Statistical Analysis Methodology for Predicting Impact of Operation Factors on Boiler Availability

Technical Report

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REPORT SUMMARY

As utilities strive to achieve higher reliability and lower operating and maintenance costs for their fossil-fired power plants, ever-changing operating conditions provide even greater challenges in meeting those objectives. This report summarizes an analytical methodology to quantify the cause-and-effect relationships that exist between operating conditions and boiler component reliability. The methodology is based on standard statistical correlations that are derived through application of commercially available software to specific boiler data.

Background

The restructuring of the utility industry continues to create major changes in how generating units are operated and maintained. With competition anticipated in the deregulated marketplace, utilities must reduce production cost. Nearly 70% of U.S. fossil power plants are reaching their design lives, and there is no plan to retire them in the near future. Evolving market conditions and emission regulations have placed more financial and operational burdens on these same fossil power plants. In today's environment, systems and equipment are required to perform at levels and under conditions not considered in their original design.

Objectives

- To develop a methodology that can be used to quantify the impact of operational changes (produced by cycling duty, fuel switching, and environmental controls) on the reliability of boiler components
- To apply a methodology to typical power plant data and illustrate the process for quantifying the relationships between operating changes and boiler component damage
- To provide an analytical basis for the economic costs associated with plant operating changes

Approach

EPRI and others have sponsored substantial research in the area of boiler reliability and operations. *Impact of Operating Factors on Boiler Availability*, EPRI Technical Report 1000560 completed in 2000, established the starting point for this current work in which the key parameters that characterize operating changes are statistically correlated in terms of their impact on boiler component reliability. For example, burner tilts and combustion settings can be correlated with temperature changes in the flue gas. The impact of such temperature changes is then correlated with metal temperature changes in superheater and reheater tubing. Because metal temperature is a key parameter for the service life of these components, an impact on tubing life can be estimated. This analytical process helps to move considerations from a qualitative basis to a quantitative basis wherein economic impact can be determined.

Results

Changing operating conditions can significantly impact boiler component reliability. In a competitive power generation market, the loss of reliability usually has severe economic consequences. In the case of boiler components, loss of reliability translates almost directly into increased forced outages of the unit. The application of a statistical methodology, using a commercial software product, to the challenge of quantifying the nature impact of the change is presented and illustrated with typical plant data. Additional case studies, using actual plant data, are planned and will provide a broader framework in which the use of statistical tools might be appropriate.

EPRI Perspective

This work is part of an initiative in the Boiler Life and Availability Improvement Target to develop technology and tools to assist utilities in fully managing the life of boiler components to achieve safe and reliable operation. Utilities report that many operating changes are made without full consideration of possible negative impacts. Coal supply, for example, might be changed to take advantage of a lower cost on the basis for energy per unit weight. As noted in this report, however, the characteristics of the new coal can increase damage rates to critical boiler tubing sections and increase both the risks and actual occurrences of forced outages to the unit. Such negative impacts might well exceed the benefits produced by the reduced fuel cost.

Utilities operating in a competitive market must fully consider all cost factors in their decision making to achieve least cost power production. A necessary step in this process is to quantify the impact of change, in a form that will allow determination of economic impact. The statistical methodology presented in this report has been successfully used in many other process industries to address the need for quantitative relationships between process variables and their impact on products. The effort here is to use a similar process for assessing impact on boiler component reliability.

Keywords

Fossil power plants
O&M costs
Reliability
Boiler operations

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INTRODUCTION

The restructuring of the utility industry has been creating major changes in how generating units are operated and maintained. With the anticipated competition in the deregulated marketplace, utilities have to reduce production cost. Nearly 70% of U.S. fossil power plants are reaching their design lives with no plan of retirement in the near future. Evolving emission regulations have placed more financial and operational burdens on these same fossil power plants. In today’s environment, systems and equipment are required to perform at levels not thought possible a decade ago. Today’s utility companies must try to maximize the following multiple-system objectives:

- Maintain capacity
- Improve efficiency
- Reduce emissions
- Preserve reliability and availability
- Ensure safety
- Minimize production cost

Some of these objectives conflict with each other. The ultimate goal is cost reduction and revenue increase within the reliability, safety, and emission constraints. It is essential to understand the constraints and to develop an integrated strategy to optimize the system performance or to conduct economical tradeoffs within these multiple constraints. Typical fossil power plants in the past were designed for a baseload operation, burning a specific coal or coals with limited variations in quality, and without stringent emission requirements. These same fossil plants in today’s environment are required to achieve the following:

- Cycling operation
- Burning low cost coals with substantial differences in quality
- Switching coal for SO_x emission considerations
- Combustion/furnace modifications for NO_x reduction
- Operational changes to optimize NO_x and heat rate
- Heat rate improvement initiatives for cost and CO_2 reduction initiatives
- Variable pressure operation for heat rate improvement and turbine protection

- Increased reliability and availability requirements
- Outage interval extension and duration reduction
- Capital, operation, and maintenance cost reduction

The impact of these changes on system/plant objectives is listed in Table 1-1. It is obvious that there are conflicting effects among the changes and the plant objectives. The overall system design is fixed. The subsystems and components may be modified or upgraded, and this is subject to economic justifications. The traditional practice is to assess the potential of the existing system and equipment to perform additional duties with operation changes, while looking to minimize capital investment. It represents a great challenge for the utilities to acquire the knowledge to deal with the situation.

Table 1-1
Impact of Operation Changes on Plant Objectives

	Reliability	Capacity	Safety	Efficiency	Emission	Cost/Revenue
Cycling and Low-Load Operation	Negative			Negative	Negative	Positive
Combustion Modification for NO_x Reduction	Negative	Negative	Negative	Negative	Positive	Negative
Selective Non-Catalytic Reduction (SNCR) and/or Selective Catalytic Reduction (SCR)		Negative		Negative	Positive	Negative
Heat Rate Improvements	Negative	Positive				Positive
Efficiency and NO_x Optimizations	Negative		Negative	Positive	Positive	Positive
Sliding Pressure Operation	Negative			Positive		Positive
Operation Beyond the Rated Capacity	Negative	Positive		Negative	Negative	Positive
Coal Switching	Negative	Negative		Negative	Positive	Positive
Outage Extension	Negative	Negative		Negative		Positive
Cost Reduction	Negative	Negative		Negative		Positive

One of the most complex, critical, and vulnerable systems in fossil power generation plants is the boiler. Boiler pressure component failures have historically contributed to the highest percentage of lost availability. Boiler tube failure (BTF) mechanisms can be divided into four major categories: creep/stress rupture, fatigue, erosion, and corrosion. The major BTF influence factors involve design inadequacies, operation changes, and maintenance practices. The relationships between these factors and four major failure mechanisms are listed in Table 1-2. EPRI has further defined 36 detailed BTF mechanisms and their relationships with these three influencing factors, which are presented in Table 1-3.

Table 1-2
BTF Influencing Factors

	Design	Operation	Maintenance
Creep	x	xxx	x
Fatigue	xxx	xx	
Erosion	x	xxx	xx
Corrosion	xx	xxx	

Note: x = weak influence, xx = medium influence, xxx = strong influence

Table 1-3
Relationship Between EPRI BTF Mechanisms and Major Influencing Factors

Water-Touched Tubes	Design	Operation	Maintenance
Corrosion fatigue	xxx	xx	
Flash erosion	x	xxx	xx
Hydrogen damage		xxx	
Acid phosphate corrosion		xxx	
Caustic gouging		xxx	
Fireside corrosion in coal-fired units		xxx	
Thermal fatigue in supercritical waterwalls	xxx	xx	
Thermal fatigue of economizer inlet headers	xx	xxx	
Erosion corrosion (economizer inlet headers)		xx	
Sootblower erosion	x	xx	xxx
Short-term overheating		xx	xx
Low-temperature creep	xx		
Chemical cleaning damage			xxx
Fatigue in water cooled circuits	xxx	xxx	

Table 1-3 (cont.)
Relationship Between EPRI BTF Mechanisms and Major Influencing Factors

Water-Touched Tubes	Design	Operation	Maintenance
Pitting in water-cooled tubes	x	xxx	
Coal particle erosion		x	xx
Falling slag damage	x	xx	x
Acid dewpoint corrosion		xx	
Steam-Touched Tubes	**Design**	**Operation**	**Maintenance**
Long-term overheating/creep	xx	xxx	
Fireside corrosion in coal-fired units	xxx	xx	
Fireside corrosion in oil-fired units		xxx	
Dissimilar metal welds	xxx	x	
Short-term overheating		xxx	xxx
Stress corrosion cracking	xxx	x	
Superheater (SH)/reheater (RH) sootblower erosion	x	xx	xxx
Fatigue in steam-touched tubes	xxx	xx	
Rubbing tubes/fretting	x		xx
Pitting (RH loops)	xx	xx	
Graphitization	x	x	
SH/RH chemical cleaning			xxx
Maintenance damage			xxx
Material flaws	xxx		
Welding flaws	xxx		xxx

Note: x = weak influence, xx = medium influence, xxx = strong influence

It can be seen from Table 1-2 and Table 1-3 that operation is one of the major factors that influences BTFs. Operation is also one of areas that has been paid little attention in the past. Once the boiler is built, the major focus should be on the operation, especially within changing environments. The utility companies have shown renewed interest in maintaining high availability of their generating units. EPRI report *Impact of Operating Factors on Boiler*

Availability (1000560) addresses the impact of major operational factors on boiler availability, provides qualitative guidelines on the impact of such operating changes on availability. As a continuation of that project, this project intends to identify and provide techniques that can be used to quantify the effect of major operation parameters on boiler availability for a specific fossil power plant.

Traditional Approach

Engineers traditionally have been trained to solve problems with physical models. Physical models typically are represented by differential equations and mathematical solutions (that is, closed-formed solutions), if available. Some of the engineering problems have been solved by numerical methods in the last two decades (that is, finite difference or finite element methods), due to the advancement of computer power. All physical models have underlying assumptions and limitations, and many engineering problems are nonlinear in nature. Solving nonlinear problems is not a simple task, even with the assistance of the computer. Nonlinear problems are often simplified with linear approximations. Most of the equipment is designed with this traditional approach.

The design of boilers is complex. A typical design of the boiler involves thermal hydraulics, heat transfer, combustion, emission, and mechanical design. It involves several physical models. The design might not be an integrated approach. Interfaces are established to simplify the calculations and to deal with the different assumptions and limitations (that is, the material might not be homogenous as the physical model assumed, the heat transfer might not be uniform, heat transfer coefficients are not constants, and many local regions are subject to plastic strains). Design, fabrication, installation, control, operation, and maintenance introduce large amounts of uncertainties. To ensure safe operation and cover those uncertainties, safety factors based on the engineering experience are introduced in the design process. This approach works well in the design of the system and equipment. However, this approach does not deal with the actual conditions in the system operation. The plant operation process control, performance monitoring, and condition monitoring typically are used to maintain safe operation, improve plant heat rate, and detect equipment deterioration, respectively. The controls are relatively simple logics based on past experience. However, the current control logics lack an integrated approach. The heat rate improvement and condition monitoring basically follow the design thinking. If problems occur in the actual operation, true root causes are difficult to determine because the actual conditions are much more complex than the design.

Nevertheless, this traditional approach has worked reasonably well in the past with simple limited objectives. The boiler reliability was often referred to as an off-line inspection and maintenance issue and solutions to the BTFs were often dealing with material upgrades or periodic components replacements. However, this condition is changing. Today's utility companies are facing multiple plant objectives (for example, capacity, heat rate, emissions, safety, reliability, and production cost). This increasing complexity of the electric power business requires detailed understanding of interrelationships among the design, operating, and plant objectives, which the traditional approach might not be able to provide.

Statistical Approach

Statistical analysis depends on the data available. The need for reliable data cannot be understated. The data can be obtained through a systematic approach (that is, Design of Experiment (DOE) or historical observational data). Data are subject to errors. Data validation and error analysis based on probabilistic thinking are important parts of statistical analysis. Once good data are available, predictions can be made by using regression equations. Regression analysis can also be used to establish the cause and effect relationship between variables and to determine the critical parameters, which can then be used in system optimization of the different plant objectives. The statistical technique has shown its power in manufacturing process control and is tested in this project to deal with complex problems associated with operational impact on the boiler availability. It is an effort to focus on the operation to minimize damage to the boiler pressure components and, subsequently, reduce BTFs and boiler maintenance activities. The statistical method might not be ready to serve as a design tool. However, it can be used for operation diagnosis and as a supplement to the engineering experience.

If the system and equipment can be operated within the design limits, then, theoretically, failures and degradation should not occur or can be minimized. If failures and degradation do not occur or can be minimized, the result is the reduction of maintenance and improvement in availability. The boiler system operation involves the following general process logic (Figure 1-1).

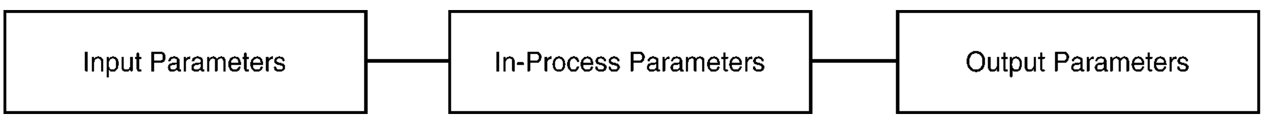

Figure 1-1
Process Logic

The output parameters are objectives. To ensure these objectives can be achieved, the operation focus should be on input and in-process control. The ideal way is to control input and in-process variables in order to avoid output variations, which cause component damages. Unfortunately, many current control logics in a typical fossil power plant are focused on output control. For boiler reliability considerations, this approach might not be adequate. The input and in-process control are extremely important for reliability and operability preservation.

There are several hundred process variables in the fossil power plant. It is neither possible nor necessary to monitor and control all these variables. Many variables are redundant or of little importance for the protection/preservation of the objectives. It is essential to pinpoint key variables that provide the maximum protection of the boiler availability for each objective. To minimize the computation and data collection, only critical and essential parameters should be selected as the input and in-process parameters for each output objective.

This project includes the following scope of work:

1. Develop a statistical technique for selecting the critical and essential input, in-process, and output operation parameters that affect the boiler performance, including: reliability/ availability, heat rate, emissions, capacity, and safety

2. Quantify the relationship among the selected input, in-process, output parameters, and BTF mechanisms

3. Establish cross-functional relationships between reliability indicators and other objectives (for example, emission, safety, capacity, efficiency, and cost indicators)

4. Use Minitab commercial statistical computer software for performing the actual examples and demonstrating the techniques

Examples are provided in Section 4 and Appendix C. The data used in the examples are obtained from plant performance testing with a best estimates approach rather than the formal DOE proposed in this report. The purpose of the examples is to demonstrate the proposed approach—formal application will follow in the future.

2
OPERATION INFLUENCES ON BOILER PERFORMANCE

Introduction

The operation of a boiler and its auxiliary equipment requires the constant exercise of intuitive reasoning and sound engineering judgment. It is in operation that all of the factors that went into the design and construction of the system are put to the test. The proper instrumentation, control logic, and control system are required to assist the operation personnel in performing safe, efficient, and reliable operation. Process control, performance diagnostics, and condition monitoring are key technologies used to decrease or mitigate uncertainties in the fossil power plants. These technologies address three requirements:

- Process control establishes safe and reliable operation
- Performance diagnostics facilitate efficiency diagnostics and monitoring
- Condition monitoring detects and prevents process and component deterioration

These requirements might share common operating parameters and databases. Some of these requirements are in conflict with each another. It is in the hands of the operator to meet these requirements simultaneously. Ideally, the operating control also achieves performance optimization without causing deterioration to the components. It is difficult to reach this ideal condition with current practices because each system control has its own evolution history. There are several hundred process variables in the fossil power plant. It is neither possible nor necessary to control all these variables. Many variables are redundant or less important than other variables for the protection/preservation of the objectives. It is essential to pinpoint key variables that provide the maximum protection of the boiler availability for each objective. To minimize the computation and data collection, only critical and essential parameters should be selected as the input and in-process parameters for each output objective. The critical operating parameter selection must consider all plant objectives. This becomes a difficult task because the list of critical operating parameters that needs to be developed must consider the interrelationships among the efficiency, capacity, reliability/availability, and environmental factors.

Another challenge is accuracy of the data and the need to obtain data in real time. While traditional performance tests or American Society of Mechanical Engineers (ASME) Performance Test Codes' accuracy typically is not cost justified or practical, there remains a need to obtain accurate and repeatable performance data for trending purposes. Additional instrumentation might be required to perform on-line performance testing.

Major Operating Parameter Selection

The major operating parameter selection has to consider the following:

- Plant objectives or operating requirements that include:
  - Heat rate
  - Emissions
  - Capacity
  - Reliability/availability
  - Safety
  - Total cost
- Modes of operation that include:
  - Base/full-load operation
  - Low-load operation
  - Load following
  - Two-shift cycling
  - Load ramping
  - Constant pressure versus variable pressure operation
  - Peaking operation
  - Startup, shutdown, and layup
  - Low NO_x operation

The major operating parameters that affect the above considerations can be obtained from the following:

- EPRI and industry publications from the last decade
- Design knowledge, material selection, fabrication and erection practice, instrumentation and control, and maintenance requirements
- Past experiences

Major Operating Factors That Influence the Plant Objectives

Major Operating Factors That Influence the Boiler Availability

The major operating parameters that influence the boiler reliability/availability can be developed by considering the BTF mechanisms. The BTFs can be influenced by inadequate original design and material selection, water chemistry control, operating factors, fuel quality, changing modes of operation, combustion conditions, environmental factors, and maintenance practice. The EPRI publication *Boiler Tube Failures: Theory and Practice* was used as the base for this work. The major operating factors affecting the boiler reliability/availability for each boiler failure mechanism is listed in Table 2-1 and Table 2-2. The fuel quality impact is not listed in the tables because this report focuses on the real-time operating parameters. Therefore, fuel quality impact is considered a given constraint that cannot be altered during the actual operation.

Table 2-1
Operation Parameters' Influence on the BTF Mechanisms in Water-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Corrosion fatigue Failures are initiated at the inside surface and are nearly always associated with tube attachments or other locations with high local or constraint stresses.	• Influence of excessive stresses/strains from the original design: – Welded attachments • Influence of environmental factors: – Poor water chemistry – Overly aggressive or improper chemical cleaning – Improper boiler shutdown and/or lay-up practices • Influence of unit cycling operation: – Operating procedures that have produced high stresses (that is, fast load ramping) – Subcooling in natural circulation boilers during two-shift or weekend shutdown operation	• Water chemistry indicators • Cycling operation • Ramp rate • Flue gas temperature • Temperature reading from thermocouples at the top and bottom of the boiler
Fly ash erosion It accelerates tube wastage by direct material removal and removal of fireside oxide. The erosion damage is usually localized.	• Excessive local velocities due to non-uniform gas flow from: – Geometry design – Maintenance (distortion or misalignment of tubing rows, misalignment or loss of gas flow guiles and baffles) – Operation (operating above the continuous design rating, operating above design airflow, high excess air, convective pass fouling, and gas laning) • Increase in particle loading and high erosive elements (for example, quartz and iron pyrite fuel) • Other influences: – Palliative shields and baffles, usually punched plates or solid baffles, that were misapplied – Inappropriate material, improperly or poorly applied coating	• Excess air • Total airflow • Slagging and fouling • Draft loss • FEGT • Peaking operation

Table 2-1 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Water-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Hydrogen damage The damage is caused by the reaction of iron carbides in the boiler tube steel with hydrogen produced as a result of corrosion reactions, particularly those taking place in low pH water.	• Influence of excessive deposits: – Flow disruption: weld bar/ring, poor weld geometry, pad welds, canoe piece repairs, deposits, locally high heat flux or steam quality, bends or sharp changes in tube direction, and horizontal or near horizontal tubing, or DNB – Fireside conditions: flame impingement, burner misalignment, and major change in fuel source • Influence of acidic contamination: – Condenser leaks (minor by occurring over an extended period) – Condenser leaks (major ingress, generally one serious event) – Water treatment plant or condensate polisher regeneration chemical upset loading to low pH condition – Error in chemical cleaning process procedures	• Water chemistry indicators • NO_x • Flame impingement
Acid phosphate corrosion It occurs when tube deposits formed from feedwater corrosion products allow a concentration of phosphate slats. This leads to under-deposit corrosion, and eventually to tube failure under congruent phosphate treatment	• Influence of excessive deposits: – Flow disruption: weld bar/ring, poor weld geometry, pad welds, canoe piece repairs, deposits, locally high heat flux or steam quality, bends or sharp changes in tube direction, and horizontal or near horizontal tubing, or DNB – Fireside conditions: flame impingement, burner misalignment, and major change in fuel source • Phosphate concentration: – Use of improper cycle chemistry controls, particularly chasing phosphate hideout by using monosodium and/or an excess of disodium phosphate	• Water chemistry indicators • NO_x • Flame impingement

Table 2-1 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Water-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Caustic gouging It occurs when boiler water pH reaches high level within tube deposits formed from feedwater corrosion products. Steam bubbles forming in deposits can create local alkaline concentration up to 10,000 times the bulk boiler water concentration.	• Influence of excessive deposits: – Flow disruption: weld bar/ring, poor weld geometry, pad welds, canoe piece repairs, and so forth, deposits, locally high heat flux or steam quality, bends or sharp changes in tube direction, horizontal or near horizontal tubing, or DNB – Fireside conditions: flame impingement, burner misalignment, or major change in fuel source • Sources of caustic concentration: – Elevated caustic level over time (units on caustic treatment) – Excessive caustic addition to units on AVT – Excessive caustic addition to control phosphate treatment – Water treatment upside leading to high pH condition (that is, regeneration of condensate polishers or makeup water on exchange resins)	• Water chemistry indicators • NO_x • Flame impingement
Fireside corrosion in coal-fired units Damage is usually found with hard, fired inner-layer deposits on tubes with loosely bonded ash on the outer layers. It causes significant tube wall thinning on the fireside.	• Influence of a sub-stoichiometric environment: – Poor general combustion conditions – Poorly adjusted or worn burners – The combustion air level and distribution has been modified (for example, low excess air operation with reducing condition, low NO_x burner combustion with overfire air, incomplete combustion with high CO and LOI with high sulfur coal, flame impingement, and high FeS deposits in areas where they are in contact with free oxygen) • Excessive internal deposits lead to increased tube metal temperatures; exacerbates mechanism • Changing to a more corrosive coal, particularly one high in Cl, Na, K, or S content • Carbon particle impingement and carbon deposition	• Excess O_2 • CO • LOI • Windbox to furnace pressure differential • Sulfur content in the coal • NO_x • Flame shape and color • Flame impingement • FEGT • Soot blowing

Table 2-1 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Water-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Supercritical waterwall cracking The damage type appears as circumferential cracking in the coal- fired supercritical boilers. It is a corrosion enhanced thermal fatigue.	• Excessive internal deposits leading to increased tube metal temperatures • Thermal cycling caused by slagging/deslagging • Fire side deposits, wastage, and surface cracking • Large cycling stresses and other influences of operation	• Water chemistry indicators • Sootblower operation • Firing condition • Tube temperatures
Thermal fatigue of economizer inlet headers The cracks are located in the ligament and bore hole of the headers and the internal surface of the stub tubes.	• Introduction of cold feedwater into a hot header during cycling operation to maintain the drum level that causes large dT (temperature differential) excursions through the wall of the header • Stress concentration	• Cycling operation • Though-wall temperature gradients during the slug-feed period.
Erosion corrosion (economizer inlet headers) Failures are induced by erosion/corrosion as tube wastage.	• Reducing feedwater conditions	• Water chemistry indicators (dissolved oxygen, N_2H_4 and Fe)

Table 2-1 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Water-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Sootblower erosion Sootblowing-induced erosion causes accelerated tube wastage by direct material removal, removal of the fireside oxide, and increasing the fireside oxidation rate.	• Improper maintenance or operation of soot blowers: – Incorrect setting of blowing temperature (insufficient superheat) – Condensate in blowing media – Improper operation of moisture traps – Excessive sootblowing pressures – Improper location of soot blower – Misalignment of soot blower – Malfunction of soot blower – Excessive soot blowing	• Slagging and fouling • Draft losses • FEGT • Excess air • Burner tilt position • Sootblowing operation (blowing temperature, pressure, travel, sequence, time, and duration)
Short-term overheating The failure appearance includes tube swelling and a ductile failure showing a thin-edged fracture surface with "fish-mouth." Thick-edged failure surfaces are also possible.	• Partial blockage caused by maintenance activities: – Tools left in tubes – Poor maintenance practices, particularly improperly executed weld repairs (for example, weld spatter is allowed to fall into tubes) • Plugging of waterwall orifices by feedwater corrosion products • Poor control of drum level • Over-firing on startup • Loss of coolant because of upstream tube failure	• Drum level during start up, load change, and transients • Tube temperatures • Pumps pressure drop
Low-temperature creep Cracking typically initiates in high stress locations and the outside surface of tube bends.	• A combination of high residual and/or service stresses	

Table 2-1 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Water-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Chemical cleaning damage The damage is a generalized corrosion in the inside tube surface.	• One or more improper operations in the chemical cleaning process including: – Use of an inappropriate cleaning agent – Excessively strong acid concentration – Excessively long cleaning times – Too high a temperature – Failure to neutralize, drain, and rinse after cleaning – Breakdown of inhibitors as result of temperature excursions	
Fatigue All failures in this category are manifested by outer diameter (OD)-initiated cracking. It occurs at high local stress areas.	• Poor design (excessive strains/stress due to constraint of thermal expansion) • Poor manufacturing (excessive mechanical stresses or residual strains/stresses) • Flue gas induced vibration by direct flow or vortex shedding • Poor welding, particularly poor geometry of final joint • Cycling operation	• Ramp rate • Cycling operation • Vibration • Header metal surface temperature
Pitting Pitting occurs on the inside tube surface. It is primarily the result of poor water chemistry and shutdown practices with oxygen-saturated, stagnant water.	• Poor shutdown procedures lead to formation of stagnant, oxygenated water • Poor water chemistry control (that is, high dissolved oxygen, condenser leak, and inadequate layup protection)	• Dissolved O_2 • Shutdown practices

Table 2-1 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Water-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Coal particle erosion Failures can occur in tubes at near the burner throats or cyclone burners.	• Protective device no longer performs their function (that is, wear liners for cyclone burners and refractory for other burners)	
Falling slag damage Damages occur from erosion or impact on sloping waterwall tubes and /or the ash hopper by falling slag.	• Erosion or impact induced by fused coal ash deposits or resolidified molten slag that detached from furnace walls and SH pendants	• Coal quality • Slagging and fouling • FEGT • Sootblowing operation
Acid dewpoint corrosion The corrosion occurs as a result of the condensation of sulfuric acid from the flue gas.	• Economizer tube temperatures are below the acid dewpoint during operation, such as with a number of feedwater heaters out of service, or during shutdown • Flue gas temperature below the acid due point • Locally low gas temperatures caused by local air ingress	• Flue gas temperature • Feedwater temperature

Table 2-2
Operation Parameters' Influence on the BTF Mechanisms in Steam-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Long-term overheating/creep The failure features low ductility thick edged "fish-mouth" appearance in SH tubes. In RH tubes, the rupture edge will be somewhat thinner.	• Influences of initial design and/or material choice: – Original alloy inadequate for actual operating temperatures – Inadequate heat treatment of original alloy – Tube failure locations have gas-touched lengths longer than design length – Side-to-side or local gas temperature differences – Radiant cavity heating effects – Lead tube/wrapper tube material not resistant enough to temperature • Build-up of internal oxide scale • Overheating because of restricted steam flow due to contaminant deposits, scale, debris, and so forth • Operating conditions or changes in operation: – Combustion conditions can lead to tube overheating: excessive flue gas temperature, displaced fireball, delayed combustion, and secondary combustion induced by high LOI carryover – Periodic over-firing or uneven firing – Blockage or laning of boiler gas passages • Increases in stress due to wall thinning	• Tube temperatures • Excess O_2 • Burner tilt • FEGT • Over-firing or uneven firing • LOI • CO • Flame carryover to convective pass • Feedwater temperature • Flue gas distribution • Draft loss • Slagging and fouling • Sootblowing operation

Table 2-2 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Steam-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Fireside corrosion in coal-fired units SH/RH fireside corrosion (also referred to as molten salt attack, coal ash, liquid-phase, or high-temperature corrosion) has been a significant problem for units operating at 1050°F (566°C) and in those burning coals with high chlorine and sulfur coal.	• Influence of overheating of tubes (see long-term overheating in steam-touched tubes) • Fuel factors—Change to fuel with corrosive ash, particularly those with high S, Na, K, or Cl • Incomplete or delayed combustion • Frequent load changes lead to breakdown of oxide scale-enhancing corrosion, sulfidation, and carburization of the alloy, particularly in austenitic steels	• FEGT • Burner tilt • Excess O_2 • CO • Tube temperatures • Draft losses • Flue gas distribution • Sootblowing operation
Fireside corrosion in oil-fired units The tube wall loss is induced by fireside deposits containing low-melting ash with sulfur, sodium, and/or vanadium.	• Influence of oil composition, that is, low-melting ash, sulfur sodium, vanadium • Influence of overheating of tubes: – Excessive temperatures caused by steamside oxide scale buildup – Excessive temperatures as caused by operating conditions: high temperature laning of gases, changes in absorption patterns between furnace and convection sections, RH overheating because of rapid startups, and tube misalignment – Using Mg-based additives leading to coating of waterwalls and increasing heat into convective passes • Influence of operating factors: – Operating with high levels of excess oxygen and/or periods of very low excess oxygen – Poor sootblowing operations	• Oil analysis • FEGT • Burner tilt • Excess O_2 • CO • Tube temperatures • Draft losses • Flue gas distribution • Sootblowing operation

Table 2-2 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Steam-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Dissimilar metal welds (DMWs) The failure occurs at weld joints between ferritic and austenitic steel tubes in the final outlet sections of SH and RH.	• Excessive tube stresses caused by improper initial design or tube supports: – Locating the DMW near the roof, furnace wall or other fixed points, the middle of a long span, or near to the header – Inadequate allowance for tube thermal expansion – Support failures or slag accumulation leading to constraint of thermal expansion • Excessive local tube temperatures: – Tube temperatures above those anticipated in the design – Tube temperature variation across the SH/RH • Changes in unit operation: – Changes to cycling operation – Change of fuel causing increased tube temperatures – Redesign of adjacent SH/RH that results in higher tube service temperatures • Field-welded DMW joints, welding detail, and initial fabrication defects	• Flue gas temperature • FEGT • Tube temperatures • Cycling operation
Short-term overheating The failure appearance includes tube swelling and a ductile failure showing a thin-edged fracture surface with "fish-mouth" and increased hardness.	• Maintenance-induced short-term overheating: – Tools left in tubes – Poor maintenance practices, particularly improperly executed weld repairs (for example, weld spatter is allowed to fall into tubes) – Improper chemical cleaning (poor flushing procedures leave deposits in bends, volatility of chemicals getting into SH circuits or poor backfilling of SH)	• FEGT • Unbalanced firing • Tube temperatures

Table 2-2 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Steam-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Short-term overheating (cont.)	• Operation-induced short-term overheating: – Blockage caused by exfoliated oxide scales (formation and exfoliation of scale is accelerated by thermal transients) – Incomplete boil-out of steam-cooled tubes during startup – Over-firing on start-up – Over-firing when top feedwater heaters are out of service – Improper shutdown and startup of unit (condensate collection in SH/RH bends) – Loss of coolant because of upstream tube failure	
Stress corrosion cracking The crack is initiated in a susceptible material by simultaneous exposure to stress and adverse chemical environment. It occurs primarily in austenitic materials and most prevalently initiated from ID.	• Influence of environment, mainly contamination from: – Carryover of chlorides from the chemical cleaning of waterwalls – Boiler water carryover – Introduction of high levels of caustic from attemperater spray – Condenser cooling water constituents from a condenser leak – Fireside contaminants such as polythionic acid – Ingress of flue gas environment into tube through primary failure, especially in RH when vacuum is drawn • Influence of excessive stresses • Influence of sensitized material • Influence of shipping protection	• Water chemistry control • Shutdown procedure

Table 2-2 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Steam-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
SH/RH sootblower erosion Sootblowing-induced erosion causes accelerated tube wastage by direct material removal, removal of the fireside oxide, and increasing fireside oxidation rate.	• Improper maintenance or operation of soot blowers: – Incorrect setting of blowing temperature (insufficient superheat) – Condensate in blowing media – Improper operation of moisture traps – Excessive sootblowing pressures – Improper location of soot blower – Misalignment of soot blower – Malfunction of soot blower – Excessive soot blowing	• Slagging and fouling • Draft losses • FEGT • Excess O_2 • Burner tilt • Sootblowing operation (blowing temperature, pressure, travel, sequence, time, and duration)
Fatigue in steam-touched tubes Cracking that is OD-initiated manifests failures in this category. It occurs at high local stress areas.	• Poor design (excessive strains/stress due to constraint of thermal expansion) • Poor manufacturing (excessive mechanical stresses or residual strains/stresses) • Flue gas-induced vibration by direct flow or vortex shedding • Poor welding, particularly poor geometry of final joint • Cycling operation	• Ramp rate • Cycling operation • Vibration • Header metal surface temperature
Rubbing tubes/fretting The damage is induced by direct metal-to-metal contact (impact, rubbing, and so forth). Tube wear will occur by rubbing/fretting and by accelerated oxidation of the tube surface.	• Tube metal-to-metal contact	

Table 2-2 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Steam-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Pitting (RH loops) Pitting occurs at the inside tube surface. It is primarily the results of poor water chemistry and shutdown practices with oxygen-saturated, stagnant water.	• Poor shutdown practice causes presence of stagnant, oxygenated water • Carry over of Na_2SO_4	• Shutdown practice
Graphitization Graphitization of carbon and carbon-molybdenum steels is a form of micro-structural degradation that occurs after prolonged exposure at temperatures of 640-1290°F° (338-699°C). It causes embrittlement in the material.	• High flue gas temperature	• Flue gas temperature
SH/RH chemical cleaning The damage is a generalized corrosion caused by one or more improper operation during the cleaning process.	• One or more improper operations in the chemical cleaning process including: – Use of an inappropriate cleaning agent, inhibitor, or other chemical – Excessively strong acid concentration – Excessively long cleaning times – Too high a temperature – Failure to neutralize, drain, and rinse properly after cleaning – Breakdown of inhibitors as a result of temperature excursions – Poor chemical cleaning practice	

Table 2-2 (cont.)
Operation Parameters' Influence on the BTF Mechanisms in Steam-Touched Tubes

Mechanisms	Potential Root Causes	Operation Parameters Influence or Indications
Fly ash erosion It accelerates tube wastage by direct material removal, and removal of fireside oxide. The erosion damage is usually localized.	• Excessive local velocities due to non-uniform gas flow from: – Geometry design – Maintenance (distortion or misalignment of tubing rows, misalignment or loss of gas flow guiles and baffles) – Operation (operating above the continuous design rating, operating above design airflow, high excess air, convective pass fouling, and gas laning) • Increase in particle loading and high erosive elements (for example, quartz and iron pyrite fuel) • Other influences: – Palliative shields and baffles, usually punched plates or solid baffles, that were misapplied – Inappropriate material, improperly or poorly applied coating	• Excess air • Total airflow • Slagging and fouling • Draft loss • FEGT • Peaking operation

Major Operating Factors That Influence the Heat Rate

Approximately 70–80% of production cost in the fossil generation facility is due to fuel. Heat rate improvement is essential to reduce fuel consumption. The major operation parameters that influence the heat rate are developed from the EPRI publication entitled, *Heat Rate Improvement Reference Manual* and other publications. The major operation parameters that affect the heat rate are presented in Table 2-3 through Table 2-5. A brief discussion of boiler heat loss is presented in Appendix A. Appendix A also includes predictions of the heat rate deviation from the unit operation parameter changes, previously described in EPRI report CS-4554, *Heat-Rate Improvement Guidelines for Existing Fossil Plants*.

Table 2-3
Heat Rate Influence from Boiler Losses

Category	Subcategory	Indicators	Operating Parameters
Moisture losses	Coal quality	• Increased volatile matter • Increased moisture	• Makeup flow • Precipitator current • Opacity
	Tube leaks	• Increased makeup flow • Increased precipitator current draw • Increased stack opacity	
	High moisture in the air	• > 0.0041 lb moisture/lb dry air	
Incomplete combustion	Coal quality	• Increased carbon content • Increased ash content	• Loss of ignition (LOI) • CO • Excess O_2 • Total air • Total fuel flow • Total steam flow • Main steam pressure • Flame color, shape, and length
	Burner tips plugged		
	Decrease in mill fineness	• Classifier vanes improperly adjusted • Loss of roller tension • Ring or roller wear • Classifier vane wear • Excess of mill capacity	

Table 2-3 (cont.)
Heat Rate Influence from Boiler Losses

Category	Subcategory	Indicators	Operating Parameters
Incomplete combustion (cont.)	Burner damper settings	• Improper primary air to total air ratio	
	Incorrect fuel to air ratio	• Incorrect combustion control signals for airflow, O_2, throttle pressure, or main steam flow • High O_2 at boiler exit	
Radiation and other losses	Boiler skin temperature Surface air velocity		• Air in-leakage

Table 2-4
Heat Rate Influence from Dry Gas Loss

Category	Subcategory	Indicators	Operating Parameters
Dry gas losses	Boiler casing air in-leakage	• Decreased flue gas temperature before economizer • Low combustion airflow at furnace exit • Decreased boiler exit temperature (BET)	• Flue gas temperature before economizer • Combustion air flow at furnace exit • BET
	Air preheater leakage	• Decreased average cold end temperature • Increased air heater and O_2 at boiler exit	• Air preheater cold end temperature • O_2 at boiler exit
	Incorrect fuel-to-air ratio	• High O_2 at boiler exit	• O_2 at boiler exit
	Fouled heat transfer service	• Boiler waterwalls – Increased main steam temperature – Increased SH spray flow	– Main steam temperature – SH spray flow
		• SH – Decreased main steam temperature – Decreased SH spray flow	– Main steam temperature – SH spray flow
		• RH – Decreased reheat temperature – Raised burner tilts	– Reheat temperature – Burner tilt position

Table 2-4 (cont.)
Heat Rate Influence from Dry Gas Loss

Category	Subcategory	Indicators	Operating Parameters
Dry gas losses (cont.)		• Air preheater – Low BET – Normal inlet air and gas temperature – Increase in air heater dP (pluggage), decrease in air – Heater dP (erosion) – Furnace pressure instability	 – BET – APH inlet air and gas temperature – APH outlet air and gas temperature – APH dP (pluggage) – Furnace pressure
		• Economizer – Decreased economizer outlet temperature – Increased main steam temperature – Increased SH spray flow	 – Economizer outlet temperature – Main steam temperature – SH spray flow

Table 2-5
Heat Rate Influence from Steam Conditions

Category	Subcategory	Indicators	Operating Parameters
Firing conditions		• Mill biasing • Excess O_2 • Mill out of service	• Feeder speed • Excess O_2 • Mill in service
High SH spray flow	Improper spray control	• Low main steam temperature	• Main steam temperature
	Leaking spray isolation valve	• Spray valve position • Spray valve internal wear	• Spray quantity
Inadequate heat transfer surface		• Low main steam temperature • Low reheat temperature • High boiler exit gas temperature • Low economizer outlet temperature	• Main steam temperature • Reheat temperature • Boiler exit gas temperature • Economizer outlet temperature
High RH spray flow	Improper spray control	• Low reheat temperature	• Reheat temperature
	Leaking spray isolation valve	• Spray valve position • Spray valve internal wear	
Fouled heat transfer surfaces	See Table 2-4 Subcategory Fouled heat transfer surface		

Major Operating Factors That Influence the Emissions

Emissions are influenced by the fuel quality, furnace conditions, combustion, air supply, and conditions of the firing equipment (that is, pulverizers and burners). The combustion plays a major role in all boiler performances—especially in emissions. The major operating factors that affect the emissions are:

- Furnace exit gas temperature (FEGT)
- Air/fuel ratio
- Excess air
- Combustion air imbalances
- Coal flow imbalance
- Secondary combustion in the convection pass
- Flue gas temperature and excess air stratification
- Loss on ignition (LOI)
- CO
- CO_2
- NO_x
- Furnace tube surface cleanness
- Soot blowing
- Casing leakage in furnace
- Ash carry-back to furnace
- Primary air/fuel ratio off the requirement
- Coal fineness
- Flame color, shape, and impingement
- Primary air temperature

Major Operating Factors That Influence the Capacity

The boiler design has its rated capacity in term of the maximum continuous rating (MCR) of steam flow. The boiler design might also present peaking capability with increased flow or feedwater heaters out of service. To preserve the reliability, boiler manufacturers normally place daily four-hour limits on a boiler’s operation. The acceptance might show high steam-generation capacity with control valves wide-open. All those represent 5–10% extra capacity, which can be used at the peaking period for high revenue return. Typically, the U.S. designed fossil power plants to have capacity limitations in the sequential order of generators, turbines, boilers, and auxiliaries, with generators having the largest tolerance. The generator typically is rated at million voltage ampere (MVA) with a specified power factor and hydrogen pressure rating. The actual power factor is based on the plant location and reactive power requirement. Transmission voltage stability and other considerations might also influence the potential capacity increase. If the existing boiler and auxiliary equipment can generate more steam, more megawatts (MW) can be available by altering the generator power factor.

Capacity increase can be provided by the following two principles:

- Improvement of efficiency at the full load
- Firing more fuel to deliver energy necessary to produce power

Proper economic evaluation is essential to determine the feasibility of the options. There are several concerns that are related to the additional duties to be placed on the existing units. With the high cost of fuel, fossil units are facing pressure to increase the efficiency of existing power plants. The reliability deterioration and capacity reduction of aged power plants are also primary concerns. The Clean Air Act Amendment requires emission reduction from the boiler. These concerns must be properly addressed prior to making the decision regarding use of those extra capacities. The increased capacity from the existing aged fossil power units is a complex issue. If those options are carefully evaluated, it can be a low-cost power option. A more detailed discussion is presented in Appendix B.

Determining the critical factors for increasing capacity is based on the basic understanding of the design and operating limitations for each steam-generation circuitry and fireside/flue-gas-side control, that is:

- The increased steam flow will increase the pressure drop and the boiler tubes starting with the economizer will be subjected to higher operating pressure.
- The increased firing rate will increase the furnace heat release rate and the slagging and fouling potential can be increased. The slagging and fouling control requires more soot blowing, which can increase the sootblowing erosion. If slag is not removed in a timely manner, the potential of fireside corrosion increases and the boiler thermal performance is affected.
- The increased usage of total air will increase the potential of fly ash erosion.
- The over-firing condition will alter the flue-gas-side conditions that can cause convective pass boiler tubes (for example, SH and RH) temperature increase that might need proper monitoring.
- The drum internals might reach their limits. The auxiliary equipment (that is, fans and pulverizers), might reach its operating limits, which might require overhaul prior to the peaking seasons.
- Out-of-service, high pressure feedwater heaters will impact the heat rate.
- NO_x emissions will increase and a proper strategy needs to be considered.
- The coal quality can be a limiting factor and the use of premium coal during the peaking season might be required.

Typically, major parameters that influence the capacity increase include all standard operating parameters.

Major Operating Factors That Influence Safety

The primary consideration for all operation is the safety of people and equipment. The control logic is established and control systems are installed to assist the operation personnel in performing safe and reliable operation. The control is an integral part of operation. It is the responsibility of operation personnel to use the control properly through automatic control or manual control/override. Operation personnel must not only have the knowledge of what is being done, but also why it is done and what results can be expected from a specific action.

The boiler control logics are provided by the vendors and deal with selected input and output operational parameters mainly based on experience for the overall plant operability and safety. There are many subprocesses between the input and output control variables. The in-process parameters, in some cases, are recorded for information only. In addition to the control, the plant is equipped with protection systems that protect the personnel and equipment from danger or destruction in case of an operating error or in case some equipment fails to function. The applications of interlocks to the plant systems vary widely. The desired interlocks depend upon the manufacturer of the equipment, design engineers, company policy, and station management. There are basically two types of interlocks used in power plants—permissive interlocks and tripping interlocks. Permissive interlocks determine the order in which things must be done. Tripping interlocks trip or shut down equipment in the event some limit is reached or some equipment fails to do its job.

In current power plants, control logics might not necessarily be focused on reliability or efficiency. As mentioned previously, there are actually three systems existent in the power plant to address different requirements. When there are conflicts among the three requirements, operability and safety take precedence. Making tradeoffs involving overly-conservative safety margins requires detailed understanding of actual margins and rationale behind the logics and careful evaluation of the consequence of the failure.

Major Operating Factors That Influence the Total Cost

The customer demands the lowest price for electricity. Electricity cost has a direct impact on the production cost of manufactured products, which makes electricity cost a global issue. In a regulated market, the price of electricity is determined by the cost of production plus reasonable profit. In a deregulated environment, the cost structure is different. The competition in the market, which sets the price and profit, is a function of the production cost of generating electricity. Low-cost power producers have a definite edge in a competitive market. Additionally, stringent clean air requirements superimpose burdens on the negative side of cost reduction. Cost reduction and emission requirements compound the problems with work force and equipment aging issues. Consequently, utility companies are facing tremendous challenges to their survival in the business.

The total cost involves the expense to meet all plant objectives. The operating parameters' impact on the total cost includes all the major parameters discussed in the heat rate, emissions, capacity, reliability/availability, and safety. Some costs are relatively simple to quantify, and some are more difficult to determine. Some of the requirements have positive impacts on the total cost and some have negative impacts on the costs. Many EPRI and industry publications make attempts to quantify the cost associated with the deviation from the expected performance.

General Discussion on Major Operation Parameters

The following important operation parameters and their association with the multiple plant objectives are discussed in the remainder of this section:

- Fire/flue-gas-side control
- Feedwater temperature
- Excess air
- Windex and furnace pressure differential
- Burner selection
- Burner tilt position
- LOI
- Carbon monoxide
- FEGT
- Draft loss
- Pressure drop
- Air in-leakage
- Flue gas recirculation
- Desuperheaters and attemperators
- BET
- Slagging and fouling control
- Soot blowing
- Low NO_x firing

Fire/Flue-Gas-Side Control

A boiler furnace is designed to absorb a specific percentage of the total heat released in the furnace. The remaining heat not absorbed in the furnace will enter the convection pass and eventually be absorbed in the SH, RH, economizer, and air heater sections. When compared with the fluid side, the boiler fireside control is relatively weak. One of the reasons for this is the high temperature instrumentation availability and instability of the fireside conditions. Many flue gas controls are initiated from the fluid side parameters. For example, in a tangentially-fired boiler, if the steam temperature is high, the automatic control will adjust the burner tilt down and then place the spray water, if necessary. The operator can add other manual options to reduce the steam temperature (that is, reduce excess air, blow soot in the furnace, and reduce the soot blowing for the SH). It is preferable to have the logic to control the fireside conditions (for example, flue gas temperature and draft losses), to eliminate the high steam temperature conditions rather than reacting to the fluid side conditions. Fireside conditions are part of the front processes of the overall steam-generation processes. It is important to control these front processes to ensure better performance in the later processes and of the final output parameters. In the current control, the fuel and air are mixed, combustion takes place in the burner system, and the next monitoring point in the flue gas path is the BET. Basically, there is nothing in between. There is a simple logic to add more fireside control to ensure the boiler performance. One example is converting from a two-point control, burner, and BET, to a three-point control (that is, burner, FEGT, then BET). The extra control point, FEGT, can have a major impact on boiler performance and reliability. A more detailed discussion on FEGT can be found in Section 4.

If the fireside control is not adequate, then the steam generation will be seriously affected. Typical boiler fireside design involves the following considerations:

- Heat release rate per furnace plan area and volume
- Gas temperature entering first pendant surface over the arch
- Gas temperature leaving the furnace
- Location and quantity of furnace wall blowers
- Burner input and burner clearance
- Ash fusion temperature
- Total heat available to burner zone (Btu/ft^2-hr)

Fireside control in the operation involves the following:

- Coal quality
- Combustion
- Slagging and fouling
- Burner tilt
- Excess air
- Draft loss
- Soot blowing
- Flue gas temperature control

- Flue gas distribution
- Flue gas recirculation
- Distribution damper for steam temperature control

The preservation of boiler operation and performance includes meeting underlying design assumptions and process control. The boiler design involves the energy balance between the fireside and steam-side parameters. In a typical fossil power plant, there is more steam-side instrumentation installed with the original control system than there is flue-gas-side instrumentation. However, the fireside provides the heat energy input to the boiler system and it is extremely important to control the fireside-operating parameters to ensure the boiler performance. Fireside-operating parameters provide valuable information for maintaining all plant objectives. Some of the important operation parameters and their association with the multiple plant objectives are discussed in the remainder of this section.

Feedwater Temperature

It is important to control the feedwater temperature that leaves the economizer. The steam flow meter is calibrated for a given feedwater temperature to the boiler. With the air flow and fuel flow constant, a lowering of the feedwater temperature—such as taking a feedwater heater out of service—will lower the steam output of the boiler. If the temperature is too low, the firing rate needs to be increased. Control of the economizer outlet temperature below the saturation temperature of water during the startup is important to prevent the economizer from a steaming condition, which can affect the circulation for both natural and controlled circulation boilers.

Excess Air

Combustion is a rapid chemical reaction of oxygen and the combustible elements of a fuel with a release of heat. For complete combustion to occur, the combustible elements should be thoroughly burned with resultant maximum heat release. The efficient combustion of fuel requires adequate combustion air. The theoretical amount of air required to burn all the fuel when the fuel and air are mixed perfectly, is called theoretical air or stoichiometric air. Perfect mixing of fuel and theoretical air is not possible because it is difficult to get the fuel particles or droplets fine enough to burn quickly. Therefore, more than the theoretical amount of air is needed for complete combustion. The extra air used is called excess air. Excess air is expressed as a percentage of the required theoretical air. Thus, 25% excess air indicates that 125% of the theoretical amount of air is being supplied.

In the past, excess air was use by operators as one of the effective techniques to solve many problems (that is, increase steam temperature, improve combustion, resolve opacity problems, protect fireside corrosion, and others). However, the heat rate incentive and NO_x reduction initiatives prohibit the use of high excess air in normal operation. Excess air needs to be established as low as possible. The excess air level affects the boiler performance in many ways, which will be discussed below:

- **Combustion:** Operating with low excess air can lead to unstable combustion with the potential for furnace puffs and resultant damage to waterwalls and other areas of the boiler.

Low excess oxygen operation also generally results in poorer combustion with increased losses in efficiency due to high CO levels in the flue gas, as well as higher percentages of carbon in the ash (that is, LOI), and other combustibles. Those represent heat rate losses and can produce secondary combustion in the convective path, which can be a reliability and safety concern. Proper combustion of fuel at the burner front is dependent upon a number of variables, including the velocity of combustion air through the burner. As excess oxygen is decreased, the mass flow rate and velocity of secondary air decreases accordingly. With a decrease in the secondary air flow rate, the burner's associated flame front tends to move closer to the nozzle, the lithe flame front moves too close to the nozzle tip, and coking (caking) will occur at the nozzle with luggage and high burner metal temperature.

- **Air:** The excess air level is one of the factors that influences combustion. Other factors include turbulence airflow and combustion air temperature. It is important to consider all three factors, rather than use excess air only.
- **Heat rate:** The low excess operation can also produce a heat rate gain. If more excess air than is needed is provided, it represents a heat loss.
- **Steam temperature:** Steam temperatures can be changed by varying the excess air. This is not recommended, but under certain conditions the excess air can be varied slightly to give results that might be advantageous. An increase in excess air will increase steam temperatures and a decrease in excess air will decrease steam temperature.
- **Fireside corrosion and erosion:** If the furnace is under the reduced condition, the potential of fireside corrosion can be a major concern. The higher excess air can increase the potential of fly ash erosion on the SH, RH, and economizer tubes. All bituminous coals contain enough sulfur and alkali metals to produce corrosive ash deposits—particularly those with sulfur and chlorine contents greater than 3.5% and 0.25%, respectively. Investigation has found that, when dry, the sulfates formed have little corrosive activity, yet when semi-molten, they corrode most alloy steels used in SH and RH tube construction. Boilers operating with high FEGTs are particularly prone to coal ash (high temperature) corrosion. Therefore, waterwall furnace deposits resulting from low excess oxygen in the furnace will most likely lead to premature SH and RH tube failures. It should be kept in mind that boilers operating with wide temperature variations across the SH tubes will often have a significant percentage of tubes with metal surface temperatures in excess of 1150°F (621°C). These hot tubes will also be prone to high rates of liquid phase corrosion from ash constituents.
- **Emissions:** The low excess air operation produces lower NO_x. The operators often use higher excess air level to reduce the opacity.
- **Operation:** There is a design excess air level used in the original design. Lowering the excess air level can alter the boiler performance, which needs to be evaluated. The operators often use extra excess air to raise the superheat and/or reheat steam temperatures. The changed excess level can also alter the FEGT, which can change the slagging and fouling characteristics of both furnace and convective pass. As furnace excess oxygen levels are reduced, the potential for creating a reduced atmosphere along the waterwalls increases. Many coals, particularly those with a high iron content in the ash, will have a significantly lower ash fusion temperature with a reduced atmosphere. The lowered fusion temperature will result in ash deposits. This increased slagging will result in poor furnace heat transfer, a potential for large clinker formation(s) and impact damage to lower slope furnace tubes when they fall, convection pass plugging, and liquid phase corrosion of SH and RH.

Realize that the optimal excess air level is important and difficult to determine. It not only needs to balance all the advantages and disadvantages, but it also needs to overcome the handling of changing practices.

Windbox and Furnace Pressure Differential

Windbox to furnace air pressure differential (dP) influences the boiler performance. In most wall-fired boilers, a common open windbox is used. It is important to balance the secondary airflow into each burner's secondary air dampers to ensure uniform combustion. The dP influences on the boiler performance is discussed below:

- The dP needs to be maintained as a set value to prevent windbox fire.
- It is essential to produce turbulent secondary airflow for good combustion. This can be accomplished by increasing the dP by throttling the burner secondary air registers or increasing the excess air. Visual observation is used to adjust the combustion.
- Low dP will produce low NO_x and long flame. The long flame might impinge on the opposite waterwall, which can cause local overheating and the potential of hydrogen damage during certain conditions.
- Higher than the required dP necessitates higher forced draft (FD) fan power, which penalizes the heat rate.

Burner Selection

For the boilers that are equipped with wall-fired burners, the steam temperature can be controlled by varying burner selection. Using burners in the upper elevation results in higher steam temperatures than when using burners in the lower elevations. The burner selection also affects the NO_x emission. A technique called burner-out-of-service is used extensively in oil and gas fire units for NO_x reduction.

Burner Tilt Position

The tangentially-fired boiler is equipped with burners that tilt for steam temperature control. By tilting the burners down, more heat is absorbed in the waterwalls and less heat is absorbed in the SH. This is because the fireball is located lower in the furnace. Operation with burners tilted down is usual when at high load or when furnace walls are coated with ash. On the other hand, if the burners are tilted up, less heat is absorbed in the waterwalls and more heat is absorbed in the SH. This is because the fireball is located higher in the furnace. Operation with burners tilted up is usual when at low load or when furnace walls are clean. By varying the position of the burner tilts between maximum up and maximum down limits, a certain amount of control over superheat temperature can be obtained.

Normally, the burner tilt is a part of automatic steam temperature control. If the burner tilt goes to its maximum downward position and if the final temperature is still too high, then the control system will signal the attemperation. The burner tilt is intended for steam temperature control in the original boiler design. However, the burner tilt position influences the boiler performance in many other ways, which are discussed in the following:

- The burner tilted down can improve the combustion with longer residence time and higher temperature, which results in lower CO and LOI. The burner tilted down also increases the NO_x.
- When the burner is tilted up, the steam temperature increases and FEGT also increases, which can increase the slagging and fouling condition. The burner tilted up reduces the NO_x.

LOI

LOI is sometimes referred to as the carbon in ash or unburned carbon in ash. In a typical pulverized coal-fired unit, there is a certain amount of unburned carbon remaining in the ash. The actual amount of LOI varies from 1-3% for normal boilers to above 10% for low NO_X conversion. In addition to causing a drop in boiler efficiency, unburned particles can travel through the flue gas system, creating a dangerous situation. If unburned fuel has been allowed to collect in the ducting, air heaters, or economizer, it can ignite and cause extensive damage. Carbon in ash has a direct impact on boiler efficiency and, hence, unit heat rate. A 1% increase in carbon in the ash typically results in a decrease of approximately 0.1% in boiler efficiency. The amount of unburned combustible in the ash is a measure of the effectiveness of the combustion process in general, and the pulverizers/burners in particular. Unburned carbon in the ash represents fuel that never burned to give up its energy in the boiler. Factors that will impact the amount of carbon in the ash are pulverizer problems, burner problems, insufficient excess air, and, most importantly, the maldistribution of air, coal, or both between the burners. Pulverizer problems that impact boiler efficiency are caused by the inability of the pulverizer to grind the coal to the desired fineness. Pulverizer problems include:

- Worn pulverizer components
- Pulverizer components in need of adjustment
- Classifier adjustment incorrect
- Primary air flow too high/low relative to coal feed
- Excessive air in-leakage into the mill (on exhauster type mills only)
- Worn orifices and riffle distributors

In addition to pulverizer problems, the combustion process itself can lead to high carbon in the ash. During combustion, coal particles are surrounded by an atmosphere of combustion products through which oxygen has to penetrate to react with the coal. If the supply of secondary air is insufficient, improperly distributed, or improperly mixed, then some unburned combustible in the ash will be produced even though coal fineness from the mill is satisfactory. Therefore, it is extremely important to maintain proper windbox-to-furnace dP, as well as to supply and distribute the combustion air properly.

CO

CO is often used as an indicator for combustion problems and inadequate excess air. Although it is considered an air pollutant, carbon monoxide is not a major emission from utility boilers. However, if carbon monoxide is present, it will cause a significant reduction in boiler efficiency. High CO can cause agitation to the human eye. CO is normally maintained below 200 ppm, depending on the plant.

FEGT

The furnace exit point separates the radiation zone from the convective pass. The FEGT is one of the critical parameters in the boiler design and operation. The FEGT can be affected by the following operational parameters:

- Excess O_2 level
- Furnace heat absorption rate
- Furnace soot blowing
- Burner/mill selections and burner tilt
- Low NO_x operations
- Coal quality
- Air in-leakage

FEGT control is a critical parameter that can be used to preserve the boiler operation and performance including, emission, reliability, and safety. If FEGT deviates from the design value, the following undesired conditions could occur:

- Increased slagging/fouling of waterwalls, SH, economizer, and air heaters
- Increased corrosion rates of SH and RH tubes
- Potential of convective pass tube overheating (creep damage), requiring more attemperation
- Altered design conditions, which are more difficult to correct by the operator
- Increased flue gas temperature in the boiler exit, which increases heat loss and lowers efficiency

FEGT provides an operational safeguard and indictor for the boiler operation. The following conditions can be influenced by the FEGT control:

- Slagging and fouling control
- Soot blowing
- Coal ash corrosion control
- Superheat steam temperature control
- Low NO_x firing

A furnace startup probe is sometimes used to protect the SH and RH tubes prior to establishing steam flow. Unfortunately, the current startup probes cannot be used for the complete flue gas temperature range. For many years, the utility industry has been actively involved in developing more accurate instrumentation, analysis methods, and performance improvement techniques for the fireside parameters control. There are many techniques that can be used to obtain the FEGT on-line, including from direct measurement or calculations. Direct measurement techniques can be intrusive and non-intrusive. Operators can use this information to balance combustion and boiler performance.

All bituminous coals contain enough sulfur and alkali metals to produce corrosive ash deposits, particularly those with sulfur and chlorine contents greater than 3.5% and 0.25%, respectively. Investigation has found that when dry, the sulfates formed have little corrosive activity, yet when semi-molten, they corrode most alloy steels used in SH and RH tube construction. Boilers operating with high FEGTs, which are often a direct function of waterwall cleanliness, are particularly prone to coal ash corrosion from ash constituents. Maintaining the FEGT at a minimum of 100°F (38°C) below the ash-softening temperature can reduce the potential of SH coal ash corrosion for high sulfur coal firing, because the dry ash entering the convective pass will not adhere to the steam tubes.

For the tangentially-fired furnace, the burner tilts typically are used as one of the methods to control the final steam temperature. The use of the tilting-up option to achieve desired steam temperatures should be applied at low and intermediate loads only. Burner tilt position should be horizontal or angled slightly downward at high loads. The reason for tilt down or horizontal is to increase residence time for complete combustion. The burner tilt up condition might increase FEGT, which can increase the potential of slagging and fouling problems as discussed previously. If the final steam temperature cannot be reached, other options such as increasing excess air should be considered in conjunction with the burner tilting to maintain FEGT within the allowable limit.

Pressure Drop

Pressure drop is referred to as the dP among the different boiler circuitry when the economizer has the higher operating pressure and the SH outlet steam has the designated operating pressures. The pressure drop is a good operation indicator for the fluid side deposition condition, which can be used as the indicator for the need of chemical cleaning. Each boiler circuitry is designed with a given pressure and temperature. Maintaining the pressures within the design limits are important to ensure boiler reliability. Operating with a higher-pressure drop will require higher boiler feed pump power, which is a heat rate penalty.

Draft Loss

Draft loss is the furnace pressure drop through the external surface of each boiler tube bundle. The draft loss is a good indicator for the convective pass fouling and pluggage and it can be used as the indicator to start the soot blowing. Flue-gas-side pluggage can increase the local flue gas velocity and cause high fly ash erosion. High draft loss will cause higher furnace pressure and require high FD and induced-draft (ID) fan power, which are heat rate penalties.

Air In-Leakage

Casing air in-leakage will result in high exit gas temperatures, an improper air/fuel ratio in the furnace, efficiency loss, and other operational problems that will have a detrimental impact on efficiency as well as availability. These problems include:

- Burner fouling
- Convection pass plugging
- Liquid phase corrosion of SH and RH tubes
- Formation of large waterwall clinkers

Flue Gas Recirculation

Flue gas recirculation is the means of introducing cool flue gas from the economizer outlet to the furnace or to the SH. This is done with ductwork from the flue gas pass between the economizer and the air heater connecting to the furnace and the SH section. The flow is controlled with a fan and dampers. This can result in controlling SH outlet steam temperatures. Some boiler manufacturers provide the flue gas recirculation systems for control of steam temperature. Recirculated flue gas is introduced to the lower part of the furnace and above the burners, allowing control of reheat steam temperatures. Recirculated gas is also introduced to the upper part of the main furnace, near the furnace exit prior to contacting SH tubes. This provides control of SH steam temperatures. The flue gas recirculation is an effective way to reduce the NO_x for natural gas and oil firing. The flue gas recirculation is not effective for coal firing.

Desuperheaters and Attemperators

One of the most important and critical factors that can improve the operating efficiency of a modern turbine is steam temperature. Operating the steam temperature above the design value has a detrimental effect on reliability. Desuperheaters and attemperators are steam cooling-equipment. High temperature steam is sent through them and is cooled to the desired steam temperature by using water—either by spraying the water into the steam or by using the cooler water to absorb heat from the steam in a heat exchanger. Direct attemperation is used more often because it can respond quickly and is a method of reducing temperature by introducing water into the steam flow just prior to the steam entering the secondary SH or RH. By adding water to the steam, the steam temperature is reduced and the water is turned to steam by absorbing the heat from the steam. The attemperation represents heat rate penalty, especially for reheat attemperation. Substantial attemperation also indicates that the steam circuitry before the attemperation station could overheat. It is important to adjust the operation to minimize the need of attemperation. Attemperation is the final step for steam temperature control. There are several methods to minimize the need of attemperation depending on the boiler design (that is, burner tilt, distribution dampers, flue gas recirculation, excess air, soot blowing, boiler seasoning, and others).

BET

An approximate 1% reduction in boiler efficiency is associated with about a 40°F (4°C) increase in exit gas temperature for coal-fired units. Exit gas temperature varies with the degree of deposits on the heat-absorbing surfaces throughout the unit, a lowered x-ratio, and the amount of excess combustion air. As heat absorbing-surfaces in the boiler “slag-up,” the temperature of the combustion gases leaving the air heater increases. This increases the dry gas loss, thereby reducing boiler efficiency.

When the flue gas is cooled below its acid dewpoint, corrosive acids are formed. These acids will attack the flue gas ductwork, electrostatic precipitators, and ID fans. Because of this potentially damaging situation, the boiler must be operated so that the BET is maintained above the acid dewpoint of the flue gas.

Slagging and Fouling Control

One of the important characteristics of the fuel from a boiler-design viewpoint is the slagging and fouling control. The formation of slag deposits is caused by the deposition of molten ash on surfaces receiving heat by radiation, such as the furnace and radiant sections of the SH. Entrained in the gas stream, molten ash particles strike the wall or tube surface, become chilled, and then solidify. If slag is allowed to accumulate on the lower furnace walls, FEGT will rise and the slagging area is forced higher into the furnace. The effect on the furnace performance can be drastic. Proper boiler operation requires keeping the ash particles away from the walls and in suspension in the gas stream until the ash is sufficiently cool to be admitted to the convection pass. Parameters that result in increased deposition include:

- Slagging
  - Coal quality
  - Improper coal fineness
  - Combustion problems and poor flame stability
  - Low excess O_2 or O_2 imbalance
  - Inadequate soot blowing
  - High FEGT
- Fouling
  - Coal quality
  - High FEGT
  - Inadequate soot blowing

Keeping the furnace hot can reduce the furnace slagging problem. Limiting FEGT to a minimum of 100°F (38°C) below the ash-softening temperature can substantially improve the convective pass fouling problem, because the dry ash leaving the furnace will not stick to the steam tubes. If the fouling and blockage in the convective pass is reduced, the superheat soot blowing and fan power can be reduced, which improves the heat rate. It also prevents sootblower erosion.

If the coal being burned is changed, the ash fusion temperature for new coals can be obtained from the laboratory test or can be provided by coal suppliers. A new FEGT limit can be established by the operator and used to adjust other operational parameters in order to minimize the potential of slagging/fouling. As a prerequisite, the combustion system should be tuned to achieve the following:

- Uniform flue gas temperature and flow distribution
- Uniform distribution of excess O_2
- Minimal fly ash unburned carbon content
- Minimal air heater leakage and casing air in-leakage
- Balanced secondary air and fuel distribution
- Proper primary air/fuel proportion
- Maintained necessary fineness and coal line temperature

Soot Blowing

Ash slag and soot deposits on the tubes act as insulators that prevent heat transfer. They can also restrict the flow of flue gas. Therefore, keeping the gas side of boiler tubes clean is essential to preserving the boiler operation. Soot blowing has proven to be the most practical method of removing the deposits. Soot blowing can also effectively be used to control steam temperatures. When a boiler is dirty and needs cleaning, the section cleaned depends on the direction the steam temperature is to move. If the steam temperatures are high and need to be lowered, clean the walls and the generating sections first. The clean walls and generating sections will absorb more heat, reducing the flue gas temperatures to the superheating sections. If the steam temperatures are low and need to be raised, the SH section should be cleaned first. The flue gases to the SHs are high because the walls and generating section are dirty and the heat absorption of the clean SH section would be higher. Furnace soot blowing also has an impact on the NO_X emission.

Observation of the boiler for slagging and fouling patterns and for soot blower effectiveness should be made on a regular basis. A prime concern in soot blower operation is to minimize the boiler tube erosion. Soot blowers must be maintained in good operating condition. Effective soot blowing should consider the following:

- Blowing frequency
- Blowing time
- Blowing sequence
- Blowing pressure
- Blowing temperature
- Nozzle position

FEGT can be used as the primary indicator to establish the scheme for automatic soot blowing or to alert the operator to start the manual sootblowing operation. If FEGT exceeds the original design value, this indicates that the furnace is dirty. The operator should initiate the furnace soot blowing and the soot blowing should be stopped when FEGT has been reduced below the original design value. The over-blowing in the furnace wastes energy and can also create soot blower erosion problem in the waterwall tube.

Low NO_x Firing

Wall-fired low NO_x burners normally result in longer flames and higher unburned carbon content. The potential of secondary combustion could become more intense and increase fouling and slagging of the convection pass and air heaters. Under-stoichiometric combustion, typically used in the low NO_x firing, will result in starvation of oxygen in the furnace areas. This can create areas of reduced atmosphere, which can accelerate fireside wastage of waterwall tubes. Delayed combustion or secondary combustion sometimes produces high FEGT. These high temperatures can cause overheating of SH and RH tubes. It is essential for the operator to maintain the original design FEGT to minimize other side effects—otherwise tradeoffs are required and can comprise the multiple system objectives.

Interrelationship Between Different Objectives

Many operating parameters are interrelated, which adds difficulty to both data manipulation and correlation detection. Interrelated operating parameters means that many redundancies exist in the use of these factors in analysis or that too many unnecessary factors have been used. This is true when discussing the conflicts and interrelationships of plant objectives. The effects of slagging/fouling, heat rate, pulverizer performance, NO_x, precipitator performance, tube wastage, tube overheating, load response, and other factors are all somewhat related and interrelated. For example, coal fineness affects combustion, which then affects heat release in the furnace. Coal fineness and varied heat release in the furnace can impact NO_x and unburned carbon content. Higher than normal unburned carbon content can cause excessive spark rates of electrostatic precipitators, which can then cause an opacity concern. Secondary combustion can contribute to overheating of the SH and RH tubes and to elevating the flue gas temperatures that enter the airheaters. If the flue gas temperature gets too high, the supporting steel and casing can be subject to damage and cracking, which then promotes air in-leakage. Air in-leakage penalizes the heat rate.

Furnace slagging, burner tilt-up, fuel and secondary air distribution, and secondary combustion all can increase the FEGT. High FEGT can cause heavy fouling on the SH and RH tubes. When these tubes are blown clean, the cinders sometimes entrain into the flue gas stream and are carried into the airheater baskets. This will cause higher draft loss, which increases the fan power usage. Pluggage of the air heater might promote ash recirculation back to the furnace. The increased frequency of soot blowing will cause sootblowing erosion and also is a heat rate penalty. The situation can become very complex. Effort to solve one problem might in turn create more problems. However, it does not have to be so complicated if the effort is focused on the front-end process control. For an example, one of the ideal situations is to ensure that the FEGT is below the ash fusion temperature. If this can be done, most of the convective pass fouling can be eliminated, dry ash will be carried to the boiler exit, and cinders will not be formed. If convective pass fouling can be controlled, the soot blowing can be minimized, which can avoid the sootblowing erosion and save energy. Controlling the FEGT within the design limits can reduce the chance of overheating the SH and RH tubes and might also eliminate the requirement of attemperation. It is important to address the cause, rather than battle the consequences. It is essential to understand the interrelationship among these factors quantitatively, which is the focus of this report.

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3
PROCESS CONTROL AND REGRESSION ANALYSIS FOR BOILER PERFORMANCE PRESERVATION

Introduction

The term boiler performance was often used in the past in relation to heat-rate improvement. The term boiler performance used in this report has a broad definition that relates to all plant objectives (for example, capacity, efficiency, emission, reliability, and cost). Some of these objectives are in conflict with each other. A major challenge facing utility companies today is how to economically achieve these plant objectives in a competitive environment.

In the reliability area, for example, forced outage is one of the major problems confronting fossil power plants. Unscheduled outages increase the maintenance and production costs. Predictive maintenance, if available, can be used to determine the condition of the equipment and the proper time for maintenance. However, condition monitoring and predictive maintenance address degradation of the equipment but cannot avoid the degradation. A proactive operation measure is necessary to reduce or eliminate the potential damage to the equipment. To achieve this proactive operation, it is necessary to monitor the process performance. If input/in-process operating parameters and the process stability/capability can be controlled adequately, then the unacceptable output variations can be reduced and the equipment degradation and damage can be minimized or avoided. The same logic and process can be applied in achieving other plant objectives. The first step in the process control is to select the critical operating parameters, which represent the plant objectives. Later steps involve establishing the interrelationship among the critical operating parameters and the process optimization.

System and Process Performance

It is important to be aware that the probability of system failure can be substantially higher than the individual component failure. It is important to examine the overall problem from the system and process point of view. The system is considered to be a set of equipment, components, and processes interactively working together as an integrated whole. Where more than one level of division is required, a number of different hierarchies may be used (that is, system, subsystem, component, and part). Processes are groups of activities that take an input, add value to it, and provide an output to meet the requirements. Flow-charting is the most elementary form of describing an explicit process. The flow chart, with block diagrams, describes the observable-measurable performance and the actions of the process. It is essential to identify critical systems and processes that contribute to the production and to ensure those items have very high performance and reliability. Non-essential or non-critical systems/processes, which do not contribute to the production, should receive less attention or should be eliminated. It might also require providing redundant systems for the critical process to ensure continuous operation of the production line. The complete line of considerations in the system and process performance should include efficiency, reliability, production cost, safety, and regulatory requirements.

The company that has developed and understands high-efficiency systems and process requirements will have advantages in the competitive environment. The term process has a broad definition, and can refer to the work processes or physical processes imbedded in the equipment design. Changing the physical process by the operating personnel to achieve the plant objectives is essentially changing the original design and should only be conducted with a full understanding of the consequence. Most of the discussion on process control in this report is related to the control of the original physical process only. Process management is managing a system by managing its processes. The process management approach ensures that processes are under real-time monitoring and control to ensure that outcomes meet the requirements and objectives. The following describes the essentials of forming process management:

1. Define the boundaries and sub-processes of the system/process and subsystems/sub-processes
2. Identify system requirements and objectives
3. Develop a macro flow diagram to examine high-level activities interactive with internal or external events
4. Develop a detailed workflow involving input, in-process, and output parameters of associated activities
5. Define the interdependencies of the sub-processes
6. Establish operating range and control levels for the selected operating parameters
7. Collect data and perform process analysis to establish interrelationship among the operating parameters
8. Finalize the list of critical operating parameters and perform system/process optimization
9. Evaluate the results, identify process deficiencies, and perform root cause analysis for continuous improvement

If the system and equipment can be operated within the design limits, failures and degradation/damage should not occur or can be minimized. If failures and degradation do not occur or can be minimized, the result is the reduction of maintenance, and improvement in availability and total cost. The operation focus should be on input and in-process control. The boiler system operation involves the following general process logic (Figure 3-1):

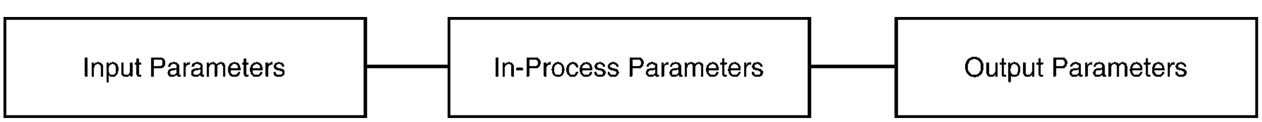

Figure 3-1
Process Logic

The output, in-process, and input operating parameters are discussed briefly in this section.

Output Parameters

The output parameters represent plant objectives (that is, efficiency, cost, emission, reliability, safety, and capacity). Some of the objectives are functional objectives (for example, reliability and safety). It is important to select operating parameters that represent these functional objectives, and then an optimization/tradeoff analysis can be performed mathematically. The output parameters can be direct, indirect (calculated), or fuzzy (observed) parameters. After the output parameters are selected, the next step is to define the quantitative constraints or targets for each parameter. Performance improvements are usually dictated by regulatory requirements (for example, reduction of NO_x emissions or opacity) and/or driven by economics (for example, need to reduce heat rate, reduce unburned carbon to make it easier to sell the fly ash, increase MW output, or preserve reliability). It is important to distinguish the firm requirements from the desired outcomes. The boiler system has inherent limitations that prevent it from meeting unreasonable requirements. Parametric tests can be used to explore the upper bound system capability for the each objective. Iterative analysis/testing has also been used to achieve the optimal values. The potential performance improvement for each objective also depends on the operating range of the input parameters and other site-specific factors, which will be discussed below in this section.

In-Process Parameters

In-process parameters are those parameters that are located between the input and output parameters. Current control logic in a typical fossil power plant is focused on output control. For boiler reliability considerations, this approach might not be adequate. For example, high final steam temperature initiates attemperation. The damage has already occurred prior to attemperation. Some in-process data is available in the control room. The majority of this in-process data is for information only or for alarm/trip purposes with relatively large tolerances. The input and in-process control are extremely important for reliability and operability preservation. The ideal way to avoid output variations is to control input and in-process variables. If this is done, then the damage will not occur and other specific performance objectives (for example, emissions, heat rate, and cost) can be achieved without sacrificing base safety and reliability. The operator might not be able to adjust in-process parameters directly. However, operators can take necessary actions to reduce in-process variations by adjusting input parameters before they reach the output parameters. In the actual optimization manipulation, the in-process parameters will be treated as output parameters. The in-process parameters can be direct, indirect (calculated), or fuzzy (observed) parameters. The in-process operating parameters might be controllable or non-controllable. The controllable in-process parameters can be treated as input variables and non-controllable parameters can be treated as output variables.

Input Parameters

Input parameters are defined as the parameters that can be controlled or adjusted by the operating personnel. Input parameter selection should be based on its importance to the output parameters. To minimize the computation and data collection, only critical and essential parameters should be selected as the input parameters for each output objective. It is clear that one input parameter can affect multiple objectives with conflicting effects (that is, high excess air improves opacity and combustion), but it also increases emission, erosion, and cost. The relationship between input and output parameters can be nonlinear. One output parameter can be influenced by multiple input parameters. Input parameters also include the output from the auxiliary equipment. The input parameters are initially selected by experience and engineering knowledge. After the input parameters are selected, the operating range needs to be defined for each input parameter. The potential performance improvement for each objective depends on the operating range of the input parameters and other site-specific factors. The operating range should be as large as possible to provide the system with safety as the only constraint. It might also mean that the hardware might require maintenance, restorations, or modifications, if they can be justified, to provide these ranges for operation and adjustment. The following list presents some examples:

- Unit operating flexibility
    - Fuel flow biasing capability (for example, mill capacity)
    - Air flow biasing capability
    - Burner out of service and burner selections
    - Simulated overfire air
    - Furnace/windbox pressure differential
    - Excess O_2 range
    - Burner tilts and overfire port titles (for t-fired units)
    - Air and gas dampers
    - Power amplifier (PA)/Fuel ratio
    - Soot blowing
    - Other equipment settings and/or limitations
- Ability to change equipment settings
    - Burner settings (for example, registers, air sleeve dampers and coal nozzle axial position inwall-fired boilers, yaw of burners and/or overfire air ports in t-fired boilers, and so forth)
    - Pulverizer settings (for example, journal spring tension, adjustment of classifier blades and clearances, adjustment of flow straighteners, and changes in outlet temperature set-point)
    - Other equipment settings

- Hardware modifications
  - Air distribution modifications (for example, addition of dampers, addition of turning vanes, and adjustment of existing directional vanes)
  - Coal pipe orificing
  - Mill modifications (for example, installation of exhausters, riffle distributors, and dynamic classifiers)
  - Other modifications

The unit objectives and their typically related operation variables are discussed in Section 2 and summarized in Table 3-1. Actual case studies need to be performed to demonstrate the effectiveness and practicality of using this approach.

Table 3-1
Unit Objectives and Their Related Operation Variables

Objectives	Output Variables	In-Process Variables	Input Variables
Capacity	• MW • Steam flow	• Intermediate steam temperatures and pressures • Process stability and capability parameters	• Air flow • Coal flow • Coal quality • Soot blowing
Emissions	• NO_x • SO_2 • CO • CO_2 • LOI • Opacity	• Flame impingement • Process stability and capability parameters	• Coal fineness • Coal quality* • Excess air level • Burner air/overfire air (OFA) air-distribution and air-register positions distribution • Burner fuel turndown and distribution • Burner selections • Burner tilts • Soot blowing • Modes of operation** • Furnace/windbox dP
Efficiency	• Heat rate	• Intermediate steam temperatures and pressures • Attemperation • Draft loss • Pressure drop • Process stability and capability parameters • Process stability and capability parameters	• Coal fineness • Coal quality • Excess air level • Burner air/OFA air-distribution and air-register positions • Burner fuel turndown and distribution • Burner selections • Burner tilts • Soot blowing • Modes of operation** • Furnace/windbox dP

Table 3-1 (cont.)
Unit Objectives and Their Related Operation Variables

Objectives	Output Variables	In-Process Variables	Input Variables
Reliability	• BET • CO • LOI • Final steam temperatures and pressures	• FEGT • Intermediate steam temperatures and pressures • Water chemistry • Draft loss • Pressure drop • Maintenance process	• Coal quality • Modes of operation • Maintenance practices • Modes of operation** • Excess air level • Soot blowing • Low NO_x operation strategies
Safety	• Furnace pressure • Final steam temperatures and pressures	• Furnace draft control • Flame stability	• Modes of operation** • Furnace/windbox dP
Cost	• Total cost		• Capacity • Emission • Efficiency • Reliability • Maintenance requirements • Safety

* Coal quality includes: Higher Heating Value (HHV), Hardgrove Grindability Index (HGI), moisture content, coal, sulfur and nitrogen content, ash content, ash fusion, chemical constitutes, quartz content, fixed carbon-to-volatile matter ratio (FC/VM) ratio, slagging/fouling potentials, and others

** Modes of operation include: cycling, low load, and peaking operation

It is important to realize that this effort can only address global reliability issues. Large numbers of BTFs are local problems that need to be addressed by fundamentals throughout the complete process (that is, design, fabrication, installation, operation, maintenance, condition assessment, and root cause analysis).

Boiler Performance Baseline

The original designed boiler performance data can be found in the plant data book or are supplied by the original equipment manufacturer. The actual boiler performance results are recorded in the acceptance tests. This baseline performance data needs to be updated to include the changes in operation, fuels, and system/equipment medications. These revised baseline performance levels should serve as the reference point for identifying performance improvement opportunities. In many utility companies, it is standard practice to conduct comprehensive performance tests periodically. These tests provide detailed information and identify the areas for improvement; however, these tests require additional instrumentation and can be expensive. Another drawback is that these tests only provide snapshot conditions of the boiler performance. The ideal case is to install minimum essential instrumentation and perform diagnostic testing on-line during normal operations so that the current boiler performance is continuously compared with the expected performance and deviations can be identified instantly. The operating personnel needs to take necessary actions to resolve identified problems and recover the loss of performance in a timely manner.

Regression Analysis

In the analysis of boiler performance, it is frequently desirable to determine whether operating parameters are associated with each other and, if so, how one parameter changes with respect to another. For example, what is the association between the heat rate and the excess air? These situations can be analyzed by the correlation analysis where variables are observed as they occur, and neither is fixed at any predetermined level. In other situations one might be interested in establishing the functional relationship between these variables. Regression analysis provides an equation derived from sample data to express the dependent (output) variables in terms of the independent (input) variables. It also provides the means for predicting the averages of the dependent variables at each given point of the independent variables.

As discussed in the Section 1, traditionally, engineering problems are analyzed by the differential equations. When the number of operating parameters becomes large or cross-functional interactions are required, the equation becomes cumbersome or not possible to analyze. In these situations, an individual’s personal experience has to be used. Each person’s experience can be different and each case might not be the same. In these situations, the statistical correlation and regression analysis can provide valuable information for decision-making. The statistical analysis is data driven.

It is important to realize that the boiler is not precision machinery. The majority of boiler performance monitoring uses bulk (average) information and on-line monitoring of local conditions is neither cost justified nor possible in the majority of situations. The boiler performance analysis has many assumptions and a high degree of precision can not be realized. Only with this understanding can statistical analysis contribute to engineering problem solving and enhance the personal knowledge and experiences.

Because most of the output parameters in the boiler performance are affected by several input and in-process parameters simultaneously, the prediction model will be based on the multiple regression analysis. Statistical multiple regression analysis also involves certain assumptions. The standard procedures have been established to verify these assumptions. Performing the multiple regression analysis computations without the assistance of a computer can be time consuming. The computational burden can be minimized by using a computer software package such as Minitab or others. Discussions on the multiple regression analysis are presented in Appendix C.

Procedures for Regression Analysis

The proposed approach involves selecting initial critical parameters, establishing a test plan, conducting the tests, collecting the data, analyzing the data, developing a regression model, and verifying the model. The process can be an iterative process. The guideline to achieve the intended purposes is outlined below:

1. There are several hundred operating parameters in the fossil plant. It is required to narrow these down to a reasonable number before data can be collected. The initial selection comes from the best guess by using the guidelines presented in Section 2.

2. Establish an operating range for the selected independent variables. Determine the number of levels to be used in conducting tests for each selected independent variable. Develop a test plan by using the DOE methodology.

3. Perform the tests and collect the data. Evaluate the data and determine if additional tests are required.

4. Analyze the test data by using multiple regression analysis to establish the relationship between the input and output variables. The steps for multiple regression analysis involves the following:

   - Check for multicollinearity using pairwise correlation coefficient and variance inflation factor (VIF)
   - Select independent variables using stepwise regression or best subset regression
   - Check for outliers and influential observations
   - Review the multiple coefficient of determination and add nonlinear terms if necessary
   - Test for significance (F-test and t-test)
   - Residual analysis
   - Review the data and modify the independent variable selection if the results are not favorable
   - Establish interval estimation of parameters

At this stage, the final selection of the critical parameters for each output variables is made and the associated regression equation is developed. The percentage of contribution from each independent variable is quantified. The regression equation can be used to predict the output due to unit change of independent variables. Two examples are presented in Section 4 to demonstrate the use of Minitab computer software for performing the multiple regression analysis.

The regression equation can be further stratified to life consumption of boiler pressure component due to unit change of independent variable (for example, a plant personnel might want to estimate the SH tube life consumption due to the amount of steam flow increase beyond the MCR or the amount of excess air increase). Developing the life-consumption prediction equation will require an additional intermediate step analysis using, for example, Larson Miller Parameter, or EPRI computer software such as TUBELIFE Code.

Once the life-consumption prediction equation is established, the following procedures can be used to conduct the analysis for evaluating the effect of component damage due to increasing the steam flow beyond the designed MCR (overflow operation):

1. Establish the current unit mission and anticipate the future requirements (that is, overflow operation for additional peak capacity).

2. Review the BTF history and root cause analysis results to determine the area of concern (that is, long-term overheating for SH tubes).

3. Review the boiler inspection/condition assessment results to determine the degree of damage, the rate of damage accumulation, and the degree of damage required to cause failure for each boiler pressure component. For example, results of the metallurgical analysis and internal oxide scale thickness measurement of the SH tubes indicate that the remaining life of the tubes is approximate 60,000 hours.

4. From the regression analysis, identify the critical operation parameters that are related to these weak components. Develop the life-consumption prediction equation to quantify the risk for operating beyond the MCR.

5. Once the risk has been quantified, the decision can be made as to the level of overflow operation. Additional actions can be taken, such as:
   - Monitoring these critical parameters and placing additional operation constraints
   - Performing system optimization to reduce the impact on the component reliability

The demonstration is not made for developing the life-consumption prediction equation, but it is anticipated that such a demonstration will be made in a future project.

Data Collection

The process control, monitoring, and analysis require data. The decision will be based on the results of the data analysis. The data collection should consider the following:

- The data should include the complete operating range for each input parameter. This is referred to as the enveloping data. A regression equation cannot be developed with data clustered at a single point. Using the regression equation to predict the output parameters outside the original data range might not be accurate and will take additional steps to verify the prediction results.
- The selection of the levels within the operating range for data collection shall consider the characteristics of the physical phenomena between the input and output variables. For example, if a linear relationship is expected, two levels might be adequate. If a nonlinear relationship is expected, then three levels or higher should be considered for the selected input variables. For the majority of the boiler performance parameters, the relationship among the input, in-process, and output variables are anticipated to be nonlinear. However, the nonlinear analysis associated with the large number of variables can be very complex and time consuming. Most of the boiler input variables adjustment ranges are limited. Within this

small range of variation, the stepwise linear approximation might be acceptable for certain cases. If the statistical analysis indicated that the linear approximation might not be adequate, the intersection term will be added prior to adding the higher order of polynomials. If the interaction among the input variables is expected to produce the better prediction of a given output variable, then these types of data must be collected. This can be accomplished by using DOE. Discussions of DOE are presented in Appendix D.

- The repeatability of the data is essential. The quality of data relies on well-calibrated instruments. There are techniques or computer packages that can be used to detect the sensor drift, bad sensors, and inaccurate data. Any improper data will be ignored or will be substituted by the estimated values in the process prior to resolving the instrumentation data problems. This process is referred to as sensor validation. The statistical data analysis can also detect the so-called outliers.
- Often, two or more of the independent variables used in the model contribute redundant information. This is referred to as multicollinearity. That is, the independent variables are correlated with each other. There are several techniques that can be used to detect the multicollinearity and to make proper selection of independent variables. Most commercial computer software packages are capable of performing these analyses. More discussion on this subject can be found in Appendix C.

The data can be obtained from the historian, real-time information, or future operation. The special data can also be obtained from performance testing or DOE. To develop the regression equation or to establish an interrelationship among the operating parameters will require quality data that ideally is developed from the well-planned DOE. The historical data might be available. However, the historical data usually is incomplete and the information surrounding how the data was collected or information about other factors is missing. Also, we might need to test the input variables at levels or combinations at which the process never operated. A proper approach is the DOE. The DOE is a systematic approach to obtain the desired amount of information in the most efficient manner. The DOE uses knowledge about statistics to select the test points that will give the maximum information on the system being studied, which dramatically minimizes the chance of missing a true optimum point. A brief discussion of the DOE is presented in Appendix D.

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4
CASE EXAMPLE

Introduction

One example is provided in this section to demonstrate multiple regression analysis. A simple regression analysis example is included in Appendix C. The data used in this example were obtained from plant performance testing with different purposes. The test plan was organized with the best estimates approach rather than formal DOE. A formal application of DOE for data collection is proposed for future consideration. The potential inadequacies of test plans, data collection, and the associated results might affect the validity of conclusions from statistical analysis. The intent is to demonstrate the techniques only. Even if the conclusions of these two examples are valid, they only represent the unique characteristics of the analyzed boilers and they might not be applicable to other boilers. Both examples were analyzed with Minitab computer software. A brief discussion of multiple regression analysis and model building is presented in Appendix C.

The process control to improve boiler reliability might not be directly demonstrated in those two examples for each BTF mechanism due to lack of proper data. Steam temperature control is essential in preventing the boiler tube from creep failure. The direct indicators in these two examples are final SH and RH steam temperatures. It is understood that the final steam temperature control is a part of the plant control system. For example, the system might be overfiring to achieve preferred steam conditions (for example, steam temperature, pressure, and flow). The final steam temperature should not exceed the operating limits because the attemperation will prevent the final steam temperature from going beyond its preset value. However, the boiler circuitry before the spray station can be subject to higher steam temperatures, which should be monitored for preservation of boiler reliability. Unfortunately, these in-process data are not available to demonstrate the prediction and prevention of boiler component damage due to potential overheating conditions. The proposed technique can easily be applied once this information is available in future demonstration projects.

Conforming to statistical requirements does not necessarily conclude that a cause-and-effect relationship is present between the dependent and independent variables. Concluding a cause-and-effect relationship is warranted only if the analysis has some type of theoretical justification that the relationship is in fact contributory. However, if the data comes from well-planned tests or DOE, a regression model shows a good fit between the data, and all statistical assumptions are satisfied, then the model would be statistical evidence for a cause-and-effect relationship.

Example

The boiler is a tangentially-fired, controlled circulation, balanced draft, drum boiler with rated capacity of 150 MW and was operated at 145 MW due to auxiliary equipment problems. Furnace soot blowing is not required. Both SH and RH steam temperatures are low. Limited boiler performance tests were conducted. The input and output operating parameters used in the tests are listed in Table 4-1 and 4-2, respectively. The test data are listed in Table 4-3. Not all preferred information is available for the statistical analysis. The results and conclusions are plant specific and relate directly to the test plan and data.

Table 4-1
Output Operating Parameters

Outputs	Units	Constraints
Boiler efficiency	%	
Superheater outlet temperature (SHO-T)	°F	< 1005
Reheater outlet temperature (RHO-T)	°F	< 1005
Air preheater gas inlet (APHGI) temperature	°F	
Air preheater gas outlet (APHGO) temperature	°F	
NO_x	lb/MBtu	< 0.50
CO	ppm	< 100
CO_2	%	
LOI	%	< 5
Gross heat rate (Gross HR)	Btu/kWh	
Unit Load	MW	< 150

Table 4-2
Input Operating Parameters

Input Parameters	Units	Operating Range
Excess O_2	%	2.5 – 3.5
Windbox dP	inches water column (i.w.c).	2 – 5
Burner tilt	degree	-30 to +30
Furnace exit temperature	°F	<2450
Coal flow	Klb/h	
A Damper	% open	50 – 100
B Damper	% open	50 – 100
C Damper	% open	50 – 100
D Damper	% open	50 – 100
AA Damper	% open	20 – 100
AB Damper	% open	20 – 100
BB Damper	% open	20 – 100
CC Damper	% open	20 – 100
CD Damper	% open	20 – 100
DD Damper	% open	20 – 100

Table 4-3
Example Test Data Sheet

Outputs	Units	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
Boiler efficiency	%	87.5	87.7	87.9	88.0	88.2	88.2	88.1	88.3
SHO-T	°F	979.2	982.1	978.0	978.5	976.5	952.9	955.4	957.7
RHO-T	°F	999.6	1004.6	1002.1	1005.0	1003.6	980.0	981.7	983.7
APHGI temperature	°F	676	675	671	668	665	661	660	660
APHGO temperature	°F	316	317	318	322	324	325	325	325
NO_x	lb/MBtu	0.68	0.66	0.61	0.6	0.6	0.51	0.51	0.47
CO	ppm	44	53	55	63	62	44	56	64
CO_2	%	15.3	15.8	15.9	16.0	16.5	16.1	16.4	16.6
LOI	%	6.6	6.9	8.1	7.7	8.5	8.5	9.4	9.1
Gross HR	Btu/kWh	9194	9329	9224	9220	9292	9344	9337	9357
Unit load	MW	145.3	145.7	145.7	145.8	143.9	142.9	143.1	142.9

Table 4-3 (cont.)
Example Test Data Sheet

Inputs	Units	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
Excess O_2	%	3.6	3.0	2.7	2.3	2.2	2.7	2.2	2.1
Windbox dP	i.w.c	5.0	5.0	4.4	4.4	4.1	1.3	2.3	2.3
Burner tilt	degree	6	6	10	10	11	22	22	22
Furnace exit temperature	°F	2440	2422	2483	2493	2507	2320	2436	2428
Coal flow	Klb/hr	102.76	104.56	103.38	103.41	102.86	102.71	102.80	102.86
A Damper	% open	100	100	100	100	100	100	60	40
B Damper	% open	100	100	100	100	100	100	60	40
C Damper	% open	100	100	100	100	100	100	60	40
D Damper	% open	100	100	100	100	100	100	60	40
AA Damper	% open	100	100	100	100	100	100	50	100
AB Damper	% open	20	20	20	20	20	100	50	50
BB Damper	% open	20	20	20	20	20	100	50	50
CC Damper	% open	20	20	20	20	20	100	50	50
CD Damper	% open	20	20	20	20	20	100	50	50
DD Damper	% open	100	100	100	100	100	100	50	100

Table 4-3 (cont.)
Example Test Data Sheet

Outputs	Units	Test 9	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16
Boiler efficiency	%	88.2	88.2	88.0	88.1	88.2	88.2	88.3	88.5
SHO-T	°F	973.5	964.6	988.9	990.2	988.6	960.4	940.3	944.2
RHO-T	°F	1005.9	996.7	1004.9	999.9	1001.2	970.0	940.5	946.9
APHGI temperature	°F	665	664	662	662	663	659	652	651
APHGO temperature	°F	326	325	319	319	320	320	320	320
NO_x	lb/MBtu	0.52	0.48	0.49	0.51	0.49	0.51	0.52	0.53
CO	ppm	72	74	51	119	97	39	39	40
CO_2	%	16.2	16.3	16.1	16.1	15.9	15.6	15.7	15.7
LOI	%	6.5	6.1	6.7	8.7	7.8	5.4	4.2	4.7
Gross HR	Btu/kWh	9333	9329	9325	9484	9461	9410	9457	9462
Unit load	MW	144.0	143.3	144.3	143.8	144.1	142.9	138.1	138.1

Table 4-3 (cont.)
Example Test Data Sheet

Inputs	Units	Test 9	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16
Excess O_2	%	2.6	2.5	2.8	2.6	2.8	3.1	2.8	2.7
Windbox dP	i.w.c	2.1	2.8	2.7	2.9	2.6	2.8	2.7	2.8
Burner tilt	degree	8	11	11	28	16	1	-14	-23
Furnace exit temperature	°F	2390	2370	2451	2486	2453	2364	2340	2338
Coal flow	Klb/hr	103.38	102.84	103.54	104.92	104.81	103.44	100.44	100.52
A Damper	% open	80	40	40	40	40	40	40	40
B Damper	% open	80	40	40	40	40	40	40	40
C Damper	% open	80	40	40	40	40	40	40	40
D Damper	% open	80	40	40	40	40	40	40	40
AA Damper	% open	100	100	100	100	100	100	100	100
AB Damper	% open	80	80	80	80	80	80	80	80
BB Damper	% open	60	60	60	60	60	60	60	60
CC Damper	% open	40	40	40	40	40	40	40	40
CD Damper	% open	20	20	20	20	20	20	20	20
DD Damper	% open	50	50	50	50	50	50	50	50

The dependent variables (output parameters) selected for discussion are SHO-T and RHO-T. Maintaining design temperature is essential to protecting the boiler tube from overheating. Four critical independent variables (input and in-process parameters) are used for demonstration purposes, including:

- Excess air (O_2)
- Windbox-to-furnace pressure differential (WP)
- Burner tilt angels (tilt)
- FEGT

The excess air is controlled by FD fan speed. The WP can be manipulated with the adjustment of burner secondary air registers. The burner tilt can be adjusted with manual operation. The FEGT is an in-process parameter that can be controlled by the furnace soot blowing and is also related to burner tilts, excess air level, and burner tilt angles as discussed in Section 2. As discussed previously, many operating parameters are interrelated and the analysis will be started with the pairwise correlation analysis to establish an understanding of the relationship among those parameters. The correlation analysis can be performed among input variables and also independent variables. If the input variables are strongly correlated, the selection of input variables to be used in the regression model becomes very important to avoid multicollinearity. Multicollinearity can cause confusions in the data analysis and also represent redundancy in the input variables. Reducing the number of input variables can substantially reduce the complexity of the regression equation. The Minitab pairwise correlation analysis results for SHO-T, RHO-T, FEGT, O_2, WP, and tilt are shown in Table 4-4. The correlation coefficient is a descriptive measure of the strength of linear association between two variables and it can be a number between -1 and +1. A value of +1 indicates that the two variables are perfectly related in a positive linear sense. A value of -1 indicates that the two variables are perfectly related in a negative linear sense. Values of the correlation coefficient close to zero indicate that two variables are not linearly related.

Table 4-4
Pairwise Correlation Coefficient for SHO-T, RHO-T, FEGT, O_2, WP, Tilt

Correlations: SHO-T, RHO-T, FEGT, O_2, WP, Tilt

	SHO-T	RHO-T	FEGT	O2	WP
RHO-T	0.883				
	0.000				
FEGT	0.765	0.715			
	0.001	0.002			
O2	0.168	-0.055	-0.248		
	0.534	0.839	0.354		
WP	0.459	0.387	0.553	0.336	
	0.074	0.139	0.026	0.204	
Tilt	0.483	0.645	0.481	-0.350	-0.175
	0.058	0.007	0.059	0.184	0.517

Cell Contents: Pearson correlation
P-Value

It can be observed from Table 4-4 that the highest correlation between the input variables is WP versus FEGT (0.553) with tilt versus FEGT (0.481) as second.

The following Minitab analyses are included:

- SHO-T
- RHO-T
- Gross Heat Rate (Gross HR)
- NO_x
- FEGT

Each analysis includes the following subanalyses:

- Regression analysis including all four input variables
- Stepwise regression and residual analysis
- Best subset regression and residual analysis

The selected final regression equations must satisfy the following:

- Reasonable value of adjusted coefficient of determination [R-sq (adj)]
- Pass F-test and individual t-test with a selected confidence interval
- VIF is less than four
- The residual pattern is normal

The regression equation including all input variables can provide the highest R-sq (adj.) value. It might not pass F-test or individual t-test. However, it provides a list for each individual input p-value, which should be compared with a selected confidence interval. The input variables with high p-value should be removed from further consideration. Stepwise regression analysis provides a selected final regression equation. Best subset regression analysis provides multiple sets of potential regression equations. Both stepwise and best subset regression analysis are still required to pass F-test, individual t-test, VIF, and residual pattern checking.

The regression equations involving interactive (nonlinear) terms are presented for SHO-T and RHO-T. These nonlinear regression equations provide substantial higher R-sq (adj) values. However, these regression equations are more complex.

SHO-T

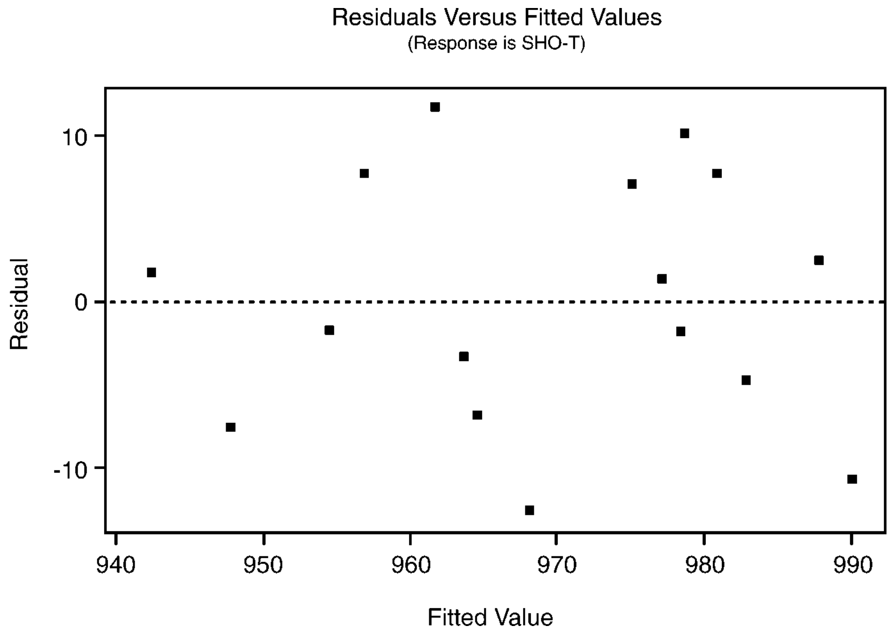
The following figure shows Minitab output for the analysis of SHO-T.

Regression Analysis: SHO-T versus O2, FEGT, WP, Tilt

```
The regression equation is

SHO-T=341+21.9 O2+0.238 FEGT-2.47 WP+0.254 Tilt

Predictor        Coef     SE Coef          T        P       VIF
Constant        340.9       174.5       1.95    0.077
O2             21.895       7.529       2.91    0.014       1.6
FEGT          0.23781     0.07209       3.30    0.007       3.8
WP             -2.473       3.656      -0.68    0.513       3.2
Tilt           0.2542      0.2449       1.04    0.322       2.1

S=8.605       R-Sq=78.9%     R-Sq(adj)=71.2%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         4     3039.33      759.83     10.26    0.001
Residual Error    11      814.52       74.05
Total             15     3853.86

Source       DF      Seq SS
O2            1      108.78
FEGT          1     2674.64
WP            1      176.19
Tilt          1       79.72
```

Stepwise Regression: SHO-T versus O2, WP, Tilt, FEGT

```
Alpha-to-Enter: 0.15  Alpha-to-Remove: 0.15

Response is  SHO-T   on  4 predictors, with N=  16


    Step          1        2        3
Constant      473.1    368.6    435.0

FEGT          0.205    0.230    0.198
T-Value        4.45     5.70     4.77
P-Value       0.001    0.000    0.000

O2                      16.1     19.1
T-Value                 2.53     3.11
P-Value                0.025    0.009

Tilt                             0.35
T-Value                          1.77
P-Value                         0.102

S              10.7     9.07     8.41
R-Sq          58.56    72.22    77.99
R-Sq(adj)     55.60    67.95    72.48
C-p             9.6      4.5      3.5

The regression equation is

SHO-T=435+0.198 FEGT+19.1 O2+0.349 Tilt

Predictor        Coef     SE Coef          T         P        VIF
Constant        435.0       102.9       4.23     0.001
FEGT          0.19847     0.04160       4.77     0.000        1.3
O2             19.095       6.144       3.11     0.009        1.2
Tilt           0.3486      0.1967       1.77     0.102        1.4

S=8.408       R-Sq=78.0%     R-Sq(adj)=72.5%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         3      3005.5      1001.8     14.17    0.000
Residual Error    12       848.4        70.7
Total             15      3853.9

Source       DF      Seq SS
FEGT          1      2256.7
O2            1       526.8
Tilt          1       222.0
```



Best Subsets Regression: SHO-T versus FEGT, O2, WP, Tilt

Vars	R-Sq	R-Sq(adj)	C-p	S	FEGT	O2	WP	Tilt
1	58.6	55.6	9.6	10.681	X			
1	23.3	17.8	27.9	14.530				X
2	72.2	68.0	4.5	9.0742	X	X		
2	60.3	54.2	10.7	10.853	X			X
3	78.0	72.5	3.5	8.4083	X	X		X
3	76.8	71.0	4.1	8.6325	X	X	X	
4	78.9	71.2	5.0	8.6051	X	X	X	X

Regression Analysis: SHO-T versus FEGT, O2

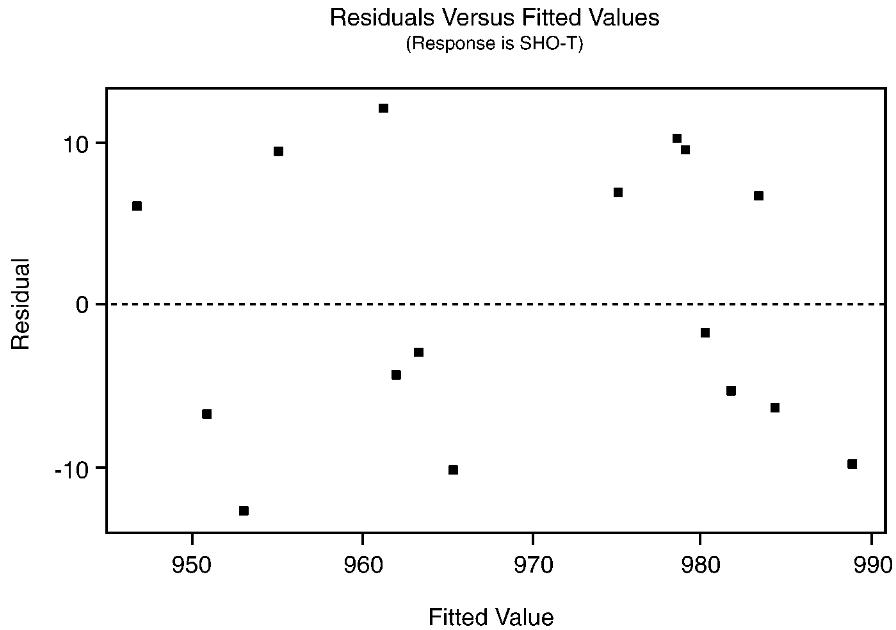
```
The regression equation is

SHO-T=369+0.230 FEGT+16.1 O2
```

Predictor	Coef	SE Coef	T	P	VIF
Constant	368.6	103.5	3.56	0.003	
FEGT	0.23049	0.04044	5.70	0.000	1.1
O2	16.143	6.382	2.53	0.025	1.1

```
S=9.074       R-Sq=72.2%     R-Sq(adj)=68.0%

Analysis of Variance
```

Source	DF	SS	MS	F	P
Regression	2	2783.4	1391.7	16.90	0.000
Residual Error	13	1070.4	82.3		
Total	15	3853.9			

Source	DF	Seq SS
FEGT	1	2256.7
O2	1	526.8

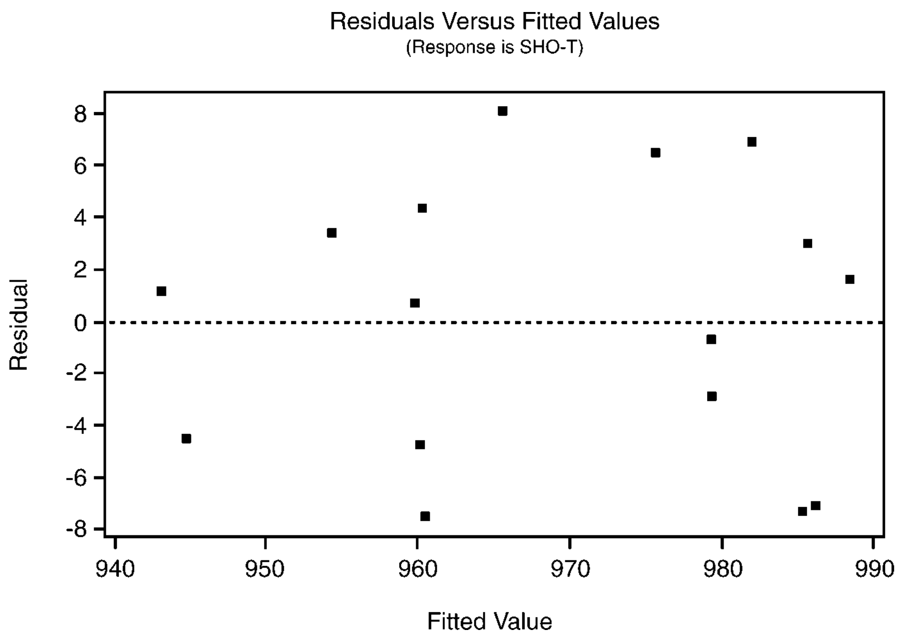


Stepwise Regression Analysis of SHO-T Involving Interactive Items

```
  Alpha-to-Enter: 0.15  Alpha-to-Remove: 0.15

 Response is  SHO-T   on 10 predictors, with N=  16

    Step         1        2        3        4        5
Constant     473.1    410.8    495.0    527.4    516.8

FEGT         0.205    0.213    0.175    0.190    0.187
T-Value       4.45     5.44     4.38     6.44     6.52
P-Value      0.001    0.000    0.001    0.000    0.000

O2FEGT              0.0067   0.0073  -0.0026
T-Value               2.55     3.10    -0.76
P-Value              0.024    0.009    0.465

O2Tilt                        0.144    2.422    1.989
T-Value                        2.02     3.61     5.76
P-Value                       0.066    0.004    0.000

Tilt                                   -6.07    -4.91
T-Value                                -3.40    -5.49
P-Value                                0.006    0.000
S             10.7     9.04     8.13     5.93     5.82
R-Sq         58.56    72.41    79.40    89.96    89.44
R-Sq(adj)    55.60    68.16    74.25    86.31    86.79
```

Regression Analysis: SHO-T versus FEGT, Tilt, O2Tilt

```
The regression equation is

SHO-T=517+0.187 FEGT-4.91 Tilt+1.99 O2Tilt

Predictor        Coef     SE Coef          T        P
Constant       516.77       68.86       7.51    0.000
FEGT          0.18687     0.02868       6.52    0.000
Tilt          -4.9112      0.8946      -5.49    0.000
O2Tilt         1.9892      0.3456       5.76    0.000

S=5.825       R-Sq=89.4%     R-Sq(adj)=86.8%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         3      3446.7      1148.9     33.86    0.000
Residual Error    12       407.1        33.9
Total             15      3853.9

Source       DF      Seq SS
FEGT          1      2256.7
Tilt          1        65.9
O2Tilt        1      1124.1
```



Best Subsets Regression Analysis of SHO-T Involving Interactive Items

Vars	R-Sq	R-Sq(adj)	C-p	S	FEGT	O2	WP	Tilt	O2WP	O2Tilt
1	58.6	55.6	26.7	10.681	X					
1	30.0	25.0	53.4	13.880						X
2	72.2	68.0	15.9	9.0742	X	X				
2	62.9	57.2	24.7	10.486	X					X
3	89.4	86.8	1.9	5.8247	X			X		X
3	79.3	74.1	11.3	8.1511	X	X				X
4	90.2	86.6	3.2	5.8696	X			X	X	X
4	90.1	86.4	3.3	5.9034	X		X	X		X
5	90.3	85.4	5.1	6.1248	X	X	X	X		X
5	90.2	85.3	5.1	6.1428	X	X		X	X	X
6	90.4	83.9	7.0	6.4232	X	X	X	X	X	X

Figure 4-1
Minitab Output for Analysis of SHO-T

The best regression equation that includes three input variables is the same as stepwise regression analysis.

RHO-T

The following figure shows Minitab output for the analysis of RHO-T.

Regression Analysis: RHO-T versus FEGT, O2, WP, Tilt

```
The regression equation is

RHO-T=671+0.113 FEGT+7.8 O2+4.99 WP+0.930 Tilt
```

Predictor	Coef	SE Coef	T	P	VIF
Constant	670.5	269.0	2.49	0.030	
FEGT	0.1131	0.1112	1.02	0.331	3.8
O2	7.80	11.61	0.67	0.516	1.6
WP	4.986	5.638	0.88	0.395	3.2
Tilt	0.9305	0.3777	2.46	0.031	2.1

S=13.27 R-Sq=70.2% R-Sq(adj)=59.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	4	4572.6	1143.2	6.49	0.006
Residual Error	11	1936.9	176.1		
Total	15	6509.6			

Source	DF	Seq SS
FEGT	1	3329.7
O2	1	104.1
WP	1	70.3
Tilt	1	1068.6

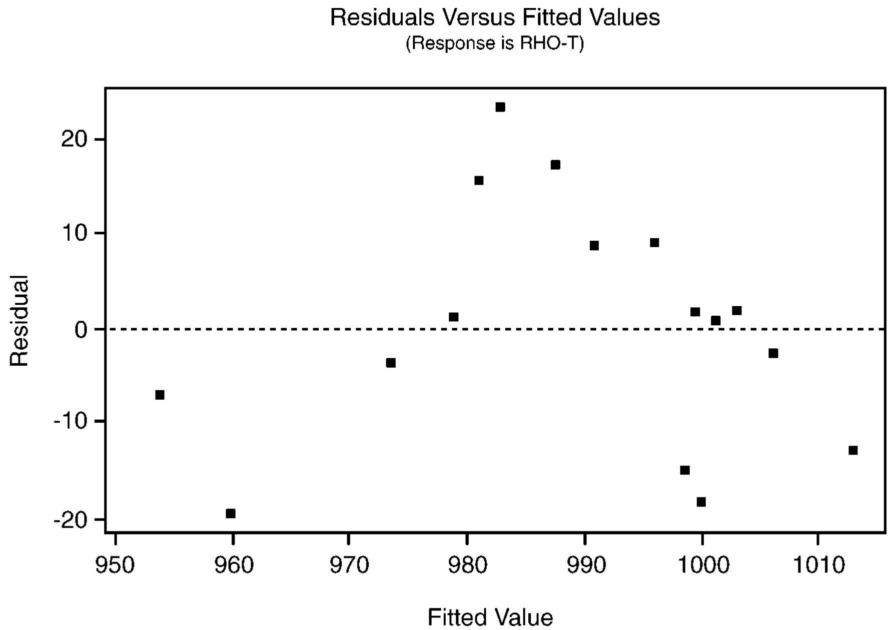
```
Unusual Observations
Obs       FEGT      RHO-T         Fit      SE Fit    Residual    St Resid
  9       2390    1005.90      978.93        4.90       26.97        2.19R

R denotes an observation with a large standardized residual
```

Stepwise Regression: RHO-T versus O2, WP, Tilt, FEGT

```
Alpha-to-Enter: 0.15  Alpha-to-Remove: 0.15

Response is  RHO-T   on  4 predictors, with N=  16


    Step          1        2
Constant      386.3    539.3

FEGT          0.249    0.184
T-Value        3.83     2.74
P-Value       0.002    0.017

Tilt                    0.62
T-Value                 2.03
P-Value                0.063

S              15.1     13.6
R-Sq          51.15    62.93
R-Sq(adj)     47.66    57.23
C-p             6.1      3.7
```

Regression Analysis: RHO-T versus FEGT, Tilt

```
The regression equation is

RHO-T=539+0.184 FEGT+0.623 Tilt

Predictor        Coef     SE Coef          T        P       VIF
Constant        539.3       161.1       3.35    0.005
FEGT          0.18352     0.06709       2.74    0.017       1.3
Tilt           0.6234      0.3068       2.03    0.063       1.3

S=13.62       R-Sq=62.9%     R-Sq(adj)=57.2%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         2      4096.4      2048.2     11.03    0.002
Residual Error    13      2413.1       185.6
Total             15      6509.6

Source       DF      Seq SS
FEGT          1      3329.7
Tilt          1       766.7
```



Best Subsets Regression: RHO-T versus FEGT, O2, WP, Tilt

Vars	R-Sq	R-Sq(adj)	C-p	S	FEGT	O2	WP	Tilt
1	51.2	47.7	6.1	15.071	X			
1	41.6	37.4	9.6	16.480				X
2	67.3	62.3	2.1	12.788			X	X
2	62.9	57.2	3.7	13.624	X			X
3	69.0	61.3	3.5	12.962	X		X	X
3	68.1	60.2	3.8	13.149	X	X		X
4	70.2	59.4	5.0	13.270	X	X	X	X

Regression Analysis: RHO-T versus Tilt, WP

The regression equation is

RHO-T=948+1.17 Tilt+9.81 WP

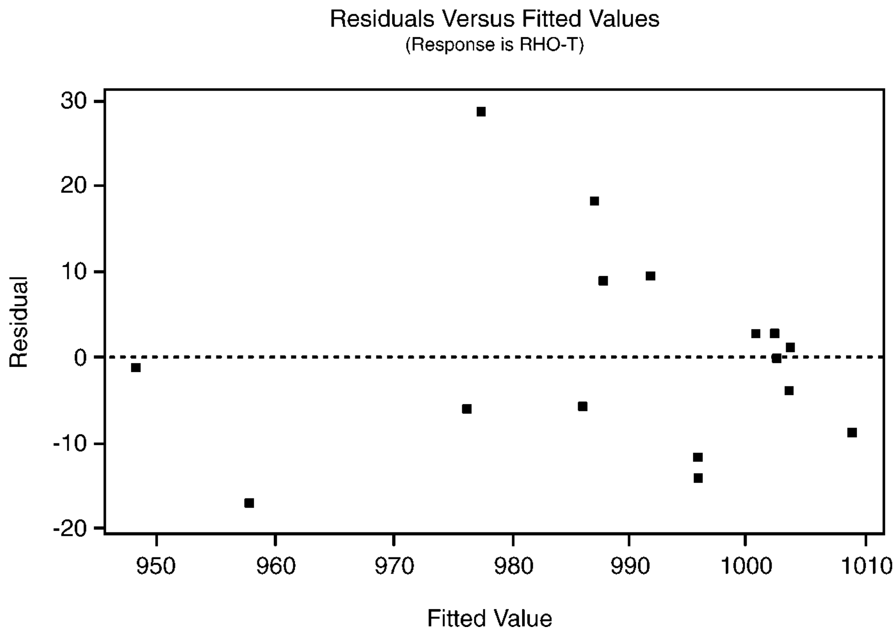
Predictor	Coef	SE Coef	T	P	VIF
Constant	947.61	10.77	87.96	0.000	
Tilt	1.1708	0.2564	4.57	0.001	1.0
WP	9.808	3.063	3.20	0.007	1.0

S=12.79 R-Sq=67.3% R-Sq(adj)=62.3%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	4383.7	2191.9	13.40	0.001
Residual Error	13	2125.9	163.5		
Total	15	6509.6			

```
Source       DF      Seq SS
Tilt          1      2707.4
WP            1      1676.3

Unusual Observations
Obs       Tilt      RHO-T         Fit      SE Fit    Residual    St Resid
  9        8.0    1005.90      977.58        4.56       28.32       2.37R

R denotes an observation with a large standardized residual
```



Stepwise Regression Analysis of RHO-T Involving Interactive Items

```
  Alpha-to-Enter: 0.15  Alpha-to-Remove: 0.15

 Response is  RHO-T   on 10 predictors, with N=  16

    Step          1        2        3        4
Constant      976.7    976.9    978.6   1057.6

WPTilt        0.469    0.959    0.917    0.984
T-Value        4.80     3.60     3.96     4.90
P-Value       0.000    0.003    0.002    0.000

FEGTTilt           -0.00058 -0.00196 -0.00400
T-Value               -1.95    -3.02    -3.82
P-Value               0.073    0.011    0.003

O2Tilt                          1.33     3.07
T-Value                         2.31     3.40
P-Value                        0.039    0.006

O2                                        -28
T-Value                                 -2.30
P-Value                                 0.042
```

S	13.2	12.1	10.5	8.98
R-Sq	62.24	70.81	79.81	86.37
R-Sq(adj)	59.55	66.32	74.76	81.42

Regression Analysis: RHO-T versus O2, WPTilt, FEGTTilt, O2Tilt

The regression equation is

RHO-T=1058-27.8 O2+0.984 WPTilt-0.00400 FEGTTilt+3.07 O2Tilt

Predictor	Coef	SE Coef	T	P
Constant	1057.58	34.41	30.73	0.000
O2	-27.84	12.09	-2.30	0.042
WPTilt	0.9836	0.2005	4.90	0.000
FEGTTilt	-0.004002	0.001048	-3.82	0.003
O2Tilt	3.0673	0.9017	3.40	0.006

S=8.980 R-Sq=86.4% R-Sq(adj)=81.4%

Analysis of Variance

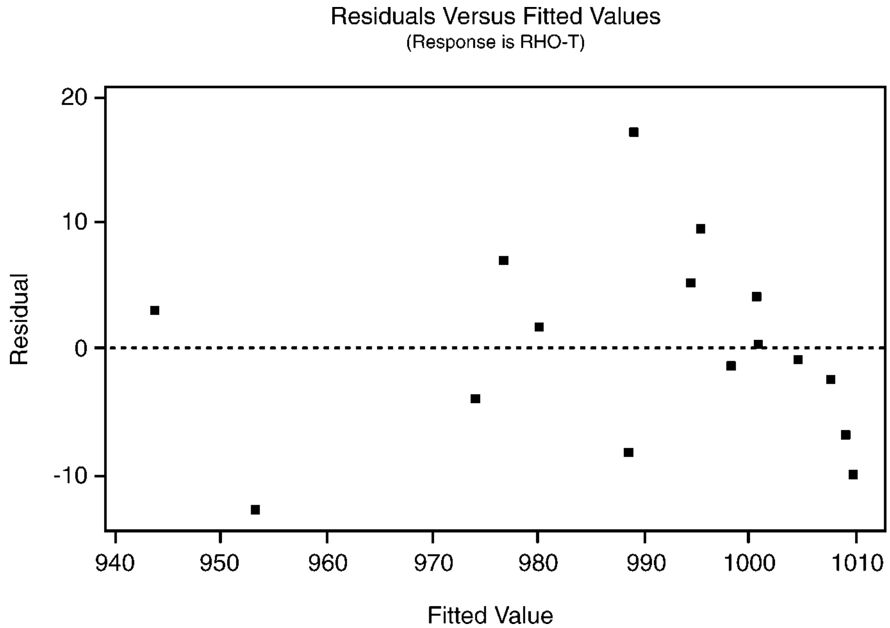
Source	DF	SS	MS	F	P
Regression	4	5622.5	1405.6	17.43	0.000
Residual Error	11	887.0	80.6		
Total	15	6509.6			

Source	DF	Seq SS
O2	1	19.8
WPTilt	1	4248.6
FEGTTilt	1	420.9
O2Tilt	1	933.2

Unusual Observations

Obs	O2	RHO-T	Fit	SE Fit	Residual	St Resid
9	2.60	1005.90	989.00	3.39	16.90	2.03R

R denotes an observation with a large standardized residual



Best Subsets Regression Analysis of RHO-T Involving Interactive Items

Vars	R-Sq	R-Sq(adj)	C-p	S	O2	WP	Tilt	O2WP	O2Tilt	O2FEGT	FEGTWP	FEGTTilt	WPTilt
1	62.2	59.5	36.4	13.250									X
1	47.2	43.4	55.7	15.668					X				
2	71.3	66.9	26.8	11.984					X		X		
2	70.9	66.4	27.3	12.074		X			X				
3	79.8	74.8	17.9	10.466					X			X	X
3	78.0	72.5	20.3	10.930			X		X				X
4	86.4	81.4	11.5	8.9800	X				X			X	X
4	85.6	80.3	12.5	9.2383					X	X		X	X
5	88.5	82.7	10.8	8.6634	X		X		X	X		X	
5	87.4	81.1	12.2	9.0635	X				X	X		X	X
6	91.5	85.8	8.9	7.8425	X	X		X	X			X	X
6	90.3	83.9	10.4	8.3664	X			X	X		X	X	X
7	93.9	88.6	7.8	7.0311	X	X	X		X	X	X	X	
7	92.9	86.7	9.1	7.5880	X			X	X	X	X	X	X
8	94.7	88.7	8.8	7.0169	X		X	X	X	X	X	X	X
8	94.5	88.3	9.0	7.1275	X	X	X		X	X	X	X	X
9	95.3	88.3	10.0	7.1234	X	X	X	X	X	X	X	X	X

Regression Analysis: RHO-T versus O2, WP, O2WP, O2Tilt, FEGTTilt, WPTilt

The regression equation is

RHO-T=1307-111 O2-55.2 WP+17.4 O2WP+4.59 O2Tilt-0.00657 FEGTTilt+1.70 WPTilt

Predictor	Coef	SE Coef	T	P
Constant	1307.5	111.5	11.73	0.000
O2	-110.63	37.37	-2.96	0.016
WP	-55.17	24.13	-2.29	0.048
O2WP	17.432	7.489	2.33	0.045
O2Tilt	4.587	1.026	4.47	0.002
FEGTTilt	-0.006566	0.001480	-4.44	0.002
WPTilt	1.7019	0.5567	3.06	0.014

S=7.842   R-Sq=91.5%   R-Sq(adj)=85.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	6	5956.02	992.67	16.14	0.000
Residual Error	9	553.54	61.50		
Total	15	6509.56			

Source	DF	Seq SS
O2	1	19.84
WP	1	1204.60
O2WP	1	35.41
O2Tilt	1	3484.42
FEGTTilt	1	637.01
WPTilt	1	574.74

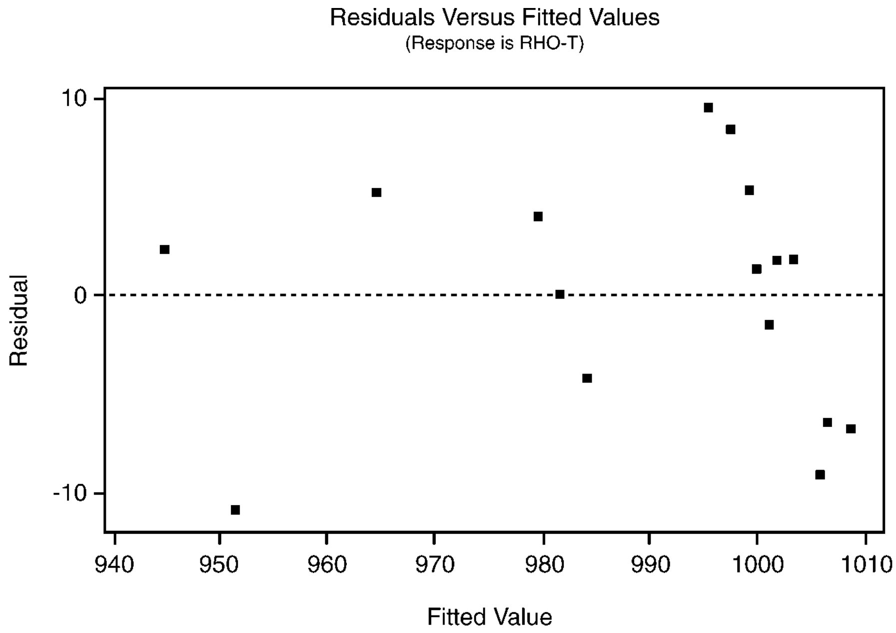


Figure 4-2
Minitab Output for Analysis of RHO-T

Gross HR

The following figure shows Minitab output analysis for gross HR.

Regression Analysis: Gross HR versus FEGT, O2, WP, Tilt

```
The regression equation is

Gross HR=8159+0.553 FEGT+43.7 O2-75.8 WP-3.16 Tilt

Predictor         Coef     SE Coef          T        P       VIF
Constant          8159        1556       5.24    0.000
FEGT            0.5530      0.6428       0.86    0.408       3.8
O2               43.67       67.13       0.65    0.529       1.6
WP              -75.84       32.60      -2.33    0.040       3.2
Tilt            -3.158       2.184      -1.45    0.176       2.1

S=76.73       R-Sq=46.2%     R-Sq(adj)=26.6%

Analysis of Variance

Source           DF          SS          MS          F        P
Regression        4       55520       13880       2.36    0.118
Residual Error   11       64766        5888
Total            15      120286

Source       DF      Seq SS
FEGT          1       20292
O2            1        3234
WP            1       19685
Tilt          1       12308
```

Unusual Observations

Obs	FEGT	Gross HR	Fit	SE Fit	Residual	St Resid
12	2486	9484.0	9339.4	39.8	144.6	2.20R

R denotes an observation with a large standardized residual

Stepwise Regression: Gross HR versus O2, WP, Tilt, FEGT

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15

Response is Gross HR on 4 predictors, with N= 16

Step	1
Constant	9496
WP	-47
T-Value	-2.67
P-Value	0.018
S	75.5
R-Sq	33.67
R-Sq(adj)	28.94
C-p	1.6

Regression Analysis: Gross HR versus WP

The regression equation is

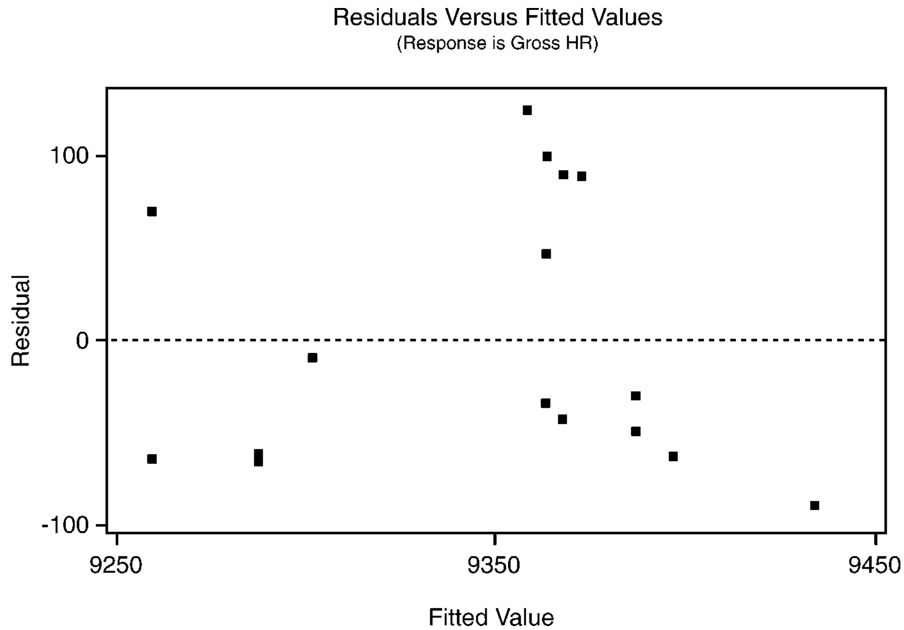
Gross HR=9496-47.5 WP

Predictor	Coef	SE Coef	T	P
Constant	9496.30	58.96	161.06	0.000
WP	-47.47	17.80	-2.67	0.018

S=75.49   R-Sq=33.7%   R-Sq(adj)=28.9%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	40504	40504	7.11	0.018
Residual Error	14	79782	5699		
Total	15	120286			



Best Subsets Regression: Gross HR versus FEGT, O2, WP, Tilt

Vars	R-Sq	R-Sq(adj)	C-p	S	FEGT	O2	WP	Tilt
1	33.7	28.9	1.6	75.490			X	
1	16.9	10.9	5.0	84.513	X			
2	42.2	33.3	1.8	73.130			X	X
2	35.8	25.9	3.1	77.062		X	X	
3	44.1	30.1	3.4	74.865	X		X	X
3	42.5	28.2	3.7	75.896		X	X	X
4	46.2	26.6	5.0	76.732	X	X	X	X

Regression Analysis: Gross HR versus WP, Tilt

The regression equation is

Gross HR=9528-51.7 WP-2.03 Tilt

Predictor	Coef	SE Coef	T	P	VIF
Constant	9528.28	61.61	154.65	0.000	
WP	-51.71	17.52	-2.95	0.011	1.0
Tilt	-2.031	1.466	-1.38	0.189	1.0

S=73.13 R-Sq=42.2% R-Sq(adj)=33.3%

```
Analysis of Variance

Source           DF         SS         MS        F        P
Regression        2      50761      25381     4.75    0.028
Residual Error   13      69524       5348
Total            15     120286

Source       DF      Seq SS
WP            1       40504
Tilt          1       10257

Unusual Observations
Obs         WP   Gross HR         Fit      SE Fit    Residual    St Resid
 12       2.90     9484.0      9321.5        32.7       162.5       2.49R

R denotes an observation with a large standardized residual
```

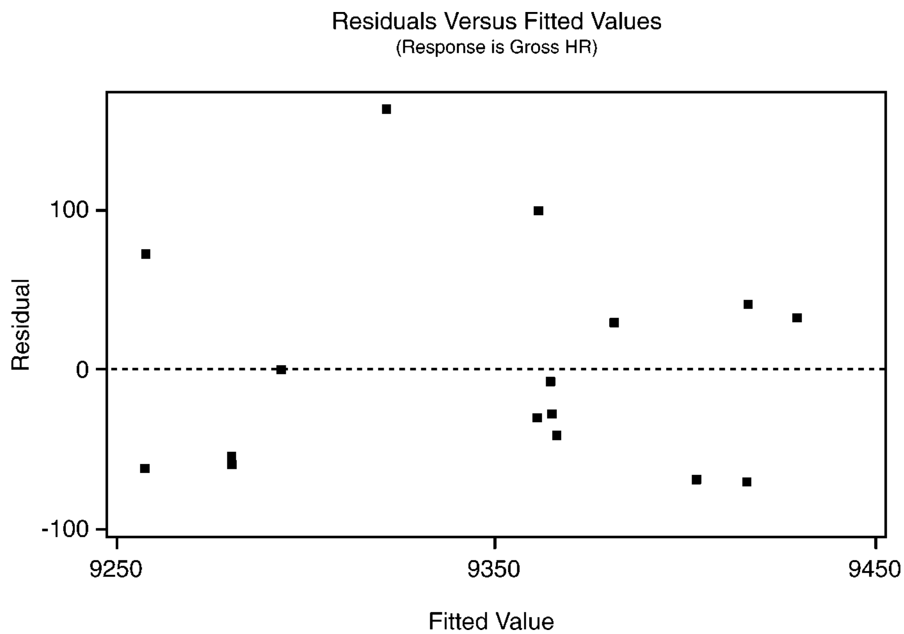


Figure 4-3
Minitab Output Analysis for Gross HR

NO_x

The following figure shows Minitab output analysis for NO_x.

Regression Analysis: NO_x versus FEGT, O2, WP, Tilt

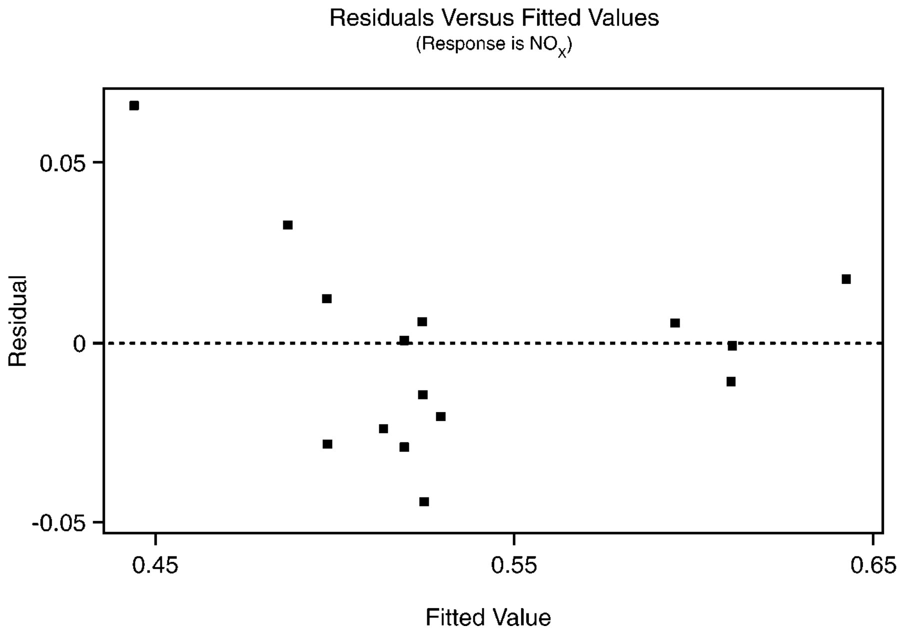
```
The regression equation is

NOx=1.06 -0.000310 FEGT+0.0101 O2+0.0635 WP +0.000808 Tilt

Predictor        Coef     SE Coef          T        P       VIF
Constant       1.0606      0.6009       1.77    0.105
FEGT       -0.0003103   0.0002483      -1.25    0.237       3.8
O2            0.01006     0.02593       0.39    0.705       1.6
WP            0.06352     0.01259       5.04    0.000       3.2
Tilt        0.0008078   0.0008436       0.96    0.359       2.1

S=0.02964     R-Sq=84.9%     R-Sq(adj)=79.4%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         4    0.054283    0.013571     15.45    0.000
Residual Error    11    0.009661    0.000878
Total             15    0.063944

Source       DF      Seq SS
FEGT          1    0.008636
O2            1    0.018514
WP            1    0.026328
Tilt          1    0.000805

Unusual Observations
Obs      FEGT        NOx         Fit      SE Fit    Residual    St Resid
  6      2320    0.51000     0.46813     0.02170     0.04187       2.07R
 10      2370    0.48000     0.53699     0.01471    -0.05699      -2.22R

R denotes an observation with a large standardized residual
```

Stepwise Regression: NO_x versus O2, WP, Tilt, FEGT

```
Alpha-to-Enter: 0.15  Alpha-to-Remove: 0.15

 Response is NOx on 4 predictors, with N=16


    Step          1
Constant     0.3749

WP           0.0536
T-Value        7.69
P-Value       0.000

S            0.0296
R-Sq          80.86
R-Sq(adj)     79.49
C-p             1.9
```

Regression Analysis: NO_x versus WP

```
The regression equation is

NOx=0.375+0.0536 WP

Predictor        Coef     SE Coef         T       P
Constant      0.37486     0.02309     16.23   0.000
WP           0.053630    0.006973      7.69   0.000

S=0.02957     R-Sq=80.9%     R-Sq(adj)=79.5%

Analysis of Variance

Source           DF          SS          MS        F       P
Regression        1    0.051706    0.051706    59.15   0.000
Residual Error   14    0.012238    0.000874
Total            15    0.063944

Unusual Observations
Obs        WP       NOx        Fit      SE Fit    Residual    St Resid
  6      1.30   0.51000    0.44458     0.01479     0.06542       2.56R

R denotes an observation with a large standardized residual
```



Best Subsets Regression: NO_x versus FEGT, O2, WP, Tilt

Vars	R-Sq	R-Sq(adj)	C-p	S	FEGT	O2	WP	Tilt
1	80.9	79.5	1.9	0.029566			X	
1	18.5	12.7	47.4	0.061019		X		
2	83.3	80.7	2.2	0.028687	X		X	
2	82.7	80.1	2.6	0.029162		X	X	
3	84.7	80.9	3.2	0.028567	X		X	X
3	83.6	79.5	3.9	0.029533	X	X	X	
4	84.9	79.4	5.0	0.029635	X	X	X	X

Regression Analysis: NO_x versus FEGT, WP

The regression equation is

NO_x=0.847 -0.000203 FEGT+0.0598 WP

Predictor	Coef	SE Coef	T	P	VIF
Constant	0.8475	0.3462	2.45	0.029	
FEGT	-0.0002032	0.0001486	-1.37	0.195	1.4
WP	0.059764	0.008117	7.36	0.000	1.4

S=0.02869   R-Sq=83.3%   R-Sq(adj)=80.7%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	0.053245	0.026623	32.35	0.000
Residual Error	13	0.010698	0.000823		
Total	15	0.063944			

Source	DF	Seq SS
FEGT	1	0.008636
WP	1	0.044609

Unusual Observations

Obs	FEGT	NO_x	Fit	SE Fit	Residual	St Resid
6	2320	0.51000	0.45364	0.01581	0.05636	2.35R

R denotes an observation with a large standardized residual

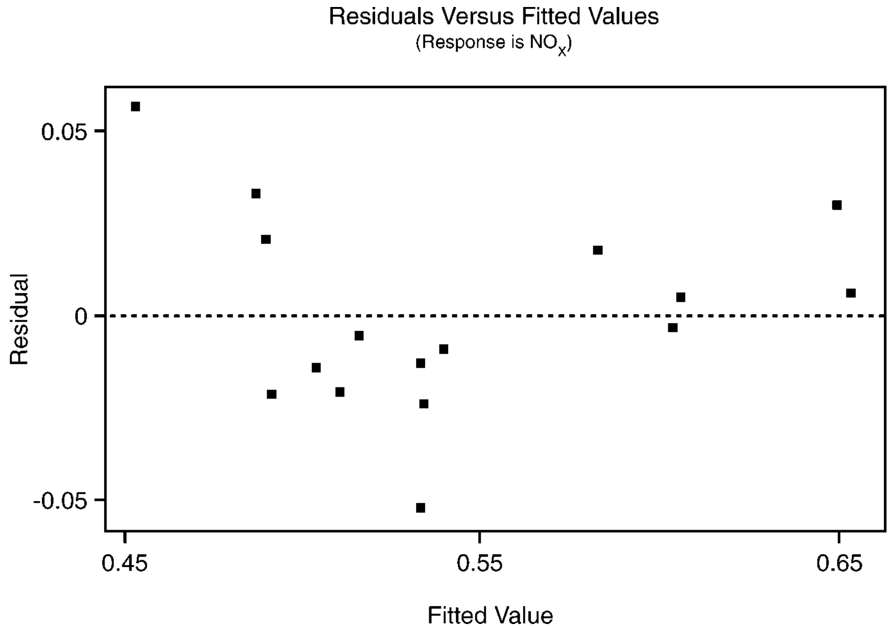


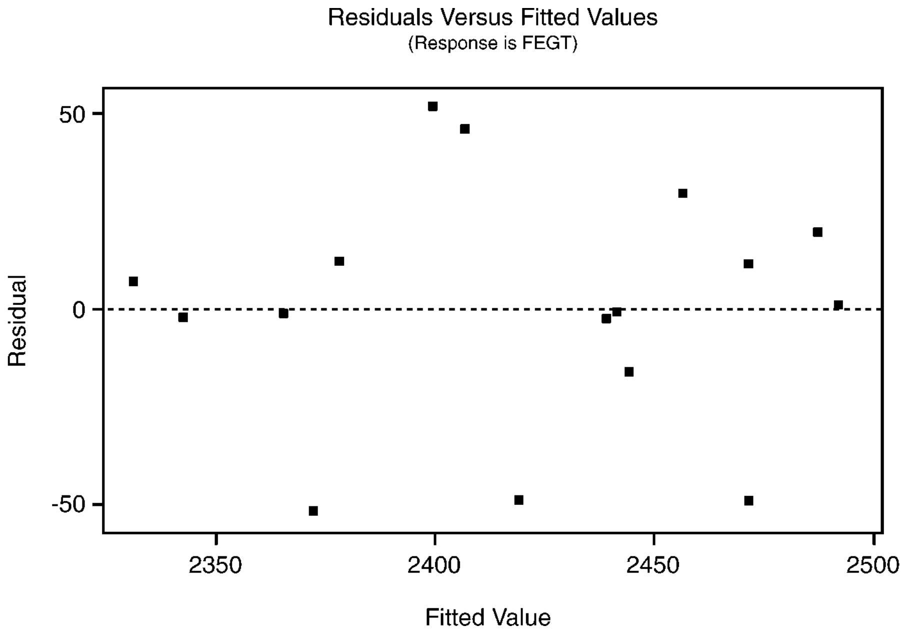
Figure 4-4
Minitab Output Analysis for NO_x

FEGT

The following figure shows Minitab output analysis for FEGT.

Regression Analysis: FEGT versus O2, WP, Tilt

```
The regression equation is

FEGT=2408-51.4 O2+40.9 WP+2.28 Tilt

Predictor        Coef     SE Coef          T        P       VIF
Constant      2407.85       70.34      34.23    0.000
O2             -51.38       26.25      -1.96    0.074       1.2
WP             40.922       8.646       4.73    0.000       1.1
Tilt           2.2786      0.7276       3.13    0.009       1.1

S=34.46       R-Sq=73.4%     R-Sq(adj)=66.8%

Analysis of Variance

Source            DF          SS          MS        F        P
Regression         3       39409       13136    11.06    0.001
Residual Error    12       14248        1187
Total             15       53657

Source       DF      Seq SS
O2            1        3312
WP            1       24452
Tilt          1       11645
```



Stepwise Regression: FEGT versus O2, WP, Tilt

```
Alpha-to-Enter: 0.15  Alpha-to-Remove: 0.15

 Response is   FEGT   on  3 predictors, with N=  16


    Step          1        2        3
Constant       2325     2282     2408

WP             30.2     35.9     40.9
T-Value        2.48     3.94     4.73
P-Value       0.026    0.002    0.000

Tilt                    2.73     2.28
T-Value                 3.57     3.13
P-Value                0.003    0.009

O2                                -51
T-Value                         -1.96
P-Value                         0.074

S              51.6     38.0     34.5
R-Sq          30.53    64.97    73.45
R-Sq(adj)     25.57    59.58    66.81
C-p            19.4      5.8      4.0
```

All three input variables are selected and the regression equation is the same as the previous one.

Best Subsets Regression: FEGT versus O2, WP, Tilt

Vars	R-Sq	R-Sq(adj)	C-p	S	O2	WP	Tilt
1	30.5	25.6	19.4	51.600		X	
1	23.1	17.6	22.7	54.275			X
2	65.0	59.6	5.8	38.026		X	X
2	51.7	44.3	11.8	44.629	X	X	
3	73.4	66.8	4.0	34.458	X	X	X

Regression Analysis: FEGT versus WP, Tilt

The regression equation is

FEGT=2282+35.9 WP+2.73 Tilt

Predictor	Coef	SE Coef	T	P	VIF
Constant	2282.42	32.04	71.24	0.000	
WP	35.888	9.109	3.94	0.002	1.0
Tilt	2.7254	0.7624	3.57	0.003	1.0

S=38.03 R-Sq=65.0% R-Sq(adj)=59.6%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	34859	17430	12.05	0.001
Residual Error	13	18797	1446		
Total	15	53657			

Source	DF	Seq SS
WP	1	16381
Tilt	1	18479

Unusual Observations

Obs	WP	FEGT	Fit	SE Fit	Residual	St Resid
6	1.30	2320.00	2389.04	20.22	-69.04	-2.14R

R denotes an observation with a large standardized residual

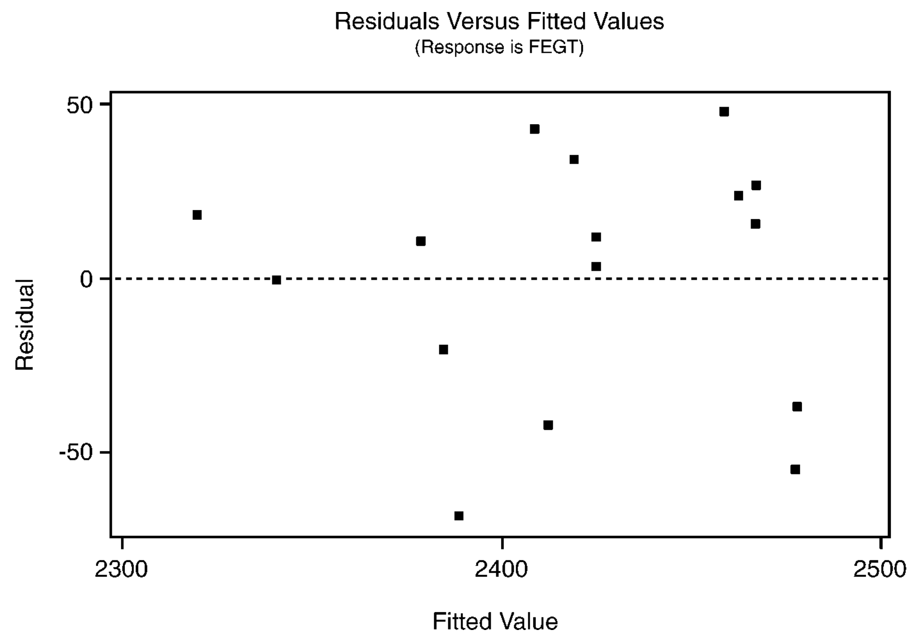


Figure 4-5
Minitab Output Analysis for FEGT

Summary

In this example, the following linear regression equation can be used to predict the designate output variables:

1. SHO-T

   SHO-T = 369 + 0.230 FEGT + 16.1 O_2
   Confidence Interval: 95%, R-sq(adj) = 68.0%

   SHO-T = 517 + 0.187 FEGT - 4.91 Tilt + 1.99 O_2Tilt
   Confidence Interval: 95%, R-sq(adj) = 86.8%

2. RHO-T

   RHO-T = 948 + 1.17 Tilt + 9.81 WP
   Confidence Interval: 95%, R-sq(adj) = 62.3%

   RHO-T = 1307-111 O_2 - 55.2 WP + 17.4 O_2WP + 4.59 O_2Tilt - 0.00657 FEGT Tilt
   + 1.70 WPTilt
   Confidence Interval: 95%, R-sq(adj) = 85.8%

3. Gross HR

   Gross HR = 9528 - 51.7 WP - 2.03 Tilt
   Confidence Interval: 80%, R-sq(adj) = 33.3% 80%

4. NO_x

   NO_x = 0.375 + 0.0536 WP
   Confidence Interval: 95%, R-sq(adj) = 79.5%

5. FEGT

   FEGT = 2408 - 51.4 O_2 + 40.9 WP + 2.28 Tilt
   Confidence Interval: 90%, R-sq(adj) = 66.8%

References

Minitab Statistical Software, Release 13, February 2000.

5
SUMMARY AND RECOMMENDATIONS

Summary

One of the most complex, critical, and vulnerable systems in fossil power generation plants is the boiler. Boiler pressure component failures have historically contributed to the highest percentage of lost availability. The major BTF influencing factors involve design inadequacies, operation changes, and maintenance practices. Boiler reliability was often referred to as an off-line inspection and maintenance issue and solutions to the BTFs were often dealt with by material upgrades or periodic component replacements. Operation is one the areas that has been given little attention in the past. Once the boiler is built, the major focus should be on the operation—especially within the changing environments.

If the system and equipment can be operated within the design limits, then theoretically, failures and degradation should not occur or can be minimized. If failures and degradation do not occur or can be minimized, the result is the reduction of maintenance and improvement in availability. To ensure that these objectives are achieved, the operation focus should be on input and in-process control. Ideally, the input and in-process variables should be controlled to avoid output variations, which cause component damage. To be successful in achieving the intended purpose, it is essential to monitor the critical operating parameters. A process is established to determine these critical operating factors for given objectives. The regression analysis technique is demonstrated to establish the relationship between the plant objectives and the critical operating parameters. A methodology is also proposed to link each boiler tube mechanism from boiler pressure components to the operating factors. Once an understanding and the quantitative relationship between the boiler failure mechanism and the critical operating factors are established, effective measures can be implemented to reduce BTFs or conscious decisions can be made with the understanding of risk involved.

Recommendations

Simple examples are provided in this report to exhibit the application of statistical regression analysis method to BTF prevention through process and operation control. Full-scale pilot projects are required to demonstrate the full benefits of this approach. It is anticipated that the proposed full-scale projects will also provide much general knowledge, which can effectively contribute to boiler availability improvement and overall cost reduction.

Today's utility companies face the challenges of achieving multiple plant objectives (for example, capacity, heat rate, emissions, safety, reliability, and production cost). All these objectives are equally important. Unfortunately, some of these objectives conflict with each other. Multiple objectives are influenced by many common operating parameters. The statistical method proposed in this report is equally applicable to all these plant objectives for the establishment of critical operating parameters. Once the overall critical operating parameters are selected, the optimization process can be applied with proper constraints to achieve the proper tradeoffs among these plant objectives. The proposed future pilot projects should encompass these overall considerations.

A
HEAT RATE INFLUENCE PREDICTION

Introduction

Heat rate (Btu/kWh) is the amount of heat input into a system divided by the amount of power generated. The direct approach to improve boiler efficiency is to identify the losses and their relative magnitude, and then concentrate first on the dominant losses that are controlling degraded efficiency. Unit heat rate losses include:

- Boiler losses
- Condensate/feedwater system losses
- Circulating water system losses
- Turbine losses
- Steam conditions

Heat-rate improvement is essential in a deregulated competitive environment. Rising fuel costs and increased environment regulations have directed electric utilities to improve the thermal performance of the fossil-generating stations. Units within a utility system and within a power pool are dissipated based upon the unit heat rate and resulting cost. EPRI has promoted the heat rate improvement for the last decades and published many guidelines for utilities companies to use. The heat rate improvement program involves performance monitoring and is dynamic and complex. To improve efficiency, the following information is required:

- Knowing the heat input, mass of fuel, the fuel analysis, and the generation capacity (MW) rating to determine actual heat rate.
- Determining the heat rate gap by comparing the actual heat rate with the original design, acceptance tested, and expected heat rate.
- Developing critical operating parameters, which characterize the unit heat rate performance. Establish the baseline and track the unit performance.
- Monitoring the critical operating parameters and identifying the reason for the heat degradation or deviation.
- Taking necessary actions (that is, operational and maintenance actions) to correct the deviations.
- Improving unit operation.

Designed, As-Built, and Best Achievable Heat Rate

The unit design heat rate can be obtained from the plant data book or original equipment manufacturers. Margins are added to the design heat rate or equipment efficiencies covering uncertainties and uncontrollable operating factors. The designed heat rate is not usually equal to the as-built (expected) heat rate. The problem is that the design is usually not representative of the unit's capability or actual operation. Normally, the best achievable heat rate refers to the net heat rate obtained from unit acceptance test when the equipment was new and the unit was operated at optimum. The recent boiler optimization effort in the industry provides additional improvement to the best achievable heat rate. It is important that designed and best achievable net heat rates be adjusted for any equipment modifications. Gaps exist between actual, designed, as-built, and unit's best achievable performance. Differences between designed and as-built conditions include:

- Superheat and reheat spray flow
- Excess air requirement
- Air preheater and feedwater heater efficiency
- Fireside condition, slagging, and fouling
- Air in-leakage of the casings
- Pressure drop and draft losses
- FEGT
- BET
- Sootblowing requirements
- Coal quality

Uncontrollable conditions include air inlet temperature, cooling water temperature, and fuel quality. The design heat rate and best achievable heat rate have to be adjusted for these conditions.

Boiler Heat Rate Losses

EPRI report CS-4554 titled *Heat Rate Improvement Guidelines for Existing Fossil Plants*, provides a logic-tree approach to identifying the root causes of declining boiler unit performance. The next level of the logic tree identifies major areas in the plant cycle that have the potential for contributing to the overall problem. This appendix will focus on the boiler portion of the heat rate. Boiler heat rate losses involve:

- Dry gas losses
- Moisture losses

- Incomplete combustion of the fuel
- Boiler surface radiation losses

Dry Gas Losses

One of the major energy losses associated with the boiler operation is the heat contained in the flue gas discharge from the stack. Flue gas losses are also referred to as stack losses, consisting of the dry gas loss and moisture loss. The dry flue gases consist of CO_2, N_2, O_2, SO_2, and others. The BET is designed for a given value. A 40°F (22.2°C) rise in boiler exit gas temperatures can raise the heat rate by 1%. High boiler exit gas temperatures can be caused by:

- High excess air
- Inadequate boiler soot blowing, causing severely plugged sections that restrict gas flow
- Improper mill operation
- Excess pulverizer mill tempering air causing low mill temperature
- Improper O_2 monitoring system
- Air in-leakage in boiler, preheater, or ducts
- Plugging or fouling of air preheaters
- Corroded or eroded air preheaters
- High slagging and fouling coal

Unburned Carbon Losses

High LOI indicates incomplete combustion. Unburned carbon loss can usually be traced to:

- Improper excess air in furnace
- Poor mixing of the fuel and air in the combustion zone
- Incorrect primary air/fuel ratio and non-uniform distribution
- Primary/secondary air temperature and velocity
- Incorrect pulverized coal fineness
- High surface moisture in the coal
- Stage combustion

Moisture Loss

The latent heat of water vapor usually comprises a large fraction (6-10%) of the total efficiency losses. Moisture losses include the loss due to inherent and surface moisture in the fuel, combustion of hydrogen, and moisture in the combustion air.

Radiation and Unaccounted for Loss

There are a number of boiler system losses that normally are not based on test measurements. Radiation losses are heat losses to the surrounding air from the casing of the boiler, ductwork, precipitators, pulverizers, and others. Unaccountable losses include losses that are difficult to measure, such as heat lost in the ash leaving the furnace through the bottom ash hoppers and economizer hoppers, and any apparent losses due to instrumentation errors.

Heat-Rate Deviation Estimates

Typical heat rate effect and utility average dollar cost values from individual output variables are provided in Appendix A. Also, possible causes of deviations and possible corrections are listed to assist the operator in what actions to be taken to eliminate or reduce the loss in the most cost-effective manner. The utility average performance deviation estimates are taken from EPRI report *Heat-Rate Improvement Guidelines for Existing Fossil Plants* (CS-4554) and similar prediction with cost estimates can be found in EPRI report *Heat Rate Improvement Reference Manual* (TR-109546). The plant-specific value can be estimated from the formulas provided in these references.

Main Steam (Throttle) Pressure

Utility average: 0.35 Btu/kWh/psi (53.55 J/kWh/kPa)
Utility range: 0.03–0.65 Btu/kWh/psi (4.59–99.45 J/kWh/kPa)

Possible causes of deviation:

- Feedwater flow too low (once-through units)
- Firing rate inadequate

Possible corrections:

- Operator Controllable:
  - Increase feedwater flow
  - Increase firing rate

Main Steam (Throttle) Temperature

Utility average: 1.4 Btu/kWh/°F (2.7 kJ/kWh/°C)
Utility range: 0.7–1.7 Btu/kWh/°F (1.3–3.2 kJ/kWh/°C)

Possible causes of deviation:

- SH spray control problems
- SH spray valve leakage

- Fouling of the SH (low temperature)
- Fouling of the boiler waterwall (high temperature)
- High excess air
- Burner tilts mispositioned
- Gas tempering flow inadequate
- Bypass dampers mispositioned
- Temperature control setting calibration drift
- SH tube leaks
- Incorrect amount of SH heat transfer surface

Possible corrections:

- Operator controllable:
  - Blow soot
  - Adjust burner tilts
  - Adjust bypass damper settings
  - Adjust attemperating air flow damper
  - Control excess air
  - Manually control SH spray flow
- Maintenance correctable:
  - Calibrate temperature control set point
  - Repair SH spray control valve
  - Clean boiler waterwalls
  - Clean SH platens
  - Repair SH tube leaks
  - Add or remove SH heat transfer surface

Reheat Temperature

Utility average: 1.3 Btu/kWh/°F (2.5 kJ/kWh/°C)
Utility range: 0.9–1.9 Btu/kWh/°F (1.7–3.6 kJ/kWh/°C)

Possible causes of deviation:

- Reheat attemperation control problems
- Reheat attemperation control valve leakage

- Fouling of the RH (low temperature)
- Fouling of the boiler waterwall (high temperature)
- Fouling of the SH
- High excess air
- Burner tilts mispositioned
- Gas-tempering flow inadequate
- Bypass dampers mispositioned
- RH tube leaks
- Incorrect amount of RH heat transfer surface

Possible corrections:

- Operator controllable:
  - Blow soot
  - Adjust burner tilts
  - Adjust bypass damper settings
  - Adjust attemperating air flow damper
  - Control excess air
  - Annually control reheat spray flow
- Maintenance correctable:
  - Repair SH spray control valve
  - Clean boiler waterwalls
  - Clean SH platens
  - Clean RH platens
  - Repair RH tube leaks
  - Add or remove RH heat transfer surface

SH Attemperation

Utility average: 2.46 Btu/kWh/10,000 lb/h spray flow (5.72 kJ/kWh/kg/h)
Utility range: 1.3–3.1 Btu/kWh/10,000 lb/h spray flow (3–7.2 kJ/kWh/kg/h)

Possible causes of deviation:

- Improperly adjusted control setpoint
- Leaking spray control valve

- Broken spray nozzle
- Fouling of boiler waterwalls
- High levels of excess air
- Improperly set gas attemperation
- Improperly set gas bypass dampers

Possible corrections:

- Operator controllable:
  - Blow waterwall soot
  - Reduce excess air to proper levels
  - Adjust gas attemperation
  - Adjust gas bypass dampers
- Maintenance controllable:
  - Repair spray valves
  - Calibrate temperature controls
  - Replace spray nozzle

RH Attemperation

Utility average: 21.5 Btu/kWh/10,000 lb/h spray flow (50 kJ/kWh/kg/h)
Utility range: 10–36.6 Btu/kWh/10,000 lb/h spray flow (23.3–85.1 kJ/kWh/kg/h)

Possible causes of deviation:

- Fouled waterwallers
- High levels of excess air
- Fouled SH sections
- Improperly set gas bypass dampers
- Improperly adjusted temperature setpoint
- Leaking spray control valve
- Broken spray nozzle

Possible corrections:

- Operator controllable:
  - Adjust gas bypass dampers
  - Adjust excess air to proper levels
  - Sootblow waterwalls
  - Sootblow SH sections
- Maintenance controllable:
  - Repair spray control valve
  - Replace spray nozzle
  - Calibrate temperature control setpoint

Excess O_2

Utility average: 29.4 Btu/kWh/% (31 kJ/kWh/%)
Utility range: 18–36 Btu/kWh/% (19–38 kJ/kWh/%)

Possible causes of deviation:

- Fuel/air flow control problems
- Change in mill fineness
- Boiler-casing leaks
- Air heater leaks
- Hot precipitator leaks
- Malfunctioning burner(s)
- FD fan inlet vanes mispositioned
- Burner registers mispositioned

Possible corrections:

- Operator controllable:
  - Adjust FD fan inlet vanes
  - Adjust FD fan speed (variable speed)
- Maintenance controllable:
  - Adjust burner registers
  - Clean or repair burners
  - Repair air leaks

  - Calibrate fuel/air flow controls
  - Adjust pulverizer classifier vanes
  - Replace pulverizer grinding wheels, balls, or rings

Boiler Exit Gas Temperature

Utility average: 2.7 Btu/kWh/°F (5.1 kJ/kWh/°C)
Utility range: 2.1–4.2 Btu/kWh/°F (4–8 kJ/kWh/°C)

Possible causes of deviation:

- Bypass dampers mispositioned
- Air heater baskets corroded/eroded
- Air heater baskets fouled
- Attemperating air flows misadjusted
- Combustion air heater in use

Possible corrections:

- Operator controllable:
  - Reduce excess air
  - Adjust bypass dampers
  - Adjust tempering air flows
  - Use air heater soot blowers
  - Adjust steam flow to coils
  - Adjust air recirculation dampers
  - Remove combustion air heater from operation
- Maintenance correctable:
  - Repair or replace air heater baskets
  - Repair air heater leakage

Condenser Backpressure

Utility average: 204 Btu/kWh/In. Hg (8466 J/kWh/mm Hg)
Utility range: 42–269 Btu/kWh/In. Hg (1743–11,164 J/kWh/mm Hg)

Possible causes of deviation:

- Attemperating air flows misadjusted

- Combustion air heater in use
- Air leakage
- Excess condenser load
- Tube fouling
- Low circulating water flow
- Increases in circulating water inlet temperature caused by:
  - Changes in ambient conditions
  - Problems with cooling tower performance

Possible corrections:

- Operator controllable:
  - Increase circulating water flow
  - Add an additional vacuum pump
  - Check cycle isolation
  - Place additional circulating water pumps in service
  - Place additional cooling tower cells in service
- Maintenance correctable:
  - Repair condenser air leaks
  - Repair cycle isolation valves
  - Clean condenser
  - Repair circulating water discharge control valve
  - Repair cooling tower

Unburned Carbon in Ash

Utility average: 11.73 Btu/kWh/% (12.38 kJ/kWh/%)
Utility range: 6–12.8 Btu/kWh/% (6.3–13.5 kJ/kWh/%)

Possible causes of deviation:

- Incorrect fuel/air ratio
- Change in mill fineness
- Change in mill airflow

Possible corrections:

- Operator controllable:
  - Adjust fuel/air ratio
  - Adjust mill secondary airflow damper settings
- Maintenance correctable:
  - Adjust classifier vane settings
  - Repair or replace grinding wheels, balls, or rings
  - Check secondary air heater for blockage
  - Calibrate fuel/air control

Coal Moisture

Utility average: 7.8 Btu/kWh/% (8.2 kJ/kWh/%)
Utility range: 6–10 Btu/kWh/% (6–11 kJ/kWh/%)

Possible cause of deviation:

- Change in coal quality

Possible corrections: None

Auxiliary Power

Utility average: 86.8 Btu/kWh/% (91.6 kJ/kWh/%)
Utility range: 64–97 Btu/kWh/% (68–102 kJ/kWh/%)

Possible causes of deviation:

- Continuous running of non-continuous loads
- Decline in efficiency of operating equipment
- Operation of redundant equipment during low-load operation

Possible corrections:

- Operator controllable:
  - Stop non-continuous loads
  - Reduce equipment operation at low loads

- Maintenance correctable:
  - Repair or replace inefficient equipment
  - Maintain equipment whose power usage increases with deteriorating performance (for example, electrostatic precipitators, pulverizers, and so forth)

Makeup Water

Utility average: 24 Btu/kWh/% (25 kJ/kWh/%)
Utility range: 4–88 Btu/kWh/% (4–93 kJ/kWh/%)

Possible causes of deviation

- Boiler tube leaks
- Excess deaerator venting to atmosphere
- Excess continuous blowdown
- Excess steam lost through condenser venting
- Valve packing leaks
- Pump seal leaks
- Steam leaks to atmosphere

Possible corrections:

- Operator controllable: None
- Maintenance correctable:
  - Check deaerator vent orifices or valve settings
  - Repair valve, pump packings, and seals
  - Repair boiler tube leaks
  - Optimize continuous blowdown
  - Isolate cycle losses

Feedwater Heater Performance

Top high pressure heater performance:

Utility average: 2.1 Btu/kWh/°F (TTD) (4 kJ/kWh/°C)
Utility range: 1.3–2.3 Btu/kWh/°F (TTD) (2.5–4.4 kJ/kWh/°C)

Next to top high pressure heater performance:

Utility average: 0.54 Btu/kWh/°F (TTD) (1.03 kJ/kWh/°C)
Utility range: 0.33–0.63 Btu/kWh/°F (TTD) (0.63–1.2 kJ/kWh/°C)

Third from top high pressure heater performance:

Utility average: 0.65 Btu/kWh/°F (TTD) (1.24 kJ/kWh/°C)
Utility range: 0.57–0.8 Btu/kWh/°F (TTD) (1.08–1.52 kJ/kWh/°C)

High pressure heater out of service:

Top heater: 94 Btu/kWh (99 kJ/kWh)

Second heater: 70 Btu/kWh (74 kJ/kWh)

Third heater: 70 Btu/kWh (74 kJ/kWh)

Possible causes of deviation:

- Changes in heater level
- Changes in extraction line pressure drop
- Reduced condensate flow through the heater
- Heater baffle leaks
- Failure to vent non-condensable gases
- Tube fouling

Possible corrections:

- Operator controllable:
  - Set feedwater heater levels
- Maintenance correctable:
  - Optimize feedwater heater level
  - Maintain heater vent valves and line orifices
  - Repair baffle leaks
  - Clean tube bundles

Reduced Load Operation

Utility average: None available
Utility range: None available

Startup

Utility average: 7.33 Btu/kWh/start up (7.73 kJ/kWh/start up)
Utility range: 0.5–19 Btu/kWh/start up (0.5–20 kJ/kWh/start up)

Possible causes of deviation:

- Forced outages
- Unscheduled outages

Possible corrections:

- Operator controllable: None
- Maintenance correctable:
  - Eliminate unscheduled outages through effective predictive and preventive maintenance

B
CAPACITY INCREASE OPTIONS

Introduction

The boiler design has its rated capacity in terms of the MCR for steam flow. The original boiler design might also have peaking capability with overflow flow or feedwater heaters out of service. To preserve the reliability, the boiler manufacturers normally place daily four-hour limits on the peaking operation. The acceptance test might show higher steam generation capacity with control valves wide-open. All those represent extra capacity, which can be used during the peaking period for high revenue return.

Typically, the U.S. designed fossil power plant has capacity limitations in the sequential order of generators, turbines, boilers, and auxiliaries, with generators having the largest tolerance. The generator is typically rated at MVA with a specified power factor and hydrogen pressure rating. The actual power factor is based on the plant location and reactive power requirement. Transmission voltage stability and other considerations might also influence the potential capacity increase. If the existing boiler and auxiliary equipment can generate more steam, more MW are available by altering the generator power factor.

With the high cost of fuel, fossil units are facing pressure to increase the efficiency of existing power plants. The reliability deterioration and capacity reduction of aged power plants are also primary concerns. The Clean Air Act Amendment requires emission reduction from the boiler. These concerns must be properly addressed prior to making the decision regarding use of those extra capacities. Proper economic evaluation is essential to determine the feasibility of the options. The increased capacity from the existing aged fossil power units is a complex issue. If those options are carefully evaluated, they can provide low-cost power sources. Capacity increases can be provided by improving efficiency and firing more fuel to generate more steam.

Capacity Increase Options

In general, a capacity increase can be provided by the following two principles:

- **Improvement of efficiency at the full load:** Efficiency improvement at the full load will require less fuel input to produce the current capacity. In turn, it can produce more capacity from the current fuel input with existing constraints. This extra capacity will not require additional fuel and will not generate additional emissions.
- **Firing more fuel to deliver energy necessary to produce power:** Capacity increase by firing more fuel will require the evaluation of the existing equipment design margins and

critical constraints. This effort will require firing additional fuel and generating additional emissions.

Proper economic evaluation is essential to determine the feasibility of the options. The following five options can be considered to determine the capacity increase potential:

- Existing capacity evaluation
- Component modification and upgrade
- System modification and upgrade
- Plant performance improvement
- Station service power reduction

Existing capacity evaluation will be discussed further in this appendix. The information for other options can be found from EPRI and other industrial sources and are not discussed in this report.

Existing Fossil Plant Capacity Evaluation

The options to generate more steam to increase capacity are plant specific. If the existing unit is derated due to system or plant equipment problems, evaluation can be made to resolve these issues and recover the capacity. For example, if the unit is derated due to coal quality, consideration should be given to burn higher quality coal to obtain the valuable output during this peaking period. The following two options are generally available and can be considered:

- **Top heaters out of service:** Top heaters out of service can be used to produce more power output. The extraction steam used to heat the incoming water will be used to push low-pressure turbines. Many units have this capability to produce peaking power. The tradeoff is the heat rate due to the boiler overfiring to compensate for the water temperature. Units not designed for top heater out of service were evaluated for the potential of peaking capability.
- **Overflow operation:** The original boiler acceptance might indicate that the boiler is capable of producing mass steam flow beyond its MCR. A study with control valves wide-open and over-firing tests can be performed to identify the potential increase capacity. The evaluation should include: furnace heat release rate, FEGT, slagging and fouling potential, pendant and platen element spacing, circulation, draft loss and pressure drop, flow and flue gas distribution, and erosion rates. The study should also identify critical components or equipment that might prevent further capacity increase. These critical components and equipment can be evaluated technically and economically for the potential of replacement and upgrade.

Concerns

There are several concerns that are related to the additional duties to be placed on the existing units. These concerns and some of the suggestions for handling these concerns are discussed in the remainder of this appendix.

- **Reliability:** Determining the reliability impact from the overflow operation requires basic understanding of the design and operating limitations for each steam generation circuitry and fireside/flue-gas-side control. Overfiring the boiler can cause the following reliability concerns:
  - The final steam temperature and pressure control are part of plant operation control. The final steam temperature will be maintained with the operating limits during peaking operation. The increased steam flow will increase pressure drops, and the boiler tubes starting with the economizer will be subject to a higher operating pressure. The bulk steam temperature, other than the final superheat and reheat steam temperature, and all boiler tube mid-wall temperatures might be somewhat higher. The original boiler manufacture should be consulted for information on these potential concerns.
  - Increasing the firing rate will increase the furnace heat release rate and the slagging and fouling potentials can be increased accordingly. The slagging and fouling control will require more soot blowing, which can increase the sootblowing erosion. If slag is not removed in a timely manner, the potential of fireside corrosion and the boiler thermal performance are affected.
  - The increased usage of total air will increase the potential of higher fly ash erosion.
  - The over-firing condition will alter the flue-gas-side conditions, which can cause the increase of steam and tube metal temperatures and the potential need for proper monitoring.
  - The drum internals might reach their operating limits and there is potential of moisture carryover to the primary SH.
  - The auxiliary equipment (that is, fans and pulverizers) might reach its operating limits, which might require additional maintenance efforts to minimize the impact.

  The condition assessment efforts will be required to establish the health status for the boiler pressure components. Maintenance actions and operation optimization efforts can be conducted to minimize the impact.

- **Coal quality:** The fuel cost contributes to the majority of the generation cost. With the high cost of fuel, fossil units are facing pressure to purchase fuel from spot markets to obtain the best price. The quality of coal might need to be compromised. In many instances, the plants are facing derating due to coal quality. The coal quality can be a limiting factor and the use of premium coals during the peaking season might be required. A detailed evaluation needs to be performed and coal procurement needs to be planned to minimize the impact when the power is needed.
- **Clean air requirements:** Burning more fuel will generate more pollutants. The emission requirements can limit the capacity increase. This issue is unit and plant specific and an overall strategy needs to be established. Combustion optimization efforts might reduce the impact.
- **Other factors influencing the generator capacity:** High pressure feedwater heaters out of service reduce the feedwater temperature, which requires overfiring to reach required steam conditions and has a major impact on the heat rate. In addition to generating the real power

(MW), the generator also serves several other functions. These might have an impact on the economic values, system network stability, fault protection, and so forth. The allowable real power generation for each generator needs to be established. A study is proposed to establish these requirements before the project commitment. System planning should initiate this effort.

C MULTIPLE REGRESSION ANALYSIS

Introduction

Regression analysis is used to develop an equation that describes the relationship between dependent variables and independent variables. The variable being predicted or explained by the equation is called the dependent variable and the variable being used to predict or explain the dependent variable is called the independent variable. The terms of output variable and response have also been used for dependent variables. The terms of input variable and predictors have also been used for independent variables. The in-process variables can be treated as either dependent or independent variables depending on applications. If the regression equation involves only one independent variable, it is called simple regression analysis. Multiple regression analysis is the study of how a dependent variable y is related to two or more independent variables. Because most of the variables in the boiler operation are affected or explained by several factors, the majority of models to be analyzed are multiple in nature. Model building is the process of developing an estimated regression equation that describes the relationship between a dependent variable and one or more independent variables. The major issues in model building are finding the proper functional form of the relationship and selecting the independent variables to be included in the model. Both quantitative and qualitative independent variables can be used in the regression analysis. A brief description of the regression analysis is presented in this appendix. Statistical books should be used for better understanding of the formulae and statistical analysis procedures.

The Regression Model and the Regression Equation

The equation that describes how the dependent variable y is related to the independent variables x_1, x_2, ---, x_p, and an error term is called the regression model. The multiple regression model has the following form:

Multiple Regression Model:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ---- + \beta_p x_p + \varepsilon \qquad \text{Eq. C-1}$$

β_0, β_1, β_2,----, β_p are the constants and ε is a random variable. This model implies that y is a linear function of x_1, x_2, ---, x_p, plus ε. The ε is an error term that accounts for the variability in y that cannot be explained by the linear effect of the p independent variables.

There are several assumptions that will be discussed later in this appendix. One of the assumptions is that the mean or expected value of ε is zero. A consequence of this assumption generates the following multiple regression equation:

Multiple Regression Equation:

$$E(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ---- + \beta_p x_p \qquad \textbf{Eq. C-2}$$

The Estimated Multiple Regression Equation

The values of β_0, β_1, β_2,----, β_p are unknown and need to be estimated from sample data. Random samples are used to compute sample statistics b_0, b_1, b_2, ---, b_p that are used as the point estimators of the parameters β_0, β_1, β_2,----, β_p. These sample statistics provide the following estimated multiple regression equation:

$$\bullet = b_0 + b_1 x_1 + b_2 x_2 + ---- + b_p x_p \qquad \textbf{Eq. C-3}$$

Where: b_0, b_1, ---, b_p, are estimates of β_o, β_1, ----, β_p,
• = estimated value of the dependent variable

The Least Squares Method

The least squares method is a procedure for finding the estimated regression equation. The least squares method provides an estimated regression equation that minimizes the sum of squared deviation between the observed values of the dependent variables y_i and the estimated values of the dependent variable $\bullet_i$. This is the least squares criterion for choosing the equation that provides the best fit. If some other criterion were used, such as minimizing the sum of the absolute deviations between y_i and $\bullet_i$, a different equation would be obtained. In practice, the least squares method is the most widely used.

Least Squares Criterion:

$$\min \sum (y_i - \bullet_i)^2$$

y_i = observed value of the dependent variable for the ith observation
$\bullet_i$ = estimated value of the dependent variable for the ith observation

For simple regression analysis, b_o and b_1 can be calculated by using formulas that are provided by statistical books. The presentation of the formulas for the regression coefficients b_0, b_1, b_2---, b_p involves the use of matrix algebra that will not be presented in this appendix. The focus here will be on computer software usage, which can be used to obtain the estimated regression equation and other information directly. In multiple regression analysis, each regression coefficient (that is b_1) represents an estimate of the change in y corresponding to a one-unit change in x, when all other independent variables are held constant.

Variable Selection and Model Building

In most practical problems, there is a list of candidate-independent variables, which potentially affect the dependent variable. The intention is to find the right subset of variables that significantly contribute to explaining the dependent variable. There are several techniques that exist to assist in this purpose. The goal is to find the minimum number of predictors that explain the most variance in the dependent variable.

Evaluating all possible regressions is often unnecessary, as efficient variable selection computer routines exist that can evaluate a small number of subset regression models by adding or deleting predictors one at a time. The statistical rule by which this is done varies. Different techniques for variable selection sometimes result in different subsets of predictors:

- **Forward Selection:** This procedure begins with just the intercept term in the model. Independent variables are selected one at a time. The first independent variable to enter the equation is the one with the highest simple correlation with the dependent variable. The second variable that enters the equation will be the one that produces the next largest partial correlation with the dependent variable, given that the first variable is already in the equation. A partial F-test or t-test is performed to see if this partial correlation is significant. If it is, the process continues until no new variables can enter at a predetermined F-value or probability level. The recommended stopping rule for forward selection is a probability level of about 0.15, which corresponds to an F-value of about 4.0. If the probability level is set too low, it might exclude some important predictors; a major drawback of the forward selection method is that once a variable is in, it does not have to remain significant to stay in the model.
- **Backward Elimination:** Backward elimination starts with all variables in the model and tests all variables at each step by the partial F-statistic. During this first step, if the variable with the lowest partial F-statistic does not meet the user-specified F-value, it is eliminated from the equation. At the second step, a regression model is once again fitted with the k-1 predictors, and the partial F-statistics for this new model are computed. Again, if the smallest partial F-value is less than the user-specified value, that variable is then eliminated. The procedure continues until all remaining variables in the model are significant at the specified F-value or probability level. The advantage to backward elimination is that all candidate variables are considered, so the effect of including all can be seen. However, the backward elimination method prevents a variable from re-entering the model at a later step once it's eliminated. Backward elimination is better than forward selection because the latter technique might result in a model with redundant variables if two or more predictors are highly correlated.
- **Stepwise Repression:** The stepwise repression method of variable selection is basically a forward selection method with the option of removing a variable already selected with two values, an F-to-enter and an F-to-remove. At the first step, the variable with the highest-computed F-to-enter value is selected. At the second step, the variable with the highest partial F-statistic is entered into the equation, assuming its value exceeds the user-specified minimum F-to-enter. Here the procedure deviates from the forward selection method. Once the second predictor is entered, the program then examines the partial F-statistic for both variables. If a variable fails to meet the F-to-remove standard, it is then removed from the model. This procedure continues so that at each step, all predictors entered into the model are reassessed to see if their probabilities or partial F-statistics have fallen

below the minimum acceptable levels. Stepwise is favored by many analysts because of this dual testing—at each stage, a test is made of the least useful predictor. So a predictor that might have been the best entry candidate earlier might now be redundant.

- **Best-Subsets Regression:** Forward selection and backward elimination are approaches to choosing the regression model by adding or deleting independent variables one at a time. There is no guarantee that the best model for a given number of variables can be found. Best-subsets regression can find the best regression model for a specified number of independent variables. For example, the Minitab output identifies the two best sets of estimated regression equations for one independent variable through k independent variables, if k is a specified number of total independent variables. However, the best-subsets regression equations are subject to the fitness tests.

The Multiple Coefficient of Determination

The term multiple coefficient of determination indicates a measure of the goodness of fit for the estimated multiple regression equation. The total sum of squares can be partitioned into two components—the sum of squares due to regression and the sum of squares due to error. The multiple coefficient of determination, denoted R^2, can be computed by the following formula:

Multiple Coefficient of Determination :

$$R^2 = SSR/SST \qquad \text{Eq. C-4}$$

Where: SST = SSR = SSE

SST = total sum of squares = $\sum(y_i - \bullet\,)^2$
SSR = sum of squares due to regression = $\sum(\bullet_i - \bullet\,)^2$
SSE = sum of squares due to error = $\sum(y_i - \bullet_i)^2$
$\bullet$ = mean value for the dependent variable

Because of the computational difficulty in computing the three sums of squares, computer packages will be used to determine those values. R^2 takes values between zero and one. The multiple coefficient of determination can be interpreted as the proportion of the variability in the dependent variable that can be explained by the estimated multiple regression equation. Hence, when multiplied by 100, it can be interpreted as the percentage of variation in y that can be explained by the estimated regression equation. It is important to note that R^2 is a measure of the variation explained by the entire regression equation, not by individual independent variables.

The drawback to using R^2 is that it almost always increases as independent variables are added to the model. Using R^2 alone might tempt the analyst to include a large number of weak predictors that might inflate R^2 but have little predictive value outside the sample.

Many analysts prefer adjusting R^2 for the number of independent variables to avoid overestimating the impact of adding an independent variable on the amount of variability explained by the estimated regression equation. With n denoting the number of observations and p denoting the number of independent variables, the adjusted multiple coefficient of determination is computed as follows:

Adjusted Multiple Coefficient of Determination:

$$R^2_{adj} = 1 – (1 – R^2) (n – 1) / (n – p – 1) \qquad \text{Eq. C-5}$$

If the value of R^2 is small and the model contains a large number of independent variables, the adjusted coefficient of determination can take a negative value; in such cases, Minitab sets the adjusted coefficient of determination to zero. As a practical matter, for data in the physical and life sciences, R^2 values of 0.60 or greater are often found and in some cases, R^2 values greater than 0.90 can be found. In business applications, R^2 values vary greatly depending on the unique characteristics of each application.

Correlation Coefficient

The correlation coefficient is a descriptive measure of the strength of linear association between two variables. Values of the correlation coefficient are always between -1 and +1. A value of 1 indicates that the two variables are perfectly related in a positive linear sense. A value of -1 indicates that two variables perfectly related in a negative linear sense. Values of the correlation coefficient close to zero indicate that x and y are not linearly related.

The coefficient of determination and the correlation coefficient are related. For a simple regression case, the sample correlation coefficient can be computed as follows:

$$r_{xy} = \text{(the sign of } b_1\text{) (coefficient of determination)}^{½} \qquad \text{Eq. C-6}$$

That is, the sample correlation coefficient is plus or minus the square root of the coefficient of determination. Although the sample correlation coefficient is restricted to a linear relationship between two variables, the coefficient of determination can be used for nonlinear relationship and for relationships that have two or more independent variables. In that sense, the coefficient of determination has a wider range of applicability.

Model Assumptions

Assumptions about the error term e in the regression model $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ---- + \beta_p x_p + \varepsilon$

- The error ε is a random variable with mean or expected value of zero (that is, E(ε) = 0)
- The variance of ε is denoted by a 2 and is the same for all values of the independent variables $x_1, x_2, ---, x_p$
- The values of ε are independent
- The error ε is a normally-distributed random variable reflecting the deviation between the y value and the expected value of y is given by $\beta_0 + \beta_1 x_1 + \beta_2 x_2 + ---- + \beta_p x_p + \varepsilon$

In regression analysis, the term response variable is often used in place of the term dependent variable. The graph of the multiple regression is in multiple dimensional space that can only be shown for simple regression or two independent variable cases. For the case of two independent variables, the multiple regression equation generates a plane or surface and its graph is called a response surface.

Test for Significance

Larger values of R^2 simply imply that the least squares provides a better fit to the data; that is, the observations are more closely grouped about the least squares line. No conclusion can be drawn about whether the relationship between variables is statistically significant by using R^2 alone. Such a conclusion must be based on considerations that involve the sample size and the properties of the appropriate sampling distributions of the least squares estimators. The significance tests used in linear regression analysis are a t-test and an F-test. In simple linear regression, both tests provide the same conclusion. In multiple regression, the t-test and the F-test have different purposes:

- **Overall significance:** The F-test is used to determine whether or not there is a significant relationship between the dependent variable and the set of all the independent variables
- **Individual significance:** If the F-test shows an overall significance, the t-test is used to determine whether or not each of the individual independent variables is significant

F-Test

The multiple regression model previously defined is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \text{----} + \beta_p x_p + \varepsilon \qquad \text{Eq. C-7}$$

F-Test for Overall Significance:

The hypotheses for the F-test involve the parameters of the multiple regression model.

H_0: $\beta_1 = \beta_2 = \text{----} = \beta_p = 0$
H_a: One or more of the parameters is not equal to zero

F-Test Statistic: F = MSR/MSE

Rejection Rule: Reject H_0 if $F > F_\alpha$

Where F_α is based on F-distribution with p degrees of freedom in the numerator and $n - p - 1$ degrees of freedom in the denominator and the value of F_α can be found from statistical books with a selected α. The α is called significance level and $1-\alpha$ is referred as confidence interval.

If H_0 is rejected, there is sufficient statistical evidence to conclude that one or more of the parameters is not equal to zero and that the overall relationship between y and the set of independent variables x_1, x_2, ---, x_p is significant. However, if H_0 cannot be rejected, then there is no sufficient evidence to conclude that a significant relationship is present.

t-Test

If the F-test has shown that the multiple regression relationship is significant, a t-test can be conducted to determine the significance of each of the individual parameters. The test for individual significance follows.

t-Test for Individual Significance:

For any given parameter β_i

H_0: $\beta_1 = 0$
H_a: $\beta_1 \neq 0$

t-Test Statistic: $t = b_i/s_{bi}$

Rejection Rule: Reject if $t < -t_{\alpha/2}$ or if $t > t_{\alpha/2}$

Where $t_{\alpha/2}$ is based on a t-distribution with n – p – 1 degrees of freedom

Minitab performs calculations automatically for the parameters, which can be used to compare with the value obtained from the statistical books.

Multicollinearity

Multicollinearity exists where two or more predictors are either perfectly or highly inter-correlated. In a multiple regression analysis, the F-test can show the relationship to be significant and t-test might show a different conclusion for certain individual parameters. This could simply mean some of the independent variables do not make a significant contribution to determining the value of the dependent variable. In t-tests for the significance of individual parameters, the difficulty caused by multicollinearity can be avoided when there is very little correlation among the independent variables.

The practical consequences of multicollinearity are:

- Inaccurate estimates of the regression coefficients.
- Larger standard errors that result in wider confidence intervals.
- A greater probability of accepting a false hypothesis.
- Regression estimates and their standard errors that are very sensitive to the slightest change in the data.

- Multicollinearity that might provide a high R^2, but none or only a few of the coefficients will be statistically significant. In other words, where there are redundant variables, it might be impossible to isolate the individual effects of the predictors on the dependent variable.

Most nonexperimental data sets show some multicollinearity. The data collected from the DOE can eliminate this type of collinearity. Detection of multicollinearity can be performed by pairwise correlation and VIF.

- **Pairwise correlation:** Detection of multicollinearity is often done by examining pairwise correlations among the predictors. The existence of high correlations is a necessary but not sufficient condition for multicollinearity, because the latter can exist even when the pairwise correlations are low. As a rule of thumb, multicollinearity is a potential problem if the absolute value of the sample correlation coefficient exceeds 0.7 for any two of the independent variables.
- **VIF:** A better method of detection is the use of a VIF. VIF measures the combined effect of the multicollinearity among the predictors for each term in the model. Practical experience indicates that if a VIF is greater than four, then the regression coefficients might be poorly estimated. Minitab has an option to provide the VIF value.

Ordinarily, multicollinearity does not necessarily affect the way in which we perform regression analysis or interpret the output from a study. However, if possible, every attempt should be made to avoid including independent variables that are highly correlated. In practice, however, strict adherence to this policy is rarely possible. In the stepwise regression analysis, generally only one of a set of multicollinear-independent variables is included in the model, because at each step every variable is tested in the presence of all the variables already in the model. Two other methods of dealing with multicollinearity are ridge regression and principal components regression, which can be found from statistical books.

Using the Estimated Regression Equation for Estimation and Prediction

The regression model is an assumption about the relationship between dependent and independent variables. If the results show a statistically significant relationship, and the fit provided by the estimated regression equation appears to be good, the estimated regression equation should be useful for estimation and prediction. The mean value of the dependent variable can be estimated by substituting all dependent variables into the regression equation: this is referred to as the point estimate. Point estimates do not provide any idea of the precision associated with the estimate. For that interval, estimates must be developed. There are two types of interval estimates:

- **Confidence interval estimate:** This is an interval estimate of the mean value of the dependent for given independent variables
- **Prediction interval estimate:** This is an interval estimate of an individual value of the independent variable for given independent variables

The formulas are not presented in this appendix. Computer packages for multiple regression analysis can provide confidence intervals once the independent variable values are specified.

Residual Analysis: Validation Model Assumptions

Residual analysis can be used to validate the assumptions and to assist in identifying outliers and influential observations. Standardized residuals were frequently used in residuals plots and in the identification of outliers. The leverage of an observation is determined by how far the values of the independent variables are from their means. The computation of the standardized residual for observation i in multiple regression analysis is too complex to be done by hand. However, the standardized residuals can be easily obtained as part of the output from statistical software packages.

The ith residual is the error resulting from using the estimated regression equation to predict the value of y_i and it is the difference between the observed value of the dependent variable y_i and the estimated value of the dependent variable • $_i$.

Residual for Observation i:

y_i – • $_i$

Where: y_i is the observed value of the dependent variable
• $_i$ is the estimated value of the dependent variable

Residual analysis will help determine whether or not the assumptions that have been made about the regression model are appropriate. As mentioned previously, the following assumptions about the error term ε were made.

- $E(\varepsilon) = 0$
- The variance of ε, denoted by σ^2, is the same for all values of ix
- The values of ε are independent
- The error term ε has a normal probability distribution

These assumptions provide the theoretical basis for the t-test and the F-test used to determine whether or not the relationship between x and y is significant, and for the confidence and prediction interval estimates. If the assumptions about the error term ε appear questionable, the hypothesis tests about significance of regression relationship and the interval estimation results might not be valid. To determine if these assumptions are valid, one method is to plot the standardized residuals against the predicted values. There are three general patterns that might be observed in any residual plot. If the first three assumptions about ε are satisfied and the assumed regression model is an adequate representation of the relationship among the variables, the residual plot should approximate a horizontal band of points. If the variance of ε is not constant, a pattern of diverged cone could be observed. If the residual plot shows a bow pattern in panel C, this suggests that the model is not an adequate representation of the relationship among the variables and that a different multiple regression model or nonlinear term should be considered. Other plots such as a normal probability plot can also be used to determine whether or not the distribution of ε appears to be normal.

Detecting Outliers

A review of the scatter diagram might reveal some suspicious data points that do not fit the pattern of the overall data set when only one independent variable is present. These points are referred to as outliers. For the case of multiple independent variables, viewing the scatter diagram to identify outliers can be misleading. Outliers represent observations that are suspect and warrant careful examination. They might represent erroneous data. If so, the data should be corrected. They might signal a violation of model assumptions. If so, another model should be considered. Finally, they might simply be unusual values that have occurred by chance. In this case, they should be retained. Minitab classifies an observation as an outlier if the value of its standardized residual is less than -2 or greater than +2. In general, the presence of one or more outliers in a data set tends to increase the value of the standard error of the estimate. As a result, it might cause the standardized residual rule to fail to identify the observation as being an outlier. Another technique called studentized deleted residuals can be used to overcome this difficulty. Minitab and other computer packages can provide the analysis of studentized deleted residuals. The formula and analysis procedures are not presented in this appendix.

Influential Observations

Sometimes one or more observations have a strong influence on the results obtained. Influential observations can be identified from a scatter diagram when only one independent variable is present. For multiple input variables, viewing the scatter diagram to identify the influential observations can be misleading. Because influential observations might have such a dramatic effect on the estimated regression equation, they must be examined carefully. It is essential to ensure that no error has been made in collecting or recording the data. If an error has occurred, it can be corrected and a new estimated regression equation can be developed. If the observation is valid, we might consider ourselves fortunate to have it. Such a point, if valid, can contribute to a better understanding of the appropriate model and can lead to a better estimated regression equation. The leverage of an observation can be used to identify observations for which the value of the independent variable might have a strong influence on the regression results. In the standardized residuals analysis, the leverage of an observation measures how far the values of the independent variables are from their mean values. The leverage values are easily obtained as part of the output from statistical software packages.

Using Cook's Distance Measure to Identify Influential Observations

A problem that can arise in using leverage to identify influential observations is that an observation can be identified as having high leverage and not necessarily be influential in terms of the resulting estimated regression equation. In some situations, using only leverage to identify influential observations can lead to wrong conclusions. Cook's distance measure uses both the leverage of observation i, h_i, and the residual for observation i, $(y_i – \bullet_i)$, to determine if the observation is influential.

Cook's Distance Measure:

$$D_i = [(y_i – \bullet_i)^2 / ((p – 1)s^2)] * [h_i / (1 – h_i)^2] \quad \textbf{Eq. C-8}$$

$y_i - \hat{y}_i$ = the residual for observation i
h_i = the leverage for observation i
p = the number of independent variables
s = the standard error of the estimate

The value of Cook's distance measure will be large and indicate an influential observation if the residual and/or the leverage is large. As a rule of thumb, values of $D_i > 1$ indicates that the ith observation is influential and should be studied further.

Example

Boiler X is a tangentially-fired, control circulation, balance draft drum boiler with rated capacity of 150 MW. Boiler performance tests were conducted by varying the burner tilt angle from -23° to +28°. It is intended to identify the relationships among burner tilt angle, FEGT, and SHO-T. The test data are shown in Table C-1.

Input parameter: Burner tilt
In-process parameter: FEGT
Output parameter: SH steam temperature

Table C-1
Test Data for SHO-T and Burner Tilt Angles for a t-Fired Boiler

Test	SH Temperature °F (°C)	Burner title Angle (Degree)	FEGT °F (°C)
1	979.2 (526.2)	12	2422 (1328)
2	982.1 (527.8)	14	2430 (1332)
3	978.0 (525.6)	10	2398 (1314)
4	978.5 (525.8)	10	2401 (1316
5	976.5 (524.7)	11	2407 (1319)
6	952.9 (511.6)	0	2365 (1296)
7	955.4 (513.0)	0	2360 (1293)
8	957.7 (514.3)	0	2362 (1294)
9	973.5 (523.1)	8	2390 (1310)
10	964.6 (518.1)	3	2370 (1299)
11	988.9 (531.6)	17	2451 (1344)
12	990.2 (532.3)	28	2486 (1363)
13	988.6 (531.4)	16	2453 (1345)
14	960.4 (515.8)	1	2364 (1296)
15	940.3 (504.6)	-23	2330 (1277)
16	944.2 (506.8)	-14	2338 (1281)

The following analyses were performed with Minitab for this example:

- Pairwise correlation
- Best subsets regression: SH temperature versus tilt, FEGT
- Regression analysis: SH temperature versus tilt, FEGT
- Regression analysis: SH temperature versus tilt
- Regression analysis: FEGT versus tilt
- Polynomial regression analysis: FEGT versus tilt
- Regression analysis: SH temperature versus FEGT
- Polynomial regression analysis: SH temperature versus FEGT

Pairwise Correlations

Correlations: SH Temp, Tilt, FEGT

```
SH Temp    Tilt
Tilt      0.951
          0.000

FEGT      0.947    0.934
          0.000    0.000
```

Figure C-1
Minitab Analysis of Pairwise Correlation

Discussion:

- The correlation coefficient, r, is in the range of -1 and +1. If r is close to -1, it means strong negative correlation. If r is close to +1, it means strong positive correlation. If r is close to zero, it means no linear correlation.
- The correlation coefficient between SH temperature and tilt is +0.951. This means that the SH temperature and tilt are strongly correlated. Positive correlation means when the tilt angle increases, the SH temperature also increases. Same conclusion can be drawn between SH temperature and FEGT.
- The correlation coefficient between tilt and FEGT is +0.934. This means that the SH temperature and FEGT are strongly correlated. Positive correlation means when the tilt angle increases, the FEGT also increases. If the FEGT is treated as an independent variable, then FEGT and tilt are redundant to each other.

Best Subsets Regression: SH Temperature vs. Tilt, FEGT

The following figure shows Minitab output analysis of best subsets regression for SH temperature versus tilt, FEGT.

```
Response is SH Temp

                                                  T F
                                                  i E
                                                  l G
Vars   R-Sq    R-Sq(adj)       C-p         S      t T

   1   90.5         89.8       6.2    5.1267    X
   1   89.7         89.0       7.6    5.3251      X
   2   93.2         92.1       3.0    4.5023    X X
```

Figure C-2
Minitab Output Analysis of Best Subsets Regression: SH Temperature vs. Tilt, FEGT

Discussion:

- R-sq is the coefficient of determination (between 0 and 1). It is similar to the correlation coefficient. R-sq can also be used for nonlinear relationships and multiple independent variables. R-sq (adj.) is the adjusted coefficient of determination that is used for the multiple regression analysis to avoid overestimating the impact of adding an independent variable on the amount of variability explained by the estimated regression equation.
- Figure C-2 indicates that if one independent variable is used, the tilt provides R-sq of 90.5% and FEGT provides R-sq of 89.7%. If both variables are used in the regression analysis, R-sq is 93.2%. R-sq also means the percentage of influence. For example, R-sq equals to 90.5% means that 90.5% of variation in SH can be explained by the linear relationship between tilt and SH temperature.

Regression Analysis: SH Temperature vs. Tilt, FEGT

The following figure shows Minitab output for analysis of regression analysis for SH temperature vs. tilt, FEGT.

```
The regression equation is

SH Temp=565+0.682 Tilt+0.167 FEGT

Predictor        Coef     SE Coef          T        P       VIF
Constant        564.7       175.1       3.22    0.007
Tilt           0.6818      0.2657       2.57    0.023       7.8
FEGT          0.16730     0.07371       2.27    0.041       7.8

S=4.502       R-Sq=93.2%     R-Sq(adj)=92.1%

Analysis of Variance

Source            DF          SS          MS         F         P
Regression         2      3590.3      1795.2     88.56     0.000
Residual Error    13       263.5        20.3
Total             15      3853.9

Source       DF      Seq SS
Tilt          1      3485.9
FEGT          1       104.4

Unusual Observations
Obs       Tilt    SH Temp         Fit      SE Fit    Residual    St Resid
 12       28.0     990.20      999.72        2.66       -9.52      -2.62R
 15      -23.0     940.30      938.84        3.76        1.46        0.59 X

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.
```

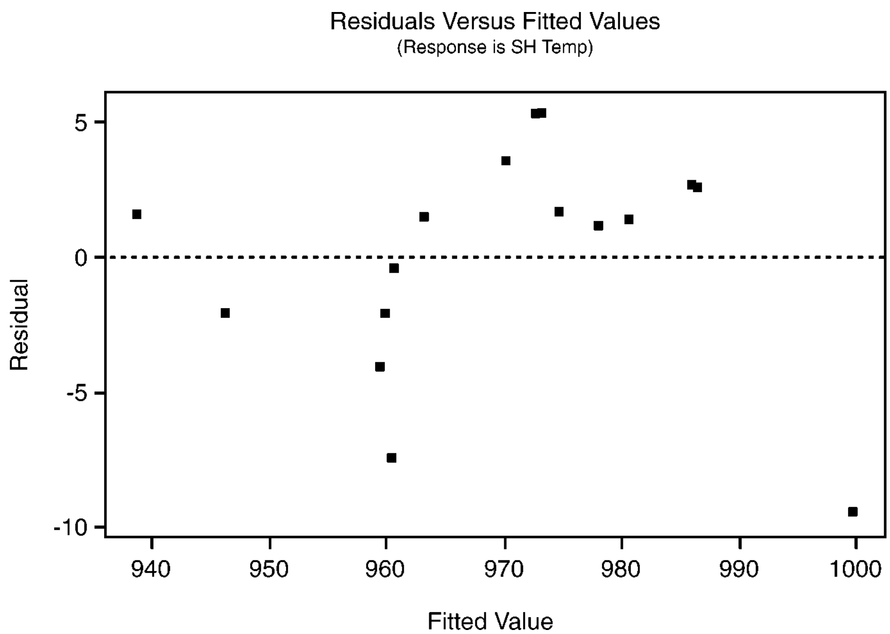


Figure C-3
Minitab Output for Analysis of Regression Analysis: SH Temperature vs. Tilt, FEGT

Discussion:

- The footnote indicates that there is an outlier (obs 12) and a large influence (obs 15) in the data set.
- The FEGT is not only affected by the burner tilt. It can also be influenced by the furnace cleanness (soot blowing). Because the FEGT is strongly related to burner tilt angle, only one of the parameters is needed in the regression equation.
- The VIF is greater than four, which indicates the regression coefficients (β's) can be poorly estimated.

Regression Analysis: SH Temperature vs. Tilt

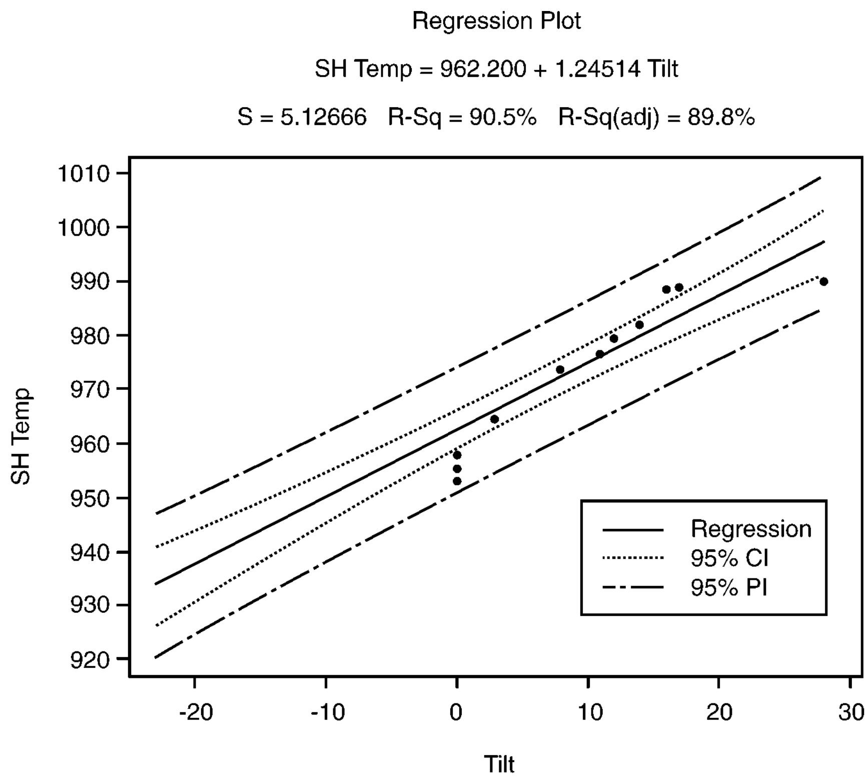
The following figure shows Minitab output for analysis of regression analysis for SH temperature versus tilt.

```
The regression equation is

SH Temp=962+1.25 Tilt

Predictor        Coef     SE Coef          T        P
Constant      962.200       1.427     674.07    0.000
Tilt           1.2451      0.1081      11.52    0.000

S=5.127       R-Sq=90.5%     R-Sq(adj)=89.8%
```

```
Analysis of Variance

Source            DF         SS         MS        F        P
Regression         1     3485.9     3485.9   132.63    0.000
Residual Error    14      368.0       26.3
Total             15     3853.9

Unusual Observations
Obs       Tilt    SH Temp         Fit      SE Fit    Residual    St Resid
 15      -23.0     940.30      933.56        3.37        6.74        1.74 X

X denotes an observation whose X value gives it large influence.
```

Discussion:

This is a good regression equation that gives a good R-sq value and passes the F-test (F = 132.631, p = 0). This scatter diagram also looks good.



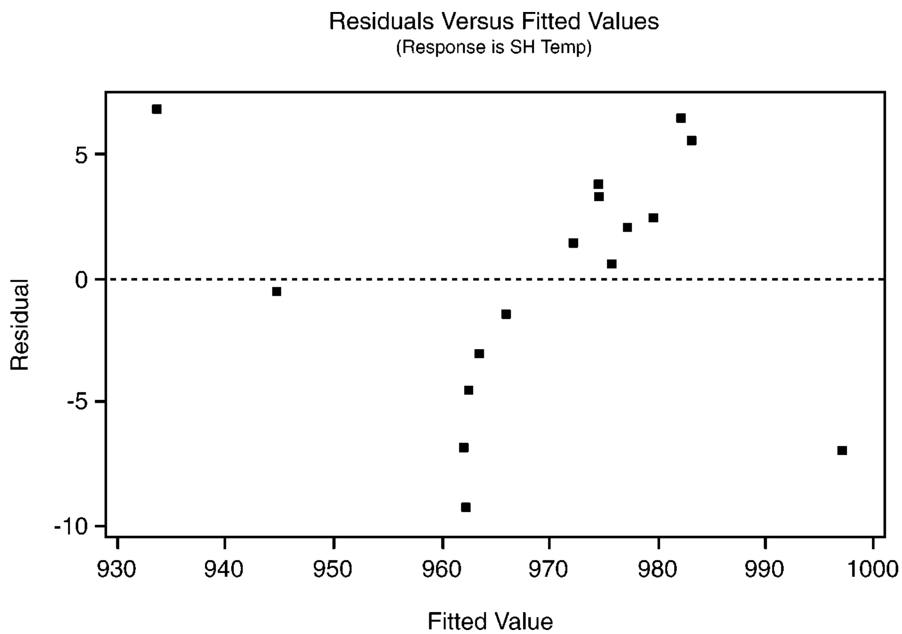
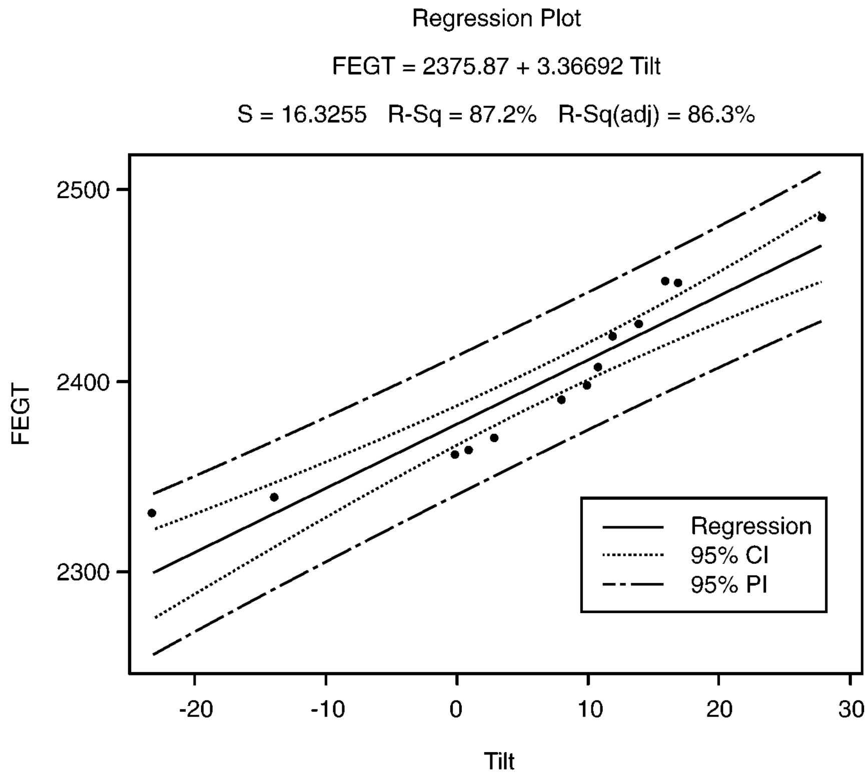


Figure C-4
Minitab Output for Analysis of Regression Analysis: SH Temperature vs. Tilt

Regression Analysis: FEGT vs. Tilt

The following figure shows Minitab output for analysis of regression analysis for FEGT versus tilt.

```
The regression equation is

FEGT = 2376+3.37 Tilt

Predictor        Coef     SE Coef          T        P
Constant      2375.87        4.55     522.68    0.000
Tilt           3.3669      0.3443       9.78    0.000

S = 16.33       R-Sq=87.2%     R-Sq(adj)=86.3%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression         1       25489       25489     95.63    0.000
Residual Error    14        3731         267
Total             15       29220

Unusual Observations
Obs       Tilt       FEGT         Fit      SE Fit    Residual    St Resid
 15      -23.0    2330.00     2298.43       10.73       31.57       2.57RX

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.
```



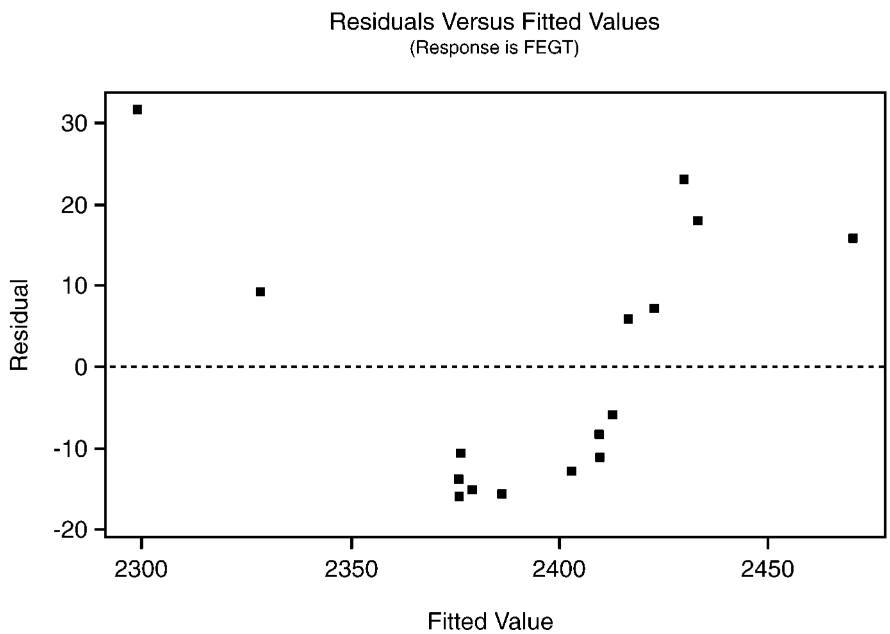


Figure C-5
Minitab Output for Analysis of Regression Analysis: FEGT vs. Tilt

Polynomial Regression Analysis: FEGT vs. Tilt

The following figure shows Minitab output for analysis of polynomial regression analysis for FEGT versus tilt.

```
The regression equation is

FEGT=2366.51+3.14456 Tilt+0.0611058 Tilt**2

S=9.81337      R-Sq=95.7 %      R-Sq(adj)=95.1 %

Analysis of Variance

Source            DF         SS         MS         F       P
Regression         2    27968.0    13984.0   145.210   0.000
Error             13     1251.9       96.3
Total             15    29219.9


Source      DF     Seq SS         F      P
Linear       1    25488.6   95.6348  0.000
Quadratic    1     2479.4   25.7456  0.000
```

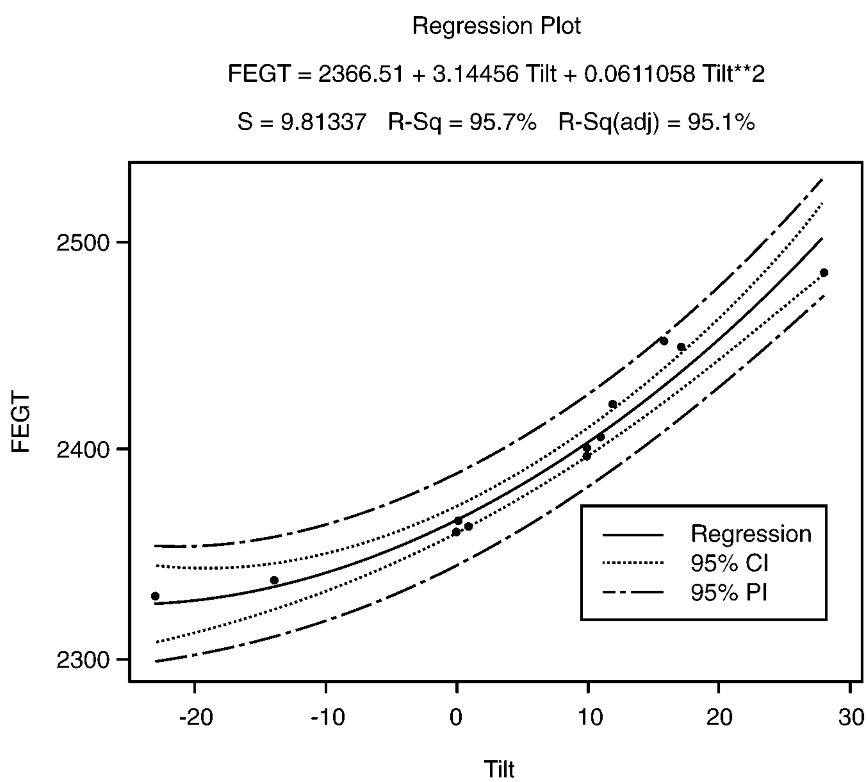
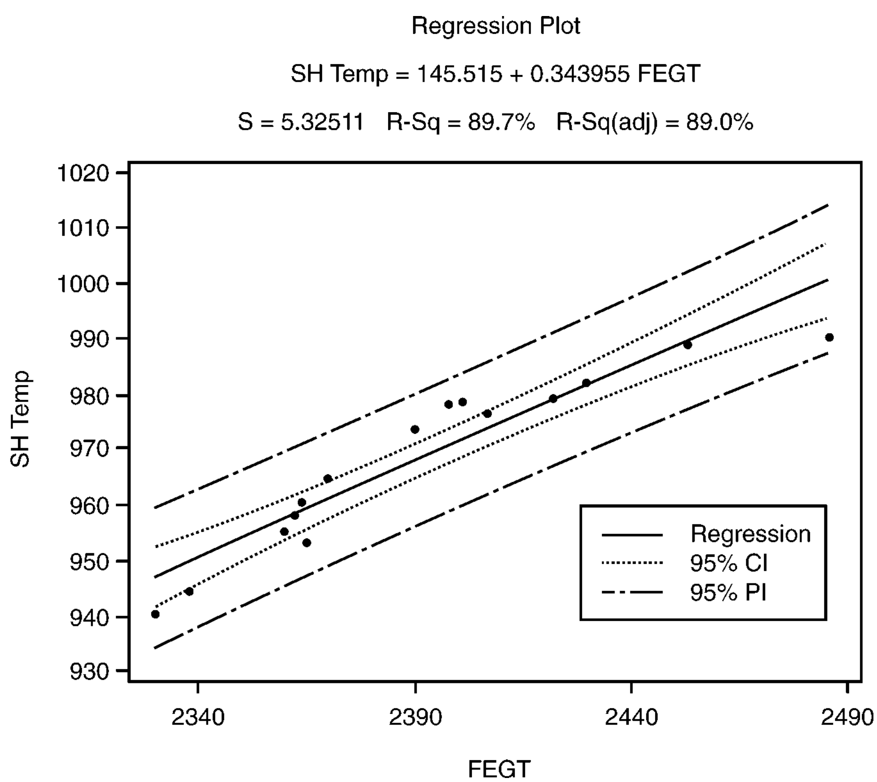


Figure C-6
Minitab Output for Analysis of Polynomial Regression Analysis: FEGT vs. Tilt

Regression Analysis: SH Temperature vs. FEGT

The following figure shows Minitab output for analysis of regression analysis for SH temperature versus FEGT.

```
The regression equation is

SH Temp=146+0.344 FEGT

Predictor        Coef     SE Coef          T        P
Constant       145.52       74.64       1.95    0.072
FEGT          0.34395     0.03115      11.04    0.000

S=5.325       R-Sq=89.7%     R-Sq(adj)=89.0%

Analysis of Variance

Source           DF          SS          MS         F        P
Regression        1      3456.9      3456.9    121.91    0.000
Residual Error   14       397.0        28.4
Total            15      3853.9

Unusual Observations
Obs       FEGT    SH Temp         Fit       SE Fit    Residual    St Resid
 12       2486     990.20     1000.59         3.12      -10.39       -2.41R

R denotes an observation with a large standardized residual
```



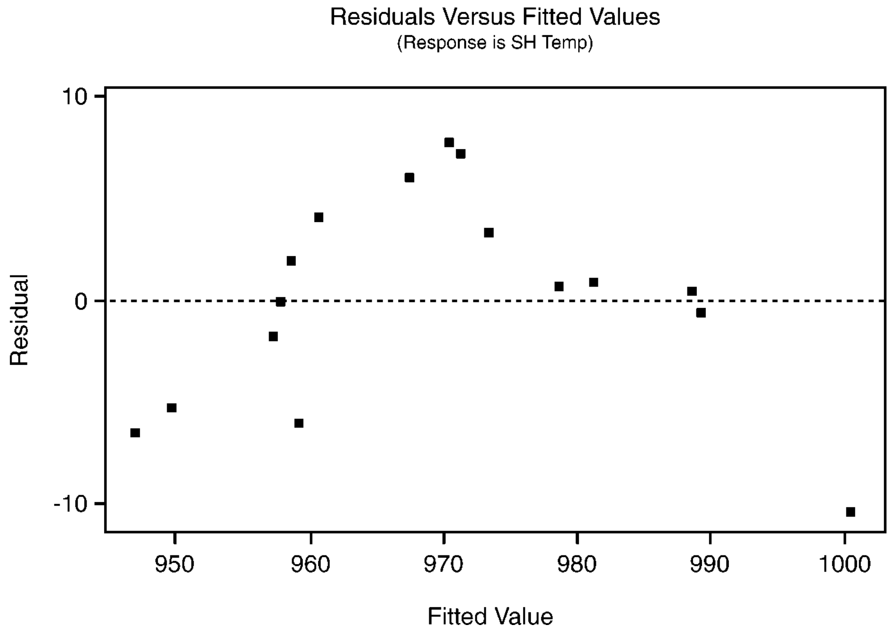


Figure C-7
Minitab Output for Analysis of Regression Analysis: SH Temperature vs. FEGT

Polynomial Regression Analysis: SH Temperature vs. FEGT

The following figure shows Minitab output for analysis of polynomial regression analysis for SH temperature versus FEGT.

```
The regression equation is

SH Temp=-12650.9+10.9904 FEGT-0.0022137 FEGT**2

S=2.76674      R-Sq=97.4 %      R-Sq(adj)=97.0 %

Analysis of Variance

Source            DF          SS          MS         F      P
Regression         2     3754.34     1877.17   245.227  0.000
Error             13       99.51        7.65
Total             15     3853.86


Source      DF     Seq SS          F      P
Linear       1    3456.86    121.906  0.000
Quadratic    1     297.48     38.862  0.000
```

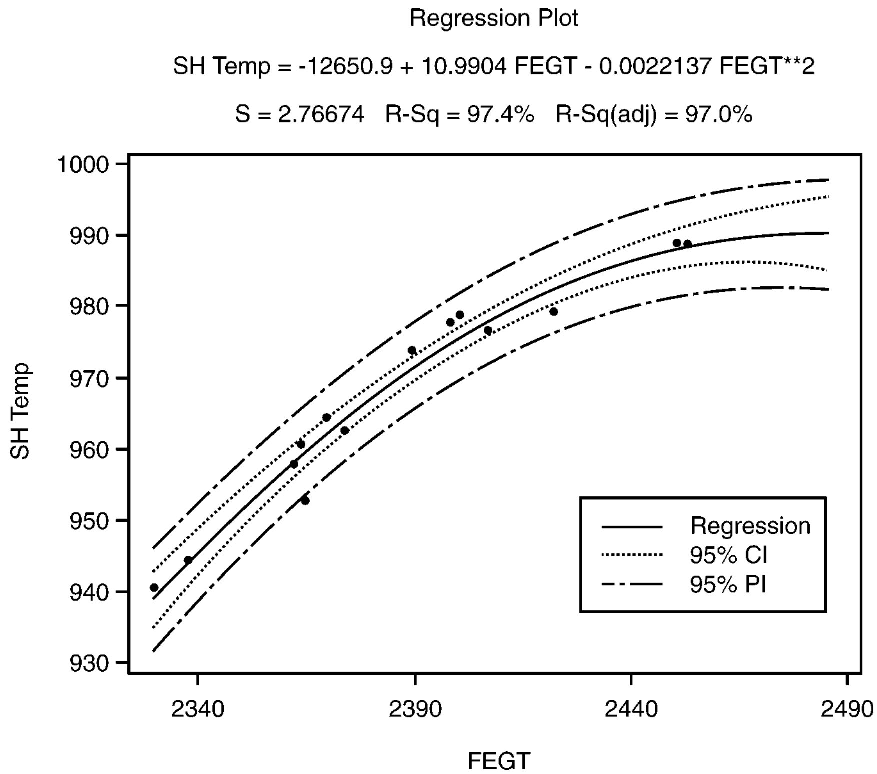


Figure C-8
Minitab Output for Analysis of Polynomial Regression Analysis: SH Temperature vs. FEGT

Glossary

Adjusted multiple coefficient of determination: A measure of the goodness of fit of the estimated multiple regression equation that adjusts for the number of independent variables in the model and thus avoids overestimating the impact of adding more independent variables.

Analysis of variance (ANOVA) table: The analysis of variance table used to summarize the computations associated with the F-test for significance.

Confidence interval: The confidence associated with an interval estimate. For example, if a procedure will include the population parameter, the interval estimate is said to be constructed at the 95% confidence level; note that .95 is referred to as the confidence coefficient.

Cook's distance measure: A measure of the influence of an observation based on the residual and leverage.

Correlation coefficient: A numerical measure of linear association between two variables that takes values between -1 and +1. Values near +1 indicate a strong positive linear relationship. Values near -1 indicate a strong negative linear relationship, and values near zero indicate lack of a linear relationship.

Degrees of freedom: When the t-distribution is used in the computation of an interval estimate of a population mean, the appropriate t-distribution has n – 1 degrees of freedom, when n is the size of the simple random sample.

Dependent variable: The variable that is being predicted or explained. It is denoted by y.

Dummy variable: A variable used to model the effect of qualitative independent variables. A dummy variable might take only the value zero or one.

Estimated multiple regression equation: The estimate of the multiple regression equation based on sample data and the least squares method; it is • $= b_0 + b_1x_1 + b_2x_2 + \text{----} + b_px_p$.

F-Test: An F-test is based on the F-probability distribution, which can be used to test for significance in regression.

Independent variable: The variable that is performing the predicting or explaining. It is denoted by x.

Influential observation: An observation that has a strong influence on the regression results.

Interval estimate: An estimate of a population parameter that provides an interval believed to contain the value of the parameter.

Least squares method: The method used to develop the estimated regression equation. It minimizes the sum of squared residuals [the deviations between the observed values of the dependent variable (y_i) and the estimated values of the dependent variable (•$_i$)].

Leverage: A measure of how far the values of the independent variables err from their mean values.

Multicollinearity: The term used to describe the correlation among the independent variables.

Multiple coefficient of determination: A measure of the goodness of fit of the estimated multiple regression equation. It can be interpreted as the proportion of the variation in the dependent variable that is explained by the estimated regression equation.

Multiple regression: Regression analysis involving two or more independent variables.

Multiple regression equation: The mathematical equation relating the expected value or mean value of the dependent variable to the values of the independent variables (that is, $E(y) = \beta_0 + \beta_1x_1 + \beta_2x_2 + \text{----} + \beta_px_p$)

Multiple regression model: The mathematical equation that describes how the dependent variable y is related to the independent variables x_1, x_2, ..., x_p, and an error term ε.

Normal probability plot: A graph of normal scores plotted against values of the standardized residuals. This plot helps determine if the assumption that the error term has a normal probability distribution appears to be valid.

Outlier: An observation that does not fit the pattern of the other data.

Prediction interval estimate: The interval estimate of an individual value of y for a given value of x.

P-value: It is often called the observed level of the probability

Qualitative independent variable: An independent variable with qualitative data,

Residual: The difference between the observed value of the dependent variable and the value predicted by using the estimated regression equation (that is, for the ith observation the residual is $y_i - \bullet_i$)

Residual analysis: The analysis of the residuals used to determine if the assumptions made about the regression model appear to be valid. Residual analysis is also used to identify unusual and influential observations.

Scatter diagram: A graph of bivariate data in which the independent variable is on the horizontal axis and the dependent variable is on the vertical axis.

Studentized deleted residuals: Standardized residuals that are based on a revised standard error of the estimate obtained by deleting observation i from the data set, and then performing the regression analysis and computations.

t-Test: A t-test is based on the t-probability distribution, which can be used to test for significance in regression.

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Minitab Statistical Software, Release 13, February 2000.

D
DESIGN OF EXPERIMENT

Introduction

In statistical analysis, decisions are made based on the results of data analysis. There are historical data—which might be available, but are usually incomplete and the information surrounding how the data was collected or information about other factors is usually missing. Also, tests might need to be done with the input variables at levels or combinations where the process never operated. A proper approach is Design of Experiment (DOE). DOE is a systematic approach to obtaining the desired amount of information in the most efficient manner. According to the Encyclopedia Americana, an experiment is an operation designed to establish or discover some truth, principle, or effect. DOE uses knowledge of statistics to select the test points that will give the maximum information on the system being studied and the chance of missing a true optimum point is dramatically minimized. This appendix briefly discusses planning and conducting experiments to obtain the necessary data. For a detailed discussion of DOE, refer to statistical books.

In any experiment, the method of data collection can adversely affect the conclusions that can be drawn from the experiment. There are several approaches that can be taken to design the experiments:

- **Best estimate:** Engineers frequently use this approach of experimentation. Engineers often make the initial selection of critical factors and ignore other less important factors. This approach often works reasonably well, because the engineers often have a great deal of technical knowledge of the process and a considerable amount of practical experience. There are two disadvantages of the best-estimate approach. First, if the initial best estimate does not produce the desired results, then the engineer has to take another estimate at a different combination. This could continue for a long time without any guarantee of success. Second, if the initial best estimate produces an acceptable result, then the engineer is tempted to stop testing, although there is no guarantee that the optimum solution has been found.
- **One-factor-at-a-time:** This is a classical experiment. This method consists of selecting a factor, and then successively varying this factor over its range with other factors held constant. Studying one factor at a time seems to be accurate because one can get a clear understanding of the performance of the observed factor. However, such an approach has the following shortcomings:
  - Confidence levels cannot be attached to the estimates of effects.
  - It does not estimate the residual (experimental) error in test data.
  - It does not estimate the effect of interactions resulting from the multiple factors or it assumes that the effect of interactions between factors is negligible. Interactions

between factors are very common in the engineering field and, if they occur, the one-factor-at-a-time strategy might not produce good results.

- **Factorial design:** Factorial design is a statistical technique that investigates the effects of multiple factors (variables) by conducting the experiments at all possible combinations of levels of the factors. This approach evaluates the effects of factors simultaneously and considers the interaction between the multiple factors. The factorial experiments make the most efficient use of the experimental data. Although it is a correct approach to dealing with multiple factors, full factorial design can be very expensive, particularly for models with many factors that vary in many levels, because the experimental size multiplies quickly.

  Interval estimates and residual error analysis can be performed through a factorial experiment with the aid of the analysis of variance. Analysis of variance is a powerful technique for analyzing experimental data involving quantitative measurements. It is particularly useful in factorial experiments where several independent sources of variation might be present. Experiments can be used to study the performance of processes and systems. A typical model is shown in Figure D-1. Some of the process variables are controllable, whereas other variables are uncontrollable.

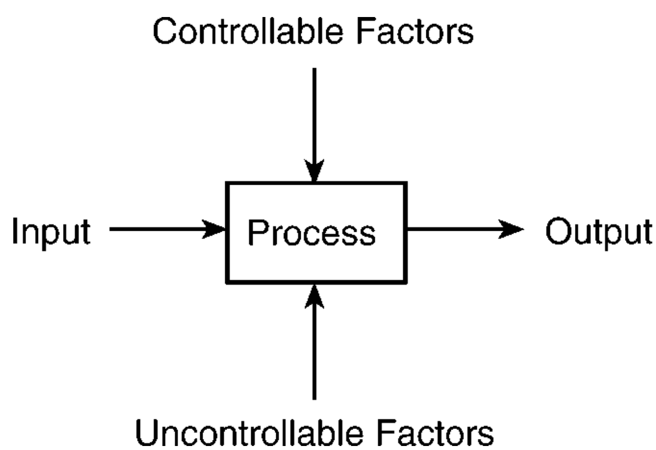

Figure D-1
General Model of a Process or System

  The total variation within an experiment can be broken down into variations due to each main factor, interacting factors, and experimental errors. The significance of each variation is then tested. Variables other than those investigated should be properly controlled. There are uncontrollable or unknown variables, such as environmental changes, operator efficiency, and drift in test instruments. The experiment can be conducted so that the influence of these variables is randomly distributed throughout the test.

- **Fractional factorial experiments:** The complete factorial design requires the use of every combination of the different levels of the factors. Generally, if there are k factors, each at n levels, the factorial design would require n^k experiments. As the number of factors and the level of testing increases, the number of tests required increases rapidly. In some situations, these experiments can be costly and become impractical. Instead, a fractional factorial experiment can be performed. A fractional factorial experiment is a variation of the basic factorial design in which only a subset of the tests is made. There are several fractional factorial experiment methods available:

- *Predetermined test combinations:* In this method, the test combinations are selected from the total of all possible combinations to obtain the desired information about the main factors and their interacting effects. Several predetermined fractional factorial design test plans are available including up to 10 factors, each at two or three levels. The most frequently used one is the Yates' procedure.
- *Randomly selected test combinations:* This method enables one to independently estimate the effect of a large number of factors with the amount of testing considerably less than the method predetermined test combinations. The disadvantage is that confidence levels cannot be established in estimating the influence of the factors because the method involves making a decision from the trend of the results when graphically plotted.
- *Orthogonal arrays:* Orthogonal arrays in combination with analysis of variance and means provide an economical, efficient method for planning and executing experiments. Developed in the 1920s by Sir Ronald Fisher to expedite agronomy experiments, the method has been expanded and applied by many investigators (for example, Box, Hunter, and Taguchi). Some of the advantages for using orthogonal arrays include:
  - Substantially more information can be extracted from a limited number of experiments.
  - Each factor's contribution can be evaluated even though several variables are changed in each experiment.
  - The experiment can show the direction of recommended changes for the values of each test factor.
  - The experiment can disclose which of the tested variables have the most influence on the variability of the performance. These are identified as the dominant parameters.
  - Parameters found by the study to have less effect upon variability of the target performance but still affect the mean values are termed signal parameters. These should be used to adjust the design to yield the desired target performance after the control parameters have been set.

Taguchi devised a technique that combines experiments using orthogonal arrays and signal/noise ratio studies to experimentally optimize for robustness. Taguchi's orthogonal arrays is a special case of these fractional orthogonal factorial matrix experiments.

Basic Principles

Statistical DOE refers to the process of planning the experiment so that appropriate data can be collected and analyzed by statistical methods to obtain valid and objective conclusions. The three basic principles of experimental design are replication, randomization, and blocking:

- **Replication:** Replication is a repetition of the basic experiment. Replication has two important properties. First, it allows the experimenter to obtain an estimate of the experimental error. This estimate of error becomes a basic unit of measurement for determining if observed differences in the data are really statistically different. Second, if the sample mean is used to estimate the effect of a factor in the experiment, replication permits the experimenter to obtain a more precise estimate of this effect.
- **Randomization:** Randomization requires that the order of the experiment being performed is randomly determined. Statistical methods require that the observations (or errors) be independently distributed random variables. Randomization usually makes this assumption valid. The random order is usually created by using a random number generator.
- **Blocking:** Blocking is a design technique used to improve the precision with which comparisons among the factors of interest are made. Often blocking is used to reduce or eliminate the variability transmitted from nuisance factors (that is, factors that might influence the experimental response but in which we are not directly interested). Generally, a block is a set of relatively homogeneous experimental conditions. Typically, each level of the nuisance factor becomes a block. Then the experimenter divides the observations from the statistical design into groups that are run in each block.

Guidelines for DOE

To use statistical approaches in designing and analyzing an experiment, it is necessary for everyone involved in the experiment to have a clear idea in advance of exactly what is to be studied, how the data are to be collected, and at least a qualitative understanding of how these data are to be analyzed. A recommended procedure includes recognition of and statement of the problem; selection of the response and choice of factors, levels, and ranges; choice of experimental design; performing the experiment; and statistical analysis of the data:

- **Recognition of and statement of the problem:** It is usually helpful to prepare a list of specific problems or questions that are to be addressed by the experiment. A clear statement of the problem often contributes substantially to a better understanding of the phenomenon being studied and the final solution of the problem. It is also important to keep the overall objective in mind. There are many possible objectives of an experiment, including confirmation, discovery, and stability. Obviously, the specific questions to be addressed in the experiment relate directly to the overall objectives. One large comprehensive experiment is sometimes unlikely to answer the key questions and a sequential approach using a series of smaller experiments is a better strategy.
- **Selection of the response variable and choice of factors, ranges, and levels:** Experimenters are usually highly knowledgeable in their fields. In some fields there is a large body of physical theory on which to draw in explaining relationships between factors and responses. This type of non-statistical knowledge is invaluable in choosing factors, determining factor levels, deciding how many replicates to run, and interpreting the results of the analysis. Using statistics is no substitute for thinking about the problem. In selecting the response variable, the experimenter should be certain that this variable really provides useful information about the process under study. The input factors can be classified as either potential design factors or nuisance factors.

The potential design factors are those factors that the experimenter might wish to vary in the experiment. Often we find that there are a lot of potential design factors, and some further classification of them is helpful. Some useful classifications are design factors, held-constant factors, and allowed-to-vary factors. The design factors are the factors actually selected for study in the experiment. Held-constant factors are variables that might exert some effect on the response, but for purposes of the present experiment these factors are not of interest or difficult to vary, so they will be held at a specific level.

Nuisance factors, on the other hand, might have large effects that must be accounted for, yet we might not be interested in them in the context of the present experiment. Nuisance factors are often classified as controllable, uncontrollable, or noise factors. A controllable nuisance factor is one whose levels might be set by the experimenter. The blocking principal is often useful in dealing with controllable nuisance factors. When a factor that varies naturally and uncontrollably in the process can be controlled for purposes of an experiment, it is called a noise factor. In such situations, our objective is usually to find the settings of the controllable design factors that minimize the variability transmitted from the noise factors.

Once the experimenter has selected the design factors, the next step is to choose the ranges over which these factors will be varied, and the specific levels at which runs will be made. Thought must also be given to how these factors are to be controlled at the desired values and how they are to be measured. The experimenter will also have to decide on a region of interest for each variable and on how many levels of each variable to use. Process knowledge is required to do this. This process knowledge is usually a combination of practical experience and theoretical understanding. It is important to investigate all factors that might be of importance and not to be overly influenced by past experience.

- **Choice of experimental design:** Choice of design involves the consideration of sample size (number of replicates), the selection of a suitable run order for the experimental trials, and the determination of whether or not blocking or other randomization restrictions are involved. There are also several interactive statistical software packages that support this phase of experimental design. The experimenter can enter information about the number of factors, levels, and ranges, and these programs will either present a selection of designs for consideration or recommend a particular design. In selecting the design, it is important to keep the experimental objectives in mind. In many engineering experiments, we already know at the outset that some of the factor levels will result in different values for the response. Consequently, we are interested in identifying which factors cause this difference and in estimating the magnitude of the response change.
- **Performing the experiment:** When running the experiment, it is vital to monitor the process carefully to ensure that everything is being done according to plan. Errors in experimental procedure at this stage will usually destroy experimental validity. Up-front planning is crucial to success.
- **Statistical analysis of the data:** The purpose of data analysis is to develop models that extract information. A model is used to extract information from existing data and predict the outcome about which a decision is to be made. Generally, a model is any device that enhances extraction of information for purposes of making decisions. There are many excellent software packages that can be used to assist in data analysis. Simple graphical methods play an important role in data analysis and interpretation. It is also usually very helpful to present the results in terms of an empirical model that expresses the relationship

between the response and the important design factors. Residual analysis and model adequacy checking are also important analysis techniques. More discussion is presented in Appendix C.

Experimentation is an important part of the learning process (for example, tentatively formulating hypotheses about a system, performing experiments to investigate these hypotheses, and formulating new hypotheses based on the results, if necessary). This suggests that experimentation is iterative. It can be a major mistake to design a single, large, comprehensive experiment at the starting point. A successful experiment requires knowledge of the important factors, the ranges over which these factors should be varied, and the appropriate number of levels to use. Generally, the answers to these questions might not be available at the beginning. As an experimental program progresses, some variables will be dropped or added and ranges/levels will be modified. Consequently, the experiment should be performed sequentially.

Statistical methods cannot prove that a factor (or factors) has a particular effect. They only provide guidelines as to the reliability and validity of results. Properly applied, statistical methods do allow us the measurement of the likely error in a conclusion or to attach a level of confidence to a statement. The primary advantage of statistical methods is that they add objectivity to the decision-making process. Statistical techniques coupled with good engineering or process knowledge and common sense will usually lead to sound conclusions.

Many engineering problems are empirical and can make extensive use of DOE. Statistical methods can greatly increase the efficiency of these experiments and often strengthen the conclusions so obtained. In summary, the proper use of experimental design requires the following important considerations:

- Use your non-statistical knowledge of the problem.
- Keep the design and analysis as simple as possible.
- Randomize experiments to average out effects of uncontrolled variables.
- Ensure the estimates of factors and response variables are unbiased.
- Evaluate factors over a wide range that the process can be or might operate.
- Ensure the repeatability of the data, record in detail how the experiment was performed, and include comments on uncontrollable variables.
- Consider the number of repetitions that will be run. This can influence the accuracy of the experiment.
- Recognize the difference between practical and statistical significance.
- Perform iterations, if required.

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