PELLET FEED TO COOLER	LTPH	447.20	387.00	417.10	417.10	447.20	386.99
GREENBALL MAGNETITE %WT		87.00	87.00	87.00	87.00	87.00	87.00
FE++ IN COOLER FEED		5.31	6.75	3.86	6.75	3.86	5.31
FE3O4 IN FEED (FE3O4=FE++/.2412)	%WT	22	28	16	28	16	22
AVG PELLET TEMP INTO COOLER	DEGF	2,250	2,250	2,250	2,250	2,250	2,250
COOLER SPEED	IN/MIN	98	85	92	92	98	85
COOLER BED DEPTH	IN	28	28	28	28	28	28
PRIMARY COOLING ZONE							
3A FAN FLOW	LBS/MIN	11,722	13,200	14,669	16,617	14,622	15,622
G/S (THRU BED)	LBS/LB	0.5129	0.6902	0.7267	0.8430	0.6751	0.8493
INLET	DEGF	39.2	39.2	39.2	39.2	39.2	39.2
O'BED	IN.H2O	-0.03822	-0.0617	-0.0563	-0.11	-0.1613	-0.1486
U'BED	IN.H2O	15.69	16.07	9.587	19.08	18.01	17.75
KFACT		545	545	545	545	545	545
KILN SECONDARY AIR AVG	DEGF	2,300	2,259	2,181	2,271	2,262	2,227
	LBS/MIN	5,156	4,937	4,989	4,469	4,171	4,232
G/S	LBS/MIN	0.3088	0.3417	0.3204	0.2870	0.2499	0.2929
OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40
FIRING HOOD AIR	DEGF	2,297	2,318	2,280	2,296	2,272	2,292
	LBS/MIN	2,761	2,720	2,792	2,892	2,757	2,773
G/S	LBS/LB	0.1654	0.1883	0.1793	0.1857	0.1651	0.1919
OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73	-0.73	-0.73
WINDBOX LEAKAGE	LBS/MIN	3,159	3,228	3,354	3,490	3,350	3,351
GAP HEIGHT	INCHES	3.62	3.62	3.62	3.62	3.62	3.62
WINDBOX DAMPER POSITION		CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER	INCHES	1.67	1.67	1.67	1.67	1.67	1.67
OVERBED DIVIDING WALL							
LOCATION (BETWEEN WBOXES)		NONE	NONE	NONE	5/6	5/6	5/6
GAP HEIGHT	INCHES				8	8	8
FLOW (- = 3A TO 3B; + = 3B TO 3A)	LBS/MIN	NA	NA	NA	82.7	214.9	133.8
SECONDARY COOLING ZONE							
3B FAN FLOW	LBS/MIN	17,001	13,500	10,000	10,000	17,001	13,500
G/S (THRU BED)	LBS/MIN	1.0080	0.9237	0.6325	0.6330	1.0088	0.9245
INLET	DEGF	39.2	39.2	39.2	39.2	39.2	39.2
O'BED	IN.H2O	-0.0131	-0.2284	-0.3354	-0.1659	0.3235	-0.0036
U'BED	IN.H2O	14.73	11.05	8.96	8.77	13.49	10.33
RECOUP B SIDE (WB 6) AVG	DEGF				1,771	1,840	1,646
	LBS/MIN				3,191	3,654	3,469
OUTLET	INH2O				-1.11	-1.11	-1.11
RECOUP B SIDE (WB 9) AVG	DEGF	1,789	1,544	1,529			
	LBS/MIN	3,039	2,926	2,766			
OUTLET	INH2O	-1.11	-1.11	-1.11			
RECOUP A SIDE (WB10) AVG	DEGF	1,393	1,232	1,294	1,210	1,204	1,001
	LBS/MIN	3,151	2,909	2,594	3,002	3,882	3,539
OUTLET	INH2O	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
COOLER VENT STACK AVG	DEGF	593	527	694	652	533	453
	LBS/MIN	11,347	9,932	8,192	9,581	13,296	11,710
OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88	-0.88	-0.88
VENT STACK SEPARATION WALL		YES	YES	YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER	DEGF	338	287.6	446	384.8	258.8	221
WINDBOX LEAKAGE	LBS/MIN	171	154	150	142	157	143
GAP HEIGHT	INCHES	1.0	1.0	1.0	1.0	1.0	1.0
O'BED LEAKAGE	LBS/MIN	(60)	(108)	(167)	(147)	(49)	(96)
GAP HEIGHT	INCHES	1	1	1	1	1	1
TOTAL AIR IN		28,783	26,807	24,837	26,763	31,671	29,218
TOTAL AIR OUT		28,785	26,807	24,837	26,768	31,268	29,217

TABLE 10: MINNTAC FIRST PARAMETRIC SERIES VARIED COOLER MODIFICATIONS

RECOUP B IN WBOX 6 POSITION

			OBED DIV WALL WBOXES 7/8 FACTORIAL POINTS				NO OBED WALL		
			3A 11722	3A 14672	3A 11672	3A 16100	3A 13200	3A 11722	3A 14670
			6_30_1500	7_6_0900	7_8_0740	7_9_0955	7_14_0740	7_15_0730	7_16_0730
FEED RATE (WET BALLS ON GRATE)		LTPH	485.00	485.00	450.00	520.00	520.00	485	450
PRODUCTION FACTOR			0.86	0.86	0.86	0.86	0.86	0.86	0.86
PELLET FEED TO COOLER		LTPH	417.10	417.10	386.99	447.20	447.20	417.10	386.99
GREENBALL MAGNETITE %WT			87.00	87.00	87.00	87.00	87.00	87.00	87.00
FE++ IN COOLER FEED			3.86	3.86	6.75	5.31	6.75	5.31	3.86
FE3O4 IN FEED (FE3O4=FE++/.2412)		%WT	16	16	28	22	28	22	16
AVG PELLET TEMP INTO COOLER		DEGF	2,250	2,250	2,250	2,250	2,250	2,250	2,250
COOLER SPEED		IN/MIN	92	92	85	98	98	92	85
COOLER BED DEPTH		IN	28	28	28	28	28	28	28
PRIMARY COOLING ZONE									
3A FAN	FLOW	LBS/MIN	11,722	14,672	11,722	16,101	13,200	11,722	14,669
	G/S (THRU BED)	LBS/LB	0.5599	0.7308	0.6017	0.7565	0.5970	0.5568	0.7916
	INLET	DEGF	39.2	39.2	39.2	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.2311	-0.0848	-0.2095	-0.0139	-0.0939	-0.1114	-0.1489
	U'BED	IN.H2O	14.81	17.29	15.08	18.99	16.96	15.34	16.6
	KFACT		545	545	545	545	545	545	545
KILN SECONDARY AIR	AVG	DEGF	2,285	2,157	2,334	2,191	2,302	2,245	2,170
		LBS/MIN	3,437	4,768	3,624	5,230	4,578	4,552	4,239
	G/S	LBS/MIN	0.2207	0.3062	0.2508	0.3132	0.2742	0.2924	0.2934
	OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40
FIRING HOOD AIR		DEGF	2,287	2,280	2,319	2,285	2,305	2,287	2,283
		LBS/MIN	2,481	2,833	2,512	3,009	2,777	2,720	2,713
	G/S	LBS/LB	0.1593	0.1819	0.1739	0.1802	0.1663	0.1747	0.1878
	OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73	-0.73	-0.73	-0.73
WINDBOX LEAKAGE		LBS/MIN	3,003	3,292	3,028	3,470	3,232	3,052	3,232
GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62	3.62	3.62	3.62
WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67	1.67	1.67	1.67
OVERBED DIVIDING WALL									
LOCATION (BETWEEN WBOXES)			7/8	7/8	7/8	7/8	NONE	NONE	NONE
GAP HEIGHT		INCHES	8	8	8	8			
FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	198.5	78.3	297.6	-97.3	NA	NA	NA
SECONDARY COOLING ZONE									
3B FAN	FLOW	LBS/MIN	13,500	13,500	17,001	10,000	13,500	17,001	10,000
	G/S (THRU BED)	LBS/MIN	0.8567	0.8574	1.1659	0.5901	0.7989	1.0815	0.6825
	INLET	DEGF	39.2	39.2	39.2	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	0.0247	-0.0521	0.2822	-0.2768	-0.0342	0.0774	-0.2953
	U'BED	IN.H2O	12.18	11.02	13.61	9.22	12.57	14.01	8.45
RECOUP B SIDE (WB 6)	AVG	DEGF	2,059	1,737	2,066	1,770	2,053	1,976	1,696
		LBS/MIN	2,534	2,969	2,580	3,056	2,777	2,611	2,860
	OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11	-1.11	-1.11	-1.11
RECOUP B SIDE (WB 9)	AVG	DEGF							
		LBS/MIN							
	OUTLET	INH2O							
RECOUP A SIDE (WB10)	AVG	DEGF	1,496	1,132	1,333	1,248	1,484	1,296	1,140
		LBS/MIN	3,108	3,300	3,678	2,720	3,019	3,379	2,768
	OUTLET	INH2O	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
COOLER VENT STACK	AVG	DEGF	734	542	521	718	747	527	606
		LBS/MIN	10,581	10,957	13,193	8,621	10,236	12,104	8,879
	OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88	-0.88	-0.88	-0.88
VENT STACK SEPARATION WALL			YES	YES	YES	YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER		DEGF	397.4	293	217.4	478.4	444.2	266	357.8
WINDBOX LEAKAGE		LBS/MIN	159	149	157	148	162	160	140
GAP HEIGHT		INCHES	1.0	1.0	1.0	1.0	1.0	1.0	1.0
O'BED LEAKAGE		LBS/MIN	(80)	(94)	(49)	(153)	(82)	(57)	(161)
GAP HEIGHT		INCHES	1	1	1	1	1	1	1
TOTAL AIR IN			25,302	28,266	28,771	26,254	26,782	28,780	24,830
TOTAL AIR OUT			25,303	28,267	28,772	26,253	26,781	28,779	24,831

TABLE 11: 1 OF 7

MINNTAC SECOND PARAMETRIC SERIES: CURRENT COOLER - NO OVER BED WALL

				16/450/100/100	16/450/135/170	16/450/170/135	16/485/100/170
	GREEN BALL FEED RATE **ON GRATE**		LTPH	450.00	450.00	450.00	485.00
	PRODUCTION FACTOR (1-NET FURNACE LOSS)			0.86	0.86	0.86	0.86
	PELLET FEED TO COOLER		LTPH	387.00	387.00	387.00	417.10
	GREENBALL MAGNETITE %WT			87.00	87.00	87.00	87.00
	FE++ IN COOLER FEED			3.86	3.86	3.86	3.86
	FE3O4 IN FEED (FE3O4=FE++/.2412)		%WT	16.00	16.00	16.00	16.00
	AVG PELLET TEMP INTO COOLER		DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE							
	3A FAN	FLOW	LBS/MIN	10,000	13,500	17,001	10,001
		G/S (THRU BED)	LBS/LB	0.5007	0.7147	0.9375	0.4573
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	-0.2821	-0.0647	0.0324	-0.1712
		U'BED	IN.H2O	12.543	16.01	18.278	13.79
		KFACT		545	545	545	545
BC 14	KILN SECONDARY AIR	AVG	DEGF	2,328	2,097	1,959	2,293
			LBS/MIN	3,222	5,684	6,444	4,601
		G/S	LBS/MIN	0.2230	0.3934	0.4460	0.2955
		OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15	FIRING HOOD AIR		DEGF	2,298	2,288	2,278	2,290
			LBS/MIN	2,155	2,702	2,957	2,388
		G/S	LBS/LB	0.1492	0.1870	0.2047	0.1534
		OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18	WINDBOX LEAKAGE		LBS/MIN	2,766	3,174	3,456	2,880
	GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
	OVERBED DIVIDING WALL:						
	LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
	GAP HEIGHT		INCHES	NA	NA	NA	NA
	FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE							
	3B FAN	FLOW	LBS/MIN	10,000	17,001	13,500	17,001
		G/S (THRU BED)	LBS/MIN	0.6823	1.1676	0.9258	1.0827
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	-0.4456	-0.1686	-0.2893	-0.1568
		U'BED	IN.H2O	10.018	12.3	9.665	14.07
BC 11	RECOUP B SIDE (WB 9)	AVG	DEGF	1,940	1,276	1,045	1,785
			LBS/MIN	2,512	3,544	3,670	3,063
		OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12	RECOUP A SIDE (WB10)	AVG	DEGF	1,684	916	789	1,338
			LBS/MIN	2,220	3,521	3,416	3,067
		OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13	COOLER VENT STACK	AVG	DEGF	905	344	352	552
			LBS/MIN	7,180	11,829	10,565	10,931
		OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF	628	183	198	322
BC 17	WINDBOX LEAKAGE		LBS/MIN	142	131	123	142
	GAP HEIGHT		INCHES	1	1	1	1
BC 16	O'BED LEAKAGE		LBS/MIN	(195)	(83)	(131)	(69)
	GAP HEIGHT		INCHES	1	1	1	1
	TOTAL AIR IN			20,195	30,583	30,632	27,071
	TOTAL AIR OUT			20,197	30,583	30,632	27,071

TABLE 11:

MINNTAC SECOND PARAMETRIC SERIES: CURRENT COOLER - NO OVER BED WALL

				16/485/135/135	16/485/170/100	16/520/100/135	16/520/135/100
	GREEN BALL FEED RATE ON GRATE		LTPH	485.00	485.00	520	520
	PRODUCTION FACTOR (1-NET FURNACE LOSS)			0.86	0.86	0.86	0.86
	PELLET FEED TO COOLER		LTPH	417.10	417.10	447.20	447.20
	GREENBALL MAGNETITE %WT			87.00	87.00	87.00	87.00
	FE++ IN COOLER FEED			3.86	3.86	3.86	3.86
	FE3O4 IN FEED (FE3O4=FE++/.2412)		%WT	16.00	16.00	16.00	16.00
	AVG PELLET TEMP INTO COOLER		DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE							
	3A FAN	FLOW	LBS/MIN	13,500	17,001	10,001	13,500
	G/S (THRU BED)		LBS/LB	0.6615	0.8672	0.4275	0.6158
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	-0.0956	0.0001	-0.2154	-0.1361
		U'BED	IN.H2O	16.27	18.73	13.55	16.45
		KFACT		545	545	545	545
BC 14	KILN SECONDARY AIR	AVG	DEGF	2,186	2,071	2,332	2,250
			LBS/MIN	5,267	6,006	4,075	4,767
		G/S	LBS/MIN	0.3382	0.3857	0.2441	0.2855
		OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15	FIRING HOOD AIR		DEGF	2,283	2,274	2,291	2,278
			LBS/MIN	2,597	2,867	2,301	2,535
		G/S	LBS/LB	0.1668	0.1841	0.1378	0.1518
		OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18	WINDBOX LEAKAGE		LBS/MIN	3,199	3,497	2,863	3,219
	GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
	OVERBED DIVIDING WALL:						
	LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
	GAP HEIGHT		INCHES	NA	NA	NA	NA
	FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE							
	3B FAN	FLOW	LBS/MIN	13,500	10,001	13,500	10,001
	G/S (THRU BED)		LBS/MIN	0.8583	0.6342	0.7995	0.5906
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	-0.2672	-0.3923	-0.2631	-0.3833
		U'BED	IN.H2O	11.25	8.3	13.3	9.91
BC 11	RECOUP B SIDE (WB 9)	AVG	DEGF	1,516	1,287	1,992	1,738
			LBS/MIN	3,150	3,249	2,765	2,802
		OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12	RECOUP A SIDE (WB10)	AVG	DEGF	1,213	1,030	1,668	1,498
			LBS/MIN	2,981	2,855	2,618	2,490
		OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13	COOLER VENT STACK	AVG	DEGF	555	548	864	854
			LBS/MIN	9,785	8,642	8,824	7,740
		OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF	336	358	595	612
BC 17	WINDBOX LEAKAGE		LBS/MIN	135	125	151	141
	GAP HEIGHT		INCHES	1	1	1	1
BC 16	O'BED LEAKAGE		LBS/MIN	(113)	(240)	(99)	(192)
	GAP HEIGHT		INCHES	1	1	1	1
	TOTAL AIR IN			27,113	27,241	23,599	23,692
	TOTAL AIR OUT			27,113	27,241	23,598	23,693

TABLE 11:

MINNTAC SECOND PARAMETRIC SERIES: CURRENT COOLER - NO OVER BED WALL

				16/520/170/170	22/450/100/170	22/450/135/135	22/450/170/100
GREEN BALL FEED RATE ON GRATE			LTPH	520	450	450	450
PRODUCTION FACTOR (1-NET FURNACE LOSS)				0.86	0.86	0.86	0.86
PELLET FEED TO COOLER			LTPH	447.20	387.00	387.00	387.00
GREENBALL MAGNETITE %WT				87.00	87.00	87.00	87.00
FE++ IN COOLER FEED				3.86	5.31	5.31	5.31
FE3O4 IN FEED (FE3O4=FE++/.2412)			%WT	16.00	22.00	22.00	22.00
AVG PELLET TEMP INTO COOLER			DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE							
		3A FAN FLOW	LBS/MIN	17,001	10,001	13,500	17,001
		G/S (THRU BED)	LBS/LB	0.8044	0.4942	0.7144	0.9367
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	0.1461	-0.1804	-0.1034	-0.0134
		U'BED	IN.H2O	19.65	13.57	16.03	18.38
		KFACT		545	545	545	545
BC 14	KILN SECONDARY AIR	AVG	DEGF	2,032	2,321	2,196	2,065
			LBS/MIN	7,193	4,486	5,182	5,919
		G/S	LBS/MIN	0.4308	0.3105	0.3587	0.4097
		OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15	FIRING HOOD AIR		DEGF	2,232	2,310	2,302	2,290
			LBS/MIN	3,075	2,358	2,557	2,833
		G/S	LBS/LB	0.1842	0.1632	0.1770	0.1961
		OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18	WINDBOX LEAKAGE		LBS/MIN	3,571	2,860	3,178	3,468
	GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
	OVERBED DIVIDING WALL:						
	LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
	GAP HEIGHT		INCHES	NA	NA	NA	NA
	FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE							
		3B FAN FLOW	LBS/MIN	17,001	17,001	13,500	10,001
		G/S (THRU BED)	LBS/MIN	1.0103	1.1671	0.9253	0.6838
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	-0.062	-0.1825	-0.2921	-0.4117
		U'BED	IN.H2O	12.55	13..53	10.73	7.915
BC 11	RECOUP B SIDE (WB 9)	AVG	DEGF	1,188	1,738	1,442	1,207
			LBS/MIN	3,894	3,063	3,173	3,292
		OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12	RECOUP A SIDE (WB10)	AVG	DEGF	894	1,266	1,123	940
			LBS/MIN	3,826	3,063	3,005	2,891
		OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13	COOLER VENT STACK	AVG	DEGF	375	479	485	480
			LBS/MIN	12,387	11,089	9,893	8,740
		OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF	210	262	277	298
BC 17	WINDBOX LEAKAGE		LBS/MIN	132	138	131	121
	GAP HEIGHT		INCHES	1	1	1	1
BC 16	O'BED LEAKAGE		LBS/MIN	(76)	(76)	(119)	(263)
	GAP HEIGHT		INCHES	1	1	1	1
	TOTAL AIR IN			34,077	27,077	27,119	27,264
	TOTAL AIR OUT			34,078	27,077	27,119	27,262

TABLE 11:

MINNTAC SECOND PARAMETRIC SERIES: CURRENT COOLER - NO OVER BED WALL

				22/485/100/135	22/485/135/100	22/485/170/170	22/520/100/100
GREEN BALL FEED RATE **ON GRATE**			LTPH	485	485	485	520
PRODUCTION FACTOR (1-NET FURNACE LOSS)				0.86	0.86	0.86	0.86
PELLET FEED TO COOLER			LTPH	417.10	417.10	417.10	447.20
GREENBALL MAGNETITE %WT				87.00	87.00	87.00	87.00
FE++ IN COOLER FEED				5.31	5.31	5.31	5.31
FE3O4 IN FEED (FE3O4=FE++/.2412)			%WT	22.00	22.00	22.00	22.00
AVG PELLET TEMP INTO COOLER			DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE							
	3A FAN	FLOW	LBS/MIN	10,001	13,500	17,001	10,001
	G/S (THRU BED)		LBS/LB	0.4593	0.6613	0.8641	0.4288
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	-0.2214	-0.143	0.1317	-0.2649
		U'BED	IN.H2O	13.4	16.27	19.34	13.28
		KFACT		545	545	545	545
BC 14	KILN SECONDARY AIR	AVG	DEGF	2,367	2,270	2,024	2,393
			LBS/MIN	3,981	4,687	7,103	3,412
		G/S	LBS/MIN	0.2556	0.3010	0.4562	0.2044
		OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15	FIRING HOOD AIR		DEGF	2,308	2,295	2,289	2,304
			LBS/MIN	2,280	2,524	3,039	2,199
		G/S	LBS/LB	0.1464	0.1621	0.1952	0.1317
		OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18	WINDBOX LEAKAGE		LBS/MIN	2,848	3,203	3,544	2,842
	GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
	OVERBED DIVIDING WALL:						
	LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
	GAP HEIGHT		INCHES	NA	NA	NA	NA
	FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE							
	3B FAN	FLOW	LBS/MIN	13,500	10,001	17,001	10,001
	G/S (THRU BED)		LBS/MIN	0.8575	0.6335	1.0834	0.5896
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	-0.2785	-0.3997	-0.0947	-0.4019
		U'BED	IN.H2O	12.83	9.47	12.08	11.5
BC 11	RECOUP B SIDE (WB 9)	AVG	DEGF	1,979	1,690	1,109	2,161
			LBS/MIN	2,751	2,809	3,939	2,470
		OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12	RECOUP A SIDE (WB10)	AVG	DEGF	1,627	1,431	814	1,946
			LBS/MIN	2,617	2,495	3,871	2,190
		OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13	COOLER VENT STACK	AVG	DEGF	781	774	327	1,192
			LBS/MIN	8,977	7,833	12,453	6,893
		OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF	507	529	176	919
BC 17	WINDBOX LEAKAGE		LBS/MIN	147	136	130	157
	GAP HEIGHT		INCHES	1	1	1	1
BC 16	O'BED LEAKAGE		LBS/MIN	(101)	(187)	(80)	(162)
	GAP HEIGHT		INCHES	1	1	1	1
	TOTAL AIR IN			23,601	23,687	34,081	20,164
	TOTAL AIR OUT			23,600	23,688	34,079	20,162

TABLE 11:

MINNTAC SECOND PARAMETRIC SERIES:
CURRENT COOLER - NO OVER BED WALL

				22/520/135/170	22/520/170/135	28/450/100/135	28/450/135/100
	GREEN BALL FEED RATE ON GRATE		LTPH	520	520	450	450
	PRODUCTION FACTOR (1-NET FURNACE LOSS)			0.86	0.86	0.86	0.86
	PELLET FEED TO COOLER		LTPH	447.20	447.20	387.00	387.00
	GREENBALL MAGNETITE %WT			87.00	87.00	87.00	87.00
	FE++ IN COOLER FEED			5.31	5.31	6.75	6.75
	FE3O4 IN FEED (FE3O4=FE++/.2412)		%WT	22.00	22.00	28.00	28.00
	AVG PELLET TEMP INTO COOLER		DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE							
	3A FAN	FLOW	LBS/MIN	13,500	17,001	10,001	13,500
	G/S (THRU BED)		LBS/LB	0.6123	0.8039	0.4962	0.7142
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	-0.0189	0.0911	-0.2281	-0.1503
		U'BED	IN.H2O	17.14	19.73	13.22	16.04
		KFACT		545	545	545	545
BC 14	KILN SECONDARY AIR	AVG	DEGF	2,232	2,117	2,398	2,283
			LBS/MIN	5,906	6,655	3,882	4,607
		G/S	LBS/MIN	0.3537	0.3986	0.2687	0.3188
		OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15	FIRING HOOD AIR		DEGF	2,292	2,284	2,329	2,314
			LBS/MIN	2,733	3,002	2,254	2,499
		G/S	LBS/LB	0.1637	0.1798	0.1560	0.1730
		OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18	WINDBOX LEAKAGE		LBS/MIN	3,277	3,579	2,831	3,182
	GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
	OVERBED DIVIDING WALL:						
	LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
	GAP HEIGHT		INCHES	NA	NA	NA	NA
	FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE							
	3B FAN	FLOW	LBS/MIN	17,001	13,500	13,500	10,001
	G/S (THRU BED)		LBS/MIN	1.0099	0.8007	0.9246	0.6831
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	-0.07	-0.2054	-0.2985	-0.4183
		U'BED	IN.H2O	13.89	10.91	12.27	9
BC 11	RECOUP B SIDE (WB 9)	AVG	DEGF	1,583	1,331	1,946	1,624
			LBS/MIN	3,411	3,506	2,745	2,825
		OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12	RECOUP A SIDE (WB10)	AVG	DEGF	1,207	1,056	1,566	1,343
			LBS/MIN	3,404	3,301	2,618	2,508
		OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13	COOLER VENT STACK	AVG	DEGF	499	504	691	689
			LBS/MIN	11,699	10,437	9,131	7,946
		OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF	288	307	417	446
BC 17	WINDBOX LEAKAGE		LBS/MIN	140	133	142	131
	GAP HEIGHT		INCHES	1	1	1	1
BC 16	O'BED LEAKAGE		LBS/MIN	(68)	(111)	(105)	(198)
	GAP HEIGHT		INCHES	1	1	1	1
	TOTAL AIR IN			30,569	30,612	23,606	23,698
	TOTAL AIR OUT			30,570	30,612	23,604	23,698

MINNTAC SECOND PARAMETRIC SERIES: CURRENT COOLER - NO OVER BED WALL

				28/450/170/170	28/485/100/100	28/485/135/170	28/485/170/135
GREEN BALL FEED RATE **ON GRATE**			LTPH	450	485	485	485
PRODUCTION FACTOR (1-NET FURNACE LOSS)				0.86	0.86	0.86	0.86
PELLET FEED TO COOLER			LTPH	387.00	417.10	417.10	417.10
GREENBALL MAGNETITE %WT				87.00	87.00	87.00	87.00
FE++ IN COOLER FEED				6.75	6.75	6.75	6.75
FE3O4 IN FEED (FE3O4=FE++/.2412)			%WT	28.00	28.00	28.00	28.00
AVG PELLET TEMP INTO COOLER			DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE							
		3A FAN FLOW	LBS/MIN	17,001	10,001	13,500	17,001
		G/S (THRU BED)	LBS/LB	0.9335	0.4604	0.6578	0.8636
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	0.1149	-0.2681	-0.0291	0.0781
		U'BED	IN.H2O	18.95	13.18	16.92	19.41
		KFACT		545	545	545	545
BC 14	KILN SECONDARY AIR	AVG	DEGF	2,004	2,428	2,242	2,112
			LBS/MIN	7,015	3,350	5,812	6,569
		G/S	LBS/MIN	0.4855	0.2151	0.3732	0.4218
		OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15	FIRING HOOD AIR		DEGF	2,305	2,321	2,309	2,299
			LBS/MIN	2,999	2,184	2,704	2,969
		G/S	LBS/LB	0.2076	0.1403	0.1737	0.1907
		OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18	WINDBOX LEAKAGE		LBS/MIN	3,514	2,831	3,257	3,554
	GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
	OVERBED DIVIDING WALL:						
	LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
	GAP HEIGHT		INCHES	NA	NA	NA	NA
	FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE							
		3B FAN FLOW	LBS/MIN	17,001	10,001	17,001	13,500
		G/S (THRU BED)	LBS/MIN	1.1679	0.6325	1.0830	0.8587
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	-0.1289	-0.4116	-0.1012	-0.2324
		U'BED	IN.H2O	11.6	11.06	13.32	10.45
BC 11	RECOUP B SIDE (WB 9)	AVG	DEGF	1,016	2,155	1,514	1,253
			LBS/MIN	4,002	2,458	3,427	3,542
		OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12	RECOUP A SIDE (WB10)	AVG	DEGF	725	1,911	1,124	972
			LBS/MIN	3,928	2,186	3,429	3,331
		OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13	COOLER VENT STACK	AVG	DEGF	283	1,104	437	445
			LBS/MIN	12,502	7,005	11,808	10,526
		OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF	147	813	239	259
BC 17	WINDBOX LEAKAGE		LBS/MIN	127	152	136	129
	GAP HEIGHT		INCHES	1	1	1	1
BC 16	O'BED LEAKAGE		LBS/MIN	(85)	(165)	(73)	(118)
	GAP HEIGHT		INCHES	1	1	1	1
	TOTAL AIR IN			34,086	20,166	30,573	30,618
	TOTAL AIR OUT			34,087	20,166	30,573	30,619

TABLE 11: 7 OF 7

MINNTAC SECOND PARAMETRIC SERIES: CURRENT COOLER - NO OVER BED WALL

					28/520/100/170	28/520/135/135	28/520/170/100
GREEN BALL FEED RATE **ON GRATE**				LTPH	520	520	520
PRODUCTION FACTOR (1-NET FURNACE LOSS)					0.86	0.86	0.86
PELLET FEED TO COOLER				LTPH	447.20	447.20	447.20
GREENBALL MAGNETITE %WT					87.00	87.00	87.00
FE++ IN COOLER FEED					6.75	6.75	6.75
FE3O4 IN FEED (FE3O4=FE++/.2412)				%WT	28.00	28.00	28.00
AVG PELLET TEMP INTO COOLER				DEGF	2,250	2,250	2,250
PRIMARY COOLING ZONE							
		3A FAN	FLOW	LBS/MIN	10,001	13,500	17,001
		G/S (THRU BED)		LBS/LB	0.4224	0.6123	0.8034
			INLET	DEGF	39.2	39.2	39.2
			O'BED	IN.H2O	-0.1486	-0.068	0.0344
			U'BED	IN.H2O	14.53	17.12	19.8
			KFACT		545	545	545
BC 14	KILN SECONDARY AIR		AVG	DEGF	2,403	2,305	2,196
				LBS/MIN	4,738	5,382	6,107
			G/S	LBS/MIN	0.2838	0.3224	0.3658
			OUTLET	INH2O	-0.40	-0.40	-0.40
BC 15	FIRING HOOD AIR			DEGF	2,314	2,304	2,292
				LBS/MIN	2,433	2,637	2,930
			G/S	LBS/LB	0.1457	0.1579	0.1755
			OUTLET	INH2O	-0.73	-0.73	-0.73
BC 18	WINDBOX LEAKAGE			LBS/MIN	2,948	3,277	3,587
	GAP HEIGHT			INCHES	3.62	3.62	3.62
	WINDBOX DAMPER POSITION				CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER			INCHES	1.67	1.67	1.67
	OVERBED DIVIDING WALL:						
	LOCATION (BETWEEN WBOXES)				NONE	NONE	NONE
	GAP HEIGHT			INCHES	NA	NA	NA
	FLOW (- = 3A TO 3B; + = 3B TO 3A)			LBS/MIN	NA	NA	NA
SECONDARY COOLING ZONE							
		3B FAN	FLOW	LBS/MIN	17,001	13,500	10,001
		G/S (THRU BED)		LBS/MIN	1.0093	0.8001	0.5911
			INLET	DEGF	39.2	39.2	39.2
			O'BED	IN.H2O	-0.0958	-0.2112	-0.3486
			U'BED	IN.H2O	15.32	12.29	9.07
BC 11	RECOUP B SIDE (WB 9)		AVG	DEGF	1,999	1,742	1,496
				LBS/MIN	3,002	3,065	3,143
			OUTLET	INH2O	-1.11	-1.11	-1.11
BC 12	RECOUP A SIDE (WB10)		AVG	DEGF	1,547	1,430	1,232
				LBS/MIN	3,012	2,921	2,789
			OUTLET	INH2O	-0.90	-0.90	-0.90
BC 13	COOLER VENT STACK		AVG	DEGF	690	689	679
				LBS/MIN	10,781	9,674	8,515
			OUTLET	INH2O	-0.88	-0.88	-0.88
	VENT STACK SEPARATION WALL				YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER			DEGF	417	437	460
BC 17	WINDBOX LEAKAGE			LBS/MIN	150	143	132
	GAP HEIGHT			INCHES	1	1	1
BC 16	O'BED LEAKAGE			LBS/MIN	(62)	(100)	(203)
	GAP HEIGHT			INCHES	1	1	1
	TOTAL AIR IN				27,063	27,100	27,205
	TOTAL AIR OUT				27,063	27,099	27,204

TABLE 12: 1 OF 7

MINNTAC THIRD PARAMETRIC SERIES: COOLER WITH OVER BED DIVIDING WALL BETWEEN WIND BOXES 6 AND 7

			16/450/100/100	16/450/135/170	16/450/170/135	16/485/100/170
GREEN BALL FEED RATE ON GRATE		LTPH	450.00	450.00	450.00	485.00
PRODUCTION FACTOR			0.86	0.86	0.86	0.86
PELLET FEED TO COOLER		LTPH	387.00	387.00	387.00	417.10
GREENBALL MAGNETITE %WT			87.00	87.00	87.00	87.00
FE++ IN COOLER FEED			3.86	3.86	3.86	3.86
FE3O4 IN FEED (FE3O4=FE++/.2412)		%WT	16.00	16.00	16.00	16.00
AVG PELLET TEMP INTO COOLER		DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE						
3A FAN	FLOW	LBS/MIN	10,000	13,500	17,001	10,001
G/S (THRU BED)		LBS/LB	0.5008	0.7149	0.9375	0.4573
	INLET	DEGF	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.2781	-0.1039	0.059	-0.2297
	U'BED	IN.H2O	12.550	16.01	18.3	13.81
	KFACT		545	545	545	545
BC 14 KILN SECONDARY AIR	AVG	DEGF	2,326	2,142	1,947	2,321
		LBS/MIN	3,281	5,239	6,669	3,905
	G/S	LBS/MIN	0.2271	0.3626	0.4616	0.2508
	OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15 FIRING HOOD AIR		DEGF	2,299	2,287	2,278	2,291
		LBS/MIN	2,162	2,579	2,925	2,282
	G/S	LBS/LB	0.1496	0.1785	0.2025	0.1466
	OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18 WINDBOX LEAKAGE		LBS/MIN	2,765	3,171	3,456	2,880
GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
OVERBED DIVIDING WALL						
LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
GAP HEIGHT		INCHES	NA	NA	NA	NA
FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE						
3B FAN	FLOW	LBS/MIN	10,000	17,001	13,500	17,001
G/S (THRU BED)		LBS/MIN	0.6823	1.1676	0.9259	1.0826
	INLET	DEGF	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.4520	-0.1021	-0.3067	-0.0485
	U'BED	IN.H2O	10.010	12.36	9.65	14.16
BC 11 RECOUP B SIDE (WB 9)	AVG	DEGF	1,935	1,326	1,028	1,844
		LBS/MIN	2,497	3,658	3,630	3,247
	OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12 RECOUP A SIDE (WB10)	AVG	DEGF	1,673	977	770	1,455
		LBS/MIN	2,207	3,621	3,383	3,214
	OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13 COOLER VENT STACK	AVG	DEGF	901	363	347	585
		LBS/MIN	7,143	12,180	10,446	11,396
	OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
VENT STACK SEPARATION WALL			YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER		DEGF	628	183	199	322
BC 17 WINDBOX LEAKAGE		LBS/MIN	141	131	123	142
GAP HEIGHT		INCHES	1	1	1	1
BC 16 O'BED LEAKAGE		LBS/MIN	(196)	(79)	(133)	(65)
GAP HEIGHT		INCHES	1	1	1	1
TOTAL AIR IN			20,196	30,579	30,634	27,067
TOTAL AIR OUT			20,195	30,578	30,633	27,066

MINNTAC THIRD PARAMETRIC SERIES:
COOLER WITH OVER BED DIVIDING WALL
BETWEEN WIND BOXES 6 AND 7

		16/485/135/135	16/485/170/100	16/520/100/135	16/520/135/100
GREEN BALL FEED RATE ON GRATE	LTPH	485.00	485.00	520.00	520.00
PRODUCTION FACTOR		0.86	0.86	0.86	0.86
PELLET FEED TO COOLER	LTPH	417.12	417.12	447.20	447.20
GREENBALL MAGNETITE %WT		87.00	87.00	87.00	87.00
FE++ IN COOLER FEED		3.86	3.86	3.86	3.86
FE3O4 IN FEED (FE3O4=FE++/.2412)	%WT	16.00	16.00	16.00	16.00
AVG PELLET TEMP INTO COOLER	DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE					
3A FAN FLOW	LBS/MIN	13,500	17,001	10,001	13,500
G/S (THRU BED)	LBS/LB	0.6616	0.8671	0.4275	0.6159
INLET	DEGF	39.2	39.2	39.2	39.2
O'BED	IN.H2O	-0.1087	0.0583	-0.2492	-0.1204
U'BED	IN.H2O	16.27	18.78	13.57	16.46
KFACT		545	545	545	545
BC 14 KILN SECONDARY AIR AVG	DEGF	2,200	2,028	2,343	2,243
	LBS/MIN	5,087	6,540	3,649	4,931
G/S	LBS/MIN	0.3267	0.4199	0.2186	0.2953
OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15 FIRING HOOD AIR	DEGF	2,284	2,275	2,288	2,280
	LBS/MIN	2,568	2,924	2,241	2,557
G/S	LBS/LB	0.1649	0.1878	0.1342	0.1532
OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18 WINDBOX LEAKAGE	LBS/MIN	3,198	3,498	2,863	3,218
GAP HEIGHT	INCHES	3.62	3.62	3.62	3.62
WINDBOX DAMPER POSITION		CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER	INCHES	1.67	1.67	1.67	1.67
OVERBED DIVIDING WALL					
LOCATION (BETWEEN WBOXES)		NONE	NONE	NONE	NONE
GAP HEIGHT	INCHES	NA	NA	NA	NA
FLOW (- = 3A TO 3B; + = 3B TO 3A)	LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE					
3B FAN FLOW	LBS/MIN	13,500	10,001	13,500	10,001
G/S (THRU BED)	LBS/MIN	0.8583	0.6342	0.7995	0.5906
INLET	DEGF	39.2	39.2	39.2	39.2
O'BED	IN.H2O	-0.2442	-0.4395	-0.2026	-0.4018
U'BED	IN.H2O	11.27	8.26	13.35	9.89
BC 11 RECOUP B SIDE (WB 9) AVG	DEGF	1,534	1,225	2,019	1,721
	LBS/MIN	3,195	3,124	2,880	2,758
OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12 RECOUP A SIDE (WB10) AVG	DEGF	1,233	977	1,731	1,478
	LBS/MIN	3,022	2,747	2,719	2,453
OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13 COOLER VENT STACK AVG	DEGF	563	528	888	847
	LBS/MIN	9,907	8,299	9,092	7,623
OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
VENT STACK SEPARATION WALL		YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER	DEGF	336	356	595	612
BC 17 WINDBOX LEAKAGE	LBS/MIN	135	125	152	141
GAP HEIGHT	INCHES	1	1	1	1
BC 16 O'BED LEAKAGE	LBS/MIN	(111)	(255)	(94)	(182)
GAP HEIGHT	INCHES	1	1	1	1
TOTAL AIR IN		27,111	27,256	23,595	23,682
TOTAL AIR OUT		27,111	27,255	23,595	23,681

TABLE 12: 3 OF 7

MINNTAC THIRD PARAMETRIC SERIES: COOLER WITH OVER BED DIVIDING WALL BETWEEN WIND BOXES 6 AND 7

			16/520/170/170	22/450/100/170	22/450/135/135	22/450/170/100
GREEN BALL FEED RATE ON GRATE		LTPH	520.00	450.00	450.00	450.00
PRODUCTION FACTOR			0.86	0.86	0.86	0.86
PELLET FEED TO COOLER		LTPH	447.20	387.00	387.00	387.00
GREENBALL MAGNETITE %WT			87.00	87.00	87.00	87.00
FE++ IN COOLER FEED			3.86	5.31	5.31	5.31
FE3O4 IN FEED (FE3O4=FE++/.2412)		%WT	16.00	22.00	22.00	22.00
AVG PELLET TEMP INTO COOLER		DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE						
3A FAN	FLOW	LBS/MIN	17,001	10,001	13,500	17,001
G/S (THRU BED)		LBS/LB	0.8046	0.4942	0.7145	0.9366
	INLET	DEGF	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	0.1085	-0.2344	-0.1129	0.0505
	U'BED	IN.H2O	19.65	13.59	16.03	18.41
	KFACT		545	545	545	545
BC 14 KILN SECONDARY AIR	AVG	DEGF	2,058	2,352	2,206	2,010
		LBS/MIN	6,870	3,830	5,045	6,509
	G/S	LBS/MIN	0.4115	0.2651	0.3492	0.4505
	OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15 FIRING HOOD AIR		DEGF	2,272	2,312	2,302	2,292
		LBS/MIN	3,030	2,260	2,547	2,895
	G/S	LBS/LB	0.1815	0.1564	0.1763	0.2004
	OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18 WINDBOX LEAKAGE		LBS/MIN	3,568	2,860	3,177	3,469
GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
OVERBED DIVIDING WALL						
LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
GAP HEIGHT		INCHES	NA	NA	NA	NA
FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE						
3B FAN	FLOW	LBS/MIN	17,001	17,001	13,500	10,001
G/S (THRU BED)		LBS/MIN	1.0103	1.1671	0.9253	0.6838
	INLET	DEGF	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.0197	-0.0825	-0.2762	-0.4618
	U'BED	IN.H2O	12.59	13.6	10.76	7.87
BC 11 RECOUP B SIDE (WB 9)	AVG	DEGF	1,218	1,801	1,455	1,135
		LBS/MIN	3,969	3,232	3,204	3,159
	OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12 RECOUP A SIDE (WB10)	AVG	DEGF	922	1,384	1,138	881
		LBS/MIN	3,895	3,215	3,034	2,773
	OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13 COOLER VENT STACK	AVG	DEGF	384	511	491	459
		LBS/MIN	12,610	11,535	9,982	8,352
	OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
VENT STACK SEPARATION WALL			YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER		DEGF	208	262	277	298
BC 17 WINDBOX LEAKAGE		LBS/MIN	133	138	131	121
GAP HEIGHT		INCHES	1	1	1	1
BC 16 O'BED LEAKAGE		LBS/MIN	(73)	(70)	(118)	(276)
GAP HEIGHT		INCHES	1	1	1	1
TOTAL AIR IN			34,074	27,071	27,118	27,277
TOTAL AIR OUT			34,074	27,070	27,119	27,278

TABLE 12:
MINNTAC THIRD PARAMETRIC SERIES: COOLER WITH OVER BED DIVIDING WALL BETWEEN WIND BOXES 6 AND 7

			22/485/100/135	22/485/135/100	22/485/170/170	22/520/100/100
GREEN BALL FEED RATE ON GRATE		LTPH	485.00	485.00	485.00	520.00
PRODUCTION FACTOR			0.86	0.86	0.86	0.86
PELLET FEED TO COOLER		LTPH	417.10	417.10	417.10	447.20
GREENBALL MAGNETITE %WT			87.00	87.00	87.00	87.00
FE++ IN COOLER FEED			5.31	5.31	5.31	5.31
FE3O4 IN FEED (FE3O4=FE++/.2412)		%WT	22.00	22.00	22.00	22.00
AVG PELLET TEMP INTO COOLER		DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE						
3A FAN	FLOW	LBS/MIN	10,001	13,500	17,001	10,001
	G/S (THRU BED)	LBS/LB	0.4594	0.6614	0.8642	0.4289
	INLET	DEGF	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.2526	-0.1228	0.1005	-0.2684
	U'BED	IN.H2O	13.41	16.28	19.33	13.29
	KFACT		545	545	545	545
BC 14 KILN SECONDARY AIR	AVG	DEGF	2,379	2,258	2,049	2,394
		LBS/MIN	3,584	4,898	6,831	3,363
	G/S	LBS/MIN	0.2302	0.3145	0.4387	0.2014
	OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15 FIRING HOOD AIR		DEGF	2,308	2,296	2,288	2,303
		LBS/MIN	2,224	2,541	3,002	2,194
	G/S	LBS/LB	0.1428	0.1632	0.1928	0.1314
	OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18 WINDBOX LEAKAGE		LBS/MIN	2,847	3,202	3,543	2,839
GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
OVERBED DIVIDING WALL						
LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
GAP HEIGHT		INCHES	NA	NA	NA	NA
FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE						
3B FAN	FLOW	LBS/MIN	13,500	10,001	17,001	10,001
	G/S (THRU BED)	LBS/MIN	0.8607	0.6335	1.0834	0.5896
	INLET	DEGF	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.2228	-0.4211	-0.05982	-0.3958
	U'BED	IN.H2O	12.88	9.45	12.11	11.5
BC 11 RECOUP B SIDE (WB 9)	AVG	DEGF	2,007	1,666	1,134	2,165
		LBS/MIN	2,855	2,758	4,001	2,483
	OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12 RECOUP A SIDE (WB10)	AVG	DEGF	1,691	1,402	836	1,951
		LBS/MIN	2,707	2,453	3,929	2,201
	OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13 COOLER VENT STACK	AVG	DEGF	804	764	336	1,195
		LBS/MIN	9,231	7,703	12,644	6,923
	OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
VENT STACK SEPARATION WALL			YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER		DEGF	505	529	176	921
BC 17 WINDBOX LEAKAGE		LBS/MIN	97	136	130	157
GAP HEIGHT		INCHES	1	1	1	1
BC 16 O'BED LEAKAGE		LBS/MIN	(276)	(190)	(78)	(162)
GAP HEIGHT		INCHES	1	1	1	1
TOTAL AIR IN			23,777	23,691	34,079	20,163
TOTAL AIR OUT			23,544	23,691	34,079	20,161

TABLE 12:

MINNTAC THIRD PARAMETRIC SERIES: COOLER WITH OVER BED DIVIDING WALL BETWEEN WIND BOXES 6 AND 7

				22/520/135/170	22/520/170/135	28/450/100/135	28/450/135/100
GREEN BALL FEED RATE ON GRATE			LTPH	520.00	520.00	450.00	450.00
PRODUCTION FACTOR				0.86	0.86	0.86	0.86
PELLET FEED TO COOLER			LTPH	447.20	447.20	387.00	387.00
GREENBALL MAGNETITE %WT				87.00	87.00	87.00	87.00
FE++ IN COOLER FEED				5.31	5.31	5.31	5.31
FE3O4 IN FEED (FE3O4=FE++/.2412)			%WT	22.00	22.00	22.00	22.00
AVG PELLET TEMP INTO COOLER			DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE							
		3A FAN FLOW	LBS/MIN	13,500	17,001	10,001	13,500
		G/S (THRU BED)	LBS/LB	0.6125	0.8040	0.4963	0.7142
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	-0.0816	0.0944	-0.256	-0.1262
		U'BED	IN.H2O	17.14	19.73	13.22	16.05
		KFACT		545	545	545	545
BC 14	KILN SECONDARY AIR	AVG	DEGF	2,267	2,117	2,412	2,266
			LBS/MIN	5,301	6,688	3,522	4,863
		G/S	LBS/MIN	0.3175	0.4006	0.2438	0.3366
		OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15	FIRING HOOD AIR		DEGF	2,291	2,284	2,328	2,314
			LBS/MIN	2,639	3,007	2,205	2,522
		G/S	LBS/LB	0.1581	0.1801	0.1526	0.1745
		OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18	WINDBOX LEAKAGE		LBS/MIN	3,274	3,577	2,830	3,180
	GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
	OVERBED DIVIDING WALL						
	LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
	GAP HEIGHT		INCHES	NA	NA	NA	NA
	FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE							
		3B FAN FLOW	LBS/MIN	17,001	13,500	13,500	10,001
		G/S (THRU BED)	LBS/MIN	1.0099	0.8006	0.9246	0.6831
		INLET	DEGF	39.2	39.2	39.2	39.2
		O'BED	IN.H2O	0.0228	-0.2089	-0.249	-0.4441
		U'BED	IN.H2O	13.97	10.9	12.31	8.98
BC 11	RECOUP B SIDE (WB 9)	AVG	DEGF	1,636	1,326	1,978	1,593
			LBS/MIN	3,563	3,501	2,839	2,764
		OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12	RECOUP A SIDE (WB10)	AVG	DEGF	1,287	1,040	1,628	1,313
			LBS/MIN	3,532	3,304	2,698	2,455
		OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13	COOLER VENT STACK	AVG	DEGF	524	503	713	672
			LBS/MIN	12,112	10,404	9,364	7,786
		OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF	286	307	419	448
BC 17	WINDBOX LEAKAGE		LBS/MIN	141	133	142	131
	GAP HEIGHT		INCHES	1	1	1	1
BC 16	O'BED LEAKAGE		LBS/MIN	(63)	(112)	(101)	(203)
	GAP HEIGHT		INCHES	1	1	1	1
	TOTAL AIR IN			30,563	30,612	23,602	23,703
	TOTAL AIR OUT			30,563	30,613	23,600	23,702

TABLE 12:
MINNTAC THIRD PARAMETRIC SERIES: COOLER WITH OVER BED DIVIDING WALL BETWEEN WIND BOXES 6 AND 7

			28/450/170/170	28/485/100/100	28/485/135/170	28/485/170/135
GREEN BALL FEED RATE ON GRATE		LTPH	450.00	485.00	485.00	485.00
PRODUCTION FACTOR			0.86	0.86	0.86	0.86
PELLET FEED TO COOLER		LTPH	387.00	417.10	417.10	417.10
GREENBALL MAGNETITE %WT			87.00	87.00	87.00	87.00
FE++ IN COOLER FEED			5.31	5.31	5.31	5.31
FE3O4 IN FEED (FE3O4=FE++/.2412)		%WT	22.00	22.00	22.00	22.00
AVG PELLET TEMP INTO COOLER		DEGF	2,250	2,250	2,250	2,250
PRIMARY COOLING ZONE						
3A FAN	FLOW	LBS/MIN	17,001	10,001	13,500	17,001
G/S (THRU BED)		LBS/LB	0.9337	0.4605	0.6579	0.8636
	INLET	DEGF	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	0.0907	-0.2697	-0.0858	0.0871
	U'BED	IN.H2O	18.95	13.19	16.92	19.42
	KFACT		545	545	545	545
BC 14 KILN SECONDARY AIR	AVG	DEGF	2,027	2,429	2,279	2,106
		LBS/MIN	6,794	3,326	5,254	6,652
	G/S	LBS/MIN	0.4702	0.2136	0.3374	0.4272
	OUTLET	INH2O	-0.40	-0.40	-0.40	-0.40
BC 15 FIRING HOOD AIR		DEGF	2,079	2,321	2,307	2,299
		LBS/MIN	3,233	2,182	2,620	2,981
	G/S	LBS/LB	0.2238	0.1401	0.1682	0.1914
	OUTLET	INH2O	-0.73	-0.73	-0.73	-0.73
BC 18 WINDBOX LEAKAGE		LBS/MIN	3,511	2,830	3,256	3,552
GAP HEIGHT		INCHES	3.62	3.62	3.62	3.62
WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED	CLOSED
LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67	1.67
OVERBED DIVIDING WALL						
LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE	NONE
GAP HEIGHT		INCHES	NA	NA	NA	NA
FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA	NA
SECONDARY COOLING ZONE						
3B FAN	FLOW	LBS/MIN	17,001	10,001	17,001	13,500
G/S (THRU BED)		LBS/MIN	1.1679	0.6325	1.0830	0.8587
	INLET	DEGF	39.2	39.2	39.2	39.2
	O'BED	IN.H2O	-0.1018	-0.4089	-0.018	-0.2439
	U'BED	IN.H2O	11.62	11.07	13.403	10.44
BC 11 RECOUP B SIDE (WB 9)	AVG	DEGF	1,038	2,157	1,569	1,246
		LBS/MIN	4,052	2,463	3,563	3,517
	OUTLET	INH2O	-1.11	-1.11	-1.11	-1.11
BC 12 RECOUP A SIDE (WB10)	AVG	DEGF	742	1,915	1,200	965
		LBS/MIN	3,977	2,191	3,544	3,309
	OUTLET	INH2O	-0.90	-0.90	-0.90	-0.90
BC 13 COOLER VENT STACK	AVG	DEGF	289	1,105	460	437
		LBS/MIN	12,654	7,020	12,197	10,479
	OUTLET	INH2O	-0.88	-0.88	-0.88	-0.88
VENT STACK SEPARATION WALL			YES	YES	YES	YES
PELLET EXIT TEMP TOP-CENTER		DEGF	147	811	239	257
BC 17 WINDBOX LEAKAGE		LBS/MIN	127	152	137	129
GAP HEIGHT		INCHES	1	1	1	1
BC 16 O'BED LEAKAGE		LBS/MIN	(83)	(164)	(68)	(120)
GAP HEIGHT		INCHES	1	1	1	1
TOTAL AIR IN			34,084	20,165	30,568	30,620
TOTAL AIR OUT			34,349	20,164	30,570	30,619

TABLE 12:

MINNTAC THIRD PARAMETRIC SERIES: COOLER WITH OVER BED DIVIDING WALL BETWEEN WIND BOXES 6 AND 7

				28/520/100/170	28/520/135/135	28/520/170/100
GREEN BALL FEED RATE ON GRATE			LTPH	520.00	520.00	520.00
PRODUCTION FACTOR				0.86	0.86	0.86
PELLET FEED TO COOLER			LTPH	447.20	447.20	447.20
GREENBALL MAGNETITE %WT				87.00	87.00	87.00
FE++ IN COOLER FEED				5.31	5.31	5.31
FE3O4 IN FEED (FE3O4=FE++/.2412)			%WT	22.00	22.00	22.00
AVG PELLET TEMP INTO COOLER			DEGF	2,250	2,250	2,250
PRIMARY COOLING ZONE						
	3A FAN	FLOW	LBS/MIN	10,001	13,500	17,001
	G/S (THRU BED)		LBS/LB	0.4225	0.6124	0.8034
		INLET	DEGF	39.2	39.2	39.2
		O'BED	IN.H2O	-0.2165	-0.0924	0.0836
		U'BED	IN.H2O	14.54	17.12	19.82
		KFACT		545	545	545
BC 14	KILN SECONDARY AIR	AVG	DEGF	2,418	2,318	2,169
			LBS/MIN	3,977	5,111	6,532
		G/S	LBS/MIN	0.2382	0.3061	0.3912
		OUTLET	INH2O	-0.40	-0.40	-0.40
BC 15	FIRING HOOD AIR		DEGF	2,311	2,302	2,294
			LBS/MIN	2,313	2,606	2,975
		G/S	LBS/LB	0.1385	0.1561	0.1782
		OUTLET	INH2O	-0.73	-0.73	-0.73
BC 18	WINDBOX LEAKAGE		LBS/MIN	2,946	3,276	3,588
	GAP HEIGHT		INCHES	3.62	3.62	3.62
	WINDBOX DAMPER POSITION			CLOSED	CLOSED	CLOSED
	LEAK GAP ACROSS DAMPER		INCHES	1.67	1.67	1.67
	OVERBED DIVIDING WALL					
	LOCATION (BETWEEN WBOXES)			NONE	NONE	NONE
	GAP HEIGHT		INCHES	NA	NA	NA
	FLOW (- = 3A TO 3B; + = 3B TO 3A)		LBS/MIN	NA	NA	NA
SECONDARY COOLING ZONE						
	3B FAN	FLOW	LBS/MIN	17,001	13,500	10,001
	G/S (THRU BED)		LBS/MIN	1.0093	0.8000	0.5911
		INLET	DEGF	39.2	39.2	39.2
		O'BED	IN.H2O	0.033	-0.175	-0.3906
		U'BED	IN.H2O	15.43	12.33	9.032
BC 11	RECOUP B SIDE (WB 9)	AVG	DEGF	2,059	1,766	1,447
			LBS/MIN	3,208	3,134	3,039
		OUTLET	INH2O	-1.11	-1.11	-1.11
BC 12	RECOUP A SIDE (WB10)	AVG	DEGF	1,674	1,462	1,185
			LBS/MIN	3,180	2,981	2,702
		OUTLET	INH2O	-0.90	-0.90	-0.90
BC 13	COOLER VENT STACK	AVG	DEGF	728	703	661
			LBS/MIN	11,280	9,848	8,246
		OUTLET	INH2O	-0.88	-0.88	-0.88
	VENT STACK SEPARATION WALL			YES	YES	YES
	PELLET EXIT TEMP TOP-CENTER		DEGF	417	437	511
BC 17	WINDBOX LEAKAGE		LBS/MIN	150	143	132
	GAP HEIGHT		INCHES	1	1	1
BC 16	O'BED LEAKAGE		LBS/MIN	(55)	(97)	(213)
	GAP HEIGHT		INCHES	1	1	1
	TOTAL AIR IN			27,056	27,097	27,214
	TOTAL AIR OUT			27,055	27,099	27,214

TABLE 13
CURRENT COOLER - NO OVERBED WALL
MEDUSA/CFD OPERATING WINDOW - OPTIMZATION SERIES

3A FAN FLOW LBS/MIN	3B FAN FLOW LBS/MIN	OPTIMIZE FACTOR	OPTIMIZED GREEN BALL FEED, LTPH	3A O'BED PRESS. IN H2O	3B O'BED PRESS. IN. H2O	DD2 OBED TEMP DEG F	DD2DD2 FLOW LBS/MIN	TOTAL PREHEAT FLOW LBS/MIN	KILN SOLIDS DISCH. MAG. %WT	AVE RECOUP TEMP AT COOLER DEG F	TOTAL RECOUP FLOW LBS/MIN	FUEL BTU/LT	COOLER FLOW TO KILN LBS/MIN
10,500	13,800	11.214	445.6	-0.22	-0.31	1,080	8,655	11,856	16.6	1,517	5,841	619,876	6,491
10,500	14,800	11.300	452.5	-0.20	-0.26	1,080	8,828	12,044	16.8	1,503	6,016	610,476	6,683
10,500	15,800	11.400	460.5	-0.18	-0.22	1,082	8,995	12,234	17.0	1,495	6,184	599,813	6,874
10,500	16,800	11.500	468.7	-0.16	-0.17	1,084	9,161	12,426	17.2	1,487	6,351	589,427	7,066
11,000	13,300	11.205	444.9	-0.21	-0.33	1,059	8,651	11,983	16.8	1,487	5,837	620,872	6,621
11,000	14,800	11.316	453.8	-0.18	-0.26	1,053	8,920	12,264	16.8	1,460	6,108	608,751	6,906
11,000	16,300	11.494	468.2	-0.15	-0.18	1,063	9,154	12,556	17.4	1,459	6,344	590,042	7,195
11,000	17,000	11.564	473.9	-0.14	-0.15	1,064	9,270	12,689	17.6	1,454	6,461	582,921	7,329
12,000	12,500	11.218	446.0	-0.18	-0.35	1,019	8,671	12,279	17.1	1,429	5,857	619,434	6,918
12,000	14,000	11.353	456.8	-0.15	-0.28	1,018	8,927	12,564	17.4	1,412	6,116	604,790	7,204
12,000	15,500	11.492	468.0	-0.12	-0.21	1,019	9,180	12,852	17.8	1,397	6,369	590,248	7,490
12,000	17,000	11.610	477.7	-0.09	-0.14	1,014	9,442	13,135	18.0	1,375	6,634	578,311	7,774
13,000	11,800	11.264	449.6	-0.15	-0.37	984	8,696	12,597	17.7	1,380	5,882	614,385	7,236
13,000	13,000	11.355	456.9	-0.13	-0.32	980	8,909	12,823	17.8	1,360	6,097	604,577	7,463
13,000	14,200	11.446	464.3	-0.10	-0.26	975	9,120	13,050	18.0	1,341	6,310	595,002	7,690
13,000	15,200	11.537	471.7	-0.08	-0.21	974	9,290	13,241	18.2	1,330	6,480	585,652	7,881
13,000	17,000	11.637	479.9	-0.05	-0.13	957	9,621	13,577	18.5	1,291	6,813	575,630	8,217
14,000	10,800	11.220	446.1	-0.13	-0.41	935	8,699	12,850	17.8	1,311	5,886	619,213	7,492
14,000	11,800	11.314	453.6	-0.11	-0.36	936	8,868	13,041	18.0	1,301	6,055	608,966	7,682
14,000	12,800	11.367	457.9	-0.09	-0.32	926	9,054	13,227	18.1	1,278	6,243	603,301	7,869
14,000	13,800	11.491	467.9	-0.07	-0.27	933	9,207	13,423	18.6	1,279	6,397	590,351	8,062
15,000	10,100	11.255	446.9	-0.09	-0.43	898	8,730	13,167	18.3	1,258	5,916	615,368	7,808
15,000	10,800	11.292	451.9	-0.08	-0.40	891	8,861	13,296	18.3	1,241	6,048	611,342	7,940
15,000	11,500	11.332	455.1	-0.07	-0.37	885	8,989	13,428	18.4	1,226	6,178	607,033	8,070

TABLE 14
COOLER WITH OVERBED WALL
MEDUSA/CFD OPERATING WINDOW - OPTIMZATION SERIES

3A FAN FLOW LBS/MIN	3B FAN FLOW LBS/MIN	OPTIMIZE FACTOR	OPTIMIZED GREEN BALL FEED, LTPH	3A O'BED PRESS. IN H2O	3B O'BED PRESS. IN. H2O	DD2 OBED TEMP DEG F	DD2DD2 FLOW LBS/MIN	TOTAL PREHEAT FLOW LBS/MIN	KILN SOLIDS DISCH. MAG. %WT	AVE RECOUP TEMP AT COOLER DEG F	TOTAL RECOUP FLOW LBS/MIN	FUEL BTU/LT	COOLER FLOW TO KILN LBS/MIN
10,500	13,800	11.031	431.2	-0.25	-0.28	1,093	8,649	11,344	15.9	1,481	5,835	640,613	5,968
10,500	14,800	11.137	439.5	-0.24	-0.22	1,106	8,910	11,430	16.0	1,476	6,099	628,477	6,056
10,500	15,800	11.220	446.1	-0.24	-0.15	1,113	9,175	11,513	16.1	1,464	6,365	619,213	6,140
10,500	16,800	11.287	451.5	-0.23	-0.09	1,116	9,441	11,595	16.1	1,448	6,633	611,883	6,223
11,000	13,300	11.068	434.1	-0.23	-0.31	1,071	8,600	11,578	16.3	1,456	5,786	636,337	6,200
11,000	14,800	11.186	443.4	-0.22	-0.21	1,081	8,998	11,705	16.3	1,436	6,187	622,983	6,334
11,000	16,300	11.292	451.9	-0.21	-0.12	1,087	9,397	11,829	16.4	1,414	6,588	611,342	6,549
11,000	17,000	11.342	455.9	-0.20	-0.08	1,090	9,582	11,887	16.4	1,404	6,775	605,963	6,518
12,000	12,500	11.149	440.5	-0.18	-0.34	1,027	8,557	12,069	17.0	1,400	5,743	627,125	6,704
12,000	14,000	11.270	450.1	-0.17	-0.25	1,038	8,953	12,197	17.1	1,383	6,142	613,731	6,830
12,000	15,500	11.348	456.4	-0.16	-0.16	1,038	9,356	12,318	17.1	1,352	6,547	605,323	6,952
12,000	17,000	11.424	462.5	-0.15	-0.07	1,036	9,758	12,441	17.1	1,322	6,952	597,296	7,074
13,000	11,800	11.201	444.6	-0.14	-0.38	976	8,545	12,562	17.5	1,332	5,731	621,315	7,203
13,000	13,000	11.275	450.5	-0.13	-0.31	980	8,866	12,661	17.5	1,311	6,054	613,186	7,301
13,000	14,200	11.378	458.8	-0.12	-0.23	988	9,182	12,767	17.7	1,300	6,371	602,135	7,404
13,000	15,200	11.408	461.2	-0.12	-0.17	982	9,452	12,845	17.7	1,273	6,644	598,972	7,483
13,000	17,000	11.475	466.6	-0.10	-0.07	973	9,937	12,991	17.8	1,231	7,132	591,998	7,626
14,000	10,800	11.273	450.3	-0.09	-0.43	932	8,449	13,040	18.1	1,281	5,634	613,404	7,682
14,000	11,800	11.311	453.4	-0.09	-0.37	930	8,718	13,119	18.1	1,256	5,905	609,289	7,762
14,000	12,800	11.350	456.5	-0.08	-0.31	927	8,988	13,199	18.1	1,232	6,177	605,109	7,841
14,000	13,800	11.455	465.0	-0.07	-0.25	938	9,248	13,291	18.4	1,230	6,439	594,067	7,929
15,000	10,100	11.295	452.1	-0.05	-0.47	874	8,442	13,530	18.4	1,202	5,627	611,017	8,178
15,000	10,800	11.328	454.7	-0.05	-0.43	874	8,630	13,587	18.4	1,188	5,816	607,462	8,234
15,000	11,500	11.398	460.4	-0.04	-0.38	881	8,812	13,652	18.7	1,185	5,999	600,024	8,295

Figure 1
Minntac Cooler

View 1

View 2

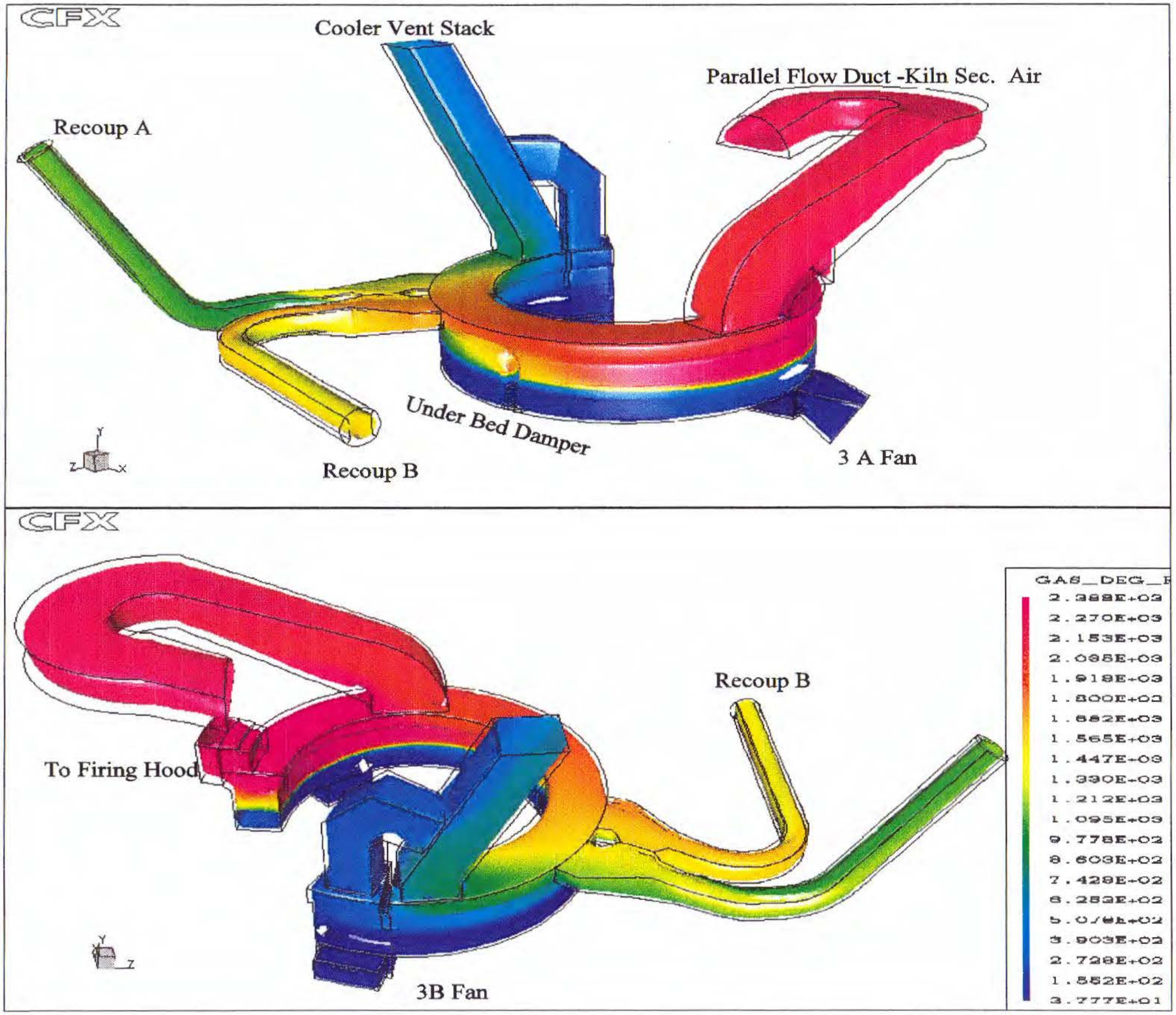
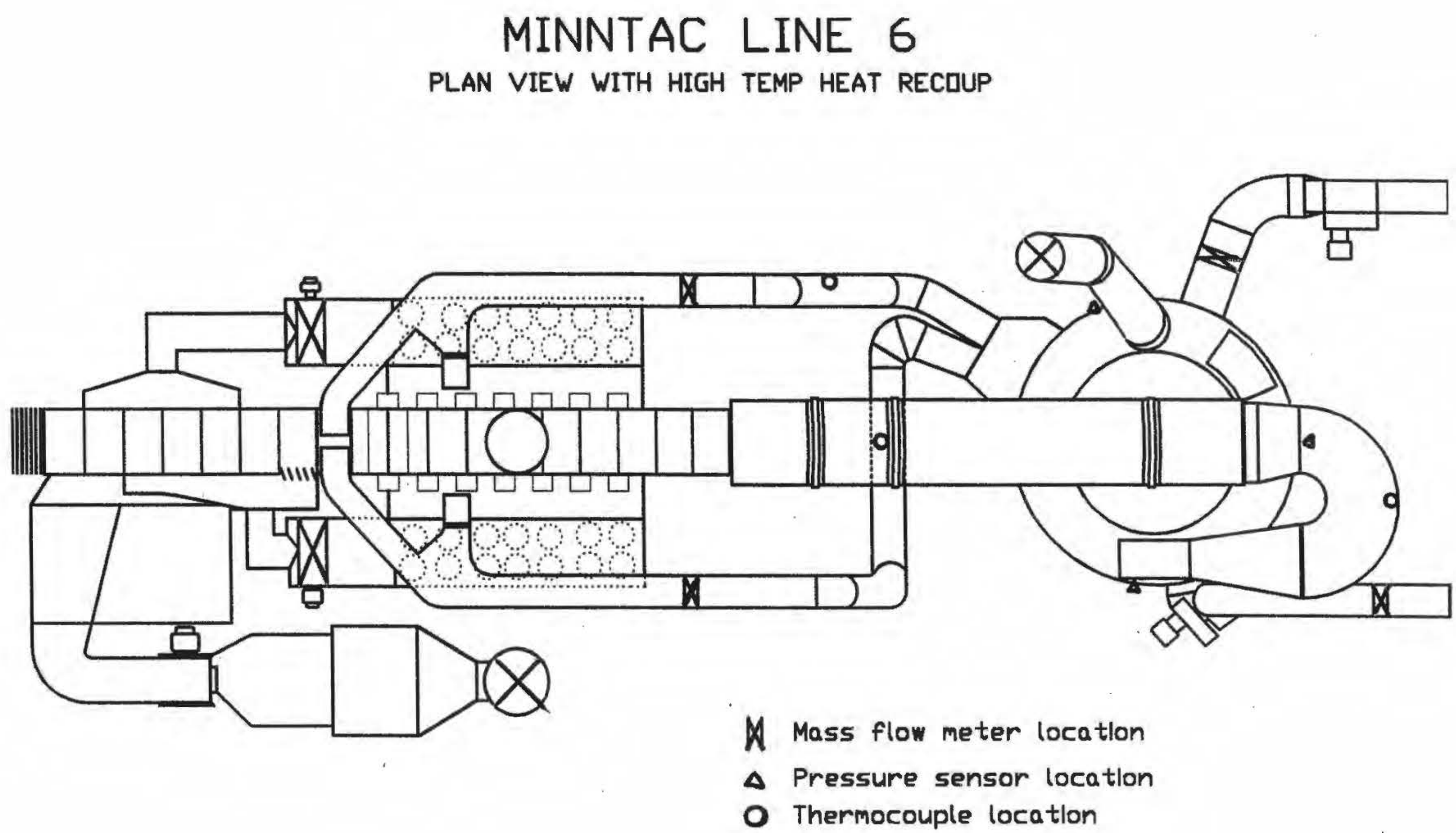


FIGURE 2



MINNTAC LINE 6
PLAN VIEW WITH HIGH TEMP HEAT RECOUP
Mass flow meter location
Pressure sensor location
Thermocouple location

FIGURE 3

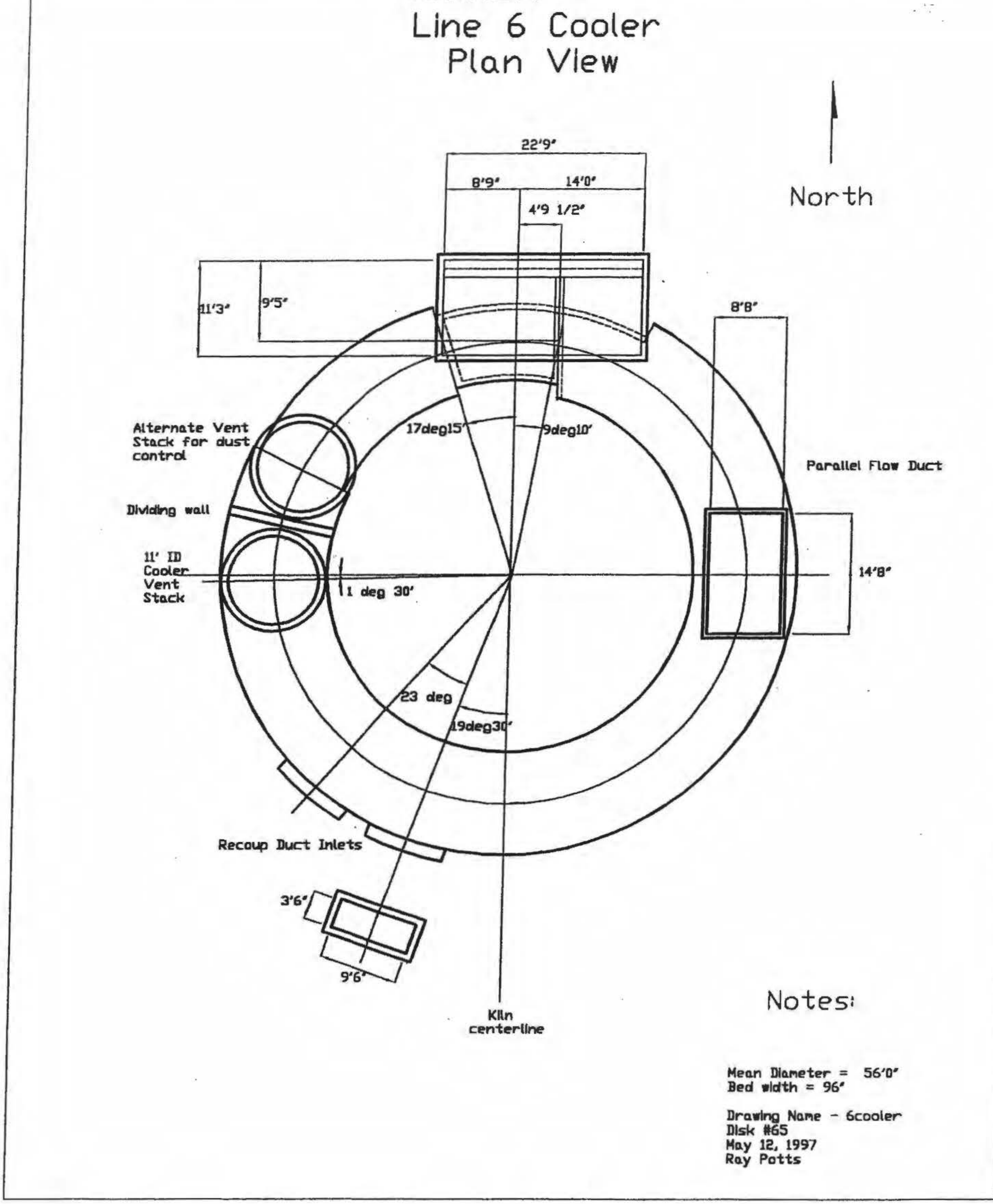

Line 6 Cooler
Plan View
North
22'9"
8'9"
14'0"
4'9 1/2"
11'3"
9'5"
8'8"
Alternate Vent Stack for dust control
17deg15'
9deg10'
Parallel Flow Duct
Dividing wall
11' ID Cooler Vent Stack
1 deg 30'
14'8"
23 deg
19deg30'
Recoup Duct Inlets
3'6"
9'6"
Kiln centerline
Notes:
Mean Diameter = 56'0"
Bed width = 96"
Drawing Name - 6cooler
Disk #65
May 12, 1997
Ray Potts

FIGURE 4

LINE 6 FEED TO COOLER

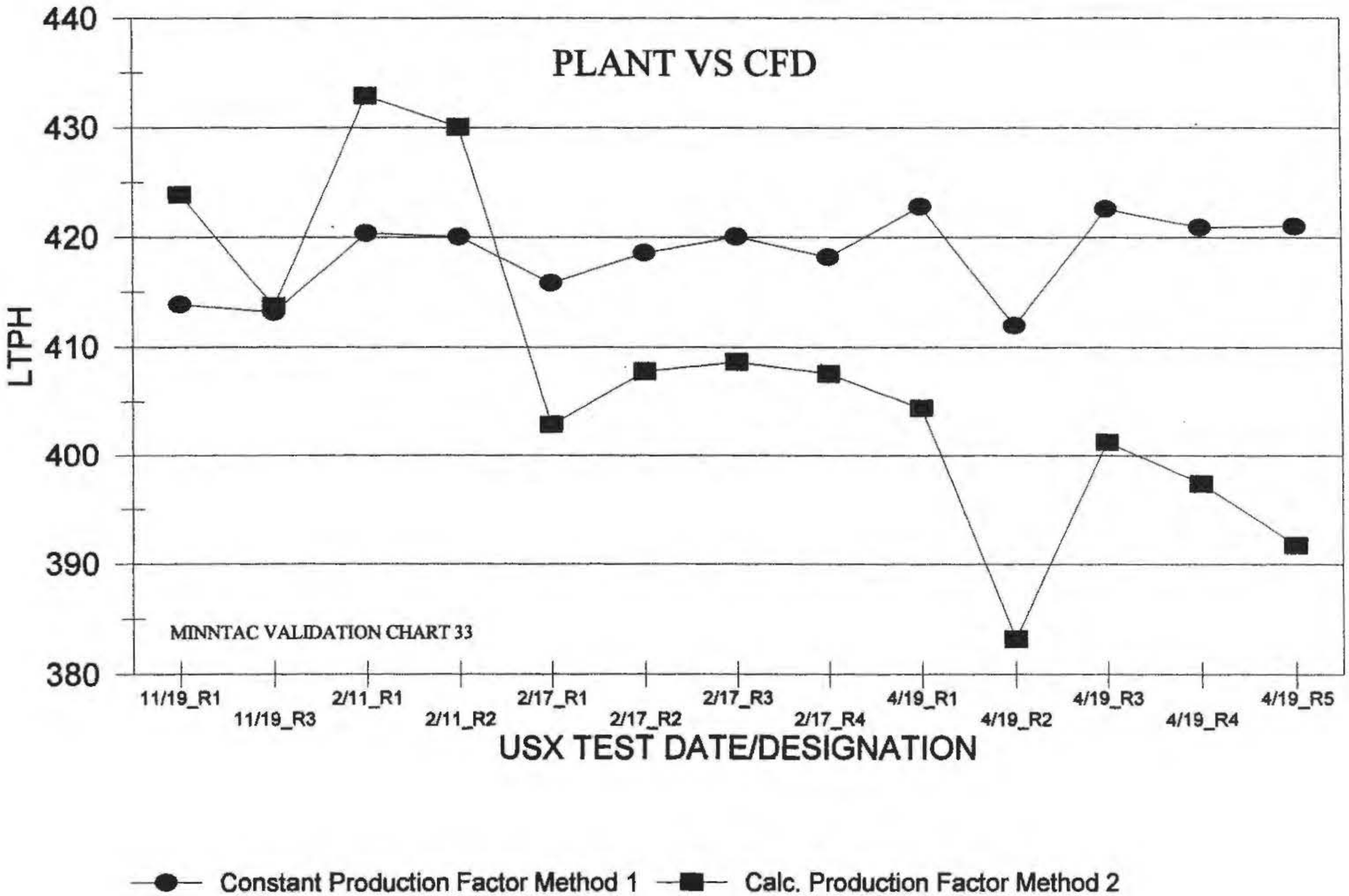


FIGURE 5

KILN DISCHG TEMP VS CFD PELLET TEMP

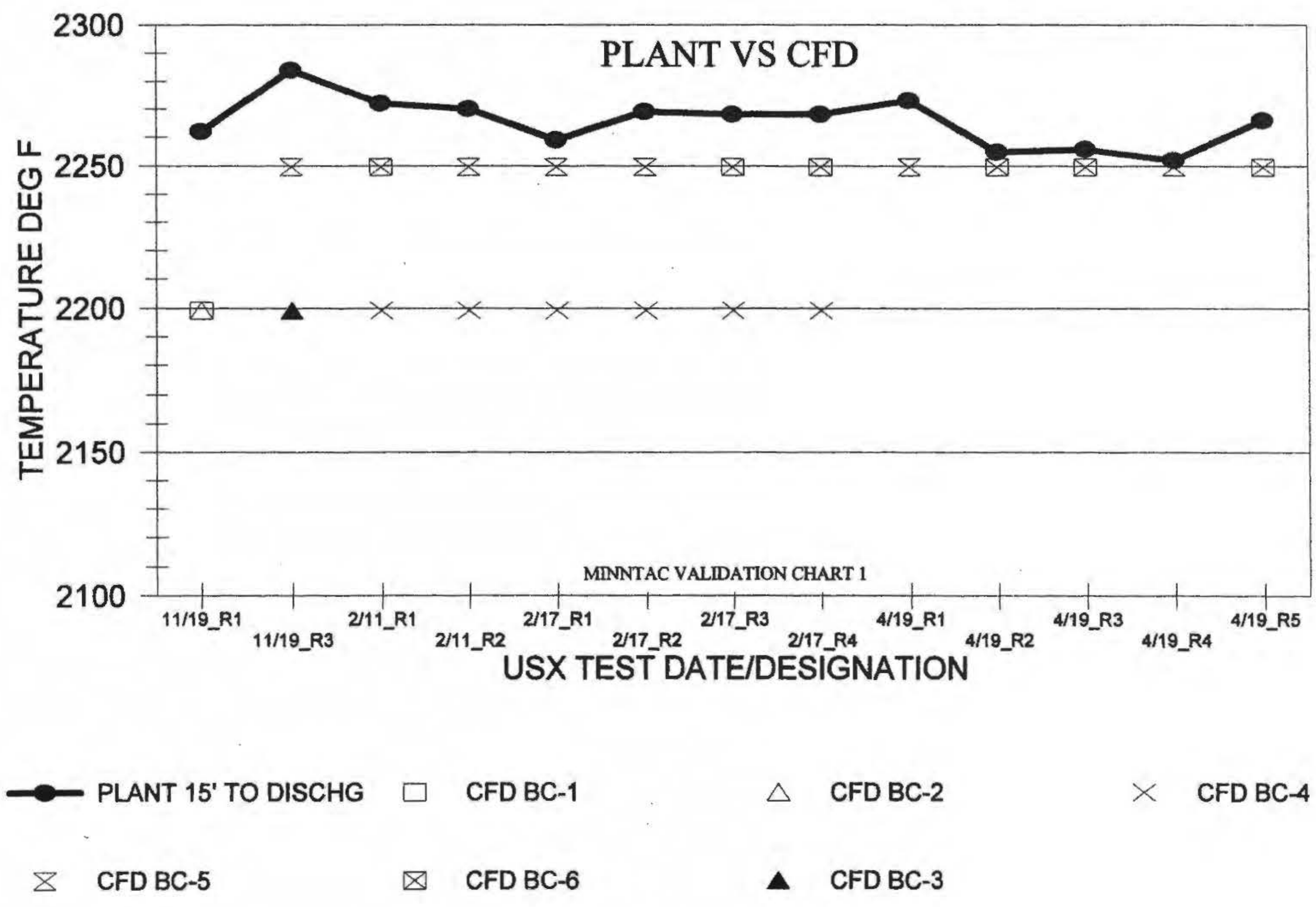


FIGURE 6

PRIMARY COOLING OVER BED PRESSURE

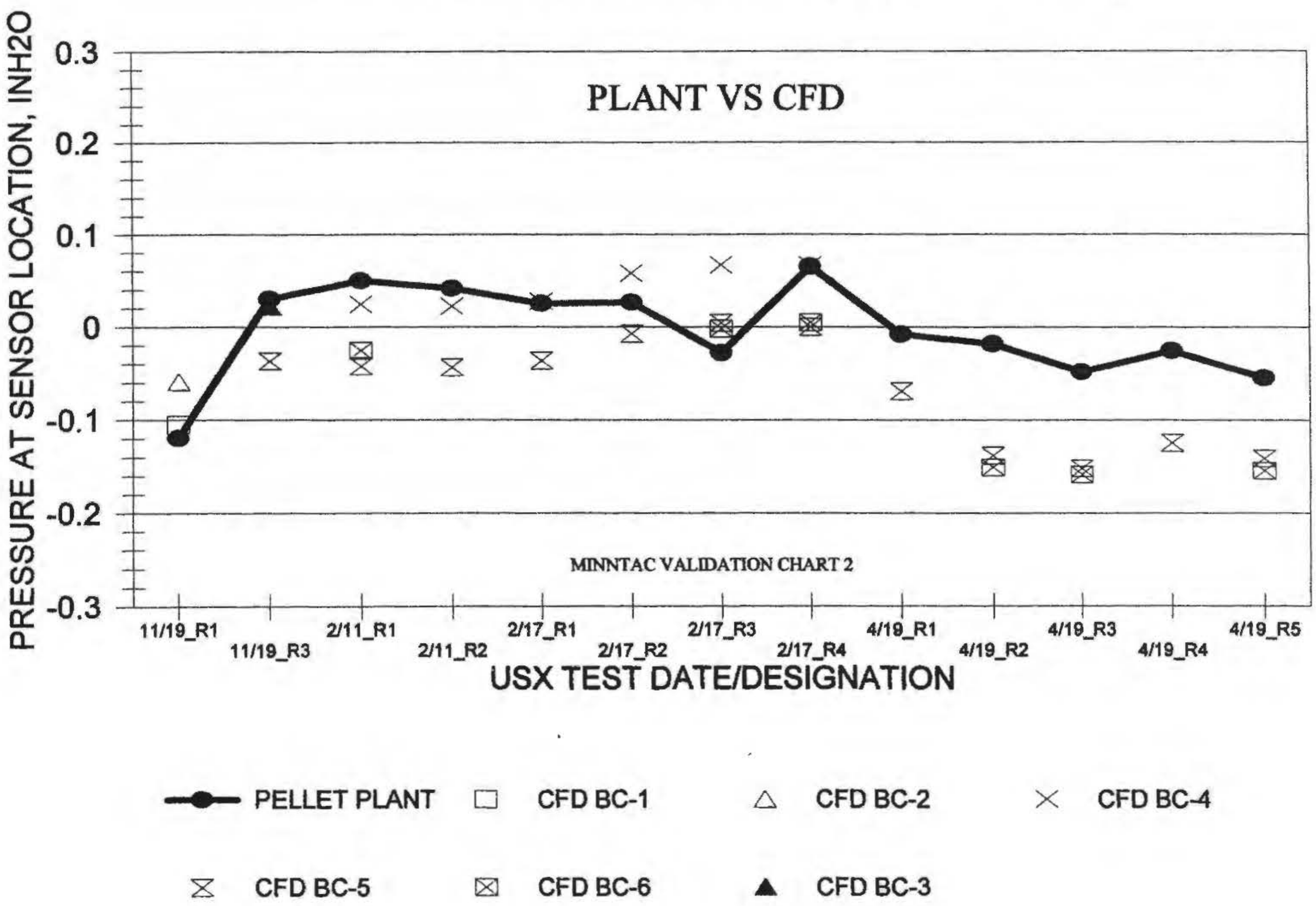


FIGURE 7

PLANT PRI OBED PRESS VS CFD PREDICTION

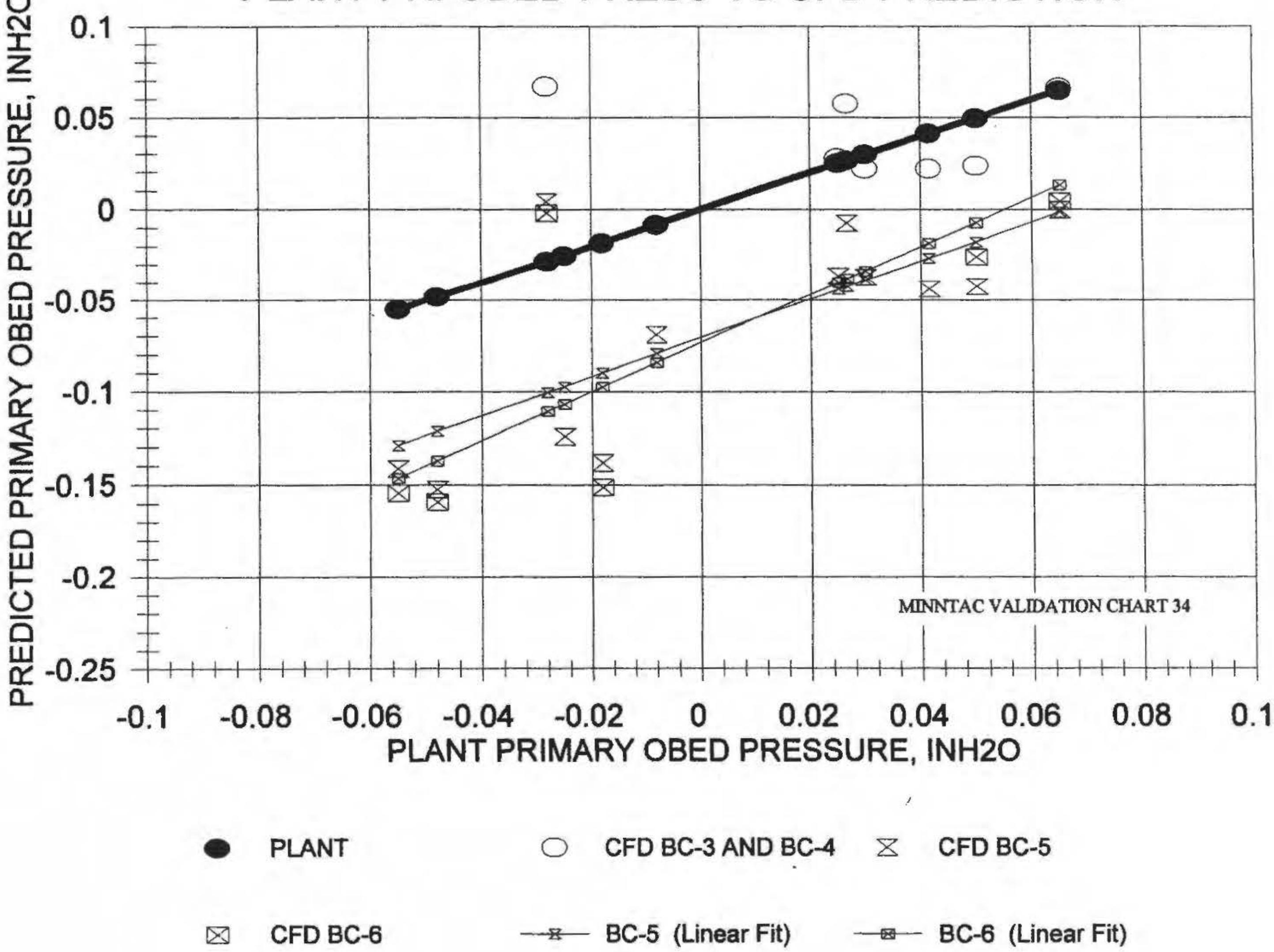


FIGURE 8
PRIMARY COOLING UNDER BED PRESSURE

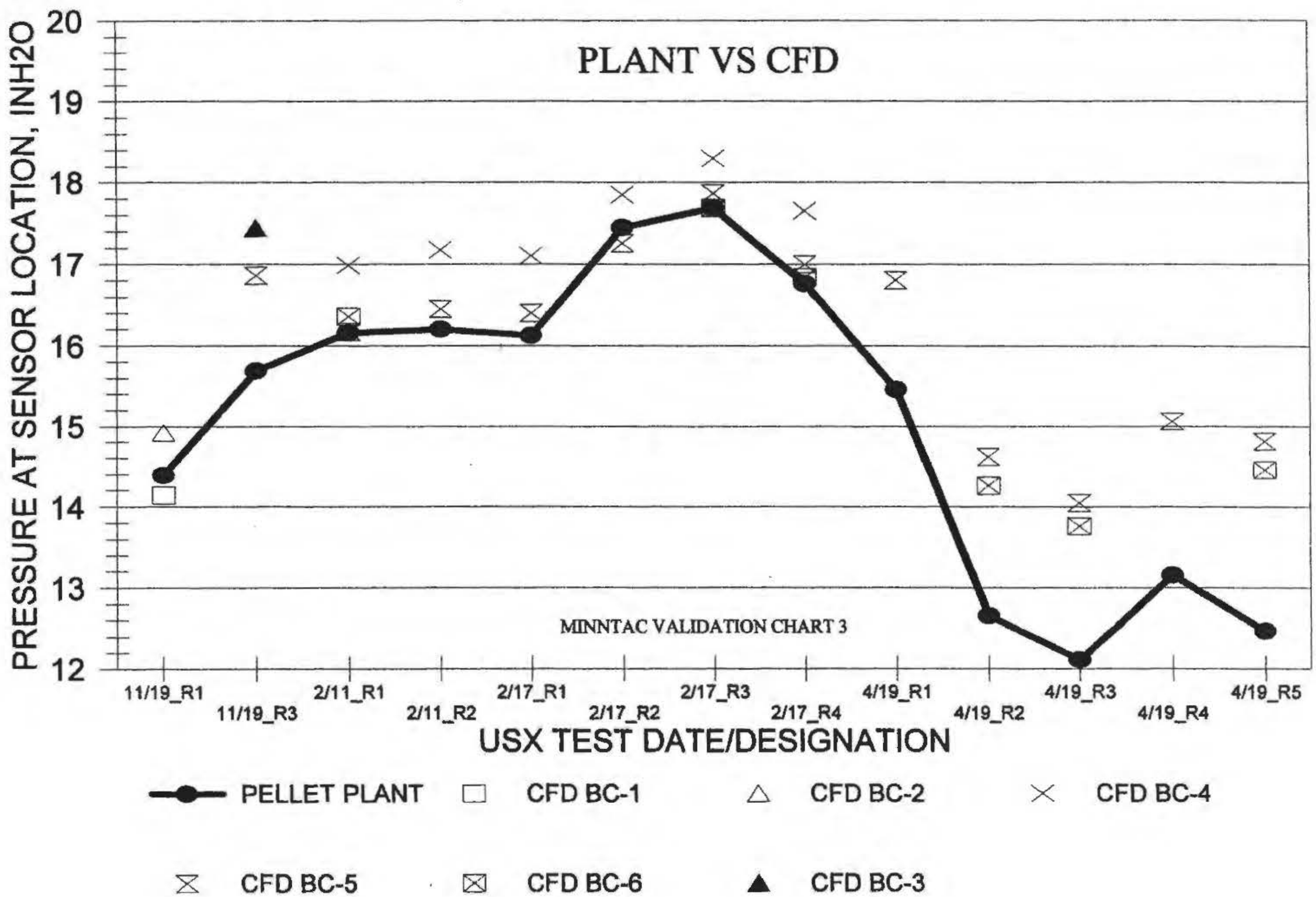


FIGURE 9
KILN SECONDARY AIR TEMPERATURE

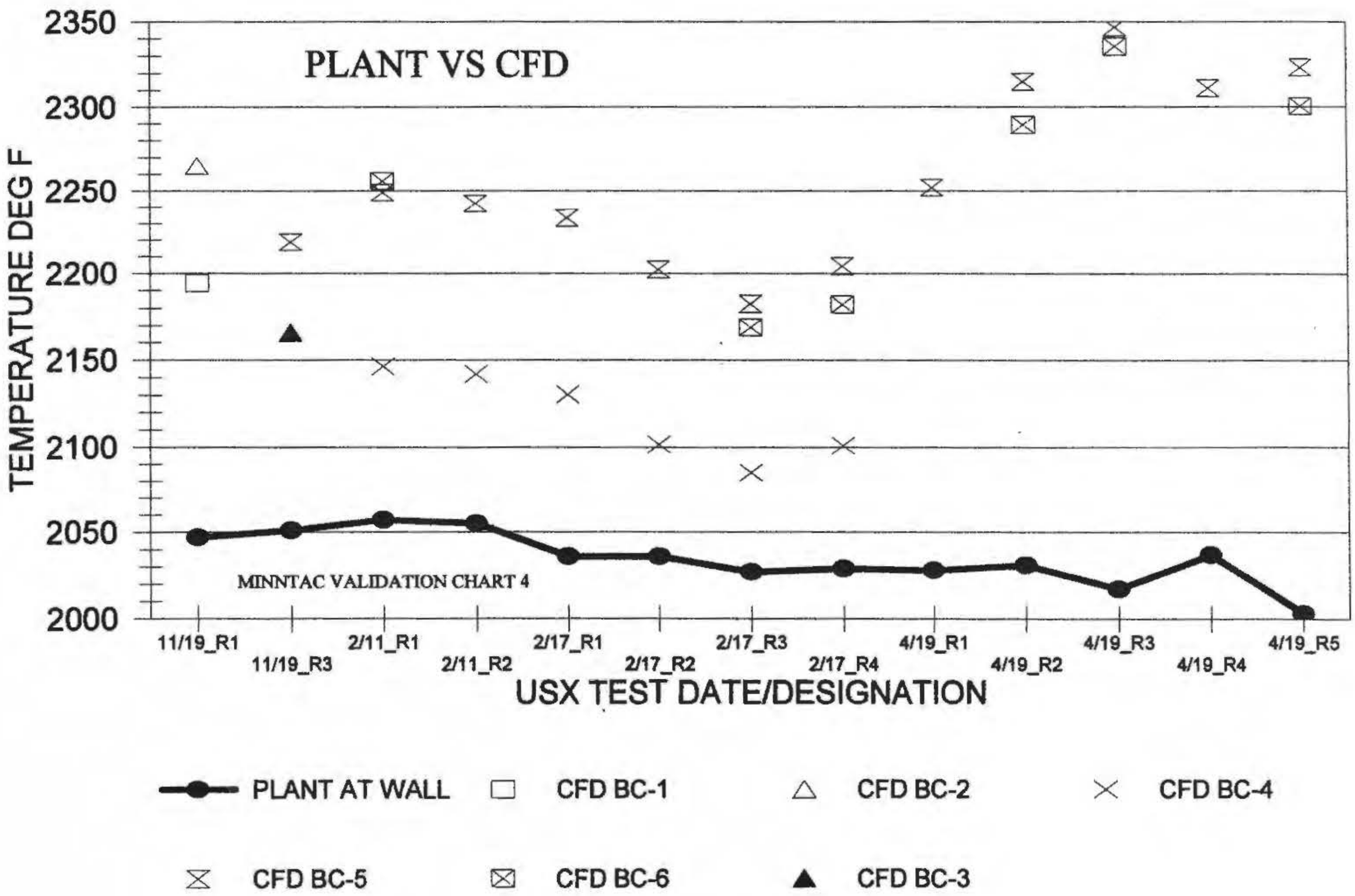


FIGURE 10
PARALLEL FLOW DUCT THERMOCOUPLE PLANE
TEMPERATURE PROFILE

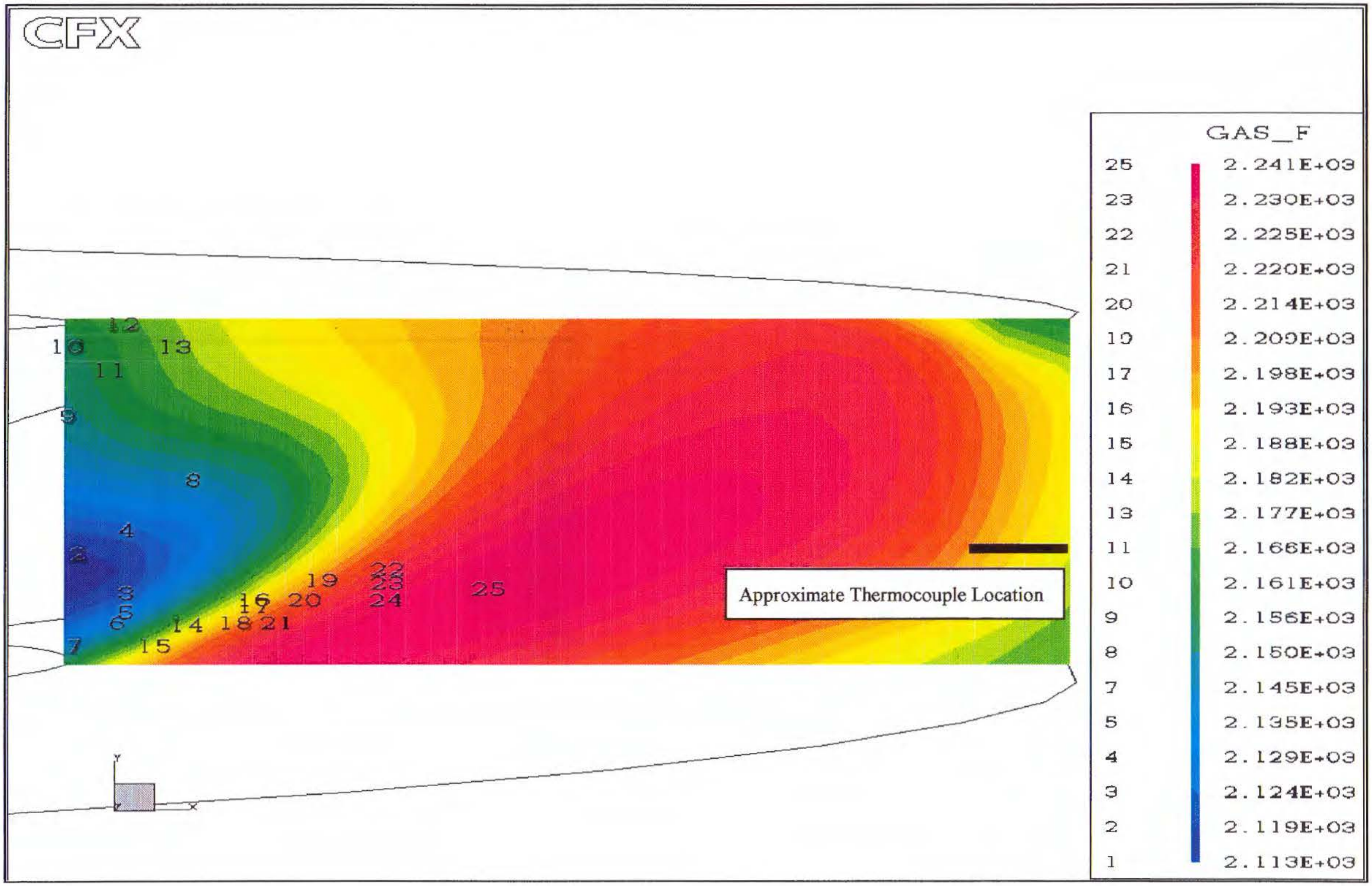


FIGURE 11

SECONDARY COOLING OVER BED PRESSURE

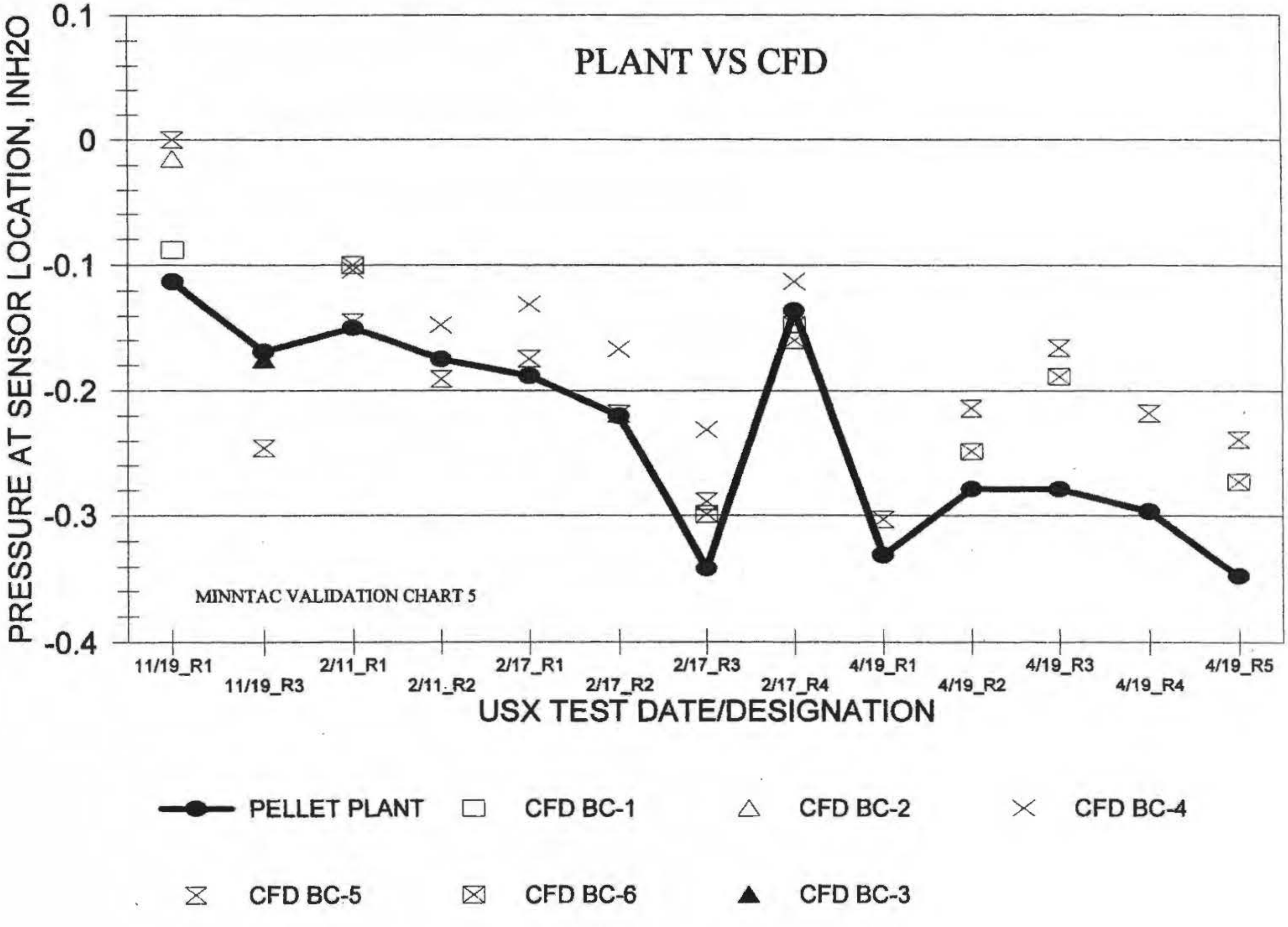


FIGURE 12

SECONDARY COOLING UNDERBED PRESSURE

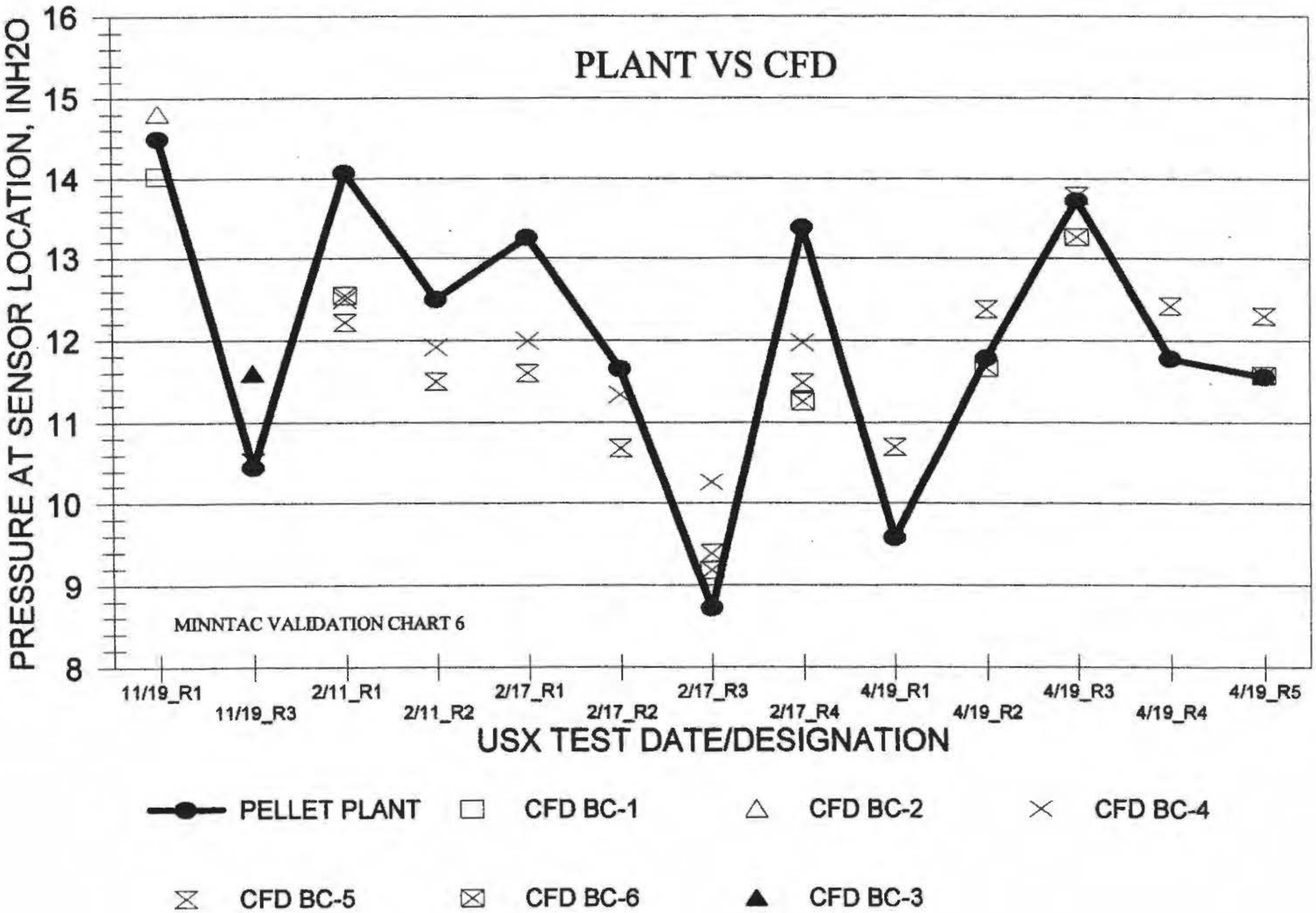


FIGURE 13
RECOUP A DUCT - TEMPERATURE

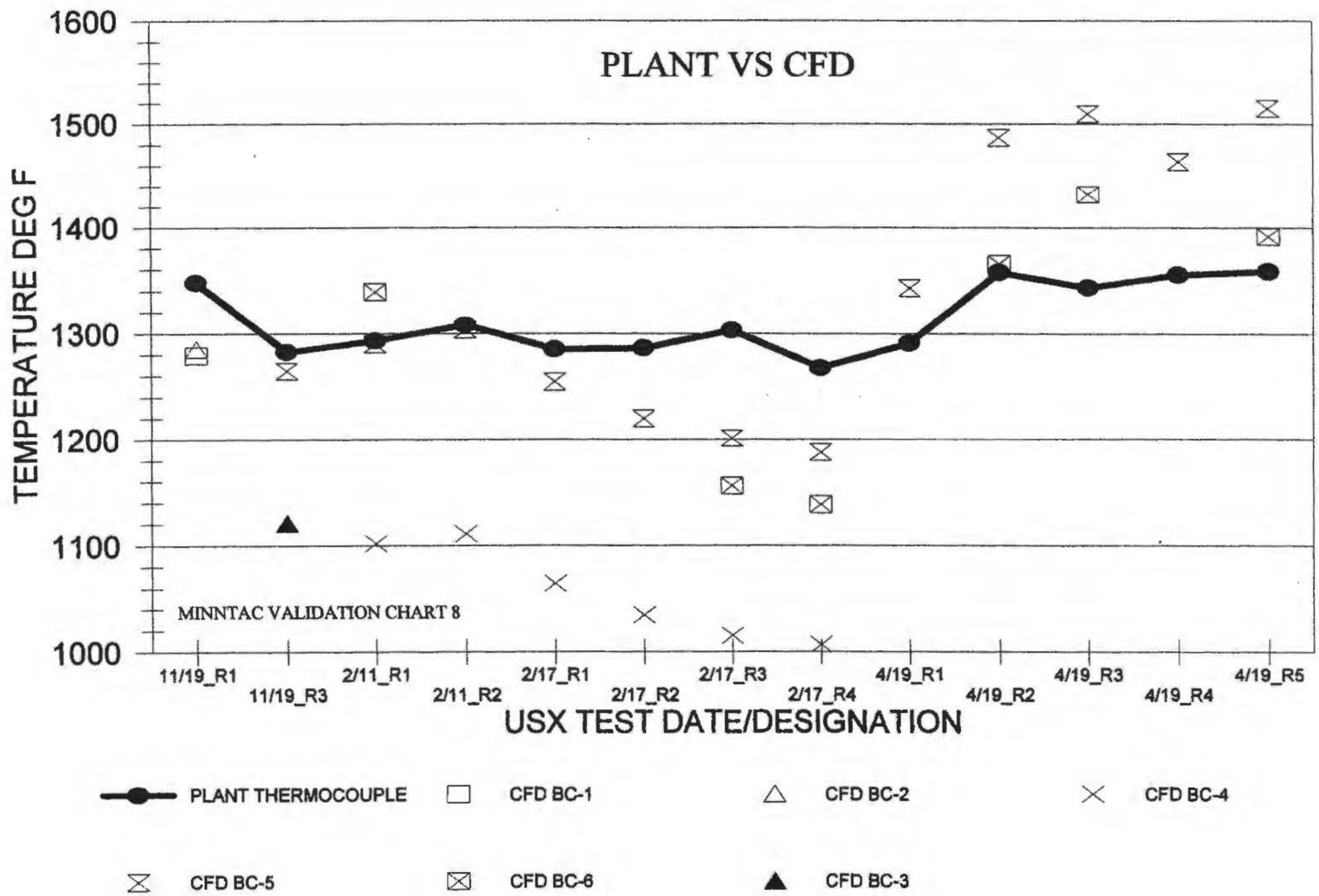


FIGURE 14
RECOUP B DUCT - TEMPERATURE

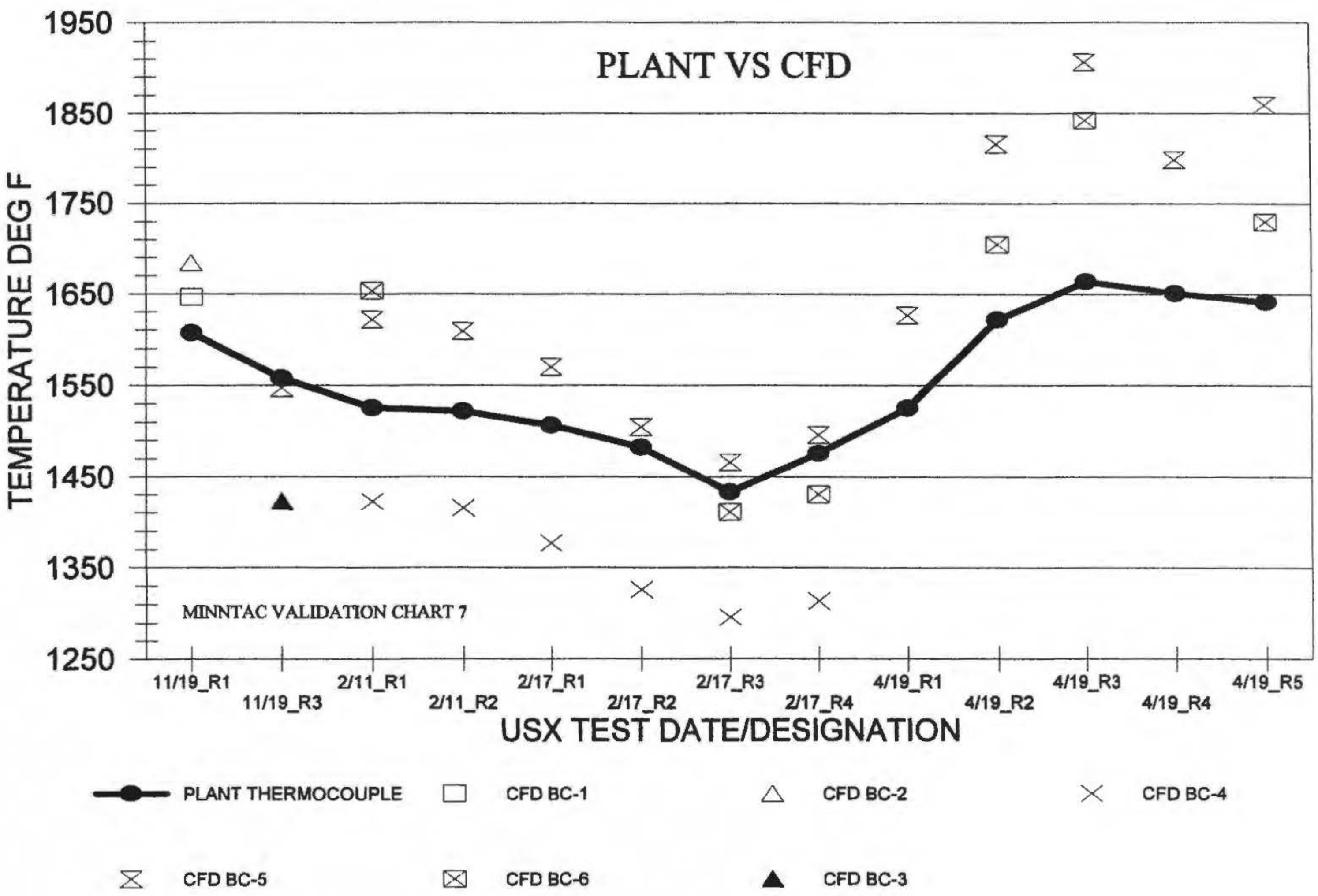


FIGURE 15
RECOUP A DUCT

THERMOCOUPLE PLANE
TEMPERATURE PROFILE

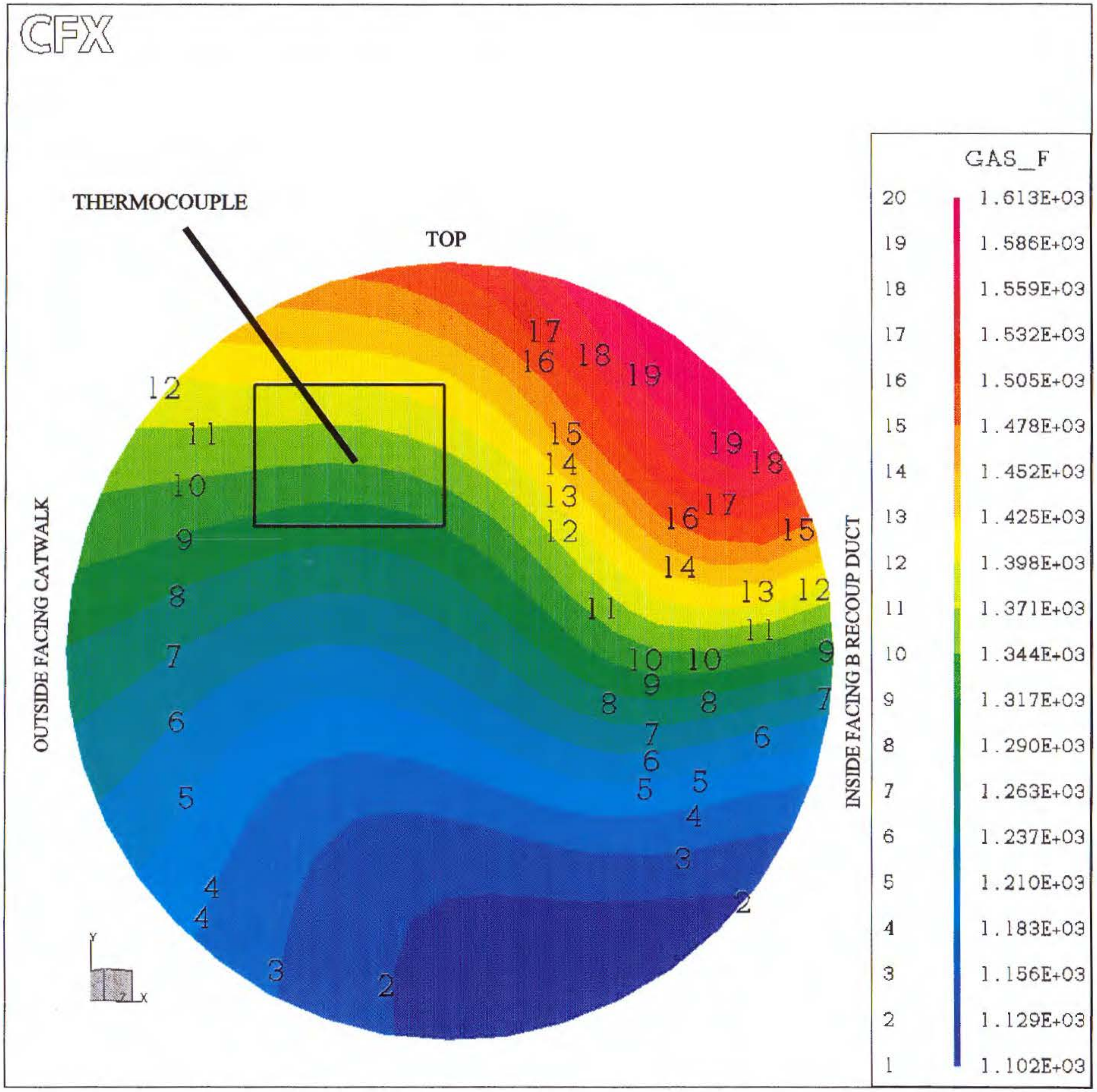


FIGURE 16
RECOUP B DUCT

THERMOCOUPLE PLANE
TEMPERATURE PROFILE

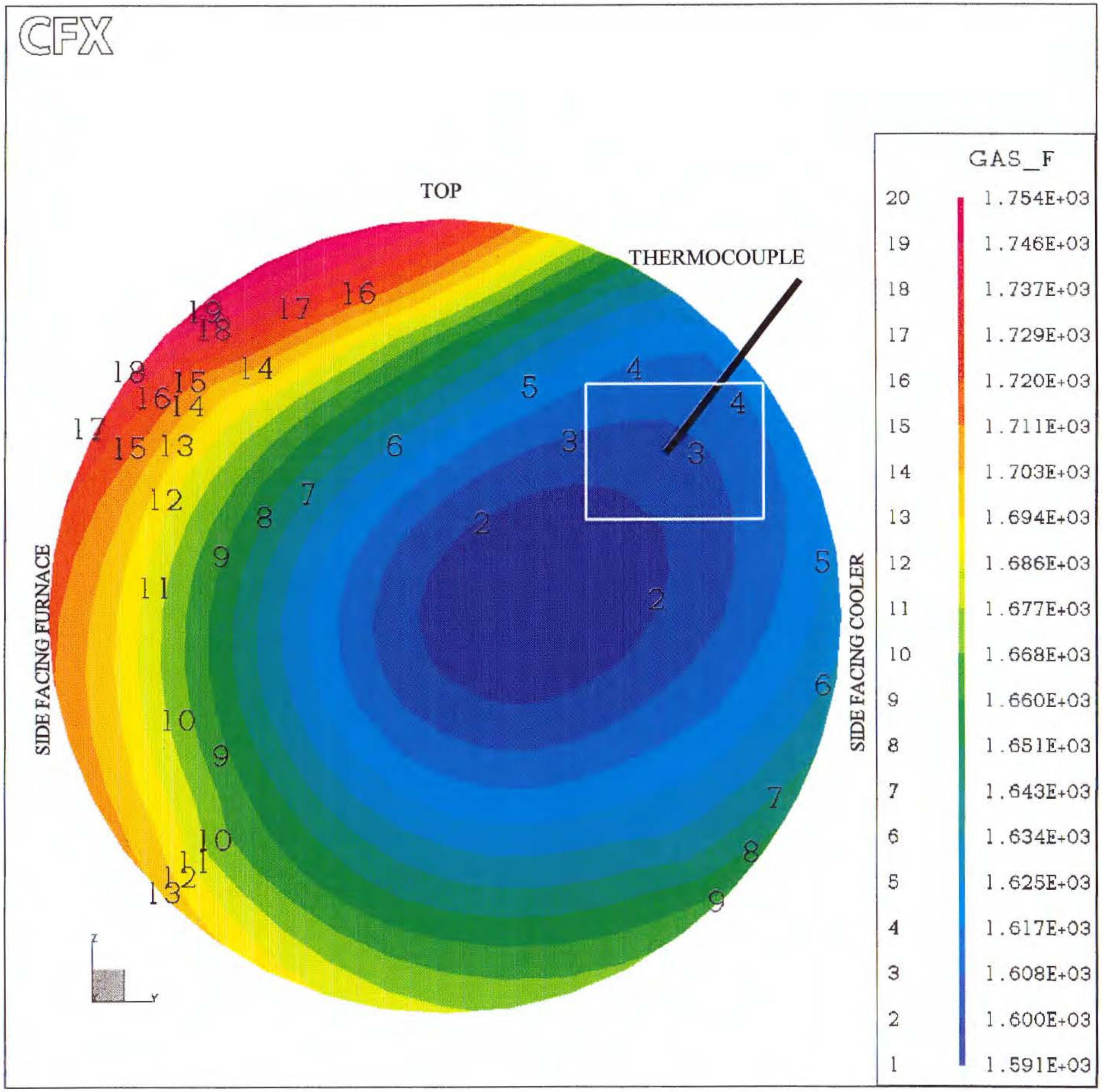


FIGURE 17
RECOUP A DUCT

VELOCITY PROFILE
IN
THERMOCOUPLE PLANE

from Parametric Series
450 WLTPH, 22% Mag,
13,500 lb/Min 3A, 13,500 lbs/min 3B

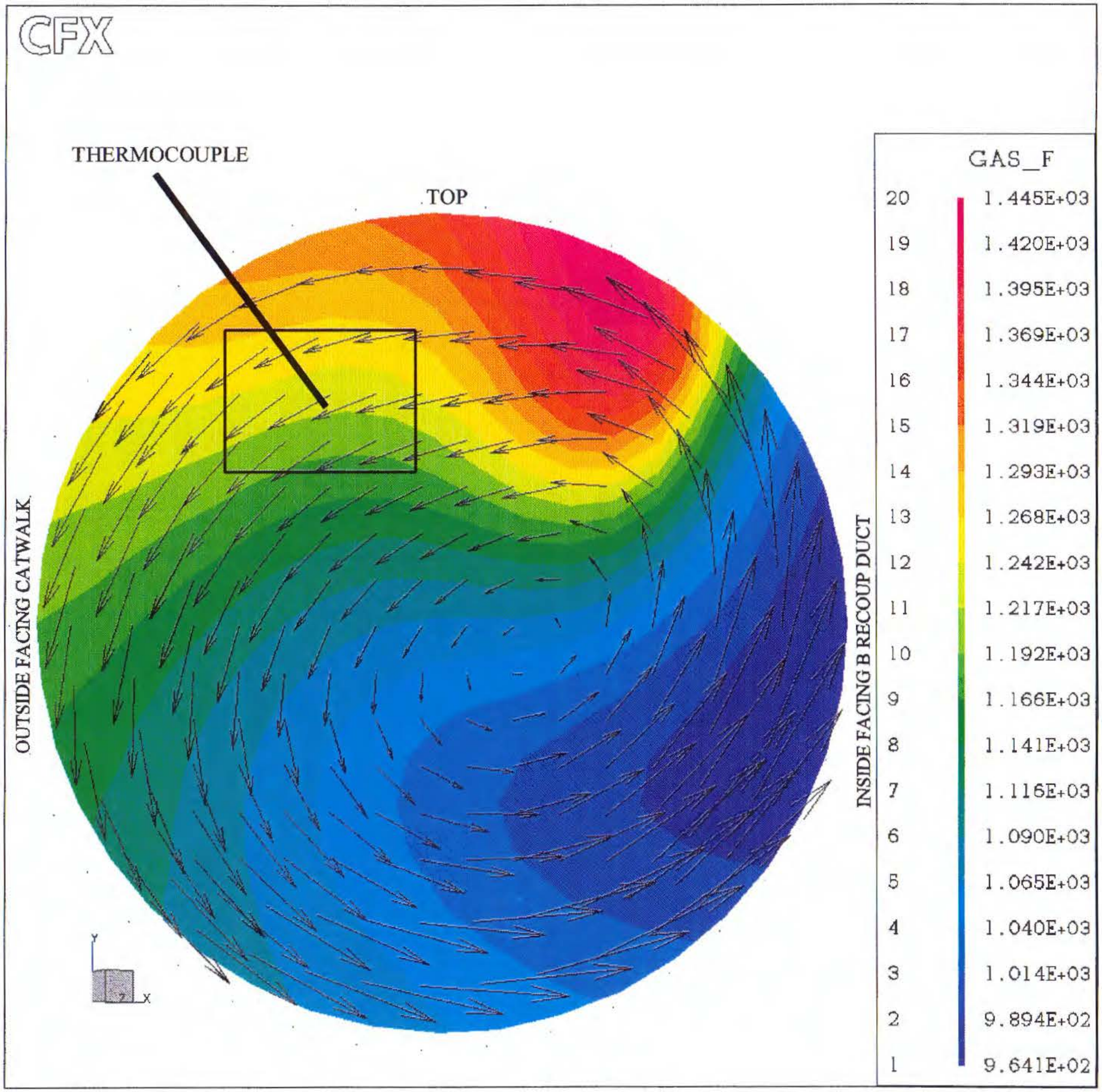


FIGURE 18

AVE RECOUP TEMP AND DD2 OBED TEMP

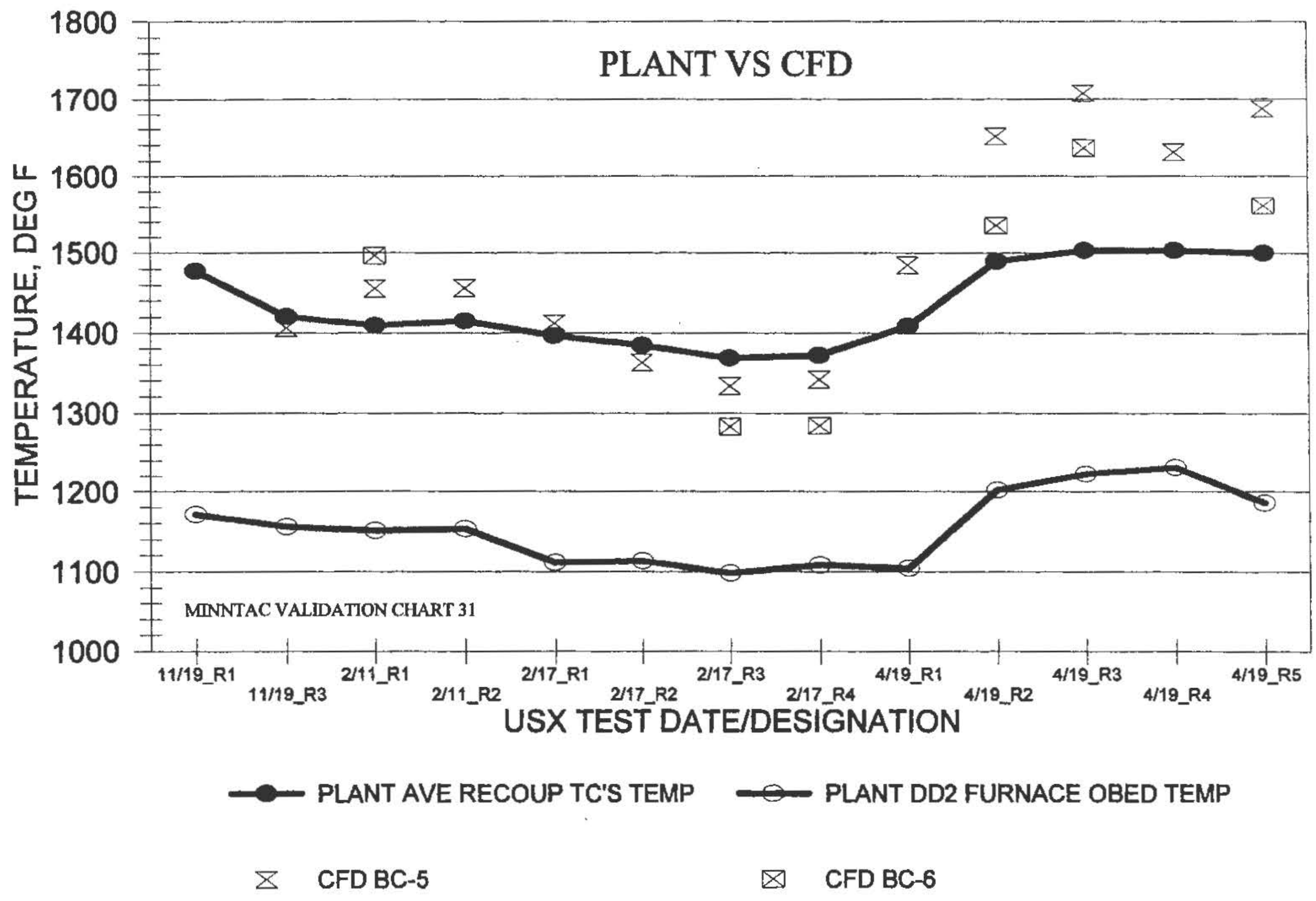


FIGURE 19
RECOUP DUCT A FLOW

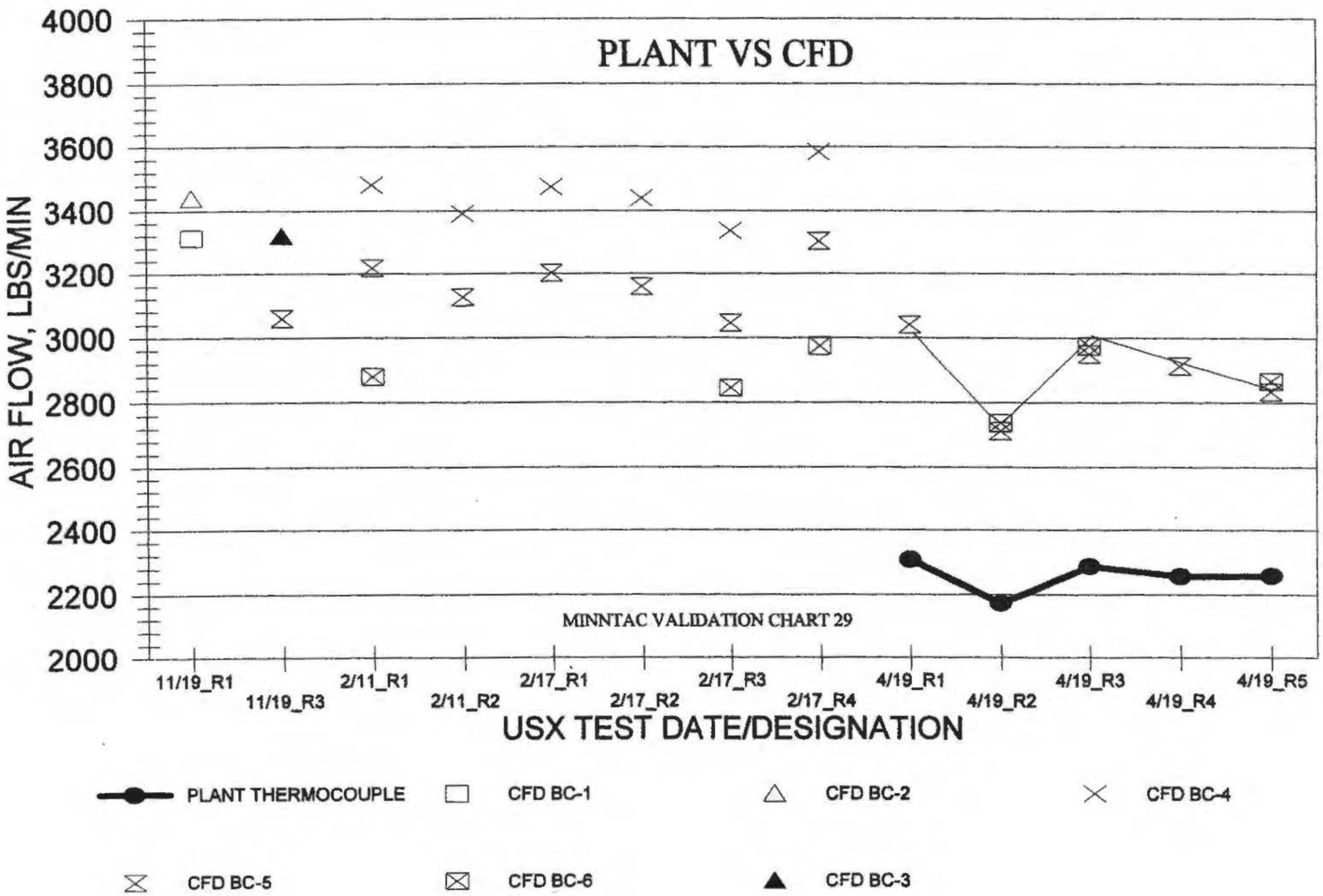


FIGURE 20

RECOUP B DUCT FLOW

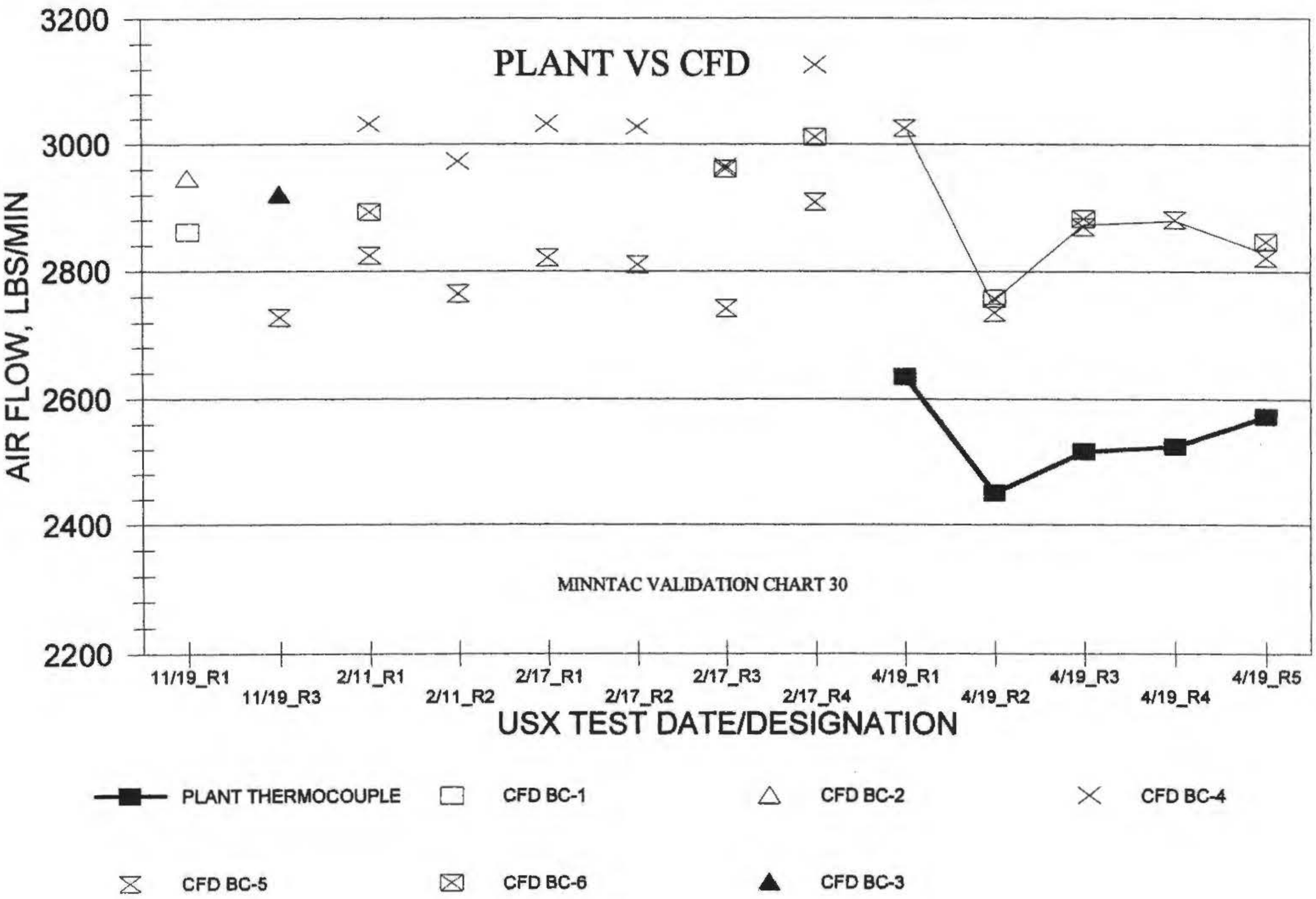


FIGURE 21
COOLER VENT STACK FLOW

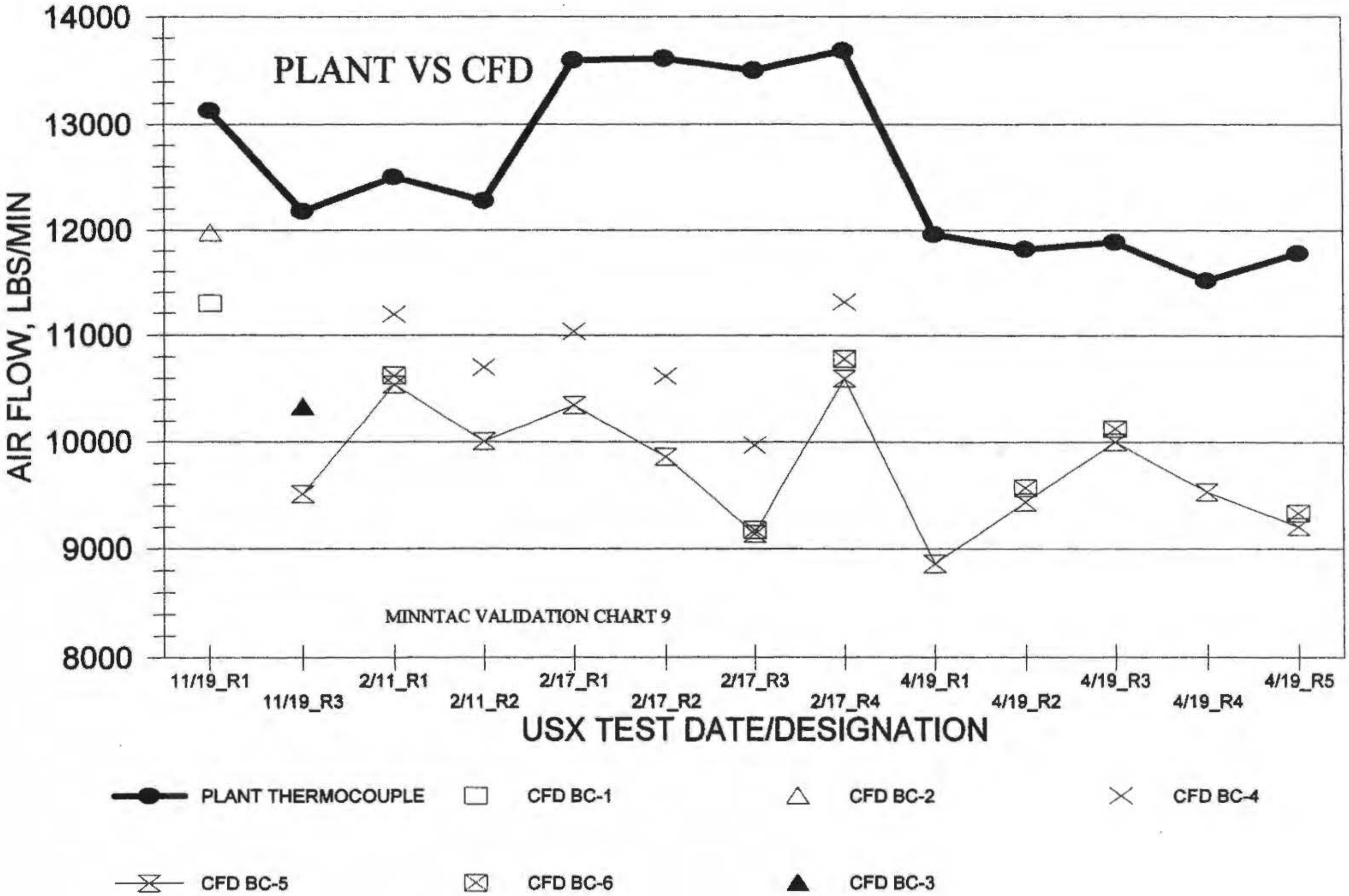


FIGURE 22
COOLER VENT STACK TEMP

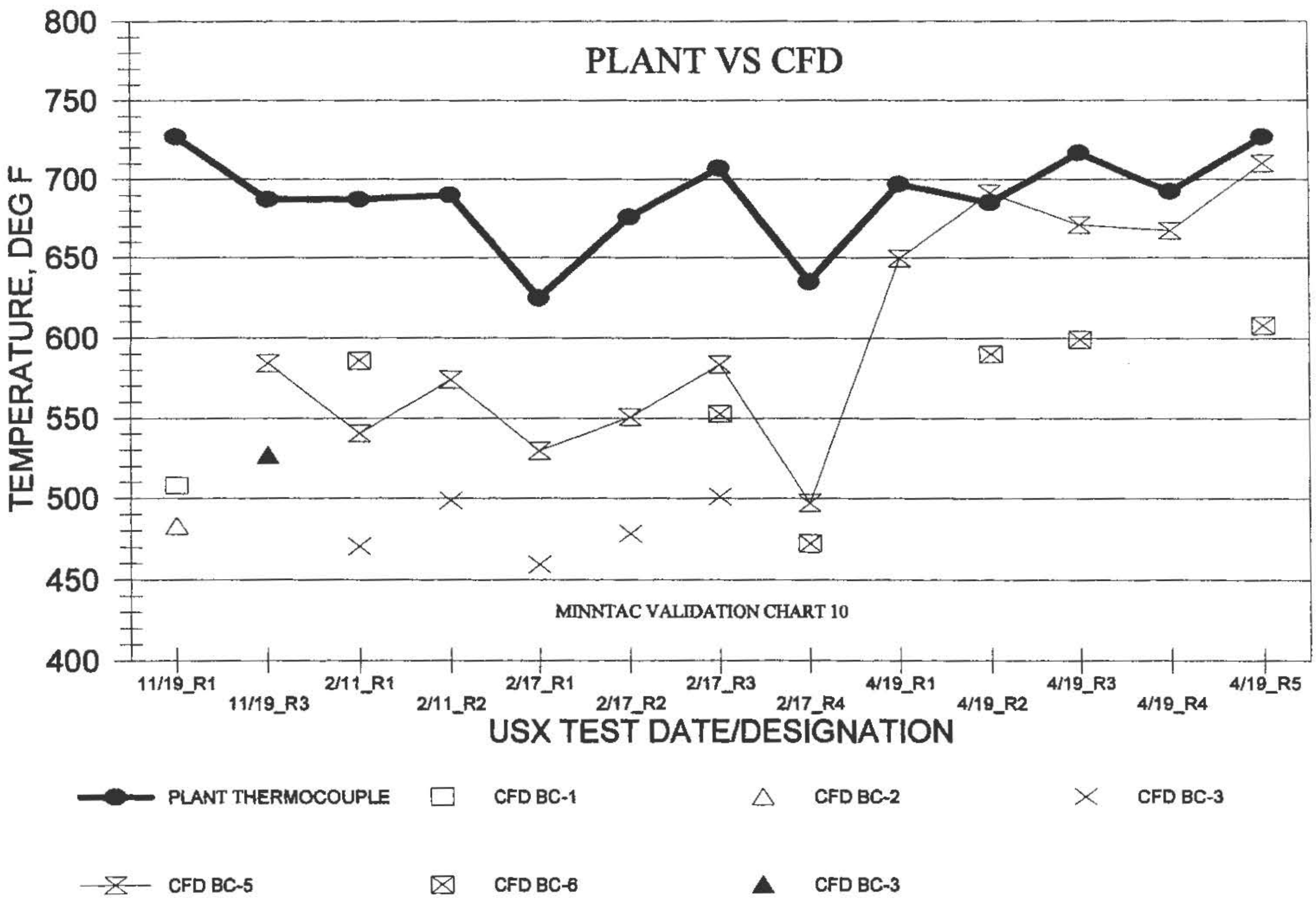


FIGURE 23

3A FLOW VS 3A WINDBOX PRESSURE

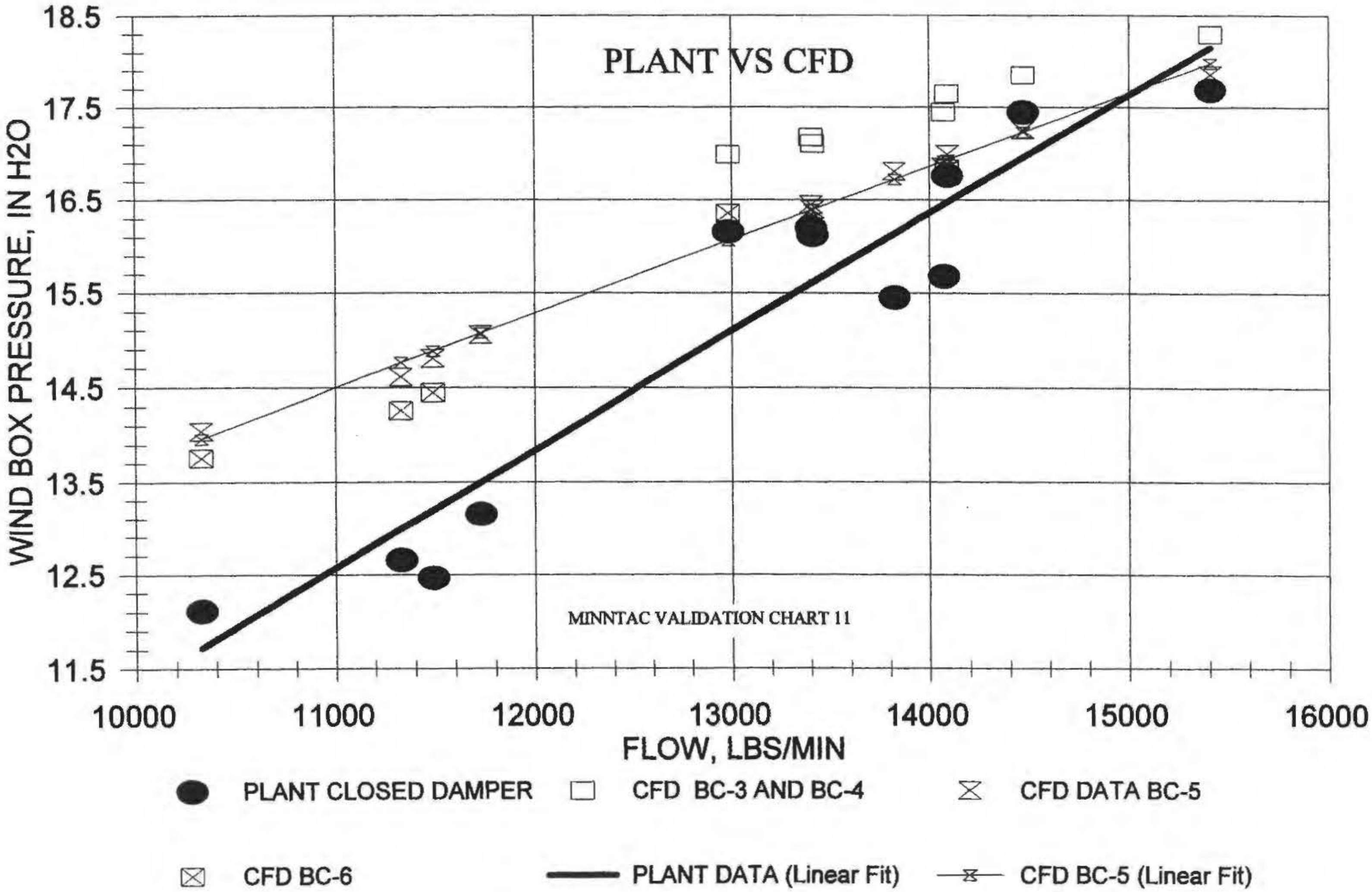


FIGURE 24

3B FLOW VS 3B WINDBOX PRESSURE

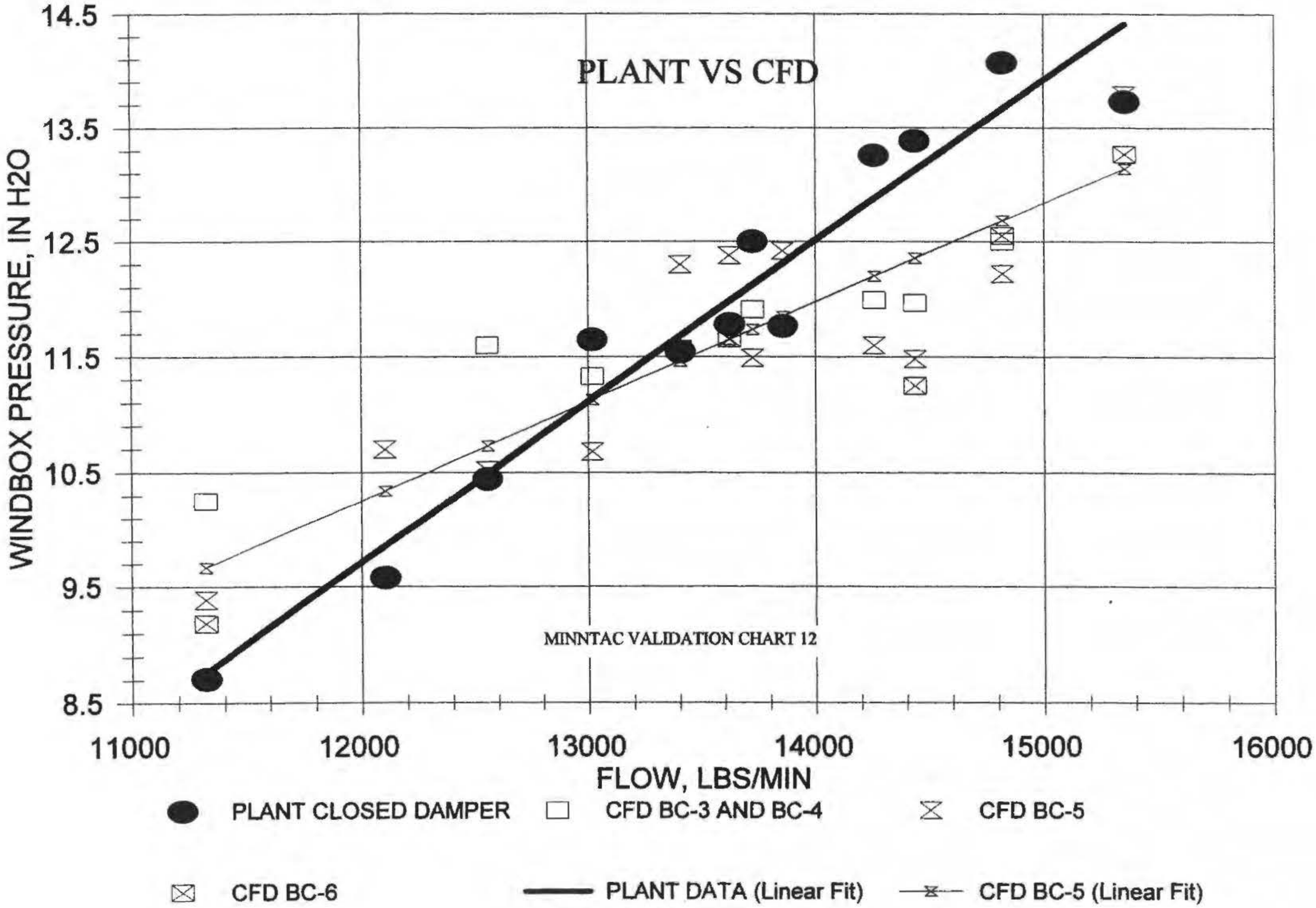


FIGURE 25

STACK FLOW VS 3B FAN FLOW

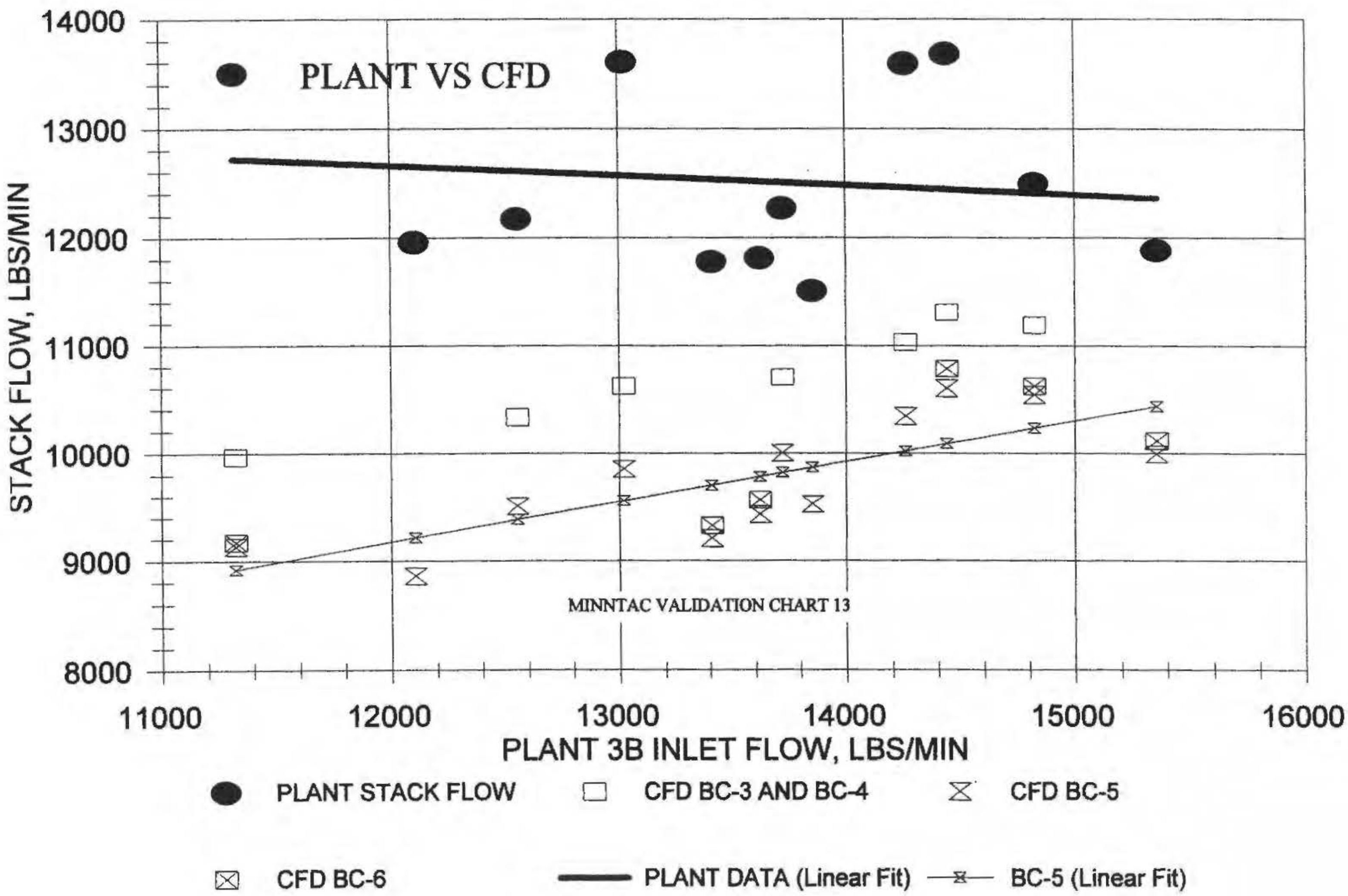


FIGURE 26

KILN SECONDARY AIR TEMP VS 3A FAN FLOW

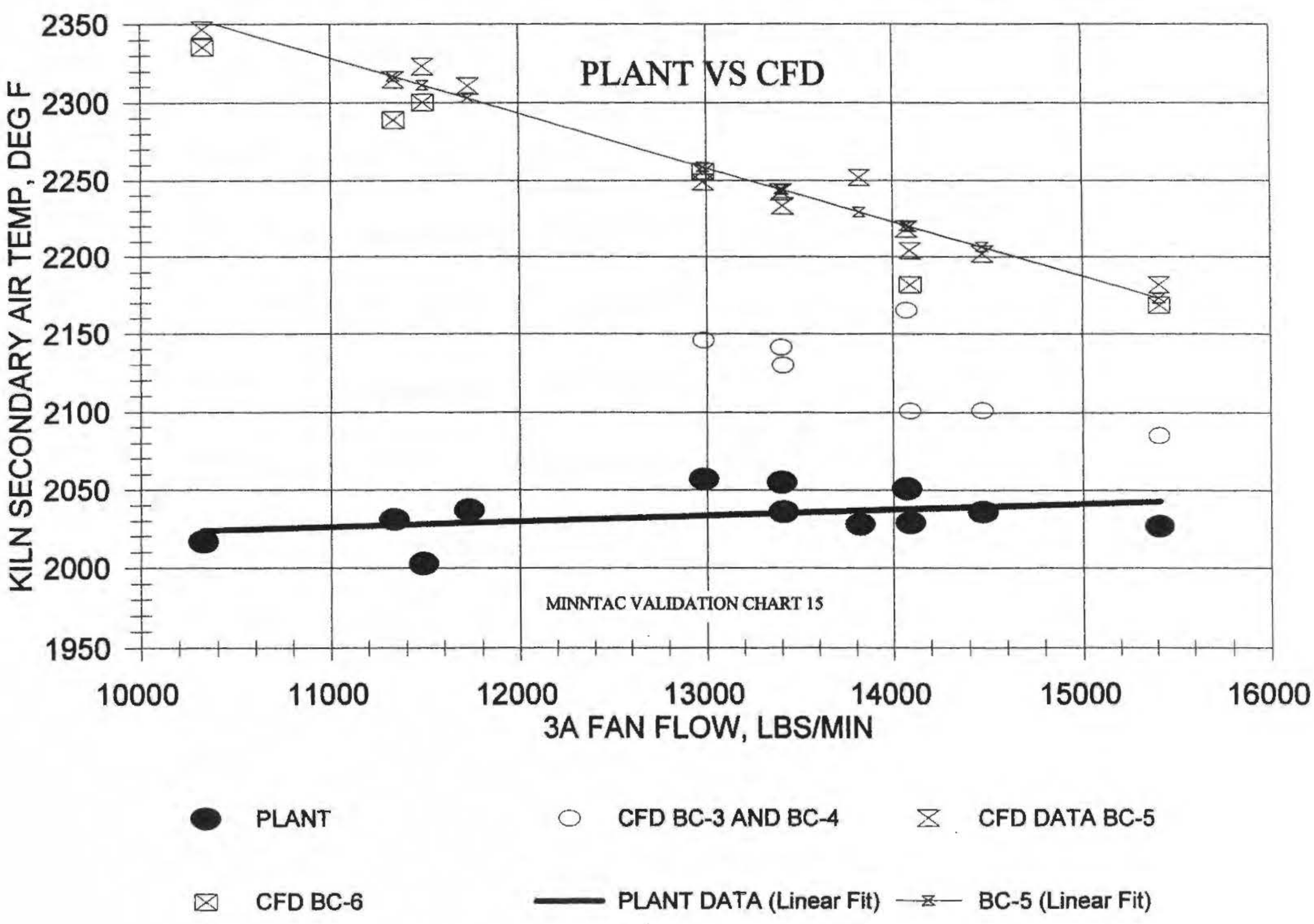


FIGURE 27

RECOUP A DUCT TEMP VS 3A FAN FLOW

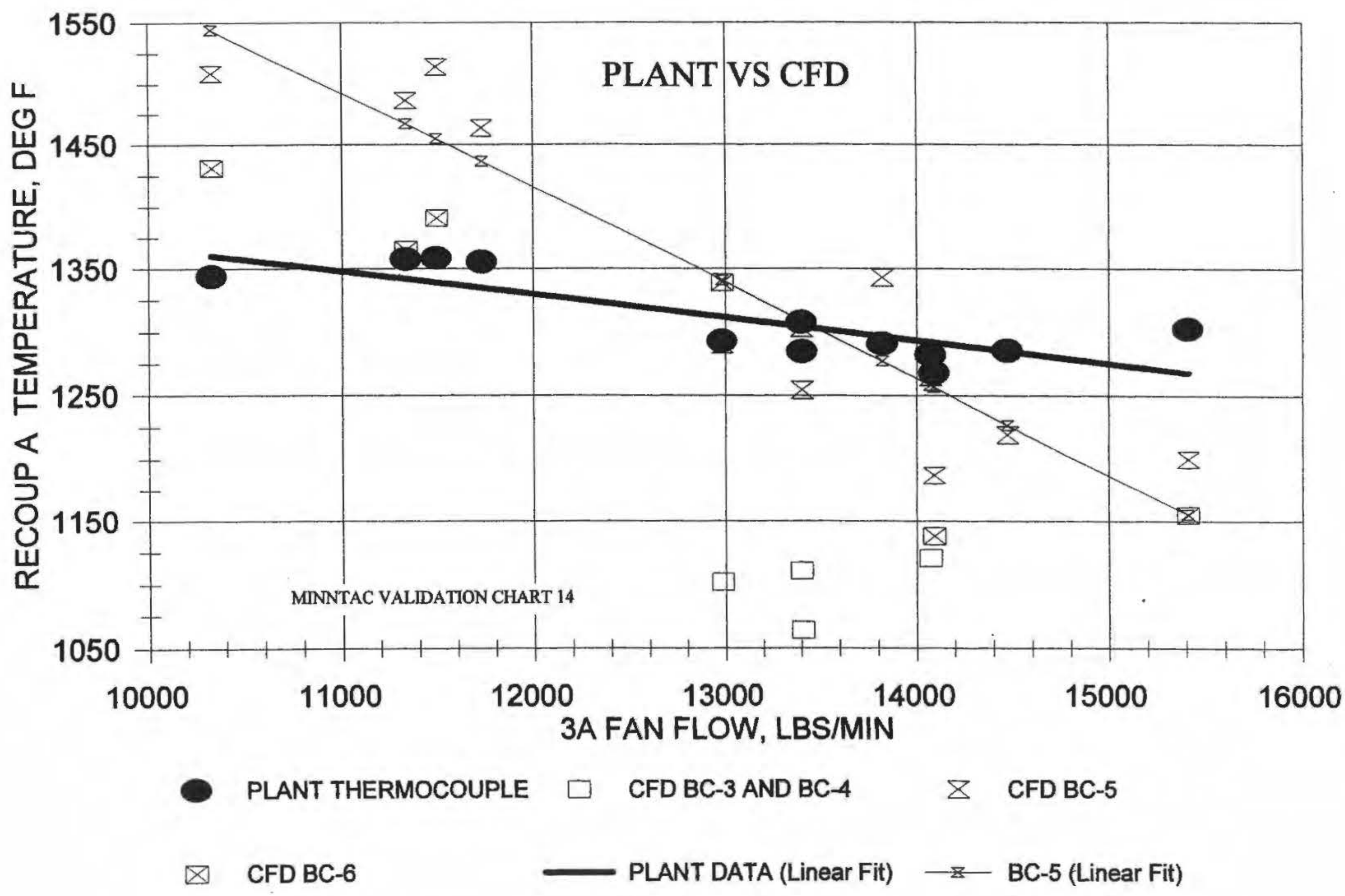


FIGURE 28

RECOUP B DUCT TEMP VS 3A FAN FLOW

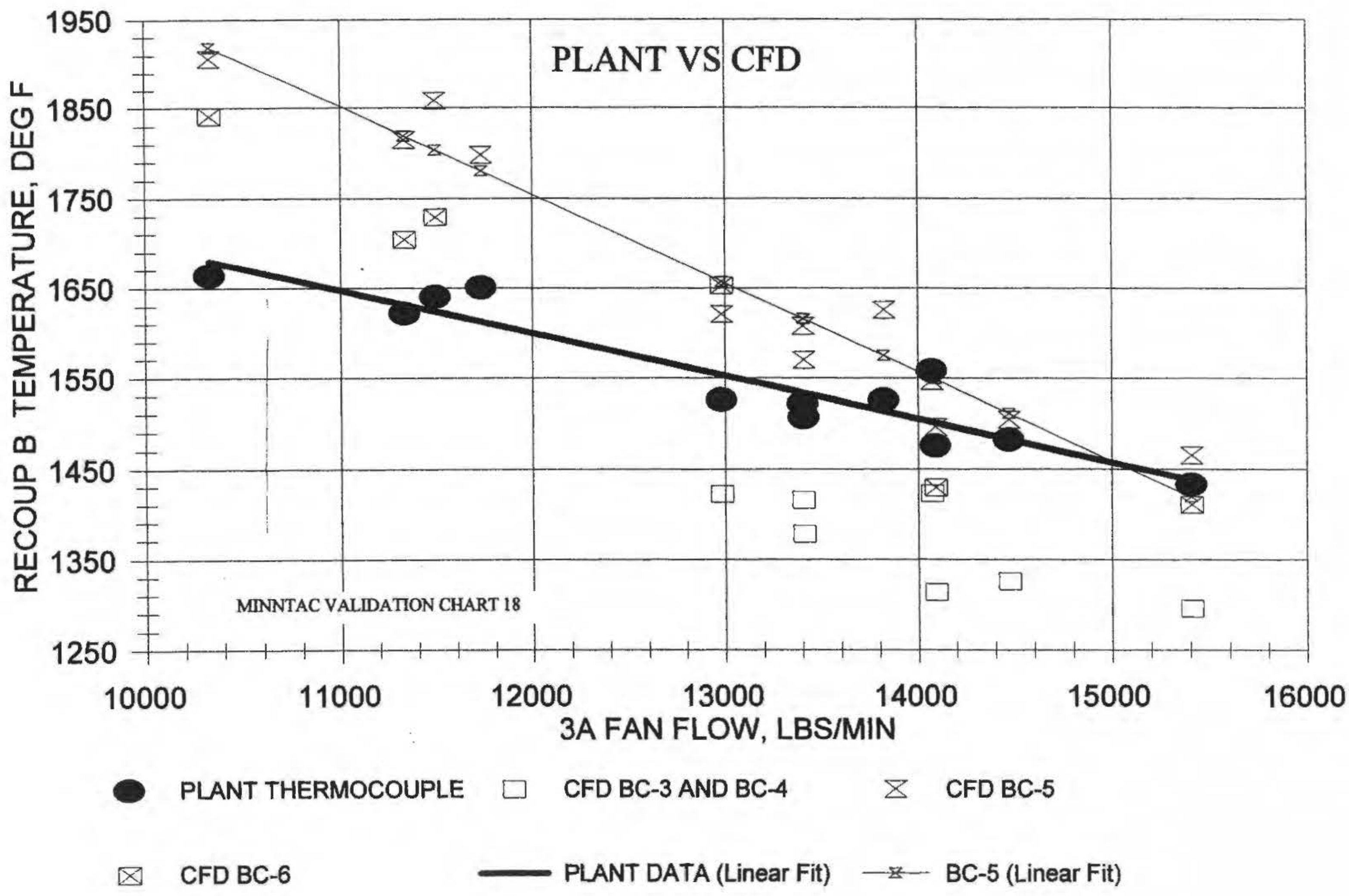


FIGURE 29

RECOUP A DUCT TEMP VS 3B FAN FLOW

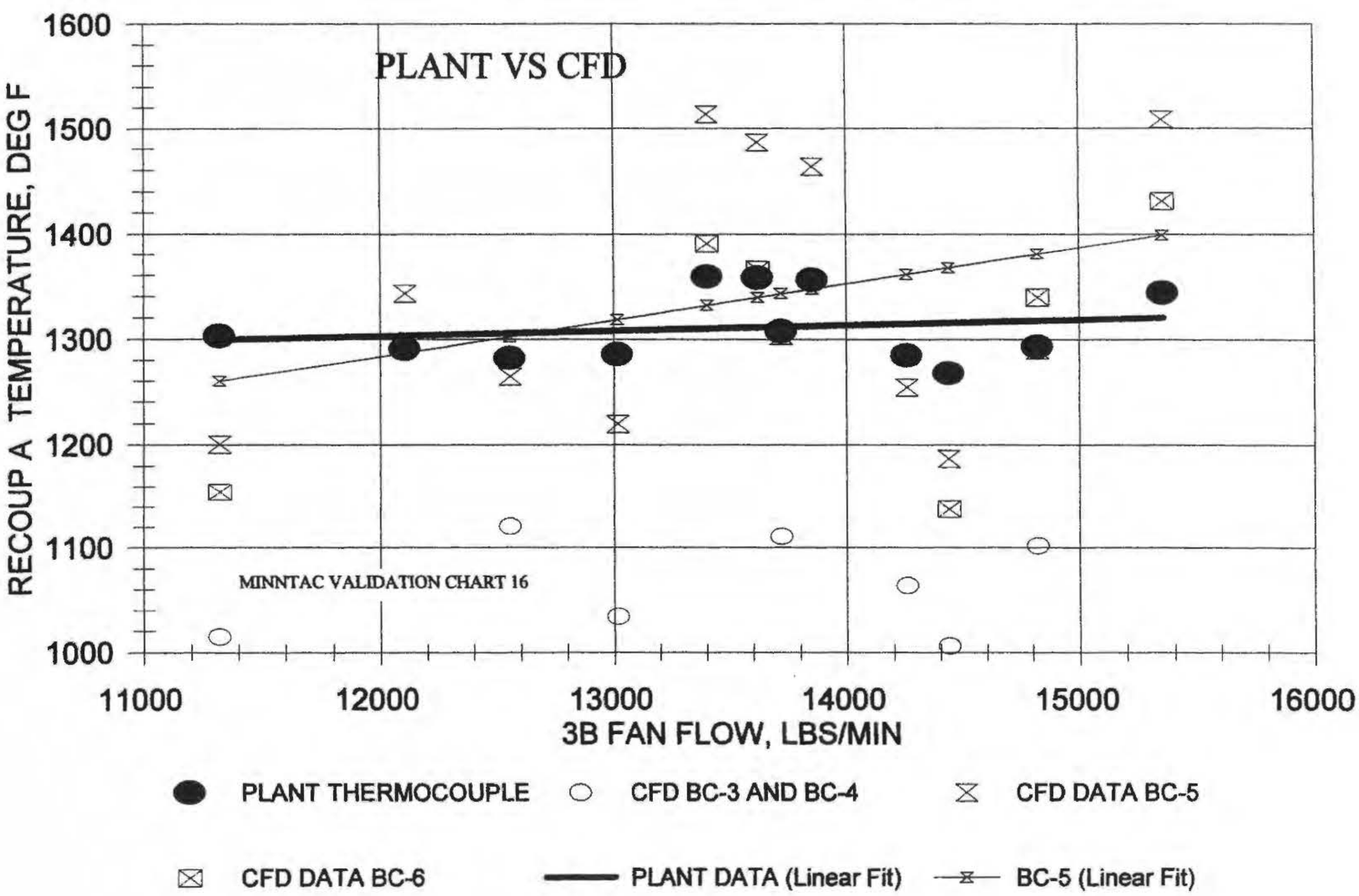


FIGURE 30

RECOUP B DUCT TEMP VS 3B FAN FLOW

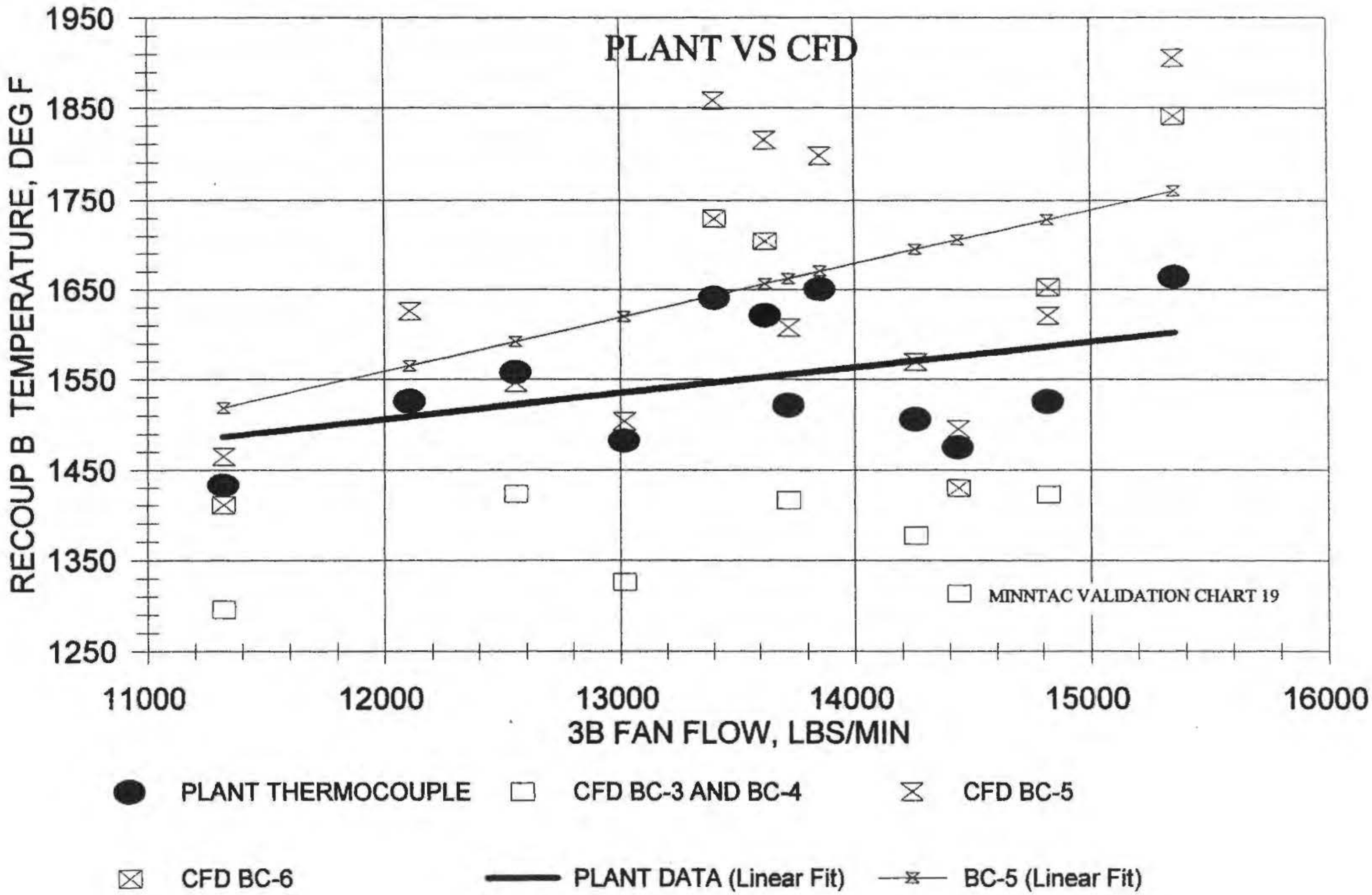


FIGURE 31
PLANT 3A FLOW VS 3B FLOW

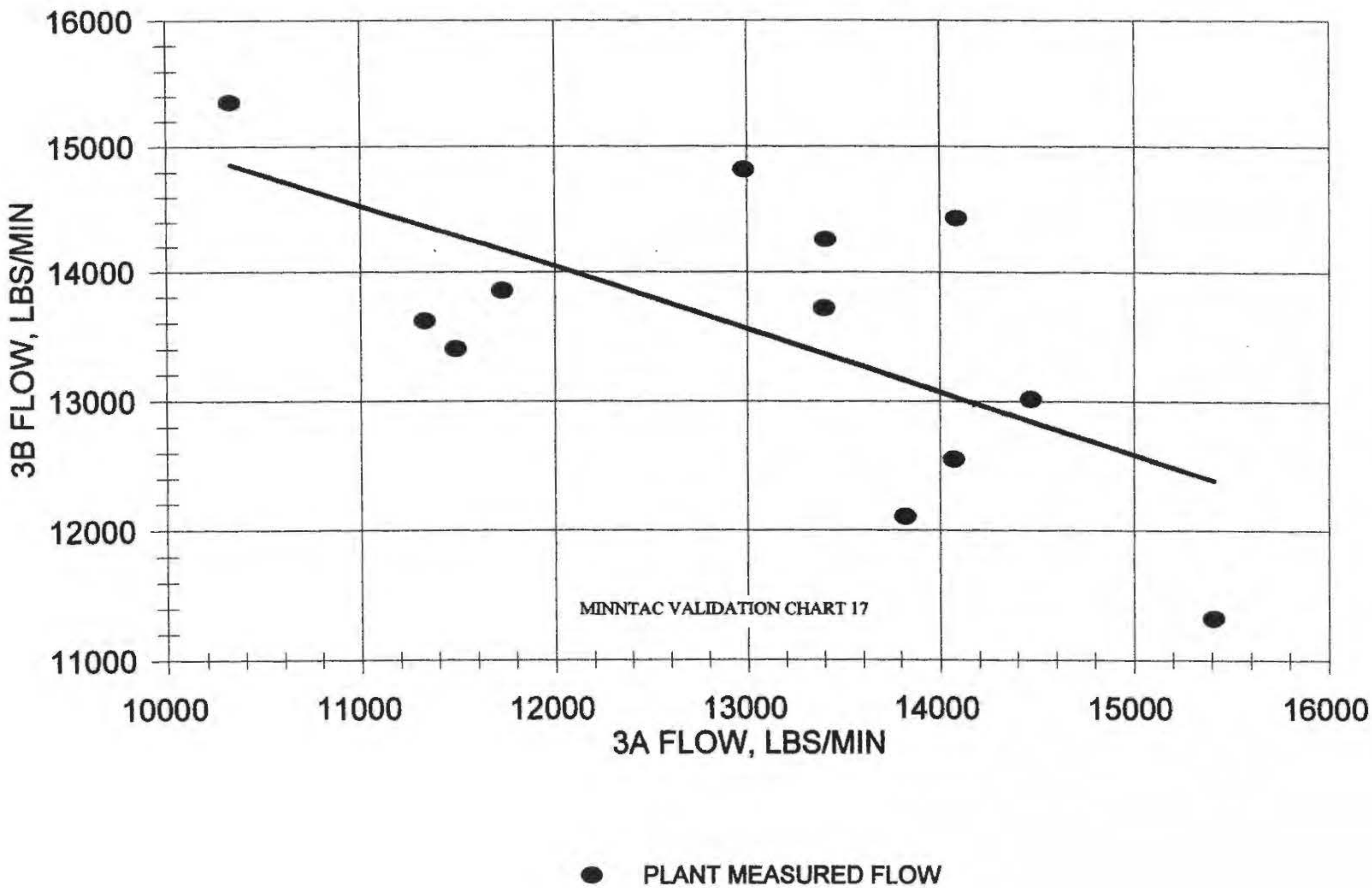


FIGURE 32
3A OVERBED PRESSURE VS 3A FLOW

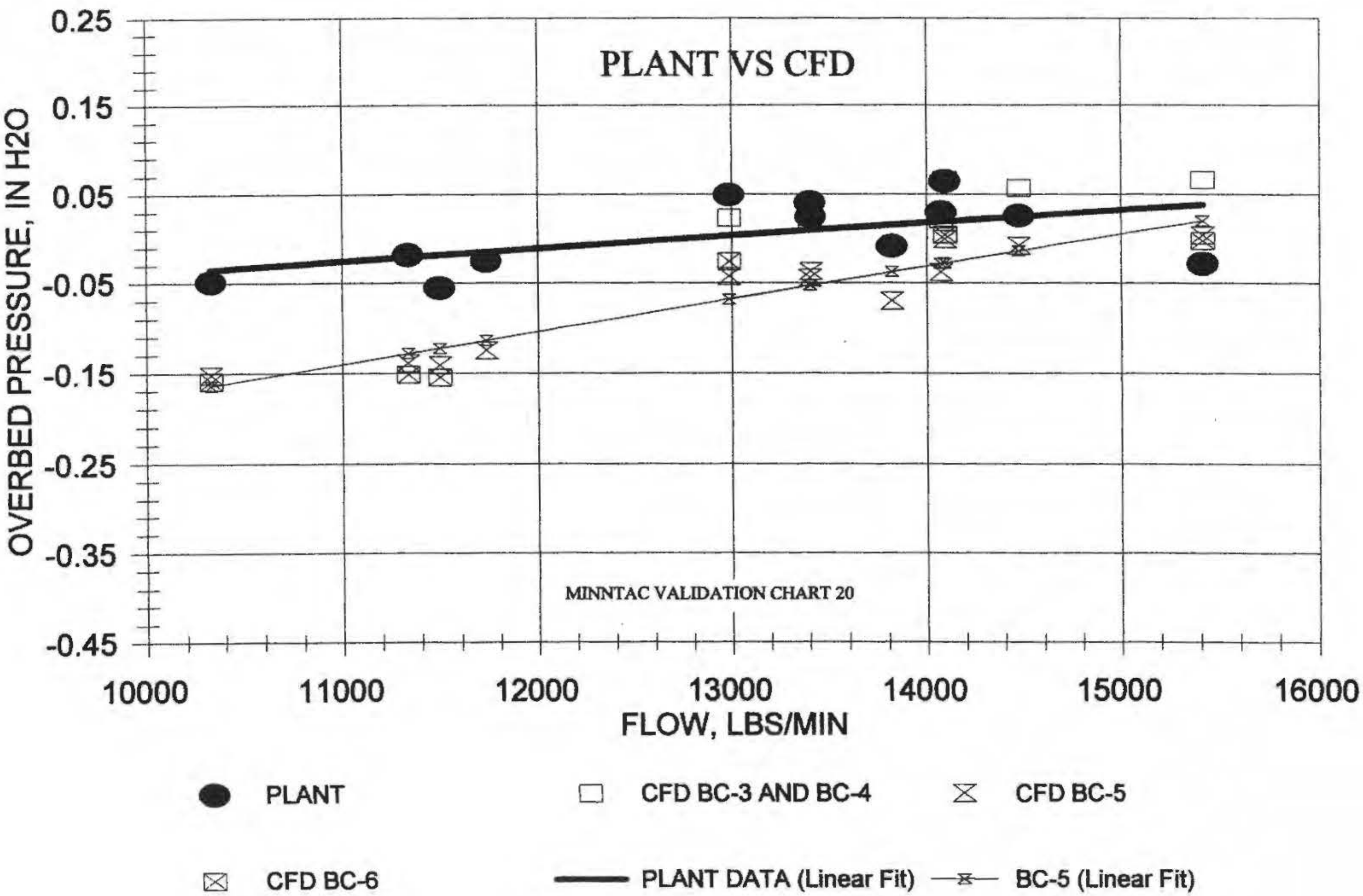


FIGURE 33

3B OVERBED PRESSURE VS 3B FLOW

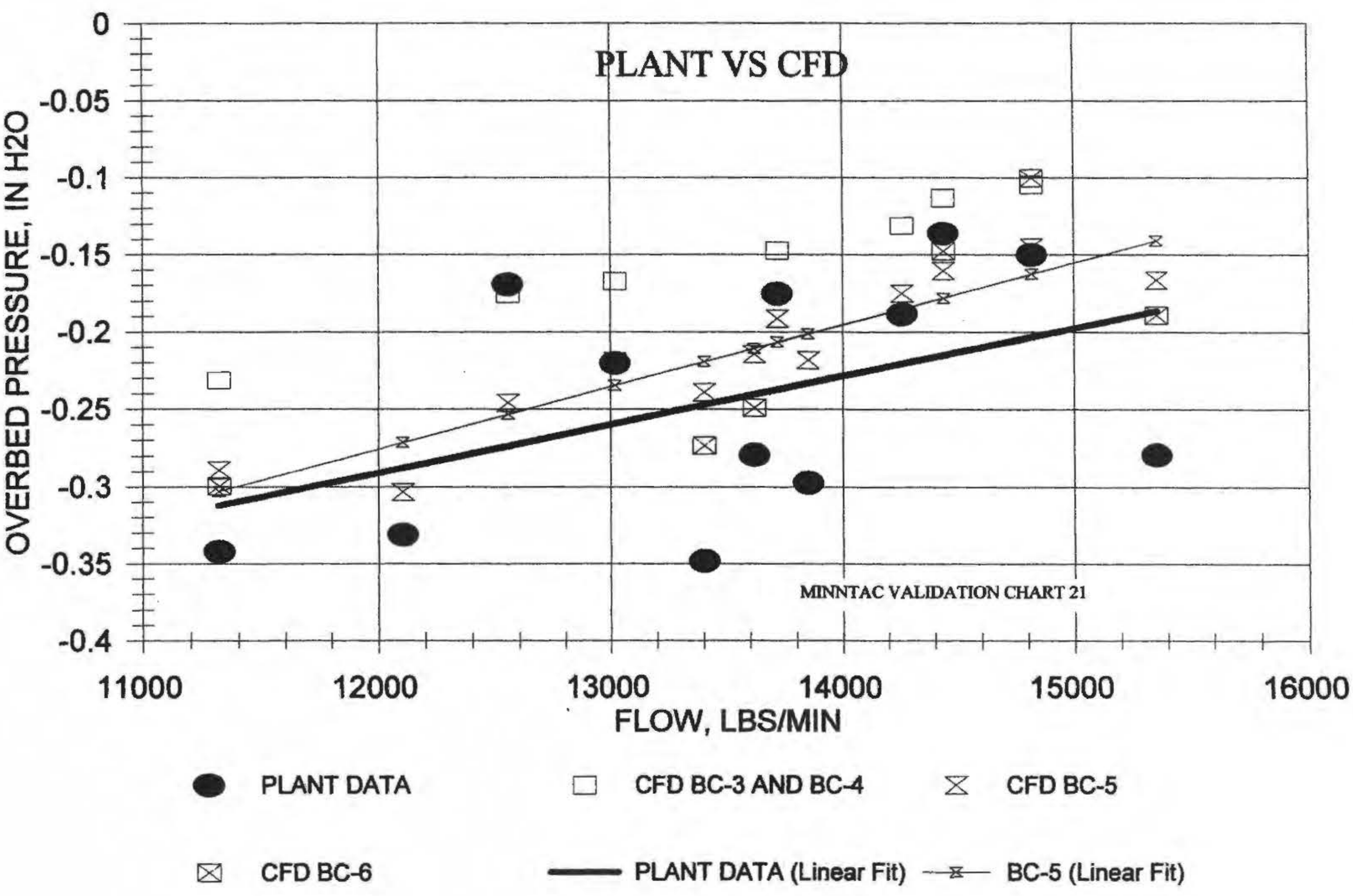


FIGURE 34

PHEAT OBED PRESS VS 3A OBED PRESSURE

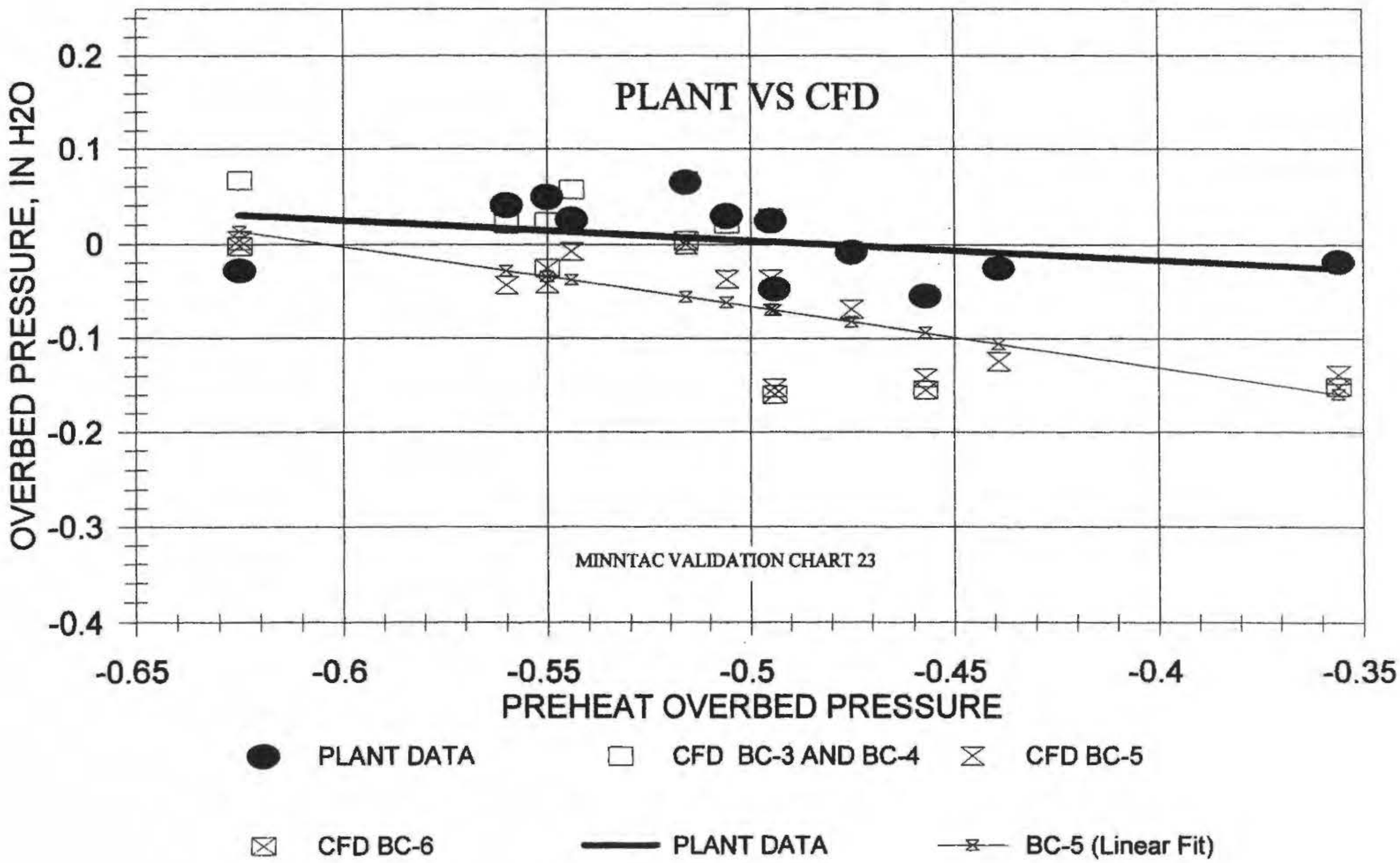


FIGURE 35

KILN FLOW VS 3A FLOW

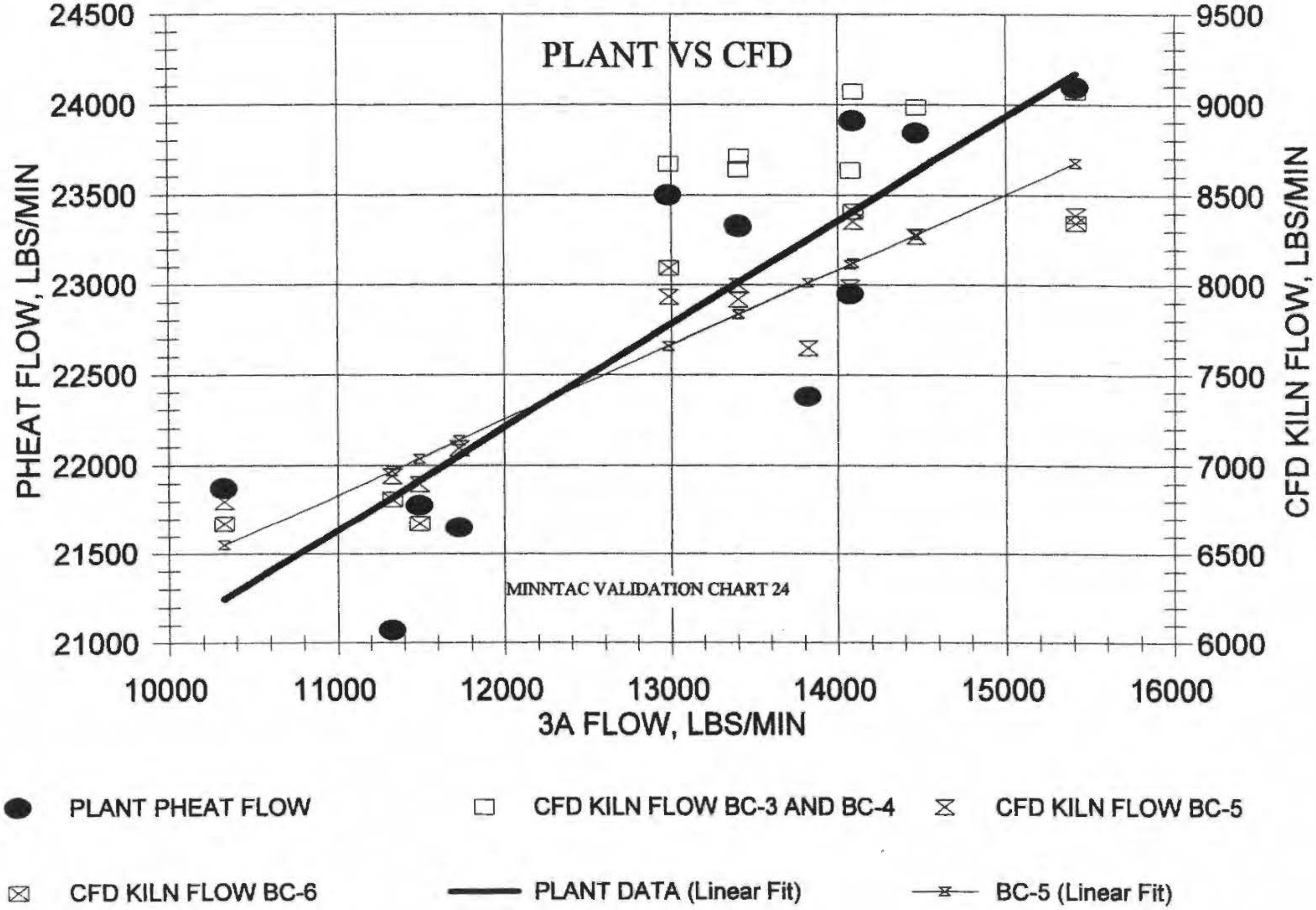


FIGURE 36
DD1 O'BED TARGET TEMP COMPARISON

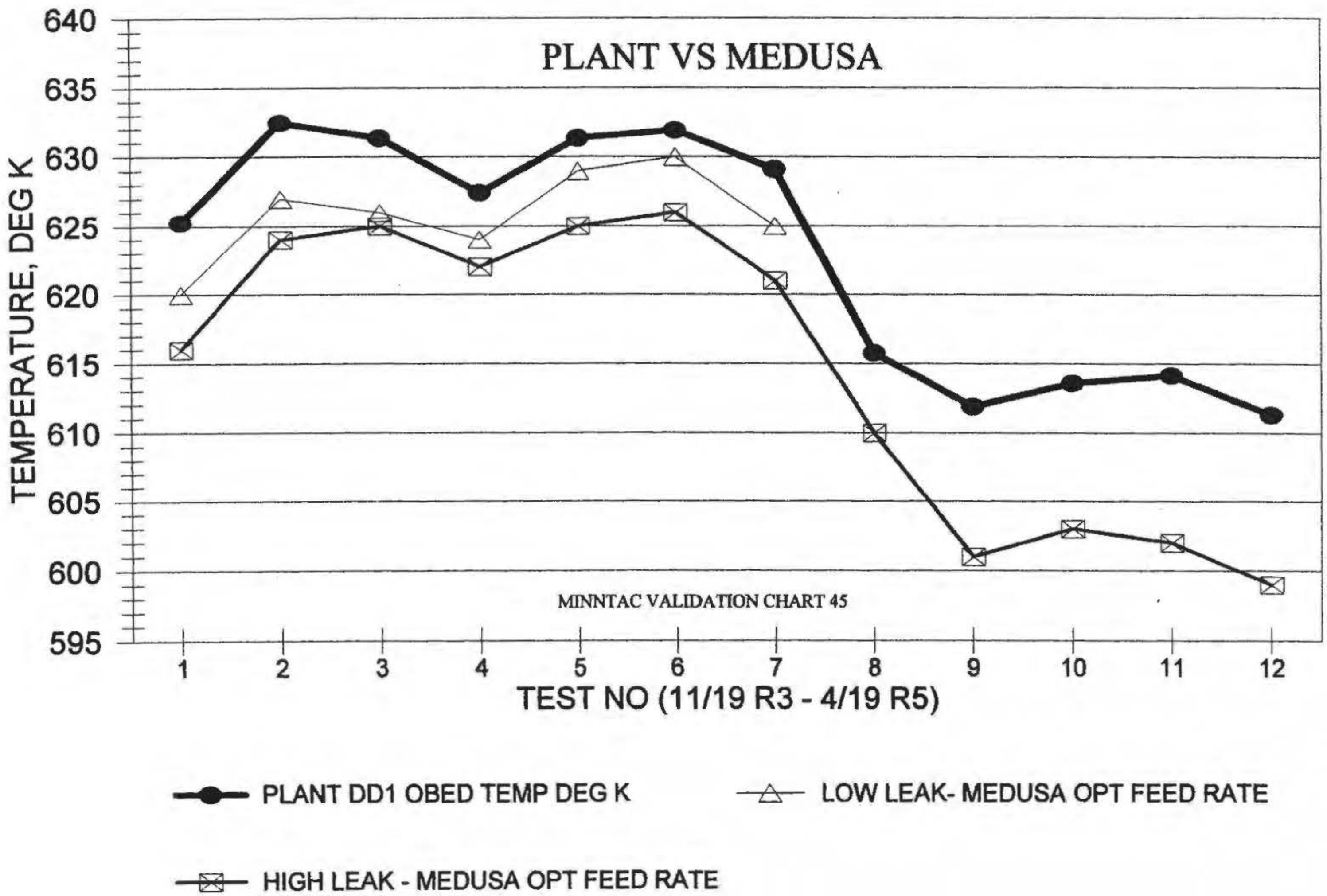


FIGURE 37

DD2 O'BED TARGET TEMP COMPARISON

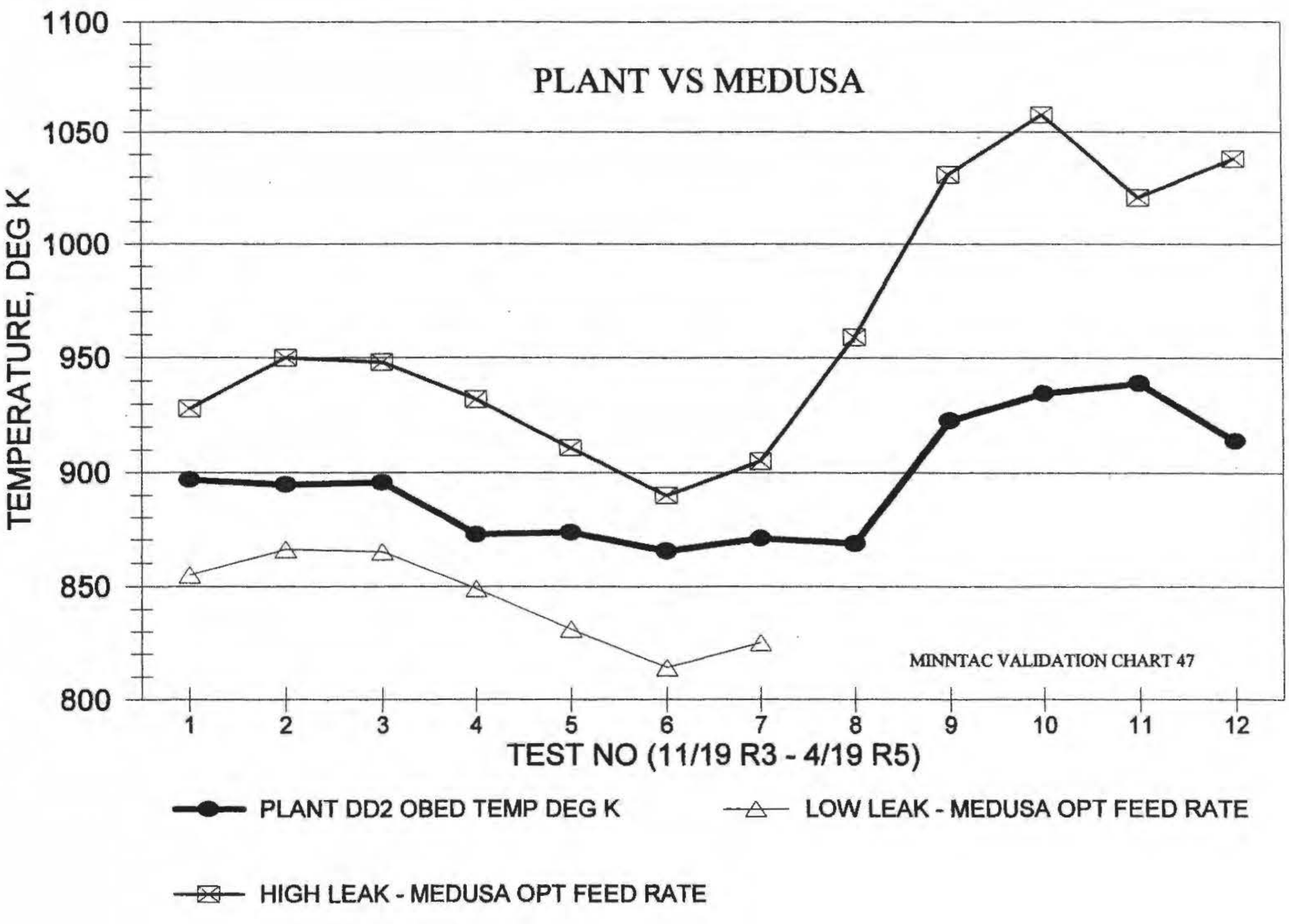


FIGURE 38
PREHEAT FAN INLET TEMP COMPARISON

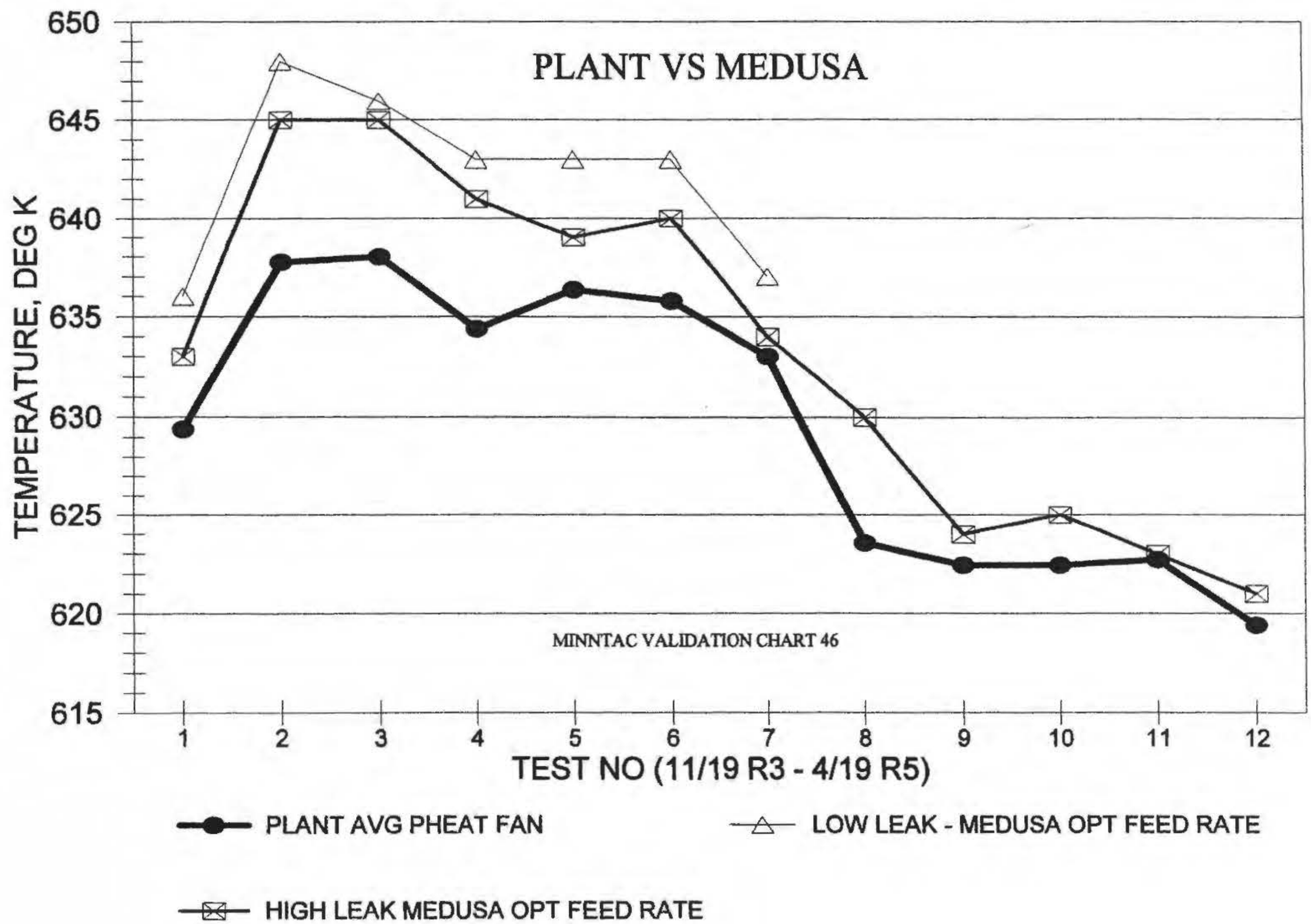


FIGURE 39
KILN SOLIDS EXIT TEMP COMPARISON

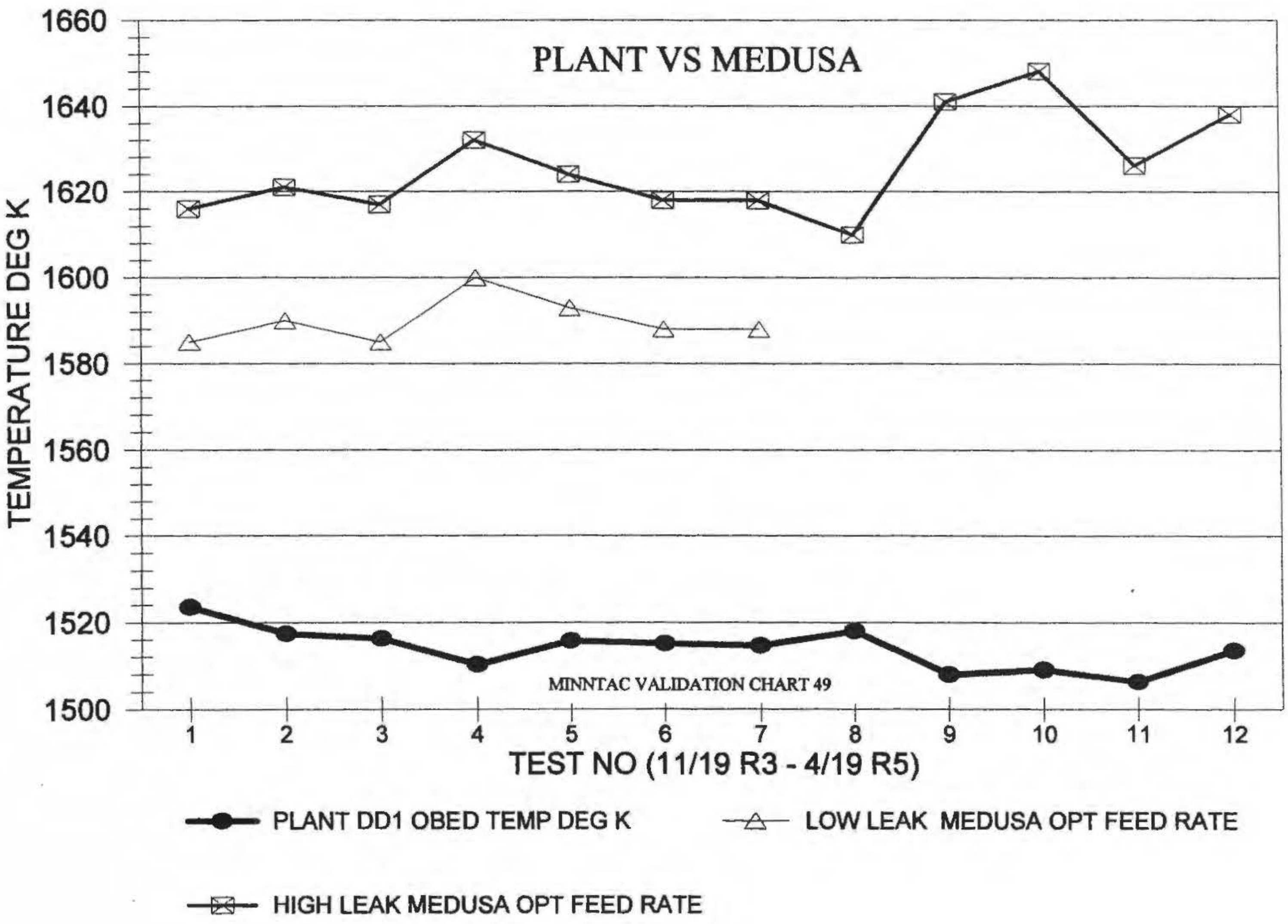
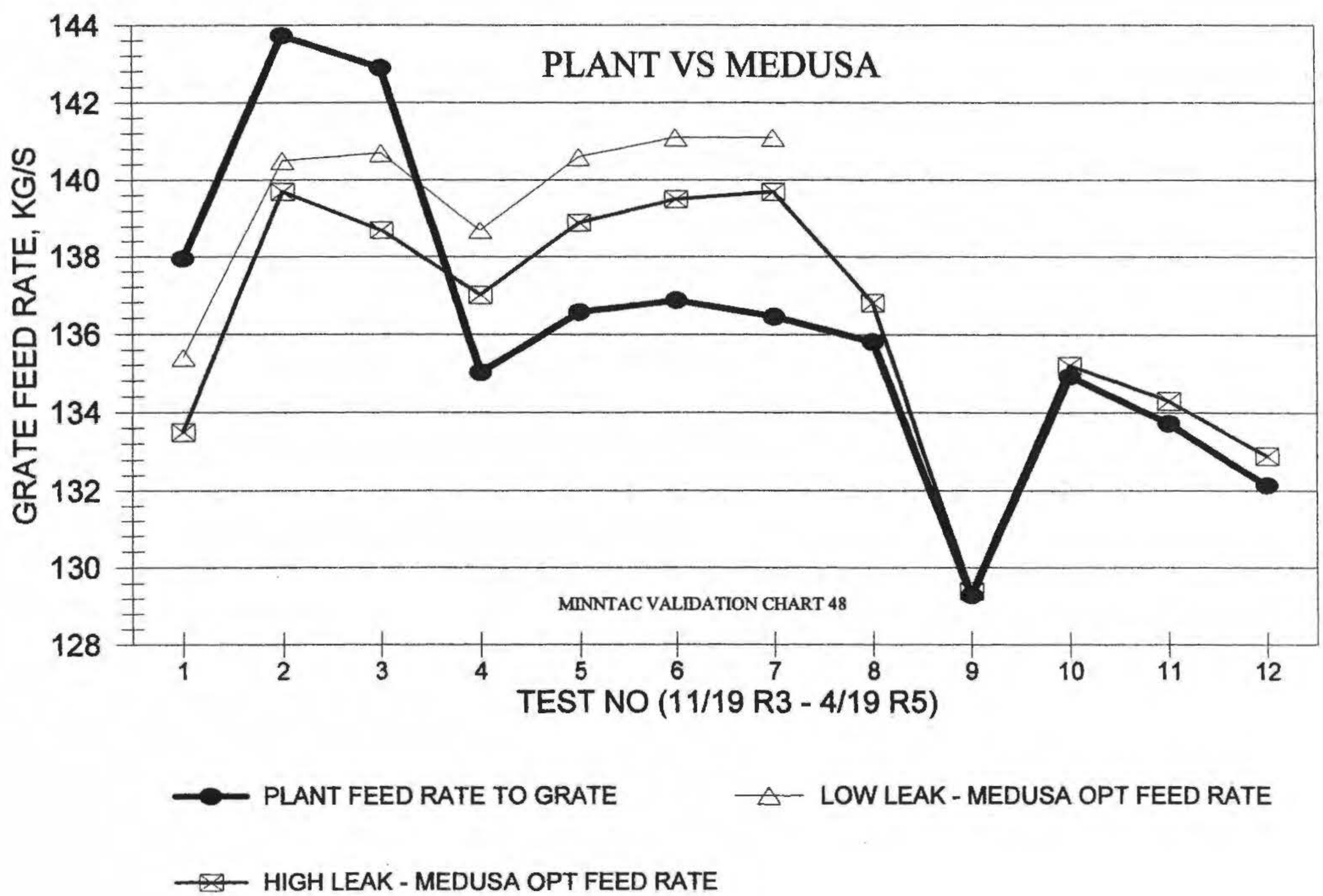


FIGURE 40
PLANT FEED VS MEDUSA OPTIMUM FEED RATE



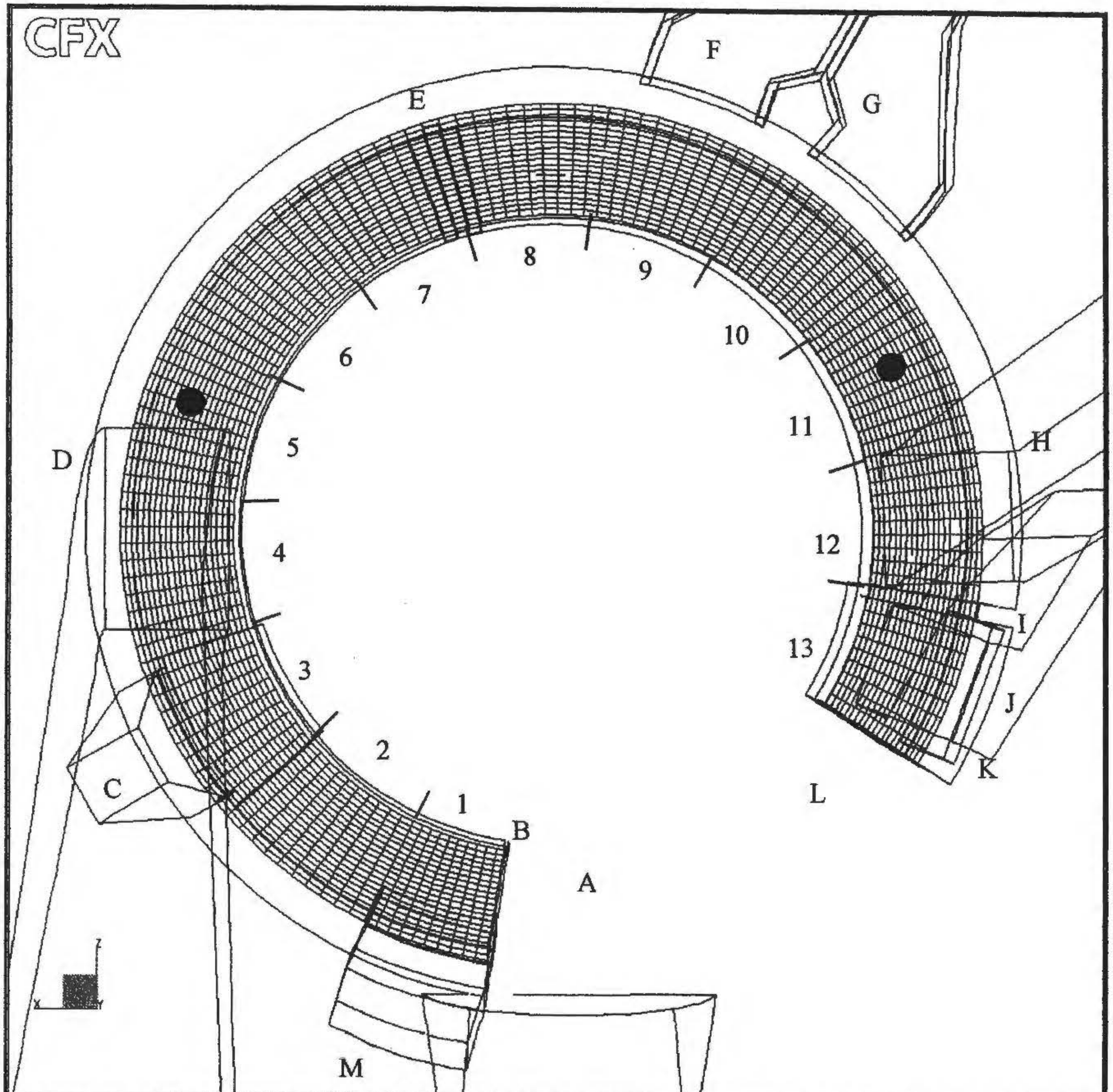


FIGURE 41

Cooler Layout

A. Kiln Discharge

B. Screed Wall

C. 3A Fan Inlet

D. Parallel Flow Duct

E. Under Bed Damper

F. Recoup B Duct

G. Recoup A Duct

H. Cooler Vent Stack

I. Baffle Wall

J. Auxiliary Vent Stack

K. 3B Fan Inlet

L. Pellet Dump

M. Firing Hood Section

● Over Bed and Under Bed Pressure Sensors

FIGURE 42
3A OBED PRESS AND PELLET EXIT TEMP

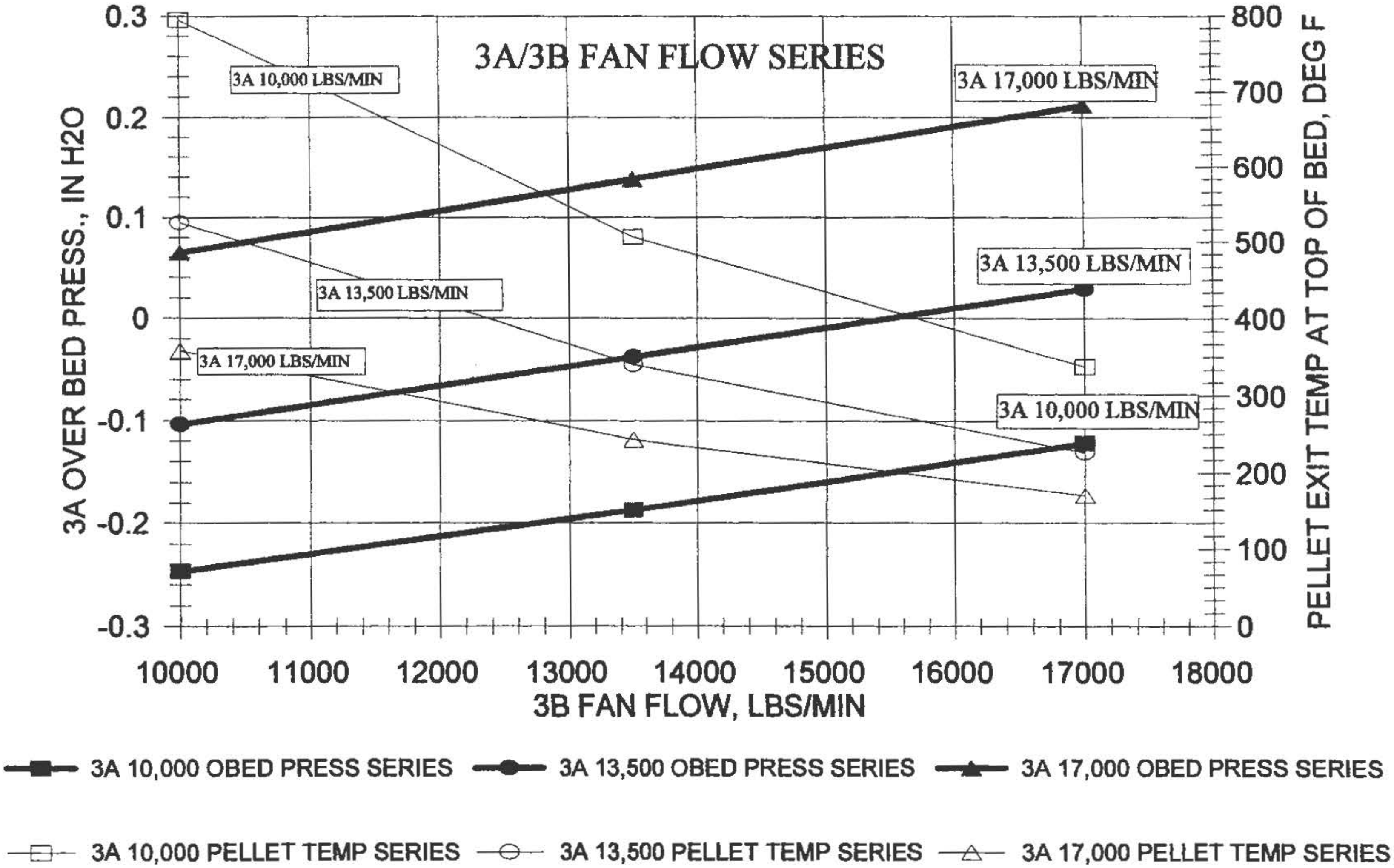


FIGURE 43

PELLET EXIT TEMP VS TOTAL COOLER FLOW

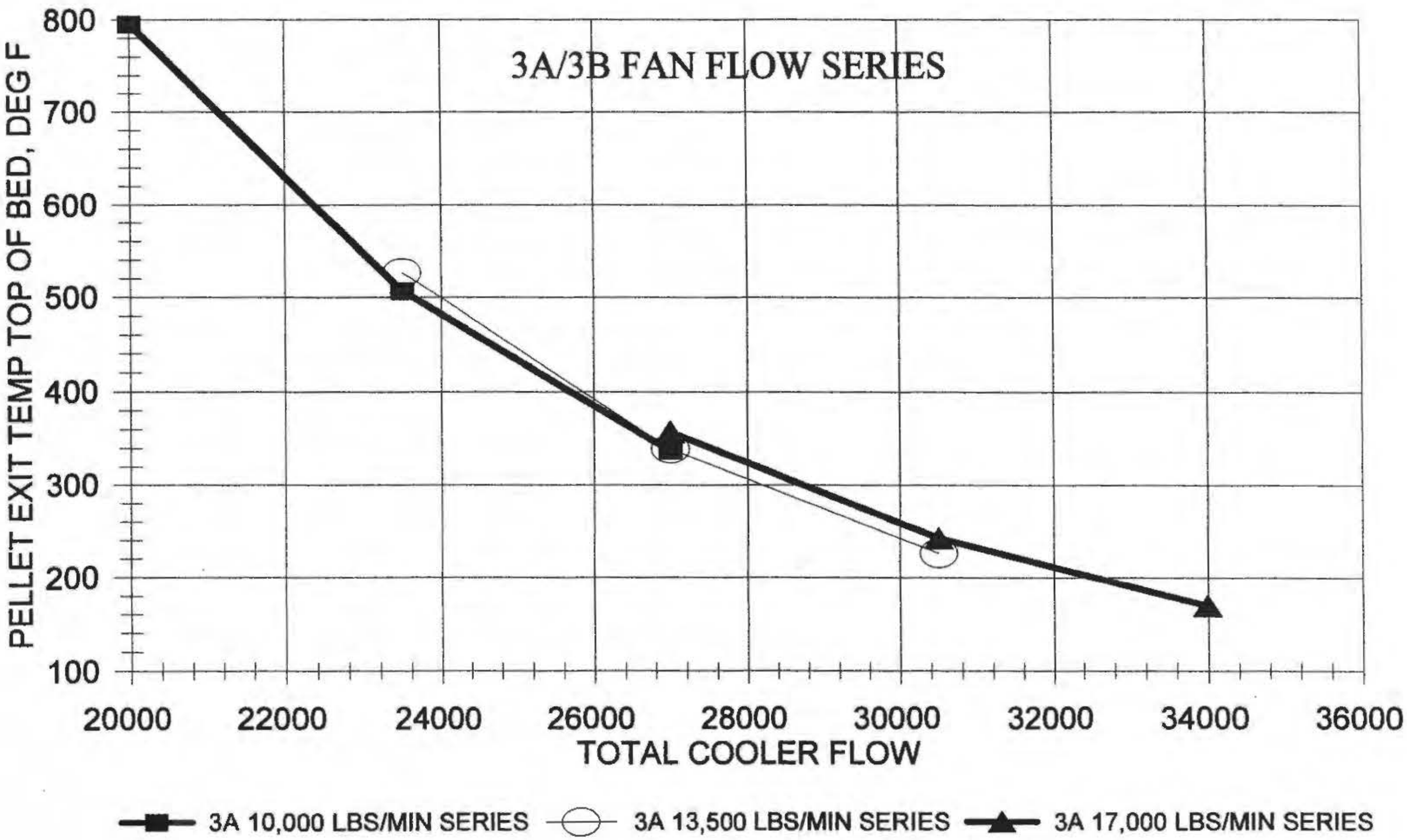


FIGURE 44
3A OBED PRESSURE VS TOTAL COOLER FLOW

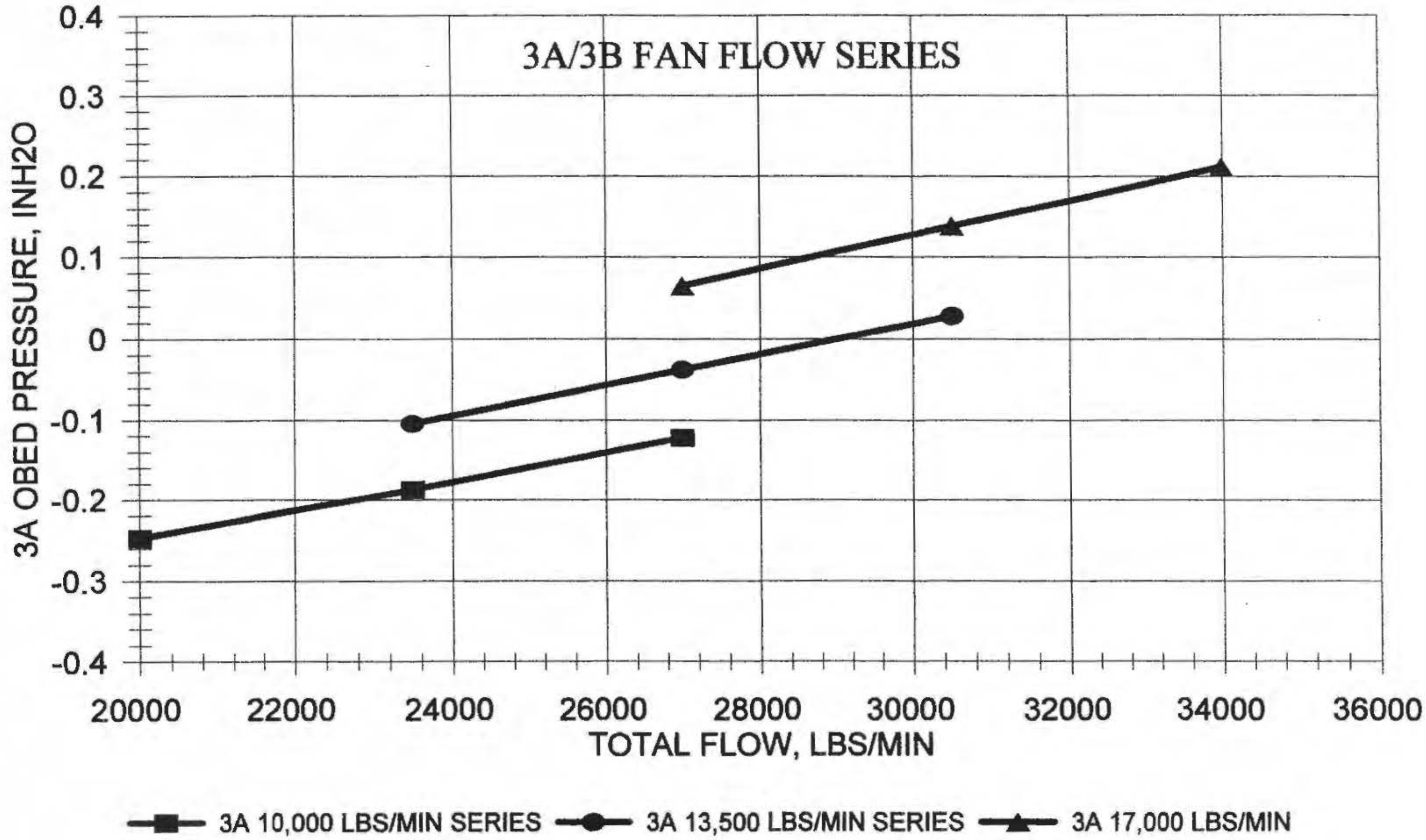


FIGURE 45

RECOUP TEMPERATURE VS 3B FAN FLOW

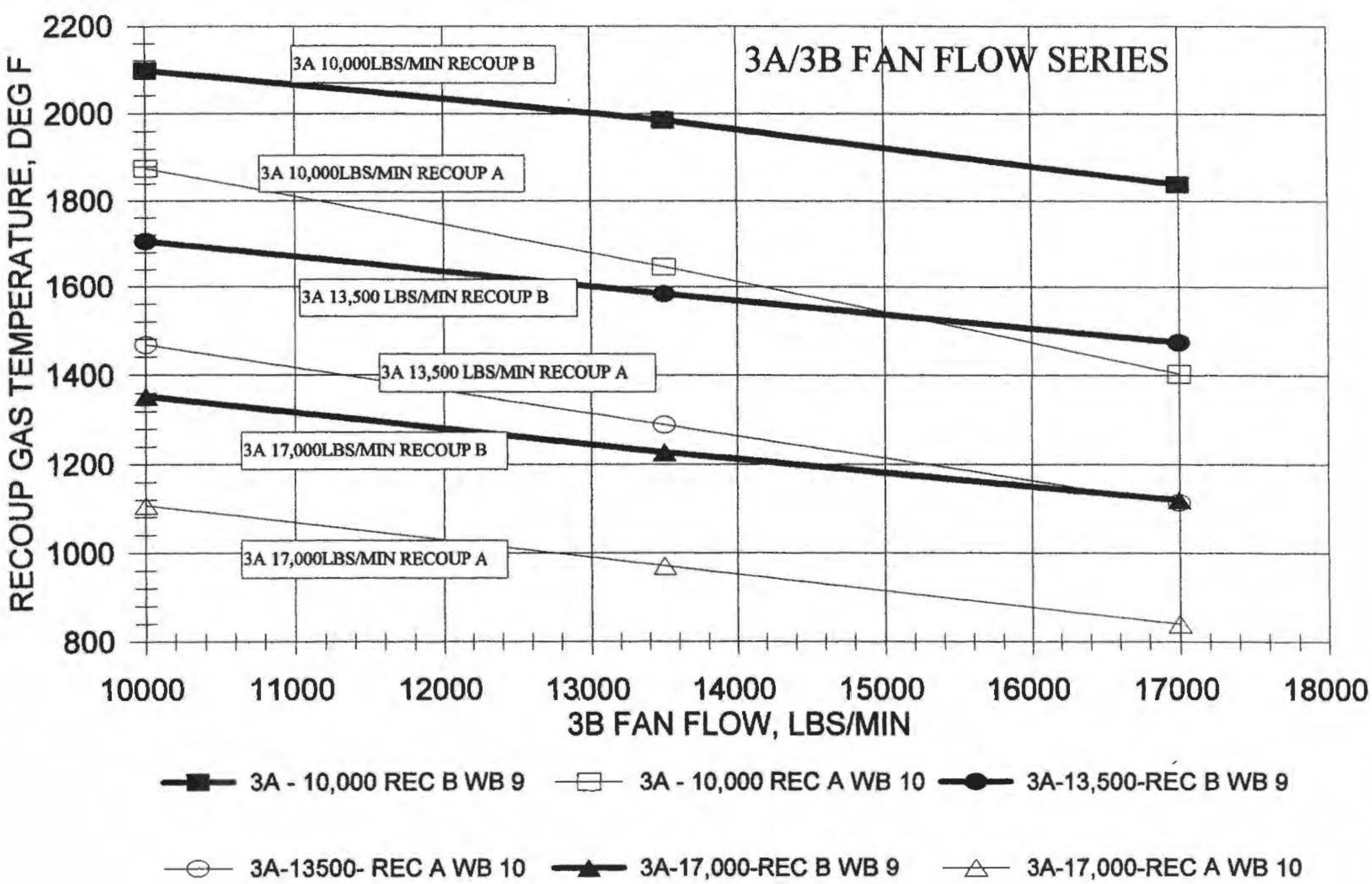


FIGURE 46
RECOUP TEMP VS TOTAL COOLER FLOW

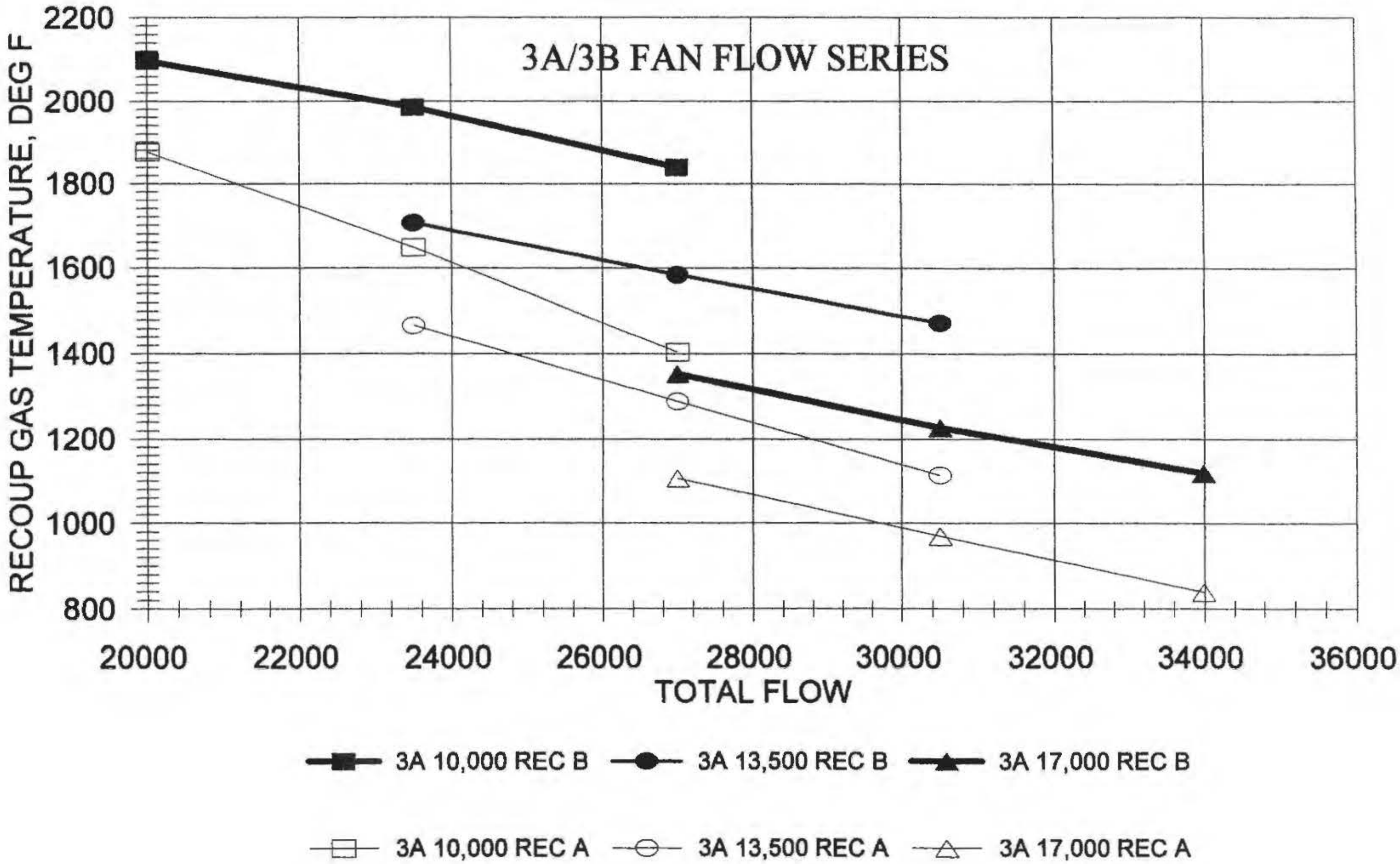


FIGURE 47
RECOUP FLOW VS 3B FAN FLOW

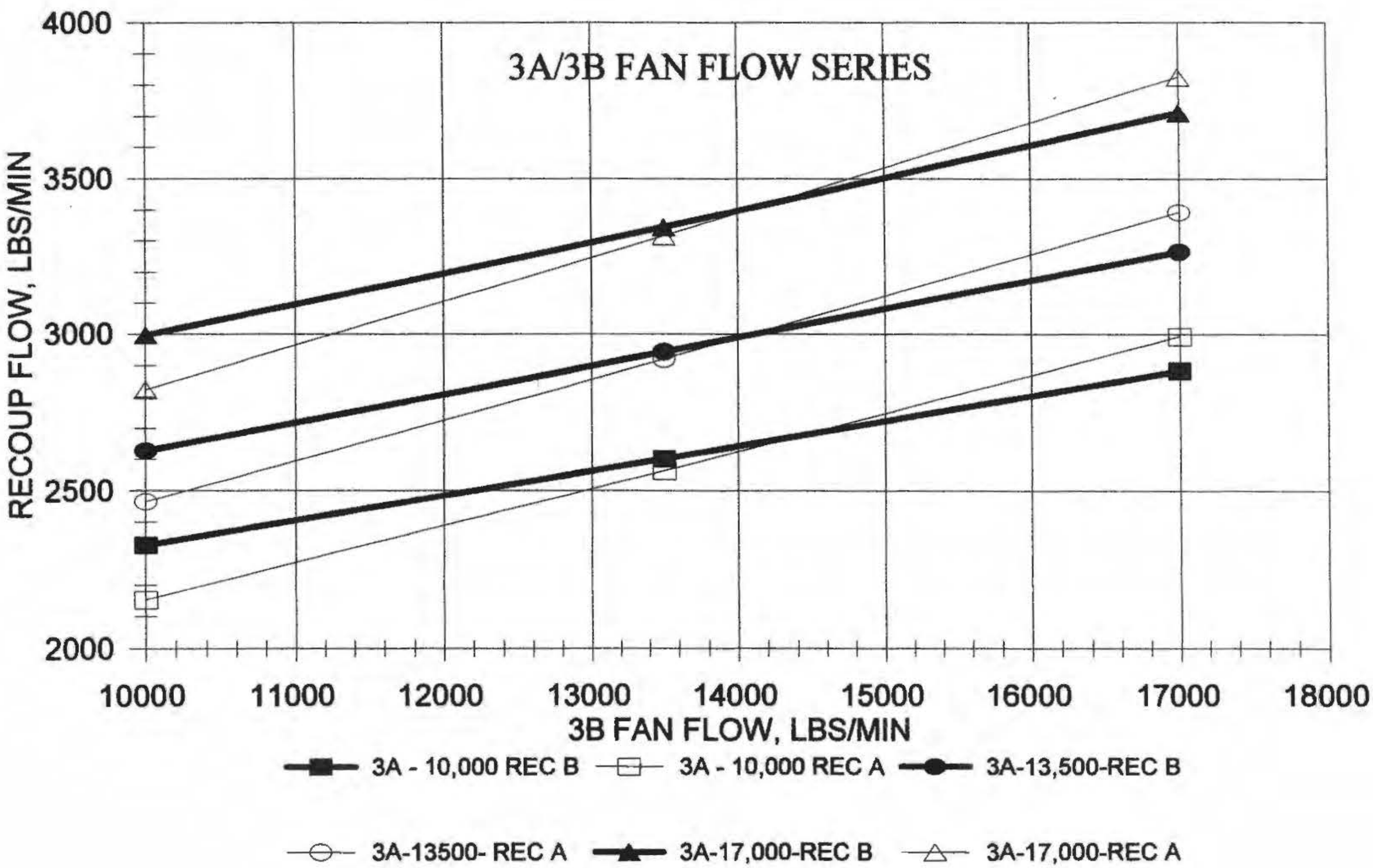


FIGURE 48

RECOUP FLOW VS TOTAL COOLER FLOW

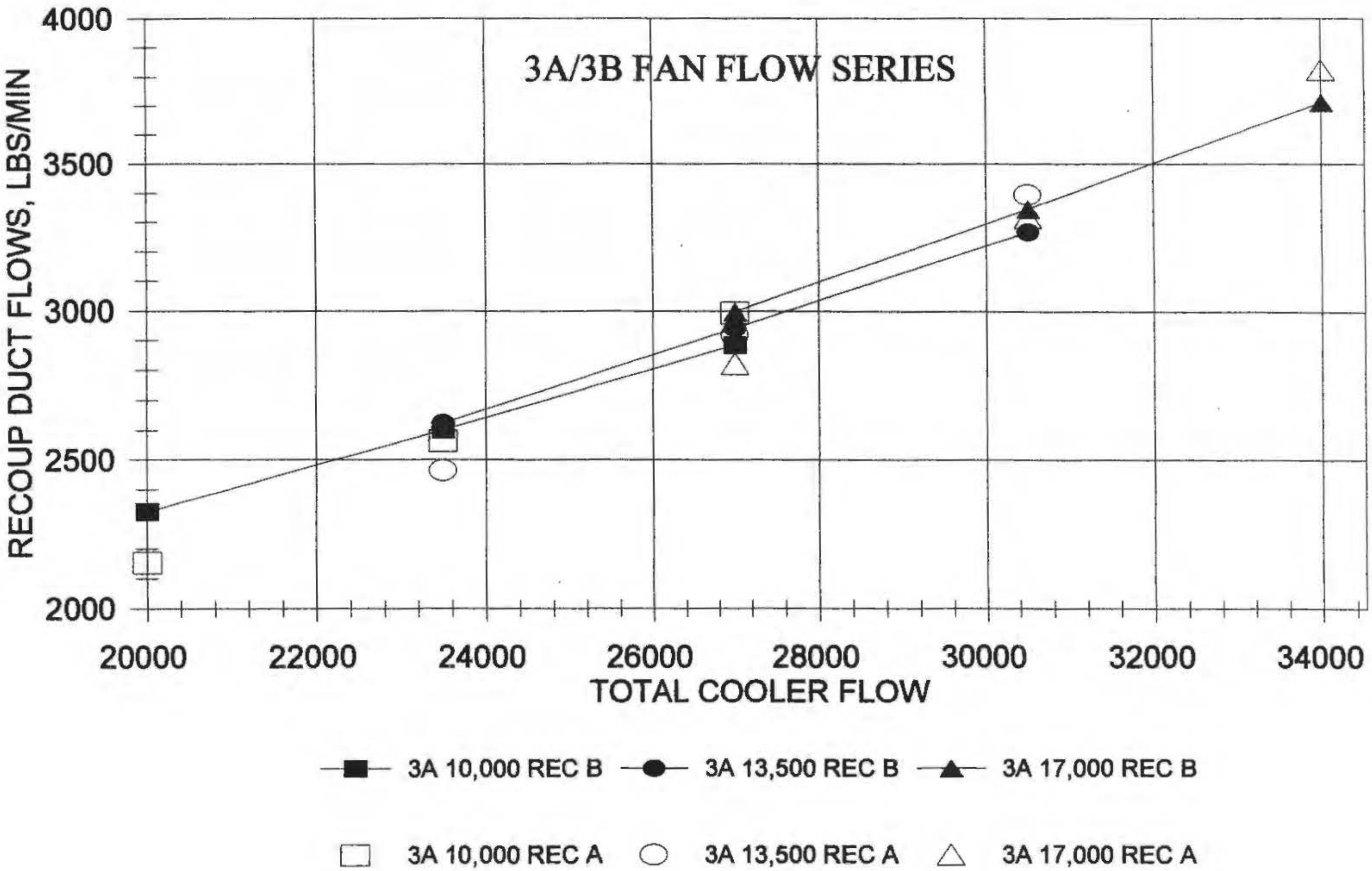


FIGURE 49

Second Parametric Series: Current Cooler Baseline - Linear Regression Model

Parameter Estimates

	3A OB PRS INH2O	T KILN LBS/MIN	A KILN TEMP F	T REC LBS/MIN	A REC TEMP F	PELL EXIT TMP F	VENT STK TMP F
Intercept	-1.1033383	-2859.7217	2327.61728	1303.89454	1620.79393	417.286658	673.568186
% MAG	0.00112499	2.15898313	5.86304477	-6.5933002	8.31046075	1.80096853	3.31826991
FEED LTPH	0.00046782	3.68837994	0.58975421	-2.2311664	3.26431472	2.20621389	2.60022154
3A LBS/MIN	0.0000412	0.46640459	-0.0299607	0.2223034	-0.1019756	-0.0391669	-0.0518239
3B LBS/MIN	0.00001592	0.19309625	-0.0071488	0.22699125	-0.0429097	-0.0447426	-0.0514126

Prediction Profile

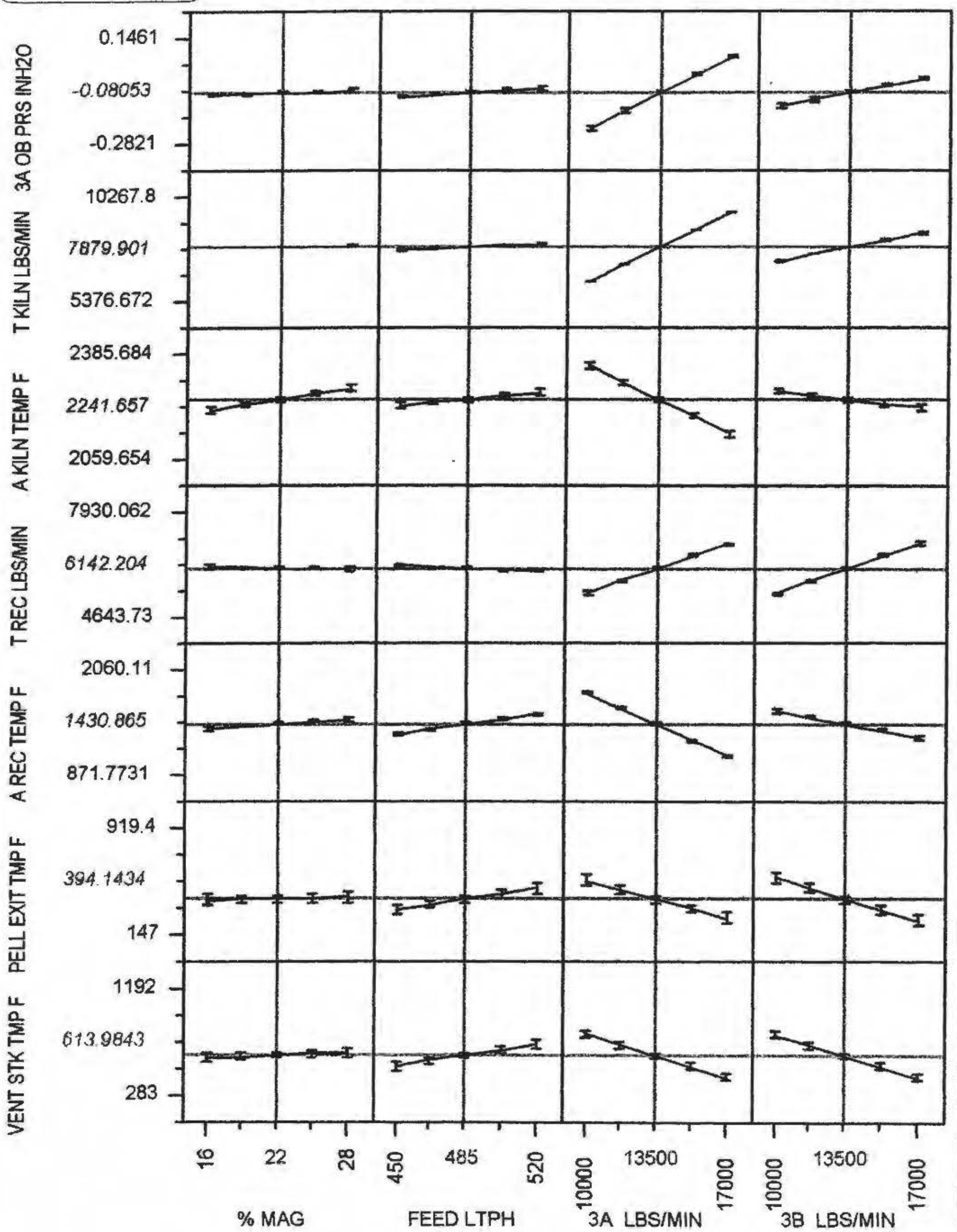
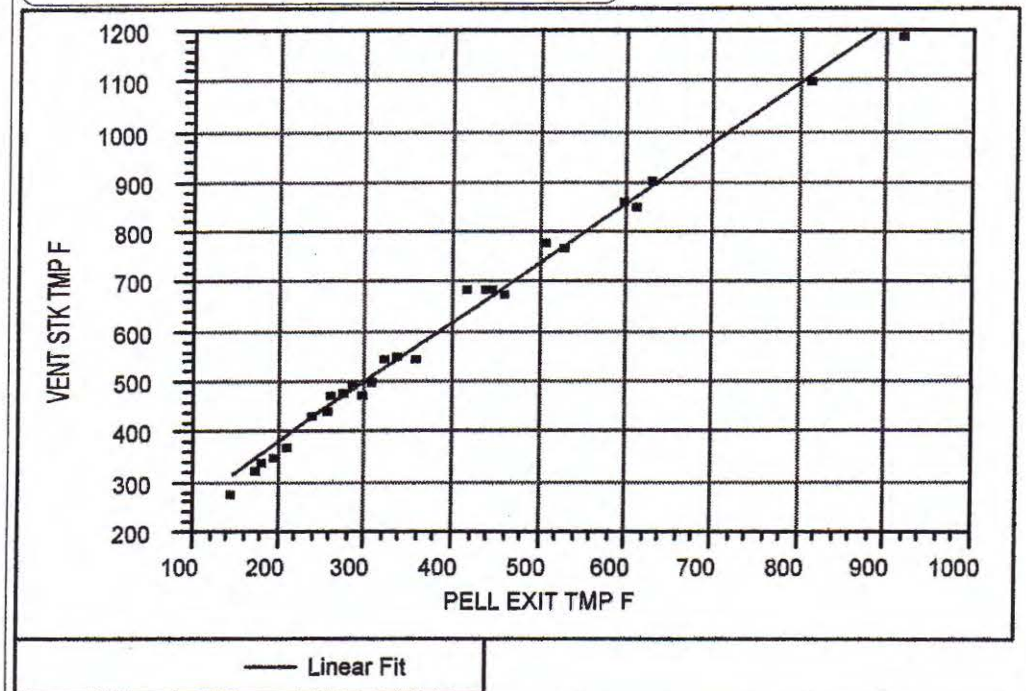


FIGURE 50

Second Parametric Series: Current Cooler Baseline
Vent Stack Temperature Vs Pellet Exit Temperature

VENT STK TMP F By PELL EXIT TMP F



Linear Fit

VENT STK TMP F = 143.574 + 1.1935 PELL EXIT TMP F

Summary of Fit

RSquare	0.988656
RSquare Adj	0.988202
Root Mean Square Error	25.20424
Mean of Response	613.963
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1384065.6	1384066	2178.76
Error	25	15881.3	635	Prob>F
C Total	26	1399947.0		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	143.57431	11.18408	12.84	<.0001
PELL EXIT TMP F	1.1934984	0.025569	46.68	<.0001

FIGURE 51

Current Cooler Operating Window
485 WLTPH Feed to Grate

High fan flow limited by maximum 3A overbed pressure of -0.05 in. H_2O
Low fan flow limited by pellet exit temperature of 500 °F or Vent stack temperature of 765 °F

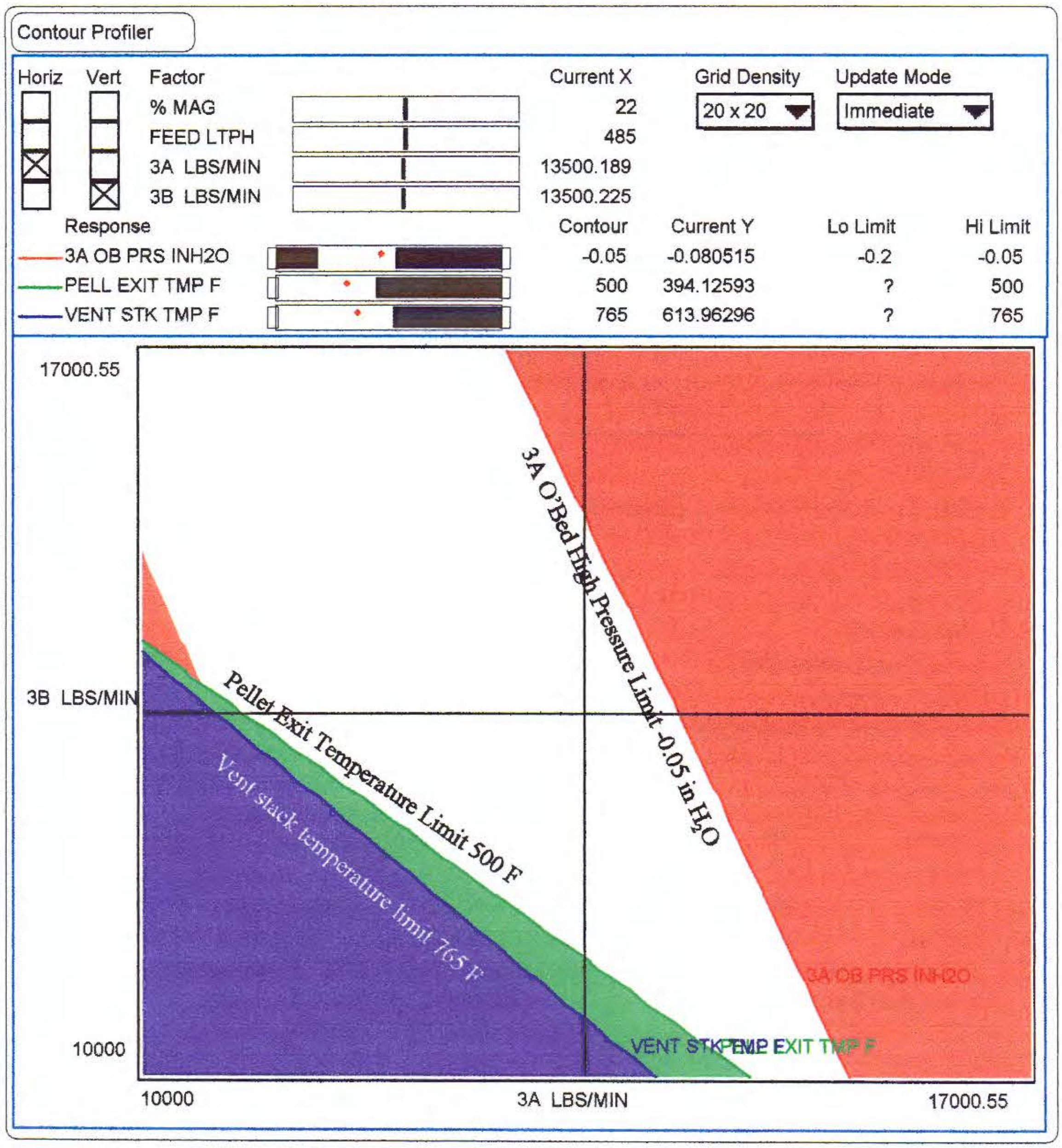


FIGURE 52

Current Cooler Operating Window
520 WLTPH Feed to Grate

High fan flow limited by maximum 3A overbed pressure of -0.05 in.H_2O
Low fan flow limited by pellet exit temperature of 500 °F or Vent stack Temperature of 765 °F

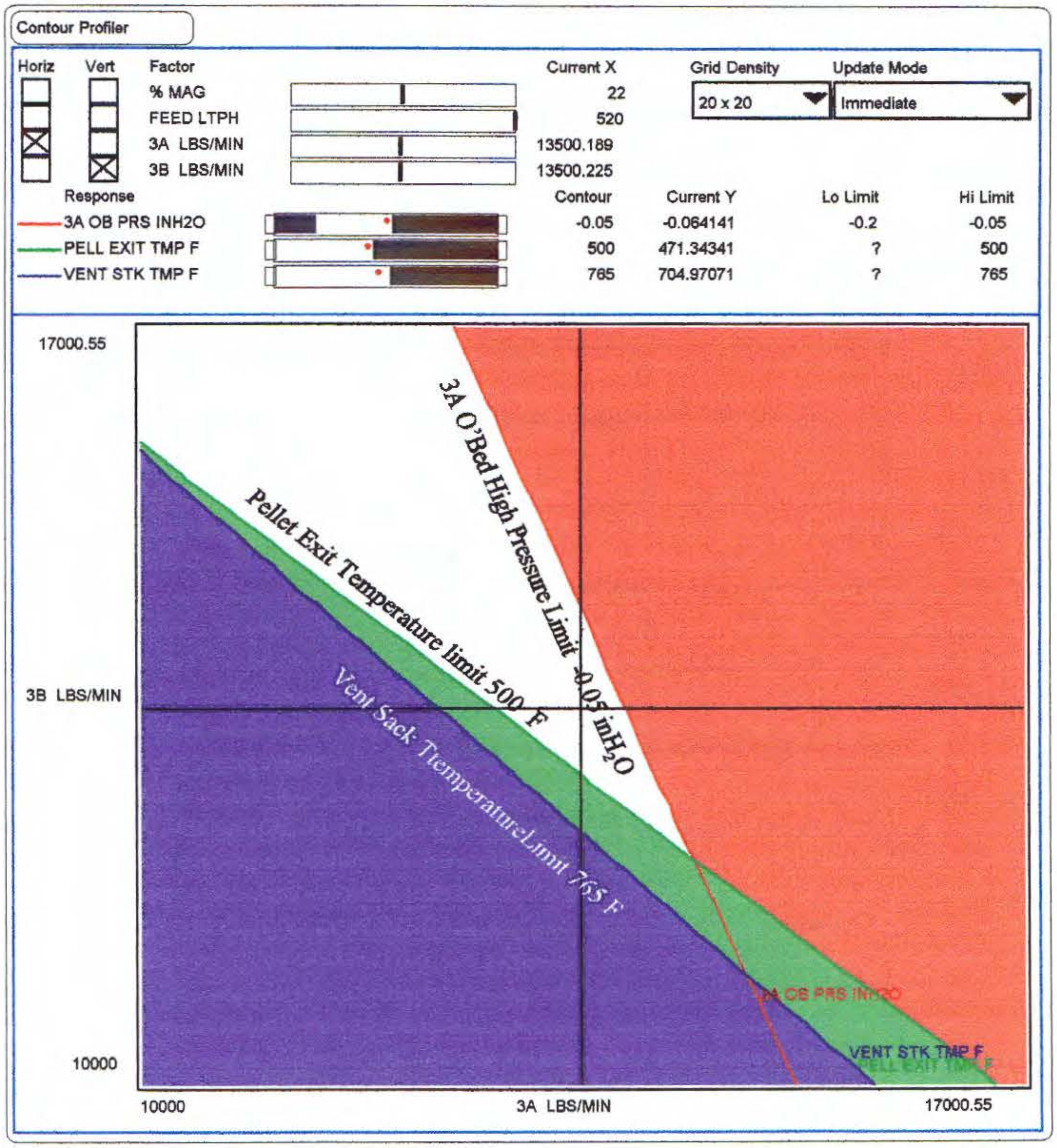


FIGURE 53

Third Parametric Series: Cooler with Over Bed Dividing Wall Offset One Wind Box - Linear Regression Model

Parameter Estimates

	3A OB PRS INH2O	T KILN LBS/MIN	A KILN TEMP F	T REC LBS/MIN	A REC TEMP F	PELL EXT TMP F	VENT STK TMP F
Intercept	-0.9513313	-1447.9381	2254.21845	735.940851	1512.44831	376.762343	628.633335
% MAG	0.00073129	2.10479894	5.08006602	-5.5628741	8.65558261	2.28543812	3.35103766
FEED LTPH	0.0002687	1.43599092	0.74806073	-1.4220514	3.4012627	2.27466569	2.67839069
3A LBS/MIN	0.00004742	0.54851581	-0.0326434	0.19004634	-0.1106692	-0.0384242	-0.0553459
3B LBS/MIN	0.00000541	0.07561741	-0.0033407	0.27576812	-0.030434	-0.045602	-0.0469163

Prediction Profile

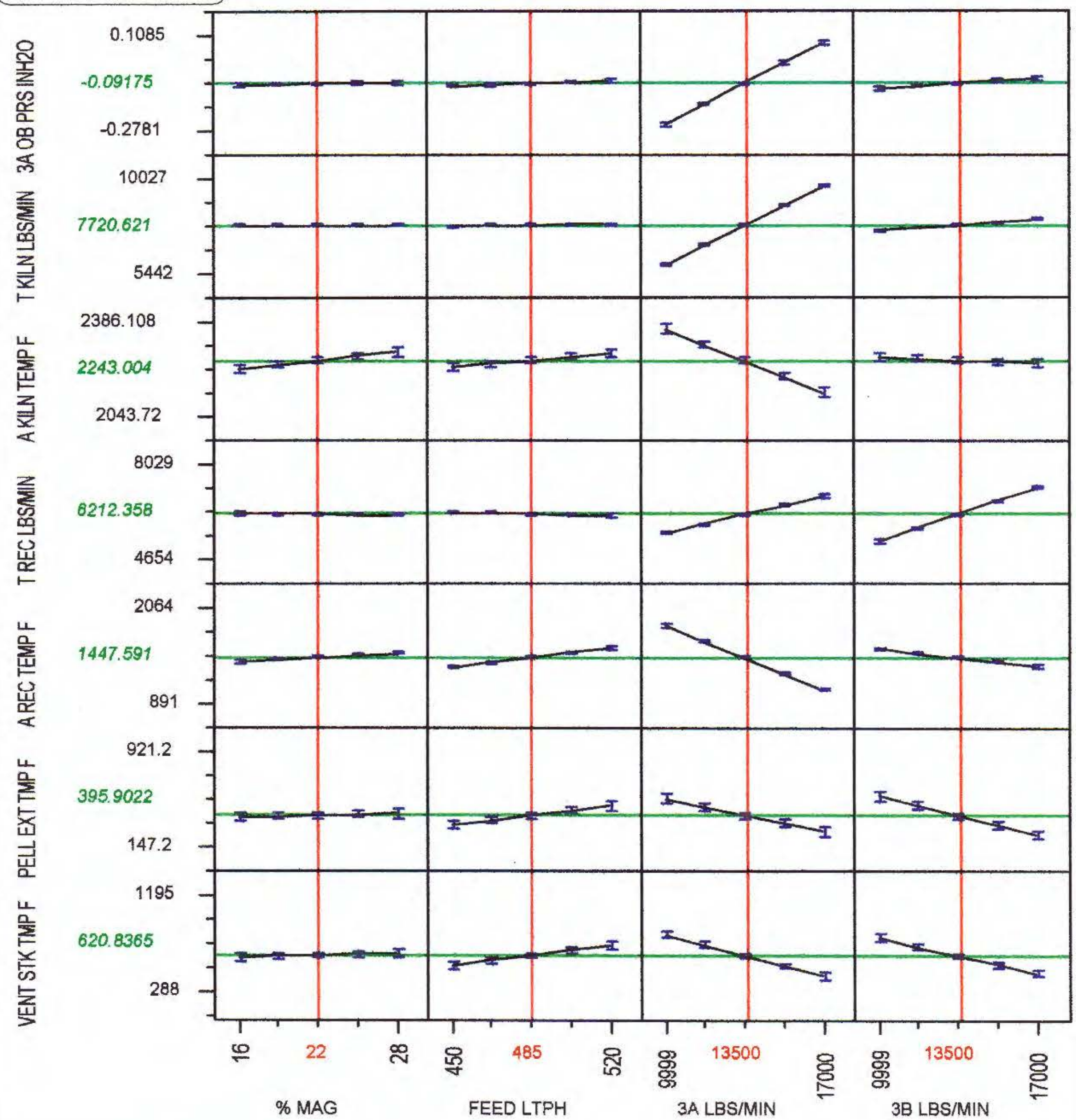
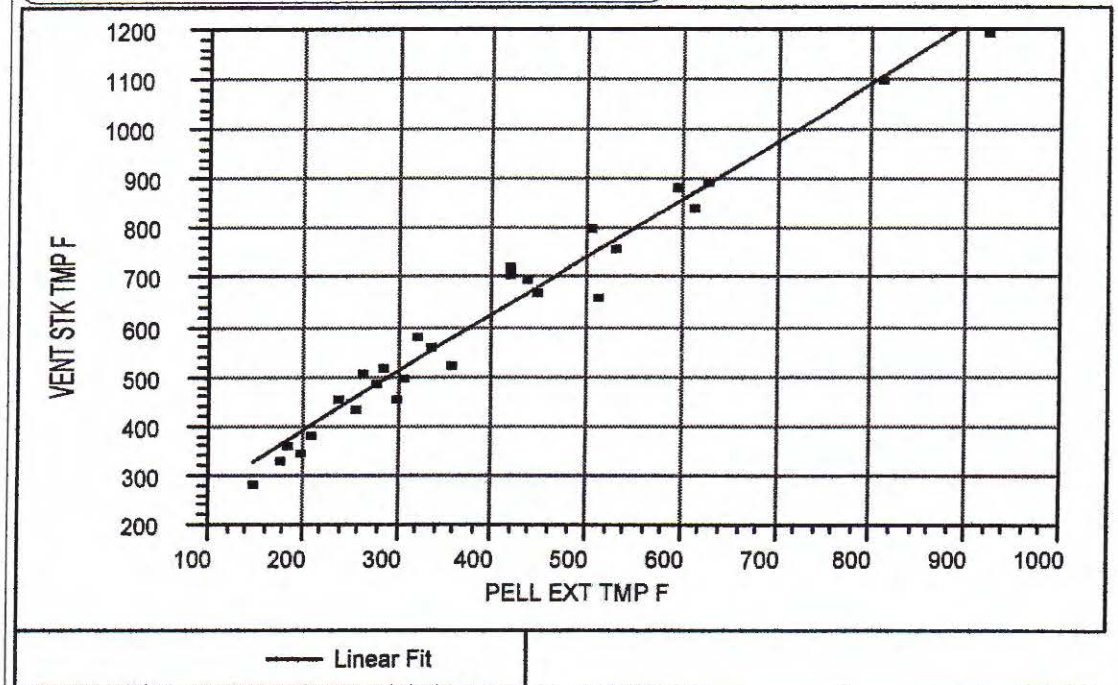


FIGURE 54

Third Parametric Series: Cooler with Over Bed Dividing Wall
Vent Stack vs Pellet Exit Temperature

VENT STK TMP F By PELL EXT TMP F



Linear Fit

VENT STK TMP F = 157.107 + 1.17132 PELL EXT TMP F

Summary of Fit

RSquare	0.968304
RSquare Adj	0.967036
Root Mean Square Error	42.00501
Mean of Response	620.8022
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1347569.2	1347569	763.7461
Error	25	44110.5	1764	Prob>F
C Total	26	1391679.8		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	157.10653	18.62455	8.44	<.0001
PELL EXT TMP F	1.1713211	0.042384	27.64	<.0001

FIGURE 55

Cooler with Over Bed Dividing Wall Operating Window

One Wind Box Offset

485 WLTPH Feed to Grate

High flow limited by maximum 3A overbed pressure of -0.05 in.H_2O.
Low fan flow limited by pellet exit temperature, or vent stack temperature and minimum 3A overbed pressure of -0.2 in. H_2O.

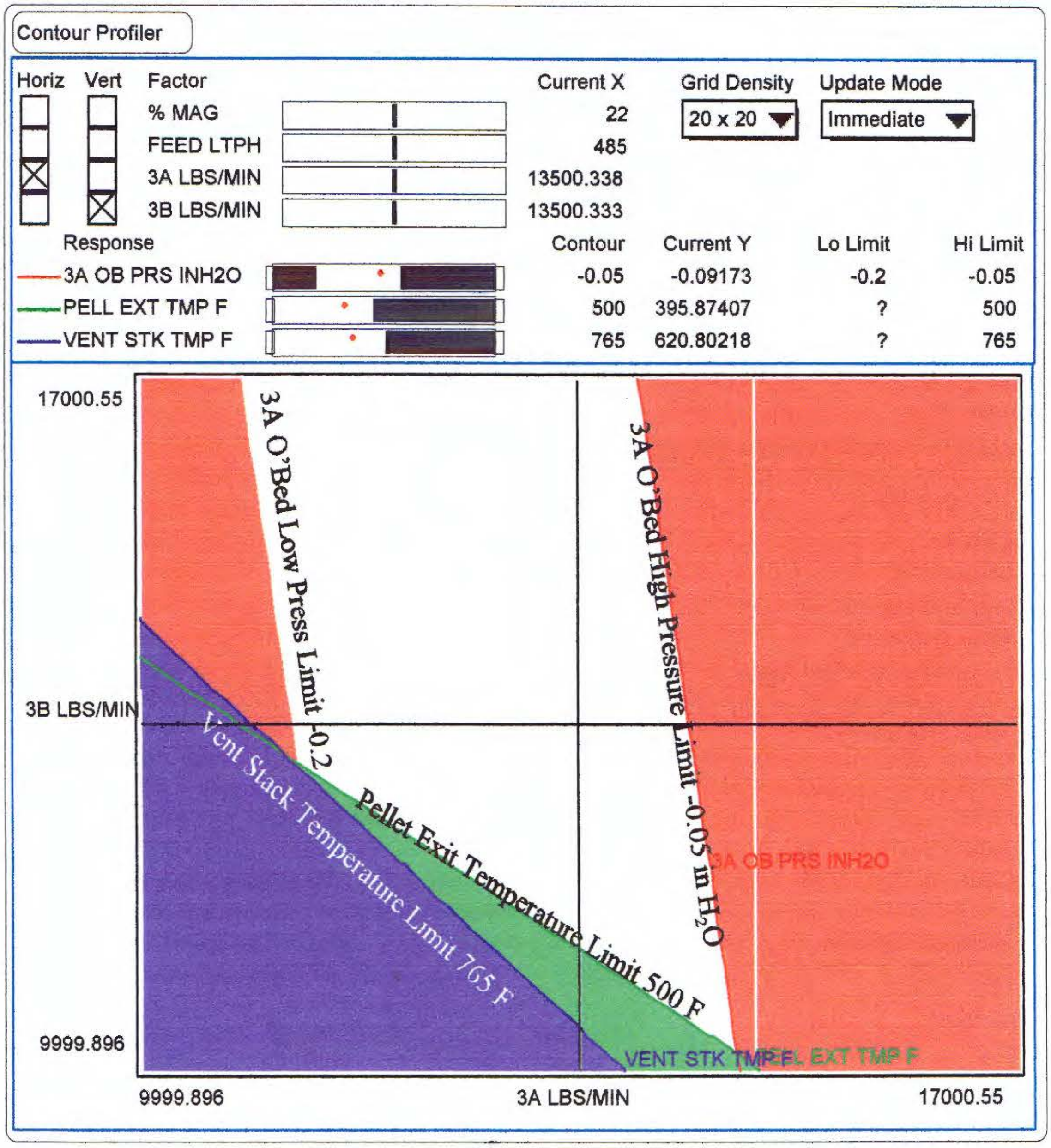


FIGURE 56

Cooler with Over Bed Dividing Wall
520 WLTPH Feed to Grate

High fan flow limited by maximum 3A overbed pressure of -0.05 in H_2O.
Low fan flow limited by pellet exit temperature, or vent stack temperature and low 3A overbed pressure of-0.2 in H_2O.

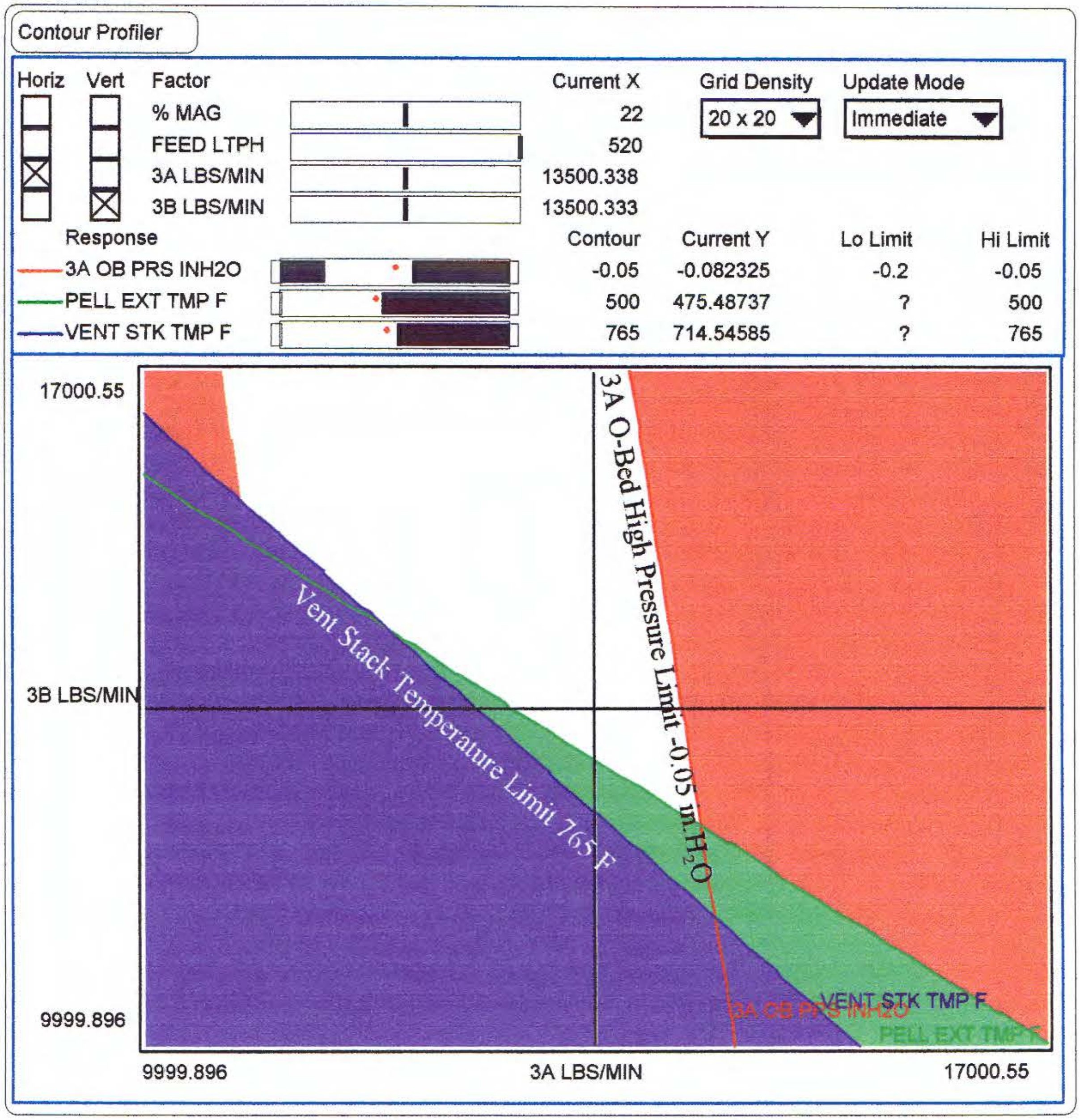


FIGURE 57

PHEAT FAN TEMP VS OPTIMIZED FEED RATE

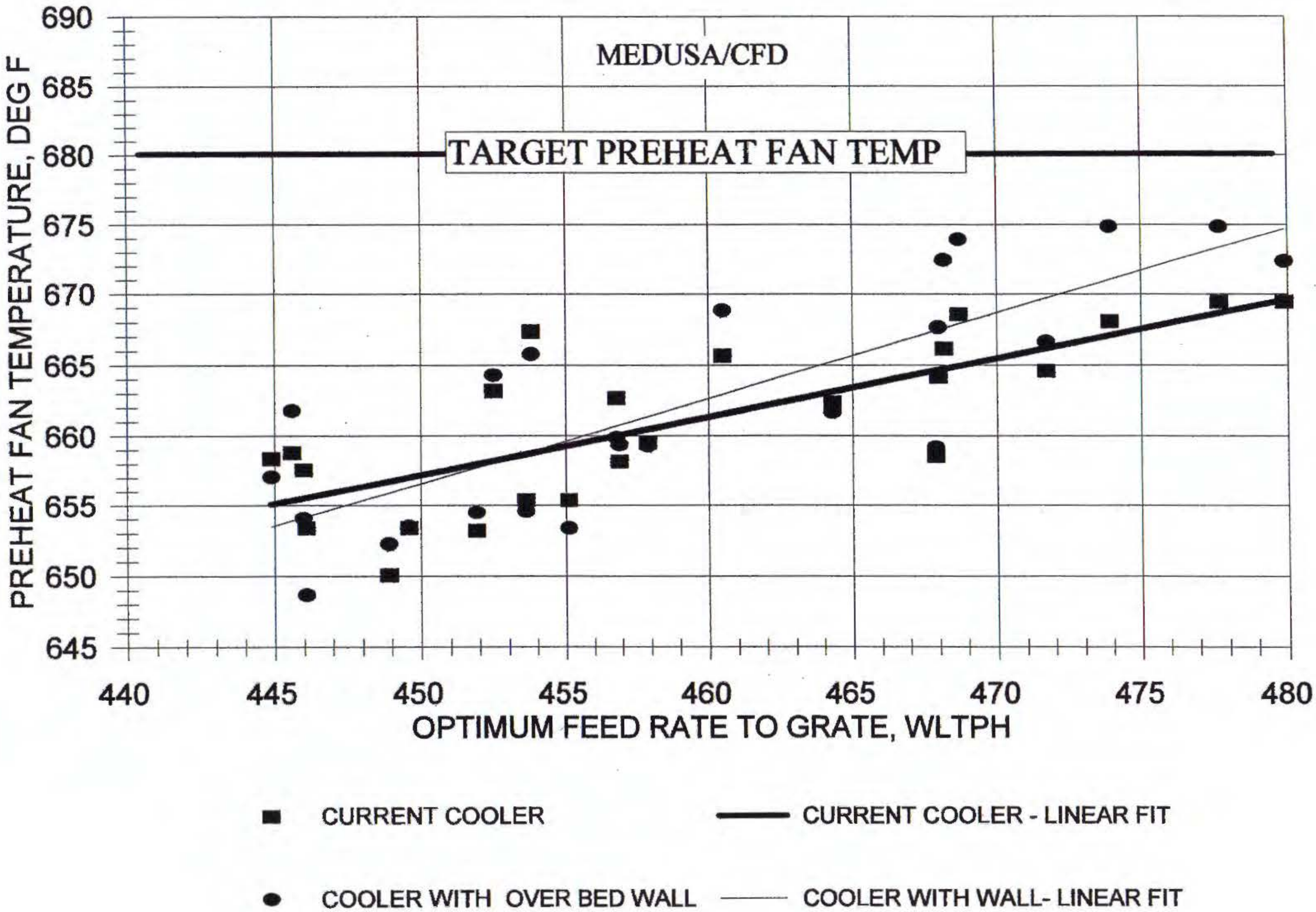


FIGURE 58

KILN DISCH TEMP VS OPTIMIZED FEED RATE

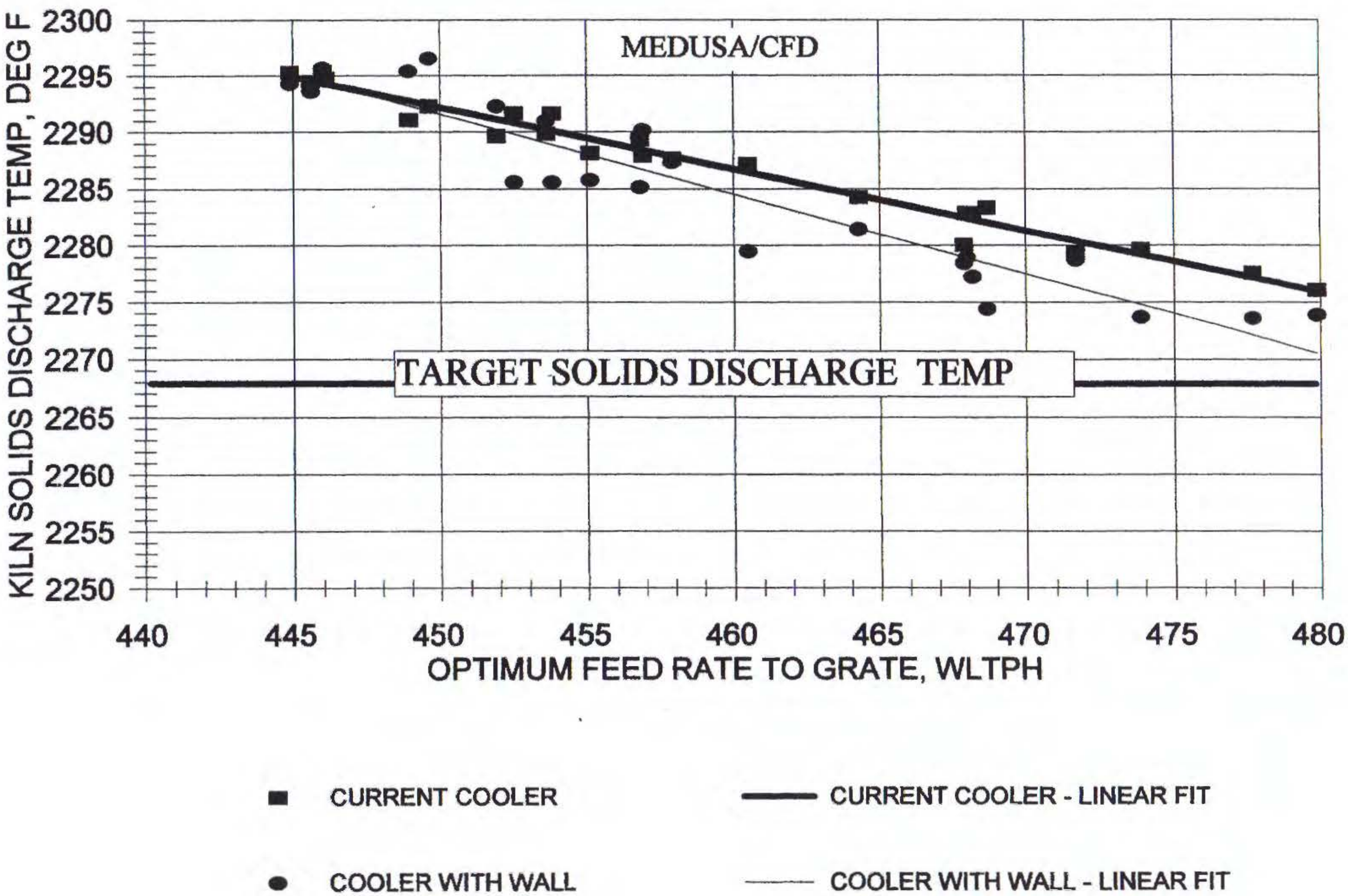


FIGURE 59
SIMULATION DEVIATION FROM TARGET VALUE

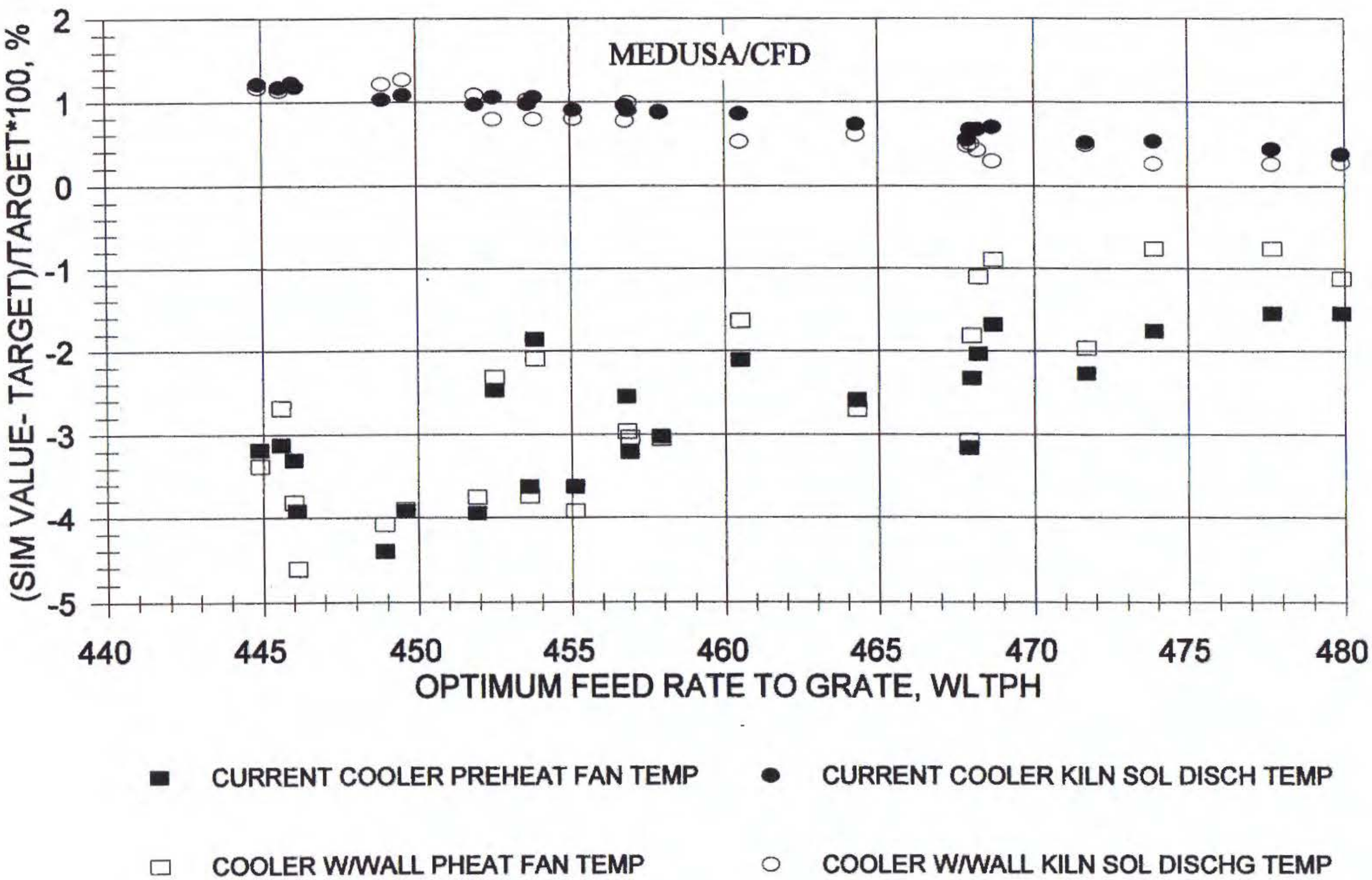


FIGURE 60

Current Cooler: 485 WLTPH Operating Window
MEDUSA/CFD: Surface Responses

LTPH

Summary of Fit

RSquare	0.980362
RSquare Adj	0.978491
Root Mean Square Error	1.563294
Mean of Response	459.1785
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	290.72799	6.208174	46.83	<.0001
3a flow	0.0057919	0.000297	19.49	<.0001
3b flow	0.0068937	0.000215	32.08	<.0001

Effect Test

Response Surface

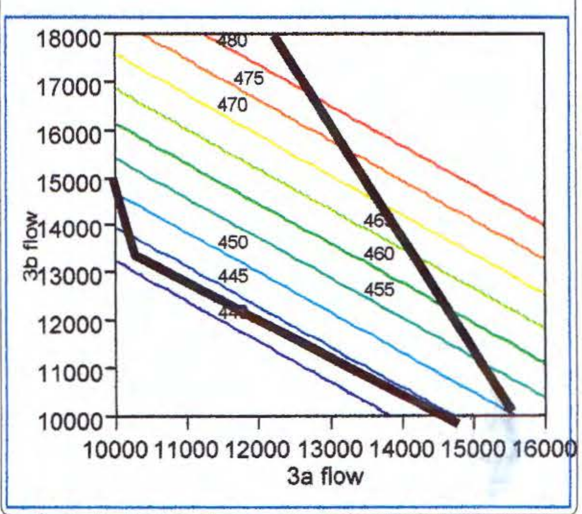
Coef	3a flow	3b flow	LTPH
3a flow	0	0	0.0057919
3b flow	?	0	0.0068937

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Contour Plots



FUEL MBTU/LT

Summary of Fit

RSquare	0.978622
RSquare Adj	0.976586
Root Mean Square Error	2120.93
Mean of Response	601907.4
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	821027.55	8422.664	97.48	<.0001
3a flow	-7.54379	0.40314	-18.71	<.0001
3b flow	-8.958573	0.291559	-30.73	<.0001

Effect Test

Response Surface

Coef	3a flow	3b flow	FUEL MBTU/LT
3a flow	0	0	-7.54379
3b flow	?	0	-8.958573

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Contour Plots

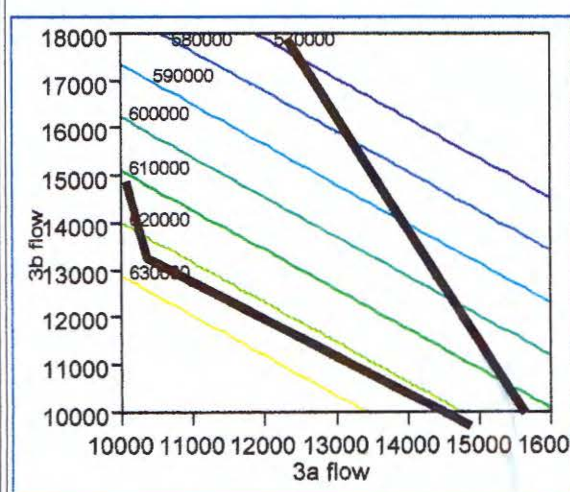


FIGURE 61

Cooler with Over Bed Dividing Wall: 485 WLTPH Operating Window
MEDUSA/CFD: Surface Response

LTPH

Summary of Fit

RSquare	0.965855
RSquare Adj	0.962603
Root Mean Square Error	1.78702
Mean of Response	451.5498
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	280.57454	7.09664	39.54	<.0001
3a flow	0.0081023	0.00034	23.85	<.0001
3b flow	0.0050021	0.000246	20.36	<.0001

Effect Test

Response Surface

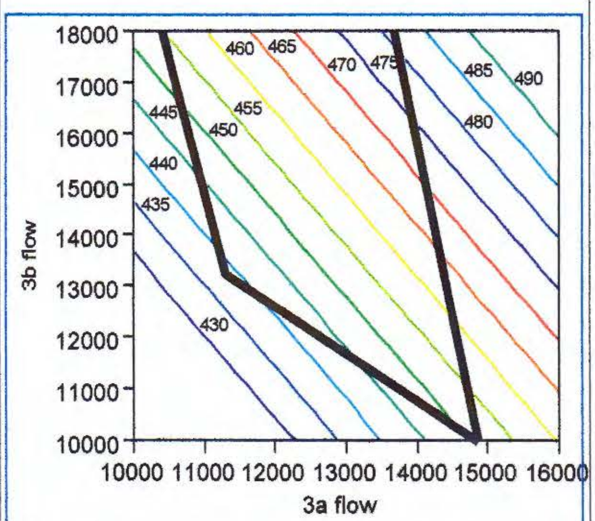
Coef	3a flow	3b flow	LTPH
3a flow	0	0	0.0081023
3b flow	?	0	0.0050021

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Contour Plots



FUEL MBTU/LT

Summary of Fit

RSquare	0.959964
RSquare Adj	0.956151
Root Mean Square Error	2649.923
Mean of Response	612010.9
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	845264.31	10523.41	80.32	<.0001
3a flow	-11.07309	0.50369	-21.98	<.0001
3b flow	-6.806684	0.364278	-18.69	<.0001

Effect Test

Response Surface

Coef	3a flow	3b flow	FUEL MBTU/LT
3a flow	0	0	-11.07309
3b flow	?	0	-6.806684

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Contour Plots

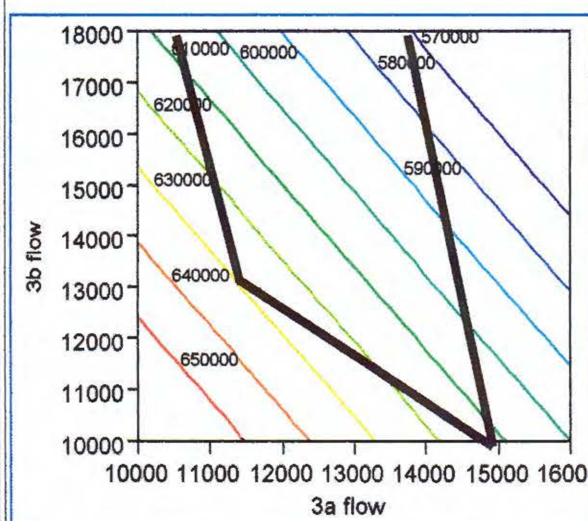
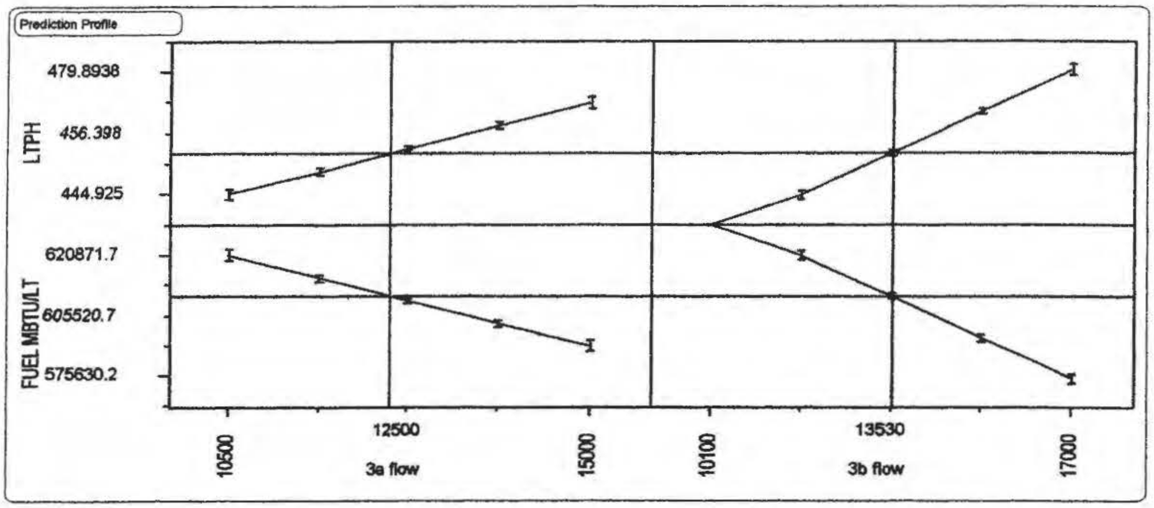


FIGURE 62
Current Cooler: 485 WLTPH Operating Window

A. Feed Rate and Fuel Prediction Profiles using Cooler Fan as Control Variables



B. Feed Rate and Fuel Prediction Profiles using Preheat Fan and Recoup Flow as Control Variables

LTPH

Summary of Fit

RSquare	0.97018
RSquare Adj	0.96734
Root Mean Square Error	1.926373
Mean of Response	459.1785
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	228.41838	11.28088	20.25	<.0001
PHEAT FLOW	-0.002319	0.000964	-2.40	0.0255
COOL REC FLOW	0.0421045	0.001821	23.12	<.0001

Effect Test

FUEL MBTU/LT

Summary of Fit

RSquare	0.96823
RSquare Adj	0.965205
Root Mean Square Error	2585.551
Mean of Response	601907.4
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	902147.78	15141.04	59.58	<.0001
PHEAT FLOW	2.9474543	1.294353	2.28	0.0334
COOL REC FLOW	-54.63798	2.444482	-22.35	<.0001

Effect Test

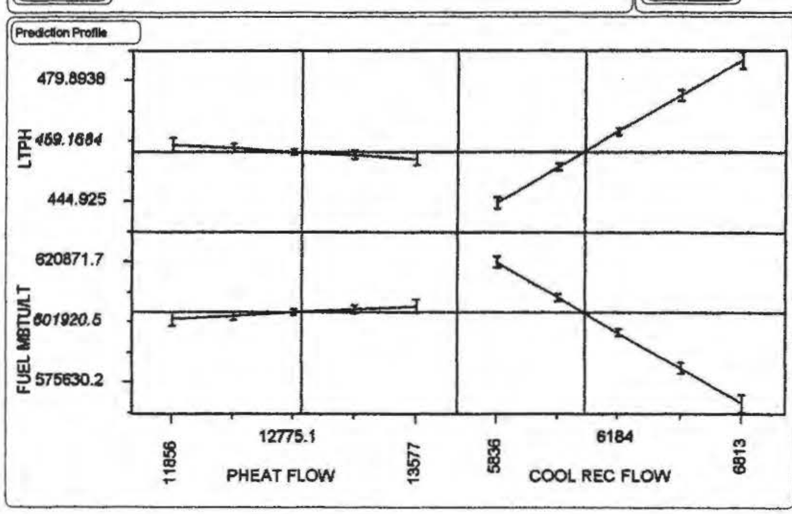
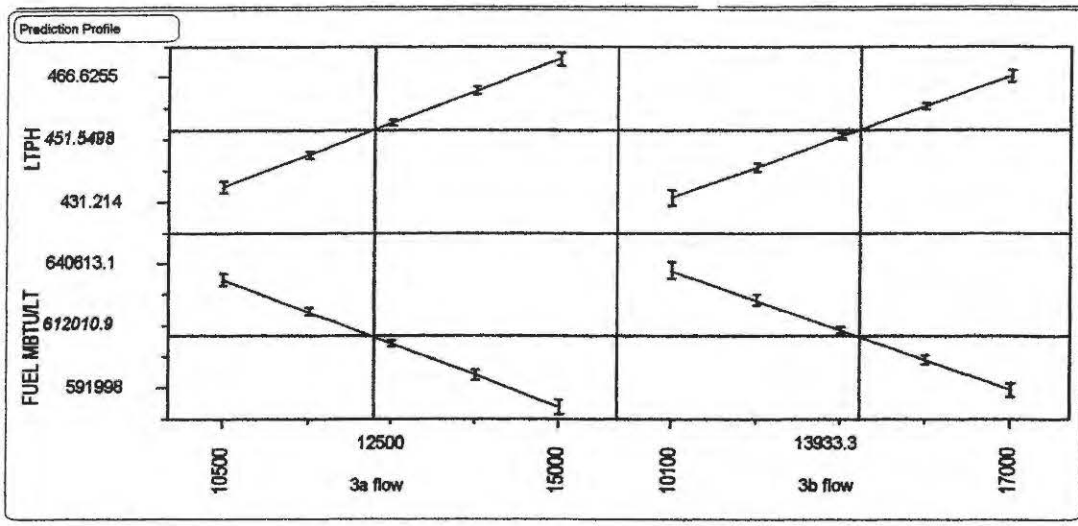


FIGURE 63

Cooler with Over Bed Dividing Wall: 485 WLTPH Operating Window

A. Feed Rate and Fuel Prediction Profiles using Cooler Fan Control Variables



B. Feed Rate and Fuel Prediction Profiles using Preheat Fan Flow and Total Recoup Flow

LTPH

Summary of Fit

RSquare	0.965038
RSquare Adj	0.961709
Root Mean Square Error	1.80827
Mean of Response	451.5498
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	233.67881	9.058812	25.80	<.0001
PHEAT FLOW	0.009683	0.000513	18.87	<.0001
COOL REC FLOW	0.0156338	0.00089	17.57	<.0001

Effect Test

FUEL MBTU/LT

Summary of Fit

RSquare	0.959066
RSquare Adj	0.955167
Root Mean Square Error	2679.49
Mean of Response	612010.9
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	909473.28	13423.33	67.75	<.0001
PHEAT FLOW	-13.27179	0.760535	-17.45	<.0001
COOL REC FLOW	-21.24185	1.318758	-16.11	<.0001

Effect Test

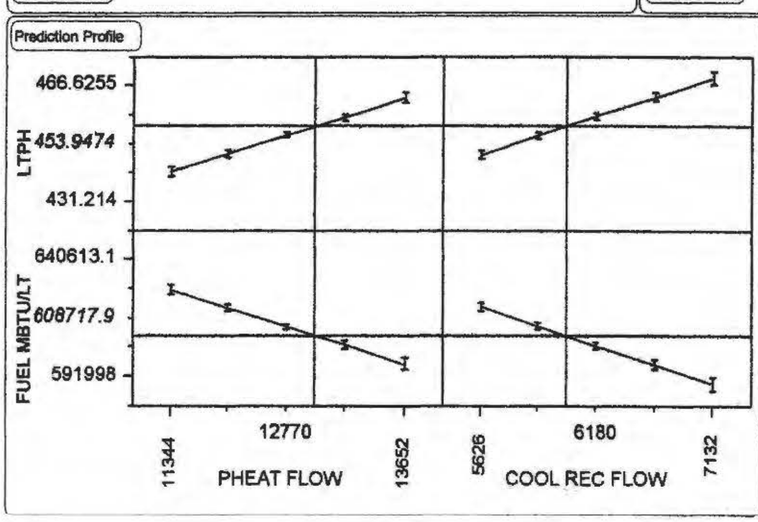


FIGURE 64

Current Cooler: MEDUSA/CFD

Response: FUEL MBTU/LT

Summary of Fit

RSquare	0.978622
RSquare Adj	0.976586
Root Mean Square Error	2120.93
Mean of Response	601907.4
Observations (or Sum Wgts)	24

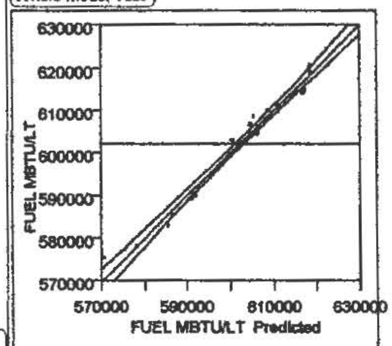
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	821027.55	8422.664	97.48	<.0001
3a flow	-7.54379	0.40314	-18.71	<.0001
3b flow	-8.958573	0.291559	-30.73	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
3a flow	1	1	1575142156	350.1606	<.0001
3b flow	1	1	4246964667	944.1177	<.0001

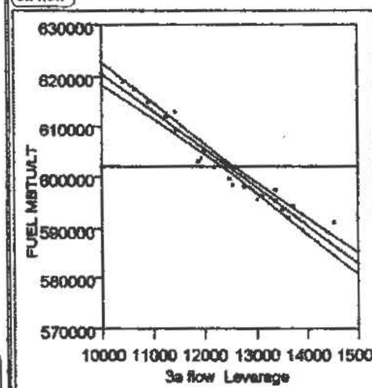
Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	4324424937	2.1622e9	480.6687
Error	21	94465193.9	4498343	Prob>F
C Total	23	4418890131		<.0001

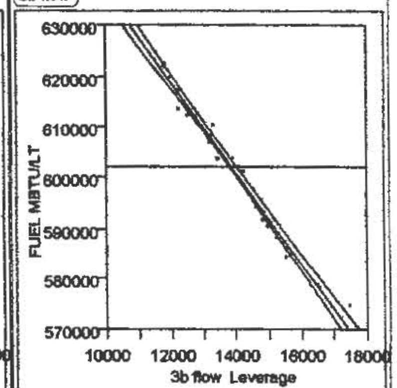
3a flow



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
1575142156	350.1606	1	<.0001

3b flow



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
4246964667	944.1177	1	<.0001

Cooler with Over Bed Dividing Wall: MEDUSA/CFD

Response: FUEL MBTU/LT

Summary of Fit

RSquare	0.959964
RSquare Adj	0.956151
Root Mean Square Error	2649.923
Mean of Response	612010.9
Observations (or Sum Wgts)	24

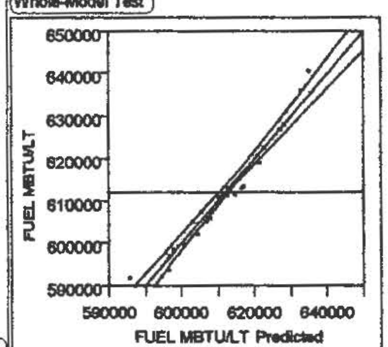
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	845264.31	10523.41	80.32	<.0001
3a flow	-11.07309	0.50369	-21.98	<.0001
3b flow	-6.806684	0.364278	-18.69	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
3a flow	1	1	3393735272	483.2940	<.0001
3b flow	1	1	2451726709	349.1447	<.0001

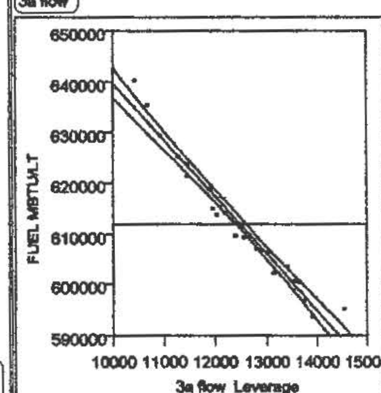
Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	3535810577	1.7679e9	251.7633
Error	21	147463953	7022093	Prob>F
C Total	23	3683274530		<.0001

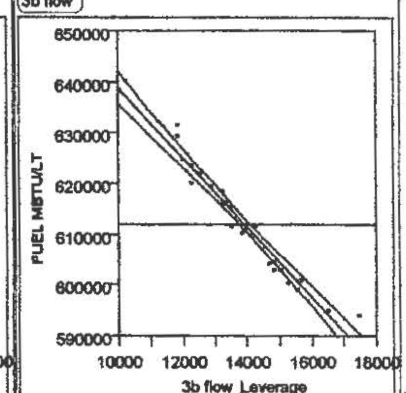
3a flow



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
3393735272	483.2940	1	<.0001

3b flow



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
2451726709	349.1447	1	<.0001

FIGURE 65

Current Cooler: MEDUSA/CFD

Response: LTPH

Summary of Fit

RSquare	0.980362
RSquare Adj	0.978491
Root Mean Square Error	1.563294
Mean of Response	459.1785
Observations (or Sum Wgts)	24

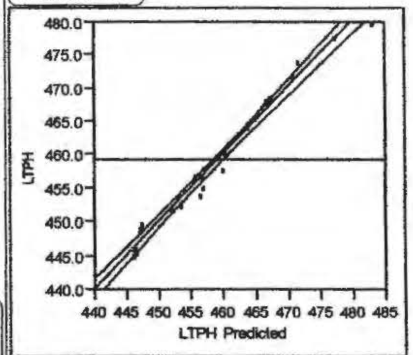
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	290.72799	6.208174	46.83	<.0001
3a flow	0.0057919	0.000297	19.49	<.0001
3b flow	0.0068937	0.000215	32.08	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
3a flow	1	1	928.4944	379.9251	<.0001
3b flow	1	1	2514.8024	1029.017	<.0001

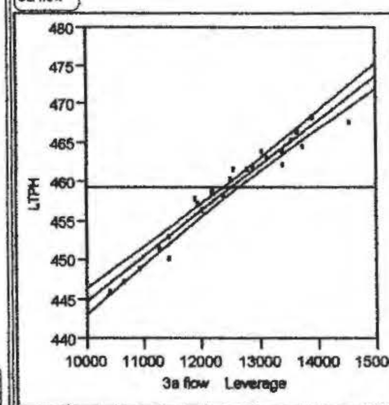
Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	2561.9975	1281.00	524.1642
Error	21	51.3217	2.44	Prob>F
C Total	23	2613.3191		<.0001

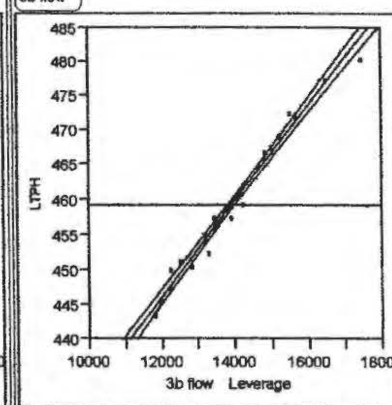
3a flow



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
928.49445	379.9251	1	<.0001

3b flow



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
2514.8024	1029.017	1	<.0001

Cooler with Dividing Wall: MEDUSA/CFD

Response: LTPH

Summary of Fit

RSquare	0.965855
RSquare Adj	0.962603
Root Mean Square Error	1.76702
Mean of Response	451.5498
Observations (or Sum Wgts)	24

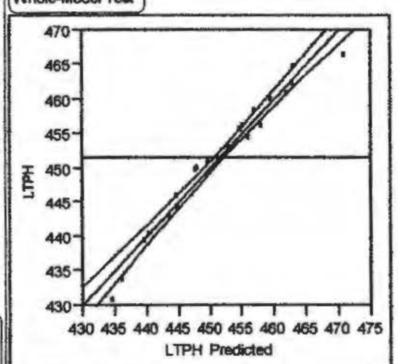
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	280.57454	7.09664	39.54	<.0001
3a flow	0.0081023	0.00034	23.85	<.0001
3b flow	0.0050021	0.000246	20.36	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
3a flow	1	1	1817.0172	568.9839	<.0001
3b flow	1	1	1324.0660	414.6203	<.0001

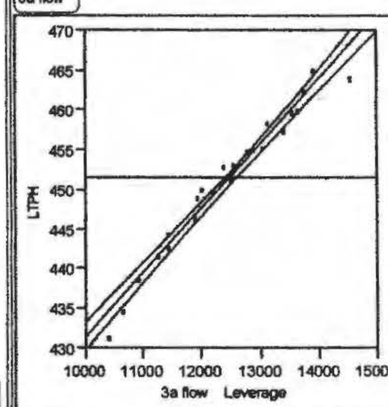
Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	1896.9950	948.498	297.0142
Error	21	67.0623	3.193	Prob>F
C Total	23	1964.0573		<.0001

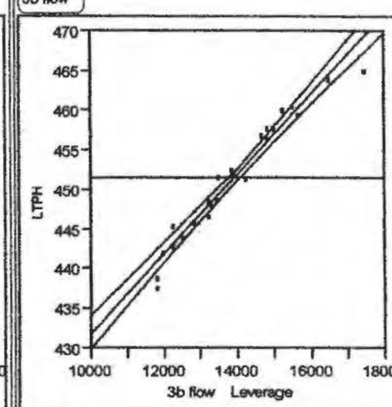
3a flow



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
1817.0172	568.9839	1	<.0001

3b flow



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
1324.0660	414.6203	1	<.0001

FIGURE 66

Current Cooler: MEDUSA/CFD:

Response: FUEL MBTU/LT

Summary of Fit

RSquare	0.96823
RSquare Adj	0.965205
Root Mean Square Error	2585.551
Mean of Response	601907.4
Observations (or Sum Wgts)	24

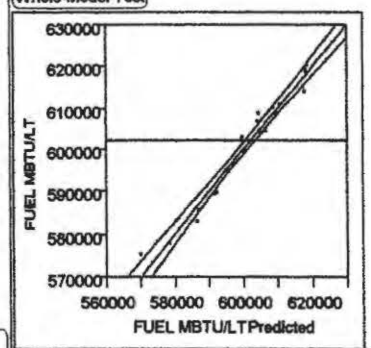
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	902147.78	15141.04	59.58	<.0001
PHEAT FLOW	2.9474543	1.294353	2.28	0.0334
COOL REC FLOW	-54.63798	2.444482	-22.35	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
PHEAT FLOW	1	1	34665318	5.1855	0.0334
COOL REC FLOW	1	1	3339810757	499.5921	<.0001

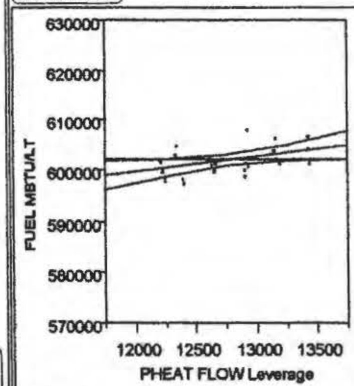
Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	4278503560	2.1393e9	320.0042
Error	21	140386571	6685075	Prob>F
C Total	23	4418890131		<.0001

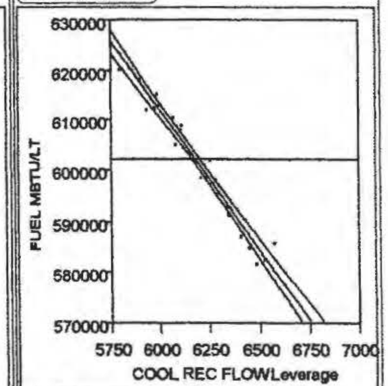
PHEAT FLOW



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
34665318	5.1855	1	0.0334

COOL REC FLOW



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
3339810757	499.5921	1	<.0001

Cooler with Over Bed Dividing Wall:

Response: FUEL MBTU/LT

Summary of Fit

RSquare	0.959066
RSquare Adj	0.955167
Root Mean Square Error	2679.49
Mean of Response	612010.9
Observations (or Sum Wgts)	24

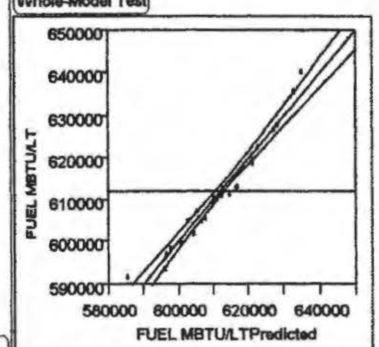
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	909473.28	13423.33	67.75	<.0001
PHEAT FLOW	-13.27179	0.760535	-17.45	<.0001
COOL REC FLOW	-21.24165	1.318758	-16.11	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
PHEAT FLOW	1	1	2186374786	304.5233	<.0001
COOL REC FLOW	1	1	1862766148	259.4503	<.0001

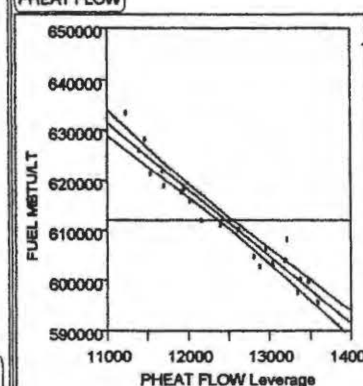
Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	3532501584	1.7663e9	246.0074
Error	21	150772946	7179664	Prob>F
C Total	23	3683274530		<.0001

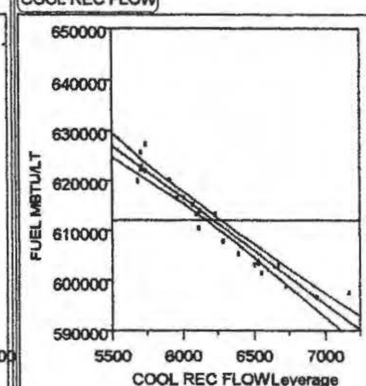
PHEAT FLOW



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
2186374786	304.5233	1	<.0001

COOL REC FLOW



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
1862766148	259.4503	1	<.0001

FIGURE 67

Current Cooler: Medusa/CFD

Response: LTPH

Summary of Fit

RSquare	0.97018
RSquare Adj	0.96734
Root Mean Square Error	1.926373
Mean of Response	459.1785
Observations (or Sum Wgts)	24

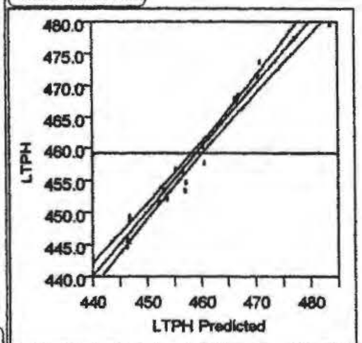
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	228.41838	11.28088	20.25	<.0001
PHEAT FLOW	-0.002319	0.000964	-2.40	0.0255
COOL REC FLOW	0.0421045	0.001821	23.12	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
PHEAT FLOW	1	1	21.4565	5.7820	0.0255
COOL REC FLOW	1	1	1983.3013	534.4511	<.0001

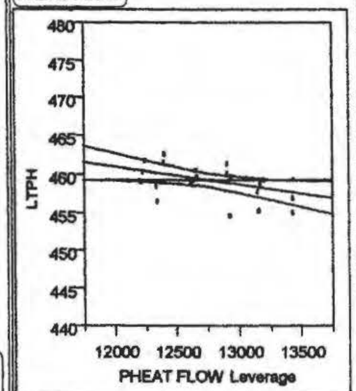
Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	2535.3900	1267.69	341.6128
Error	21	77.9292	3.71	Prob>F
C Total	23	2613.3191		<.0001

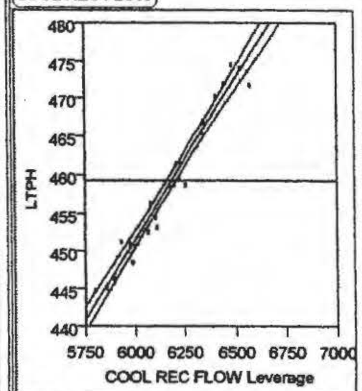
PHEAT FLOW



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
21.456530	5.7820	1	0.0255

COOL REC FLOW



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
1983.3013	534.4511	1	<.0001

Cooler with Over Bed Dividing Wall:

Response: LTPH

Summary of Fit

RSquare	0.965038
RSquare Adj	0.961709
Root Mean Square Error	1.80827
Mean of Response	451.5498
Observations (or Sum Wgts)	24

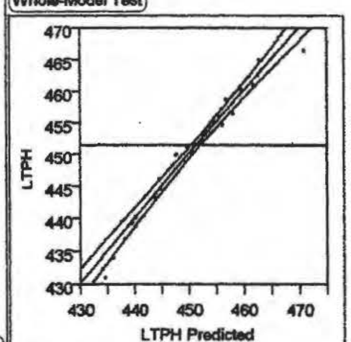
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	233.67881	9.058812	25.80	<.0001
PHEAT FLOW	0.009683	0.000513	18.87	<.0001
COOL REC FLOW	0.0156338	0.00089	17.57	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
PHEAT FLOW	1	1	1163.8167	355.9248	<.0001
COOL REC FLOW	1	1	1009.0269	308.5861	<.0001

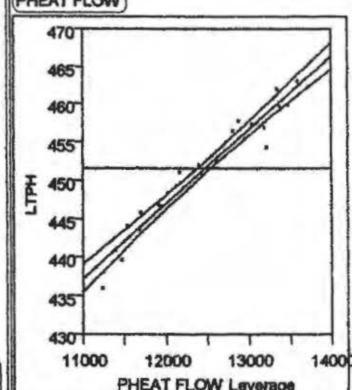
Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	1895.3907	947.695	289.8294
Error	21	68.6666	3.270	Prob>F
C Total	23	1964.0573		<.0001

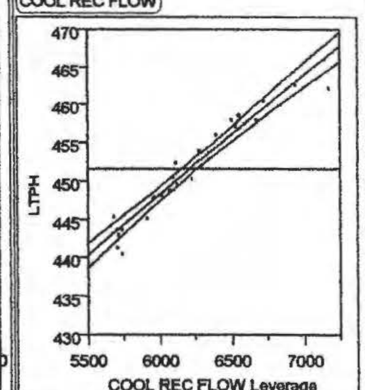
PHEAT FLOW



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
1163.8167	355.9248	1	<.0001

COOL REC FLOW



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
1009.0269	308.5861	1	<.0001

FIGURE 68

Current Cooler: MEDUSA/CFD:

Response: PHEAT FLOW

Summary of Fit

RSquare	0.664068
RSquare Adj	0.648799
Root Mean Square Error	294.6391
Mean of Response	12775.08
Observations (or Sum Wgts)	24

Lack of Fit

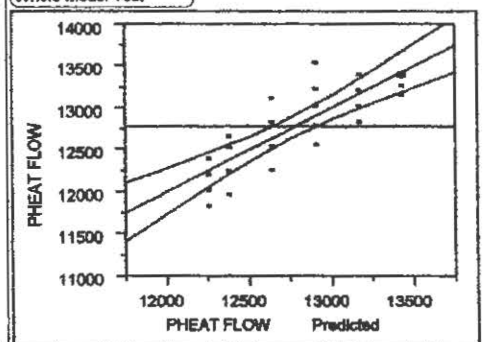
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	9500.0833	500.2426	18.99	<.0001
3a flow	0.262	0.039729	6.59	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
3a flow	1	1	3775420.0	43.4895	<.0001

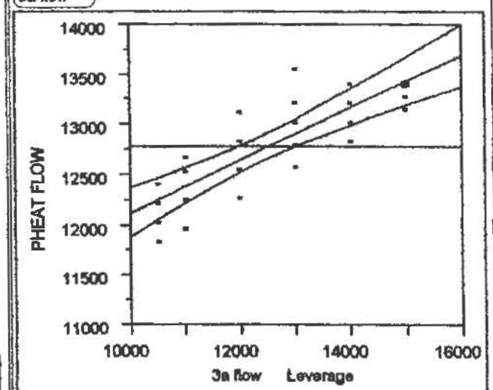
Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	3775420.0	3775420	43.4895
Error	22	1909867.8	86812	Prob>F
C Total	23	5685287.8		<.0001

3a flow



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
3775420.0	43.4895	1	<.0001

Cooler with Over Bed Dividing Wall: MEDUSA/CFD:

Response: PHEAT FLOW

Summary of Fit

RSquare	0.971361
RSquare Adj	0.97006
Root Mean Square Error	128.509
Mean of Response	12464.58
Observations (or Sum Wgts)	24

Lack of Fit

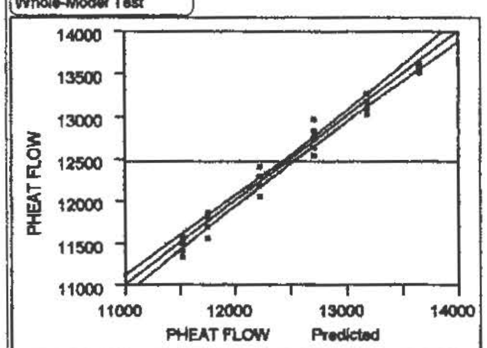
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	6547.7652	218.1845	30.01	<.0001
3a flow	0.4733455	0.017328	27.32	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
3a flow	1	1	12323076	746.1947	<.0001

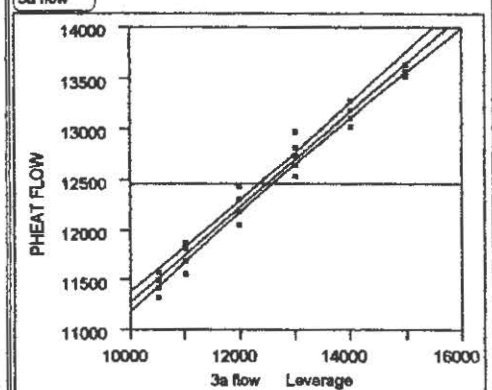
Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	12323076	12323076	746.1947
Error	22	363320	16514.56	Prob>F
C Total	23	12686396		<.0001

3a flow



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
12323076	746.1947	1	<.0001

FIGURE 69

Current Cooler: MEDUSA/CFD:

Response: PHEAT FLOW

Summary of Fit

RSquare	0.999979
RSquare Adj	0.999977
Root Mean Square Error	2.390289
Mean of Response	12775.08
Observations (or Sum Wgts)	24

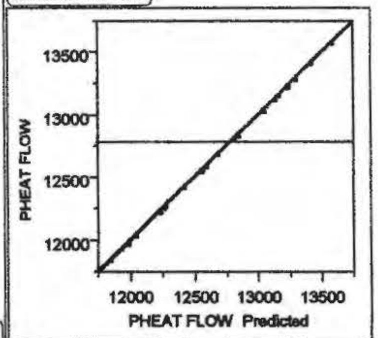
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4538.9592	9.492347	478.17	<.0001
3a flow	0.4471355	0.000454	984.14	<.0001
3b flow	0.1899711	0.000329	578.15	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
3a flow	1	1	5533741.1	968541.2	<.0001
3b flow	1	1	1909747.9	334253	<.0001

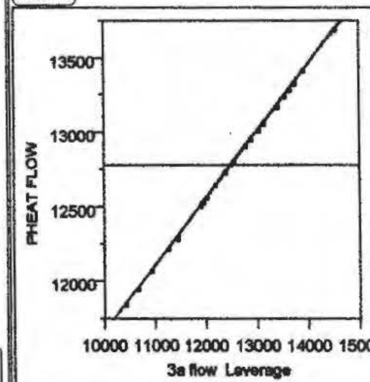
Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	5685167.9	2842584	497522.3
Error	21	120.0	6	Prob>F
C Total	23	5685287.8		<.0001

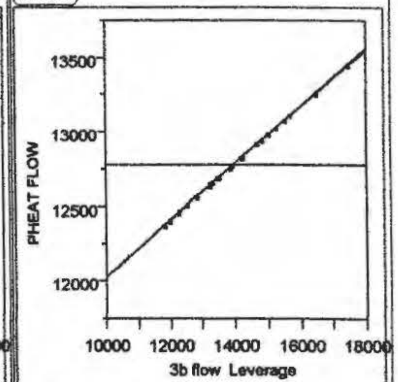
3a flow



Effect Test

Sum of Squares	F Ratio	DF	Prob>F
5533741.1	968541.2	1	<.0001

3b flow



Effect Test

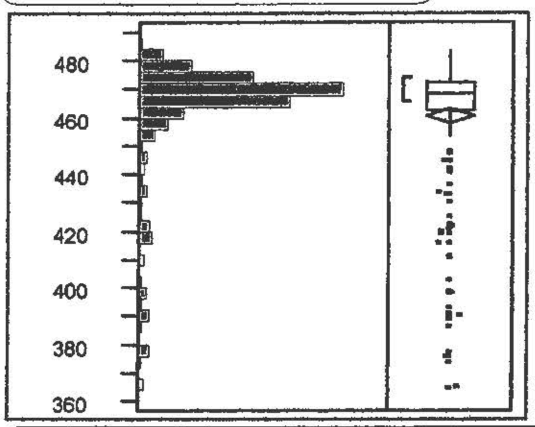
Sum of Squares	F Ratio	DF	Prob>F
1909747.9	334253	1	<.0001

FIGURE 70

Estimated Feed to Grate Before and After Data Deletion

Test 1 Unedited

EST FEED TO GRATE1



Quantiles

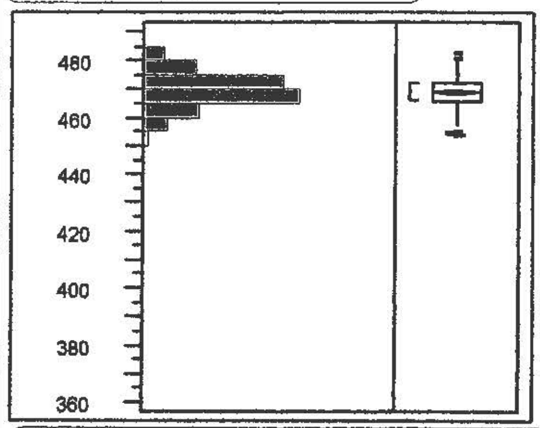
maximum	100.0%	484.00
	99.5%	483.28
	97.5%	480.30
	90.0%	476.20
quartile	75.0%	472.40
median	50.0%	468.70
quartile	25.0%	462.80
	10.0%	422.28
	2.5%	377.63
	0.5%	365.21
minimum	0.0%	365.10

Moments

Mean	460.7829
Std Dev	23.4989
Std Error Mean	1.4170
Upper 95% Mean	463.5726
Lower 95% Mean	457.9932
N	275.0000
Sum Weights	275.0000

Test 1 Edited

EST FEED TO GRATE



Quantiles

maximum	100.0%	484.00
	99.5%	483.93
	97.5%	480.71
	90.0%	476.60
quartile	75.0%	472.42
median	50.0%	469.45
quartile	25.0%	466.05
	10.0%	462.34
	2.5%	456.15
	0.5%	454.51
minimum	0.0%	454.50

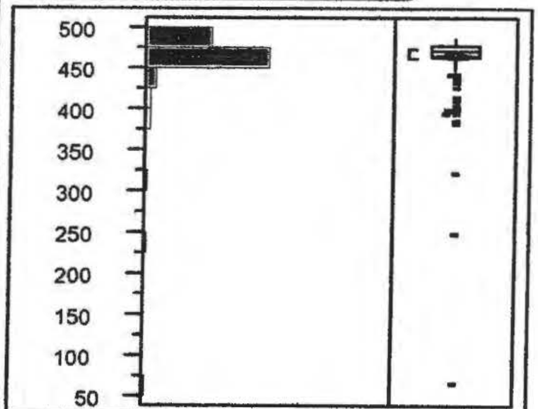
Moments

Mean	469.3078
Std Dev	5.5837
Std Error Mean	0.3890
Upper 95% Mean	470.0748
Lower 95% Mean	468.5407
N	206.0000
Sum Weights	206.0000

FIGURE 71
Estimated Feed to Grate Before and After Data Deletion

Test 2 Unedited

EST FEED TO GRATE



Quantiles

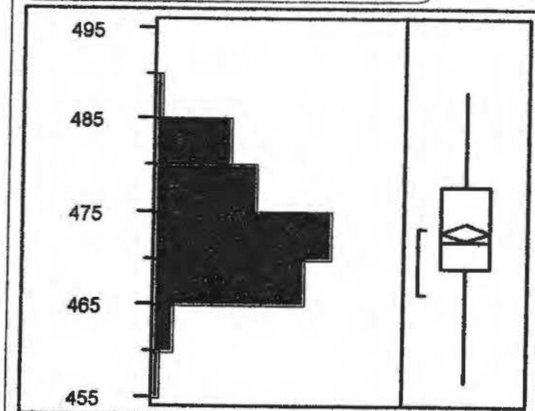
maximum	100.0%	488.10
	99.5%	487.51
	97.5%	485.44
	90.0%	482.48
quartile	75.0%	477.52
median	50.0%	470.80
quartile	25.0%	465.35
	10.0%	451.21
	2.5%	395.11
	0.5%	149.66
minimum	0.0%	67.30

Moments

Mean	465.1834
Std Dev	32.8194
Std Error Mean	1.9272
Upper 95% Mean	468.9767
Lower 95% Mean	461.3902
N	290.0000
Sum Weights	290.0000

Test 2 Edited

EST FEED TO GRATE



Quantiles

maximum	100.0%	488.10
	99.5%	488.10
	97.5%	483.95
	90.0%	481.70
quartile	75.0%	477.70
median	50.0%	471.90
quartile	25.0%	469.00
	10.0%	466.00
	2.5%	463.40
	0.5%	456.70
minimum	0.0%	456.70

Moments

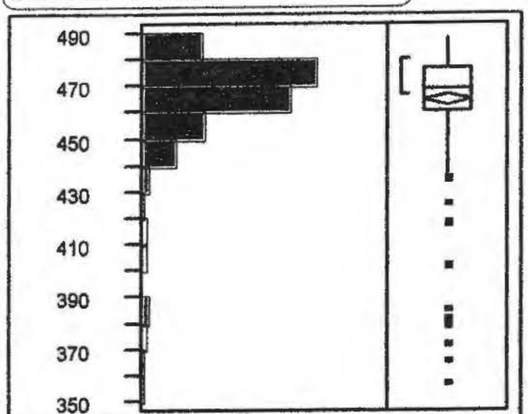
Mean	472.9637
Std Dev	5.8450
Std Error Mean	0.4369
Upper 95% Mean	473.8258
Lower 95% Mean	472.1016
N	179.0000
Sum Weights	179.0000

FIGURE 72

Estimated Feed to Grate Before and After Data Deletion

Test 3 Unedited

EST FEED TO GRATE



Quantiles

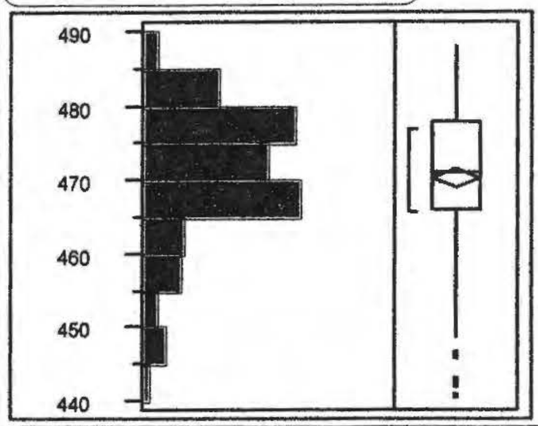
maximum	100.0%	488.20
	99.5%	487.71
	97.5%	484.98
	90.0%	480.40
quartile	75.0%	476.80
median	50.0%	469.00
quartile	25.0%	460.63
	10.0%	447.08
	2.5%	389.17
	0.5%	361.15
minimum	0.0%	357.10

Moments

Mean	465.0316
Std Dev	19.4261
Std Error Mean	1.1447
Upper 95% Mean	467.2847
Lower 95% Mean	462.7785
N	288.0000
Sum Weights	288.0000

Test 3 Edited

EST FEED TO GRATE



Quantiles

maximum	100.0%	488.20
	99.5%	488.06
	97.5%	485.11
	90.0%	480.85
quartile	75.0%	478.08
median	50.0%	471.20
quartile	25.0%	466.13
	10.0%	455.95
	2.5%	447.89
	0.5%	441.09
minimum	0.0%	440.90

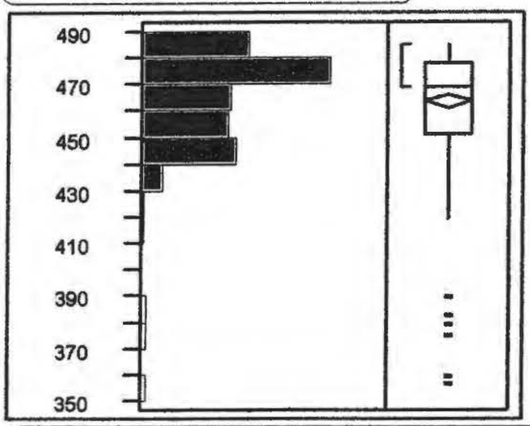
Moments

Mean	470.4902
Std Dev	9.5197
Std Error Mean	0.6361
Upper 95% Mean	471.7437
Lower 95% Mean	469.2367
N	224.0000
Sum Weights	224.0000

FIGURE 73
Estimated Feed to Grate Before and After Data Deletion

Test 4 Unedited

EST FEED TO GRATE



Quantiles

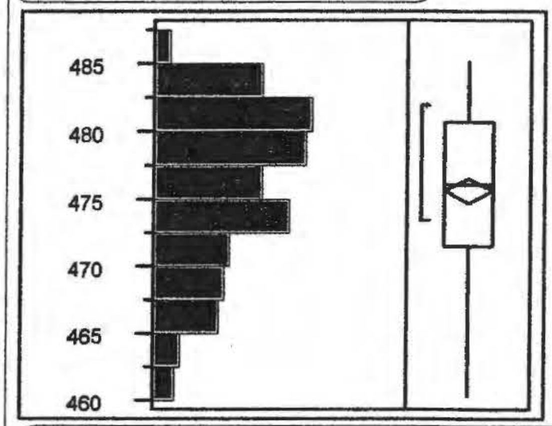
maximum	100.0%	485.20
	99.5%	485.15
	97.5%	484.60
	90.0%	482.00
quartile	75.0%	478.10
median	50.0%	469.20
quartile	25.0%	451.45
	10.0%	443.50
	2.5%	421.18
	0.5%	358.08
minimum	0.0%	357.00

Moments

Mean	463.9135
Std Dev	19.4702
Std Error Mean	1.1453
Upper 95% Mean	466.1678
Lower 95% Mean	461.6592
N	289.0000
Sum Weights	289.0000

Test 4 Edited

EST FEED TO GRATE



Quantiles

maximum	100.0%	485.20
	99.5%	485.20
	97.5%	484.90
	90.0%	483.32
quartile	75.0%	480.80
median	50.0%	476.20
quartile	25.0%	471.60
	10.0%	467.04
	2.5%	462.27
	0.5%	460.40
minimum	0.0%	460.40

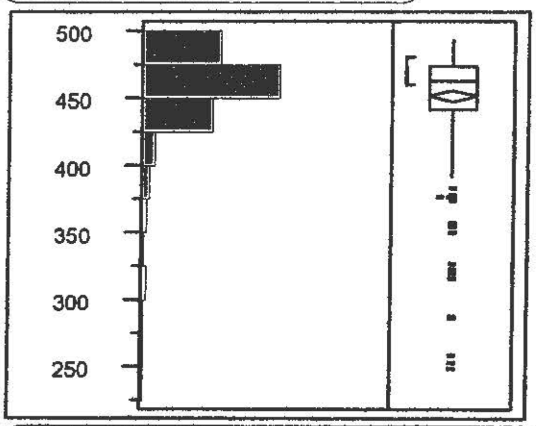
Moments

Mean	475.6977
Std Dev	6.1862
Std Error Mean	0.4703
Upper 95% Mean	476.6261
Lower 95% Mean	474.7693
N	173.0000
Sum Weights	173.0000

FIGURE 74
Estimated Feed to Grate Before and After Data Deletion

Test 5 Unedited

EST FEED TO GRATE



Quantiles

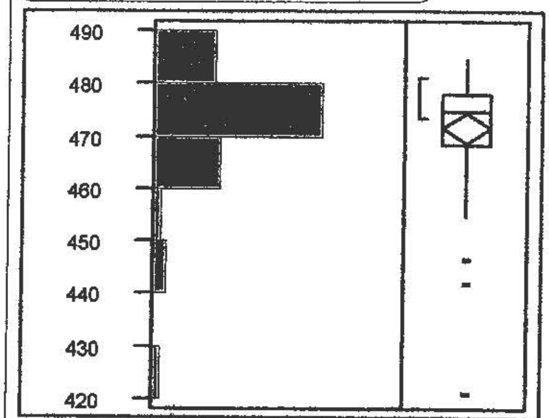
maximum	100.0%	494.00
	99.5%	493.28
	97.5%	485.68
	90.0%	480.40
quartile	75.0%	474.90
median	50.0%	463.70
quartile	25.0%	441.90
	10.0%	423.90
	2.5%	321.20
	0.5%	250.98
minimum	0.0%	249.50

Moments

Mean	452.2758
Std Dev	38.3457
Std Error Mean	2.2556
Upper 95% Mean	456.7154
Lower 95% Mean	447.8361
N	289.0000
Sum Weights	289.0000

Test 5 Edited

EST FEED TO GRATE



Quantiles

maximum	100.0%	484.70
	99.5%	484.70
	97.5%	484.04
	90.0%	481.32
quartile	75.0%	478.30
median	50.0%	474.85
quartile	25.0%	468.58
	10.0%	461.13
	2.5%	431.12
	0.5%	421.10
minimum	0.0%	421.10

Moments

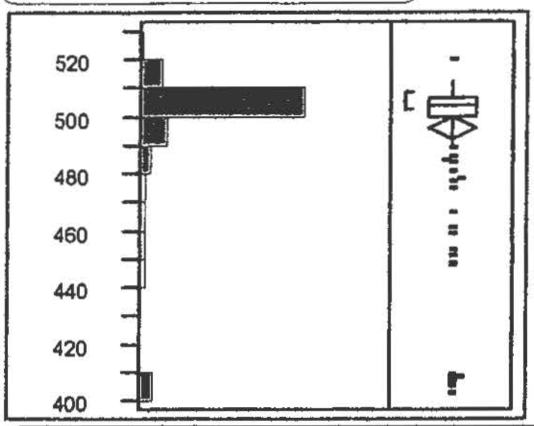
Mean	471.8259
Std Dev	10.8552
Std Error Mean	1.4254
Upper 95% Mean	474.6801
Lower 95% Mean	468.9716
N	58.0000
Sum Weights	58.0000

FIGURE 77

Estimated Feed to Grate Before and After Data Deletion

Test 9 Unedited

EST FEED TO GRATE



Quantiles

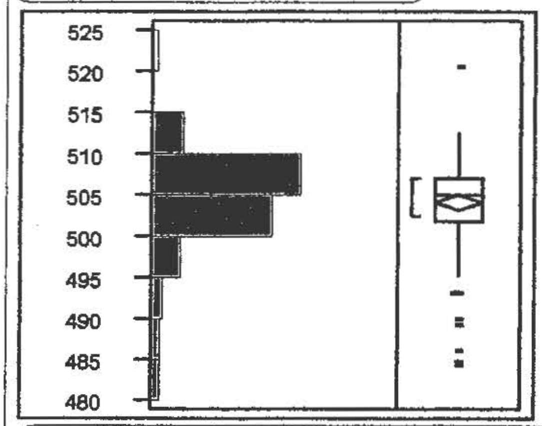
maximum	100.0%	520.66
	99.5%	520.66
	97.5%	511.87
	90.0%	509.21
quartile	75.0%	506.80
median	50.0%	504.37
quartile	25.0%	500.00
	10.0%	471.13
	2.5%	407.30
	0.5%	402.70
minimum	0.0%	402.70

Moments

Mean	496.3706
Std Dev	23.6618
Std Error Mean	1.9718
Upper 95% Mean	500.2683
Lower 95% Mean	492.4729
N	144.0000
Sum Weights	144.0000

Test 9 Edited

EST FEED TO GRATE



Quantiles

maximum	100.0%	520.66
	99.5%	520.66
	97.5%	512.05
	90.0%	509.94
quartile	75.0%	507.09
median	50.0%	505.11
quartile	25.0%	501.85
	10.0%	499.35
	2.5%	486.73
	0.5%	484.52
minimum	0.0%	484.52

Moments

Mean	504.2528
Std Dev	5.2844
Std Error Mean	0.4726
Upper 95% Mean	505.1883
Lower 95% Mean	503.3173
N	125.0000
Sum Weights	125.0000

FIGURE 78

Plant Validation Tests
Tests 1-6 Feb 7-19, 2000 - 48 hrs/test
Tests 7-9 Mar 3-6, 2000 - 24 hrs/test
5 Test Regions

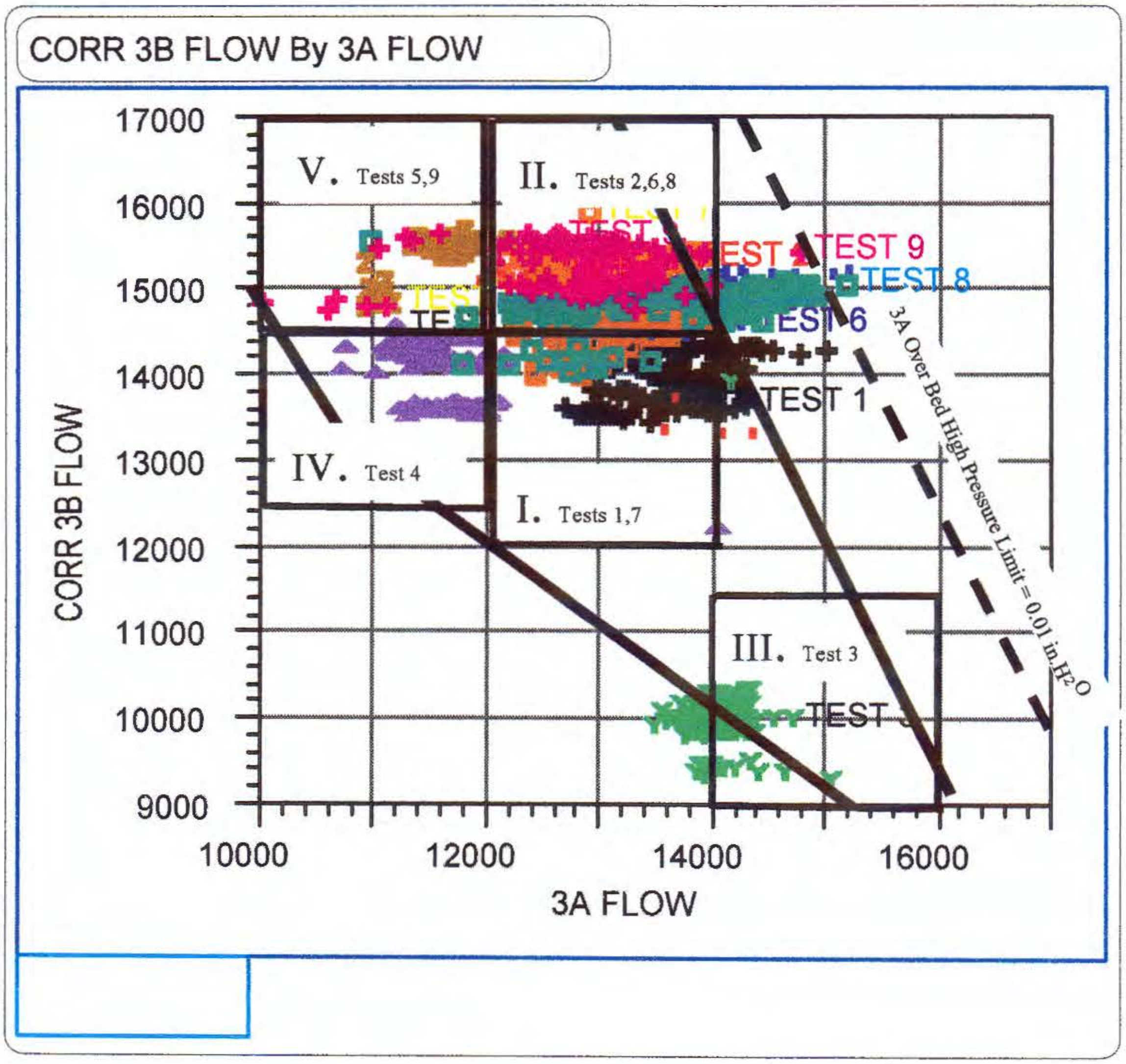
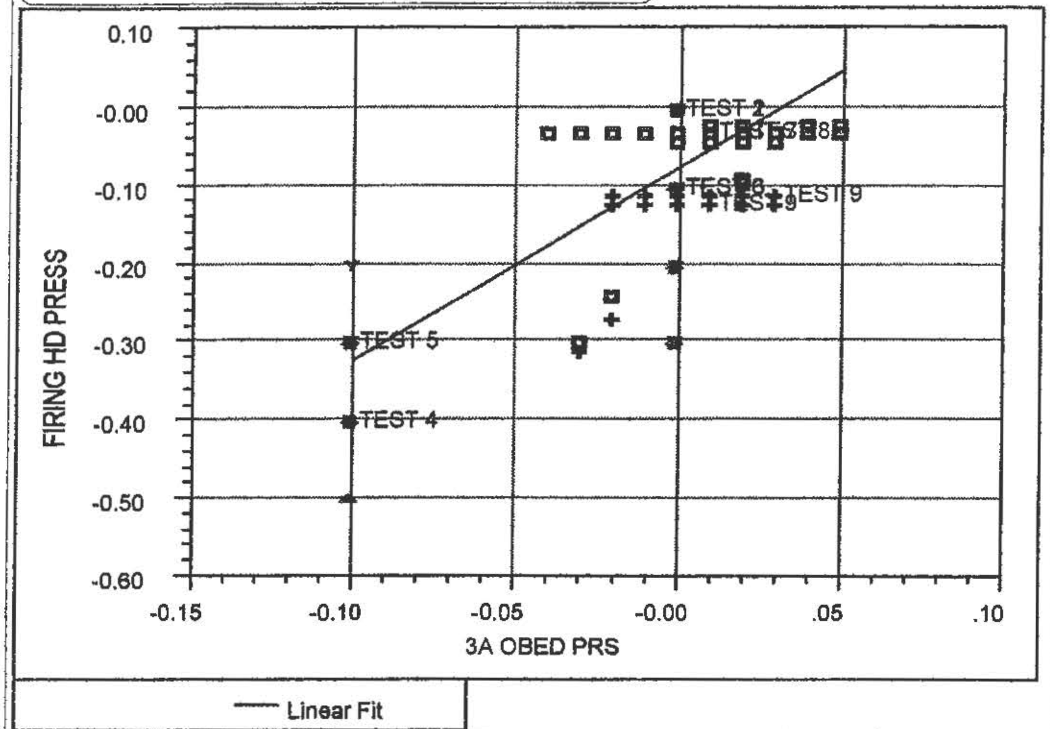


FIGURE 79

Plant Data:
Correlation Between Primary Cooling Over Bed Pressure and Firing Hood Pressure

FIRING HD PRESS By 3A OBED PRS



Linear Fit

FIRING HD PRESS = -0.0769 + 2.46888 3A OBED PRS

Summary of Fit

RSquare	0.50919
RSquare Adj	0.508838
Root Mean Square Error	0.07974
Mean of Response	-0.09278
Observations (or Sum Wgts)	1395

Analysis of Variance

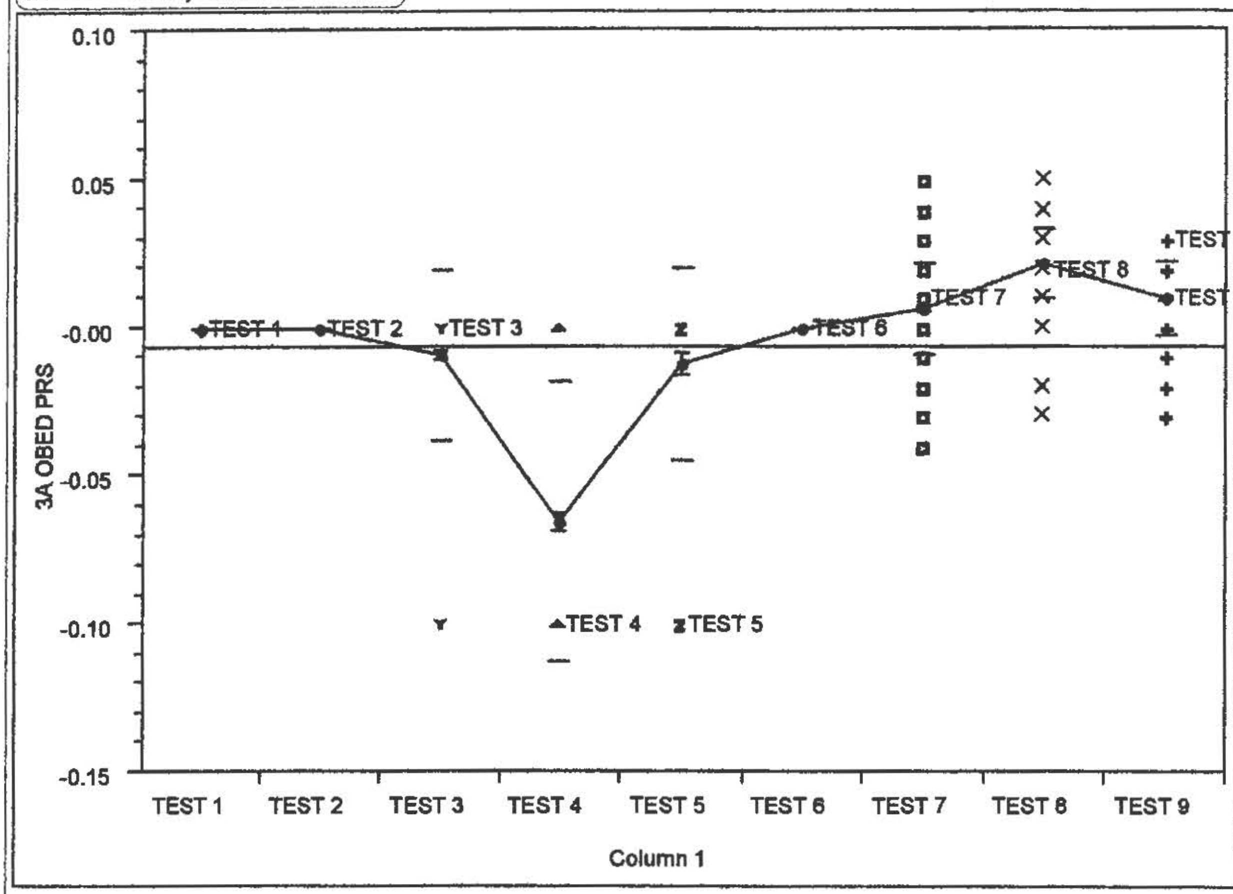
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	9.189160	9.18916	1445.168
Error	1393	8.857448	0.00636	Prob>F
C Total	1394	18.046608		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.076871	0.002176	-35.33	<.0001
3A OBED PRS	2.4688799	0.064944	38.02	<.0001

FIGURE 80

Plant Data: Primary Cooling Over Bed Pressure Statistics by Test



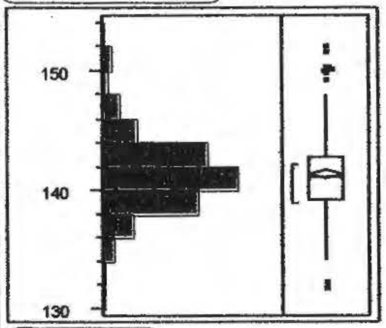
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	0.000000	0.000000	0.00000
TEST 2	179	0.000000	0.000000	0.00000
TEST 3	224	-0.00938	0.029213	0.00195
TEST 4	173	-0.06532	0.047734	0.00363
TEST 5	58	-0.01207	0.032861	0.00431
TEST 6	154	0.000000	0.000000	0.00000
TEST 7	142	0.006761	0.015599	0.00131
TEST 8	134	0.021791	0.011880	0.00103
TEST 9	125	0.009840	0.012762	0.00114

FIGURE 81

Plant Data: Test 1 - Unedited

1A/B AVE AMPS

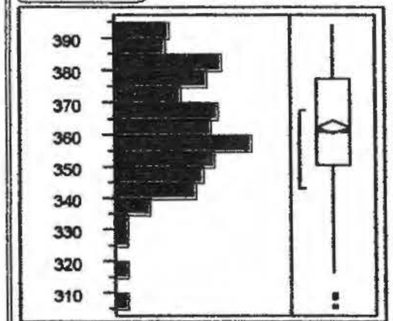


Quantiles

Moments

Mean	141.4084
Std Dev	3.0306
Std Error Mean	0.1828
Upper 95% Mean	141.7681
Lower 95% Mean	141.0486
N	275.0000
Sum Weights	275.0000

2A AMPS

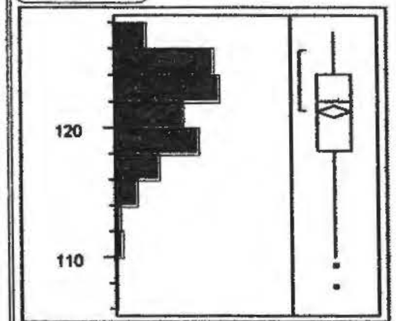


Quantiles

Moments

Mean	362.6691
Std Dev	17.4512
Std Error Mean	1.0523
Upper 95% Mean	364.7408
Lower 95% Mean	360.5973
N	275.0000
Sum Weights	275.0000

3A AMPS

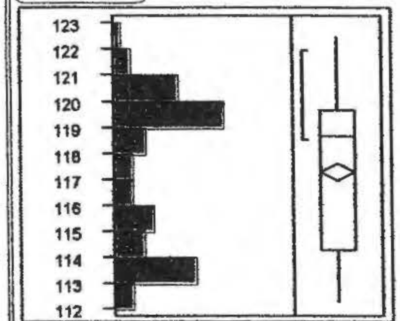


Quantiles

Moments

Mean	121.2367
Std Dev	3.7053
Std Error Mean	0.2234
Upper 95% Mean	121.6766
Lower 95% Mean	120.7968
N	275.0000
Sum Weights	275.0000

3B AMPS

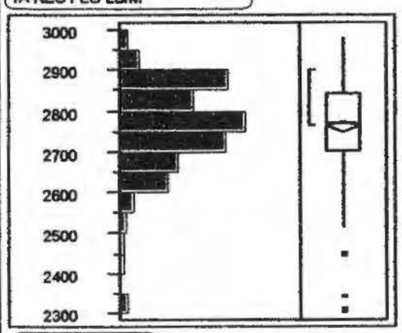


Quantiles

Moments

Mean	117.3055
Std Dev	2.9017
Std Error Mean	0.1750
Upper 95% Mean	117.6499
Lower 95% Mean	116.9610
N	275.0000
Sum Weights	275.0000

1A REC FLO LB/M

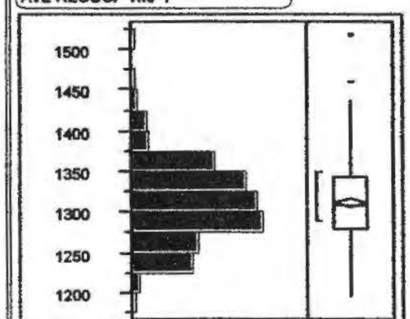


Quantiles

Moments

Mean	2763.415
Std Dev	104.193
Std Error Mean	6.283
Upper 95% Mean	2775.784
Lower 95% Mean	2751.046
N	275.000
Sum Weights	275.000

AVE RECOUP TMP F

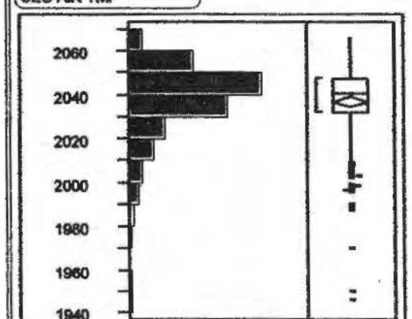


Quantiles

Moments

Mean	1311.696
Std Dev	46.956
Std Error Mean	2.832
Upper 95% Mean	1317.270
Lower 95% Mean	1306.121
N	275.000
Sum Weights	275.000

SEC AIR TMP

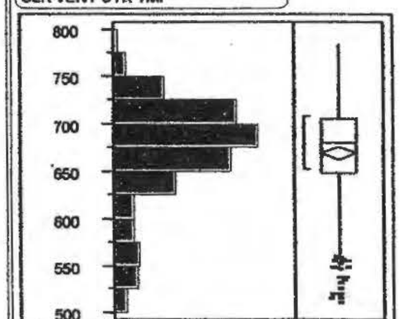


Quantiles

Moments

Mean	2037.094
Std Dev	17.337
Std Error Mean	1.045
Upper 95% Mean	2039.152
Lower 95% Mean	2035.036
N	275.000
Sum Weights	275.000

CLR VENT STK TMP



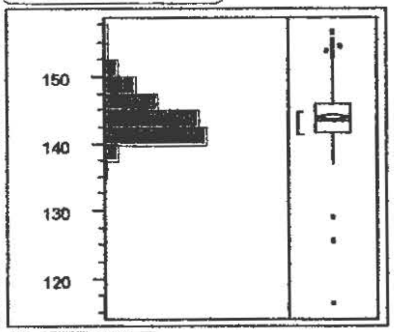
Quantiles

Moments

Mean	669.7956
Std Dev	54.6866
Std Error Mean	3.2977
Upper 95% Mean	676.2878
Lower 95% Mean	663.3035
N	275.0000
Sum Weights	275.0000

FIGURE 82
Plant Data: Test 2 - Unedited

1A/B AVE AMPS

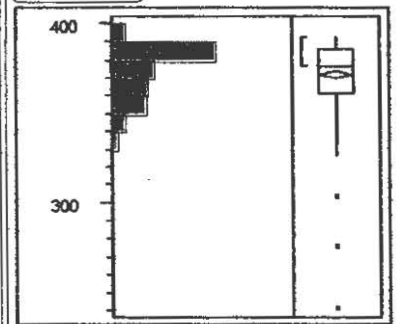


Quantiles

Moments

Mean	144.0924
Std Dev	4.1747
Std Error Mean	0.2451
Upper 95% Mean	144.5749
Lower 95% Mean	143.6099
N	290.0000
Sum Weights	290.0000

2A AMPS

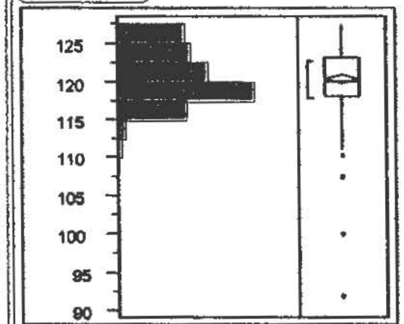


Quantiles

Moments

Mean	372.3576
Std Dev	18.2783
Std Error Mean	1.0733
Upper 95% Mean	374.4702
Lower 95% Mean	370.2450
N	290.0000
Sum Weights	290.0000

3A AMPS

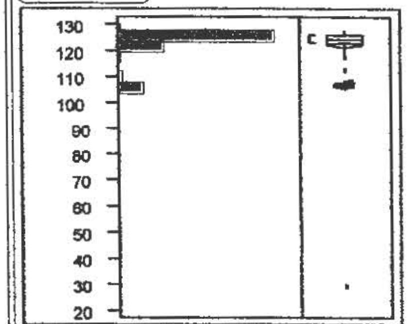


Quantiles

Moments

Mean	120.4207
Std Dev	4.2975
Std Error Mean	0.2524
Upper 95% Mean	120.9174
Lower 95% Mean	119.9240
N	290.0000
Sum Weights	290.0000

3B AMPS

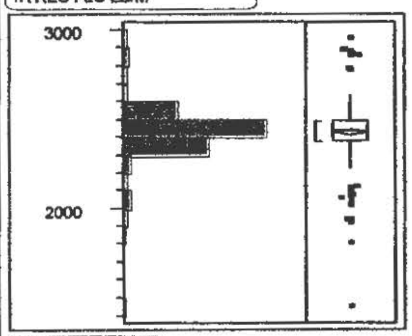


Quantiles

Moments

Mean	122.5638
Std Dev	8.1904
Std Error Mean	0.4810
Upper 95% Mean	123.5104
Lower 95% Mean	121.6172
N	290.0000
Sum Weights	290.0000

1A REC FLO LB/M

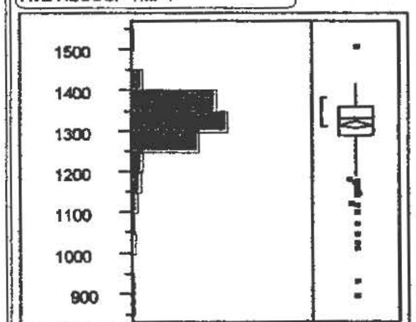


Quantiles

Moments

Mean	2430.599
Std Dev	147.866
Std Error Mean	8.683
Upper 95% Mean	2447.689
Lower 95% Mean	2413.509
N	290.000
Sum Weights	290.000

AVE RECOUP TMP F

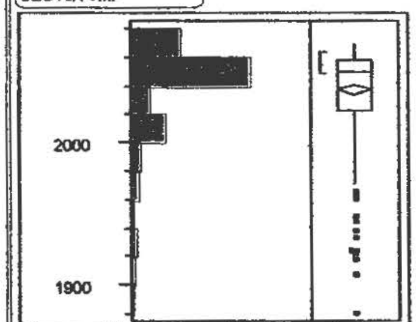


Quantiles

Moments

Mean	1316.579
Std Dev	74.034
Std Error Mean	4.347
Upper 95% Mean	1325.136
Lower 95% Mean	1308.022
N	290.000
Sum Weights	290.000

SEC AIR TMP

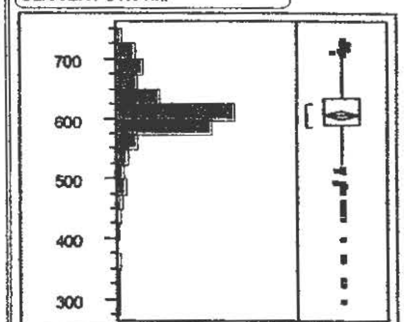


Quantiles

Moments

Mean	2037.756
Std Dev	32.629
Std Error Mean	1.916
Upper 95% Mean	2041.527
Lower 95% Mean	2033.984
N	290.000
Sum Weights	290.000

CLR VENT STK TMP



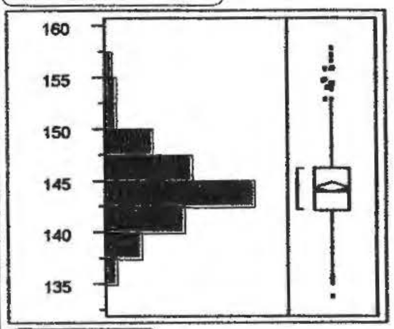
Quantiles

Moments

Mean	606.8621
Std Dev	63.7230
Std Error Mean	3.7419
Upper 95% Mean	614.2271
Lower 95% Mean	599.4971
N	290.0000
Sum Weights	290.0000

FIGURE 83
Plant Data: Test 3 - Unedited

1A/B AVE AMPS

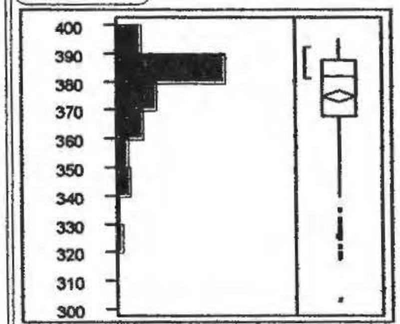


Quantiles

Moments

Mean	144.4368
Std Dev	4.0683
Std Error Mean	0.2397
Upper 95% Mean	144.9087
Lower 95% Mean	143.9650
N	288.0000
Sum Weights	288.0000

2A AMPS

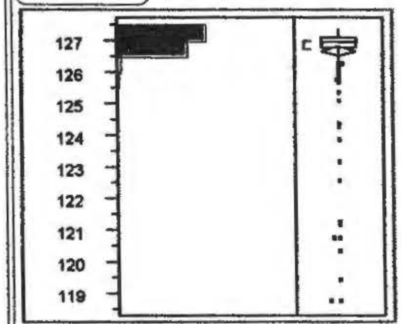


Quantiles

Moments

Mean	375.2344
Std Dev	17.4461
Std Error Mean	1.0280
Upper 95% Mean	377.2578
Lower 95% Mean	373.2109
N	288.0000
Sum Weights	288.0000

3A AMPS

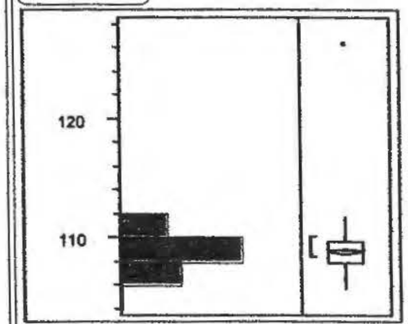


Quantiles

Moments

Mean	126.6792
Std Dev	1.2268
Std Error Mean	0.0723
Upper 95% Mean	126.8214
Lower 95% Mean	126.5369
N	288.0000
Sum Weights	288.0000

3B AMPS

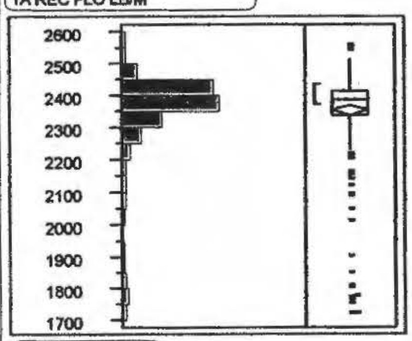


Quantiles

Moments

Mean	108.8941
Std Dev	1.7517
Std Error Mean	0.1032
Upper 95% Mean	109.0973
Lower 95% Mean	108.6909
N	288.0000
Sum Weights	288.0000

1A REC FLO LB/M

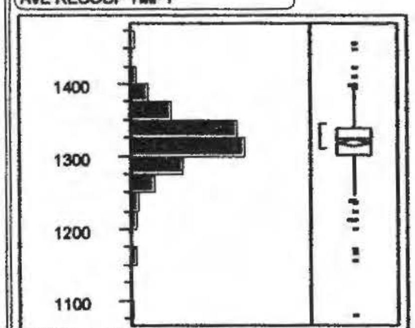


Quantiles

Moments

Mean	2354.904
Std Dev	129.135
Std Error Mean	7.609
Upper 95% Mean	2369.882
Lower 95% Mean	2339.927
N	288.000
Sum Weights	288.000

AVE RECOUP TMP F

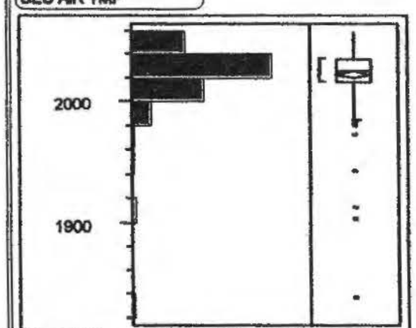


Quantiles

Moments

Mean	1319.277
Std Dev	41.285
Std Error Mean	2.433
Upper 95% Mean	1324.065
Lower 95% Mean	1314.488
N	288.000
Sum Weights	288.000

SEC AIR TMP

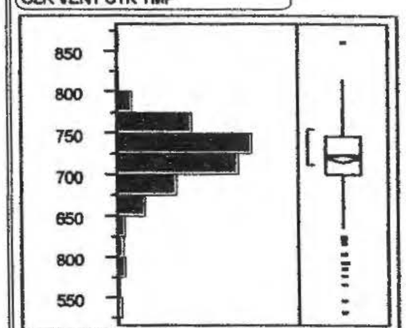


Quantiles

Moments

Mean	2023.530
Std Dev	22.369
Std Error Mean	1.318
Upper 95% Mean	2026.124
Lower 95% Mean	2020.935
N	288.000
Sum Weights	288.000

CLR VENT STK TMP



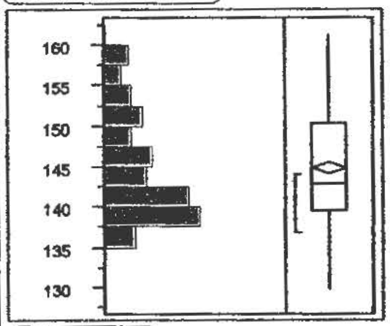
Quantiles

Moments

Mean	719.7580
Std Dev	41.4110
Std Error Mean	2.4402
Upper 95% Mean	724.5609
Lower 95% Mean	714.9550
N	288.0000
Sum Weights	288.0000

FIGURE 84
Plant Data: Test 4 - Unedited

1A/B AVE AMPS

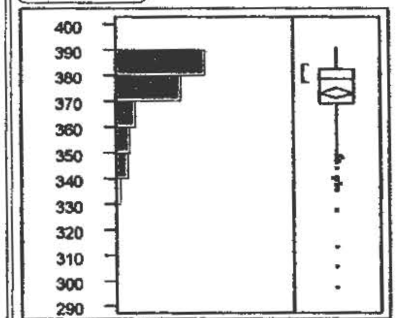


Quantiles

Moments

Mean	144.9273
Std Dev	6.6580
Std Error Mean	0.3916
Upper 95% Mean	145.6982
Lower 95% Mean	144.1565
N	289.0000
Sum Weights	289.0000

2A AMPS

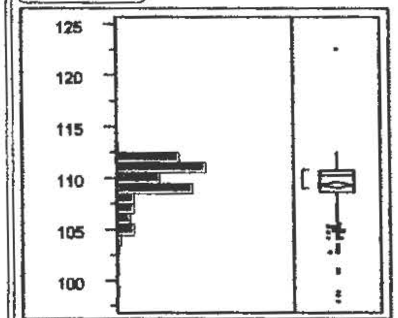


Quantiles

Moments

Mean	373.3253
Std Dev	14.5311
Std Error Mean	0.8548
Upper 95% Mean	375.0077
Lower 95% Mean	371.6428
N	289.0000
Sum Weights	289.0000

3A AMPS

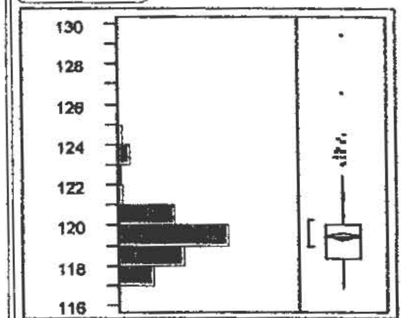


Quantiles

Moments

Mean	109.3858
Std Dev	2.5884
Std Error Mean	0.1523
Upper 95% Mean	109.6855
Lower 95% Mean	109.0861
N	289.0000
Sum Weights	289.0000

3B AMPS

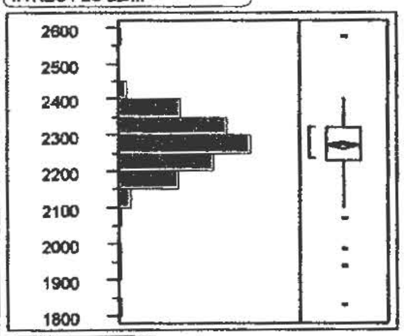


Quantiles

Moments

Mean	119.4886
Std Dev	1.5855
Std Error Mean	0.0933
Upper 95% Mean	119.6721
Lower 95% Mean	119.3050
N	289.0000
Sum Weights	289.0000

1A REC FLO LB/M

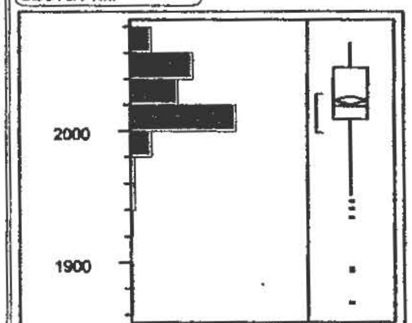


Quantiles

Moments

Mean	2272.970
Std Dev	77.245
Std Error Mean	4.544
Upper 95% Mean	2281.914
Lower 95% Mean	2264.027
N	289.000
Sum Weights	289.000

SEC AIR TMP

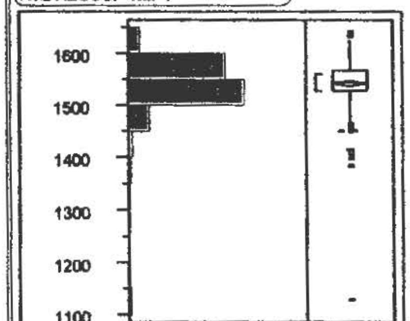


Quantiles

Moments

Mean	2023.852
Std Dev	27.965
Std Error Mean	1.645
Upper 95% Mean	2027.090
Lower 95% Mean	2020.614
N	289.000
Sum Weights	289.000

AVE RECOUP TMP F

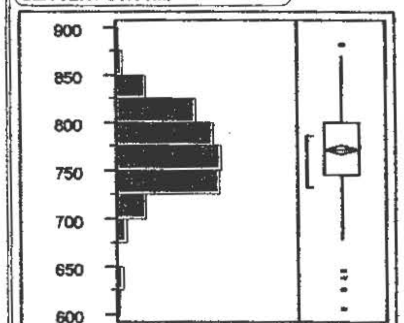


Quantiles

Moments

Mean	1542.552
Std Dev	44.779
Std Error Mean	2.634
Upper 95% Mean	1547.736
Lower 95% Mean	1537.367
N	289.000
Sum Weights	289.000

CLR VENT STK TMP



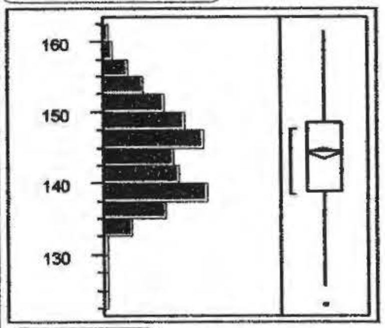
Quantiles

Moments

Mean	771.6931
Std Dev	40.7440
Std Error Mean	2.3967
Upper 95% Mean	776.4104
Lower 95% Mean	766.9757
N	289.0000
Sum Weights	289.0000

FIGURE 85
Plant Data: Test 5 - Unedited

1A/B AVE AMPS

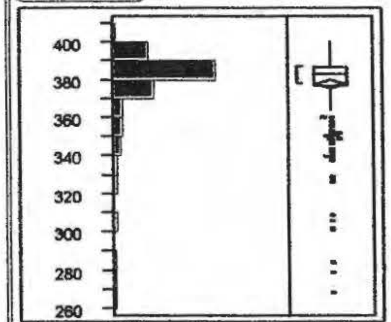


Quantiles

Moments

Mean	144.3332
Std Dev	6.5476
Std Error Mean	0.3852
Upper 95% Mean	145.0913
Lower 95% Mean	143.5751
N	289.0000
Sum Weights	289.0000

2A AMPS

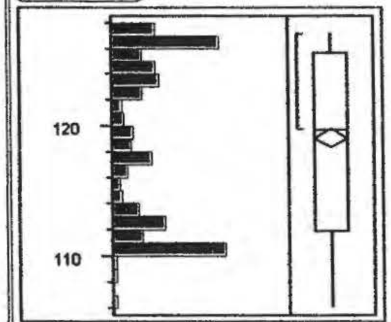


Quantiles

Moments

Mean	378.0381
Std Dev	18.7394
Std Error Mean	1.1023
Upper 95% Mean	380.2077
Lower 95% Mean	375.8684
N	289.0000
Sum Weights	289.0000

3A AMPS

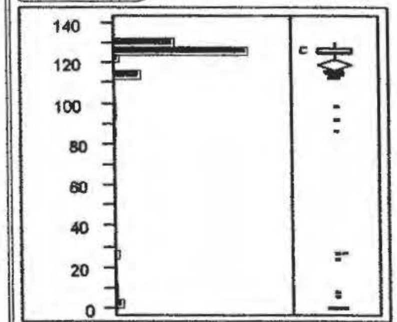


Quantiles

Moments

Mean	119.1000
Std Dev	6.4820
Std Error Mean	0.3813
Upper 95% Mean	119.8505
Lower 95% Mean	118.3495
N	289.0000
Sum Weights	289.0000

3B AMPS

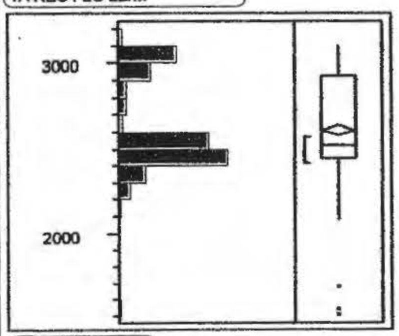


Quantiles

Moments

Mean	119.2439
Std Dev	26.1018
Std Error Mean	1.5354
Upper 95% Mean	122.2660
Lower 95% Mean	116.2219
N	289.0000
Sum Weights	289.0000

1A REC FLO LB/M

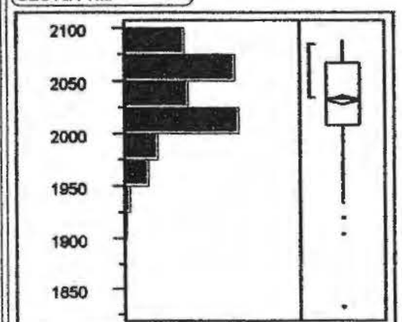


Quantiles

Moments

Mean	2615.618
Std Dev	278.571
Std Error Mean	16.387
Upper 95% Mean	2647.871
Lower 95% Mean	2583.365
N	289.000
Sum Weights	289.000

SEC AIR TMP

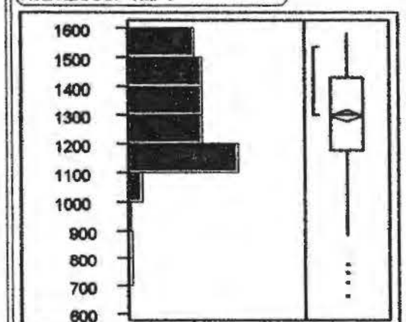


Quantiles

Moments

Mean	2032.676
Std Dev	39.393
Std Error Mean	2.317
Upper 95% Mean	2037.237
Lower 95% Mean	2028.116
N	289.000
Sum Weights	289.000

AVE RECOUP TMP F

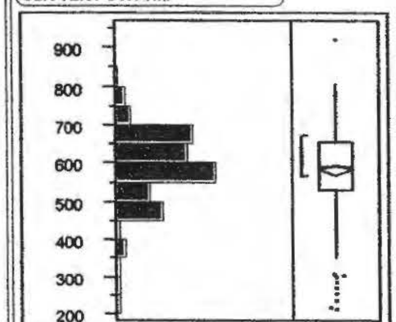


Quantiles

Moments

Mean	1299.067
Std Dev	166.152
Std Error Mean	9.774
Upper 95% Mean	1318.305
Lower 95% Mean	1279.830
N	289.000
Sum Weights	289.000

CLR VENT STK TMP



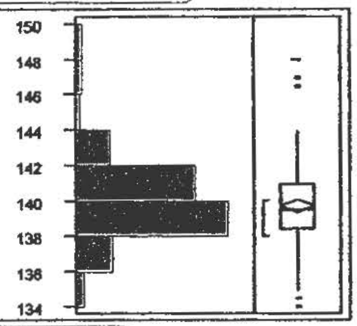
Quantiles

Moments

Mean	582.9654
Std Dev	104.8647
Std Error Mean	6.1685
Upper 95% Mean	595.1066
Lower 95% Mean	570.8242
N	289.0000
Sum Weights	289.0000

FIGURE 86
Plant Data: Test 7 - No Editing

1A/B AVE AMPS

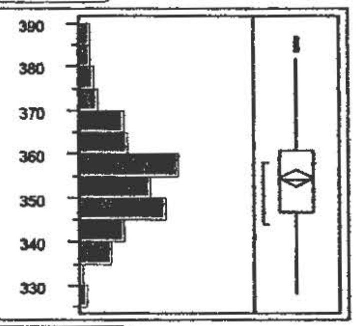


Quantiles

Moments

Mean	139.7430
Std Dev	2.1967
Std Error Mean	0.1843
Upper 95% Mean	140.1074
Lower 95% Mean	139.3785
N	142.0000
Sum Weights	142.0000

2A AMPS

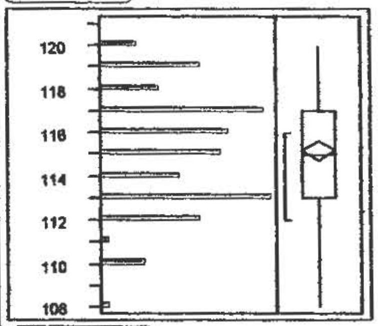


Quantiles

Moments

Mean	354.8310
Std Dev	12.0295
Std Error Mean	1.0095
Upper 95% Mean	356.8267
Lower 95% Mean	352.8353
N	142.0000
Sum Weights	142.0000

3A AMPS

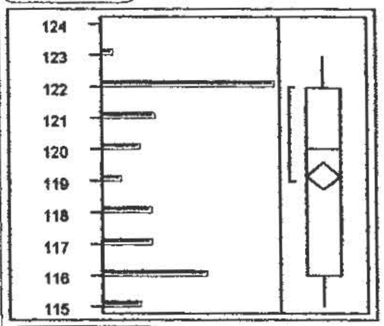


Quantiles

Moments

Mean	115.1901
Std Dev	2.6281
Std Error Mean	0.2205
Upper 95% Mean	115.6261
Lower 95% Mean	114.7541
N	142.0000
Sum Weights	142.0000

3B AMPS

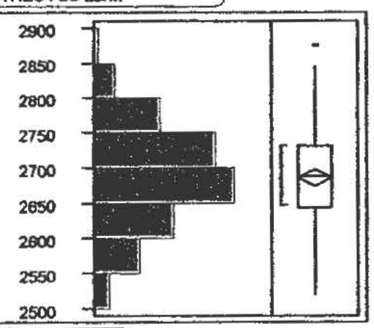


Quantiles

Moments

Mean	119.1761
Std Dev	2.6639
Std Error Mean	0.2236
Upper 95% Mean	119.6180
Lower 95% Mean	118.7341
N	142.0000
Sum Weights	142.0000

1A REC FLO LB/M

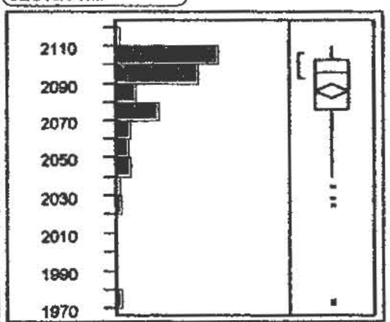


Quantiles

Moments

Mean	2687.479
Std Dev	70.864
Std Error Mean	5.947
Upper 95% Mean	2699.235
Lower 95% Mean	2675.722
N	142.000
Sum Weights	142.000

SEC AIR TMP

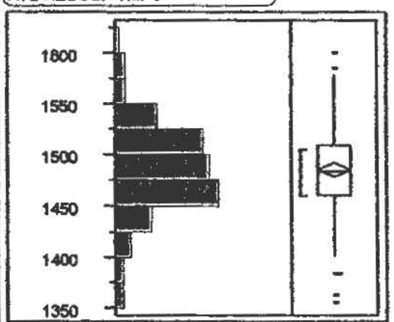


Quantiles

Moments

Mean	2086.437
Std Dev	23.492
Std Error Mean	1.971
Upper 95% Mean	2090.334
Lower 95% Mean	2082.539
N	142.000
Sum Weights	142.000

AVE RECOUP TMP F

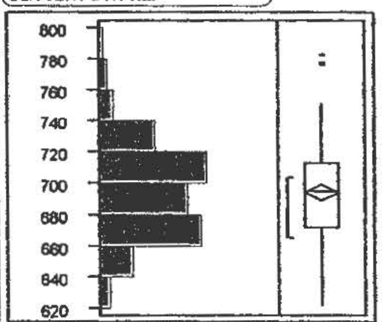


Quantiles

Moments

Mean	1484.937
Std Dev	41.732
Std Error Mean	3.502
Upper 95% Mean	1491.860
Lower 95% Mean	1478.013
N	142.000
Sum Weights	142.000

CLR VENT STK TMP



Quantiles

Moments

Mean	694.3944
Std Dev	29.0482
Std Error Mean	2.4377
Upper 95% Mean	699.2135
Lower 95% Mean	689.5752
N	142.0000
Sum Weights	142.0000

FIGURE 87
Plant Data: Test 1 - Unedited
Process Fan Damper Cycles - 70 min averages

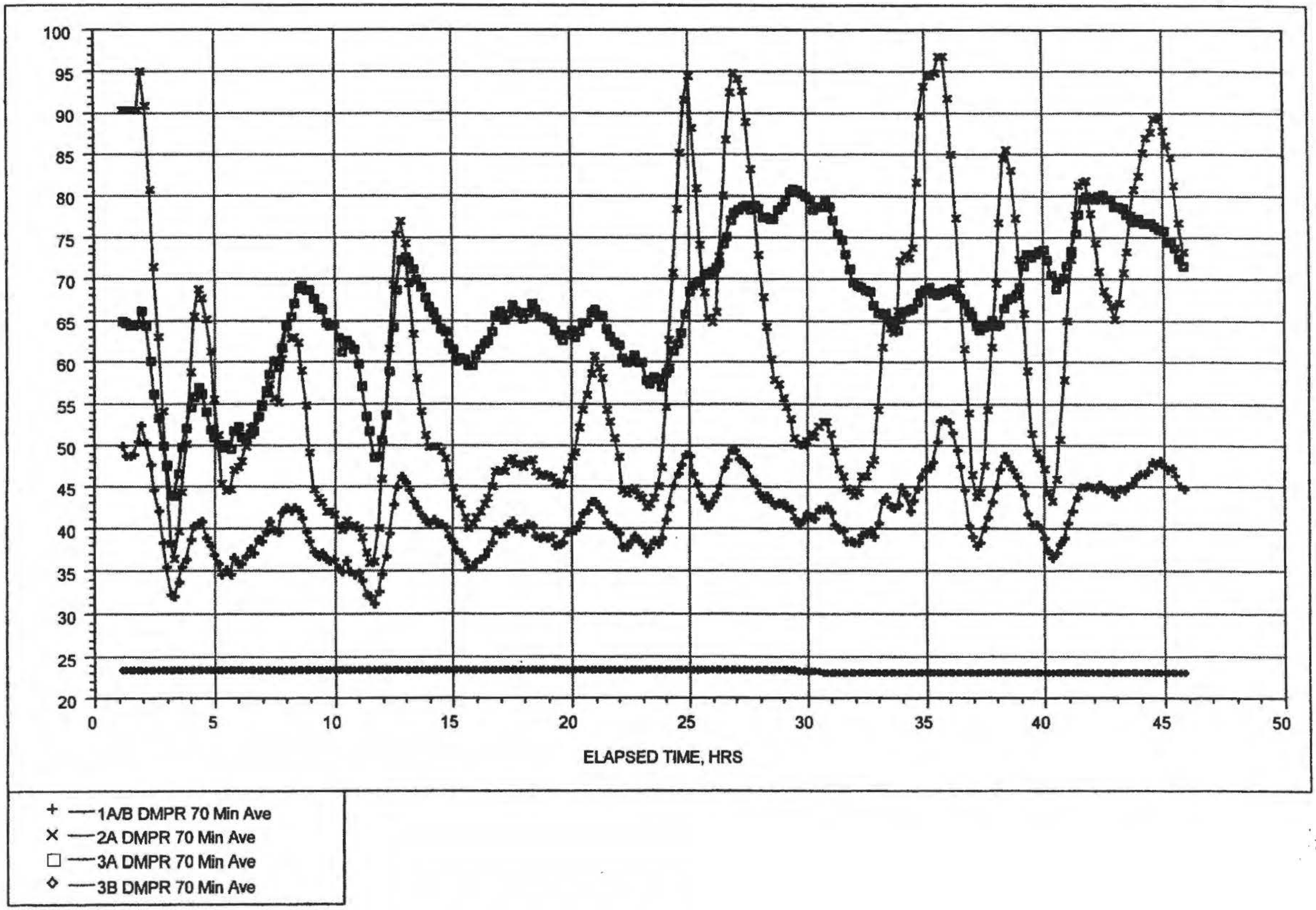


FIGURE 88

Plant Data: Test 2 - Unedited
Process Fan Damper Cycles

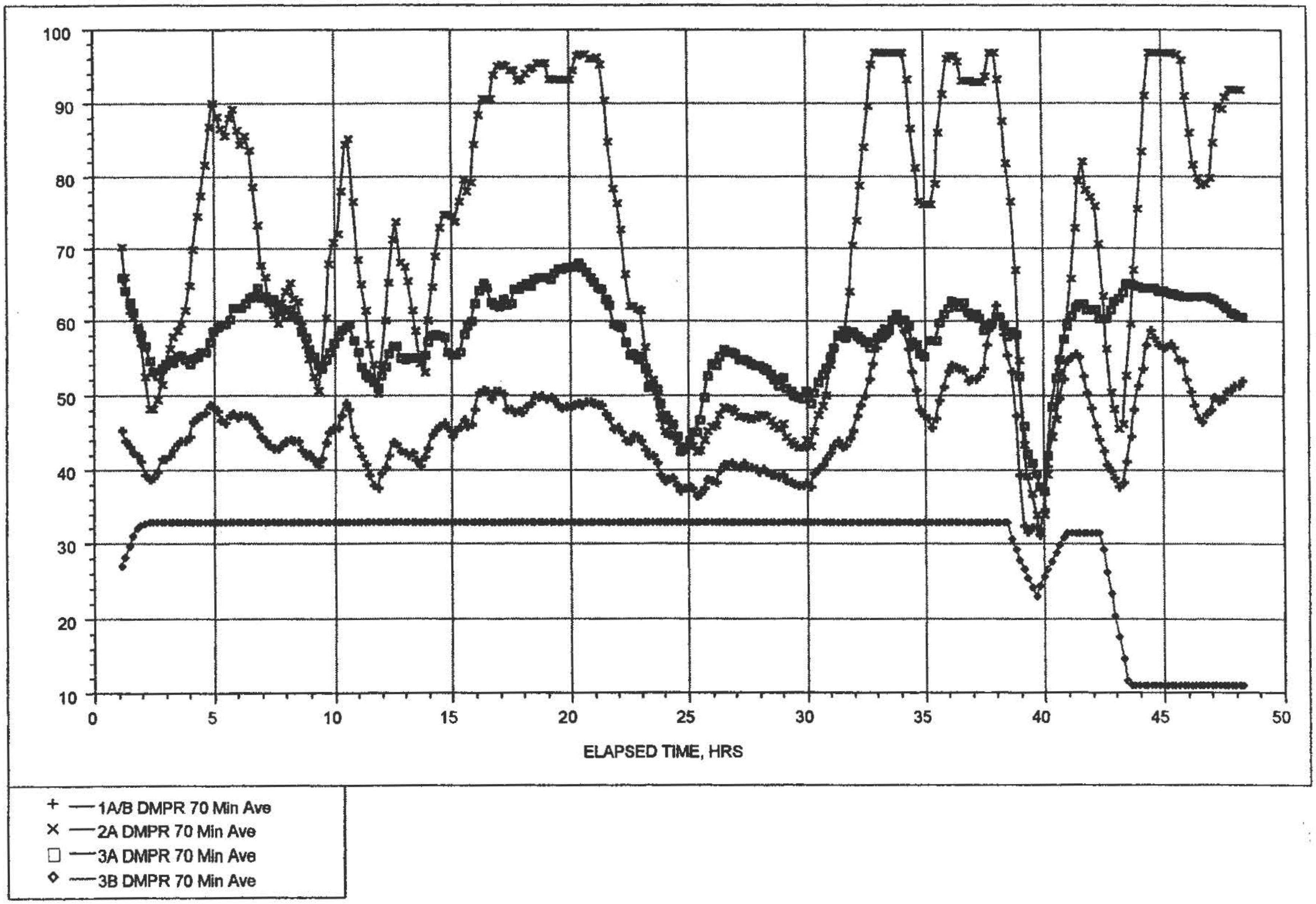


Figure 89
Plant Data: Test 3 - Unedited
Process Fan Damper Cycles

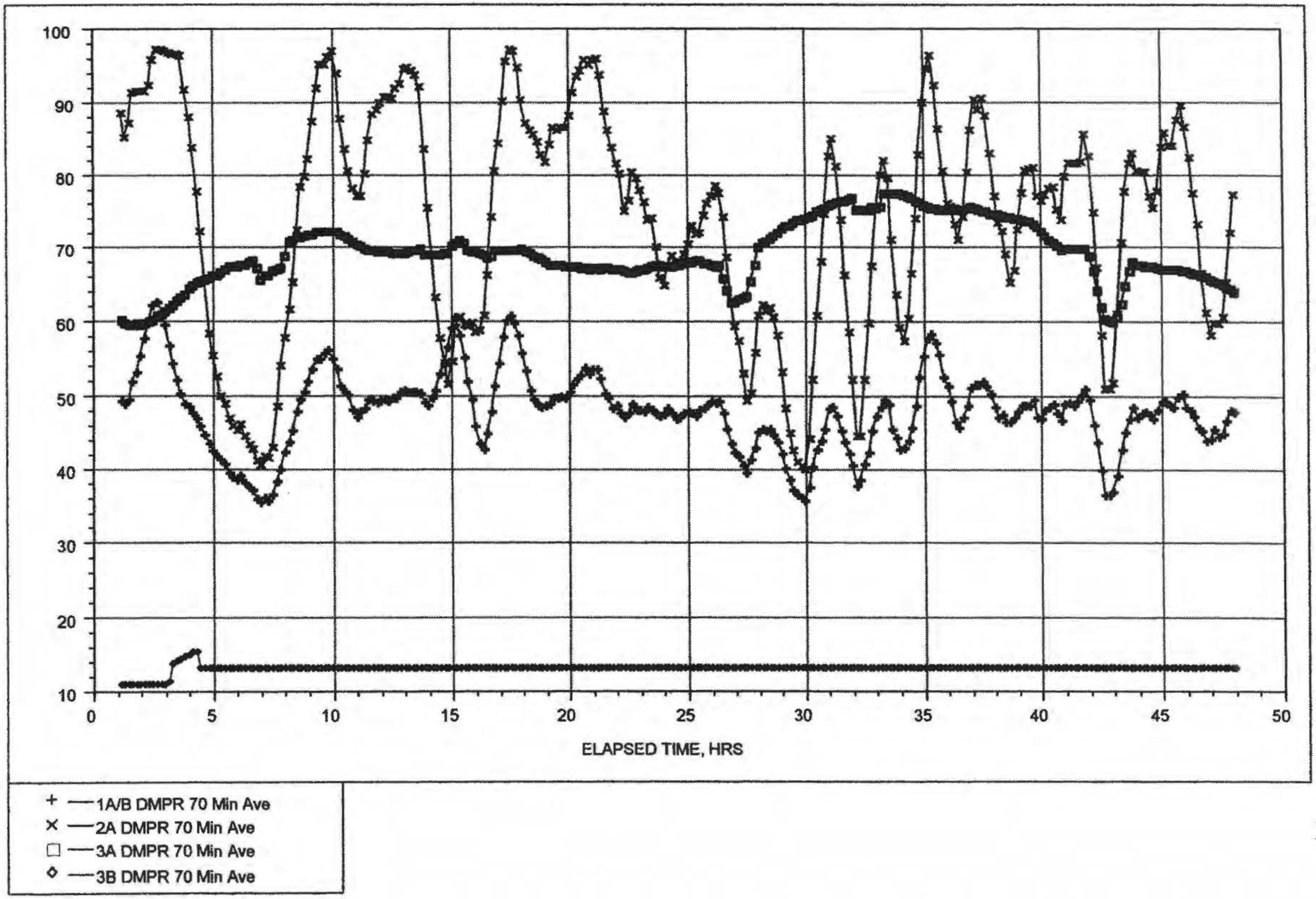


FIGURE 90

Plant Data: Test 4 - Unedited
Process Fan Damper Cycles

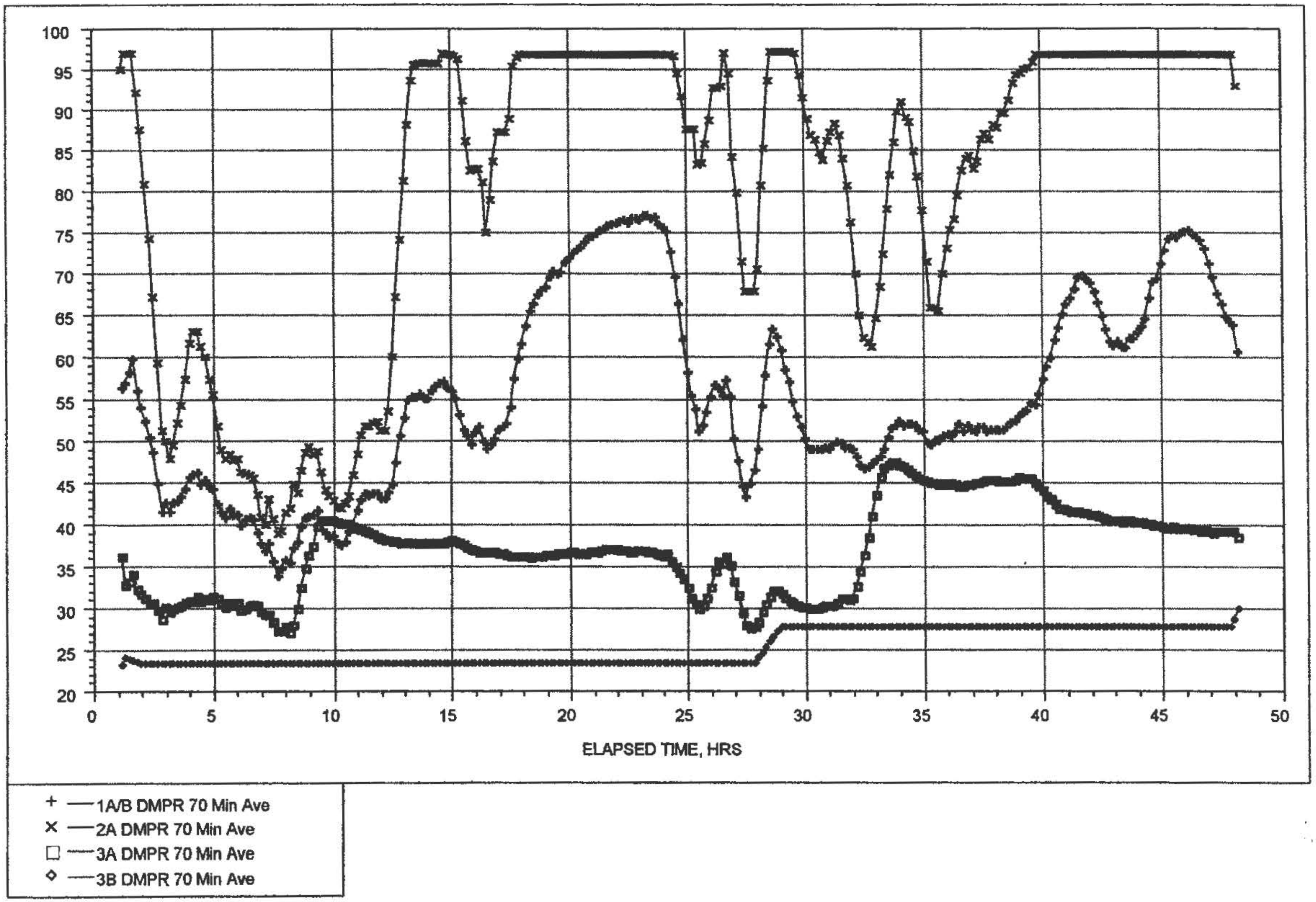


FIGURE 91

Plant Data: Test 5 - Unedited
Process Fan Damper Cycles

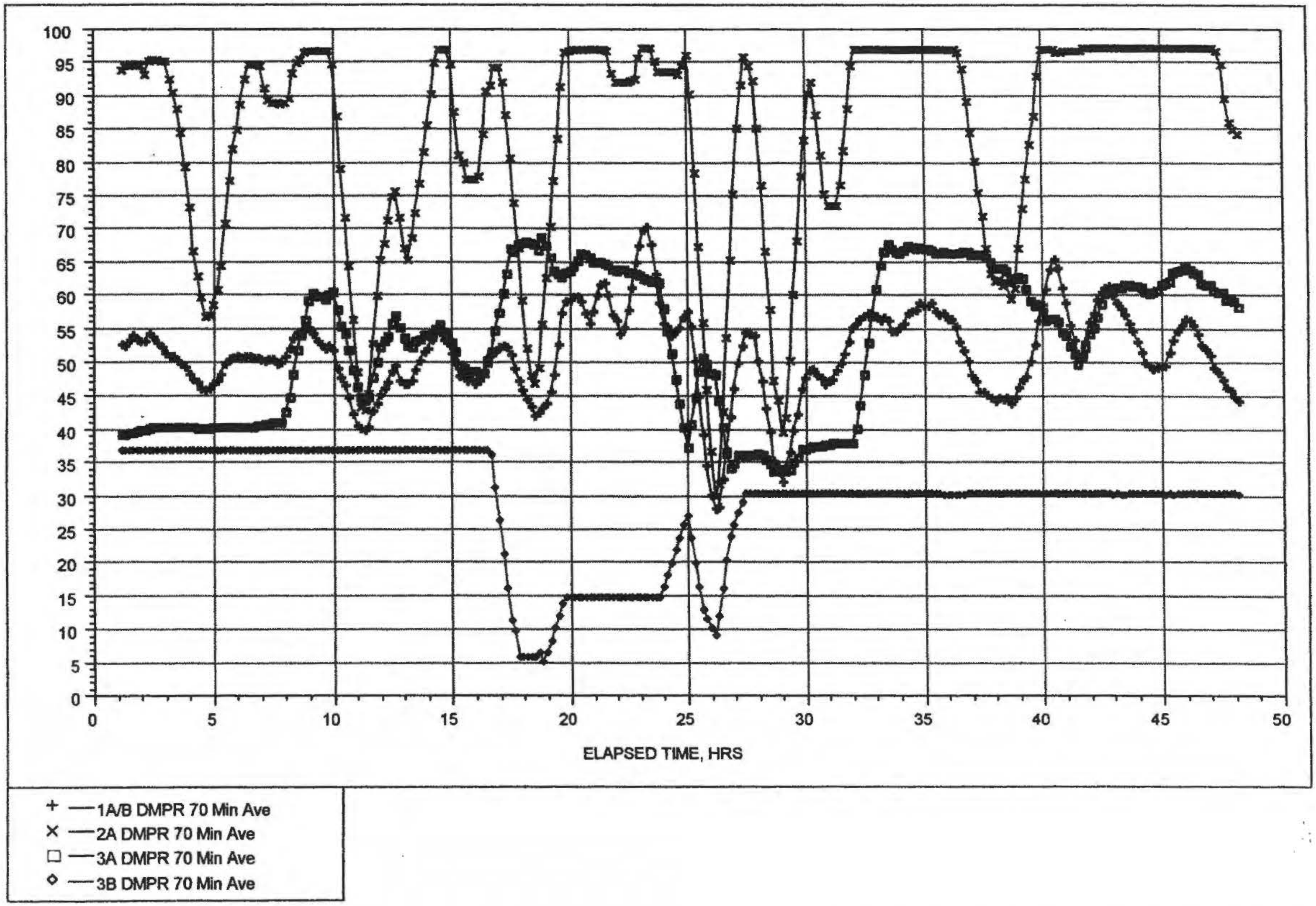


FIGURE 92
Test 7 No Editing
Process Fan Damper Cycles

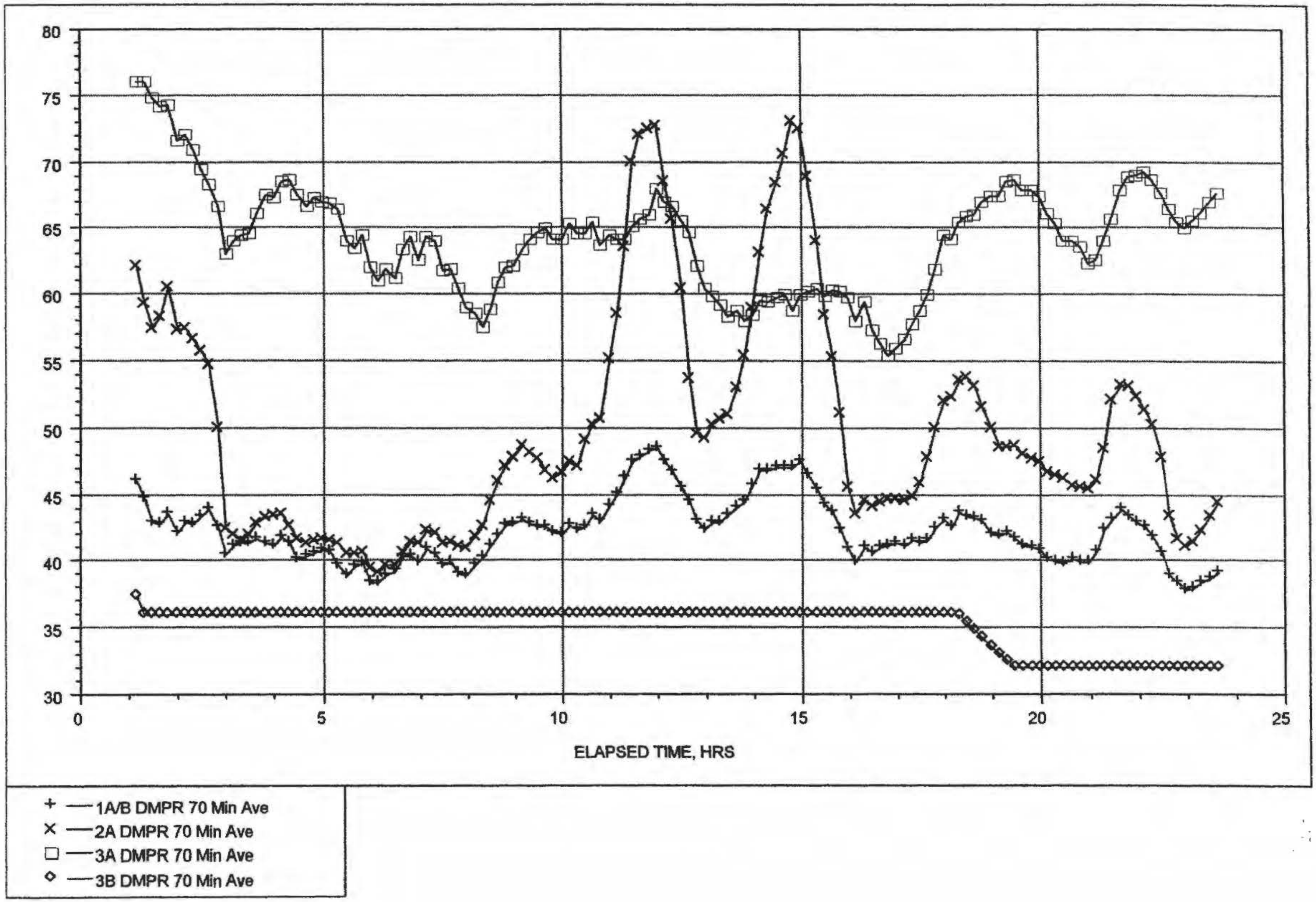
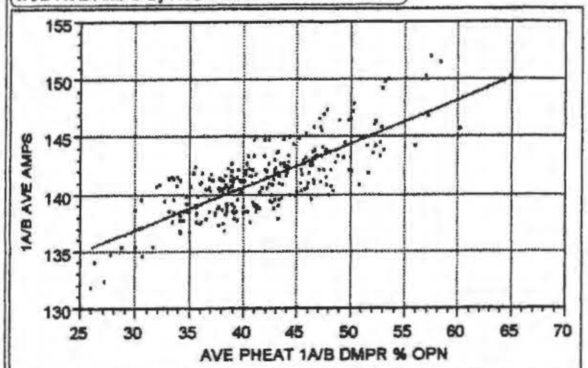


FIGURE 93

Process Fan Power vs Percent Damper Open
Plant Data: Test 1- Unedited

1A/B AVE AMPS By AVE PHEAT 1A/B DMPR % OPN



— Linear Fit

Linear Fit

1A/B AVE AMPS = 125.554 + 0.37864 AVE PHEAT 1A/B DMPR % OPN

Summary of Fit

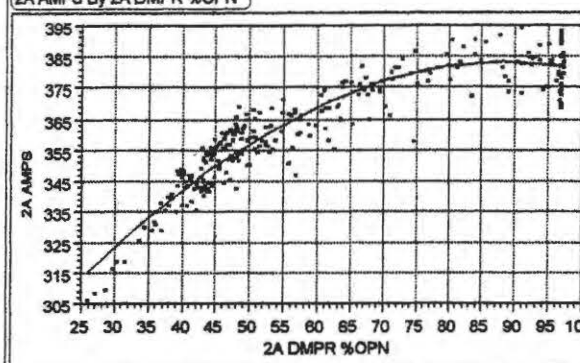
RSquare	0.617607
RSquare Adj	0.616206
Root Mean Square Error	1.877475
Mean of Response	141.4064
Observations (or Sum Wgts)	275

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	125.55417	0.763467	164.45	<.0001
AVE PHEAT 1A/B DMPR % OPN	0.3786397	0.018032	21.00	<.0001

2A AMPS By 2A DMPR %OPN



— Polynomial Fit degree=2

Polynomial Fit degree=2

2A AMPS = 247.303 + 3.06983 2A DMPR %OPN 0 0.01731 2A DMPR %OPN^2

Summary of Fit

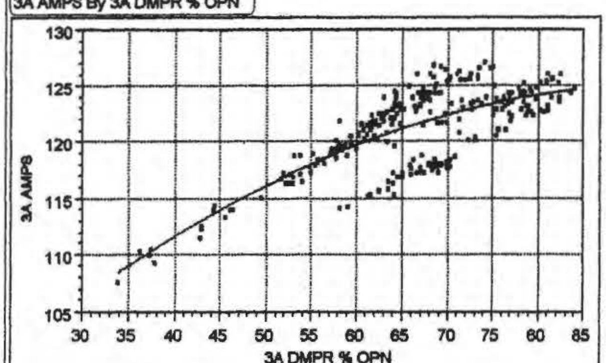
RSquare	0.877781
RSquare Adj	0.876882
Root Mean Square Error	6.123312
Mean of Response	362.6691
Observations (or Sum Wgts)	275

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	247.30293	4.662042	53.05	<.0001
2A DMPR %OPN	3.0698293	0.15064	20.38	<.0001
2A DMPR %OPN^2	-0.017306	0.001109	-15.60	<.0001

3A AMPS By 3A DMPR % OPN



— Polynomial Fit degree=2

Polynomial Fit degree=2

3A AMPS = 84.475 + 0.86238 3A DMPR % OPN 0 0.00457 3A DMPR % OPN^2

Summary of Fit

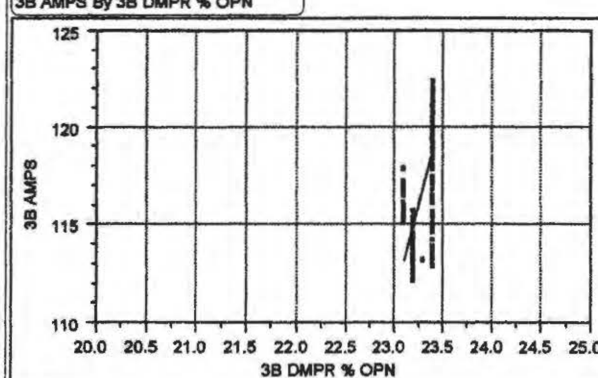
RSquare	0.572334
RSquare Adj	0.569189
Root Mean Square Error	2.43202
Mean of Response	121.2367
Observations (or Sum Wgts)	275

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	84.474958	4.251979	19.87	<.0001
3A DMPR % OPN	0.8623778	0.135053	6.39	<.0001
3A DMPR % OPN^2	-0.004569	0.001063	-4.30	<.0001

3B AMPS By 3B DMPR % OPN



— Linear Fit

Linear Fit

3B AMPS = -317.41 + 18.6399 3B DMPR % OPN

Summary of Fit

RSquare	0.483311
RSquare Adj	0.481419
Root Mean Square Error	2.089562
Mean of Response	117.3055
Observations (or Sum Wgts)	275

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-317.4119	27.20391	-11.67	<.0001
3B DMPR % OPN	[illegible]	1.160145	16.06	<.0001

FIGURE 94

Plant Data: Test 1 - Unedited
Process Fan Power - Relative Deviation from Mean

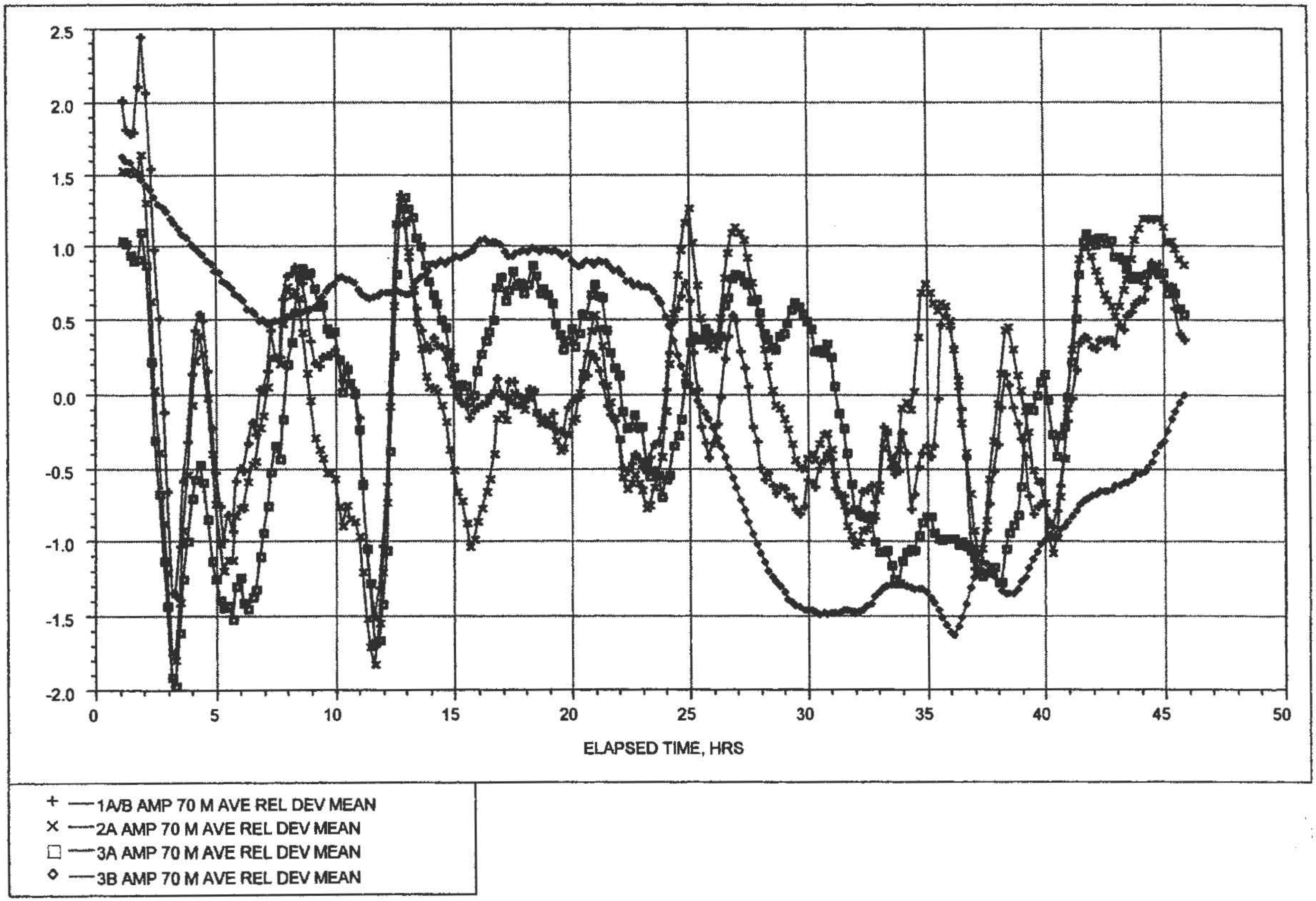


FIGURE 95
Plant Data: Test 1 - Unedited
Net Fan Power Relative Deviation from Mean and Recoup A Duct Flow Relative Deviation from Mean

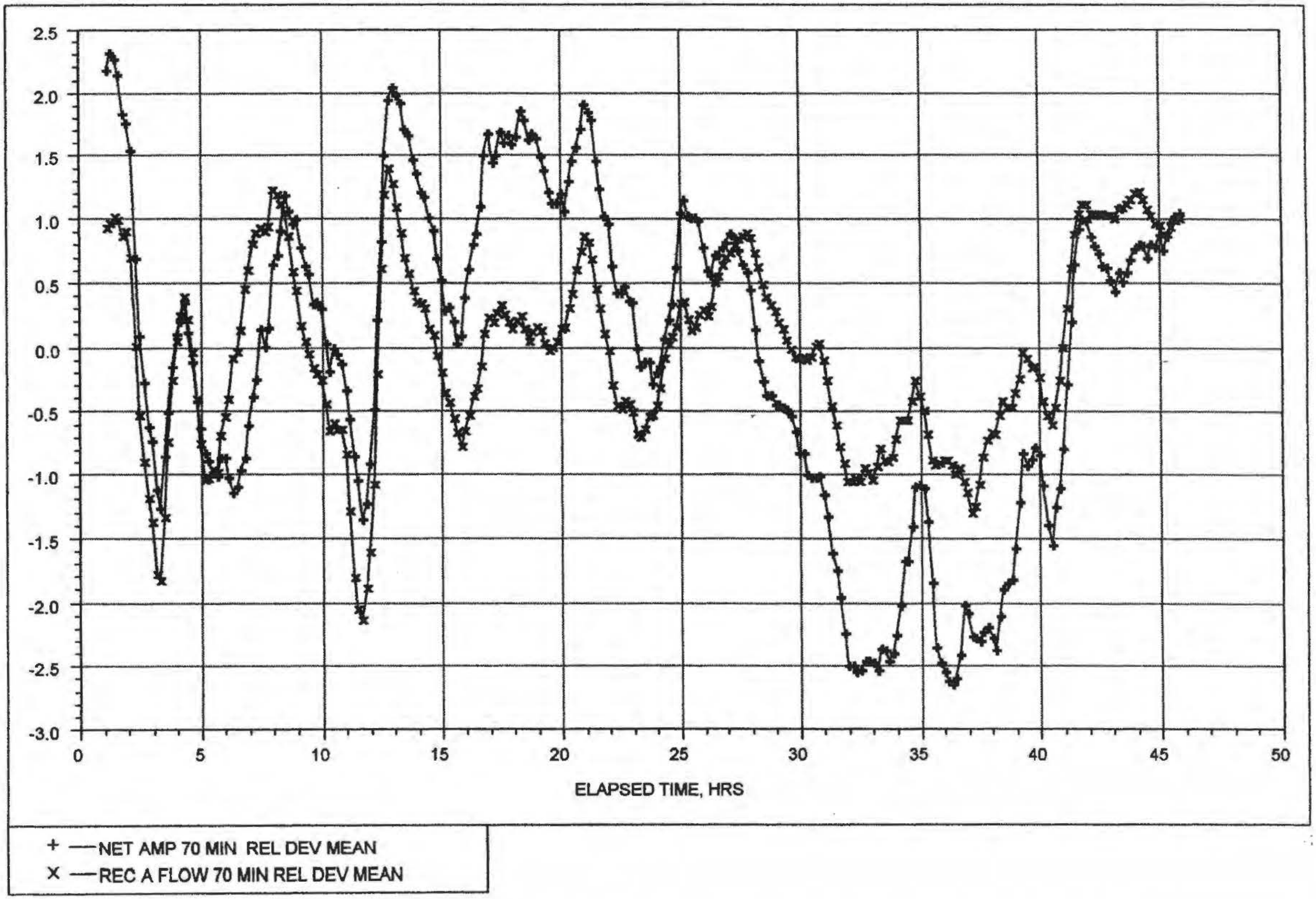


FIGURE 96
Plant Data: Test 2 - Unedited
Net Fan Power Relative Deviation from Mean and Recoup A Duct Flow Relative Deviation from Mean

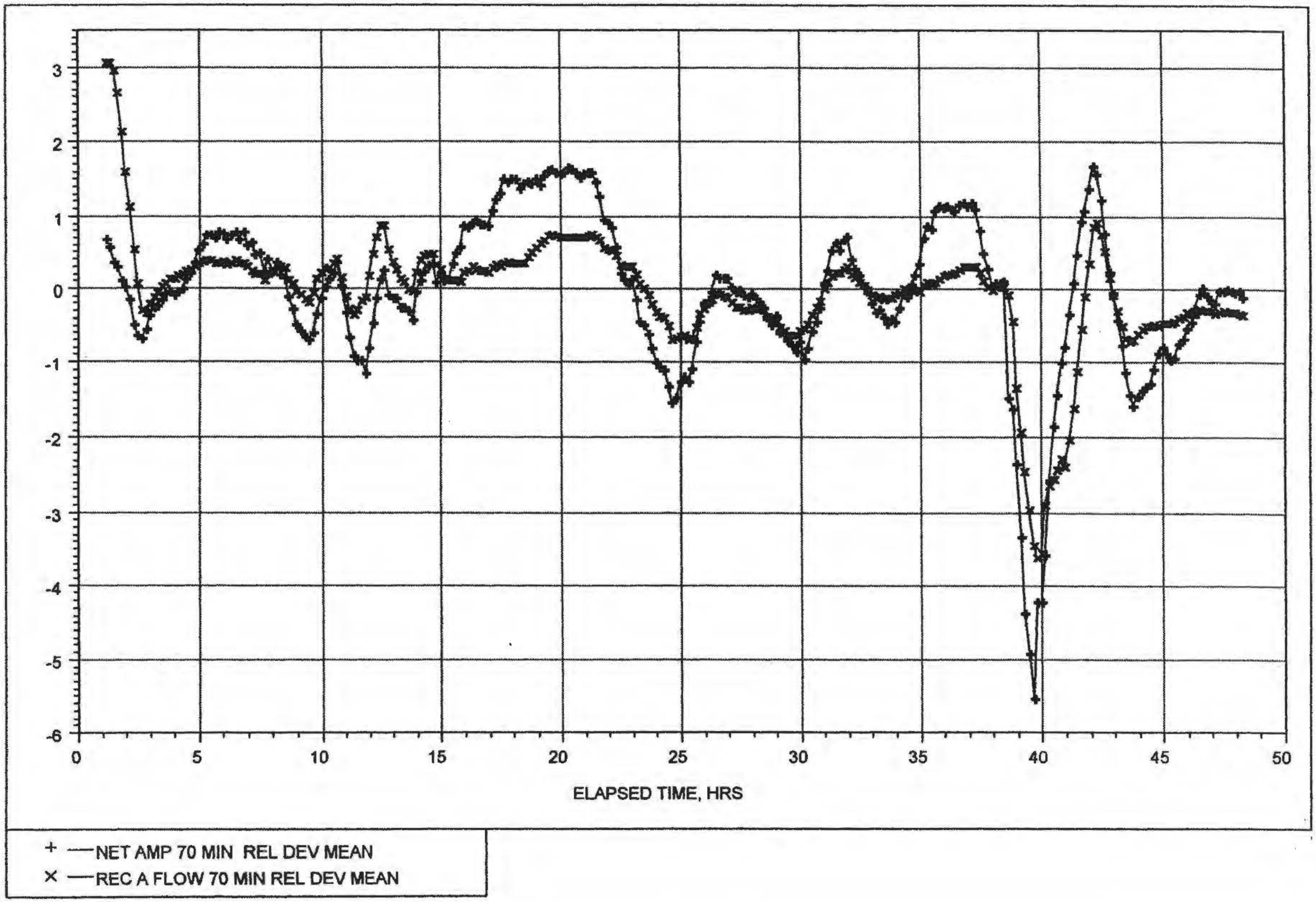


FIGURE 97

Plant Data: Test 3 - Unedited

Net Fan Power Relative Deviation from Mean and Recoup A Duct Flow Relative Deviation from Mean

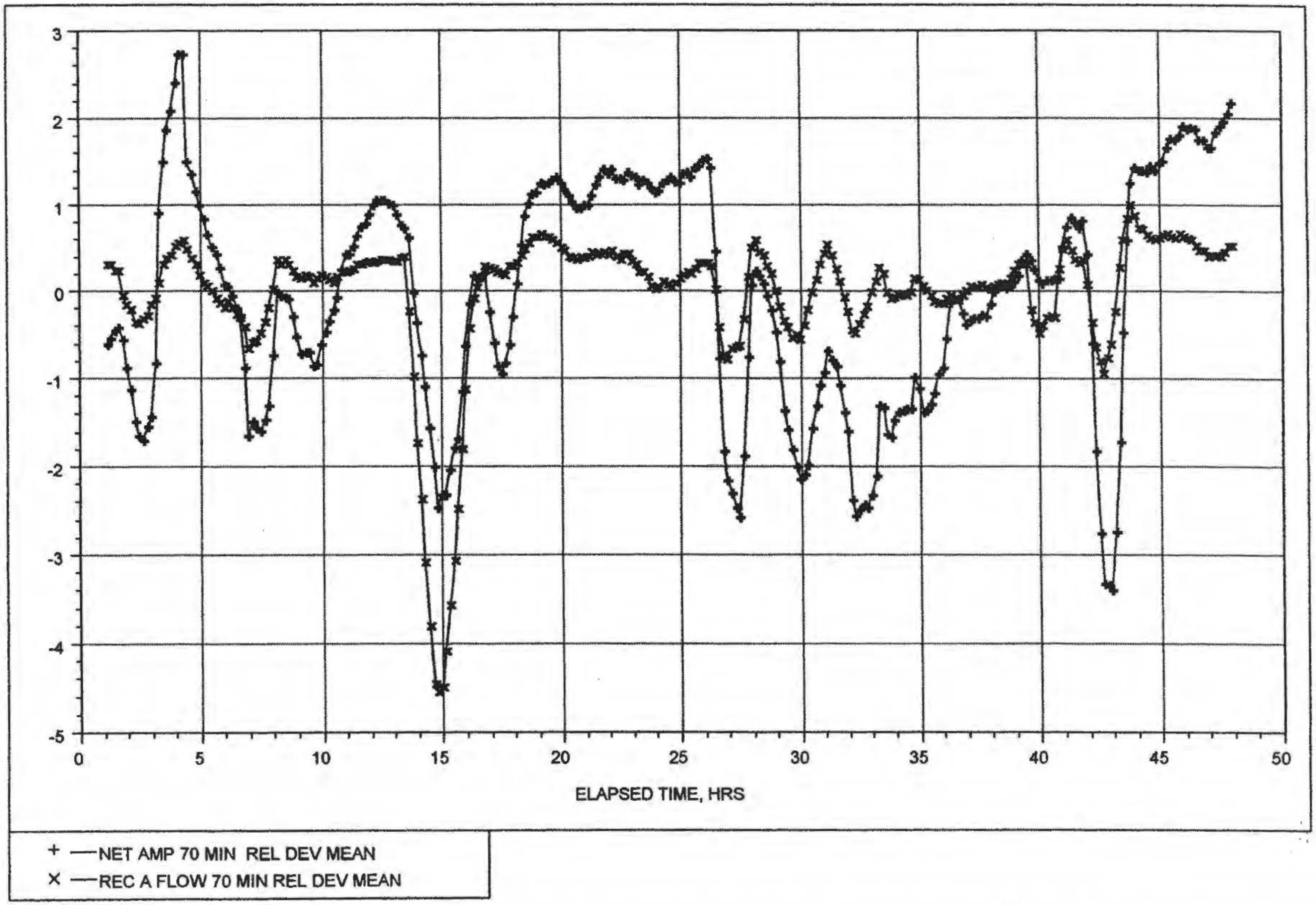


FIGURE 98

Plant Data: Test 4 - Unedited

Net Fan Power Relative Deviation from Mean and Recoup A Duct Flow Relative Deviation from Mean

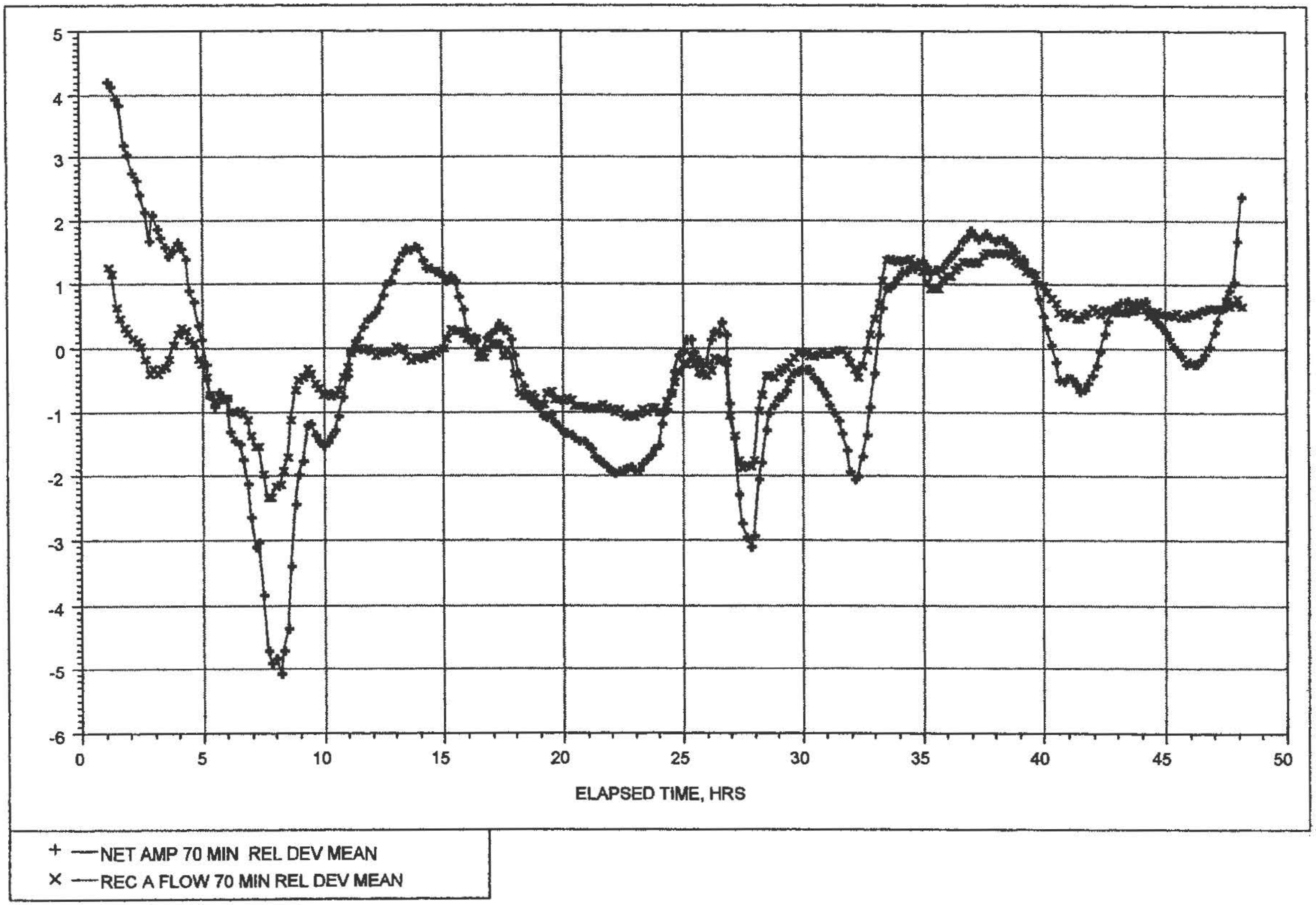


FIGURE 99

Plant Data: Test 5 - Unedited

Net Fan Power Relative Deviation from Mean and Recoup A Duct Flow Relative Deviation from Mean

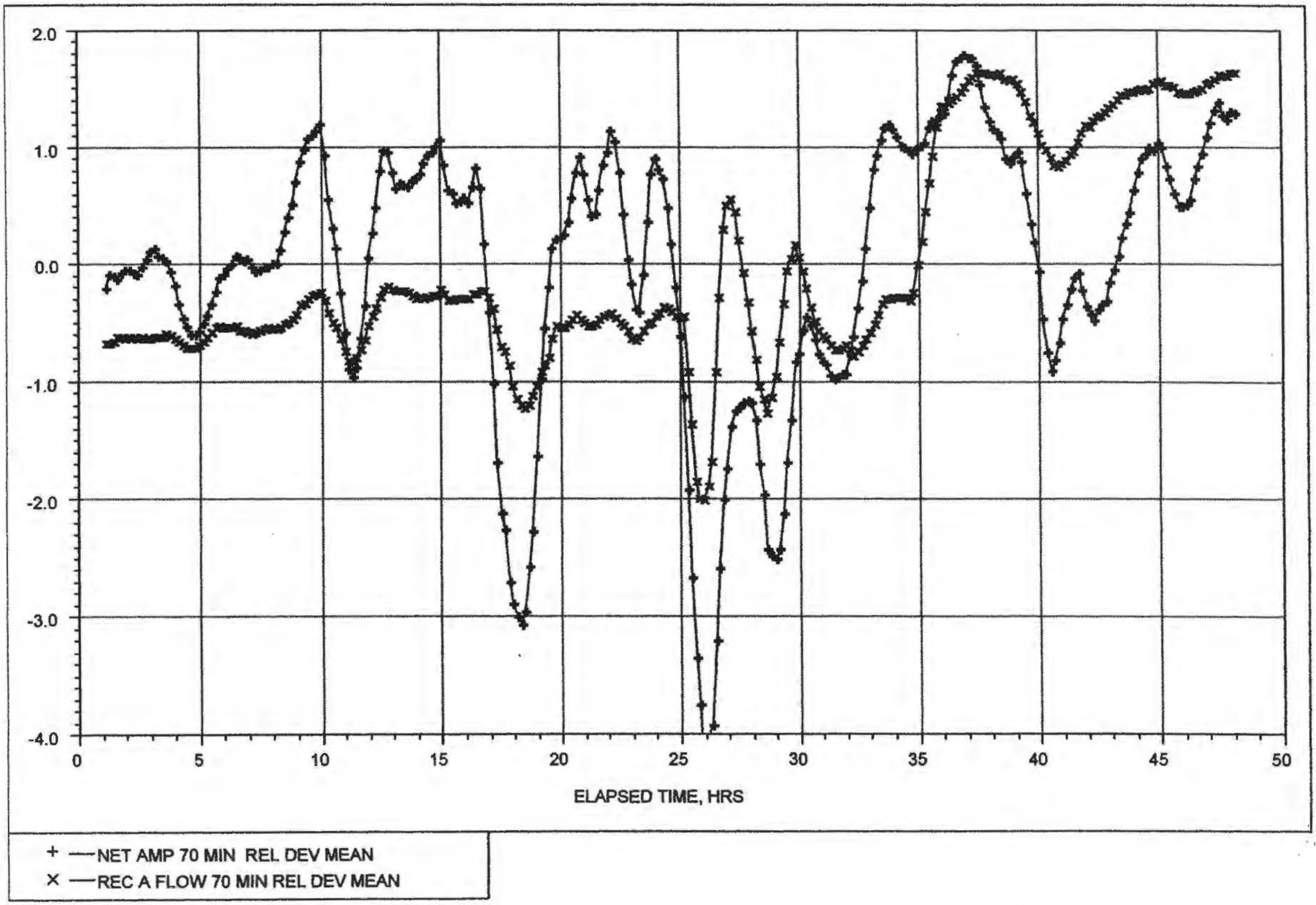


FIGURE 100

Plant Data: Test 7 - Unedited

Net Fan Power Relative Deviation from Mean and Recoup A Duct Flow Relative Deviation from Mean

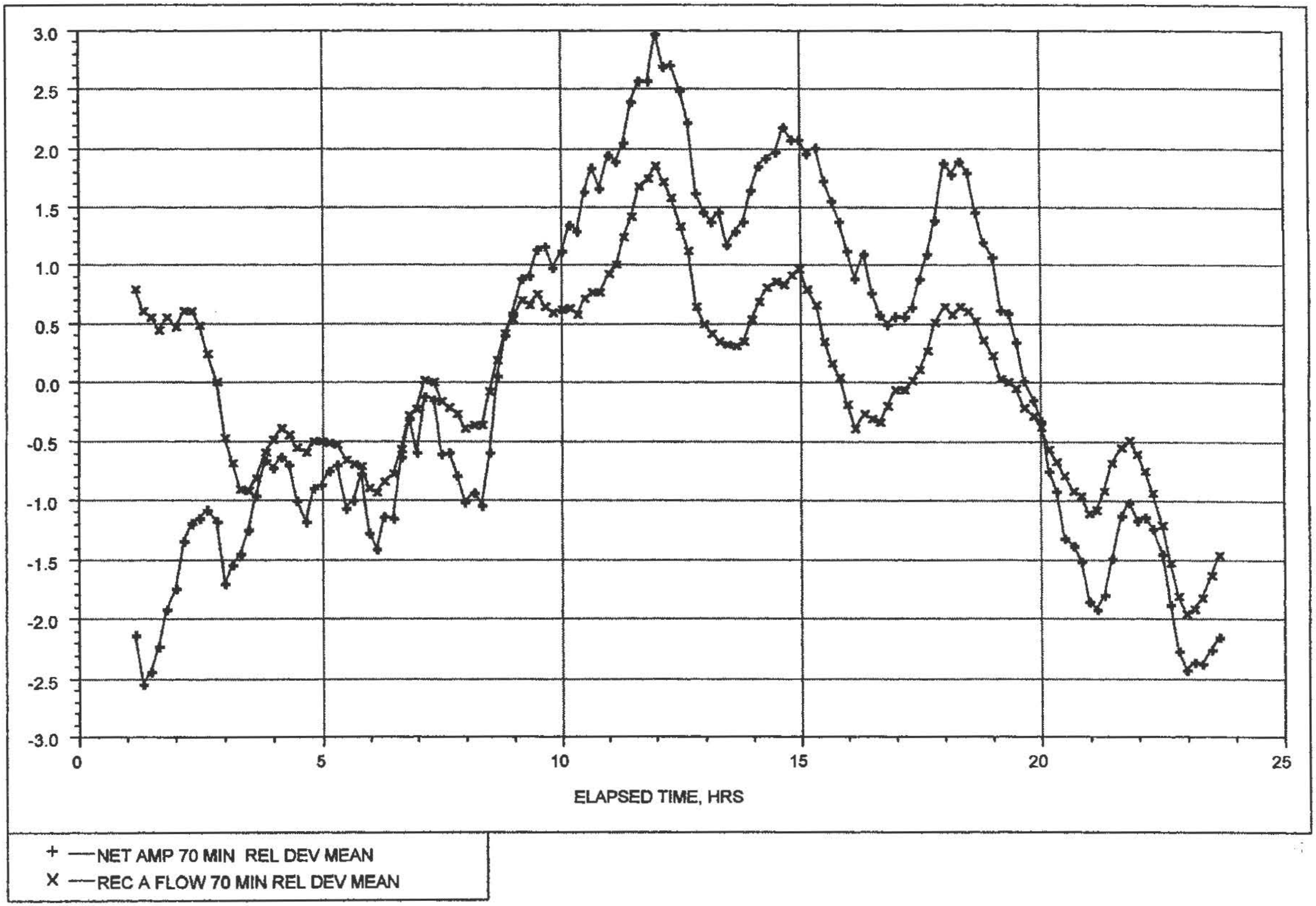


FIGURE 101

Plant Data: Test 1 - Unedited

Recoup A Duct Flow Rel. Dev. from Mean and Average Recoup Temperature (Both Ducts) Rel. Dev. from Mean

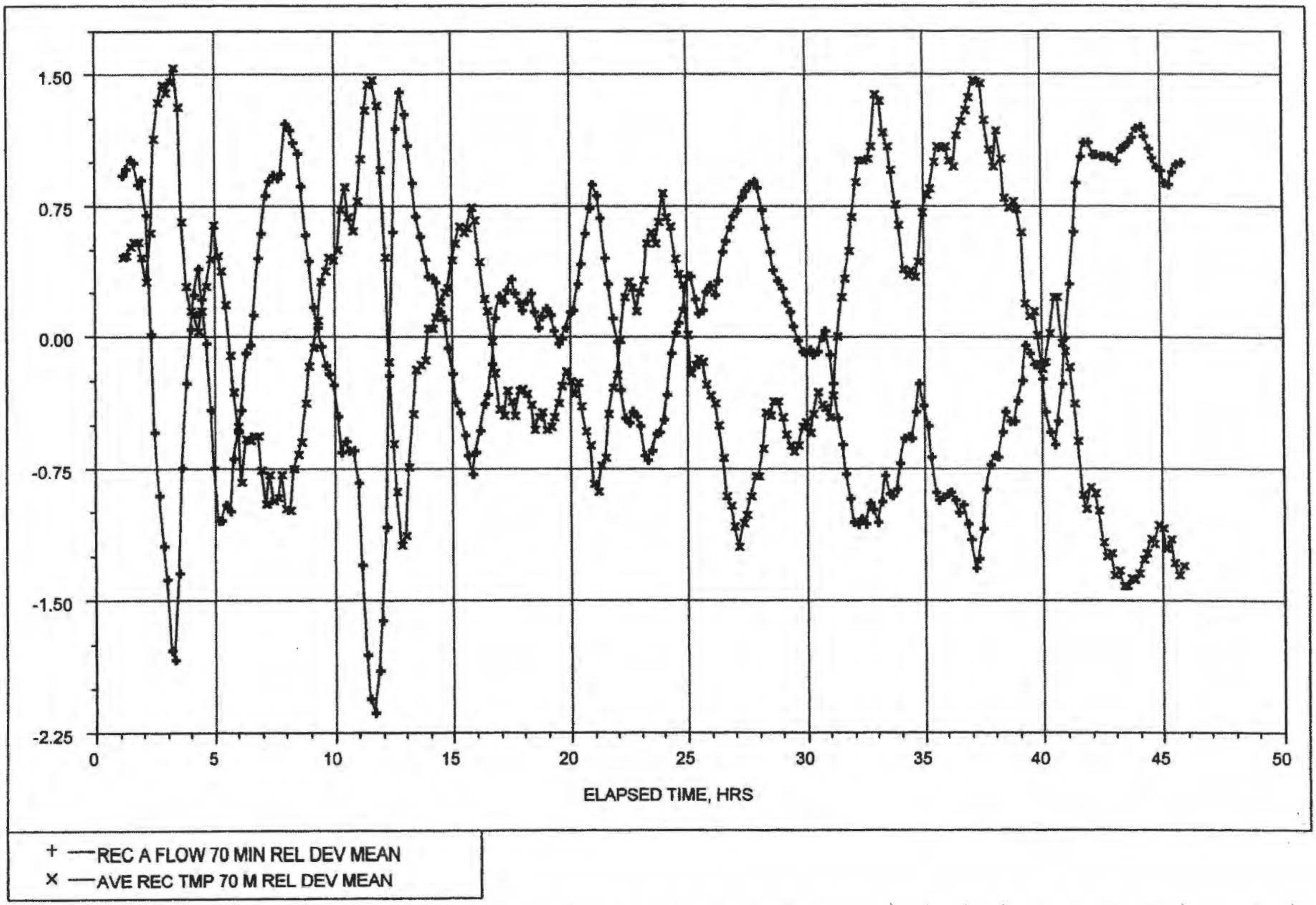


FIGURE 102

Plant Data: Test 2 - Unedited

Recoup A Duct Flow Rel. Dev. from Mean and Average Recoup Temperature (Both Ducts) Rel. Dev. from Mean

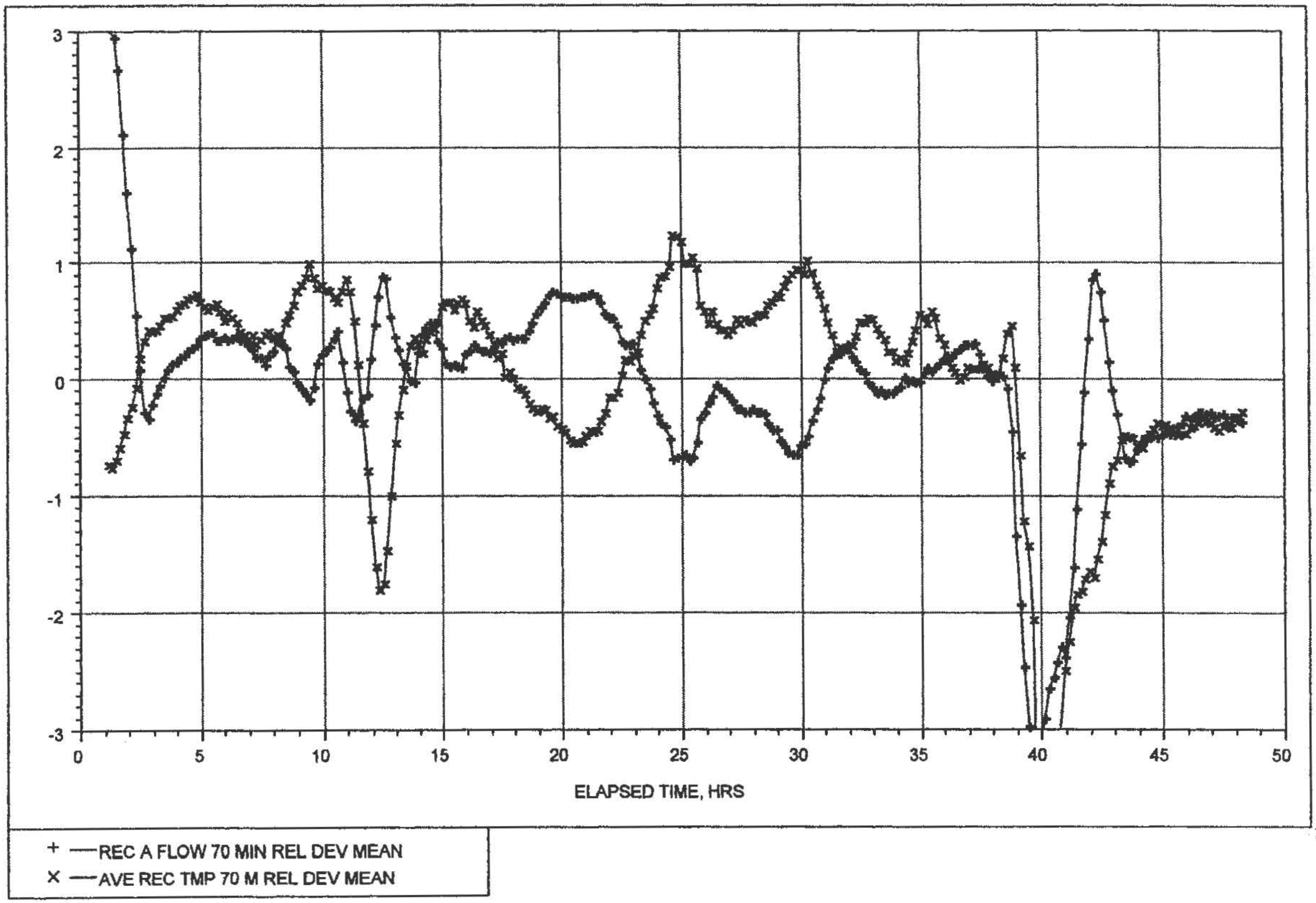


FIGURE 103

Plant Data: Test 3 - Unedited

Recoup A Duct Flow Rel. Dev. from Mean and Average Recoup Temperature (Both Ducts) Rel. Dev. from Mean

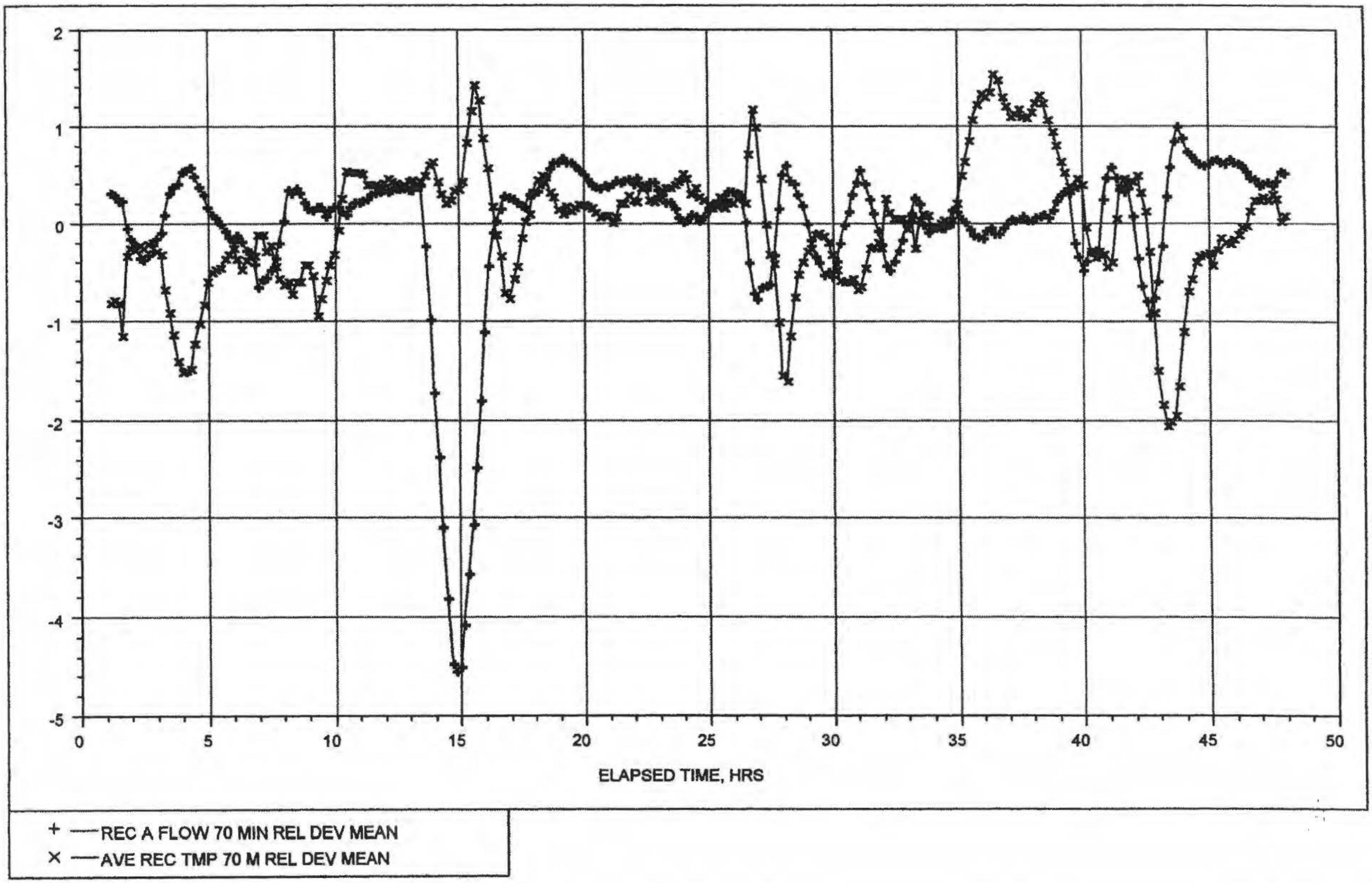


FIGURE 104

Plant Data: Test 4 - Unedited

Recoup A Duct Flow Rel. Dev. from Mean and Average Recoup Temperature (Both Ducts) Rel. Dev. from Mean

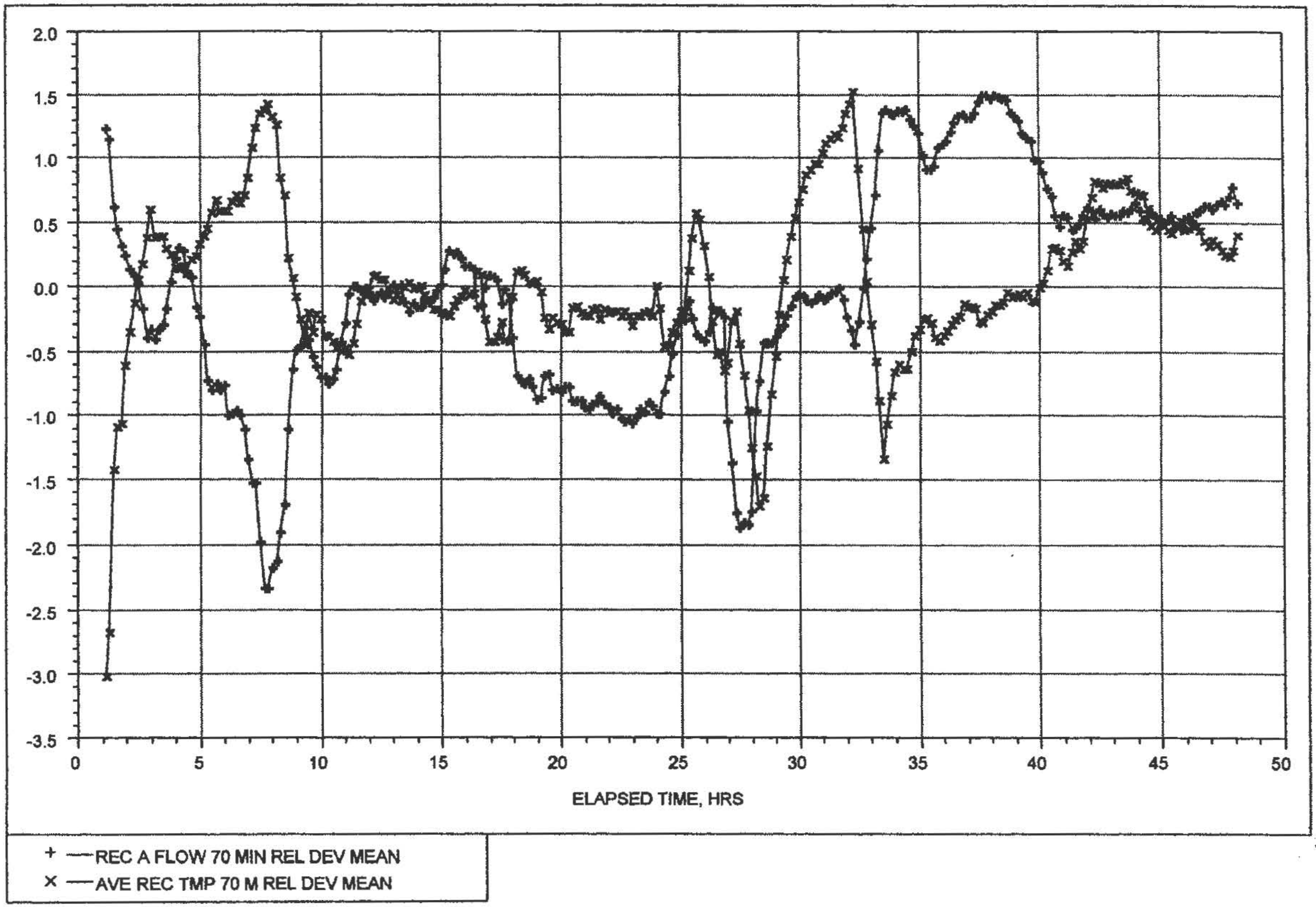


FIGURE 105

Plant Data: Test 5 - Unedited

Recoup A Duct Flow Rel. Dev. from Mean and Average Recoup Temperature (Both Ducts) Rel. Dev. from Mean

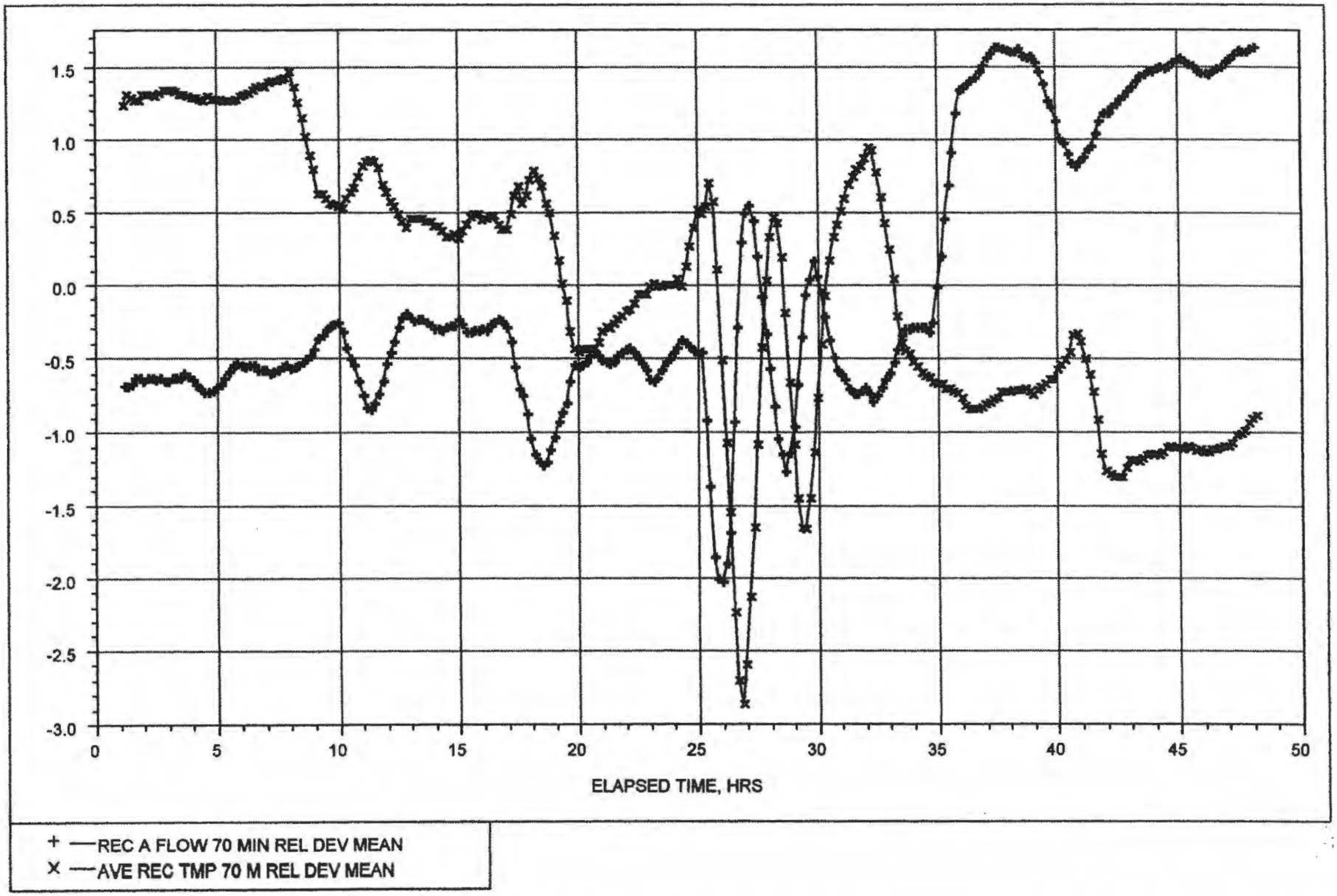


FIGURE 106

Plant Data: Test 7 - Unedited

Recoup A Duct Flow Rel. Dev. from Mean and Average Recoup Temperature (Both Ducts) Rel. Dev. from Mean

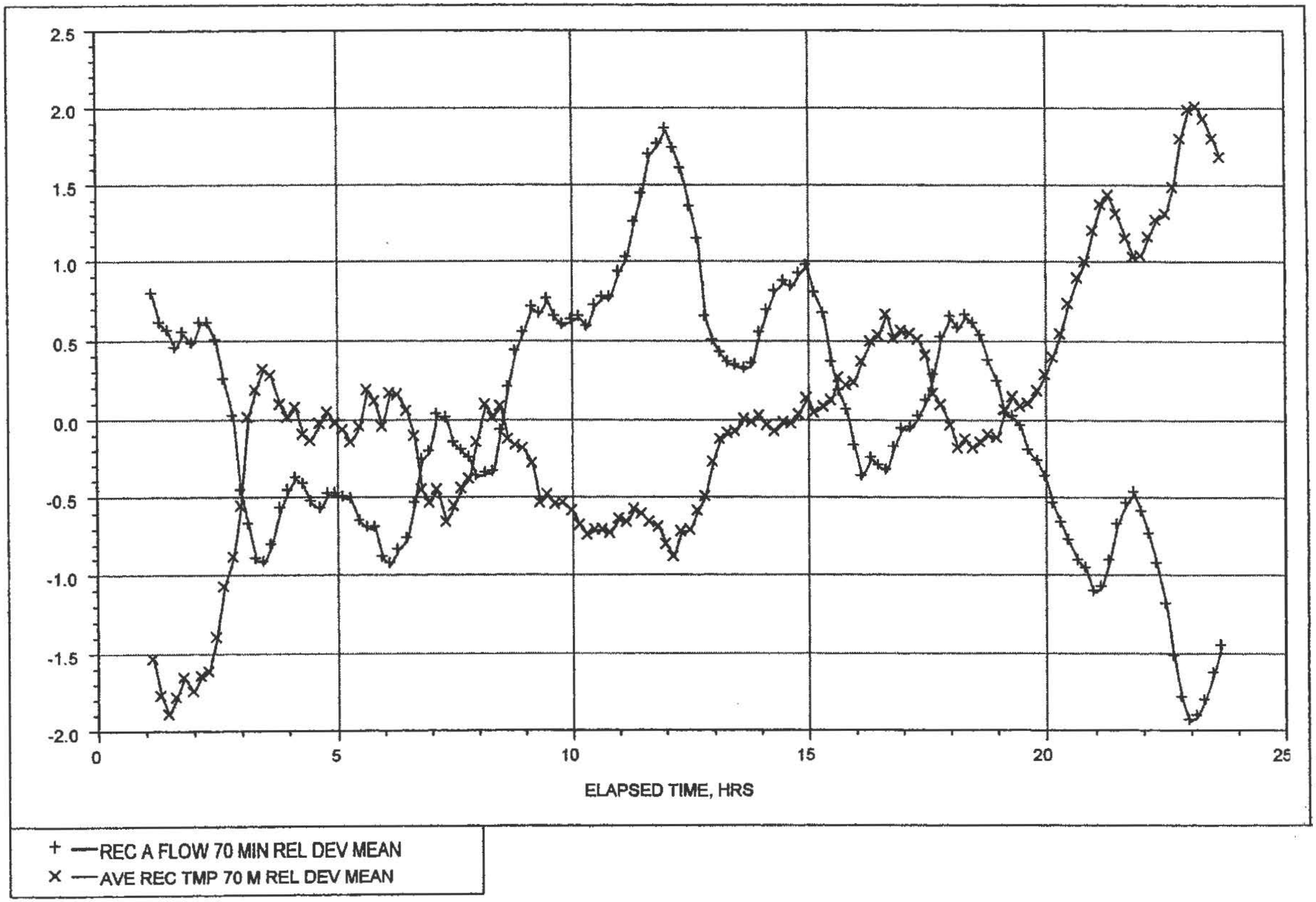


FIGURE 107

Plant Data: Test 1 - Unedited

Kiln Secondary Air, Average Recoup, and Vent Stack Temperature Relative Deviation from Mean

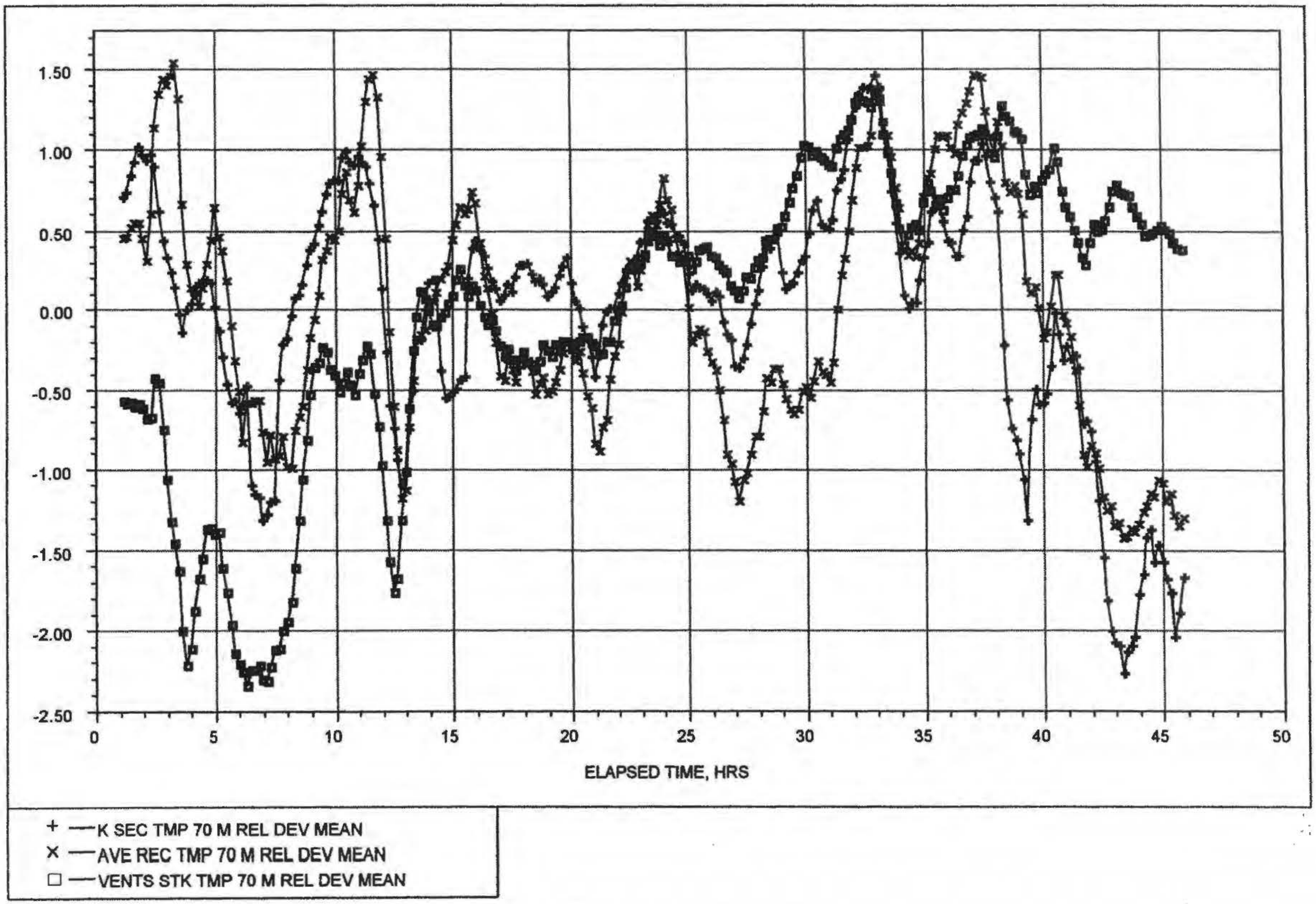


FIGURE 108

Plant Data: Test 2 - Unedited

Kiln Secondary Air, Average Recoup, and Vent Stack Temperature Relative Deviation from Mean

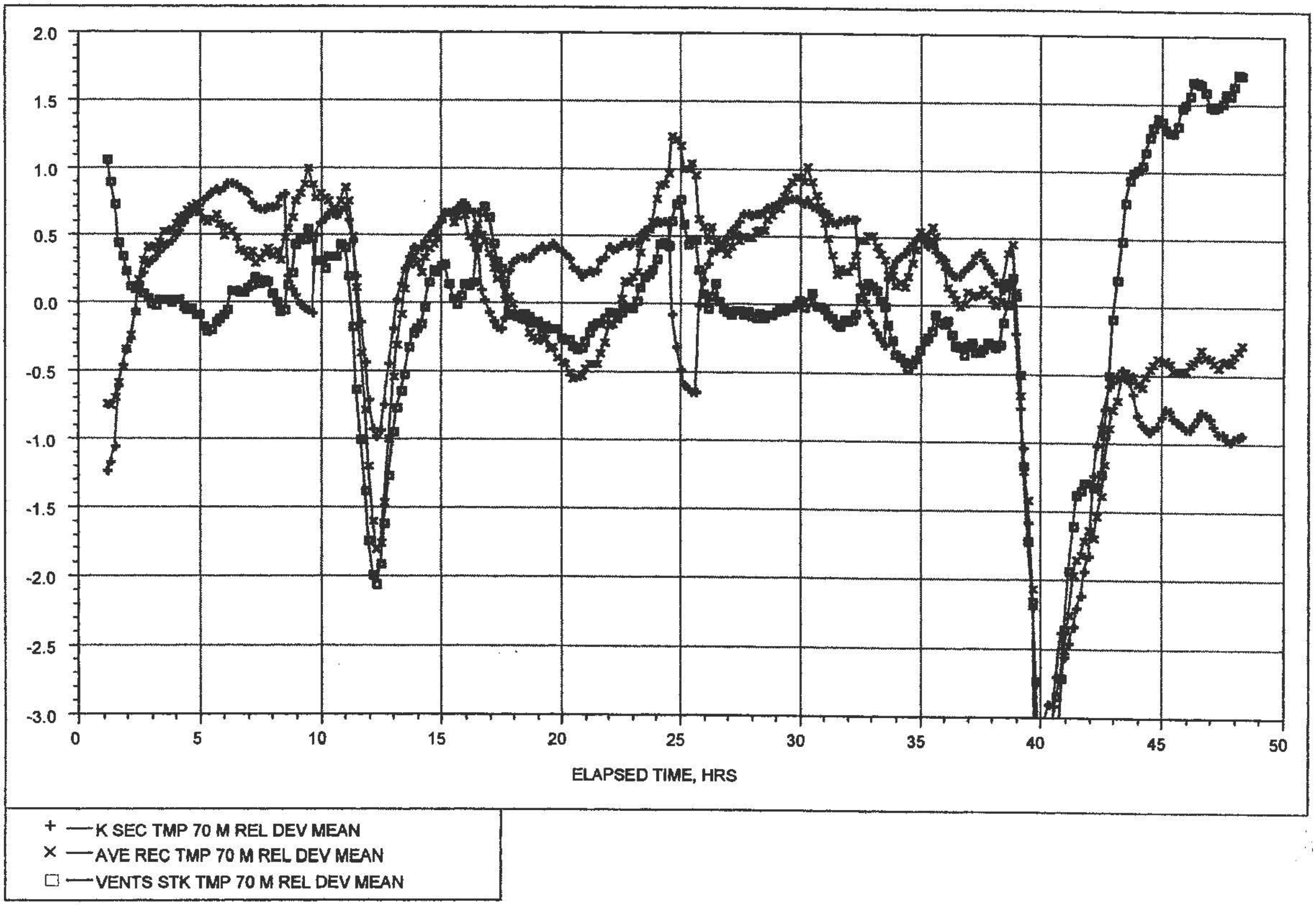


FIGURE 109

Plant Data: Test 3 - Unedited

Kiln Secondary Air, Average Recoup, and Vent Stack Temperature Relative Deviation from Mean

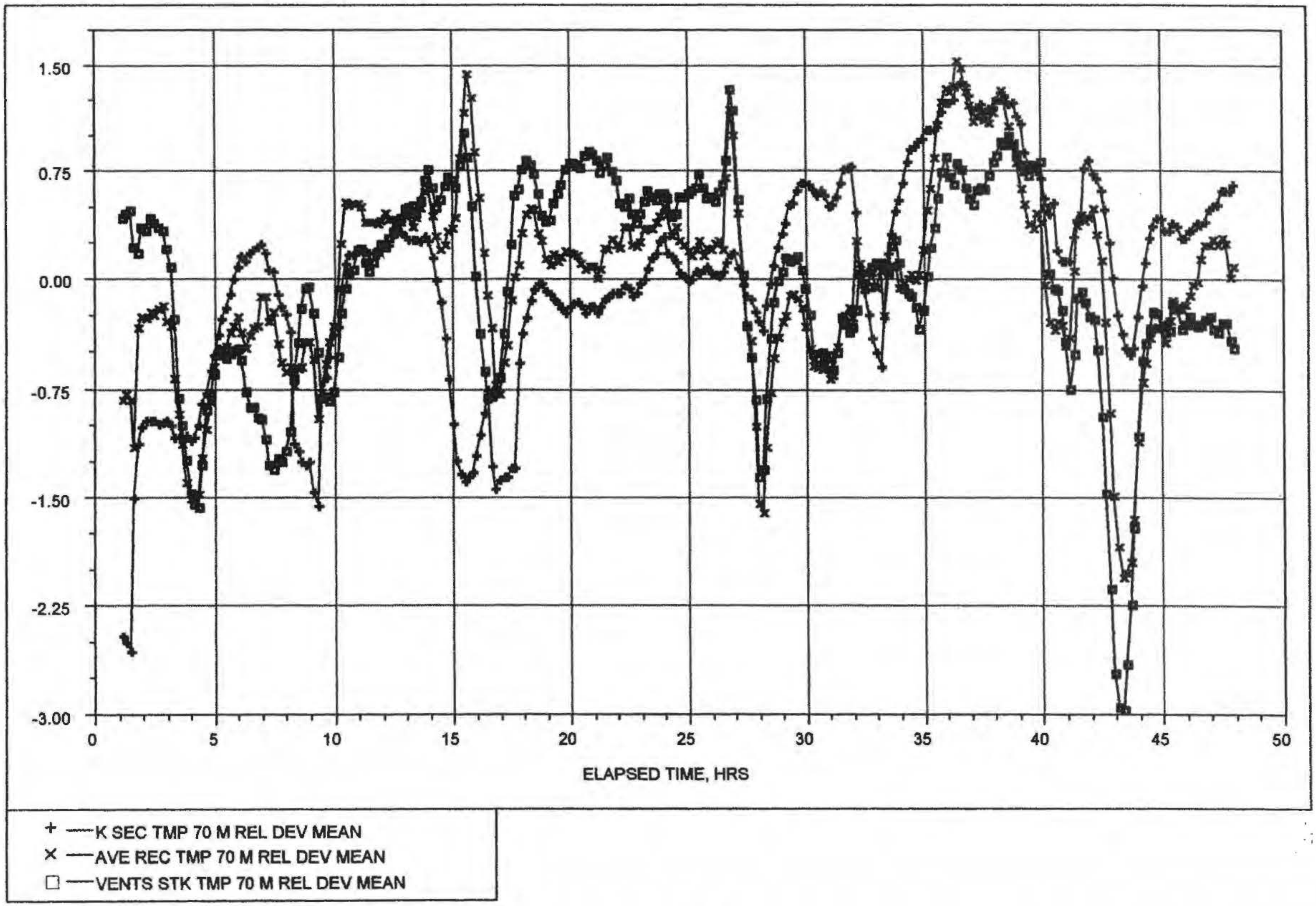


FIGURE 110

Plant Data: Test 4 - Unedited

Kiln Secondary Air, Average Recoup, and Vent Stack Temperature Relative Deviation from Mean

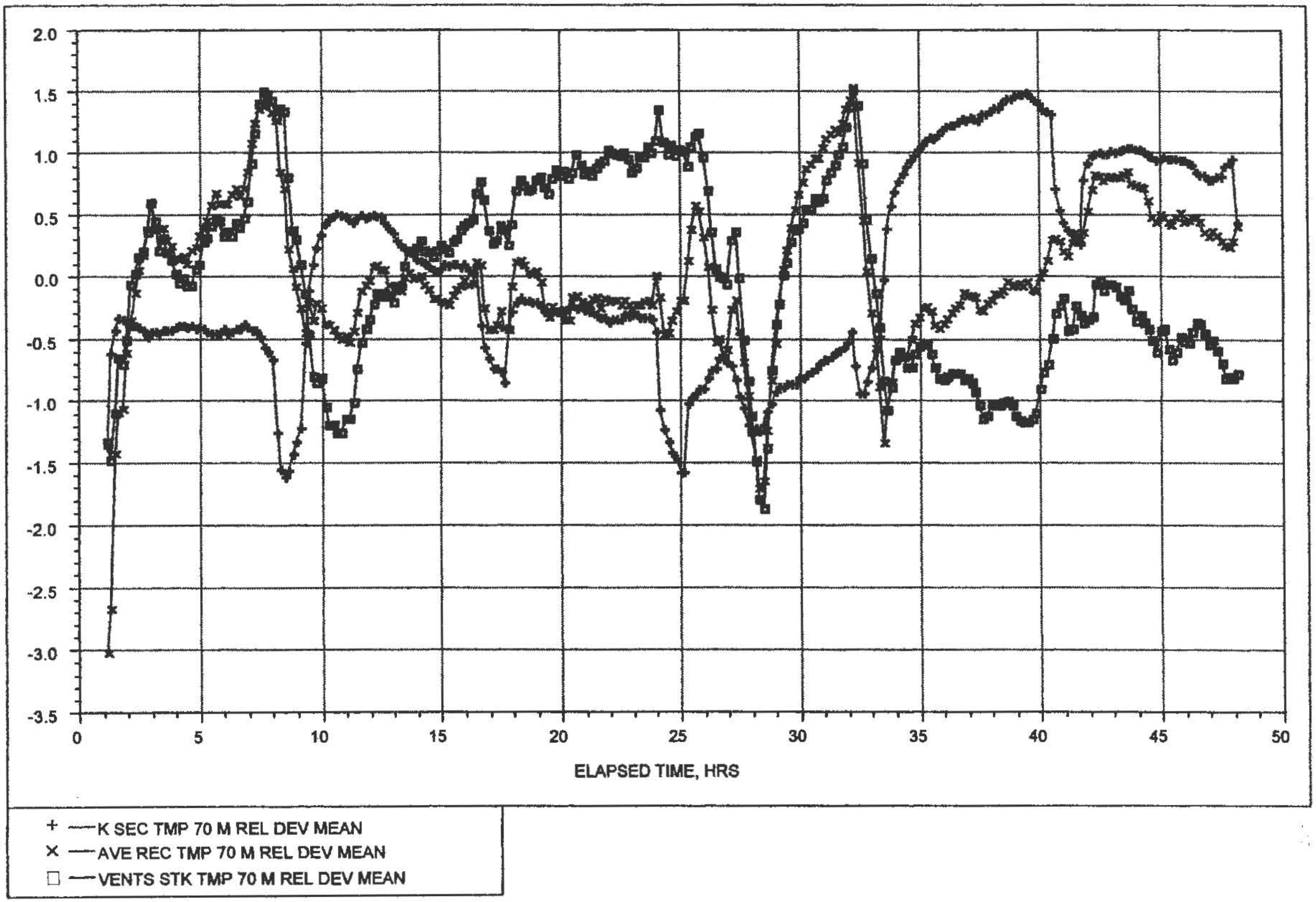


FIGURE 111

Plant Data: Test 5 - Unedited

Kiln Secondary Air, Average Recoup, and Vent Stack Temperature Relative Deviation from Mean

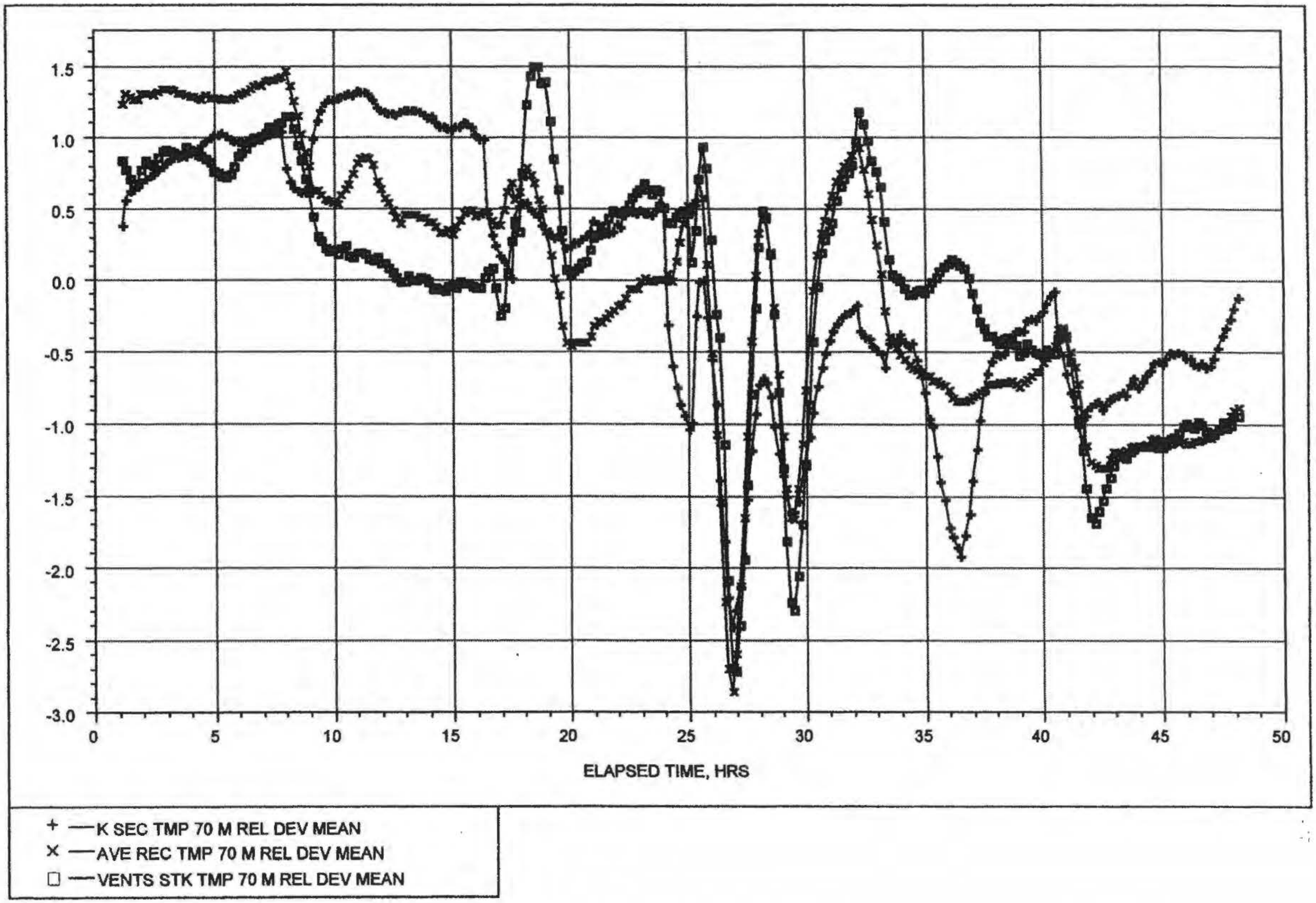


FIGURE 112

Plant Data: Test 7 - Unedited

Kiln Secondary Air, Average Recoup, and Vent Stack Temperature Relative Deviation from Mean

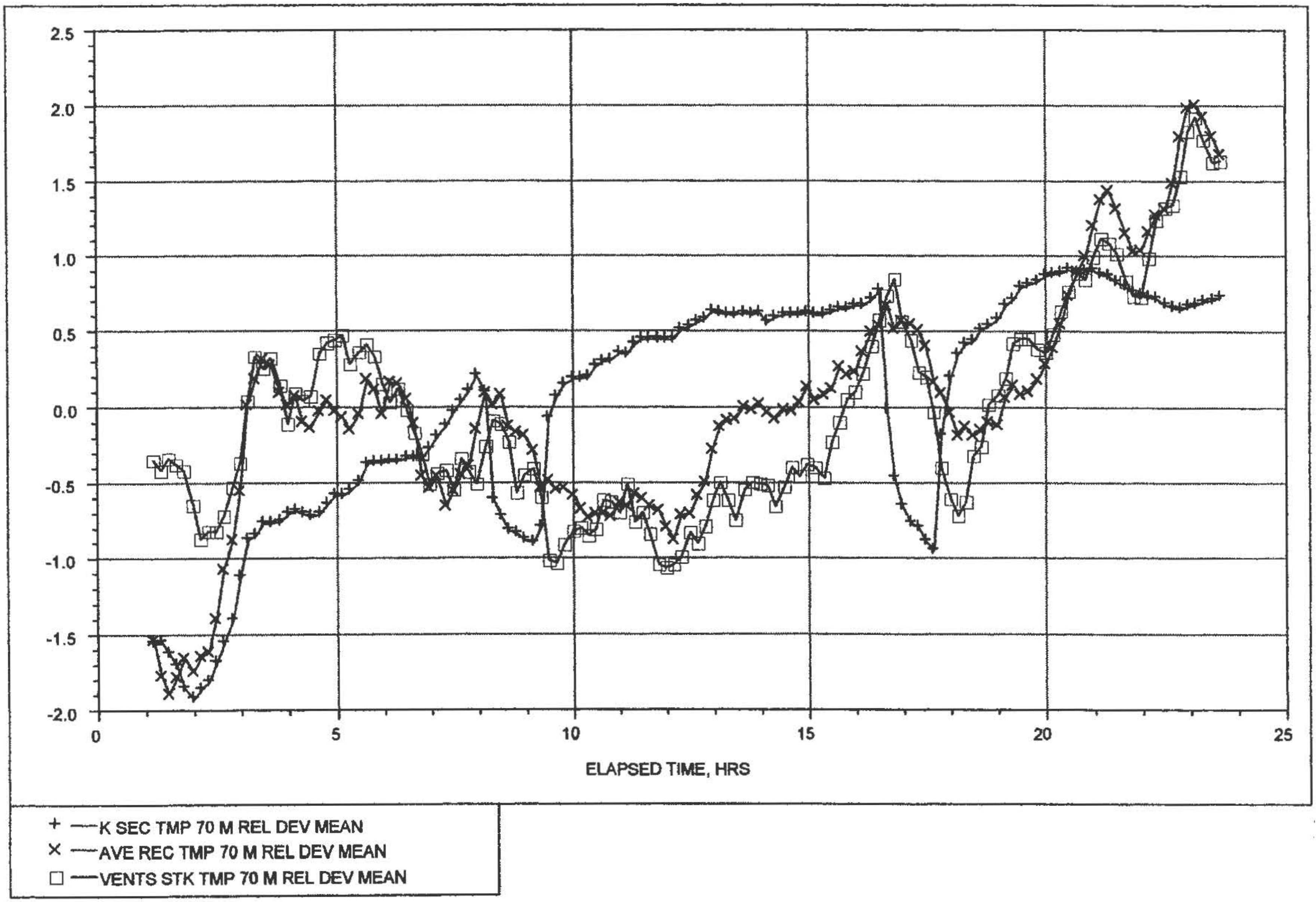
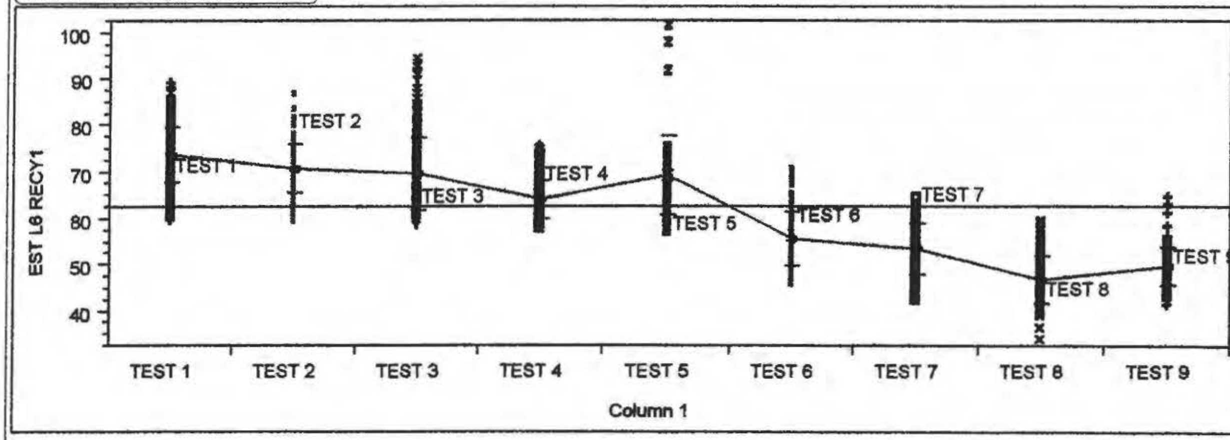


FIGURE 113

Plant Data: Test 1-9 Edited Composite

Estimated Line 6 Roll Feeder Returns and Line 6 Feed to Grate

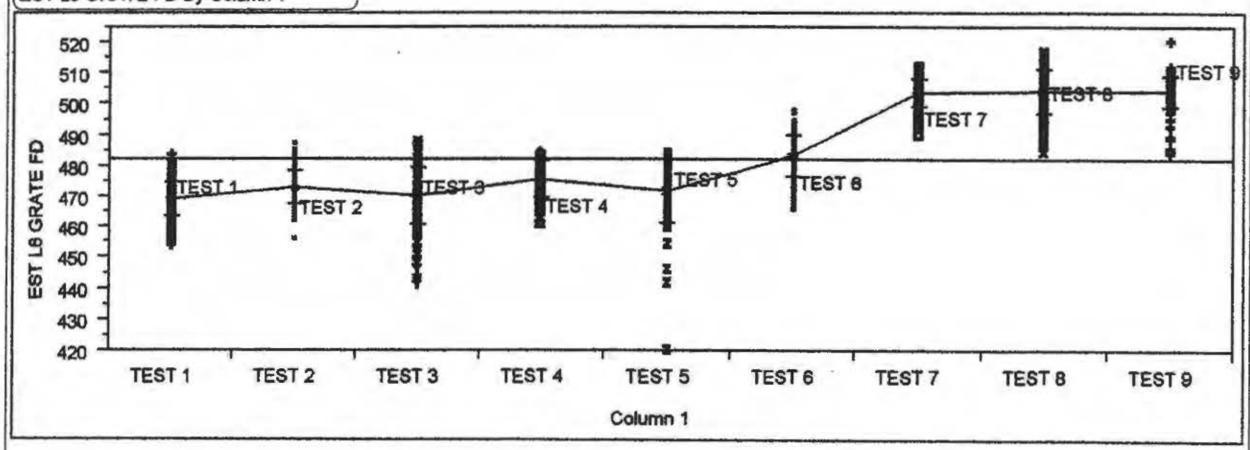
EST L6 RECY1 By Column 1



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	73.9209	5.92328	0.4127
TEST 2	179	70.7067	5.41186	0.4045
TEST 3	224	69.8040	7.97971	0.5332
TEST 4	173	64.0324	4.06511	0.3091
TEST 5	58	69.5069	8.45919	1.1107
TEST 6	154	55.7146	5.93166	0.4780
TEST 7	142	53.7209	5.80800	0.4874
TEST 8	134	46.9514	5.15960	0.4457
TEST 9	125	49.8272	4.15631	0.3718

EST L6 GRATE FD By Column 1



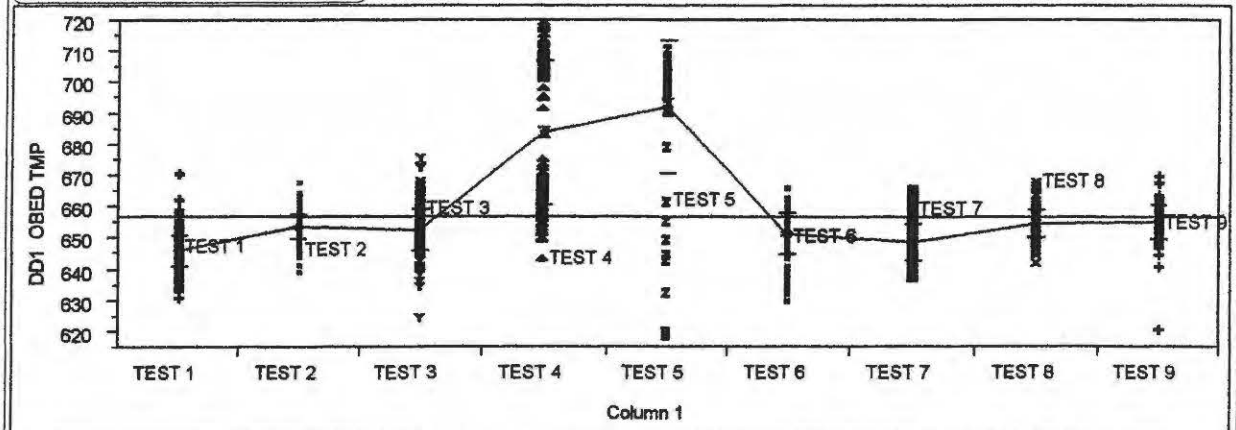
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	469.308	5.5837	0.3890
TEST 2	179	472.964	5.8450	0.4369
TEST 3	224	470.490	9.5197	0.6361
TEST 4	173	475.698	6.1862	0.4703
TEST 5	58	471.826	10.8552	1.4254
TEST 6	154	483.778	6.8784	0.5543
TEST 7	142	503.990	4.7581	0.3993
TEST 8	134	504.556	7.4950	0.6475
TEST 9	125	504.253	5.2844	0.4726

FIGURE 114

Plant Data: Test 1-9 Edited Composite
DD1 Overbed Temperature and DD2 Overbed Temperature

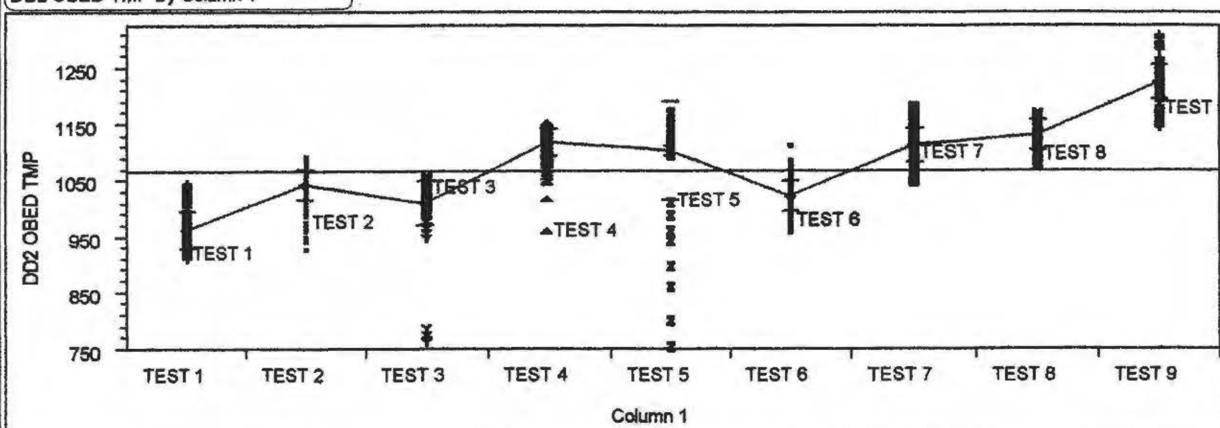
DD1 OBED TMP By Column 1



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	646.017	5.2430	0.3653
TEST 2	179	653.650	4.2149	0.3150
TEST 3	224	652.494	6.9067	0.4615
TEST 4	173	684.217	23.4025	1.7793
TEST 5	58	692.516	21.9736	2.8853
TEST 6	154	651.389	7.0619	0.5691
TEST 7	142	649.085	6.2370	0.5234
TEST 8	134	654.873	4.4997	0.3887
TEST 9	125	655.608	5.5633	0.4976

DD2 OBED TMP By Column 1



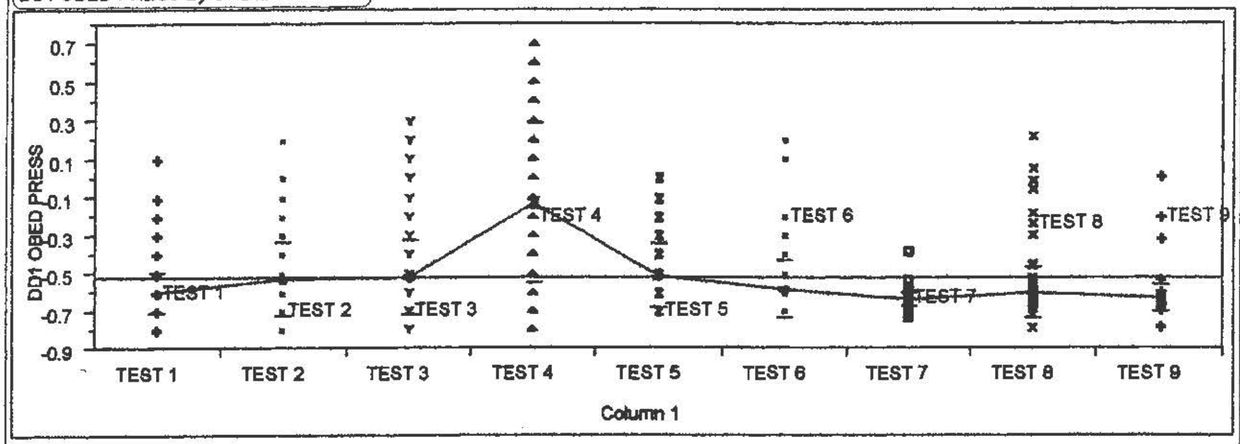
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	962.75	33.1697	2.311
TEST 2	179	1044.35	27.9847	2.092
TEST 3	224	1009.73	39.4599	2.637
TEST 4	173	1118.15	26.3102	2.000
TEST 5	58	1104.89	88.4127	11.609
TEST 6	154	1022.36	27.3763	2.206
TEST 7	142	1111.86	31.2951	2.626
TEST 8	134	1129.62	27.9166	2.412
TEST 9	125	1224.37	31.3131	2.801

FIGURE 115

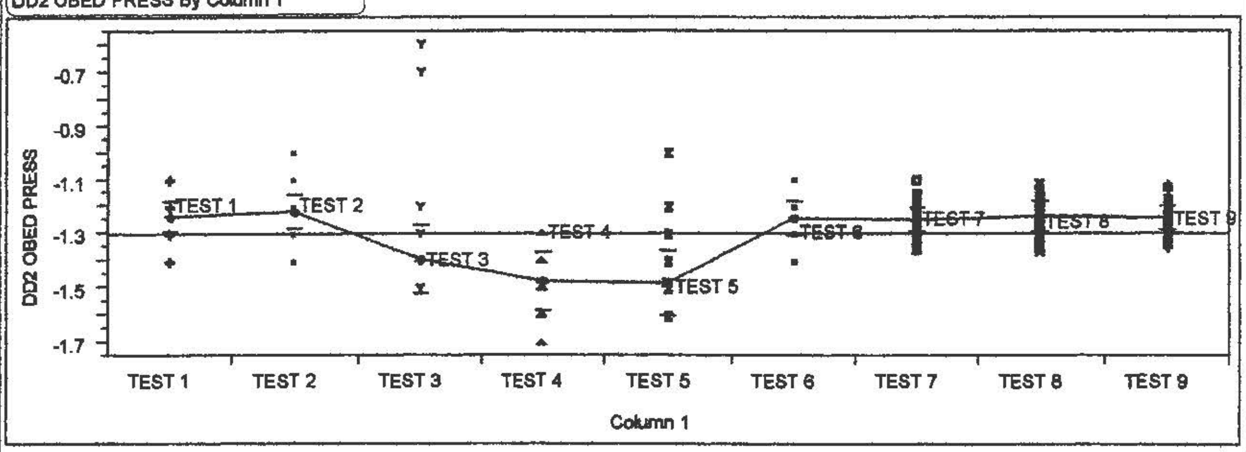
Plant Data: Test 1-9 Edited Composite

DD1 Overbed Pressure and DD2 Overbed Pressure



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	-0.59854	0.114542	0.00798
TEST 2	179	-0.52737	0.196541	0.01469
TEST 3	224	-0.52098	0.197420	0.01319
TEST 4	173	-0.1341	0.422539	0.03213
TEST 5	58	-0.51552	0.169418	0.02225
TEST 6	154	-0.58701	0.151550	0.01221
TEST 7	142	-0.63803	0.038449	0.00323
TEST 8	134	-0.60246	0.140356	0.01212
TEST 9	125	-0.62856	0.079613	0.00712

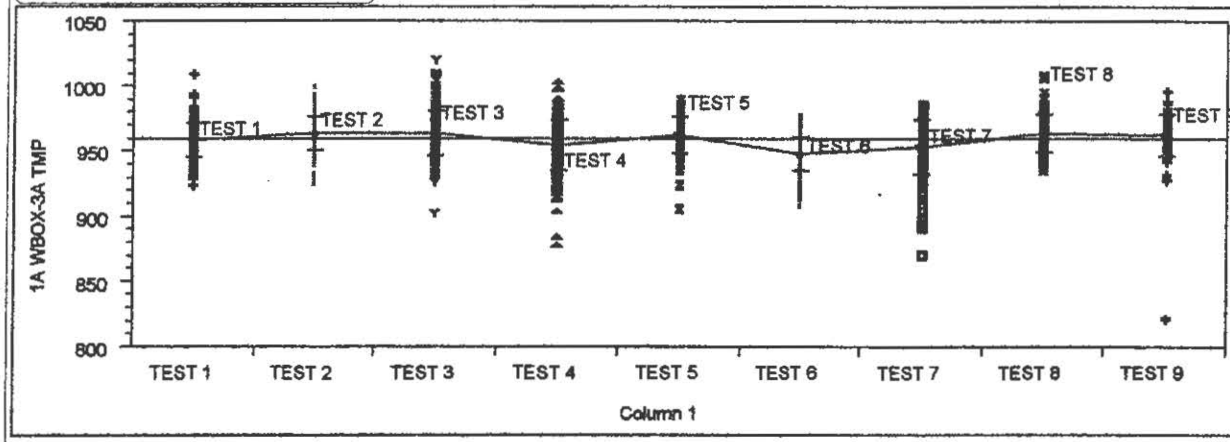


Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	-1.23786	0.058629	0.00408
TEST 2	179	-1.21620	0.064606	0.00483
TEST 3	224	-1.39196	0.129253	0.00864
TEST 4	173	-1.47803	0.111453	0.00847
TEST 5	58	-1.48276	0.121595	0.01597
TEST 6	154	-1.24481	0.066708	0.00538
TEST 7	142	-1.24817	0.047440	0.00398
TEST 8	134	-1.24037	0.057601	0.00498
TEST 9	125	-1.24384	0.046763	0.00418

FIGURE 116
Plant Data: Test 1-9 Edited Composite
Preheat Fan Damper Controlling Thermocouples

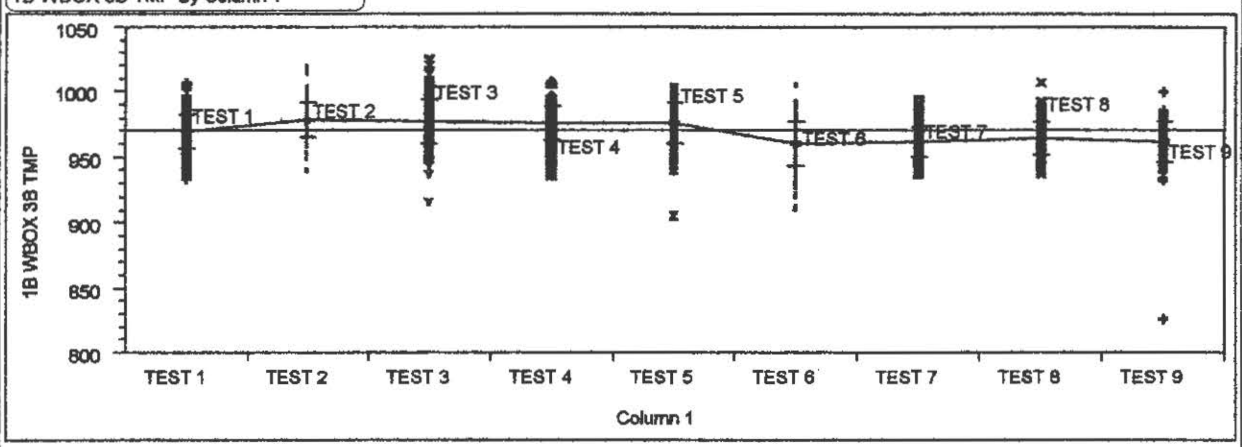
1A WBOX-3A TMP By Column 1



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	960.159	13.6617	0.9519
TEST 2	179	964.732	14.2398	1.0643
TEST 3	224	965.180	17.7619	1.1868
TEST 4	173	956.408	20.1314	1.5308
TEST 5	58	964.016	15.5442	2.0411
TEST 6	154	949.560	14.0279	1.1304
TEST 7	142	955.162	21.5455	1.8081
TEST 8	134	965.239	14.7466	1.2739
TEST 9	125	963.720	16.7946	1.5022

1B WBOX 3B TMP By Column 1



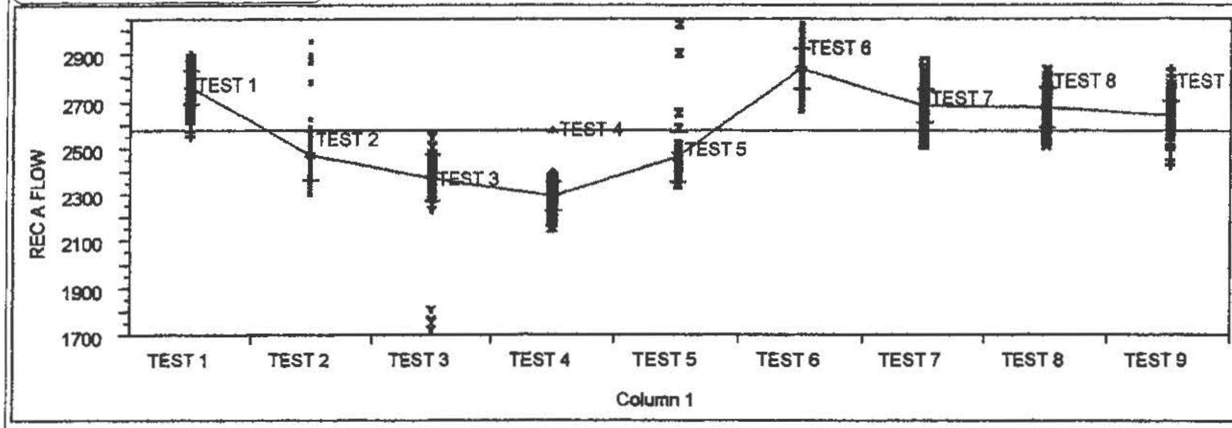
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	970.215	13.8116	0.9623
TEST 2	179	980.137	13.4515	1.0054
TEST 3	224	978.956	16.9839	1.1348
TEST 4	173	977.052	13.9485	1.0605
TEST 5	58	977.117	16.7051	2.1935
TEST 6	154	962.021	17.2184	1.3875
TEST 7	142	962.944	12.7451	1.0695
TEST 8	134	965.575	13.6725	1.1811
TEST 9	125	963.264	16.1536	1.4448

FIGURE 117

Plant Data: Test 1-9 Edited Composite
Recoup A Duct Flow and Thermocouple Temperature

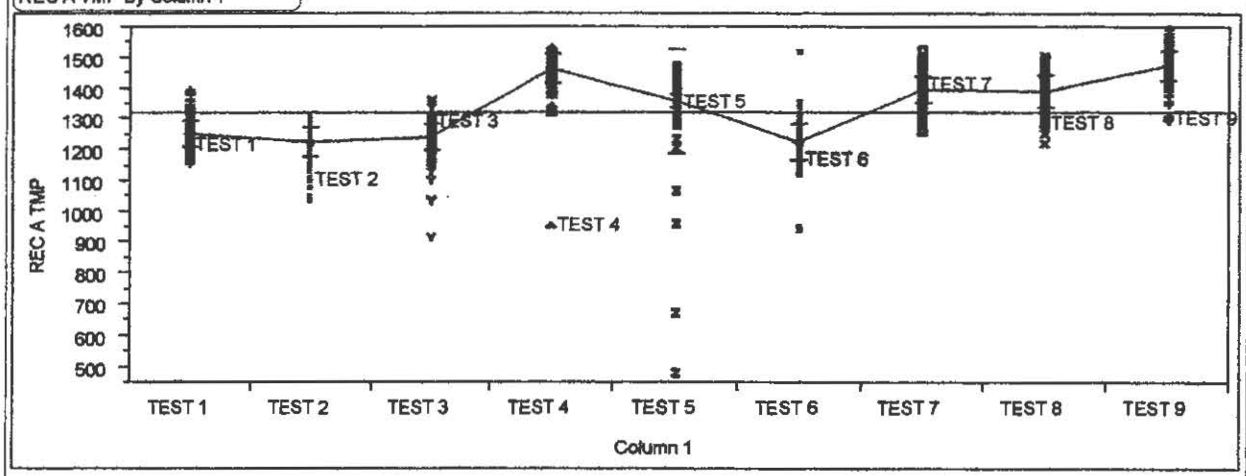
REC A FLOW By Column 1



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	2766.80	77.129	5.374
TEST 2	179	2474.06	110.143	8.232
TEST 3	224	2377.27	102.904	6.876
TEST 4	173	2297.72	67.845	5.158
TEST 5	58	2470.04	107.852	14.162
TEST 6	154	2842.34	89.980	7.251
TEST 7	142	2687.48	70.864	5.947
TEST 8	134	2678.79	85.012	7.344
TEST 9	125	2643.46	64.822	5.798

REC A TMP By Column 1



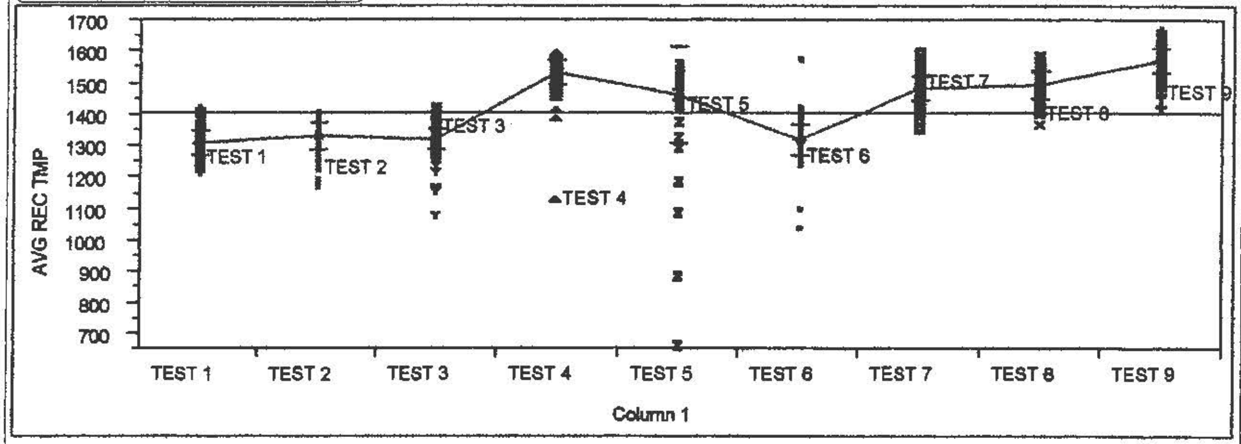
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	1250.12	44.002	3.066
TEST 2	179	1226.86	49.237	3.680
TEST 3	224	1241.27	47.848	3.197
TEST 4	173	1466.15	52.099	3.961
TEST 5	58	1360.51	173.627	22.798
TEST 6	154	1226.45	60.463	4.872
TEST 7	142	1394.46	45.573	3.824
TEST 6	134	1388.89	57.426	4.961
TEST 9	125	1474.59	49.200	4.401

FIGURE 118

Plant Data: Test 1-9 Edited Composite
Average Recoup Temp and Total Preheat Flow

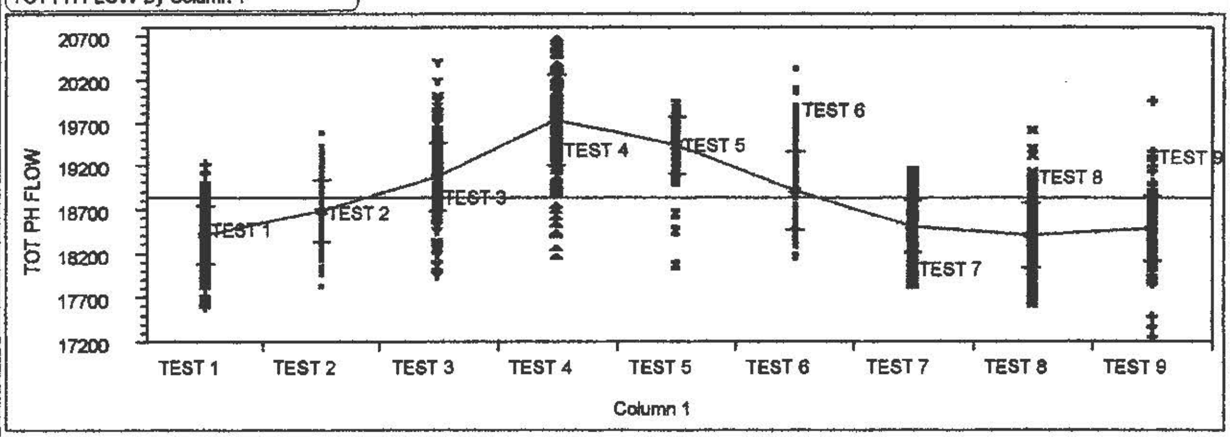
AVG REC TMP By Column 1



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	1308.72	41.273	2.876
TEST 2	179	1331.72	44.628	3.336
TEST 3	224	1320.87	38.122	2.547
TEST 4	173	1535.54	42.834	3.257
TEST 5	58	1464.00	156.642	20.568
TEST 6	154	1321.47	53.528	4.313
TEST 7	142	1484.94	41.732	3.502
TEST 8	134	1493.28	44.409	3.836
TEST 9	125	1569.48	42.013	3.758

TOT PH FLOW By Column 1



Means and Std Deviations

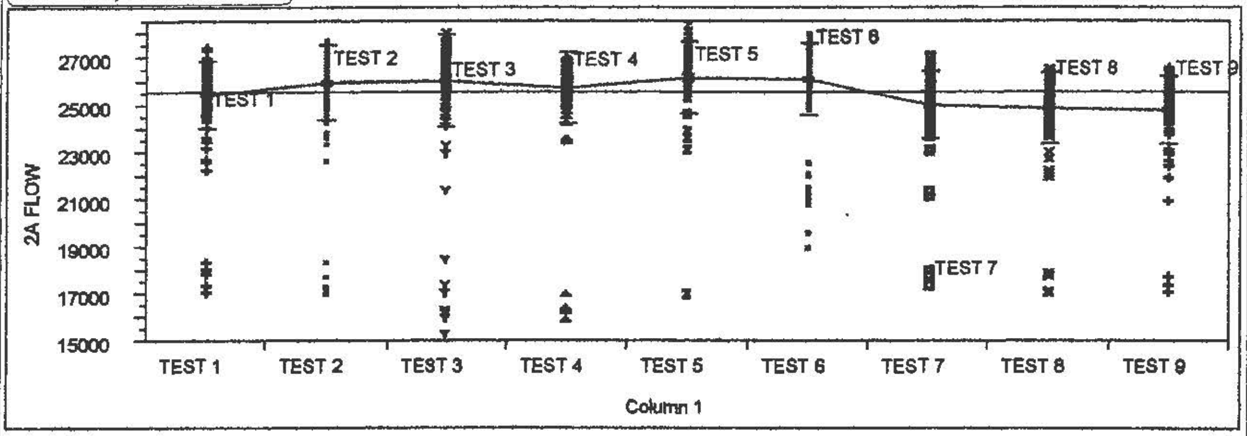
Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	18424.5	348.145	24.256
TEST 2	179	18689.2	363.008	27.133
TEST 3	224	19070.0	408.526	27.296
TEST 4	173	19741.6	530.285	40.317
TEST 5	58	19446.5	340.182	44.668
TEST 6	154	18931.9	463.805	37.374
TEST 7	142	18516.1	293.417	24.623
TEST 8	134	18425.0	383.861	33.161
TEST 9	125	18486.8	374.779	33.521

FIGURE 119

Plant Data: Test 1-9 Edited Composite

Waste Gas Fan (2A) Flow and Primary Cooling Fan (3A) Flow

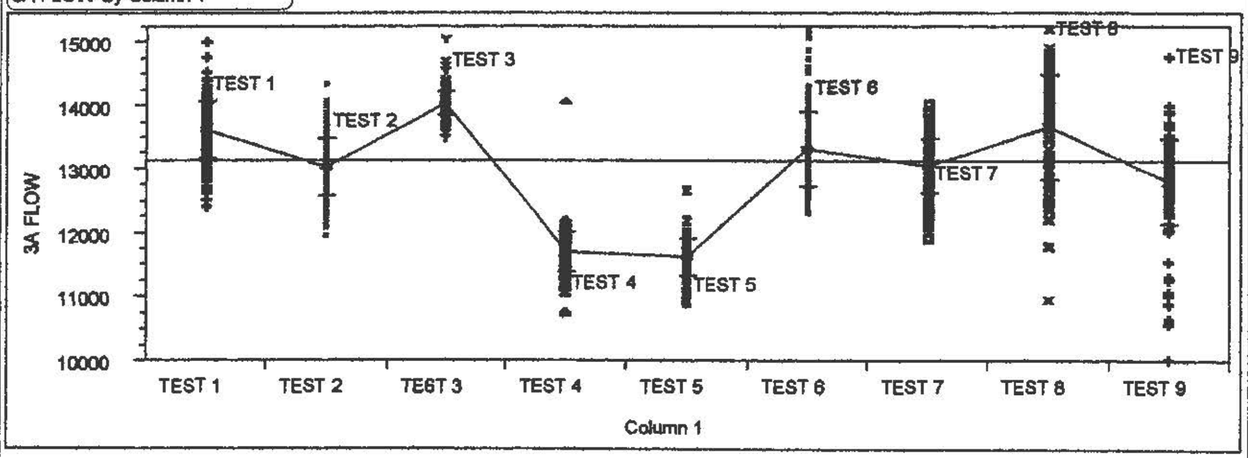
2A FLOW By Column 1



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	25440.5	1435.69	100.03
TEST 2	179	25976.6	1624.59	121.43
TEST 3	224	26011.1	1996.91	133.42
TEST 4	173	25730.8	1544.26	117.41
TEST 5	58	26157.7	1510.40	198.33
TEST 6	154	26098.8	1523.49	122.77
TEST 7	142	25011.1	1481.70	124.34
TEST 8	134	24870.4	1563.93	135.10
TEST 9	125	24810.7	1444.64	129.21

3A FLOW By Column 1



Means and Std Deviations

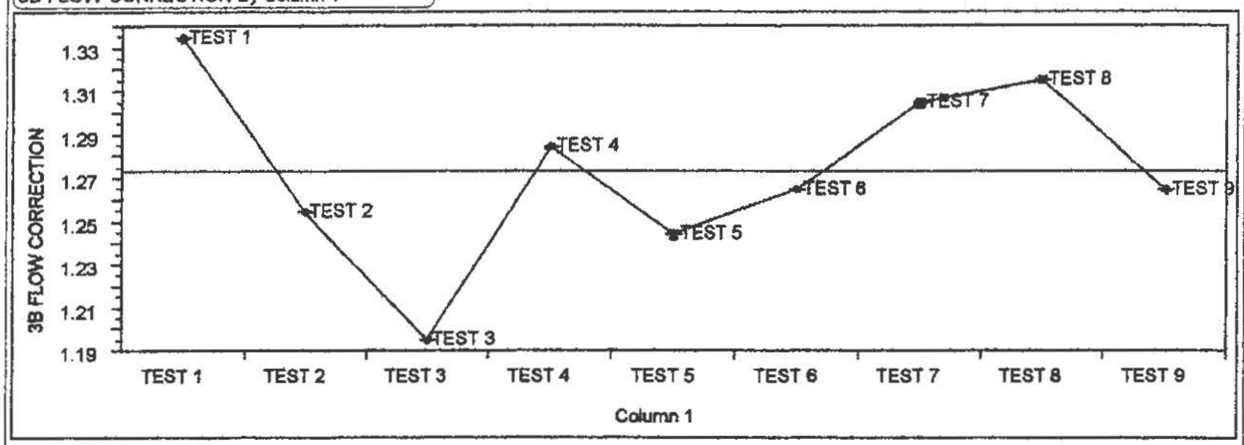
Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	13618.7	461.852	32.179
TEST 2	179	13033.7	465.078	34.762
TEST 3	224	14035.2	203.320	13.585
TEST 4	173	11701.9	324.108	24.641
TEST 5	58	11620.8	310.654	40.791
TEST 6	154	13328.8	599.247	48.289
TEST 7	142	13058.4	429.524	36.045
TEST 8	134	13683.3	843.108	72.833
TEST 9	125	12835.2	676.216	60.483

FIGURE 120

Plant Data: Test 1-9 Edited Composite

Secondary Cooling Fan (3B) Correction Factor and Cooler Fan Inlet Temperature

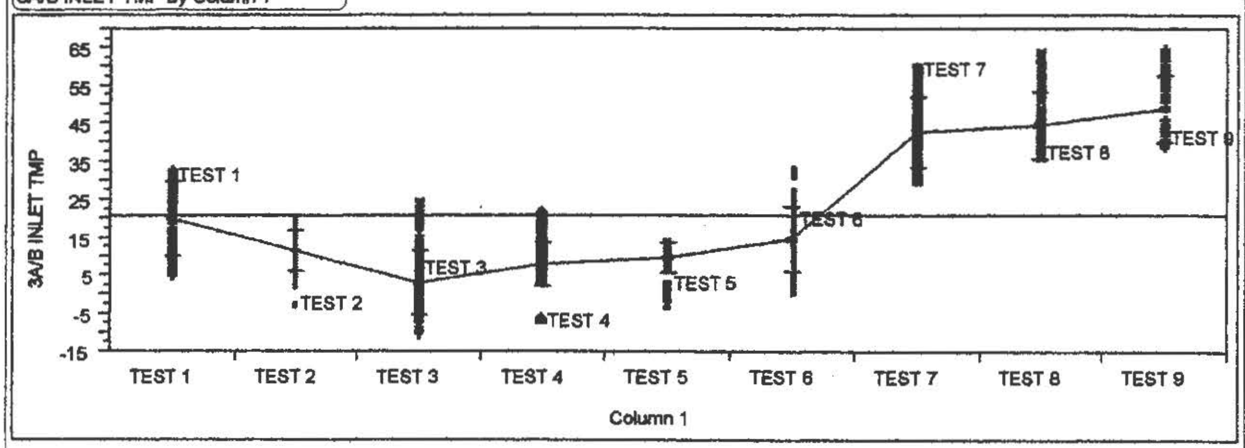
3B FLOW CORRECTION By Column 1



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	1.33000	0	0
TEST 2	179	1.25000	0	0
TEST 3	224	1.19000	0	0
TEST 4	173	1.28000	0	0
TEST 5	58	1.24000	0	0
TEST 6	154	1.26000	8.512e-8	6.86e-9
TEST 7	142	1.30000	0	0
TEST 8	134	1.31000	0	0
TEST 9	125	1.26000	3.706e-8	3.32e-9

3A/B INLET TMP By Column 1



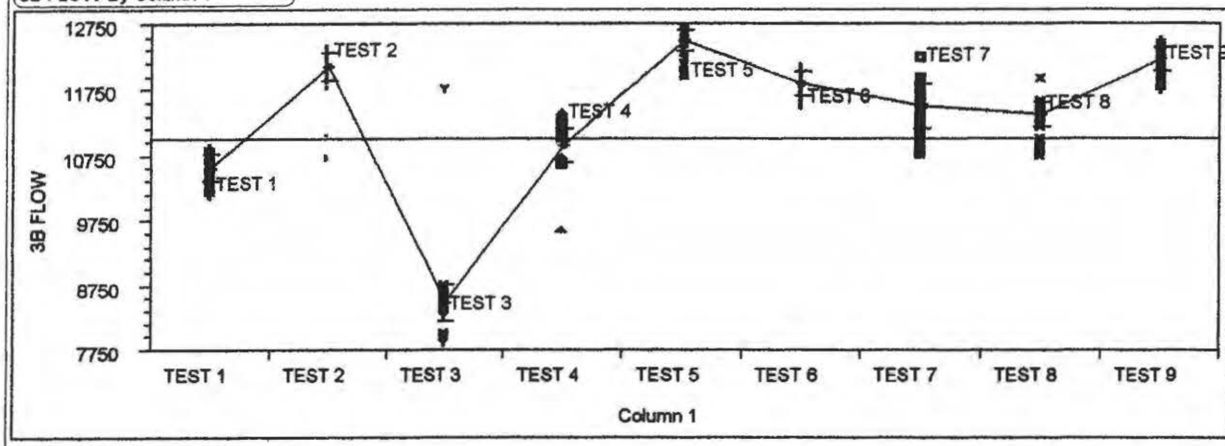
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	19.7374	10.2001	0.71068
TEST 2	179	11.5704	5.7356	0.42870
TEST 3	224	3.2402	8.8992	0.59460
TEST 4	173	7.8358	5.8442	0.44433
TEST 5	58	9.5845	4.0206	0.52792
TEST 6	154	14.7091	8.5464	0.68869
TEST 7	142	42.5282	9.5707	0.80316
TEST 8	134	44.8119	8.9223	0.77077
TEST 9	125	48.8000	9.2012	0.82298

FIGURE 121

Plant Data: Test 1-9 Edited Composite
Secondary Cooling Fan (3B) Uncorrected and Corrected Flow

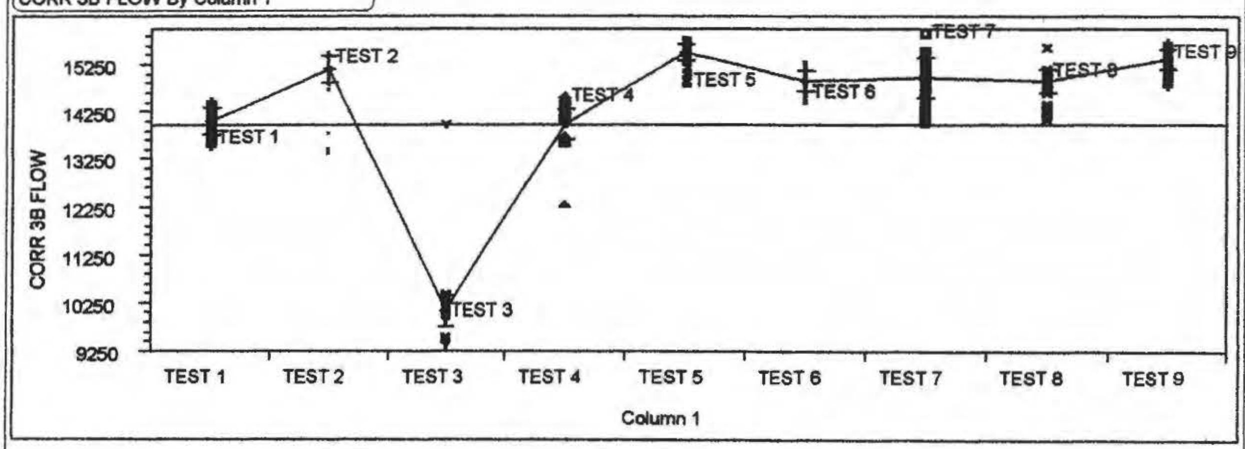
3B FLOW By Column 1



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	10571.0	214.976	14.978
TEST 2	179	12123.9	232.116	17.349
TEST 3	224	8481.0	289.931	19.372
TEST 4	173	10919.9	269.656	20.502
TEST 5	58	12511.9	163.769	21.504
TEST 6	154	11847.7	184.280	14.850
TEST 7	142	11523.6	352.500	29.581
TEST 8	134	11379.2	190.683	16.472
TEST 9	125	12208.3	187.443	16.765

CORR 3B FLOW By Column 1



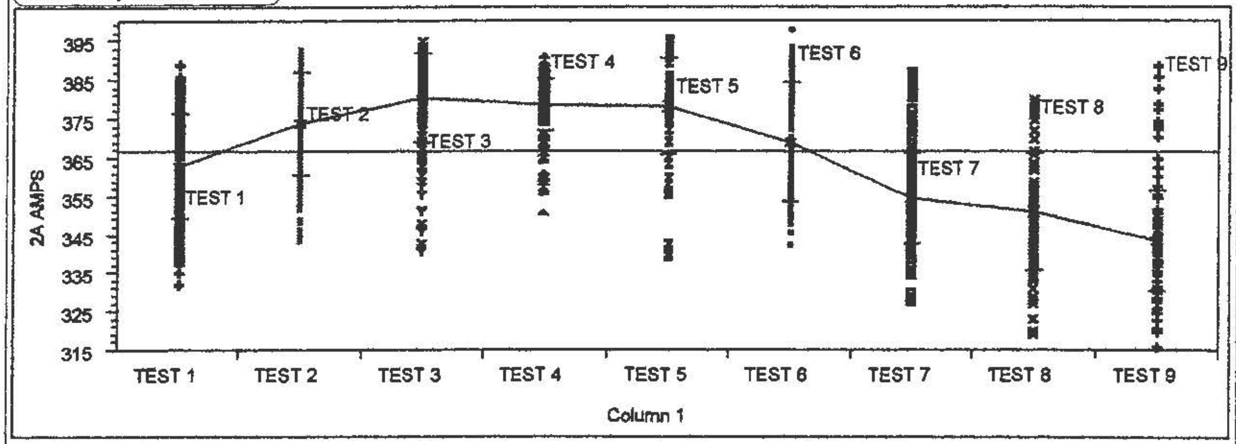
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	14059.5	285.919	19.921
TEST 2	179	15154.9	290.147	21.687
TEST 3	224	10092.4	345.018	23.052
TEST 4	173	13977.5	345.159	26.242
TEST 5	58	15514.8	203.073	26.665
TEST 6	154	14928.1	232.193	18.711
TEST 7	142	14980.7	458.250	38.456
TEST 8	134	14906.8	249.794	21.579
TEST 9	125	15382.5	236.178	21.124

FIGURE 122

Plant Data: Test 1-9 Edited Composite
Waste Gas Fan (2A) and Average Preheat Fan (1A/B) Amps

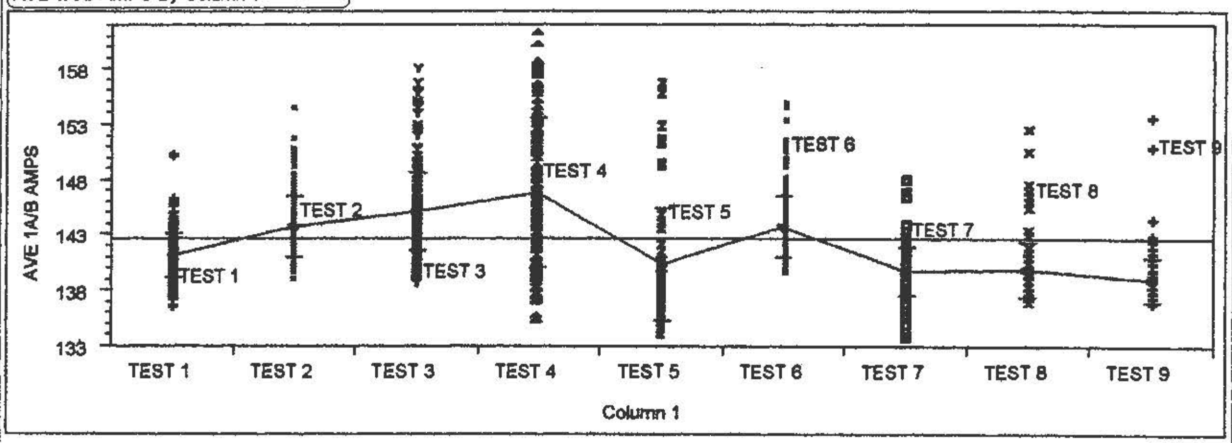
2A AMPS By Column 1



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	362.989	13.6664	0.9522
TEST 2	179	374.059	13.4738	1.0071
TEST 3	224	380.375	11.6554	0.7788
TEST 4	173	378.894	6.7397	0.5124
TEST 5	58	378.450	12.4175	1.6305
TEST 6	154	369.245	15.6343	1.2598
TEST 7	142	354.831	12.0295	1.0095
TEST 8	134	351.015	15.7260	1.3585
TEST 9	125	343.792	13.3007	1.1896

AVE 1A/B AMPS By Column 1



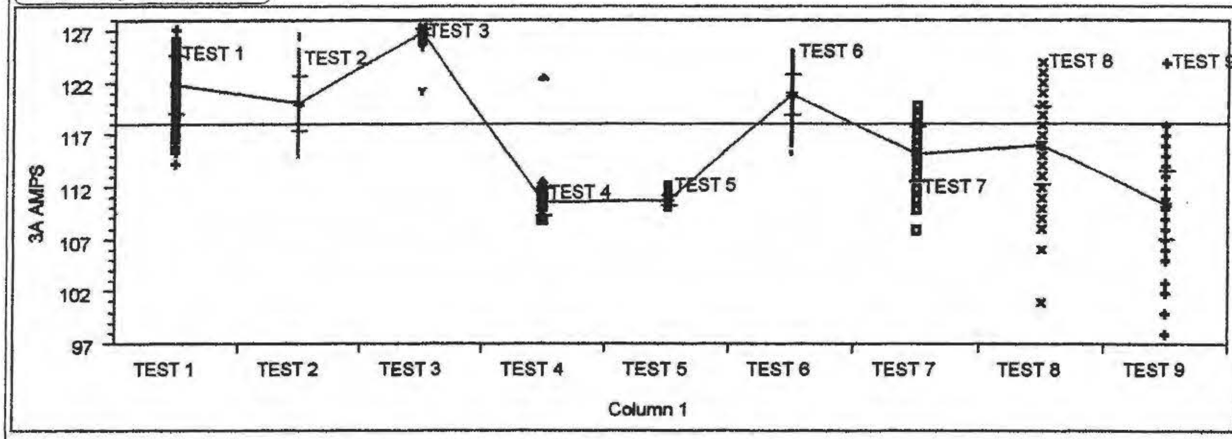
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	141.172	1.99842	0.13924
TEST 2	179	143.826	2.80542	0.20969
TEST 3	224	145.122	3.66312	0.24475
TEST 4	173	146.858	6.83311	0.51951
TEST 5	58	140.478	5.10136	0.66984
TEST 6	154	143.812	2.78699	0.22458
TEST 7	142	139.743	2.19666	0.18434
TEST 8	134	139.888	2.45535	0.21211
TEST 9	125	139.036	2.05781	0.18406

FIGURE 123

Plant Data: Test 1-9 Edited Composite
Primary Cooling Fan (3A) and Secondary Cooling Fan (3B) Amps

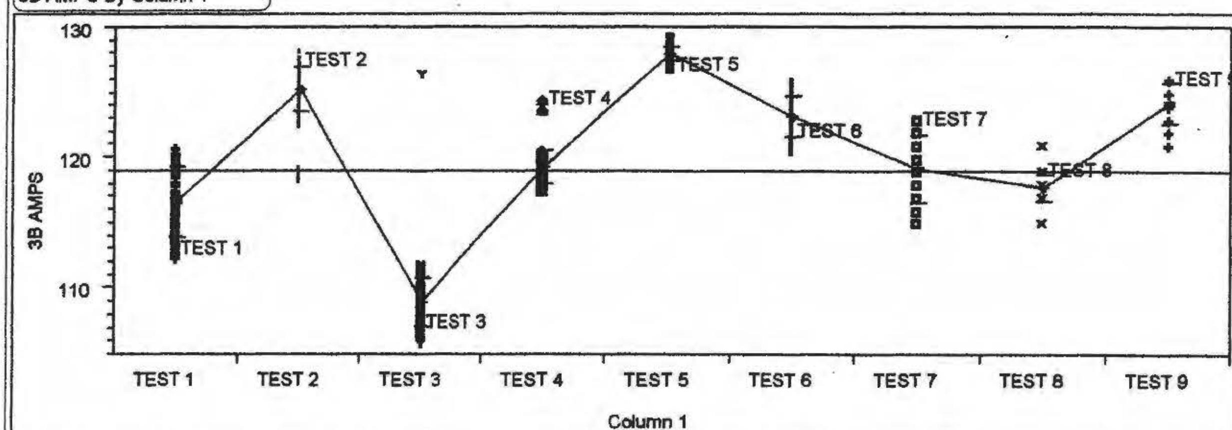
3A AMPS By Column 1



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	121.846	2.83309	0.19739
TEST 2	179	120.139	2.68726	0.20086
TEST 3	224	126.924	0.46945	0.03137
TEST 4	173	110.586	1.44160	0.10960
TEST 5	58	110.772	0.58333	0.07660
TEST 6	154	120.921	2.06233	0.16619
TEST 7	142	115.190	2.62809	0.22054
TEST 8	134	115.978	3.88842	0.33591
TEST 9	125	110.240	3.33215	0.29804

3B AMPS By Column 1



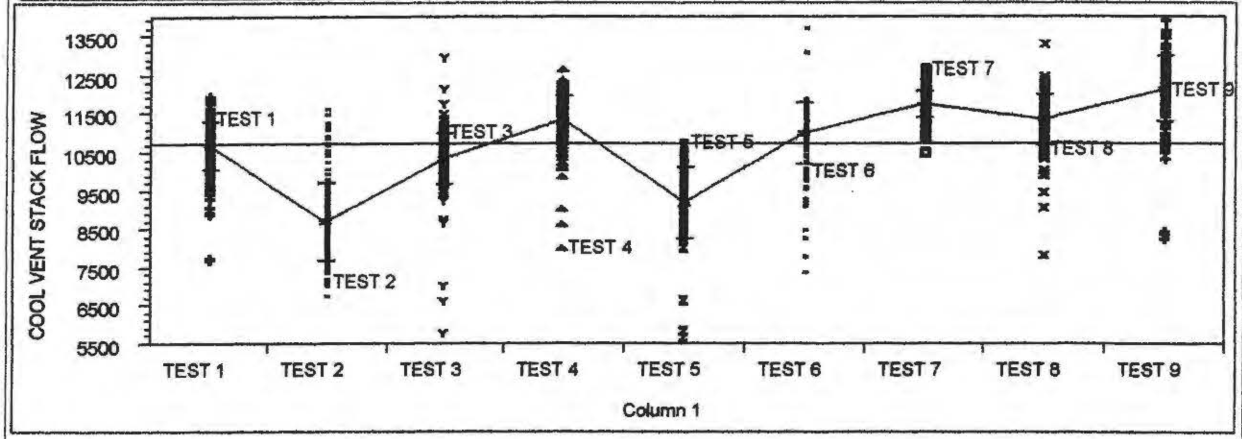
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	116.637	2.80957	0.19575
TEST 2	179	125.253	1.69736	0.12687
TEST 3	224	109.008	1.87447	0.12524
TEST 4	173	119.320	1.29972	0.09882
TEST 5	58	128.053	0.54747	0.07189
TEST 6	154	123.236	1.57819	0.12717
TEST 7	142	119.176	2.66392	0.22355
TEST 8	134	117.799	1.16193	0.10038
TEST 9	125	124.256	1.63561	0.14631

FIGURE 124

Plant Data: Test 1-9 Edited Composite
Cooler Vent Stack Flow and Thermocouple Temperature

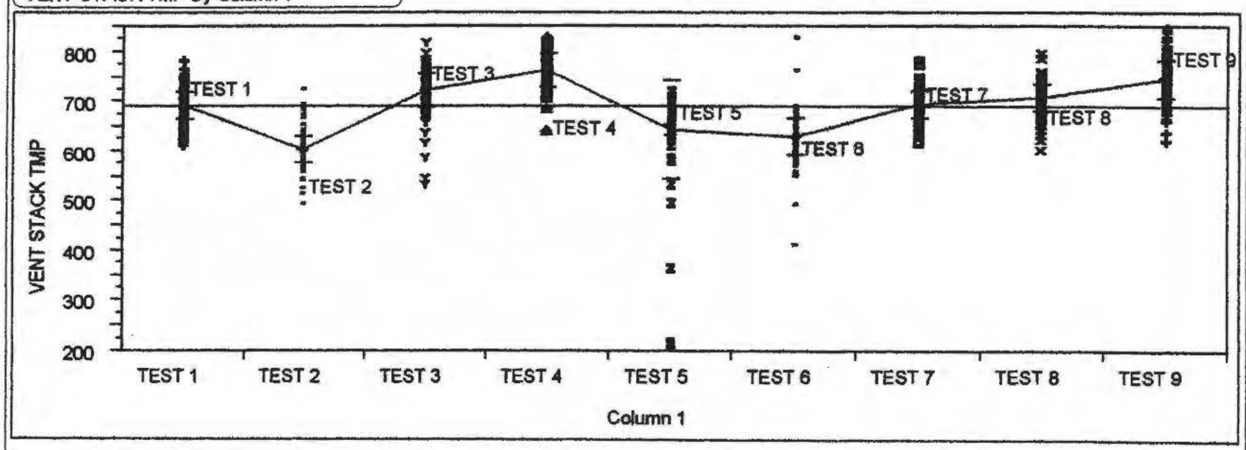
COOL VENT STACK FLOW By Column 1



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	10690.6	653.62	45.54
TEST 2	179	8710.3	1051.27	78.58
TEST 3	224	10357.0	702.52	46.94
TEST 4	173	11363.9	625.56	47.56
TEST 5	58	9185.5	968.32	127.15
TEST 6	154	10997.2	813.75	65.57
TEST 7	142	11745.1	366.39	30.75
TEST 8	134	11351.8	679.19	58.67
TEST 9	125	12179.8	863.58	77.24

VENT STACK TMP By Column 1



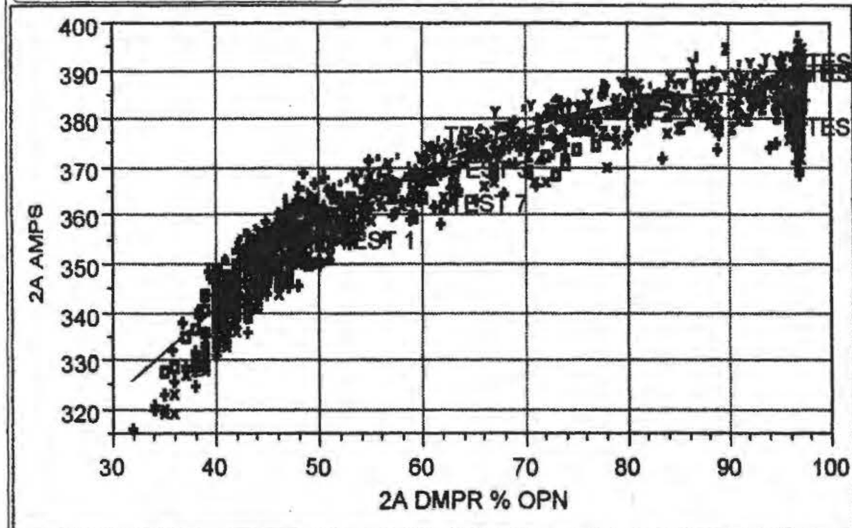
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	691.124	30.4233	2.120
TEST 2	179	604.971	29.2598	2.187
TEST 3	224	723.954	35.1280	2.347
TEST 4	173	765.403	35.2013	2.676
TEST 5	58	643.569	98.7663	12.969
TEST 6	154	630.785	37.5023	3.022
TEST 7	142	694.394	29.0482	2.438
TEST 8	134	708.291	29.5706	2.555
TEST 9	125	747.728	38.8725	3.477

FIGURE 125

Waste Gas Fan Amps vs Damper Position

2A AMPS By 2A DMPR % OPN



— Polynomial Fit degree=2

Polynomial Fit degree=2

2A AMPS = 241.372 + 3.21127 2A DMPR % OPN û 0.01794 2A DMPR % OPN^2

Summary of Fit

RSquare	0.92076
RSquare Adj	0.920646
Root Mean Square Error	4.992376
Mean of Response	366.8064
Observations (or Sum Wgts)	1395

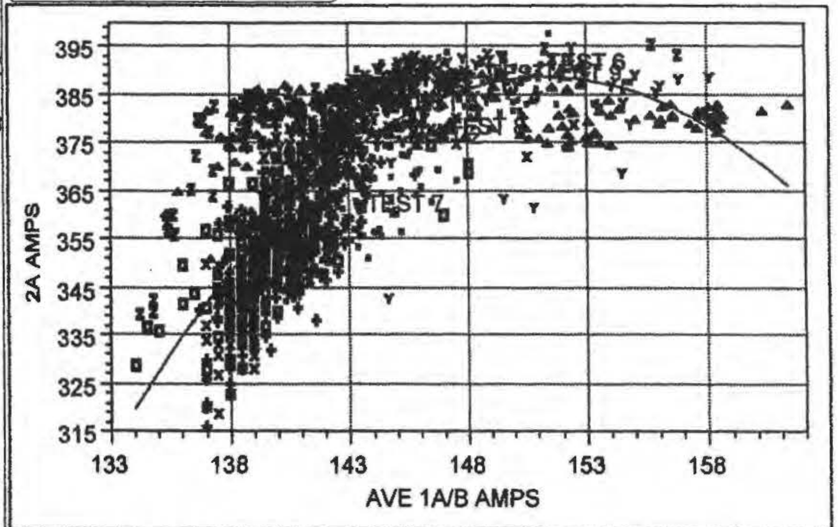
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	241.37226	2.023423	119.29	0.0000
2A DMPR % OPN	3.2112699	0.064053	50.13	0.0000
2A DMPR % OPN^2	-0.017944	0.000459	-39.10	<.0001

Waste Gas Fan Amps vs Preheat Fan Amps

2A AMPS By AVE 1A/B AMPS



— Polynomial Fit degree=2

Polynomial Fit degree=2

2A AMPS = -4854.3 + 69.2842 AVE 1A/B AMPS û 0.2289 AVE 1A/B AMPS^2

Summary of Fit

RSquare	0.560684
RSquare Adj	0.560052
Root Mean Square Error	11.75501
Mean of Response	366.8064
Observations (or Sum Wgts)	1395

Analysis of Variance

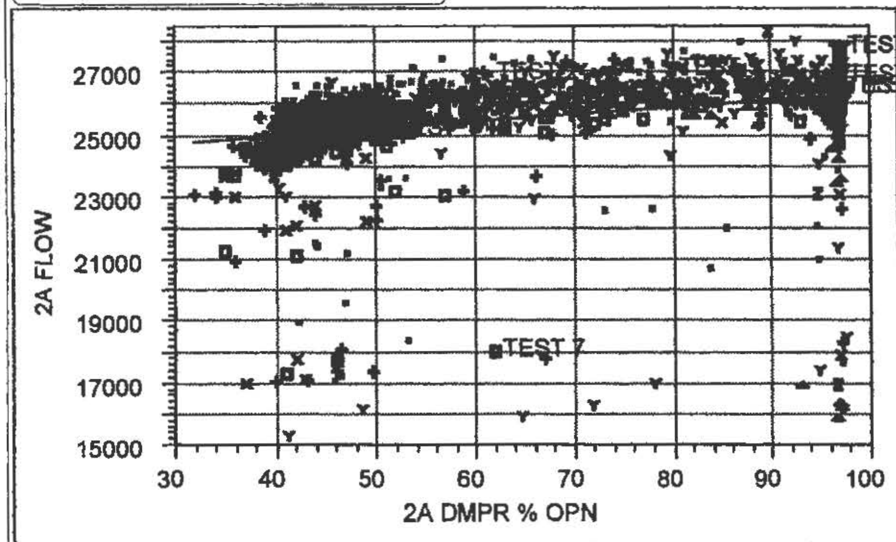
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-4854.291	227.8074	-21.31	<.0001
AVE 1A/B AMPS	69.28415	3.128982	22.14	<.0001
AVE 1A/B AMPS^2	-0.228896	0.010735	-21.32	<.0001

FIGURE 126

Waste Gas Fan Flows vs Damper Position

2A FLOW By 2A DMPR % OPN



— Linear Fit

Linear Fit

2A FLOW = 24066.2 + 22.6845 2A DMPR % OPN

Summary of Fit

RSquare	0.093596
RSquare Adj	0.092945
Root Mean Square Error	1592.281
Mean of Response	25584.48
Observations (or Sum Wgts)	1395

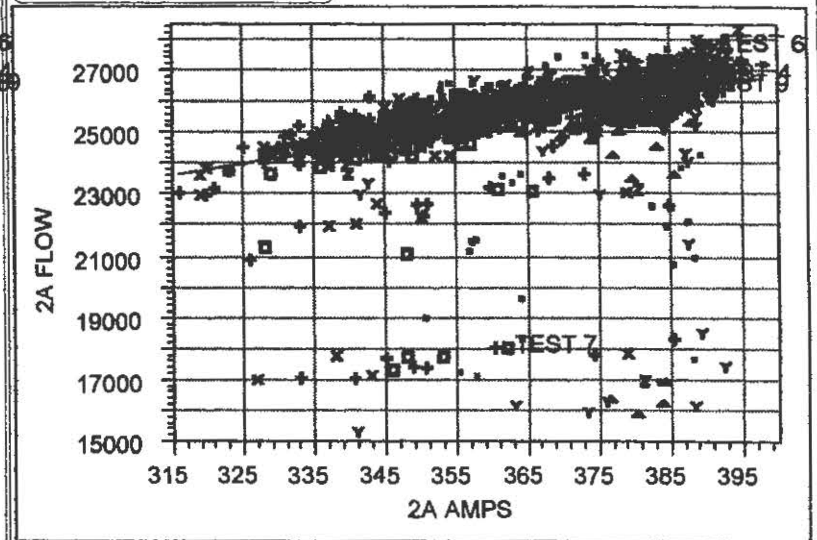
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	24066.175	133.5808	180.16	0.0000
2A DMPR % OPN	22.68448	1.891413	11.99	<.0001

Waste Gas Fan Flow vs Amps

2A FLOW By 2A AMPS



— Linear Fit

Linear Fit

2A FLOW = 11730.6 + 37.769 2A AMPS

Summary of Fit

RSquare	0.160292
RSquare Adj	0.159689
Root Mean Square Error	1532.579
Mean of Response	25584.48
Observations (or Sum Wgts)	1395

Analysis of Variance

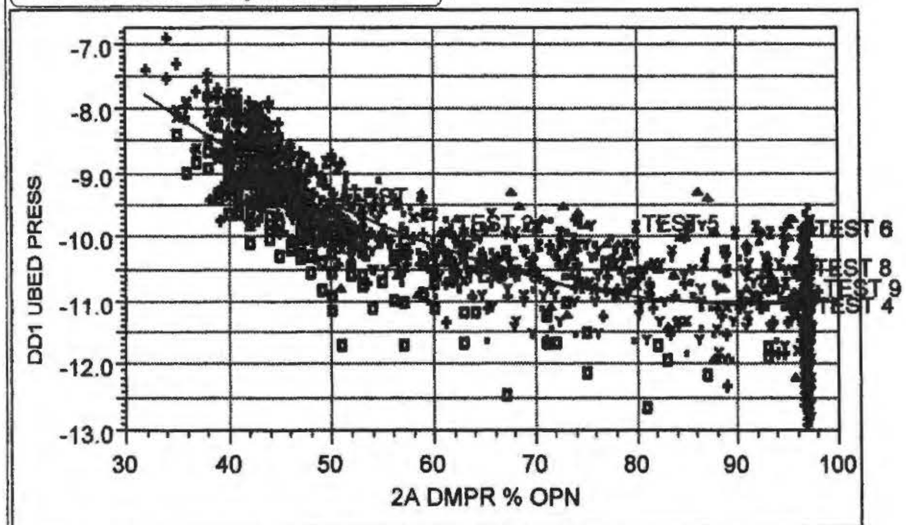
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	11730.563	850.5736	13.79	<.0001
2A AMPS	37.76903	2.316163	16.31	<.0001

FIGURE 127

DD1 Wind Box Pressure vs Waste Gas Fan Damper

DD1 UBED PRESS By 2A DMPR % OPN



— Polynomial Fit degree=2

Polynomial Fit degree=2

DD1 UBED PRESS = -3.353 û 0.16761 2A DMPR % OPN + 0.00091 2A DMPR % OPN^2

Summary of Fit

RSquare	0.72204
RSquare Adj	0.721641
Root Mean Square Error	0.597606
Mean of Response	-10.0283
Observations (or Sum Wgts)	1395

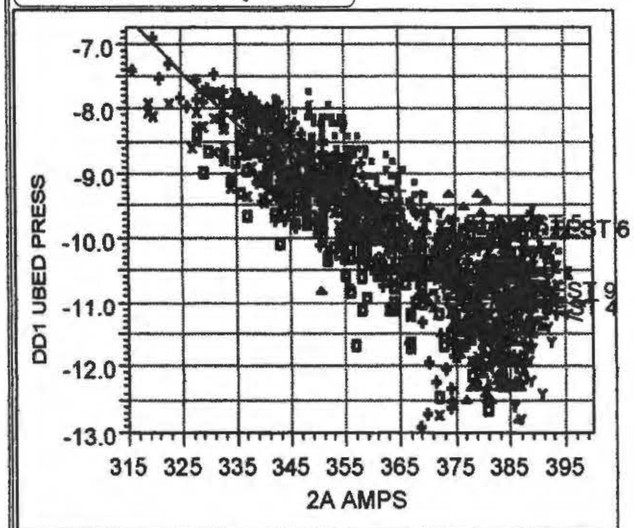
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-3.353023	0.242211	-13.84	<.0001
2A DMPR % OPN	-0.167612	0.007667	-21.86	<.0001
2A DMPR % OPN^2	0.0009109	0.000055	16.58	<.0001

DD1 Wind Box Pressure vs Waste Gas Fan Amps

DD1 UBED PRESS By 2A AMPS



— Polynomial Fit degree=2

Polynomial Fit degree=2

DD1 UBED PRESS = 62.8015 û 0.34897 2A AMPS + 0.00041 2A AMPS^2

Summary of Fit

RSquare	0.662716
RSquare Adj	0.662231
Root Mean Square Error	0.658296
Mean of Response	-10.0283
Observations (or Sum Wgts)	1395

Analysis of Variance

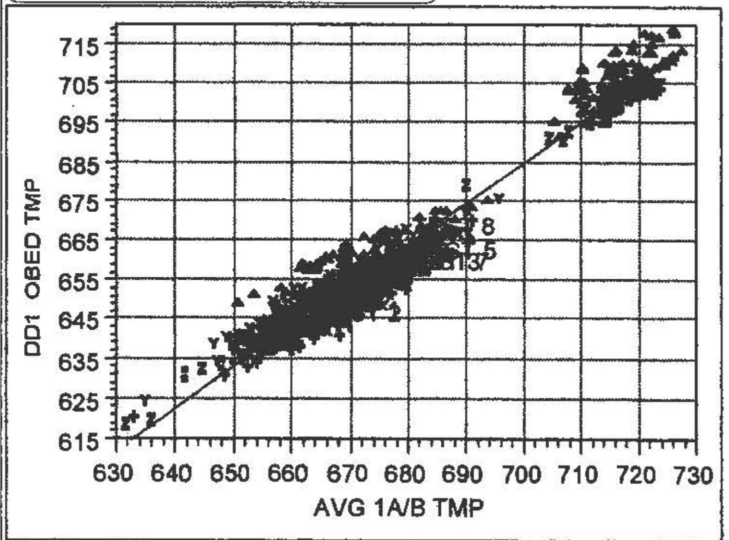
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	62.801486	8.016029	7.83	<.0001
2A AMPS	-0.348972	0.044188	-7.90	<.0001
2A AMPS^2	0.0004091	0.000061	6.73	<.0001

FIGURE 128

DD1 Overbed Temp vs Ave Preheat Fan Temp

DD1 OBED TMP By AVG 1A/B TMP



— Linear Fit

Linear Fit

DD1 OBED TMP = -37.311 + 1.0311 AVG 1A/B TMP

Summary of Fit

RSquare	0.946782
RSquare Adj	0.946744
Root Mean Square Error	3.94792
Mean of Response	657.3226
Observations (or Sum Wgts)	1395

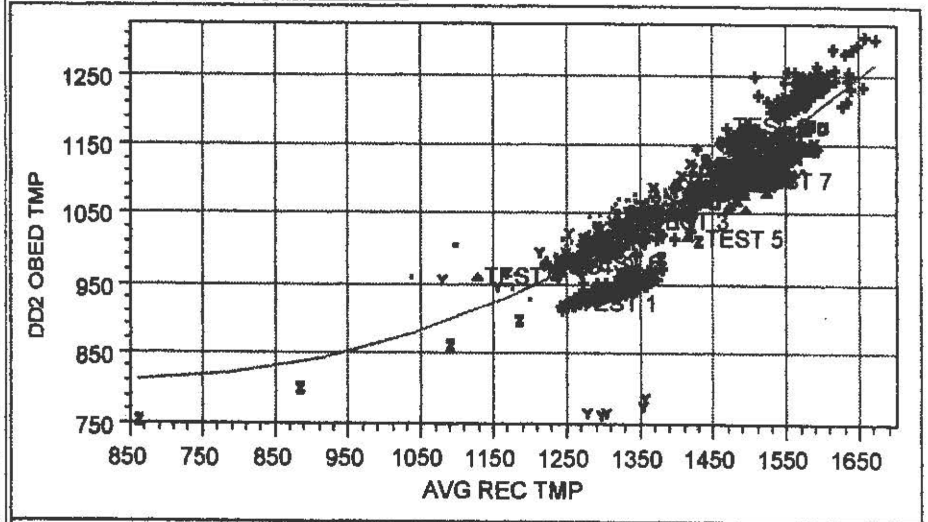
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-37.31052	4.413768	-8.45	<.0001
AVG 1A/B TMP	1.0311009	0.00655	157.42	0.0000

DD2 Overbed Temp vs Average Recoup Thermocouple Temp

DD2 OBED TMP By AVG REC TMP



— Polynomial Fit degree=2

Polynomial Fit degree=2

DD2 OBED TMP = 997.042 û 0.56759 AVG REC TMP + 0.00044 AVG REC TMP^2

Summary of Fit

RSquare	0.810464
RSquare Adj	0.810192
Root Mean Square Error	36.09706
Mean of Response	1067.176
Observations (or Sum Wgts)	1395

Analysis of Variance

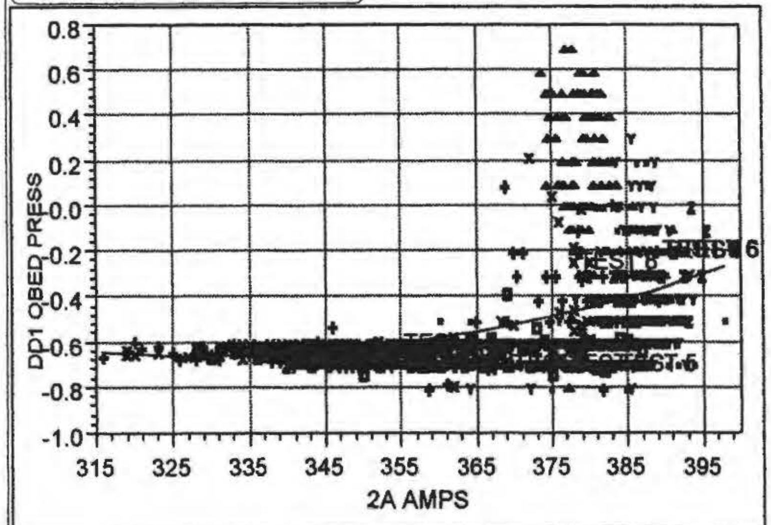
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	997.04189	96.17582	10.37	<.0001
AVG REC TMP	-0.567595	0.137241	-4.14	<.0001
AVG REC TMP^2	0.0004355	0.000049	8.92	<.0001

FIGURE 129

DD1 Overbed Pressure vs Waste Gas Fan Amps

DD1 OBED PRESS By 2A AMPS



— Polynomial Fit degree=2

Polynomial Fit degree=2

DD1 OBED PRESS = 8.7406 û 0.05695 2A AMPS + 0.00009 2A AMPS^2

Summary of Fit

RSquare	0.168915
RSquare Adj	0.167721
Root Mean Square Error	0.23158
Mean of Response	-0.52172
Observations (or Sum Wgts)	1395

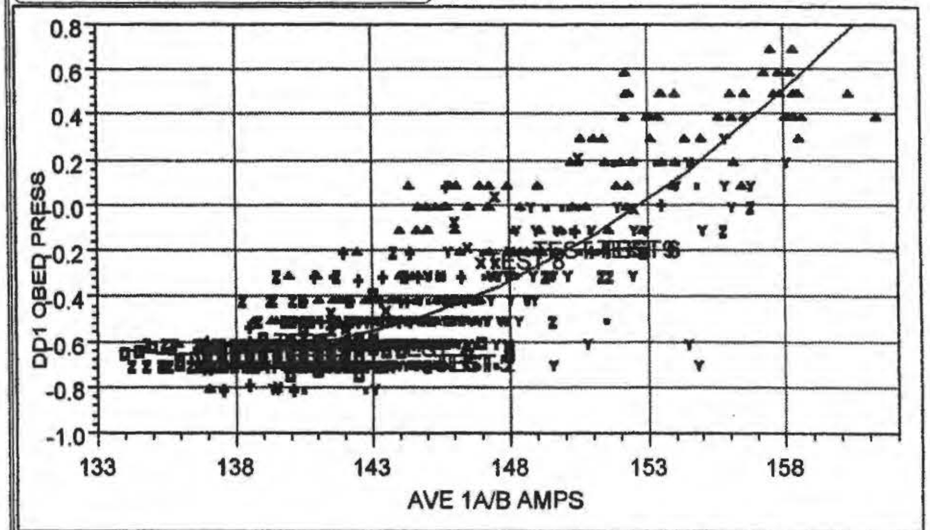
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	8.740596	2.819931	3.10	0.0020
2A AMPS	-0.056948	0.015545	-3.66	0.0003
2A AMPS^2	0.0000862	0.000021	4.03	<.0001

DD1 Overbed Pressure vs Average Preheat Fan Amps

DD1 OBED PRESS By AVE 1A/B AMPS



— Polynomial Fit degree=2

Polynomial Fit degree=2

DD1 OBED PRESS = 47.8969 û 0.70986 AVE 1A/B AMPS + 0.00259 AVE 1A/B AMPS^2

Summary of Fit

RSquare	0.739039
RSquare Adj	0.738664
Root Mean Square Error	0.129767
Mean of Response	-0.52172
Observations (or Sum Wgts)	1395

Analysis of Variance

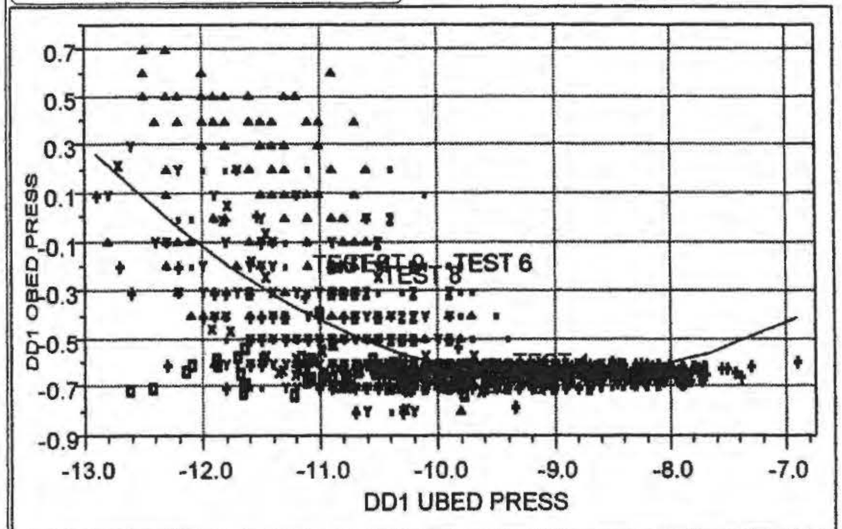
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	47.896937	2.514841	19.05	<.0001
AVE 1A/B AMPS	-0.709863	0.034542	-20.55	<.0001
AVE 1A/B AMPS^2	0.0025943	0.000119	21.89	<.0001

FIGURE 130

DD1 Overbed Pressure vs Wind Box Pressure

DD1 OBED PRESS By DD1 UBED PRESS



— Polynomial Fit degree=2

Polynomial Fit degree=2

DD1 OBED PRESS = 4.15512 + 1.07511 DD1 UBED PRESS + 0.05994 DD1 UBE

Summary of Fit

RSquare	0.425926
RSquare Adj	0.425101
Root Mean Square Error	0.192469
Mean of Response	-0.52172
Observations (or Sum Wgts)	1395

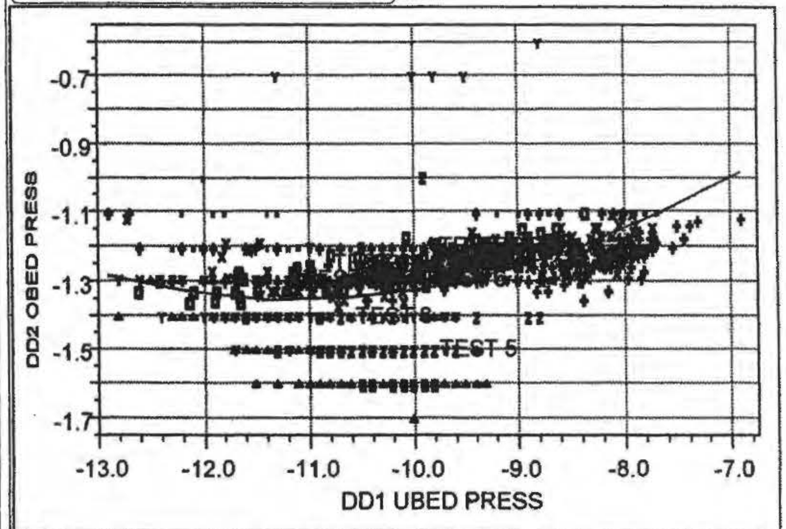
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4.1551242	0.344911	12.05	<.0001
DD1 UBED PRESS	1.0751124	0.06943	15.48	<.0001
DD1 UBED PRESS^2	0.0599389	0.003465	17.30	<.0001

DD2 Overbed Pressure vs Wind Box Pressure

DD2 OBED PRESS By DD1 UBED PRESS



— Polynomial Fit degree=2

Polynomial Fit degree=2

DD2 OBED PRESS = 1.19359 + 0.45846 DD1 UBED PRESS + 0.02063 DD1 UBE

Summary of Fit

RSquare	0.221529
RSquare Adj	0.220411
Root Mean Square Error	0.113275
Mean of Response	-1.30239
Observations (or Sum Wgts)	1395

Analysis of Variance

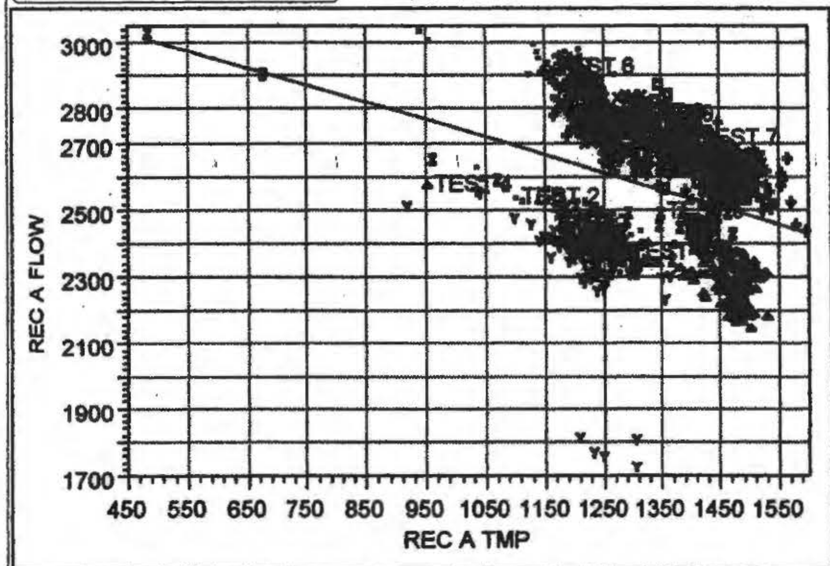
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.1935875	0.202993	5.88	<.0001
DD1 UBED PRESS	0.4584617	0.040862	11.22	<.0001
DD1 UBED PRESS^2	0.0206346	0.002039	10.12	<.0001

FIGURE 131

Recoup A Duct Flow vs Thermocouple Temperature

REC A FLOW By REC A TMP



— Linear Fit

Linear Fit

REC A FLOW = 3255.19 0 0.51281 REC A TMP

Summary of Fit

RSquare	0.084996
RSquare Adj	0.084339
Root Mean Square Error	194.431
Mean of Response	2576.936
Observations (or Sum Wgts)	1395

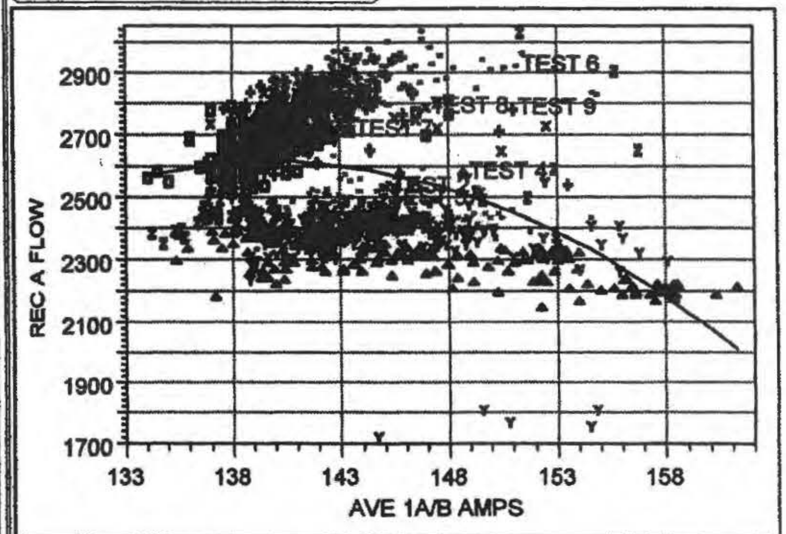
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3255.1855	59.85139	54.39	0.0000
REC A TMP	-0.512808	0.045081	-11.38	<.0001

Recoup A Duct Flow vs Preheat Fan Amps

REC A FLOW By AVE 1A/B AMPS



— Polynomial Fit degree=2

Polynomial Fit degree=2

REC A FLOW = -2.31e4 + 367.884 AVE 1A/B AMPS 0 1.31498 AVE 1A/B AMPS^2

Summary of Fit

RSquare	0.147556
RSquare Adj	0.146331
Root Mean Square Error	187.734
Mean of Response	2576.936
Observations (or Sum Wgts)	1395

Analysis of Variance

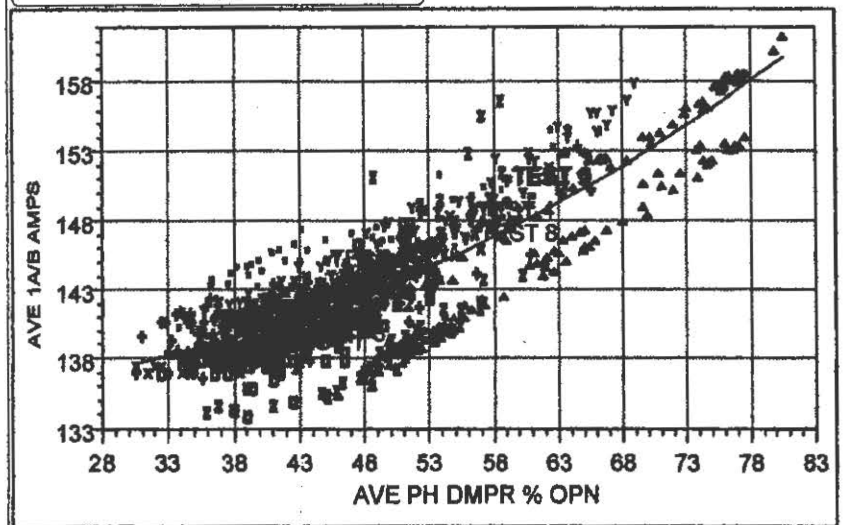
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-23117.32	3638.211	-6.35	<.0001
AVE 1A/B AMPS	367.88409	49.97159	7.36	<.0001
AVE 1A/B AMPS^2	-1.31498	0.17144	-7.67	<.0001

FIGURE 132

Preheat Fan Amps vs Damper Position

AVE 1A/B AMPS By AVE PH DMPR % OPN



— Polynomial Fit degree=2

Polynomial Fit degree=2

AVE 1A/B AMPS = 135.882 û 0.08283 AVE PH DMPR % OPN + 0.00475 AVE PH DMPR

Summary of Fit

RSquare	0.720911
RSquare Adj	0.72051
Root Mean Square Error	2.343318
Mean of Response	142.6542
Observations (or Sum Wgts)	1395

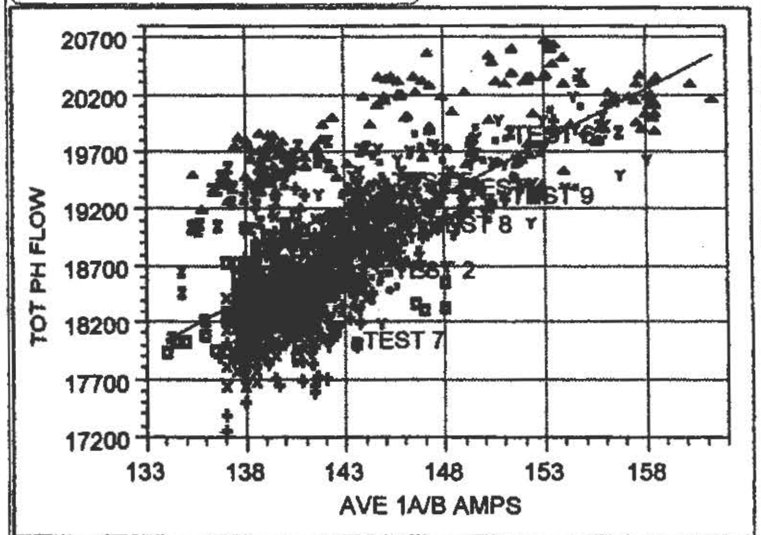
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	135.88183	1.38951	97.79	0.0000
AVE PH DMPR % OPN	-0.082831	0.054618	-1.52	0.1296
AVE PH DMPR % OPN^2	0.0047507	0.000521	9.12	<.0001

Total Preheat Flow vs Average Preheat Fan Amps

TOT PH FLOW By AVE 1A/B AMPS



— Linear Fit

Linear Fit

TOT PH FLOW = 5838.79 + 91.1302 AVE 1A/B AMPS

Summary of Fit

RSquare	0.463373
RSquare Adj	0.462988
Root Mean Square Error	434.8474
Mean of Response	18838.91
Observations (or Sum Wgts)	1395

Analysis of Variance

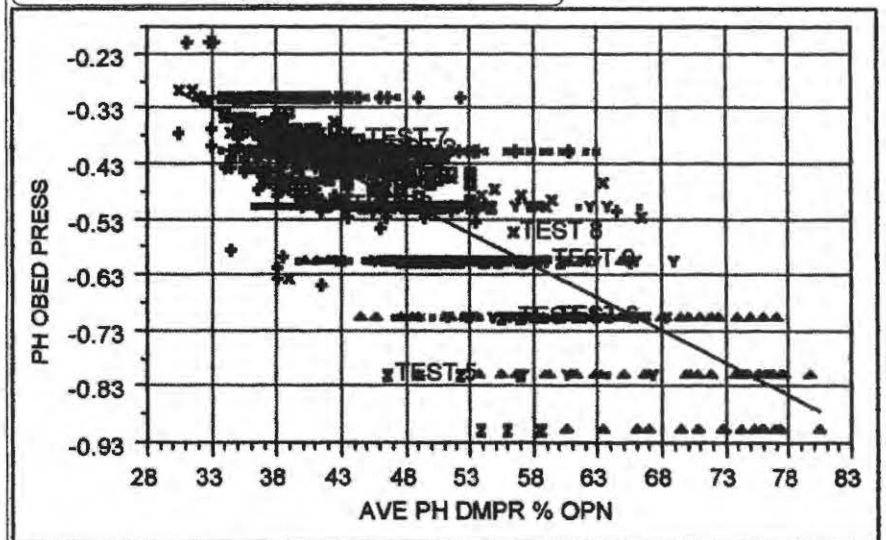
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	5838.7943	375.0175	15.57	<.0001
AVE 1A/B AMPS	91.130228	2.627589	34.68	<.0001

FIGURE 133

Preheat Overbed Pressure vs Average Damper Position

PH OBED PRESS By AVE PH DMPR % OPN



— Linear Fit

Linear Fit

PH OBED PRESS = 0.04769 û 0.01142 AVE PH DMPR % OPN

Summary of Fit

RSquare	0.589975
RSquare Adj	0.589681
Root Mean Square Error	0.086102
Mean of Response	-0.48224
Observations (or Sum Wgts)	1395

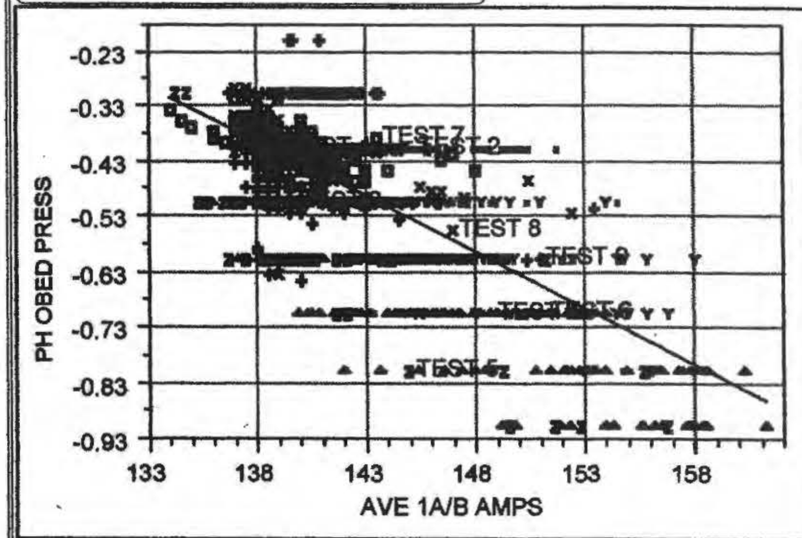
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.0476862	0.012059	3.95	<.0001
AVE PH DMPR % OPN	-0.011421	0.000255	-44.77	<.0001

Preheat Overbed Pressure vs Average Amps

PH OBED PRESS By AVE 1A/B AMPS



— Linear Fit

Linear Fit

PH OBED PRESS = 2.37675 û 0.02004 AVE 1A/B AMPS

Summary of Fit

RSquare	0.436769
RSquare Adj	0.436364
Root Mean Square Error	0.100914
Mean of Response	-0.48224
Observations (or Sum Wgts)	1395

Analysis of Variance

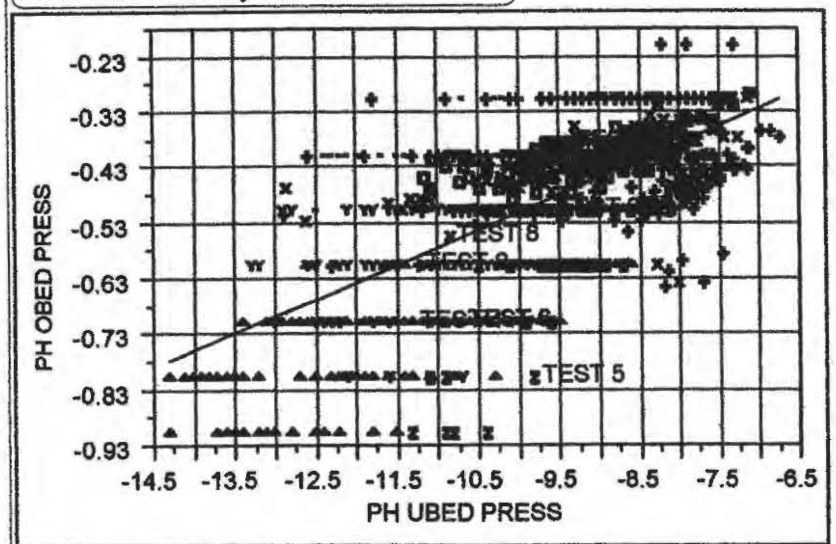
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2.3767526	0.087029	27.31	<.0001
AVE 1A/B AMPS	-0.020041	0.00061	-32.87	<.0001

FIGURE 134

Preheat Overbed Pressure vs Wind Box Pressure

PH OBED PRESS By PH UBED PRESS



— Linear Fit

Linear Fit

PH OBED PRESS = 0.11502 + 0.06218 PH UBED PRESS

Summary of Fit

RSquare	0.391368
RSquare Adj	0.390931
Root Mean Square Error	0.104902
Mean of Response	-0.48224
Observations (or Sum Wgts)	1395

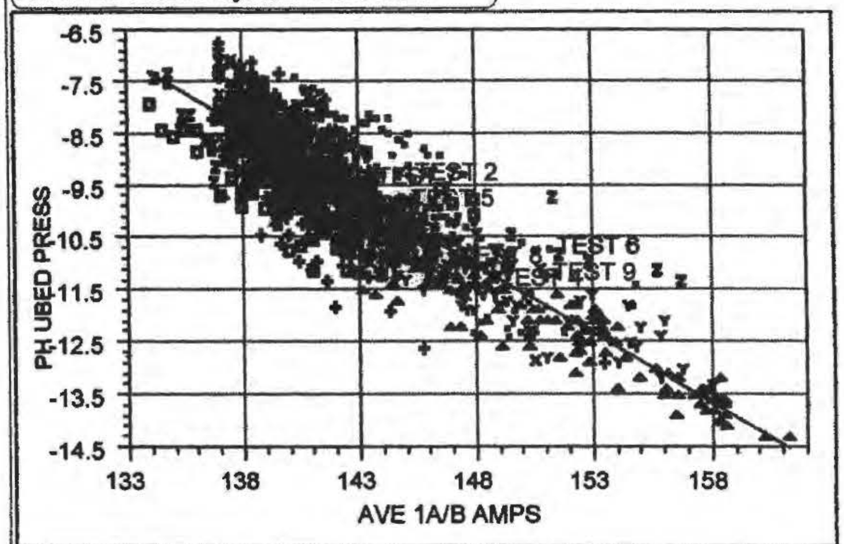
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.1150173	0.020152	5.71	<.0001
PH UBED PRESS	0.062177	0.002077	29.93	<.0001

Preheat Wind Box Pressure vs Average Amps

PH UBED PRESS By AVE 1A/B AMPS



— Linear Fit

Linear Fit

PH UBED PRESS = 27.8831 û 0.26279 AVE 1A/B AMPS

Summary of Fit

RSquare	0.74183
RSquare Adj	0.741644
Root Mean Square Error	0.68742
Mean of Response	-9.6057
Observations (or Sum Wgts)	1395

Analysis of Variance

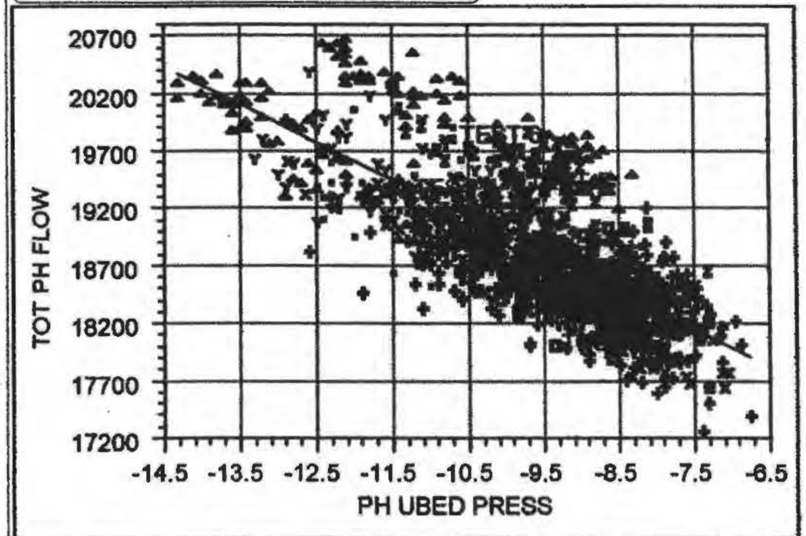
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	27.883109	0.592839	47.03	<.0001
AVE 1A/B AMPS	-0.262795	0.004154	-63.27	0.0000

FIGURE 135

Total Preheat Fan Flow vs Wind Box Pressure

TOT PH FLOW By PH UBED PRESS



— Linear Fit

Linear Fit

TOT PH FLOW = 15701.2 û 326.65 PH UBED PRESS

Summary of Fit

RSquare	0.554243
RSquare Adj	0.553923
Root Mean Square Error	396.3237
Mean of Response	18838.91
Observations (or Sum Wgts)	1395

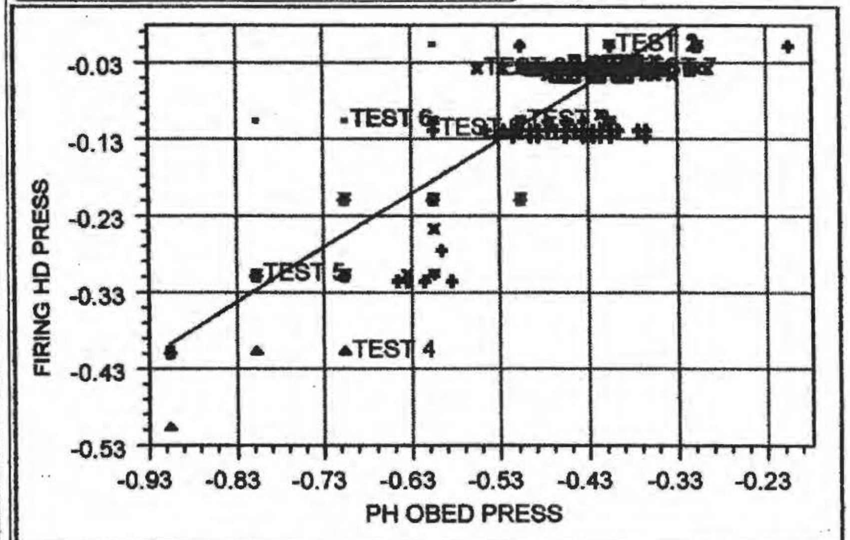
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	15701.21	76.1367	206.22	0.0000
PH UBED PRESS	-326.6495	7.848844	-41.62	<.0001

Firing Hood Pressure vs Preheat Overbed Pressure

FIRING HD PRESS By PH OBED PRESS



— Linear Fit

Linear Fit

FIRING HD PRESS = 0.25286 + 0.71675 PH OBED PRESS

Summary of Fit

RSquare	0.716965
RSquare Adj	0.716762
Root Mean Square Error	0.060554
Mean of Response	-0.09278
Observations (or Sum Wgts)	1395

Analysis of Variance

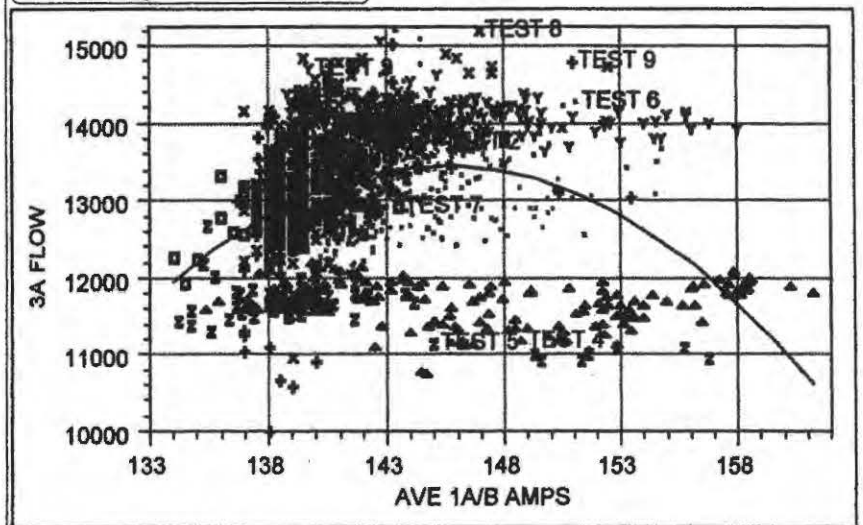
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.2528597	0.00604	41.86	<.0001
PH OBED PRESS	0.7167459	0.012066	59.40	0.0000

FIGURE 136

Primary Cooling Fan Flow vs Average Preheat Fan Amps

3A FLOW By AVE 1A/B AMPS



— Polynomial Fit degree=2

Polynomial Fit degree=2

3A FLOW = -227097 + 3306.13 AVE 1A/B AMPS 0 11.3599 AVE 1A/B AMPS^2

Summary of Fit

RSquare	0.13796
RSquare Adj	0.136721
Root Mean Square Error	834.7431
Mean of Response	13136.69
Observations (or Sum Wgts)	1395

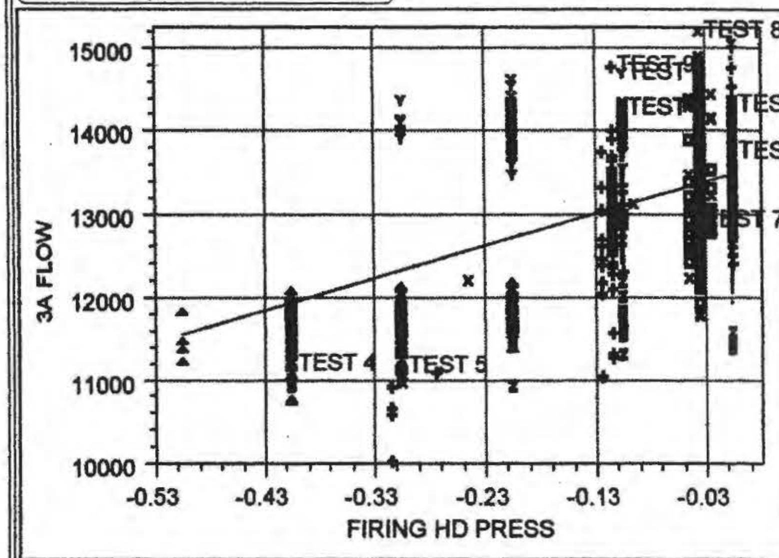
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-227096.7	16176.99	-14.04	<.0001
AVE 1A/B AMPS	3306.1258	222.1944	14.88	<.0001
AVE 1A/B AMPS^2	-11.35989	0.762295	-14.90	<.0001

Primary Cooling Fan Flow vs Firing Hood Pressure

3A FLOW By FIRING HD PRESS



— Linear Fit

Linear Fit

3A FLOW = 13494.9 + 3860.71 FIRING HD PRESS

Summary of Fit

RSquare	0.239063
RSquare Adj	0.238516
Root Mean Square Error	783.9848
Mean of Response	13136.69
Observations (or Sum Wgts)	1395

Analysis of Variance

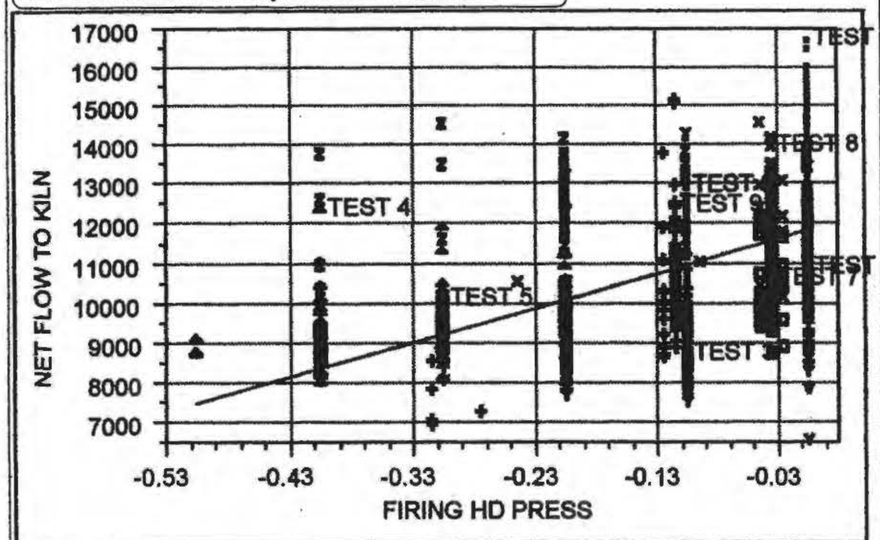
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	13494.891	27.0884	498.18	0.0000
FIRING HD PRESS	3860.7064	184.5482	20.92	<.0001

FIGURE 137

Net Flow to Kiln vs Firing Hood Pressure

NET FLOW TO KILN By FIRING HD PRESS



— Linear Fit

Linear Fit

NET FLOW TO KILN = 11814.5 + 8693.54 FIRING HD PRESS

Summary of Fit

RSquare	0.265066
RSquare Adj	0.264538
Root Mean Square Error	1647.654
Mean of Response	11007.94
Observations (or Sum Wgts)	1395

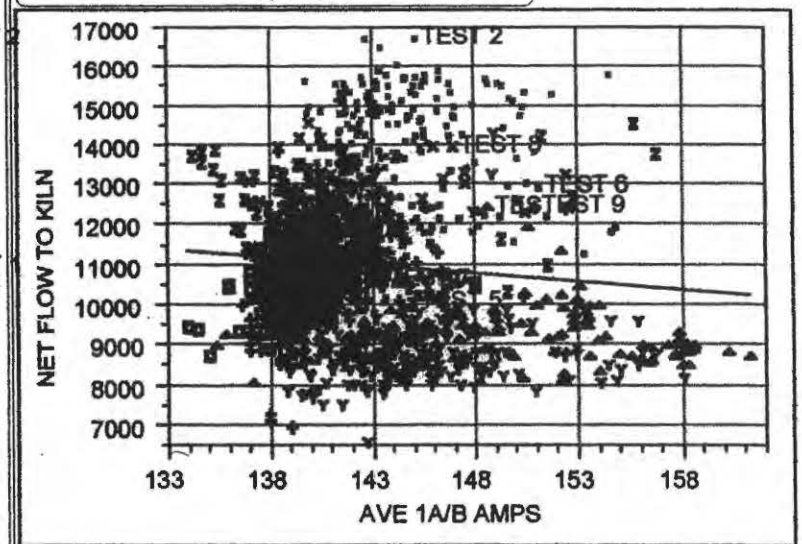
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	11814.536	56.93005	207.53	0.0000
FIRING HD PRESS	8693.5353	387.8539	22.41	<.0001

Net Flow to Kiln vs Average Preheat Fan Amps

NET FLOW TO KILN By AVE 1A/B AMPS



— Linear Fit

Linear Fit

NET FLOW TO KILN = 16749.3 û 40.2467 AVE 1A/B AMPS

Summary of Fit

RSquare	0.008622
RSquare Adj	0.00791
Root Mean Square Error	1913.645
Mean of Response	11007.94
Observations (or Sum Wgts)	1395

Analysis of Variance

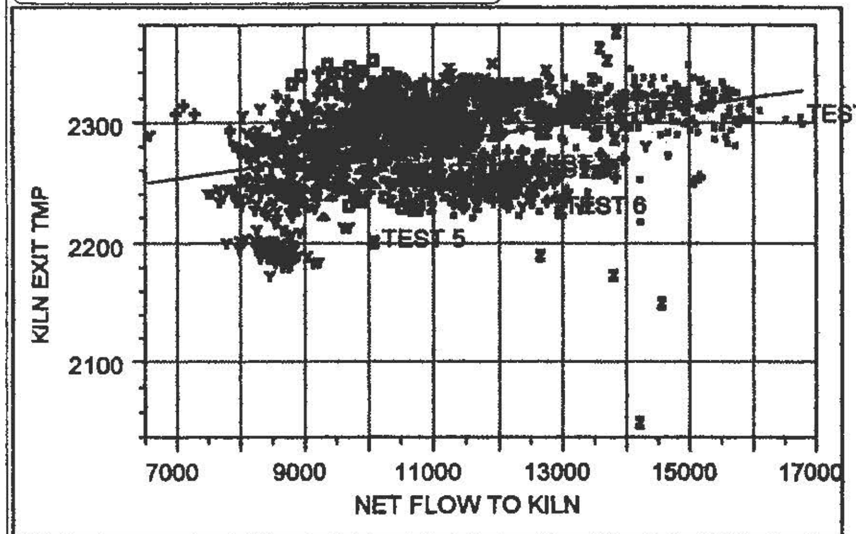
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	16749.304	1650.35	10.15	<.0001
AVE 1A/B AMPS	-40.24673	11.56331	-3.48	0.0005

FIGURE 138

Kiln Exit Gas Temperature vs Net Flow to Kiln

KILN EXIT TMP By NET FLOW TO KILN



— Linear Fit

Linear Fit

KILN EXIT TMP = 2201.67 + 0.00742 NET FLOW TO KILN

Summary of Fit

RSquare	0.15505
RSquare Adj	0.154444
Root Mean Square Error	33.27373
Mean of Response	2283.304
Observations (or Sum Wgts)	1395

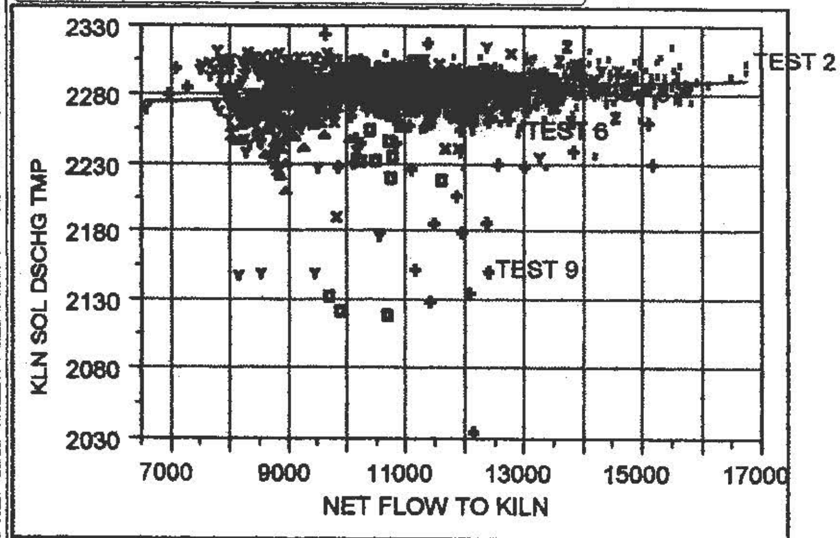
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2201.6666	5.183242	424.77	0.0000
NET FLOW TO KILN	0.0074162	0.000464	15.99	<.0001

Kiln Solids Discharge Temperature vs Net Flow to Kiln

KLN SOL DSCHG TMP By NET FLOW TO KILN



— Linear Fit

Linear Fit

KLN SOL DSCHG TMP = 2263.03 + 0.00164 NET FLOW TO KILN

Summary of Fit

RSquare	0.022441
RSquare Adj	0.02174
Root Mean Square Error	20.78812
Mean of Response	2281.051
Observations (or Sum Wgts)	1395

Analysis of Variance

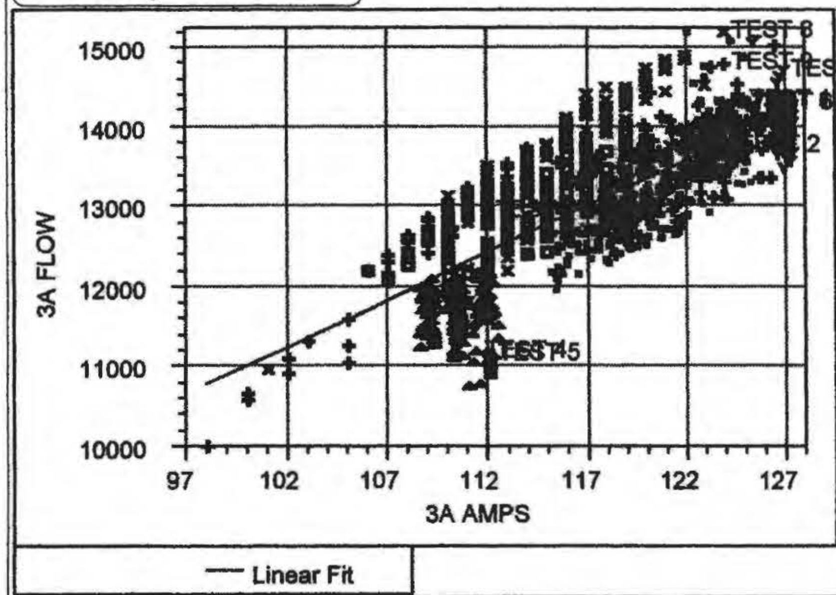
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2263.0286	3.235171	699.51	0.0000
NET FLOW TO KILN	0.0016372	0.00029	5.65	<.0001

FIGURE 139

Primary Cooling Fan Flow vs Amps

3A FLOW By 3A AMPS



Linear Fit

3A FLOW = -635.77 + 116.516 3A AMPS

Summary of Fit

RSquare	0.640282
RSquare Adj	0.640024
Root Mean Square Error	539.0319
Mean of Response	13136.69
Observations (or Sum Wgts)	1395

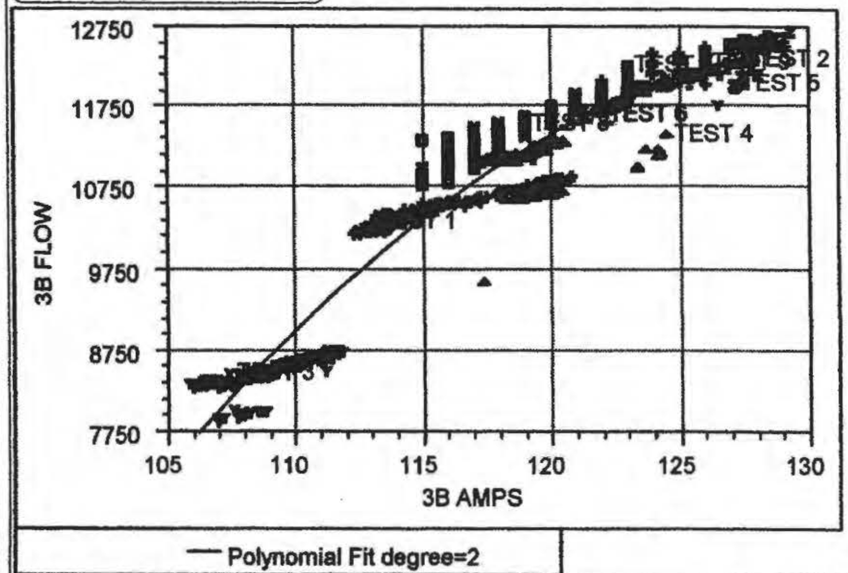
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-635.7743	276.9633	-2.30	0.0219
3A AMPS	116.51626	2.33995	49.79	<.0001

Secondary Cooling Fan Flow (Uncorrected) vs Fan Amps

3B FLOW By 3B AMPS



Polynomial Fit degree=2

3B FLOW = -100608 + 1688.72 3B AMPS û 6.2946 3B AMPS^2

Summary of Fit

RSquare	0.925534
RSquare Adj	0.925427
Root Mean Square Error	347.212
Mean of Response	11020.89
Observations (or Sum Wgts)	1395

Analysis of Variance

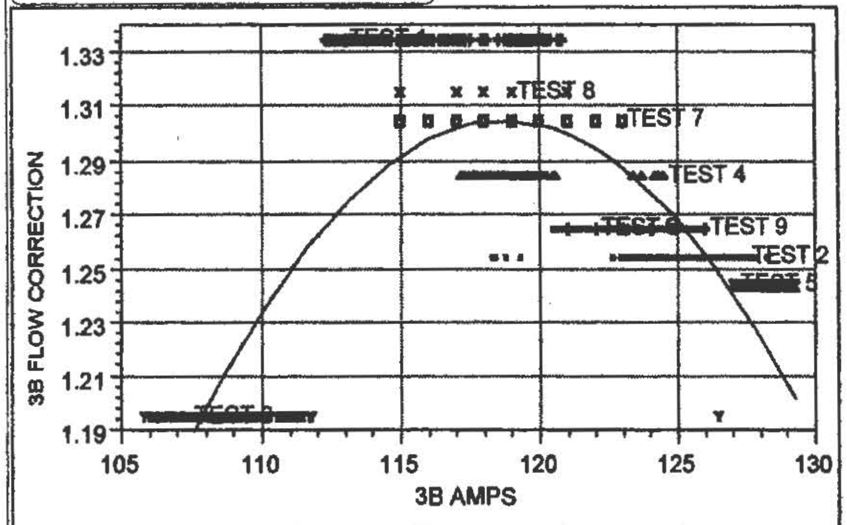
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-100607.5	3578.386	-28.12	<.0001
3B AMPS	1688.7161	60.91654	27.72	<.0001
3B AMPS^2	-6.294596	0.258776	-24.32	<.0001

FIGURE 140

Secondary Cooling Fan Correction Factor vs Amps

3B FLOW CORRECTION By 3B AMPS



— Polynomial Fit degree=2

Polynomial Fit degree=2

3B FLOW CORRECTION = -11.79 + 0.22047 3B AMPS û 0.00093 3B AMPS^2

Summary of Fit

RSquare	0.648438
RSquare Adj	0.647933
Root Mean Square Error	0.026029
Mean of Response	1.268337
Observations (or Sum Wgts)	1395

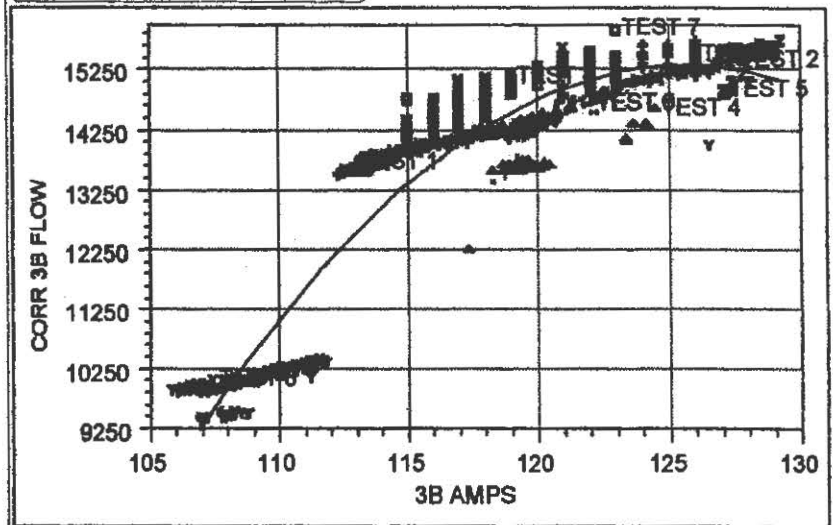
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-11.78987	0.268255	-43.95	<.0001
3B AMPS	0.2204747	0.004567	48.28	<.0001
3B AMPS^2	-0.000928	0.000019	-47.86	<.0001

Secondary Cooling Fan Flow (Corrected) vs Amps

CORR 3B FLOW By 3B AMPS



— Polynomial Fit degree=2

Polynomial Fit degree=2

CORR 3B FLOW = -257283 + 4340.33 3B AMPS û 17.2769 3B AMPS^2

Summary of Fit

RSquare	0.895304
RSquare Adj	0.895153
Root Mean Square Error	584.7051
Mean of Response	14002.97
Observations (or Sum Wgts)	1395

Analysis of Variance

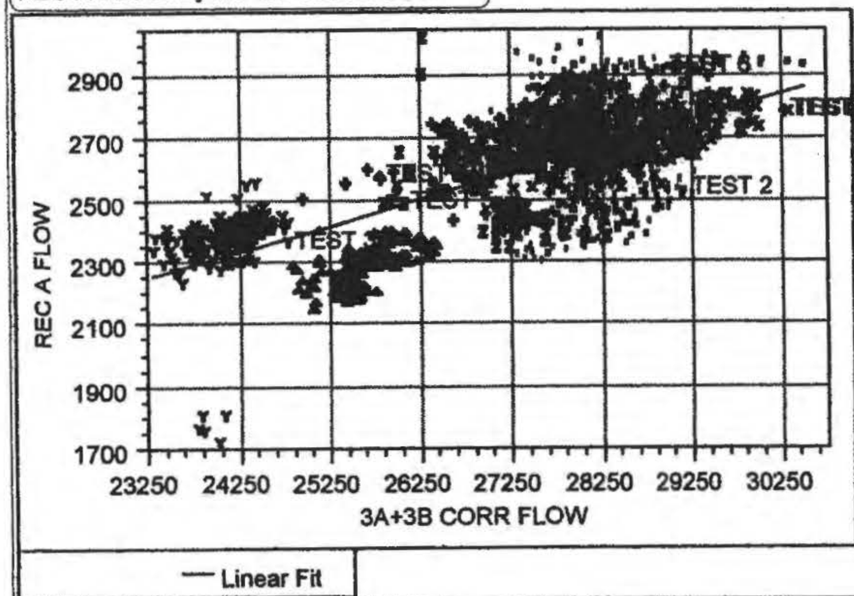
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-257282.7	6026.003	-42.70	<.0001
3B AMPS	4340.3258	102.5835	42.31	<.0001
3B AMPS^2	-17.27685	0.435779	-39.65	<.0001

FIGURE 141

Recoup A Duct Flow vs Total Cooling Flow

REC A FLOW By 3A+3B CORR FLOW



Linear Fit

REC A FLOW = 289.634 + 0.08428 3A+3B CORR FLOW

Summary of Fit

RSquare	0.484203
RSquare Adj	0.483833
Root Mean Square Error	145.98
Mean of Response	2576.936
Observations (or Sum Wgts)	1395

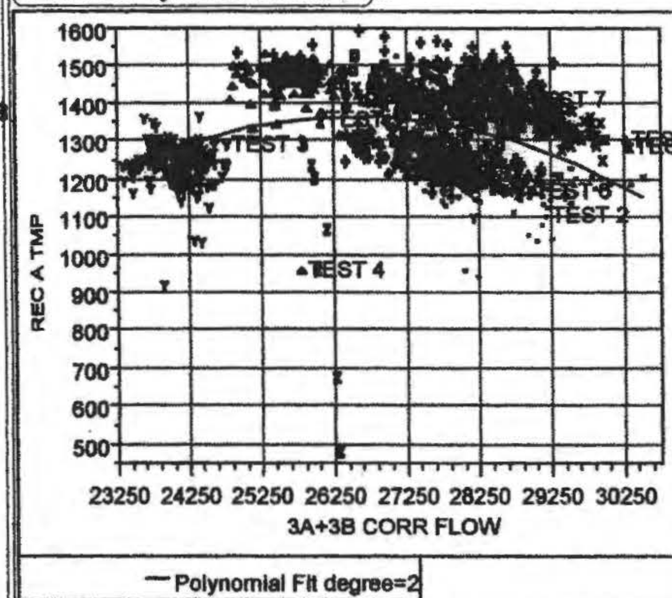
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	289.63376	63.37254	4.57	<.0001
3A+3B CORR FLOW	0.084279	0.002331	36.16	<.0001

Recoup A Duct Temperature vs Total Cooling Flow

REC A TMP By 3A+3B CORR FLOW



Polynomial Fit degree=2

REC A TMP = -8255.9 + 0.7242 3A+3B CORR FLOW 0 0.00001 3A+3B CORR FLO

Summary of Fit

RSquare	0.097138
RSquare Adj	0.095841
Root Mean Square Error	109.8413
Mean of Response	1322.618
Observations (or Sum Wgts)	1395

Analysis of Variance

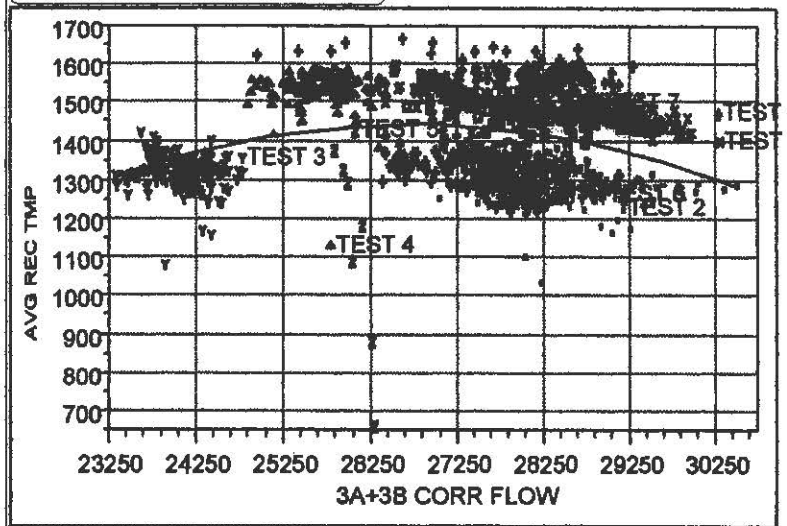
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-8255.883	783.5539	-10.54	<.0001
3A+3B CORR FLOW	0.7241981	0.059184	12.24	<.0001
3A+3B CORR FLOW^2	-0.000014	0.000001	-12.24	<.0001

FIGURE 142

Ave. Recoup Temp (Both Ducts) vs Tot. Cooling Flow

AVG REC TMP By 3A+3B CORR FLOW



— Polynomial Fit degree=2

Polynomial Fit degree=2

AVG REC TMP = -6708.8 + 0.60858 3A+3B CORR FLOW 0 0.00001 3A+3B CORI

Summary of Fit

RSquare	0.075938
RSquare Adj	0.074611
Root Mean Square Error	109.0164
Mean of Response	1408.647
Observations (or Sum Wgts)	1395

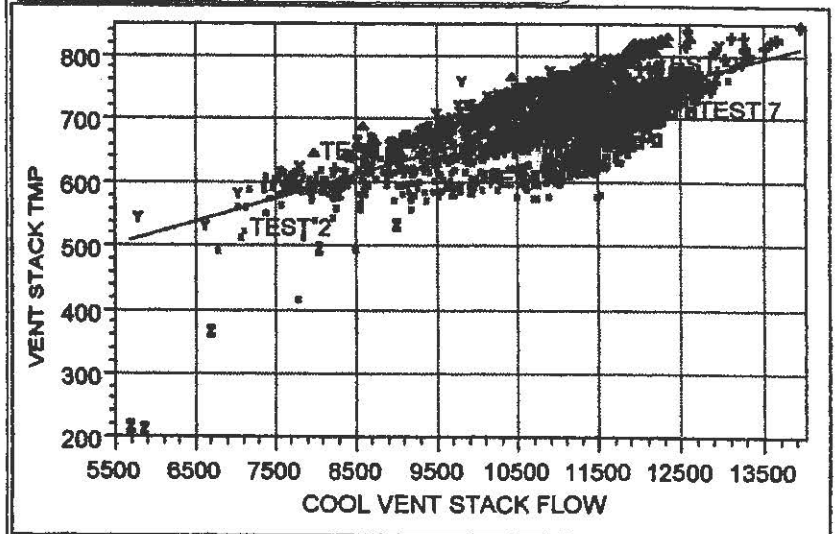
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-6708.82	777.6693	-8.63	<.0001
3A+3B CORR FLOW	0.6085798	0.05874	10.36	<.0001
3A+3B CORR FLOW^2	-0.000011	0.000001	-10.28	<.0001

Vent Stack Thermocouple Temperature vs Stack Flow

VENT STACK TMP By COOL VENT STACK FLOW



— Linear Fit

Linear Fit

VENT STACK TMP = 304.089 + 0.0362 COOL VENT STACK FLOW

Summary of Fit

RSquare	0.514862
RSquare Adj	0.514514
Root Mean Square Error	44.46658
Mean of Response	692.9682
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	304.08888	10.18392	29.86	<.0001
COOL VENT STACK FLOW	0.0362018	0.000942	38.45	<.0001

FIGURE 143

Plant Data: Edited Test Composite

Model Summary of Fit and Parameter Estimates - CFD Model Control Variable Criteria

3A OBED PRS

Summary of Fit

RSquare	0.37169
RSquare Adj	0.370335
Root Mean Square Error	0.026095
Mean of Response	-0.00644
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.532785	0.02304	-23.12	<.0001
EST L6 GRATE FD	0.0003556	0.00005	7.09	<.0001
3A FLOW	0.0000208	8.727e-7	23.85	<.0001
CORR 3B FLOW	0.0000058	4.813e-7	12.07	<.0001

Effect Test

NET FLOW TO KILN

Summary of Fit

RSquare	0.662688
RSquare Adj	0.661961
Root Mean Square Error	1117.042
Mean of Response	11007.94
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	7878.4019	986.2414	7.99	<.0001
EST L6 GRATE FD	-52.80419	2.147685	-24.59	<.0001
3A FLOW	1.0347812	0.037357	27.70	<.0001
CORR 3B FLOW	1.0722316	0.020601	52.05	0.0000

Effect Test

FIRING HD PRESS

Summary of Fit

RSquare	0.588248
RSquare Adj	0.58736
Root Mean Square Error	0.073089
Mean of Response	-0.09278
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.322894	0.064531	-20.50	<.0001
EST L6 GRATE FD	-0.001441	0.000141	-10.25	<.0001
3A FLOW	0.0000983	0.000002	40.21	<.0001
CORR 3B FLOW	0.0000453	0.000001	33.60	<.0001

Effect Test

KLN SEC TMP

Summary of Fit

RSquare	0.475318
RSquare Adj	0.474186
Root Mean Square Error	25.95944
Mean of Response	2053.691
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1425.6423	22.9197	62.20	0.0000
EST L6 GRATE FD	1.2465568	0.049911	24.98	<.0001
3A FLOW	-0.002597	0.000868	-2.99	0.0028
CORR 3B FLOW	0.0043338	0.000479	9.05	<.0001

Effect Test

FIGURE 144

Plant Data: Edited Test Composite

Model Summary of Fit and Parameter Estimates - CFD Model Control Variable Criteria

REC A FLOW

Summary of Fit

RSquare	0.582215
RSquare Adj	0.581314
Root Mean Square Error	131.4748
Mean of Response	2576.936
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-641.9206	116.0797	-5.53	<.0001
EST L6 GRATE FD	0.3378581	0.25278	1.34	0.1818
3A FLOW	0.1493326	0.004397	33.96	<.0001
CORR 3B FLOW	0.0781335	0.002425	32.22	<.0001

Effect Test

TOT REC FLOW

Summary of Fit

RSquare	0.582215
RSquare Adj	0.581314
Root Mean Square Error	242.9838
Mean of Response	5389.733
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-559.1651	214.5315	-2.61	0.0092
EST L6 GRATE FD	0.6244091	0.467174	1.34	0.1816
3A FLOW	0.2759875	0.008126	33.96	<.0001
CORR 3B FLOW	0.1444017	0.004481	32.22	<.0001

Effect Test

REC A TMP

Summary of Fit

RSquare	0.598443
RSquare Adj	0.597577
Root Mean Square Error	73.27987
Mean of Response	1322.618
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	511.9558	84.69912	7.91	<.0001
EST L6 GRATE FD	4.5090719	0.140892	32.00	<.0001
3A FLOW	-0.086529	0.002451	-35.31	<.0001
CORR 3B FLOW	-0.016304	0.001351	-12.06	<.0001

Effect Test

AVG REC TMP

Summary of Fit

RSquare	0.66328
RSquare Adj	0.662553
Root Mean Square Error	65.83124
Mean of Response	1408.647
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	399.76046	58.12268	6.88	<.0001
EST L6 GRATE FD	4.7184091	0.126571	37.28	<.0001
3A FLOW	-0.0833	0.002202	-37.84	<.0001
CORR 3B FLOW	-0.012391	0.001214	-10.21	<.0001

Effect Test

FIGURE 145

Plant Data: Edited Test Composite

Model Summary of Fit and Parameter Estimates and Prediction Profiles - CFD Criteria

VENT STACK TMP

Summary of Fit

RSquare	0.412731
RSquare Adj	0.411465
Root Mean Square Error	48.95887
Mean of Response	692.9682
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	468.36784	43.226	10.84	<.0001
EST L6 GRATE FD	2.1132406	0.094131	22.45	<.0001
3A FLOW	-0.032773	0.001637	-20.02	<.0001
CORR 3B FLOW	-0.026032	0.000903	-28.83	<.0001

Effect Test

Prediction Profile

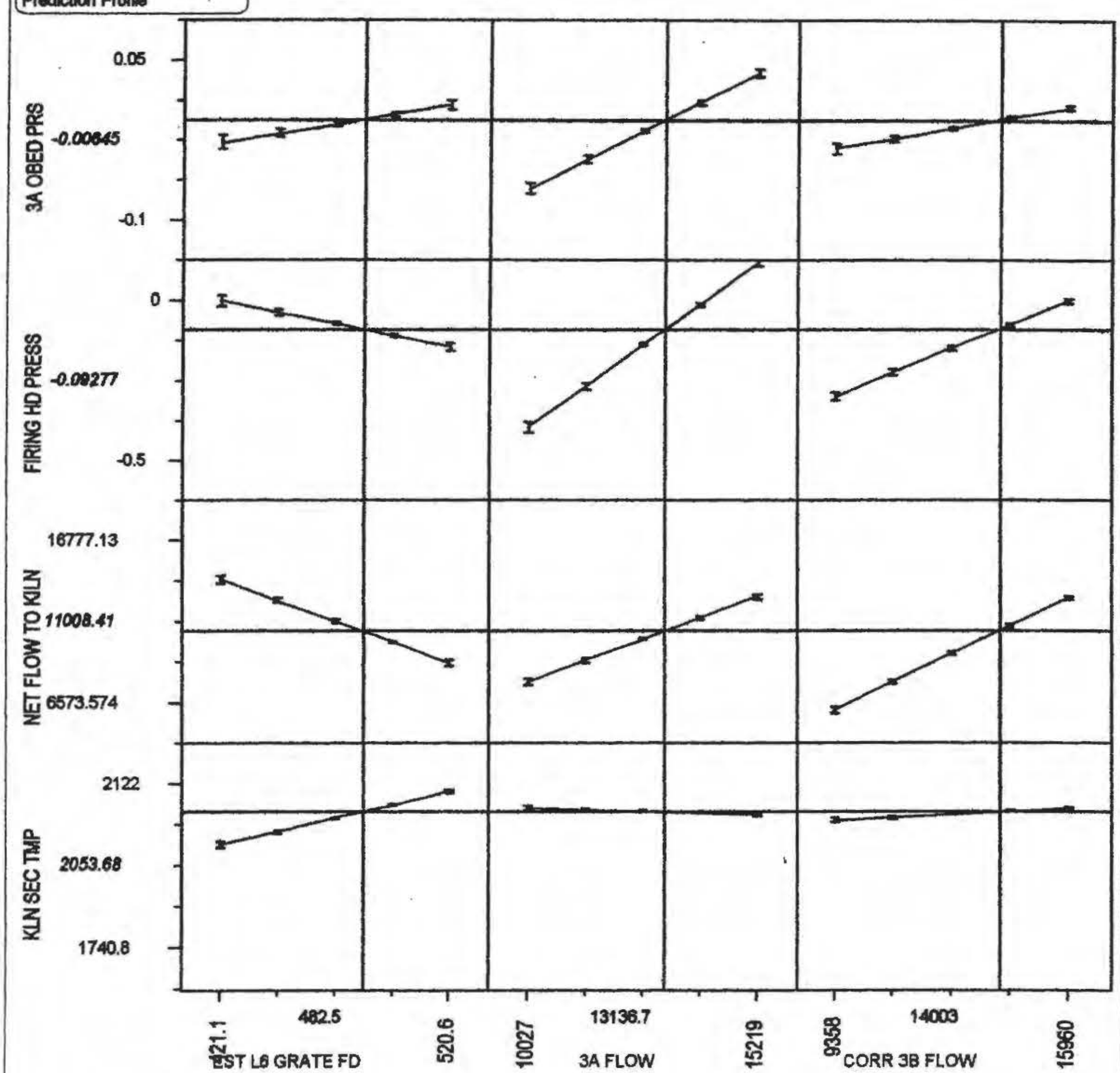


FIGURE 146

Plant Data: Edited Test Composite
Model Prediction Profiles - CFD Model Control Variable Criteria

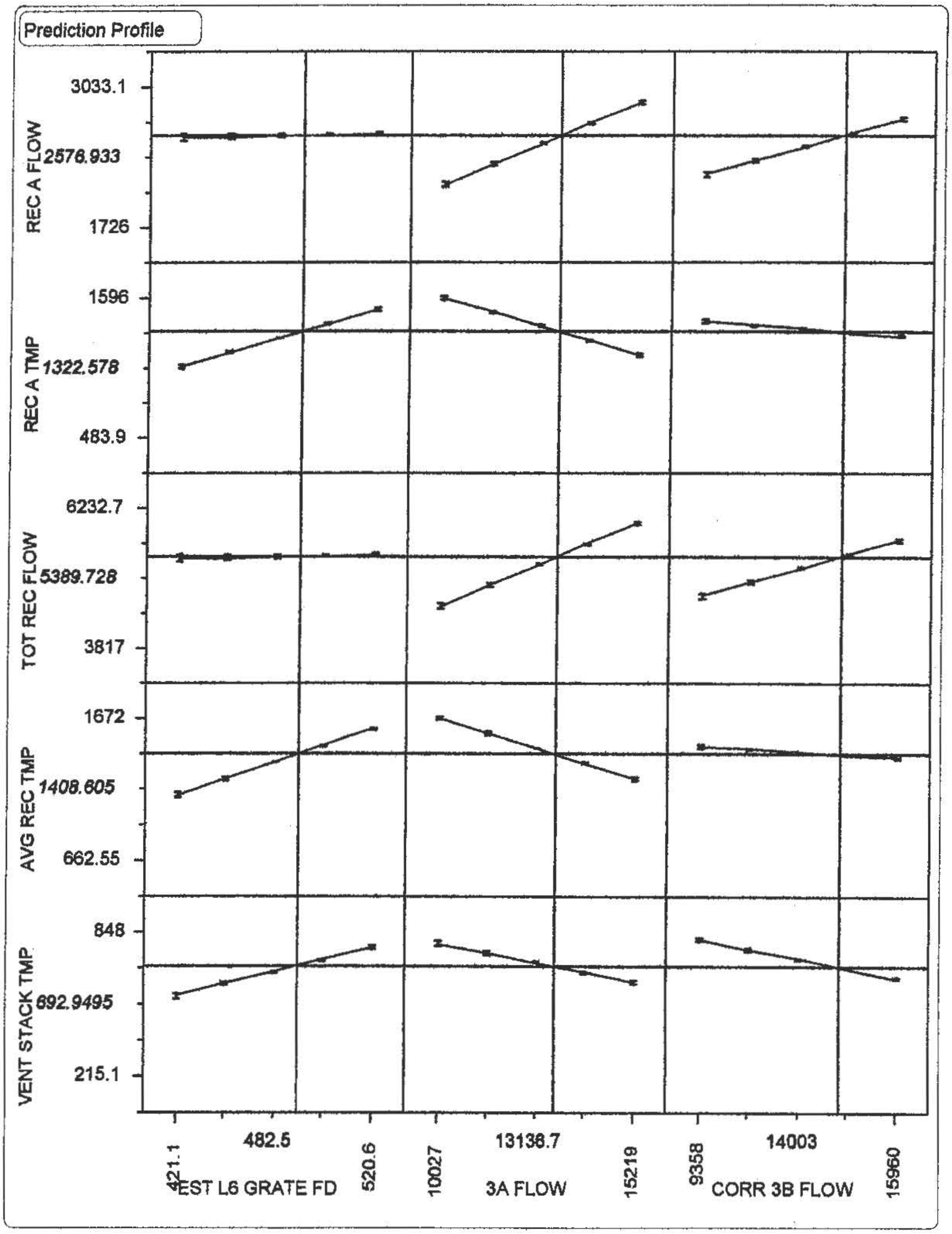


FIGURE 147

Plant Data Model

Current Cooler (No Overbed Wall) Operating Window

485 WLTPH Feed to Grate

High flow limited by 3A overbed pressure of +0.01 in.H_2O.
Low flow limited by Vent Stack temperature of 765 °F.

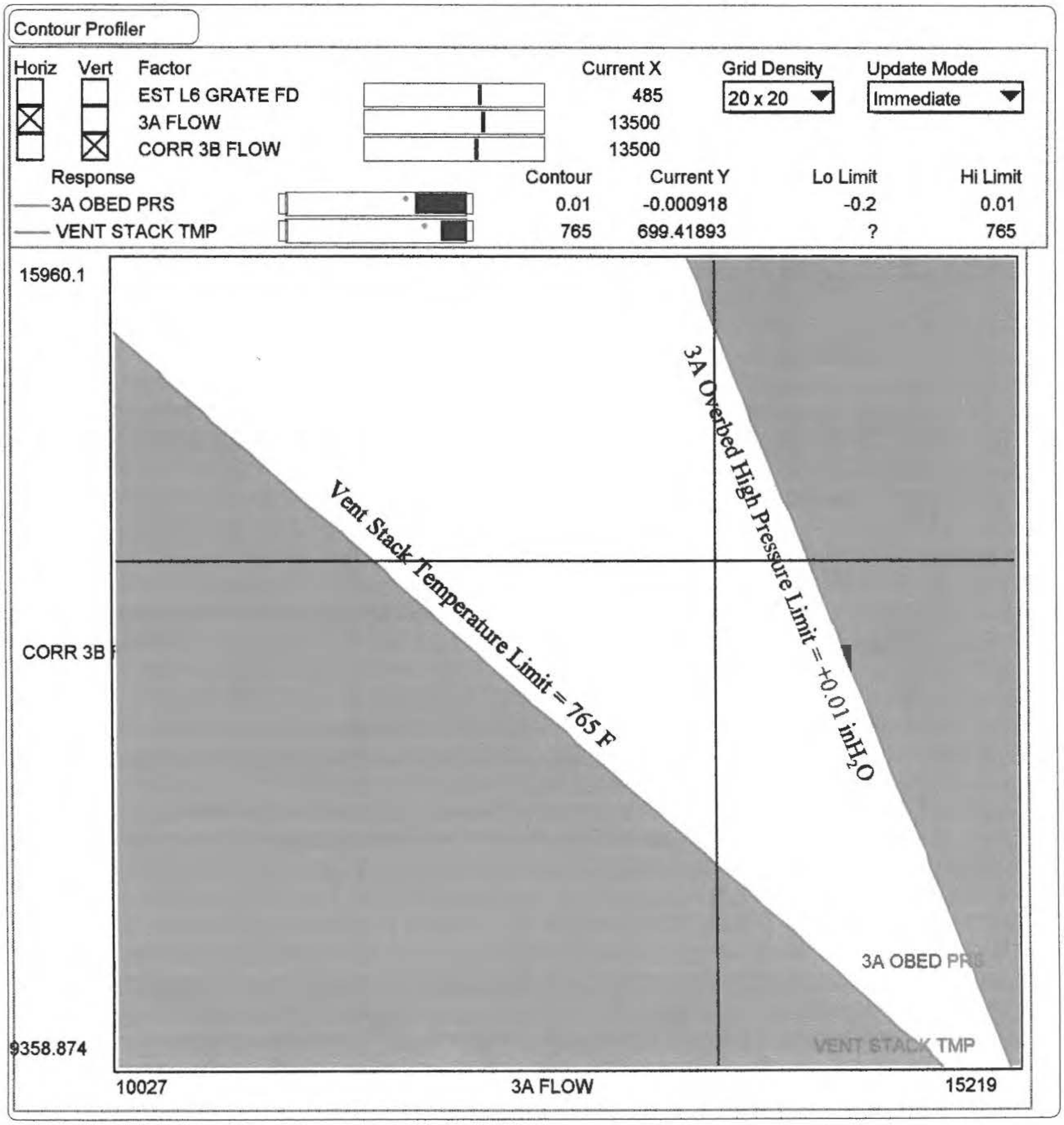


FIGURE 148
Plant Data Test Distribution in Operating Window
Plant Model

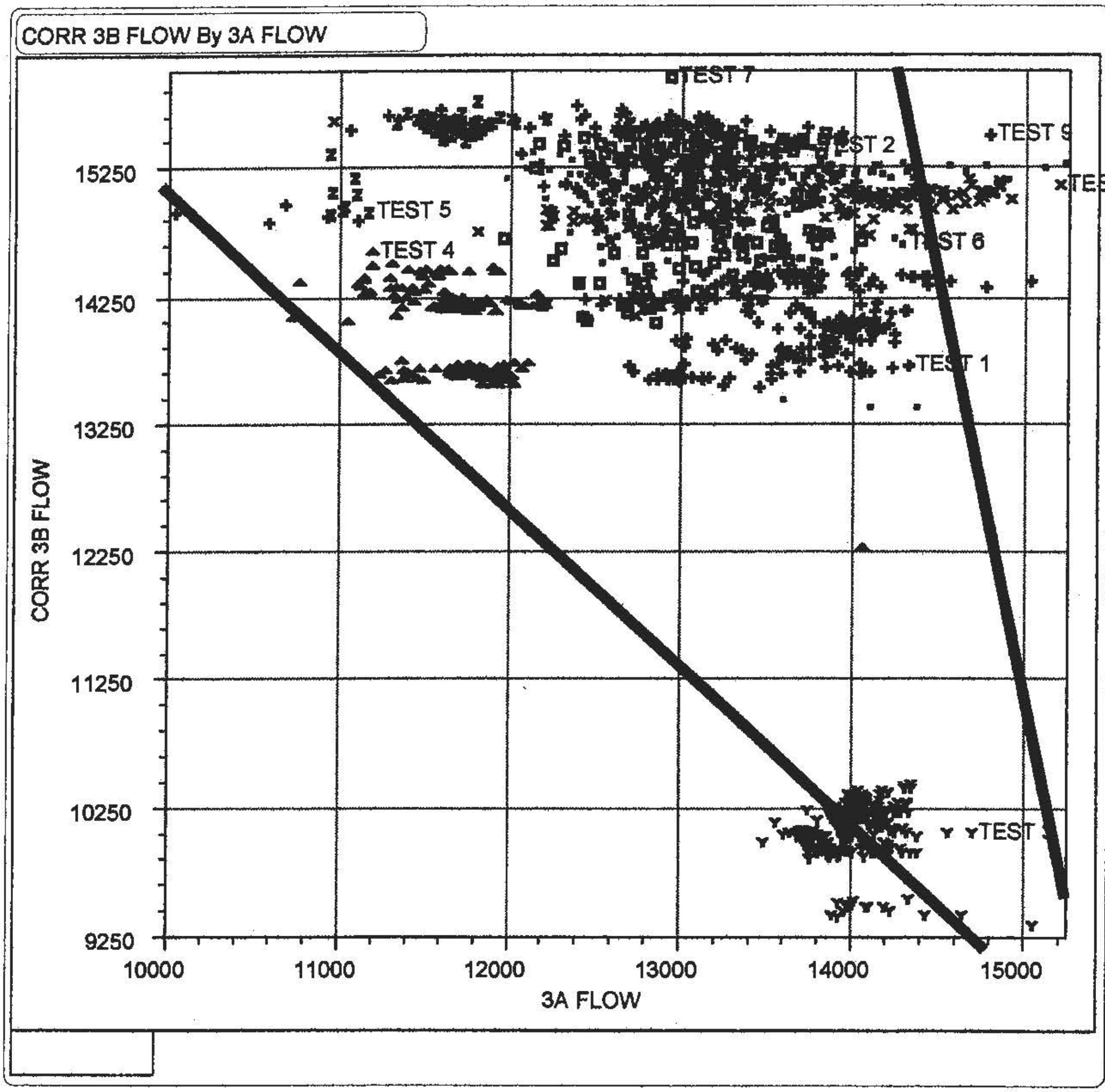


FIGURE 149

Current Cooler - Plant Data Model

Feed to Grate and Fuel Consumption Response Surfaces

EST L6 GRATE FD

Summary of Fit

RSquare	0.241318
RSquare Adj	0.240228
Root Mean Square Error	13.94053
Mean of Response	482.5088
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	358.06405	7.706227	46.46	<.0001
3A FLOW	0.0044671	0.000451	9.91	<.0001
CORR 3B FLOW	0.0046963	0.000224	20.95	<.0001

Effect Test

Response Surface

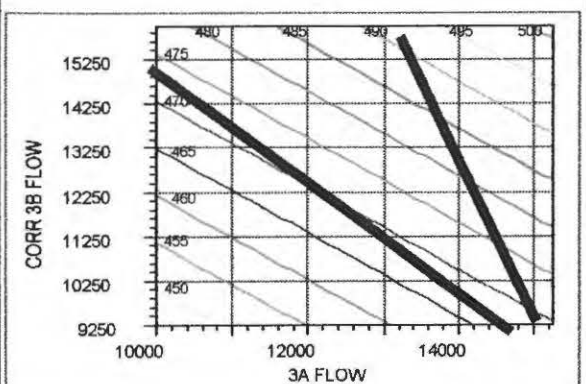
Coef	3A FLOW	CORR 3B FLOW		EST L6 GRATE FD
3A FLOW	0		0	0.0044671
CORR 3B FLOW	?		0	0.0046963

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Contour Plots



Fuel mbtu/ton

Summary of Fit

RSquare	0.181776
RSquare Adj	0.180601
Root Mean Square Error	29.58433
Mean of Response	606.4433
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	887.50958	16.35401	54.27	0.0000
3A FLOW	-0.013939	0.000956	-14.58	<.0001
CORR 3B FLOW	-0.006995	0.000476	-14.70	<.0001

Effect Test

Response Surface

Coef	3A FLOW	CORR 3B FLOW		Fuel mbtu/ton
3A FLOW	0		0	-0.013939
CORR 3B FLOW	?		0	-0.006995

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Contour Plots

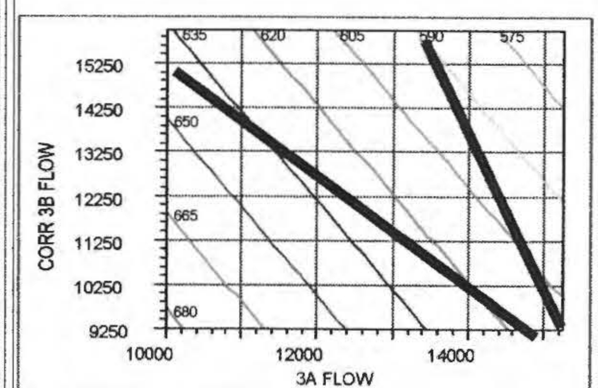


FIGURE 150

CFD Model: No Cooler Wall - Parametric Series
Primary and Secondary Cooling Overbed Pressure Prediction Profiles

3A OB PRS INH2O

Summary of Fit

RSquare	0.994887
RSquare Adj	0.993957
Root Mean Square Error	0.01009
Mean of Response	-0.08051
Observations (or Sum Wgts)	27

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.103338	0.036527	-30.21	<.0001
% MAG	0.001125	0.000396	2.84	0.0096
FEED LTPH	0.0004678	0.000068	6.88	<.0001
3A LBS/MIN	0.0000412	6.795e-7	60.63	<.0001
3B LBS/MIN	0.0000159	6.795e-7	23.43	<.0001

Effect Test

3B OBED PRESS

Summary of Fit

RSquare	0.995826
RSquare Adj	0.995067
Root Mean Square Error	0.008631
Mean of Response	-0.25967
Observations (or Sum Wgts)	27

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.380081	0.031243	-44.17	<.0001
% MAG	0.0016808	0.000339	4.96	<.0001
FEED LTPH	0.0009431	0.000058	16.23	<.0001
3A LBS/MIN	0.0000059	5.812e-7	10.08	<.0001
3B LBS/MIN	0.0000405	5.812e-7	69.71	<.0001

Effect Test

Prediction Profile

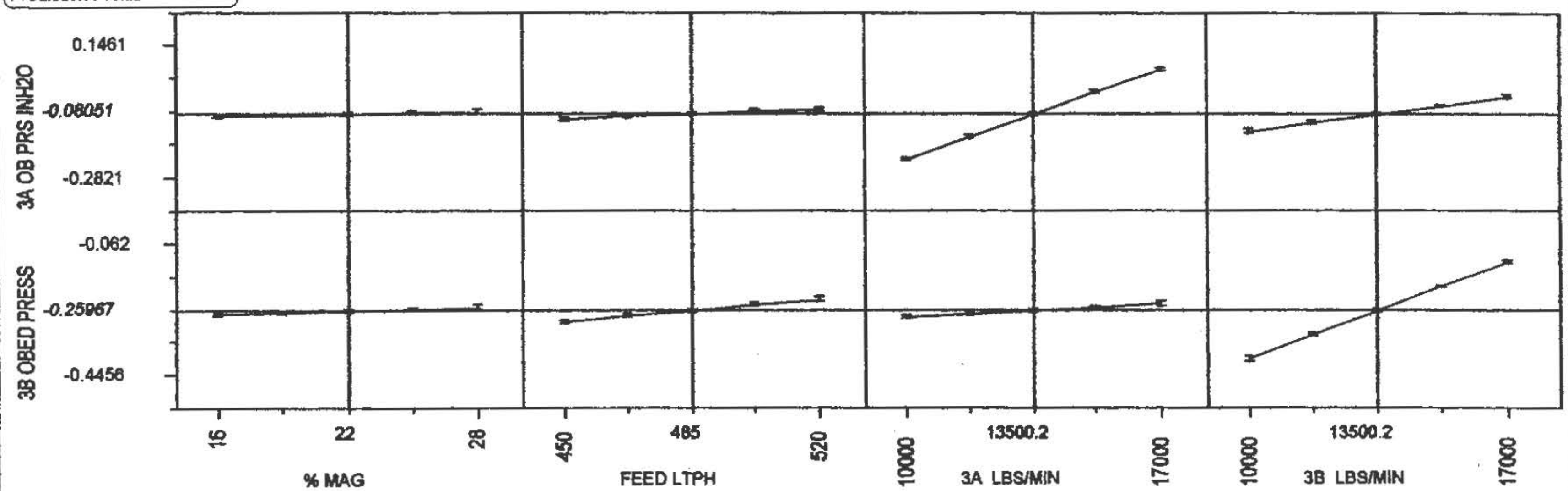


FIGURE 151

CFD Model: Cooler with Wall - Parametric Series
Primary and Secondary Cooling Overbed Pressure Prediction Profiles

3A OB PRS INH2O

Summary of Fit

RSquare	0.993622
RSquare Adj	0.992462
Root Mean Square Error	0.012129
Mean of Response	-0.09173
Observations (or Sum Wgts)	27

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.951331	0.043906	-21.67	<.0001
% MAG	0.0007313	0.000476	1.53	0.1391
FEED LTPH	0.0002687	0.000082	3.29	0.0033
3A LBS/MIN	0.0000474	8.168e-7	58.05	<.0001
3B LBS/MIN	0.0000054	8.168e-7	6.63	<.0001

Effect Test

3B OBED PRESS

Summary of Fit

RSquare	0.995498
RSquare Adj	0.99468
Root Mean Square Error	0.011929
Mean of Response	-0.23413
Observations (or Sum Wgts)	27

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.539805	0.043182	-35.66	<.0001
% MAG	0.0020258	0.000469	4.32	0.0003
FEED LTPH	0.0011707	0.00008	14.57	<.0001
3A LBS/MIN	-0.000003	8.033e-7	-4.02	0.0006
3B LBS/MIN	0.0000546	8.033e-7	67.95	<.0001

Effect Test

Prediction Profile

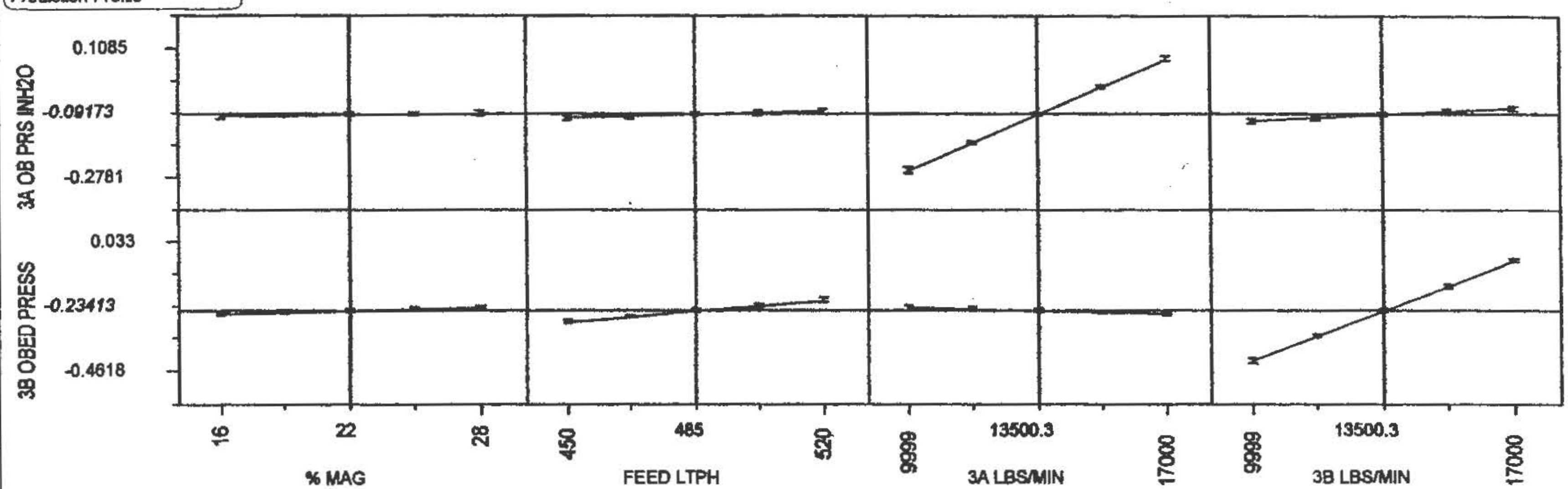


FIGURE 152

Plant Data: Test Composite

Firing Hood, Primary, and Secondary Cooling Overbed Pressure Prediction Profiles

FIRING HD PRESS

Summary of Fit

RSquare	0.588248
RSquare Adj	0.58736
Root Mean Square Error	0.073089
Mean of Response	-0.09278
Observations (or Sum Wgts)	1395

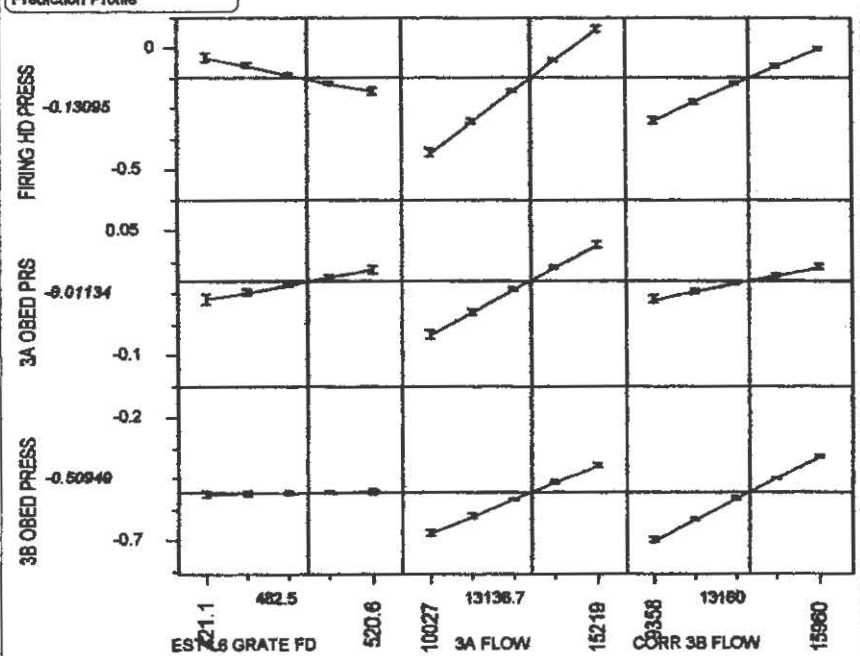
Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.322894	0.064531	-20.50	<.0001
EST L6 GRATE FD	-0.001441	0.000141	-10.25	<.0001
3A FLOW	0.0000963	0.000002	40.21	<.0001
CORR 3B FLOW	0.0000453	0.000001	33.60	<.0001

Effect Test

Prediction Profile



3A OBED PRS

Summary of Fit

RSquare	0.37169
RSquare Adj	0.370335
Root Mean Square Error	0.026095
Mean of Response	-0.00644
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.532785	0.02304	-23.12	<.0001
EST L6 GRATE FD	0.0003556	0.00005	7.09	<.0001
3A FLOW	0.0000208	8.727e-7	23.85	<.0001
CORR 3B FLOW	0.0000058	4.813e-7	12.07	<.0001

Effect Test

3B OBED PRESS

Summary of Fit

RSquare	0.722137
RSquare Adj	0.721538
Root Mean Square Error	0.054365
Mean of Response	-0.46601
Observations (or Sum Wgts)	1395

Analysis of Variance

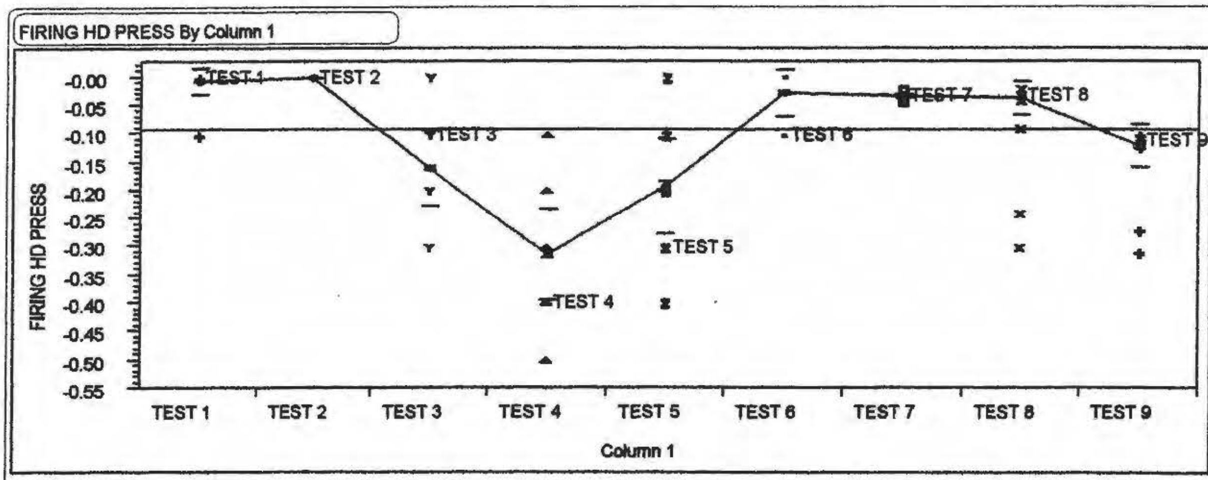
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.937781	0.047999	-40.37	<.0001
EST L6 GRATE FD	0.0001018	0.000105	0.97	0.3302
3A FLOW	0.0000533	0.000002	29.32	<.0001
CORR 3B FLOW	0.0000516	0.000001	51.45	0.0000

Effect Test

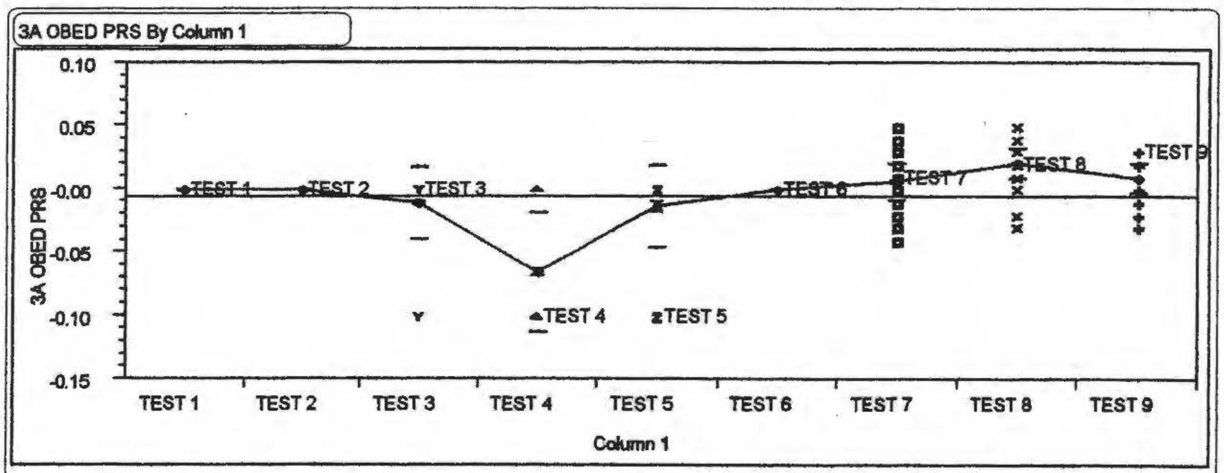
FIGURE 153

Plant Data: Test Composite
Firing Hood and Primary Cooling Overbed Pressure



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	-0.0068	0.025229	0.00176
TEST 2	179	0.000000	0.000000	0.00000
TEST 3	224	-0.15759	0.066532	0.00445
TEST 4	173	-0.31272	0.082547	0.00628
TEST 5	58	-0.19138	0.086419	0.01135
TEST 6	154	-0.02468	0.043253	0.00349
TEST 7	142	-0.03035	0.003654	0.00031
TEST 8	134	-0.03433	0.029974	0.00259
TEST 9	125	-0.11856	0.037903	0.00339

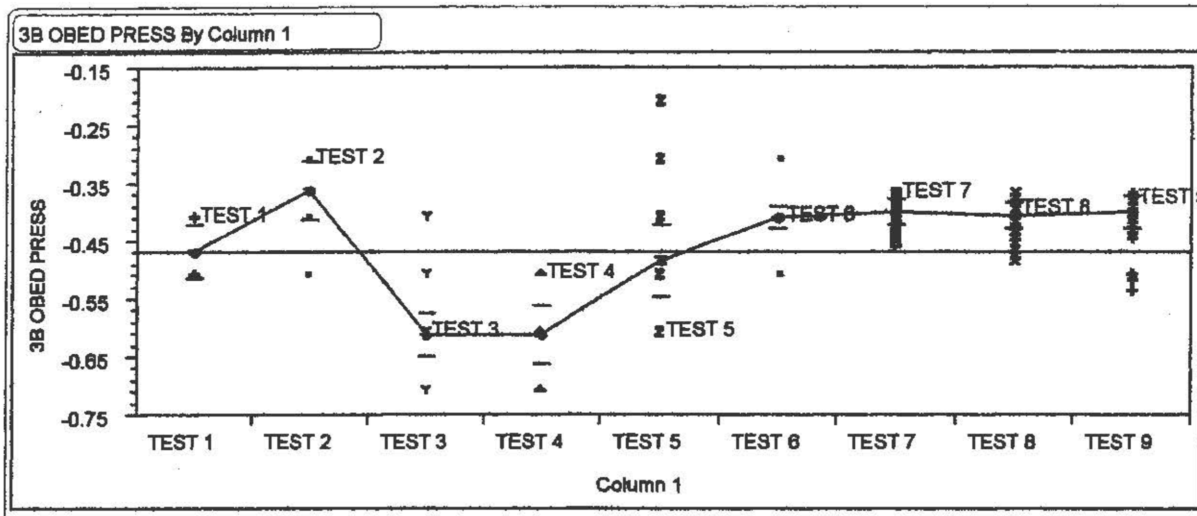


Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	0.000000	0.000000	0.00000
TEST 2	179	0.000000	0.000000	0.00000
TEST 3	224	-0.00938	0.029213	0.00195
TEST 4	173	-0.06532	0.047734	0.00363
TEST 5	58	-0.01207	0.032861	0.00431
TEST 6	154	0.000000	0.000000	0.00000
TEST 7	142	0.006761	0.015599	0.00131
TEST 8	134	0.021791	0.011880	0.00103
TEST 9	125	0.009840	0.012762	0.00114

FIGURE 154

Plant Data: Test Composite
Secondary Cooling Overbed Pressure



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
TEST 1	206	-0.46456	0.047949	0.00334
TEST 2	179	-0.3581	0.052774	0.00394
TEST 3	224	-0.60625	0.038541	0.00258
TEST 4	173	-0.60809	0.051074	0.00388
TEST 5	58	-0.48103	0.063403	0.00833
TEST 6	154	-0.40325	0.021140	0.00170
TEST 7	142	-0.39606	0.022659	0.00190
TEST 8	134	-0.40007	0.022293	0.00193
TEST 9	125	-0.39544	0.029798	0.00267

FIGURE 155

Plant Data: Current Cooler - Test Composite
Summary of Fit and Parameter Estimates - MEDUSA/CFD Model Criteria

3A OBED PRS

Summary of Fit

RSquare	0.348998
RSquare Adj	0.348063
Root Mean Square Error	0.026553
Mean of Response	-0.00644
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.405452	0.014678	-27.62	<.0001
3A FLOW	0.0000224	8.582e-7	26.10	<.0001
CORR 3B FLOW	0.0000075	4.27e-7	17.51	<.0001

Effect Test

EST L6 GRATE FD

Summary of Fit

RSquare	0.241318
RSquare Adj	0.240228
Root Mean Square Error	13.94053
Mean of Response	482.5088
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	358.06405	7.706227	46.46	<.0001
3A FLOW	0.0044671	0.000451	9.91	<.0001
CORR 3B FLOW	0.0046963	0.000224	20.95	<.0001

Effect Test

3B OBED PRESS

Summary of Fit

RSquare	0.721947
RSquare Adj	0.721548
Root Mean Square Error	0.054364
Mean of Response	-0.46601
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.901323	0.030052	-63.27	0.0000
3A FLOW	0.0000538	0.000002	30.60	<.0001
CORR 3B FLOW	0.0000521	8.742e-7	59.55	0.0000

Effect Test

Fuel mbtu/ton

Summary of Fit

RSquare	0.181776
RSquare Adj	0.180601
Root Mean Square Error	29.58433
Mean of Response	606.4433
Observations (or Sum Wgts)	1395

Analysis of Variance

Parameter Estimates

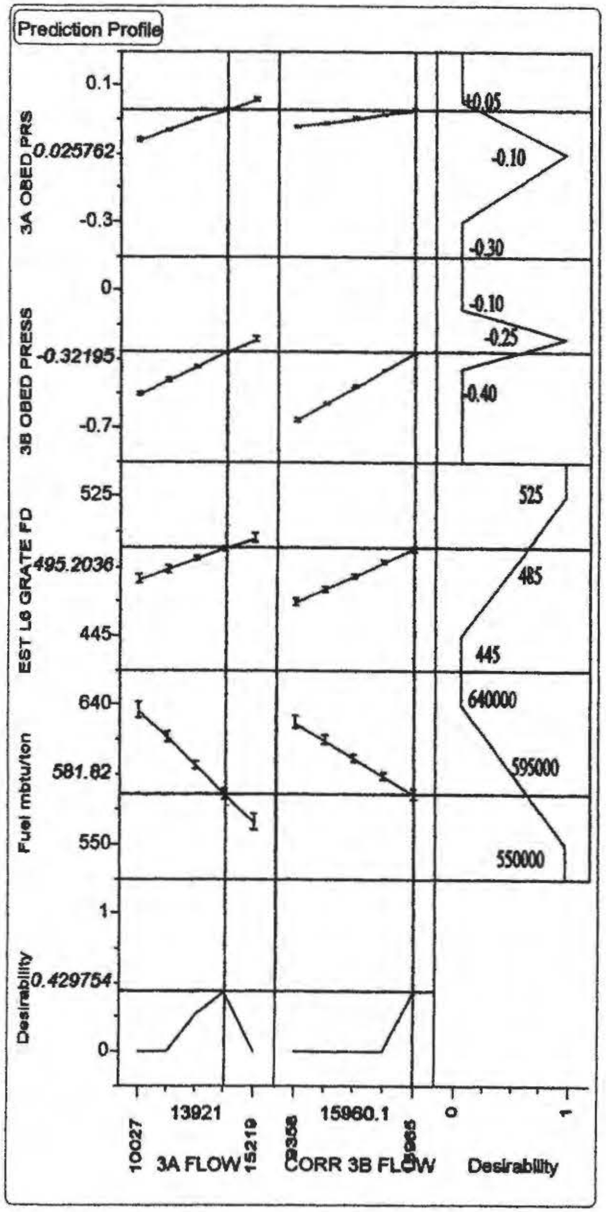
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	887.50958	16.35401	54.27	0.0000
3A FLOW	-0.013939	0.000956	-14.58	<.0001
CORR 3B FLOW	-0.006995	0.000476	-14.70	<.0001

Effect Test

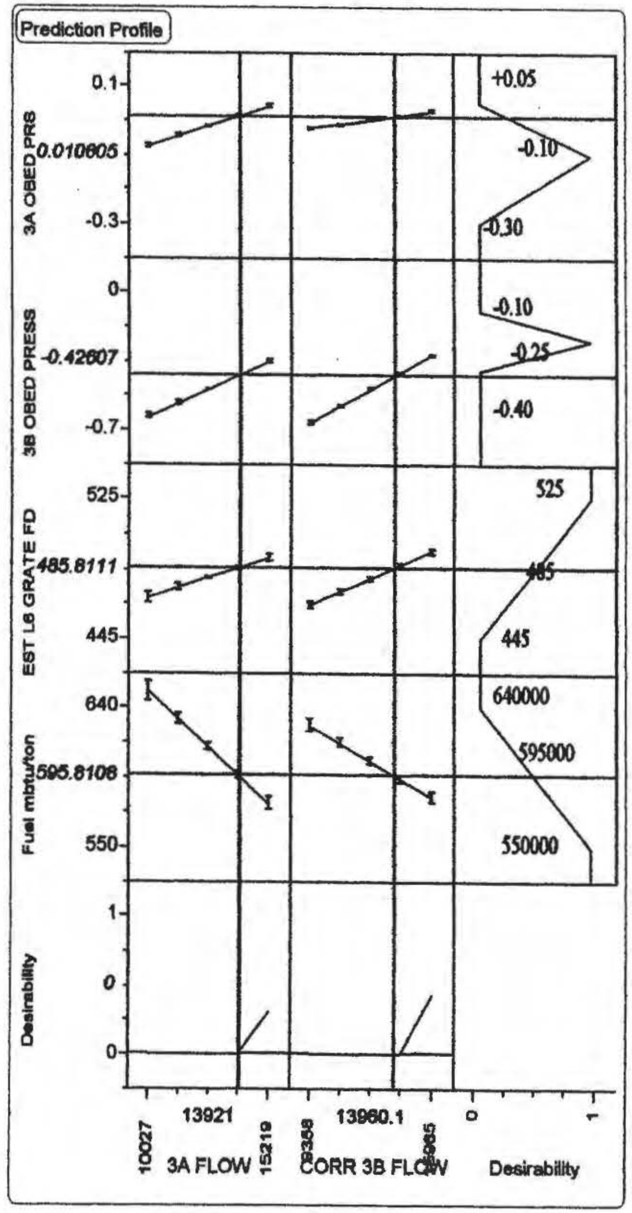
FIGURE 156

Plant Data: Current Cooler Test Composite

1. Optimized Conditions



2. Low 3B Flow Condition



3. High 3A Flow/Low 3B Flow Condition

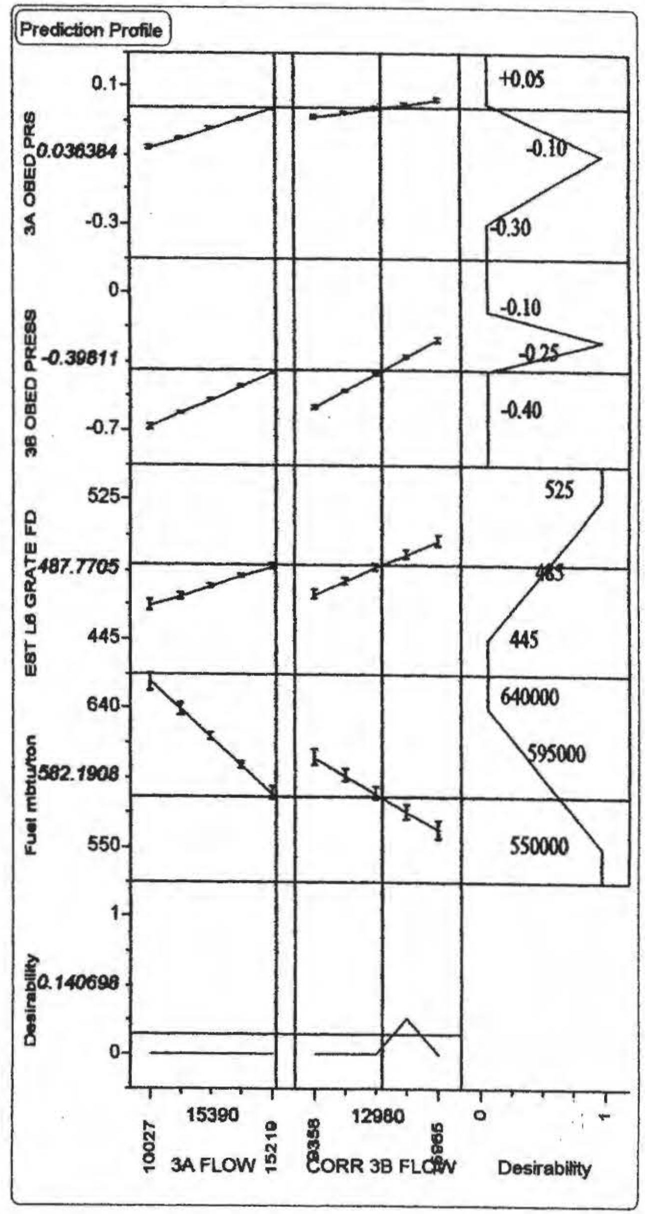


FIGURE 157

MEDUSA/CFD Model: Current Cooler - No Wall

Parameter Estimates

3A OBED PRESS

Summary of Fit

RSquare	0.999756
RSquare Adj	0.999732
Root Mean Square Error	0.000807
Mean of Response	-0.13212
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.958272	0.003206	-298.9	<.0001
3a flow	0.0000445	1.534e-7	290.03	<.0001
3b flow	0.0000194	1.11e-7	174.55	<.0001

Effect Test

3B OBED PRESS

Summary of Fit

RSquare	0.999709
RSquare Adj	0.999681
Root Mean Square Error	0.001588
Mean of Response	-0.27929
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.092092	0.006308	-173.1	<.0001
3a flow	0.0000123	3.019e-7	40.58	<.0001
3b flow	0.0000473	2.184e-7	216.81	<.0001

Effect Test

LTPH

Summary of Fit

RSquare	0.980362
RSquare Adj	0.978491
Root Mean Square Error	1.563294
Mean of Response	459.1785
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	290.72799	6.208174	46.83	<.0001
3a flow	0.0057919	0.000297	19.49	<.0001
3b flow	0.0068937	0.000215	32.08	<.0001

Effect Test

FUEL MBTU/LT

Summary of Fit

RSquare	0.978622
RSquare Adj	0.976586
Root Mean Square Error	2120.93
Mean of Response	601907.4
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	821027.55	8422.664	97.48	<.0001
3a flow	-7.54379	0.40314	-18.71	<.0001
3b flow	-8.958573	0.291559	-30.73	<.0001

Effect Test

FIGURE 158

MEDUSA/CFD Model: Current Cooler - No Wall -Desirability Profiles

1. Optimized Conditions
2. Low 3B Flow Conditon
3. High 3B Low 3A Condition

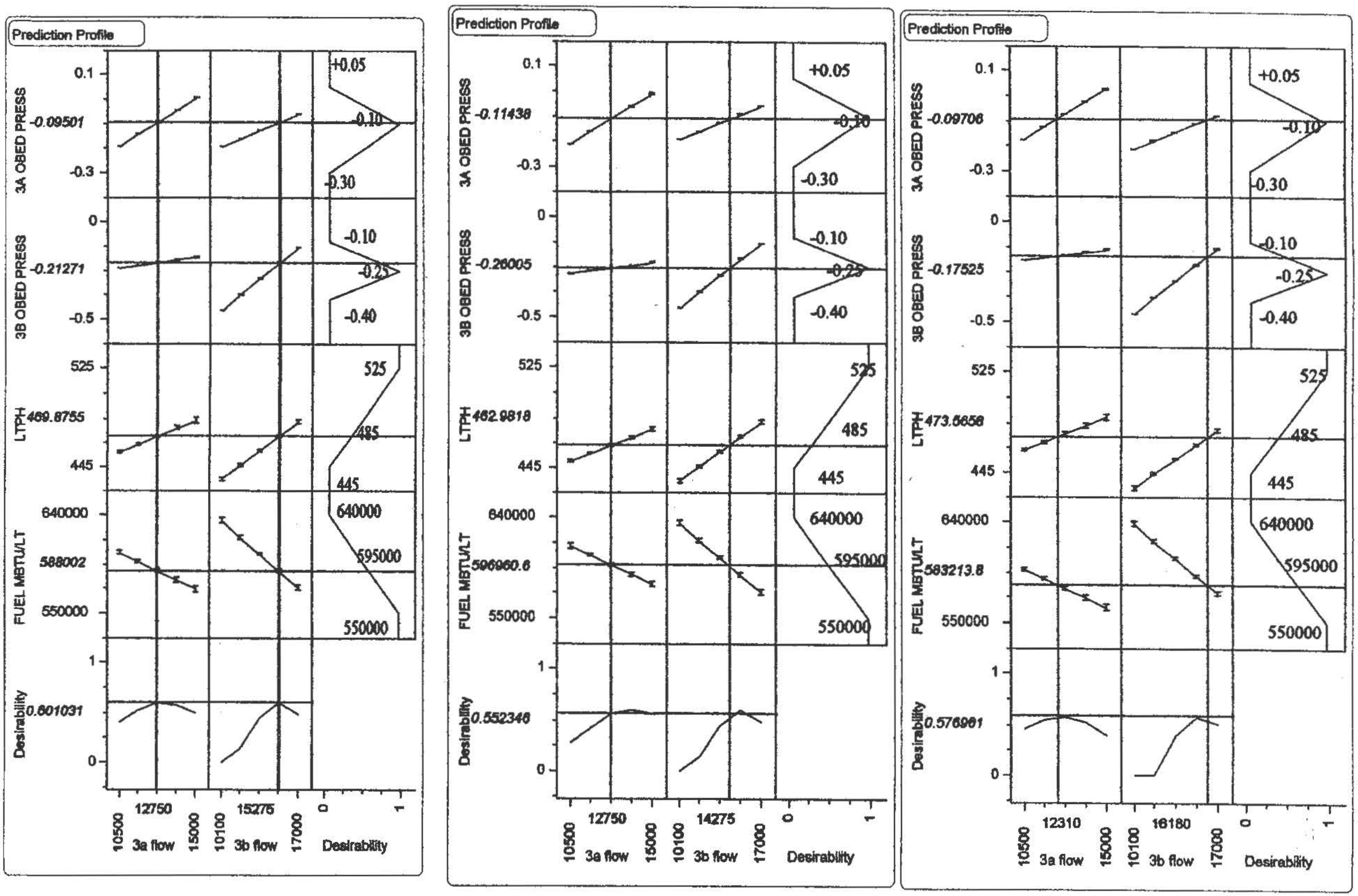


FIGURE 159
MEDUSA/CFD: Cooler with Wall
Summary of Fit and Parameter Estimates

3A OBED PRESS

Summary of Fit

RSquare	0.999946
RSquare Adj	0.999941
Root Mean Square Error	0.000521
Mean of Response	-0.14926
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.869853	0.002071	-420.1	<.0001
3a flow	0.0000501	9.911e-8	505.10	<.0001
3b flow	0.0000068	7.168e-8	94.95	<.0001

Effect Test

3B OBED PRESS

Summary of Fit

RSquare	0.9997
RSquare Adj	0.999671
Root Mean Square Error	0.002201
Mean of Response	-0.25297
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.194471	0.008741	-136.7	<.0001
3a flow	0.0000078	4.184e-7	18.58	<.0001
3b flow	0.0000606	3.026e-7	200.28	<.0001

Effect Test

LTPH

Summary of Fit

RSquare	0.965855
RSquare Adj	0.962603
Root Mean Square Error	1.78702
Mean of Response	451.5498
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	280.57454	7.09664	39.54	<.0001
3a flow	0.0081023	0.00034	23.85	<.0001
3b flow	0.0050021	0.000246	20.36	<.0001

Effect Test

FUEL MBTU/LT

Summary of Fit

RSquare	0.959964
RSquare Adj	0.956151
Root Mean Square Error	2649.923
Mean of Response	612010.9
Observations (or Sum Wgts)	24

Analysis of Variance

Parameter Estimates

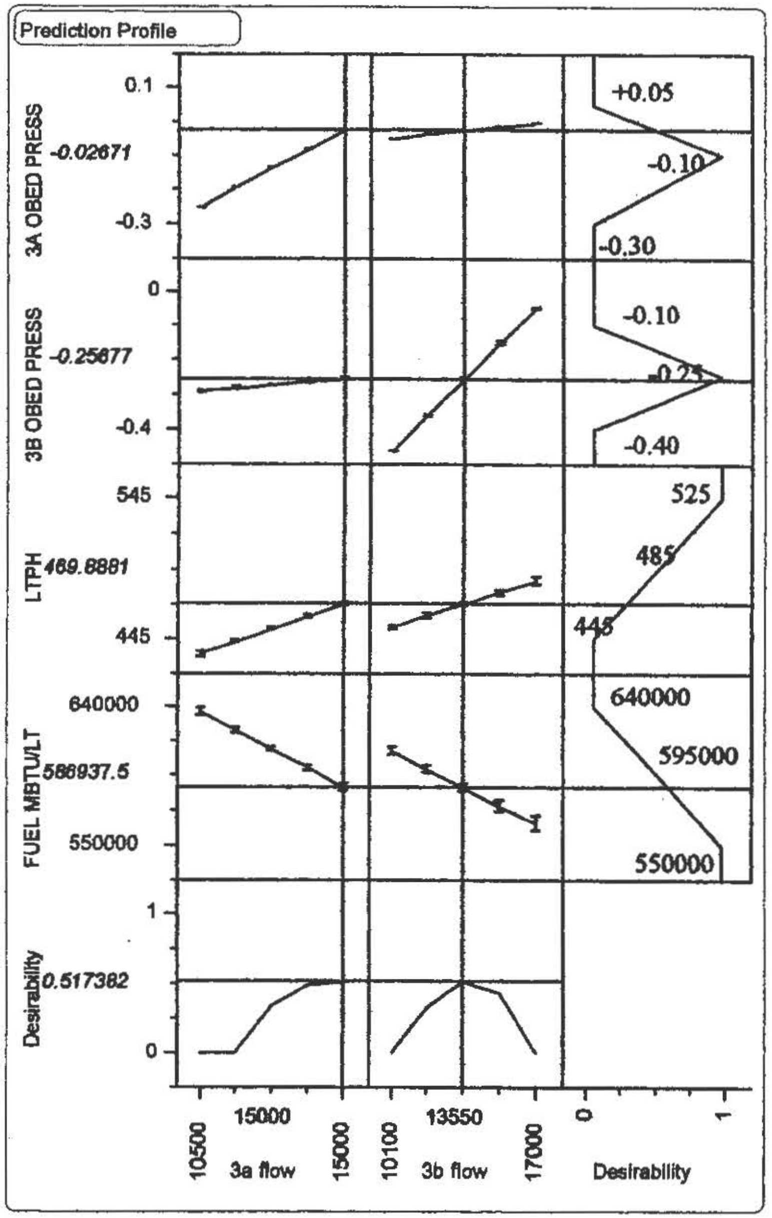
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	845264.31	10523.41	80.32	<.0001
3a flow	-11.07309	0.50369	-21.98	<.0001
3b flow	-6.806684	0.364278	-18.69	<.0001

Effect Test

FIGURE 160

MEDUSA/CFD Model: Cooler with Wall -Desirability Profiles

1. Optimized with Baseline Set Points



2. Optimized with Narrowed 3B Set Point Range

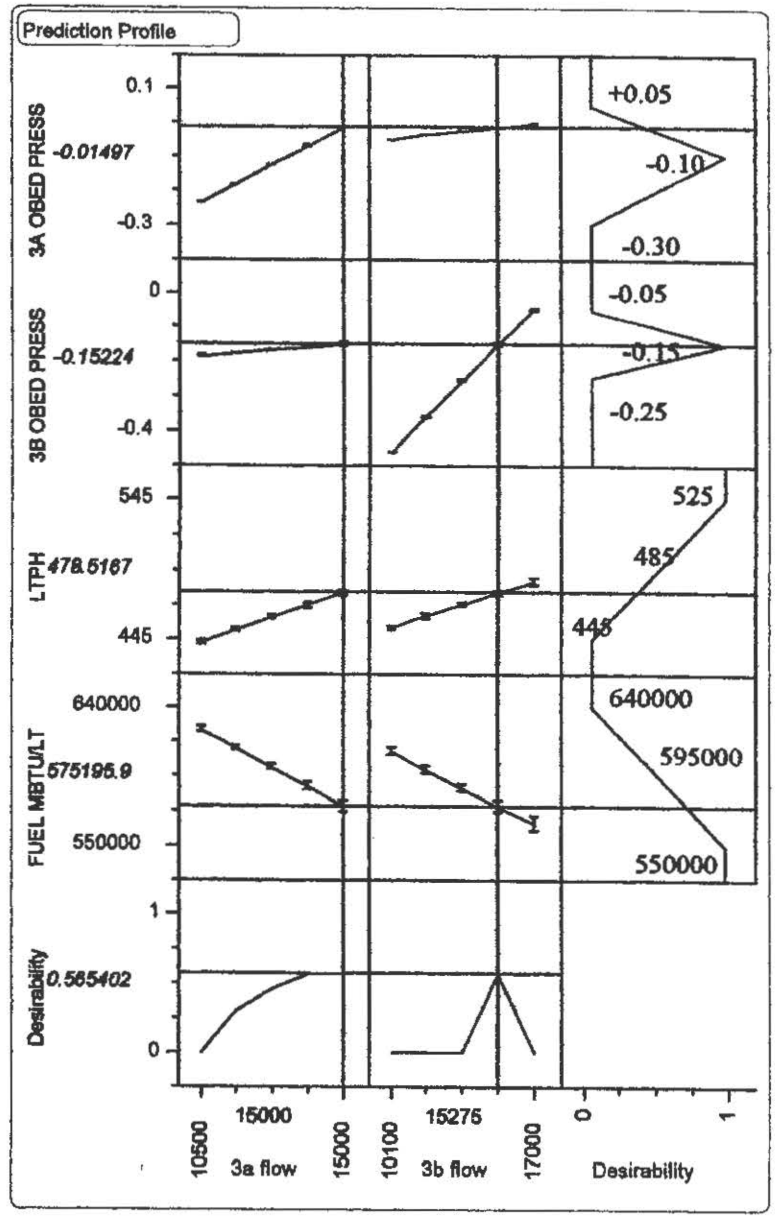


FIGURE 161

PRIMARY COOLING OVERBED PRESSURES

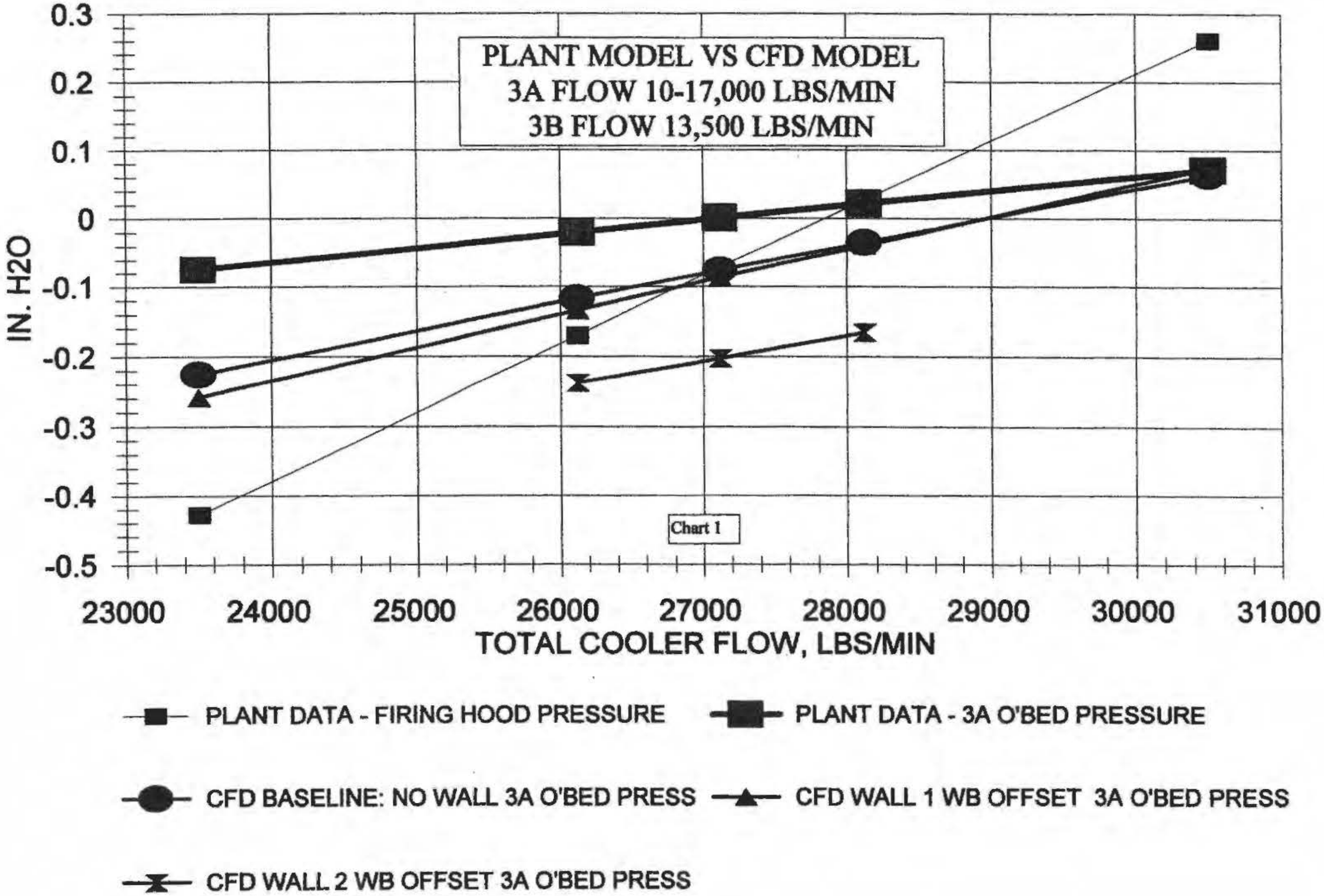


FIGURE 162

KILN SECONDARY AIR TEMPERATURE

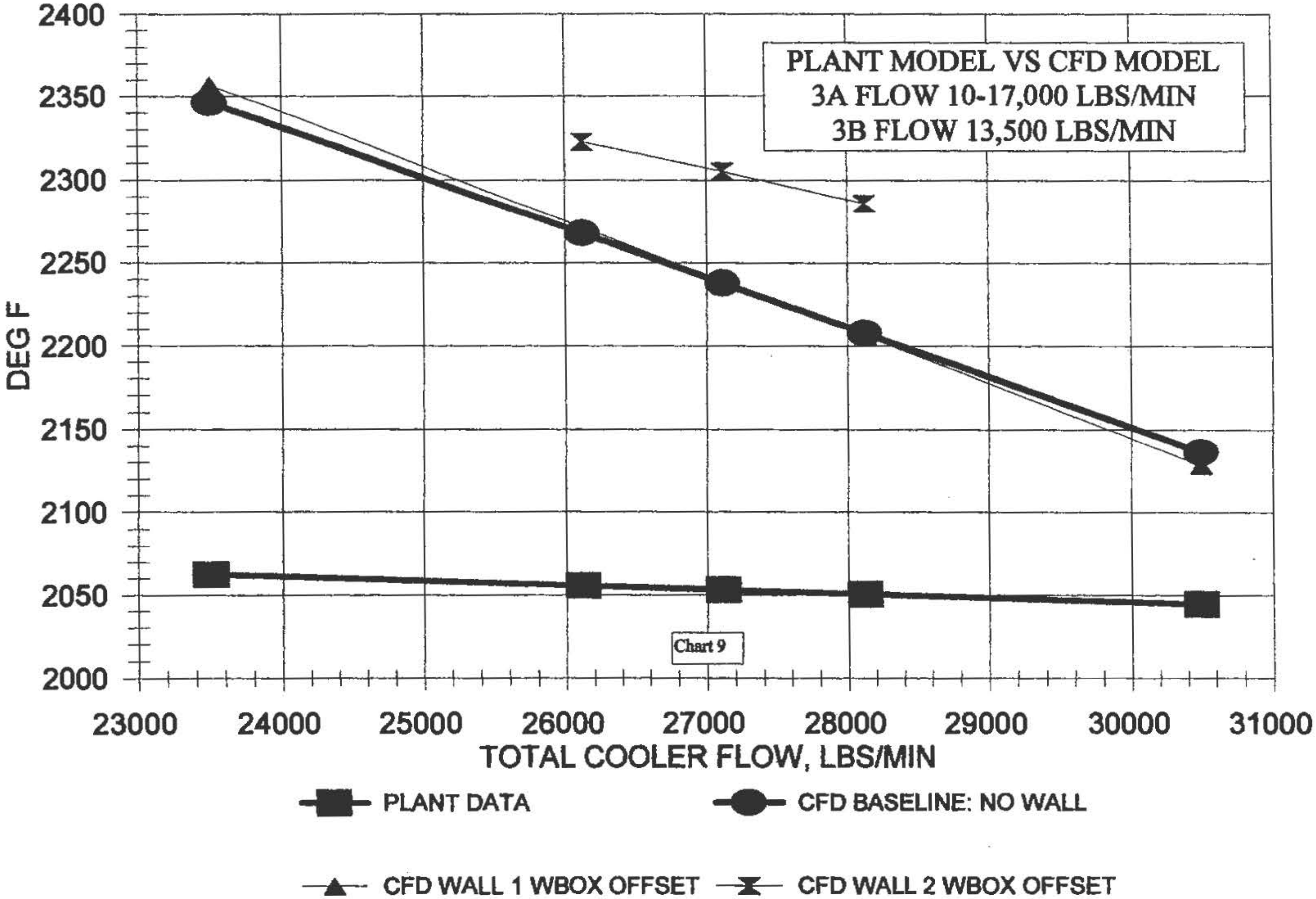


FIGURE 163
COOLER FLOW TO KILN

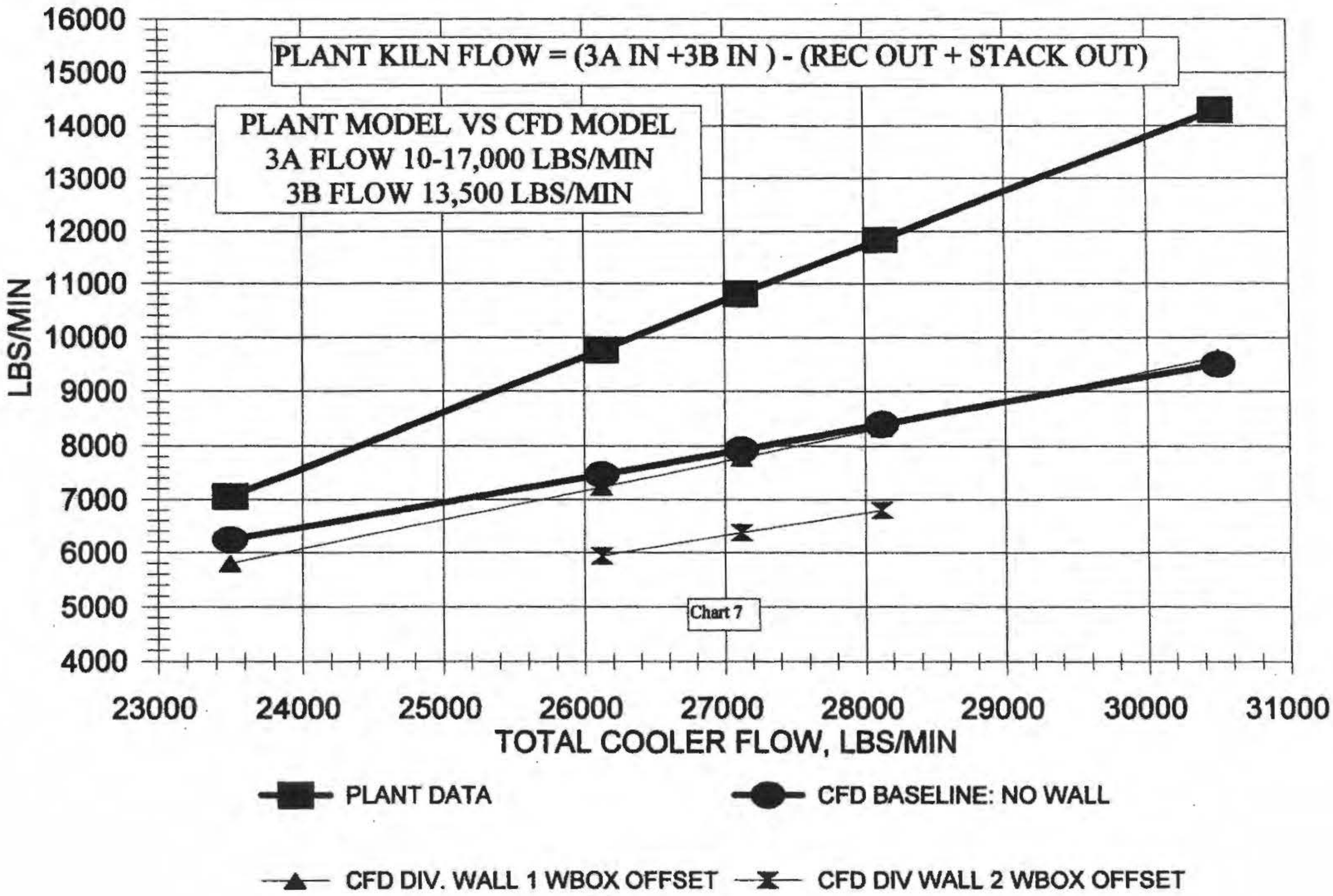
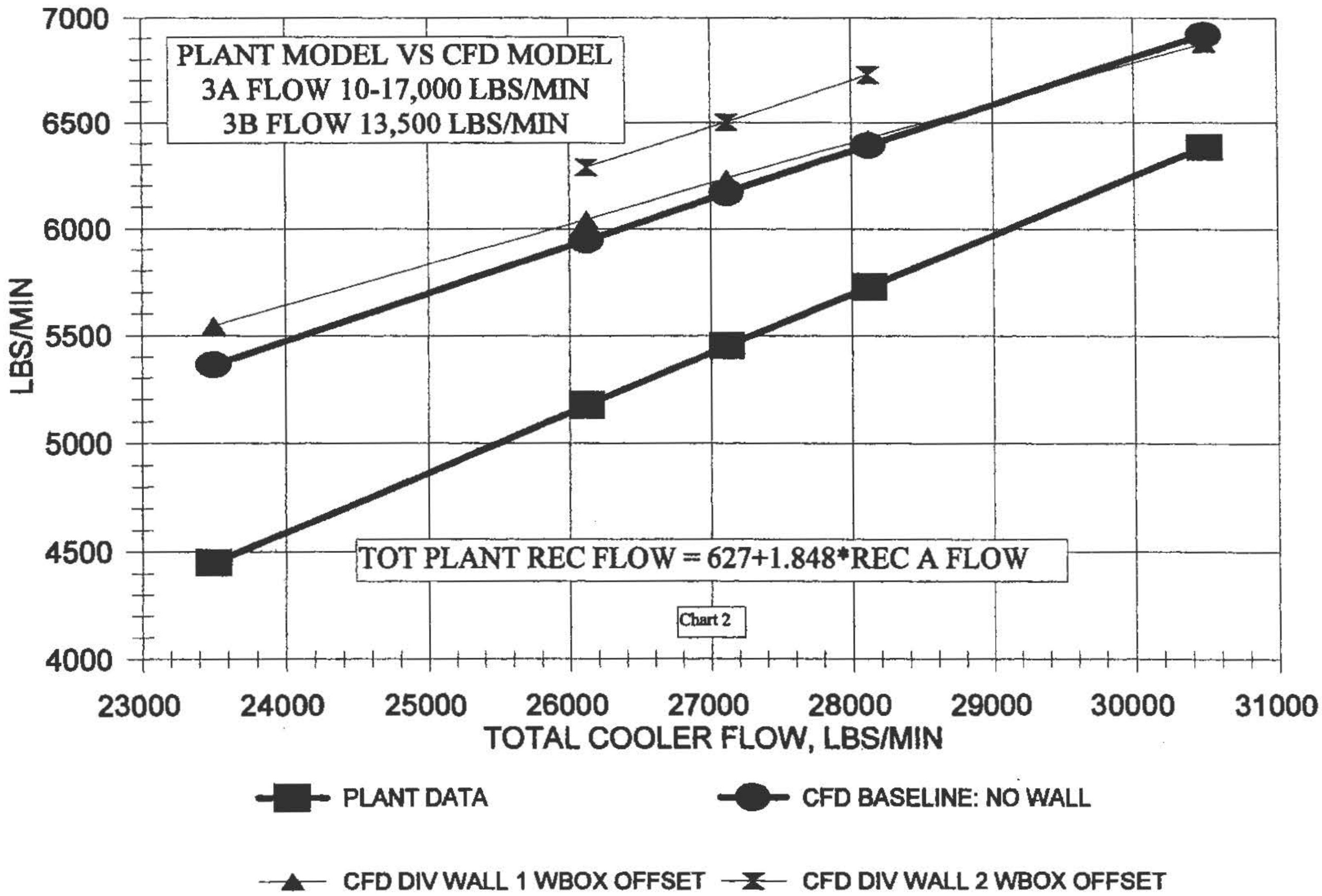


FIGURE 164

TOTAL RECOUP FLOW



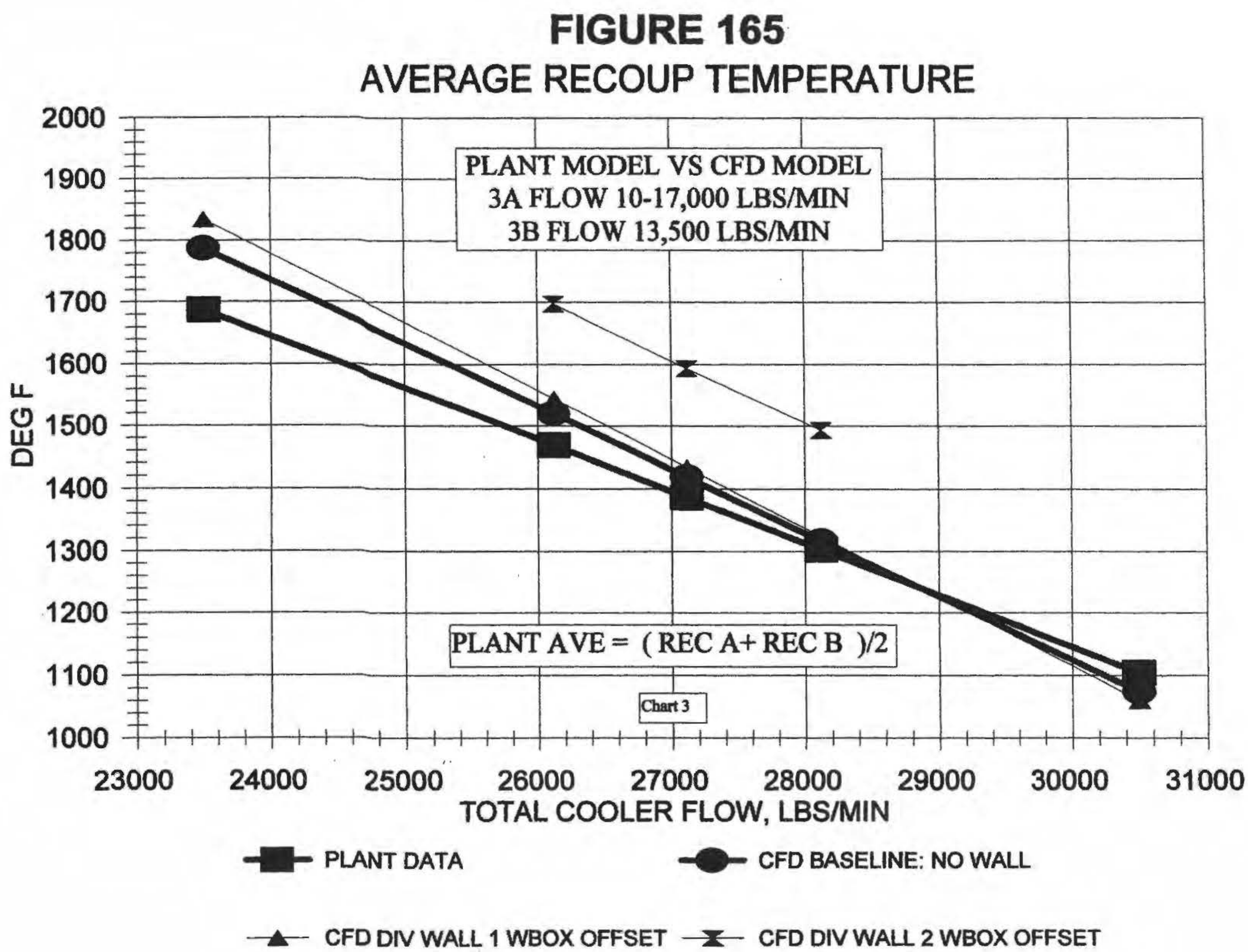


FIGURE 165
AVERAGE RECOUP TEMPERATURE
PLANT MODEL VS CFD MODEL
3A FLOW 10-17,000 LBS/MIN
3B FLOW 13,500 LBS/MIN
PLANT AVE = (REC A+ REC B)/2
Chart 3
DEG F
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
23000
24000
25000
26000
27000
28000
29000
30000
31000
TOTAL COOLER FLOW, LBS/MIN
PLANT DATA
CFD BASELINE: NO WALL
CFD DIV WALL 1 WBOX OFFSET
CFD DIV WALL 2 WBOX OFFSET

FIGURE 166
COOLER VENT STACK TEMPERATURE

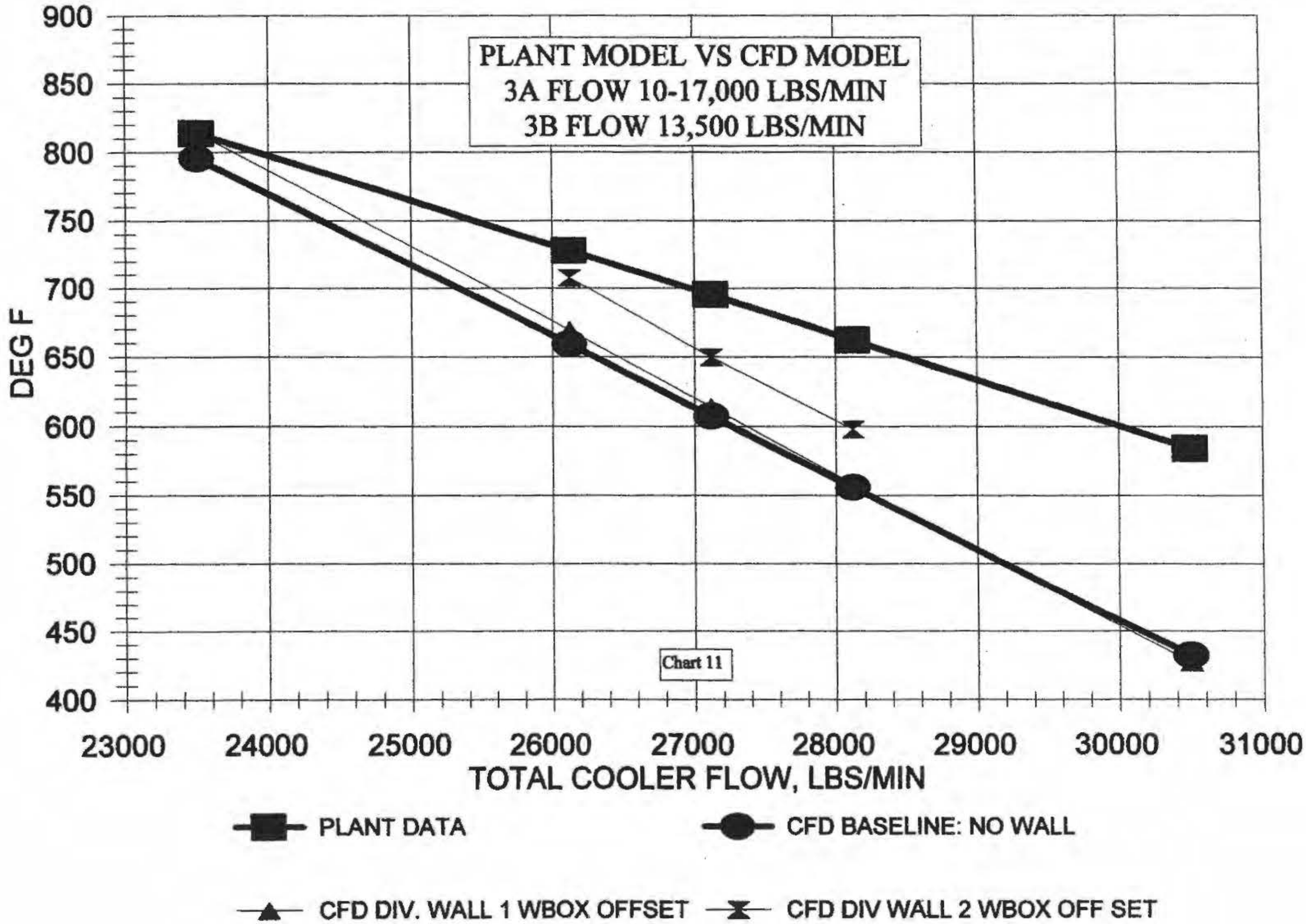


FIGURE 167

PREDICTED GREEN BALL FEED TO GRATE

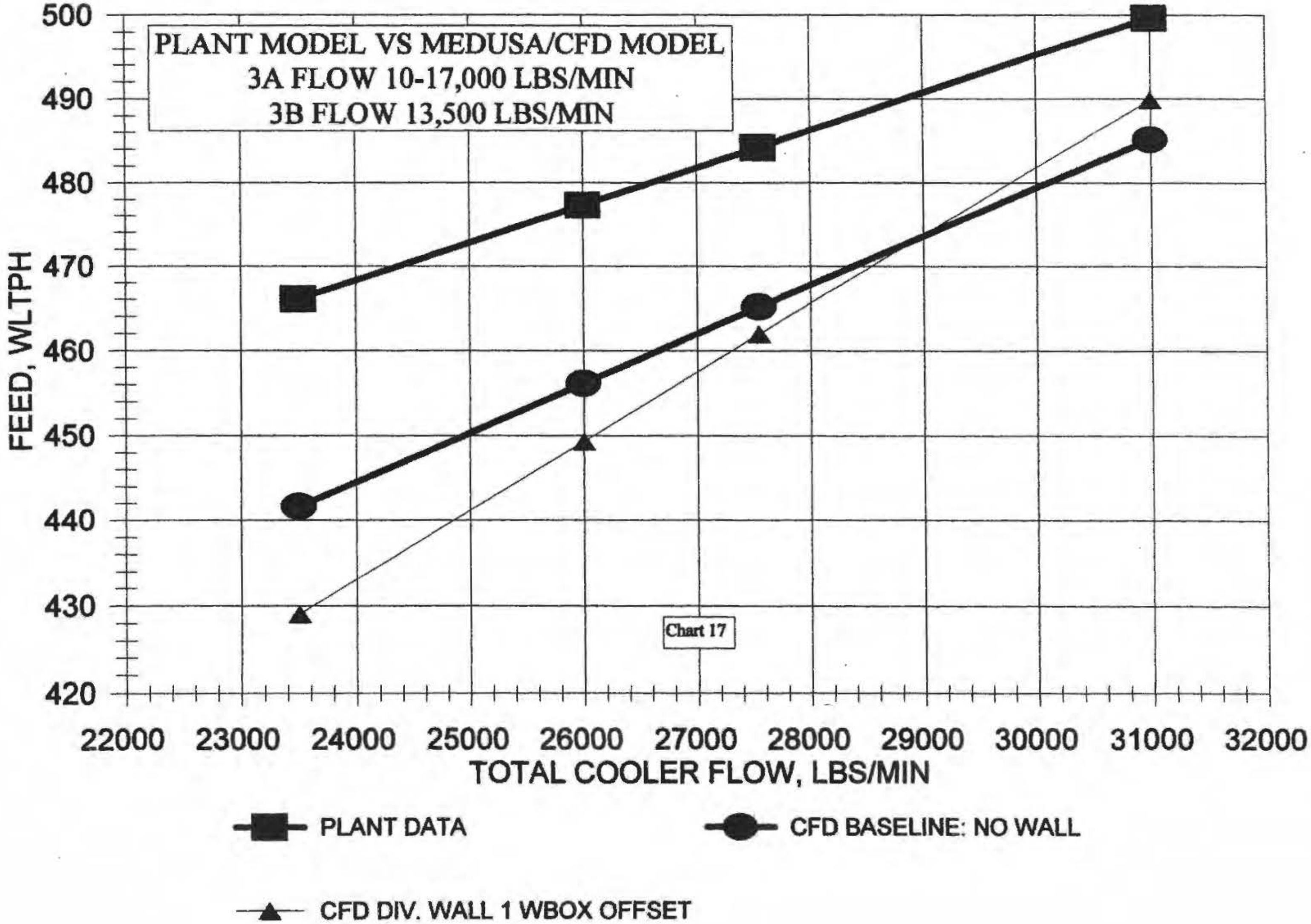


FIGURE 168
PREDICTED FLOW TO KILN

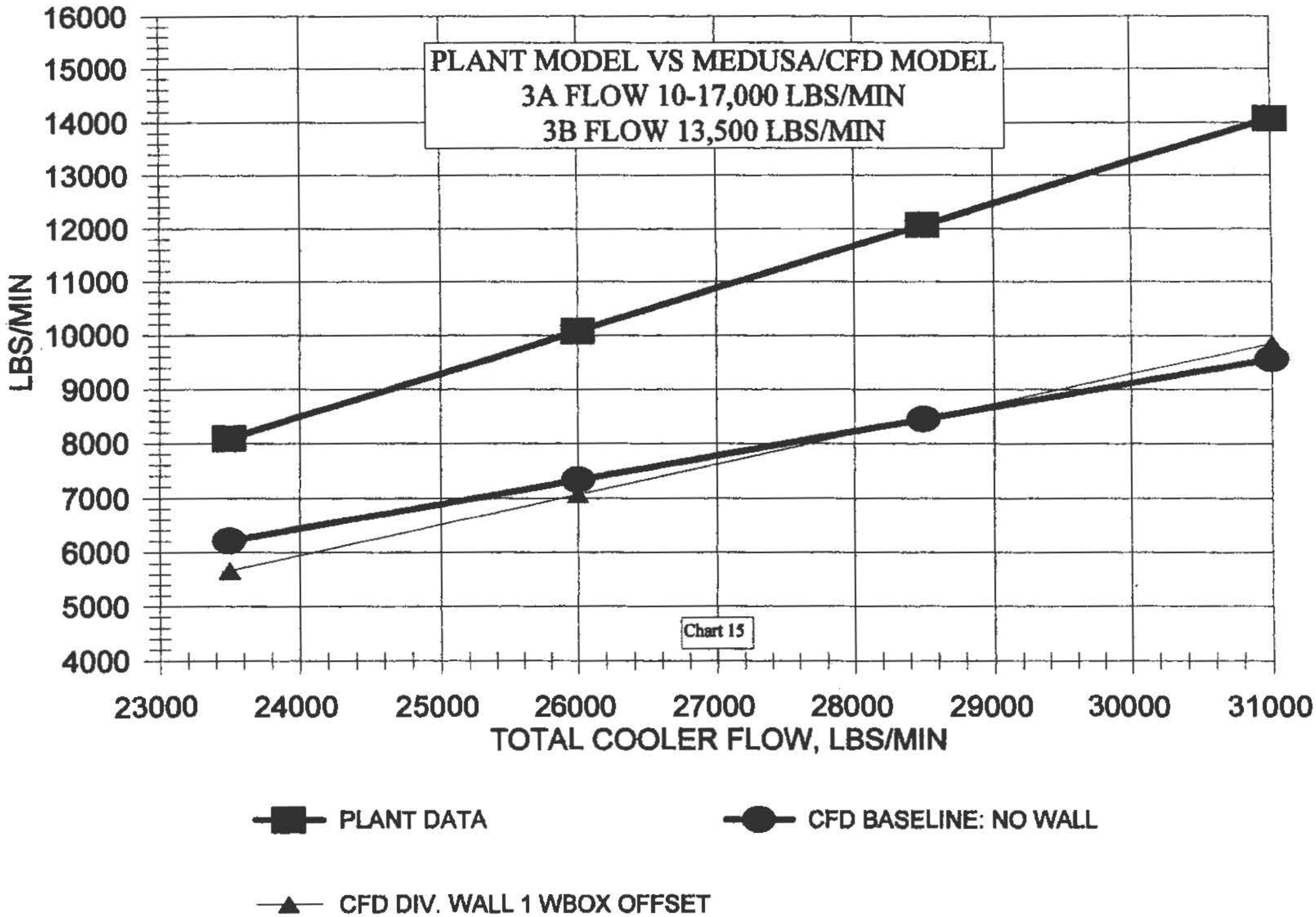
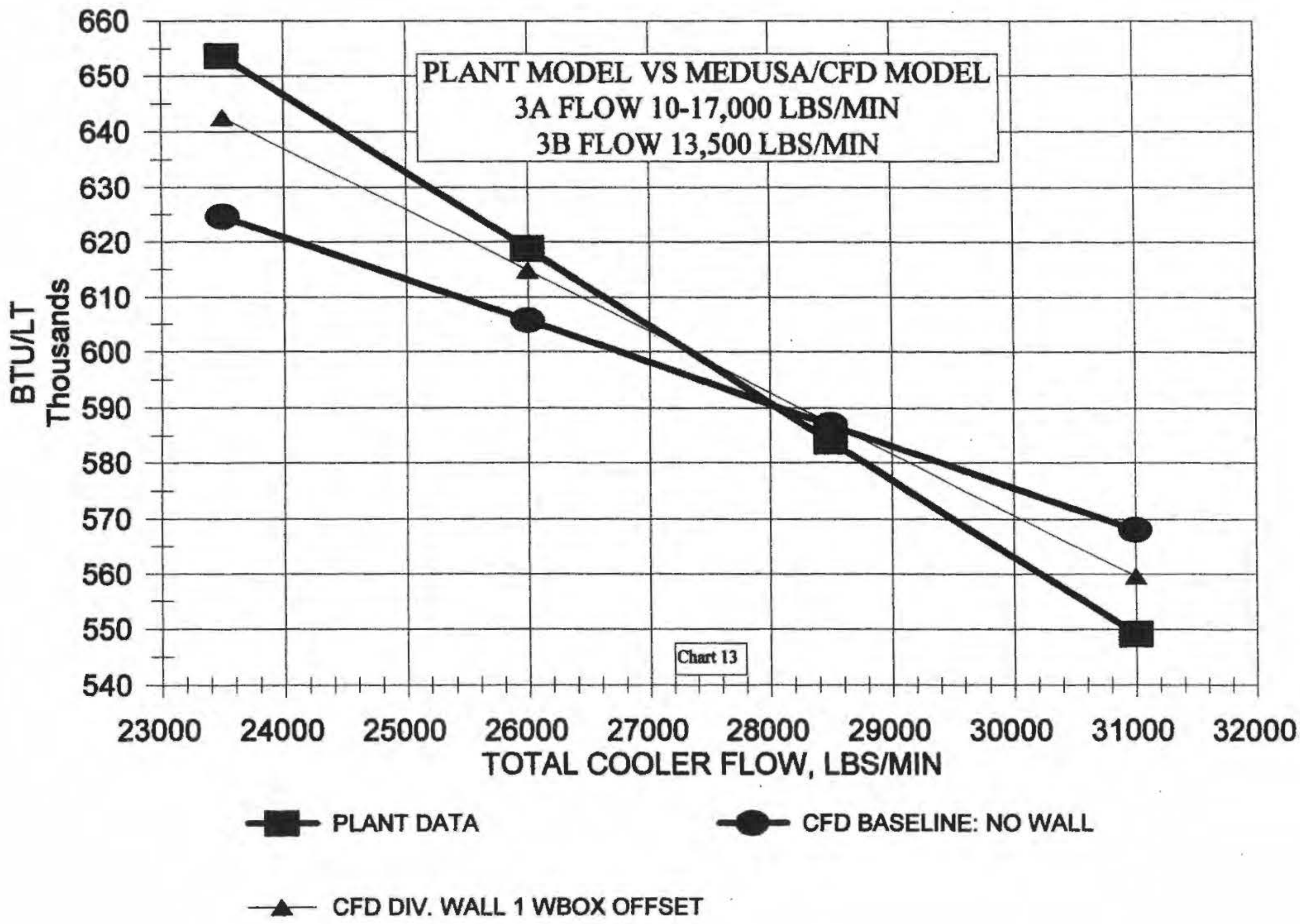


FIGURE 169

PREDICTED FUEL CONSUMPTION



APPENDIX I
LISTING OF MINNTAC DATA COLLECTION PARAMETERS

1. Time		
2. Green Ball Feed Rate	WLTPH	Line 6
3. Green Ball Feed Rate	WLTPH	Line 7
4. Roll Feeder Recycle	WLTPH	Line 6 & 7
5. Grate Speed	In/min	
6. Bed Depth	In.	
7. Line 6 - Drum 1 Green Ball Rate	WLTPH	
8. Line 6 - Drum 2 Green Ball Rate	WLTPH	
9. Line 6 - Drum 3 Green Ball Rate	WLTPH	
10. Line 6 - Drum 4 Green Ball Rate	WLTPH	
12. Line 6 - Drum 5 Green Ball Rate	WLTPH	
13. Bentonite Total Rate	Lbs/hr	
14. Drying Zone 1 O'Bed Pressure	InH_2O	
15. Drying Zone 1 O'Bed Temperature	°F	
16. Drying Zone 1 & 2 U'Bed Pressure	InH_2O	
17. Drying Zone 2 O'Bed Pressure	InH_2O	
18. Drying Zone 2 O'Bed Temperature	°F	
19. Grate Burners Gas	SMCFH	
20. Kiln Exit Gas Temperature	°F	
21. Preheat O'Bed Pressure	InH_2O	
22. Preheat U'Bed Pressure	InH_2O	
23. Preheat Wind Box Temps A side - 1	°F	
24. Preheat Wind Box Temps A side - 2	°F	
25. Preheat Wind Box Temps A side - 3	°F	
26. Preheat Wind Box Temps A side - 4	°F	
27. Preheat Wind Box Temps A side - 5	°F	
28. Preheat Wind Box Temps A side - 6	°F	
29. Preheat Wind Box Temps A side - 7	°F	
30. Preheat Wind Box Temps B side - 1	°F	
31. Preheat Wind Box Temps B side - 2	°F	
32. Preheat Wind Box Temps B side - 3	°F	
33. Preheat Wind Box Temps B side - 4	°F	
34. Preheat Wind Box Temps B side - 5	°F	
35. Preheat Wind Box Temps B side - 6	°F	
36. Preheat Wind Box Temps B side - 7	°F	
37. Preheat 1A Fan Power	Amps	
38. Preheat 1A Fan Outlet Temperature	°F	
39. Preheat 1A Fan Damper	% Open	
40. Preheat 1A Fan Tempering Damper	% Open	
41. Preheat 1A Fan Mass Flow	Lbs/min	
42. Preheat 1B Fan Power	Amps	
43. Preheat 1B Fan Outlet Temperature	°F	
44. Preheat 1B Fan Damper	% Open	

45. Preheat 1B Fan Tempering Damper	% Open	
46. Preheat 1B Fan Mass Flow	Lbs/min	
47. Recoup A Duct Temperature	°F	
48. Recoup A Duct Auxiliary Damper	% Open	
49. Recoup A Duct Mass Flow	Lbs/min	
50. Recoup B Duct Temperature	°F	
51. Recoup B Duct Auxiliary Damper	% Open	
52. Recoup B Duct Mass Flow	Lbs/min	
53. Waste Gas Fan Power	Amps	
54. Waste Gas Fan Inlet Temperature	°F	
55. Waste Gas Fan Damper	% Open	
56. Waste Gas Stack Temperature	°F	
57. Kiln Speed	Rev/hr	
58. Kiln Burning Zone Temperature	°F	
59. Kiln Solids Discharge Temperature	°F	15' from end
60. Kiln Spyrometer Temperature - 1	°F	
61. Kiln Spyrometer Temperature - 2	°F	
62. Kiln Spyrometer Temperature - 3	°F	
63. Kiln Spyrometer Temperature - 4	°F	
64. Kiln Spyrometer Temperature - 5	°F	
65. Kiln Spyrometer Temperature - 6	°F	
66. Kiln Secondary Air Temperature	°F	
67. Kiln Gas Flow	ACF/hr	
68. Kiln Gas Temperature	°F	
69. Kiln Gas Pressure	InH_2O	
70. Kiln Burner Tip Pressure	InH_2O	
71. Kiln Firing Hood Pressure	InH_2O	
72. Cooler Speed	In/min	
73. Primary (3A) Cooling O'Bed Pressure	InH_2O	
74. Primary (3A) Cooling U'Bed Pressure	InH_2O	
75. Primary (3A) Cooling Fan Power	Amps	
76. Primary (3A) Cooling Damper	% Open	
77. Primary (3A) Cooling Mass Flow	Lbs/min	
78. Secondary (3B) Cooling O'Bed Pressure	InH_2O	
79. Secondary (3B) Cooling U'Bed Pressure	InH_2O	
80. Secondary (3B) Cooling Fan Power	Amps	
81. Secondary (3B) Cooling Damper	% Open	
82. Secondary (3B) Cooling Mass Flow	Lbs/min	
83. Cooling Fan Inlet Temperature	°F	
84. Cooler Vent Stack Damper	% Open	
85. Cooler Vent Stack Temperature	°F	
86. Cooler Vent Stack Mass Flow	Lbs/min	
87. Cooler Secondary Vent Stack Temperature	°F	
88. Bentonite Consumption	Lbs/lt	
89. Coal Consumption	Lbs/hr	
90. Total Line Fuel Consumption	Btu/lt	
91. % of Gas through Grate Burners	%	

APPENDIX II

JMP STATISTICAL SOFTWARE - DEFINITIONS

Parameter Estimates

The Parameter Estimates table lists the estimates and standard errors for each parameter in the model. The t ratio and observed probability for the t test are given that compare each parameter to zero. The terms in the Parameter Estimates table for a linear fit are the intercept and the single X variable. For a polynomial fit of order k, there is an estimate for the model intercept and a parameter estimate for each of the k powers of the X variable.
click on a table item for more help

Parameter Estimates: t Ratio

t Ratio lists the test statistics for the hypotheses that each parameter is zero. It is formed by the ratio of the parameter estimate to its standard error. If the hypothesis is true, then this statistic has a Student's t distribution. Looking for a t ratio greater than 2 in absolute value is a common rule-of-thumb for judging significance because it approximates the .05 significance level.

Effect Tests

The Effect Tests in the Effect Test Table are joint tests that all the parameters making up an individual effect are zero. If an effect has only one parameter, as is the case with simple regressors, then the tests are no different from the t tests in the Parameter Estimates table.

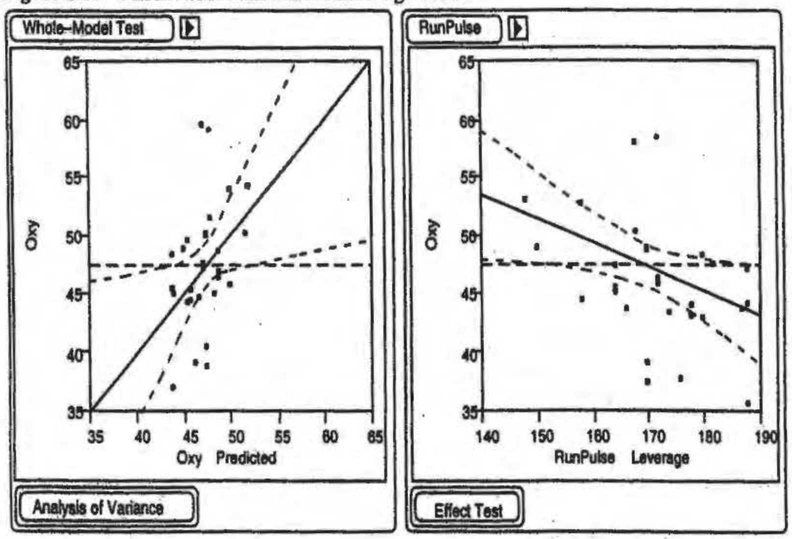
Effect Tests: F Ratio

F Ratio is the F statistic for testing that the effect is zero. It is formed as the ratio of the mean square for the effect divided by the mean square for Error. The mean square for the effect is the Sum of Squares for the effect divided by its degrees of freedom. In situations where a subsequent term is specified to be an error term, the mean square for this error term is used instead of Mean Square for Error as the denominator of the F Ratio. Effects designated as error terms are marked with the message {Error Effect} on the right. This specification is used in split-plot and repeated-measure models where there are different observational units for different layers of the model.

The leverage plot for the linear effect in a simple regression is the same as the traditional plot of actual response values and the regressor. The example leverage plots in **Figure 8.10** result from a simple linear regression to predict the variable Oxy with RunPulse (see the FITNESS (or fitness.jmp) data table in the SAMPLE DATA folder). The plot on the left is the Whole Model test for all regressors, and the plot on the right is the leverage plot for the effect RunPulse. Because there is only one regressor, the two plots are equivalent. The X scales of the two plots are related by a simple linear transformation.

Figure 8.9 is a schematic of **Figure 8.10.** Recall that the distance from a point to the line of fit is the actual residual, and the distance from the point to the mean is the residual error if the regressor is removed from the model.

Figure 8.10 Whole Model and Effect Leverage Plots

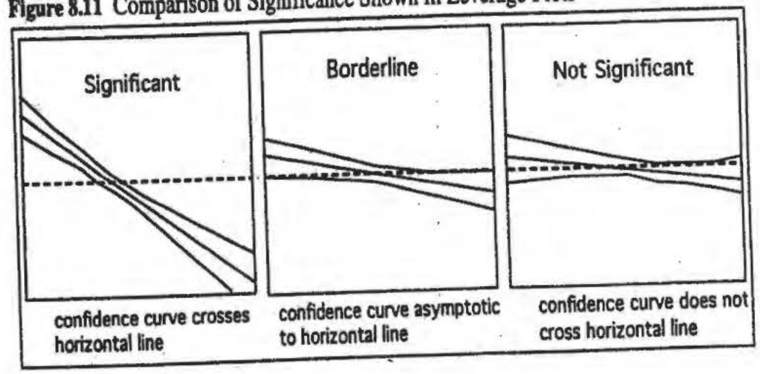


The points on a leverage plot for simple regression are actual data coordinates, and the horizontal line for the constrained model is the sample mean of the response. But when the leverage plot is for one of multiple effects, the points are no longer actual data values. The horizontal line then represents a partially constrained model instead of a model fully constrained to one mean value. However, the intuitive interpretation of the plot is the same whether for simple or multiple regression. The idea is to judge if the line of fit on the effect's leverage plot carries the points significantly better than does the horizontal line.

Confidence Curves

The leverage plots show with confidence curves. These indicate whether the test is significant at the 5% level by showing a confidence region for the line of fit. If the confidence region between the curves contains the horizontal line, then the effect is not significant. If the curves cross the line, the effect is significant.

Figure 8.11 Comparison of Significance Shown in Leverage Plots



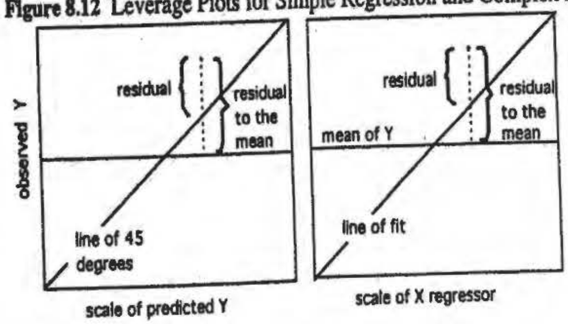
Interpretation of X Scales

If the modeling type of the regressor is interval, then the X axis is scaled like the regressor and the slope of the line of fit in the leverage plot is the parameter estimate for the regressor as illustrated to the right in **Figure 8.12.**

If the effect is a nominal or ordinal effect or a complex effect, like an interaction instead of a simple regressor, then the X axis cannot represent the values of the effect directly. In this case the X axis is scaled like the Y axis, and the line of fit is a diagonal with a slope of 1. The whole model leverage plot is a version of this, where the X axis turns out to be the predicted response of the whole model as illustrated by the plot to the left in **Figure 8.12.**

The influential points in all leverage plots are the ones far out on the X axis. If two effects in a model are closely related, then these effects as a whole don't have much leverage. This problem is called *collinearity*. By scaling regressor axes by their original values, collinearity shows as shrinkage of points in the X direction.

Figure 8.12 Leverage Plots for Simple Regression and Complex Effects



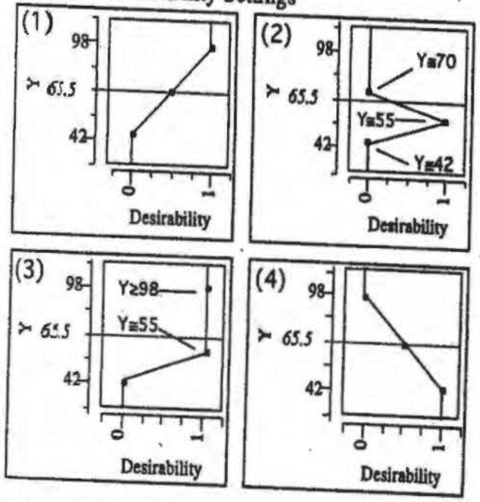
See Appendix A, "Statistical Details," for the details of leverage plot construction.

The Desirability Function

To use a variable's desirability function, drag each of the three function points vertically to represent a response value and horizontally to choose the desirability of that response.

Figure 9.6 shows and describes four commonly used desirablity settings.

Figure 9.6 Desirability Settings



As you drag a desirability function point, the changing response value and the desirability value (between 0 and 1) show in the cell labeled Desirability at the lower right of the plots. The dotted line is the response for the current factor settings. The overall desirability shows to the left of the row of desirability traces. Alternatively, you can OPTION–click (ALT–click under Windows) in a desirability function to enter specific values for the points in a dialog.

(1) The default desirability function setting is "higher is better." The top function point is positioned at the maximum Y value and aligned with the maximum desirability of 1. The bottom function point is positioned at the minimum Y value and aligned with the minimum desirability of 0.

(2) You can designate a target value as "best." In this example, the middle function point is positioned at a Y value of 55 and aligned with the maximum desirability of 1. Y becomes less desirable as its value approaches either 70 or 42. The top and bottom function points at Y=70 and Y=42 are positioned at the minimum desirability of 0.

(3) You can show a response constraint. This example constrains Y to be greater than 55. The middle function point is positioned at Y=55 and set to most desirable. Likewise, the top function point (Y=98) is set to most desirable. A Y value less than 55 becomes less desirable. The bottom function point is positioned at the minimum Y value and is set to least desirable.

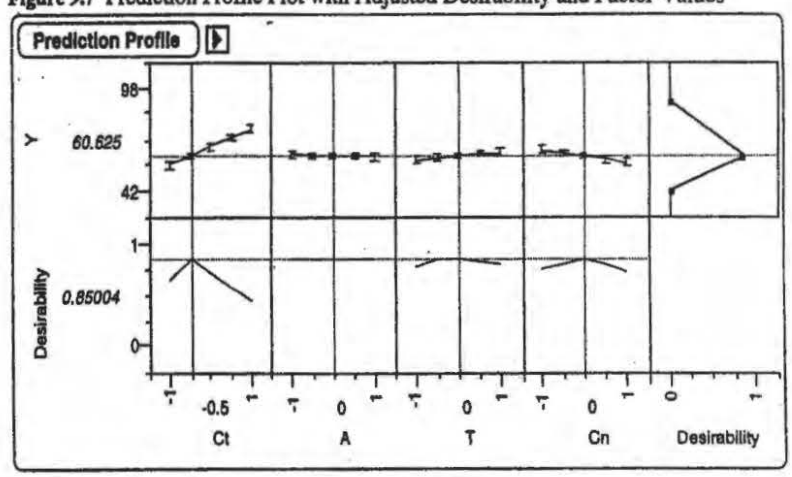
(4) The "lower is better" desirability function is constructed by setting the top function point to the maximum Y value and minimum desirability, and the bottom function point to the minimum Y value and the maximum desirability.

The Desirability Profile

The last row of plots shows the desirability trace for each response. The numerical value beside the word Desirability on the vertical axis is the geometric mean of the desirability measures. This row of plots shows both the current desirability, and the trace of desirabilities that result from changing one factor at a time.

For example, suppose the desirability function in Figure 9.5 is set for a target value of 60. The plots in Figure 9.7 indicate that you could reach the optimum desirability for the target by either lowering Ct halfway to the left toward its low value, or by lowering T to its minimum value. Increasing Cn is also an option. The profile in Figure 9.7 results from changing Ct to –.5. The desirability is at a maximum, and the Y response is close to the target of 60.

Figure 9.7 Prediction Profile Plot with Adjusted Desirability and Factor Values



Desirability Profiling for Multiple Responses

A desirability index becomes especially useful when there are multiple responses. The idea was pioneered by Derringer and Suich (1980), who give the following example:

Suppose there are four responses, ABRASION, MODULUS, ELONG, and HARDNESS.

- ABRASION and MODULUS are to be maximized
- ELONG is to be near a target of 500
- HARDNESS near a target of 67.5.

Three factors, SILICA, SILANE, and SULPHUR , were used in a central composite design.

The data are in the TIRETREAD data table in the SAMPLE DATA folder (tiretred.jmp file in the data folder under Windows). Use the Fit Model dialog to define a screening fit for the