Advanced Monitoring to Improve Combustion Turbine/Combined Cycle Reliability, Availability & Maintainability

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ABSTRACT

Power generators are concerned with the maintenance costs associated with the advanced turbines that they are purchasing. Since these machines do not have fully established *Operation and Maintenance* (O&M) track records, power generators face financial risk due to uncertain future maintenance costs. This risk is of particular concern, as the electricity industry transitions to a competitive business environment in which unexpected O&M costs cannot be passed through to consumers.

These concerns have accelerated the need for intelligent software-based diagnostic systems that can monitor the health of a combustion turbine in real time and provide valuable information on the machine's performance to its owner/operators. EPRI, Impact Technologies, Boyce Engineering, and Progress Energy have teamed to develop a suite of intelligent software tools integrated with a diagnostic monitoring platform that, in real time, interpret data to assess the "total health" of combustion turbines. The *Combustion Turbine Health Management System* (CTHMS) will consist of a series of *Dynamic Link Library* (DLL) programs residing on a diagnostic monitoring platform that accepts turbine health data from existing monitoring instrumentation.

CTHMS interprets sensor and instrument outputs, correlates them to a machine's condition, provide interpretative analyses, project servicing intervals, and estimate remaining component life. In addition, the CTHMS enables real-time anomaly detection and diagnostics of performance and mechanical faults, enabling power producers to more accurately predict critical component remaining useful life and turbine degradation.

ACRONYMS

ANN	Artificial Neural Network
ASME	American Society of Mechanical Engineers
CSBHX	Compressor bleed valve position
CC	Combined Cycle
CCPFDM	Combined Cycle Performance and Fault Diagnostic Module
CDP	Compressor Discharge Pressure
CDT	Compressor Discharge Temperature
CIT	Compressor Inlet Temperature
COND	Condenser/cooling water system
COTS	Commercially Available Off-the-Shelf
CSBHX	Compressor Bleed Valve Position
CT	Combustion Turbine
CTDHMP	Combustion Turbine Diagnostic Health Monitoring Program
CTHM	Combustion Turbine Health Management
CTHMS	Combustion Turbine Health Management System
CTPFDM	Combustion Turbine Performance and Fault Diagnostic Module
DLL	Dynamic Link Library
DOD	Department of Defense (US)
DOE	Department of Energy (US)
DWATT	Generator output power
EGT	Exhaust Gas Temperature
FFT	Fast Fourier Transform
FQG	Gas fuel flow rate
FSNL	Full Speed, No Load
FSR	Fuel Valve Position
GUI	Graphic User Interface
HRSG	Heat Recovery Steam Generator
HSLMP	Hot Section Life Management Platform
IGV	Inlet Guide Vane
ISA	International Standard Atmosphere
ISO	International Organization of Standardization
LAN	Local Area Network
LHV	Lower Heating Value
MF	Maintenance Factor
NB	Normal Base Load Start
NN	Number of Normal Starts

O&M	Operations and Maintenance
ODBC	Open Data Base Connectivity
OEM	Original Equipment Manufacturer
OSI	OSIsoft, Inc.
PI	OSIsoft's data historian system
PXI	PCI eXtension for Instrumentation
RAM	Reliability, Availability and Maintenance
RLM	Remaining Life Module
RMS	Root Mean Square
SI	International System of Units
SQL	Structured Query Language
ST	Steam Turbine
SUDM	Start-up Diagnostics Module
SVRM	Sensor Validation and Recovery Module
SWPC	Siemens Westinghouse Power Corp.
TMF	Thermal Mechanical Fatigue
TNH	Turbine Shaft Speed
TSL	Transient Speed Limit
TTI	Turbine Technology, Inc.
VFDS	Vibration Fault Diagnostic System
VPN	Virtual Private Network

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1 INTRODUCTION

Power producers are justifiably concerned with the maintenance costs associated with the advanced *Combustion Turbines* (CTs) they are purchasing today. While more efficient and environmentally clean than previous models, some advanced CT models do not have fully established *Operation and Maintenance* (O&M) track records and without accurate information upon which to base maintenance decisions, optimizing system life while minimizing costs can be extremely difficult for operators. As a result, power producers face financial risk due to uncertain future maintenance costs and turbine life. This risk is of particular concern in today's increasingly competitive business environment in which reserve margins are shrinking and unexpected O&M costs usually cannot be passed through to consumers.

These concerns have accelerated the need for intelligent software-based diagnostic systems that can monitor the health of a CT in real time and provide owners and operators with valuable information on machine performance. While commercial systems - ranging from time-history database/display systems to model-specific operation/performance monitoring systems - are available, they have limited diagnostic capability and their results typically require expert interpretation. To date, neither CT manufacturers nor owners have developed a comprehensive diagnostic monitoring system, primarily because of the cost and the need for historical data from many units operating over the entire commercial operating spectrum.

To meet this need, the *Department of Energy* (DOE) selected EPRI to lead the development of a comprehensive suite of intelligent diagnostic tools for assessing the total health of CTs. The resulting *Combustion Turbine Health Management System* (CTHMS) will improve the *Reliability, Availability and Maintainability* (RAM) of CTs in simple-cycle and combined-cycle configurations.

EPRI, Impact Technologies, Boyce Engineering, and Progress Energy have teamed to develop a suite of intelligent software tools integrated with a diagnostic monitoring platform that will, in real time, interpret data to assess the "total health" of combustion turbines. The CTHMS consists of a series of *Dynamic Link Library* (DLL) programs residing on a diagnostic monitoring platform that accepts turbine health data from existing monitoring instrumentation.

CTHMS interprets sensor and instrument outputs, correlate them to a machine's condition, provide interpretative analyses, project servicing intervals, and estimate remaining component life. In addition, CTHMS enables real-time anomaly detection and diagnostics of performance and mechanical faults, enabling power producers to more accurately predict critical component remaining useful life and turbine degradation.

Project Objective

The objective of the proposed project was to develop new monitoring techniques for CT power generation in simple or combined-cycle configurations aimed at improving the RAM and overall performance/capacity factor. The project team developed advanced, probabilistic and artificially intelligent performance and mechanical fault diagnostics algorithms, sensor validation and recovery modules, as well as prognostics for maintenance-intensive CT areas.

Program Goals, Research Objectives and Project Objectives

The goal of this proposed project is to improve the *Reliability, Availability and Maintainability* (RAM) and overall performance/capacity factor of combustion turbines by developing advanced health monitoring and management techniques. The objective is to develop a suite of intelligent software tools integrated with a diagnostic monitoring platform that will, in real time, interpret data to assess the “total health” of combustion turbines.

Methodology

The project team applied and adapted know-how developed under prior *Department of Defense* (DOD)/Navy/NASA programs aimed at advanced health monitoring of aviation gas turbines. The project team will develop advanced probabilistic and artificially intelligent performance and mechanical fault diagnostics algorithms, sensory validation and recovery modules, and prognostics for maintenance-intensive CT areas.

Description of the Technology

The *Combustion Turbine Health Management System* (CTHMS) consists of a series of *Dynamic Link Library* (DLL) programs residing on a diagnostic monitoring platform that accepts turbine health data from existing monitoring instrumentation. The real-time CTHMS application algorithms proposed are intended to produce a comprehensive array of intelligent tools for assessing the “total health” of a combustion turbine, both mechanically and thermodynamically. CTHMS includes the integration of real-time anomaly detection and diagnostics of performance and mechanical faults in addition to the prediction of critical component remaining useful life and turbine degradation.

Advanced signal processing algorithms utilizing correlation and coherence detection are combined with artificial intelligence and model-based algorithms to provide comprehensive coverage of the critical CT failure modes of interest. Prognostic algorithms have also been developed that accept diagnostic system results, model-based remaining useful life predictions, operating/maintenance histories and historical RAM data to provide real-time predictions on reliability and degraded performance of key CT components. Through proper utilization of these health management technologies, timely decisions can be made regarding unit operation and maintenance practices.

The neural network algorithm operates by comparing the physical relationships between signals as determined from either a baseline empirical model or computer model of the turbine's performance parameters. The fuzzy logic based sensor validation continuously checks the "normal" bands (membership functions) associated with each sensor signal at the current operating condition. When a signal goes outside these membership functions, while others remain within, an anomaly is detected associated with those specific sensors. Finally, signal correlation and special digital filters are used to determine if even small levels of noise are present on a particular signal. These approaches are implemented in parallel and then combined in a probabilistic data fusion process that determines the final confidence levels that a particular sensor has either failed or has suspect operation.

The integration of prognostic technologies within existing diagnostic systems begins with validated sensor information on the engine being fed directly into the diagnostic algorithms for fault detection/isolation and classification. The ability of an enhanced diagnostic system to fuse information from multiple diagnostic sources together to provide a more confident diagnosis is emphasized along with a system's ability to estimate confidence and severity levels associated with a particular diagnosis. In a parallel mode, the validated sensor data and real-time current/past diagnostic information is utilized by the prognostic modules to predict future time-to-failure, failure rates and/or degraded engine condition (i.e., vibration alarm limits, performance margins, etc.). The prognostic modules will utilize physics-based, stochastic models taking into account randomness in operation profiles, extreme operating events and component forcing. In addition, the diagnostic results will be combined with past history information to train real-time algorithms (such as neural networks or real-time probabilistic models) to continuously update the projections on remaining life.

Once predictions of time-to-failure or degraded condition are determined with associated confidence bounds, the prognostic failure distribution projections can be used in a risk-based analysis to optimize the time for performing specific maintenance tasks. A process that examines the expected value between performing maintenance on an engine or component at the next opportunity (therefore reducing risk but at a cost of doing the maintenance) versus delaying maintenance action (potential continued increased risk but delaying maintenance cost) can be used for this purpose.

The difference in risk between the two maintenance or operating scenarios and associated consequential and fixed costs can then be used to optimize the maintenance intervals or alter operational plans. As key aspect of the proposed technical approach, this project will tap a unique resource of engine fault data developed under the Navy and Air Force with its resulting diagnostic knowledge base. This test cell engine fault data is unavailable for heavy frame machines and will require many machine-operating years to duplicate. The project substantially reduces its development costs and subsequent field validation by using experts and limited land-based CT data to modify the existing flight engine diagnostic database.

Anticipated Benefits

There is a great opportunity for power generation combustion turbines to become more reliable, operationally available and economically maintained through the use of enhanced diagnostic and prognostic strategies such as those presented in this proposal. The development and integration of enhanced diagnostic and prognostic algorithms that can predict, within a specified confidence bound, time-to-failure of critical engine components can provide many benefits including:

- Reduced overall life cycle costs of engines from installation to retirement
- Ability to optimize maintenance intervals for specific engines or fleets of engines and prioritization of tasks to be performed during the planned maintenance events
- Increased up-time/availability of all engines within a fleet
- Provides engineering justification for scheduling maintenance actions with corresponding economic benefits clearly identifiable
- Improved safety associated with operating and maintaining combustion turbine engines

The maintenance outage factors for the F/FA frame and the mature frame technology are significantly divergent, with CT core systems being the primary drivers with outage factors of 10.074% and 5.080%, respectively. The core combustion turbine system problems can be attributed to new-design introduction centered on inherent design flaws, manufacturing/assembly problems, and the combustion system. These design break-in issues will eventually be supplanted by service-imposed mechanical/electrical degradation and outage assembly problems. Diagnostic monitoring as an integral component of a proactive maintenance program should certainly meet mature fleet RAM performance. By avoidance of serious damage and improved maintenance scheduling, 2% availability points are achievable.

For each 500 MW combined cycle, this improvement represents 72,000 MWhr valued at $3M per year. For a 100 unit combined cycle fleet, or approximately half of the 30 GW new generation projected, a $300M per year cost-avoidance savings appears achievable.

Scope of Project

As discussed above, development of a comprehensive *Combustion Turbine Health Management System* (CTHMS) will play a critical role in reducing the cost of electricity by improving reliability, availability, and maintainability. The real-time health management technologies described in this report use a combination of probabilistic and artificial-intelligence-based tools to assess both thermodynamic and mechanical health of combustion turbines. These technologies include software modules:

- *Sensor Validation and Recovery Module* (SVRM)
- *Combustion Turbine/Combined Cycle Performance and Fault Diagnostic Modules* (CTPFDM and CCPFDM)
- *Start-Up Diagnostic Module* (SUDM)
- *Vibration Fault Diagnostic System* (VFDS)
- *Remaining Life Module* (RLM)

Sensor Validation and Recovery Module (SVRM)

Sensor validation is an important front end of the health management system that checks the integrity of sensed data before it is passed to the diagnostic and prognostic modules. The sensor validation software utilizes a combination or fusion of neural network model-based and generic signal-processing approaches to ensure the highest possible sensor fault detection confidence with minimal false alarms. In the event that a gas path sensor fault is detected, neural network models are used in calculating proxy or "recovered" signal values that allow diagnostic and component life assessments until the fault is corrected. Section 2 describes the *Sensor Validation and Recovery Module* (SVRM) developed for a GE Frame 7FA application.

Combustion Turbine/Combined Cycle Performance and Fault Diagnostic Modules (CTPFDM and CCPFDM)

Section 3 describes the *Combustion Turbine Performance and Fault Diagnostic Module* (CTPFDM) - a low-cost, easy-to-use program for monitoring CT performance, both on an overall basis and on a component-by-component basis. The CTPFDM carries out six main functions– data checking, measured (or actual) performance, expected performance, corrected performance, evaporative cooling performance, and fault diagnostics. Section 4 describes the CCPFDM — an add-on, low-cost, easy-to-use program for monitoring and diagnosing the condition of the plant and determining the benefits of maintenance actions. Both programs - which operate as spreadsheets with macros in Microsoft's Excel (97 or later) and run under Windows NT/95/98/2000 operating systems - can be used simultaneously for monitoring multiple combustion turbines and combined cycle units.

Start-Up Diagnostic Module (SUDM)

Section 5 describes the *Start-Up Diagnostic Module* (SUDM) – a low-cost, easy-to-use software tool that operators can use to diagnosis problems that arise during the start-up phase of a *Combustion Turbine* (CT). The SUDM should be particularly useful for CTs in peaking or cycling service that start and stop frequently and are relied upon to provide power on short notice. Reliable starting is an important characteristic for CTs in peaking service, and therefore a tool that can help operators detect starting problems before they impact reliability should provide significant value. The SUDM facilitates the diagnosis of problems by comparing the start-up trends versus time from one start to another. By comparing the trends of a CT that may have equipment health issues to the trends from a start when the machine was known to be in good condition, it is possible to identify potential problems.

Remaining Life Module (RLM)

Section 6 describes the design of a remaining life module (RLM) - a low-cost, easy-to-use software program for calculating the remaining life of the hot section components of General Electric (GE) heavy frame (CTs). The spreadsheet-based RLM incorporates the remaining life formulas described in GE's GER-3620J technical report. It also incorporates the *Hot Section Life Management Platform* (HSLMP) algorithms EPRI has developed for the GE 7FA+ first stage buckets. These two methods for estimating remaining life will allow CT operators to plan maintenance actions in a manner that reduces overall life cycle costs. RLM features automated access to CT operating data, which allows the actual operating history of the engine to be factored into the remaining life calculations.

Vibration Fault Diagnostic System

Section 7 describes the *Vibration Fault Diagnostics System* (VFDS). A real-time health monitoring system requires sophisticated hardware and software technology to accurately identify a mechanical vibration fault. A comprehensive vibration analysis system was developed to aid personnel in detecting incipient mechanical fault conditions and planning appropriate maintenance actions. The VFDS utilizes high bandwidth vibration data to extract low bandwidth feature data. The low bandwidth feature data, in addition to being posted to an available PI Historian, is used by the diagnostic reasoner to identify actionable failure modes development of this system to enhance real-time fault identification and reduce the likelihood of unscheduled maintenance.

A suite of algorithms have been refined and are employed by the VFDS module to pre-process and analyze raw vibration signals, screening the data for indications of performance irregularities.

Section 7 outlines many of the design decisions made during development of the VFDS. The issues include, but are not limited to a discussion of the hardware selected for housing the host embedded controller and data acquisition equipment, a discussion of the development and operation of the software, and material detailing the calculation of features used to feed the diagnostic reasoner. This is followed by a presentation of the Dempster-Shafer method of data fusion in determining the final fault diagnosis.

2
SENSOR VALIDATION AND RECOVERY MODULE

Introduction

The industry wide interest in condition-based maintenance strategies has prompted development of sophisticated, automated condition assessment tools. Comprehensive *Combustion Turbine Health Management* (CTHM) includes the integration of real-time anomaly detection and diagnostics of performance and mechanical faults in addition to the prediction of critical component remaining useful life and turbine degradation. Through proper utilization of these health management technologies, timely decisions can be made regarding unit operation and maintenance practices. A primary concern when implementing real-time or off-line health management technologies is to insure the reliability of the measured parameters. When automated algorithms identify a performance or vibration fault, the diagnostic system must be confident that the faults are indeed occurring and are not the result of normal system transients or faulty sensors. Therefore, a comprehensive sensor analysis module is recommended as a front-end to validate the integrity of sensor signals, recover failed signals, and predict important parameters that are not sensed on the CT.

The purpose of this module to act as a pre-processing step utilized by automated condition assessment tools, validating the integrity of the sensor output before being utilized by health assessment algorithms. This module obtains data directly from the data archive and determines the presence of erroneous data. Here, erroneous data refers to data which do not reflect the current state of the underlying parameter. EPRI obtained the support of Progress Energy's Asheville plant for the data required for development. Upon completion of the validation determination, should anomalous values be detected, the 'recovery' portion of the module offers a reasonable replacement value for utilization in further health assessment algorithms.

The sensor validation process employed in the CTHM *Sensor Validation and Recovery Module* (SVRM) utilizes technically independent, but collaborative techniques. Neural networks, fuzzy-logic, and generic signal processing techniques are employed to thoroughly examine the integrity of the output received from the sensors being validated. The neural network operates by comparing the physical relationships between signals as determined from a baseline empirical data from the turbine's performance parameters. The fuzzy logic based sensor validation continuously checks the "normal" bands (membership functions) associated with each sensor signal at the current operating condition. When a signal goes outside these membership functions, while others remain within, an anomaly is detected associated with those specific sensors. Finally, generic signal processing techniques are utilized to determine the presence of any anomalies that may manifest themselves as jump discontinuities or excessive noise in the underlying signals. These parallel algorithms are combined in a probabilistic data fusion process that determines the final confidence levels that a particular sensor has either failed or has suspect operation.

As previously stated, robust, automated CT condition assessment tools require verification of the integrity of the inputs. As such, the selection of parameters to be validated by the SVRM is based on the requirements of the performance algorithms to insure that the inputs are valid. The current CT health assessment utility requires a selection of inputs covering the gas path parameters in addition to ambient condition information (see Table 2-1).

The SVRM has been developed to operate in two modes in an effort to maximize its utility. The first is a batch analysis mode, which was established based on discussions with on-site personnel, to operate in an automated manner. A timer is utilized to initiate an analysis, in the early hours of the morning when network traffic is at its low point, on data from the previous day's operation. The second mode features a user defined, interactive mode. In this mode personnel can specify the time period over which the analysis will take place from a user interface.

An in depth discussion is presented in this report covering the components of the SVRM. This will include topics covering; the architecture of the SVRM, the selection of sensors to be validated, consideration of hysteretic effects on the parameters, validation techniques and finally sensor recovery.

Data Retrieval

Development of the *Sensor Validation and Recovery Module* (SVRM) requires large amounts of data. In order to build in the desired level of robustness the data must span all modes of operation encountered by the CT unit. Data for the development of the algorithms utilized by the SVRM was obtained from the two GE Frame 7FA units operating at Progress Energy's Asheville, North Carolina facility. The CT units are single spool turbines capable of running on either liquid fuel or gas fuel. The base load for the generator units is approximately 165 MW in the summer and 192 MW in the winter.

The development of any automated condition assessment program is contingent upon the seamless flow of this data between the plant's data archive and the health appraisal tool. *Open DataBase Connectivity*, ODBC, has been developed to create an abstract means of passing data, using *Structured Query Language* (SQL), between the database and the application analyzing the data. Utilizing this architecture liberates the process from restrictions due to specific database Input/Output interaction. Secured queries are possible either internally, accessing the system through the plant's internal network, or externally by accessing the local network utilizing a Virtual Private Network to establish connectivity via the Internet.

Process Overview

Implementation of the various modules being developed for the *Combustion Turbine Diagnostic Health Monitoring Program* (CTDHMP) is dependent upon the supply of data being provided from the Asheville PI Historian system. For the development of this program, OSIsoft's PI system offers a Microsoft Excel Add-In called DataLink that is commonly used throughout the industry and can easily interface with the PI Historian via Excel in obtaining data. While the test facility utilizes the PI Historian, the same functionality can be replicated with any data archiving system utilizing the process outlined above.

The data exchange, which takes place between the CTDHMP, Excel, PI DataLink, and the PI Historian, will take place behind the scene, invisible to the operator. The DataLink utility is comprised of several pre-defined functions, which can be called from within the cells of Excel. The data querying process begins with Excel starting as an ActiveX *server*. The application being developed becomes the ActiveX *client*. Information is passed back and forth seamlessly between the client and server as required by the necessary data queries. Queries are conducted based on the sensor *tags*, which are the sensor designations obtained from the *Mark V* control system utilized at the Asheville site. The basic process used in querying the tags is the same regardless of the current operating mode of SVRM, only the periods covered by the queries changes. Initially, a query of the *DWATT* (Generator Output), PI tag is conducted to determine if the unit in question reached a level of operation sufficient for further analysis, i.e. generator output in excess of 65 Megawatts. Upon confirmation of positive results, the remaining PI tags are queried. This process is followed by each query required to satisfy the investigation period defined by the user.

The ActiveX approach stems from the ability of ActiveX to handle formula arrays within Excel. Formula arrays are single formulas applied to a range of cells. The PI DataLink utility is based upon a set of function calls of this type. Upon completion of a data query initiated by PI DataLink from within Excel, examination of the cells reveals that each cell has the identical formula active within it. The formula consists of the DataLink function call with its' accompanying arguments, all contained in curly brackets, {}. This curly brackets designation is what signifies the contents of the cell as a formula array within Excel. Function calls of the type required the Ctrl+Shift+Enter keystroke to enter the function.

Data Querying

As stated above, the querying process is initiated by querying the *DWATT* tag to determine if the unit reached a sufficient level of operation. The search type (DataLink function) utilized here is *Compressed Data (start time/end time)…* This function will conduct a search of the compressed data based on the desired tag and encompassing the date/time between the start time and the end time. Here, the start time and the stop time propagate in one hour increments until the entire period defined by the user for analysis has been covered. Arguments to be supplied to this function call include: "*Tagname*", "*Start Time*", "*End Time*", "*Output Cell*" and "*Filter Expression*." The data query process occurs in two steps. The first step is an initial inquiry, placed into only two adjacent cells, that yields the number of points which satisfy the search criteria. In this case the data archive is queried for data from the desired parameters, over a time period specified by the "*Start Time*" and "*End Time*" and filtered by an expression requesting only values corresponding to periods of generator output in excess of 65 MW. The result from this initial query will be the number of data points found that satisfy the search criteria. In the event that no points satisfy the query requirements, the next hour is queried. If a number of data points is returned, as shown in the left half of Figure 2-1, this integer value is then utilized in redefining a new region of cells to be activated in preparation for the second step in the querying process. This subsequent step of the query process then places the identical formula into each cell contained in the activated region, in the form of a formula array, and executes the function. This results in the designated region being populated by the sought after data values, as shown in the right half of Figure 2-1. The example shown illustrates the results obtained from querying the *CTD* tag for all values from July 11, 2003 for which the level of output from the generator exceeded 65 MW.

	A	B	C	D	E	F
1	G4:CTD					
2	data point	353				
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						

	A	B	C	D	E	F
1	G4:CTD					
2	data points:	353				
3	11-Jul-03 12:08:31	679.125				
4	11-Jul-03 12:08:38	684.75				
5	11-Jul-03 12:08:53	687.375				
6	11-Jul-03 12:09:16	688.625				
7	11-Jul-03 12:10:06	687.625				
8	11-Jul-03 12:10:22	689.625				
9	11-Jul-03 12:11:44	689.125				
10	11-Jul-03 12:12:33	690.1875				
11	11-Jul-03 12:13:36	690.4375				
12	11-Jul-03 12:13:46	692.5				
13	11-Jul-03 12:15:39	691.6875				

Figure 2-1
Screen Captures from Excel Illustrating the Results Obtained from the Two Data Querying Steps

The data values obtained from the queries are then returned to the SVRM for subsequent analysis. Table 2-1 is included to outline the sensors utilized by the performance assessment utility. The column *Comments* lists the availability of the respective sensors at the Asheville site. Sensors that are not available either have a default value, which is substituted into subsequent calculations or will restrict the performance calculations conducted.

Table 2-1
SCAMP Inputs Data Source
(Adapted from the SCAMP Spreadsheet, Version 2, Computer Manual, Table 4-1)

Inputs Row #	Description	English Units	SI Units	Comments
3	Unit Name	N/A	N/A	Displays Name of Unit Being Evaluated
4	Date of Data Capture	N/A	N/A	MM-DD-YYYY
5	Time of Data Capture	N/A	N/A	HH:MM:SS
6	Firing Mode Option	N/A	N/A	0 = base, 1 = peak
7	Fuel Type Option	N/A	N/A	0 = natural gas fuel, 1 = liquid fuel
8	Ambient Temperature	°F	°C	Measurement Available
9	Barometric Pressure	" Hga	bara	Measurement Available
10	Relative Humidity	%	%	Calculated from Dew point
11	Compressor Inlet Temperature	°F	°C	Measurement Available
12	Inlet Filter Pressure Drop	" H_2O	mbar	Measurement Available
13	Total Inlet Pressure Drop	" H_2O	mbar	Default value available
14	Exhaust Pressure Drop	" H_2O	mbar	Default value available
15	Bellmouth Static Pressure Drop	" H_2O	mbar	Optional, used in air flow formula
16	Reserved for Future Use	N/A	N/A	
17	Compressor Discharge Press.	psig	barg	Measurement Available
18	Compressor Discharge Temp.	°F	°C	Measurement Available
19	Inlet Guide Vane Position	degrees	degrees	Measurement Available
20	Power	MW	MW	Measurement Available
21	Natural Gas Fuel Flow	lb/sec	kg/sec	Measurement Available
22	Liquid Fuel Flow	lb/sec	kg/sec	Measurement Available
23	Inlet Air Flow	lb/sec	kg/sec	Not Available on Asheville Units
24	Water Injection Flow	lb/sec	kg/sec	Measurement Available
25	Steam Injection Flow	lb/sec	kg/sec	Default value available
26	Dew Point Temperature	°F	°C	Measurement Available
27	Injected Water Temperature	°F	°C	Default value available
28	Injected Steam Temperature	°F	°C	Default value available
29	Gas Fuel Temperature	°F	°C	Measurement Available
30	Gas Fuel Pressure	psig	barg	Default value available
31	Liquid Fuel Temperature	°F	°C	Default value available
32	Exhaust Temperature	°F	°C	Measurement Available

Data Corrections

Here we will discuss the considerations that went into laying out the architecture of the sensor validation and recovery module. Specifically, an analysis of the hysteretic effects experienced by the parameters as a result of normal operating transients is presented. Sensor output resulting from transient operating modes would require separate consideration if deviations from expected values resulting from hysteretic effects are severe. This study was completed to address this issue and determine the necessity of treating transient modes separately from steady-state operation.

Also presented is the procedure followed for correcting the effects of humidity on gas path parameters utilized in performance calculations. Humidity can have a great effect on performance calculations largely due to the effect it has the properties of air. As such, if one wishes to eliminate as many variabilities due to atmospheric conditions as possible, it becomes necessary to address humidity as well as ambient temperature and pressure.

Transient Effects Transient events manifest themselves in the gas path parameters as a deviation from the expected value for a given level of operation. The variance is due to the response lag of the parameters as the operating levels transition from one to the next. In the event that the response lags become too great, the difference between the parameter's value and the expected value becomes large enough to be interpreted by the sensor validation algorithms as an anomalous signal. To determine the necessity of accounting for hysteretic effects, a mode detection algorithm was applied to the GE Frame 7F data set. Corrected *Compressor_Discharge_Temperature* (CTD) values corresponding to steady-state operating mode data were compared to the complete data set for *Generator Load* (DWATT) values of 98 Mega Watts and above. Figure 2-2 and 2-3 illustrate the results obtained for corrected values of CTD.

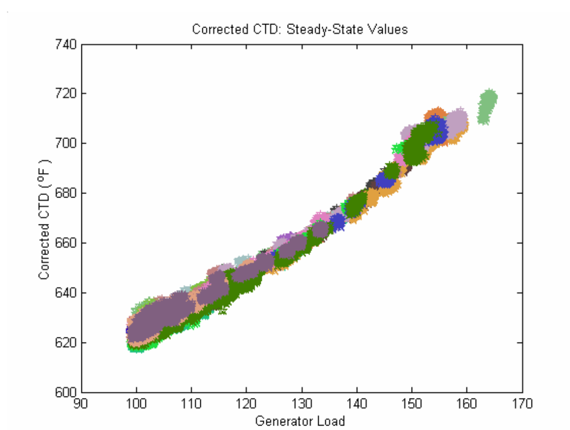


Figure 2-2
CTD Steady-State Values

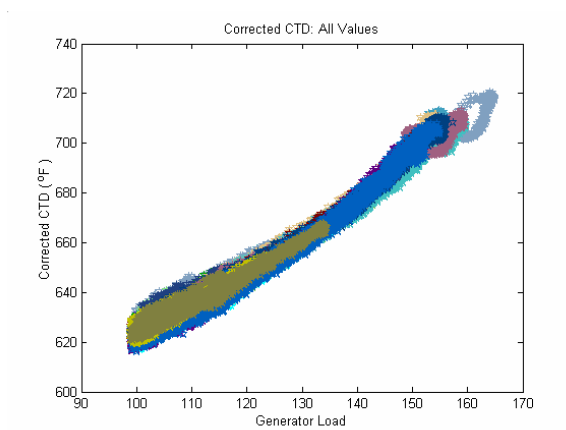


Figure 2-3
CTD Steady-State and Transient Value

Clearly the results shown in Figure 2-3 illustrate slightly broader data scatter across the range of operation characteristic of hysteresis as transient events occur. The scatter differential between the steady-state only data and the data set including transient data, however, is less than 1% of the expected value and therefore of little consequence with regard to the sensor validation module which focuses on much larger differentials.

Figure 2-4 illustrates the analysis behind the determination. The curves represent the distribution of compressor discharge temperature values, corrected to "ISO standard day" conditions as covered in the following two sections, corresponding to a generator load of 110 Megawatts. This region of output was selected because it was one of the most densely populated. The distributions do appear to be different; however, within the framework of the sensor validation module these differences are not significant enough to warrant separation of the steady-state data from the transient data.

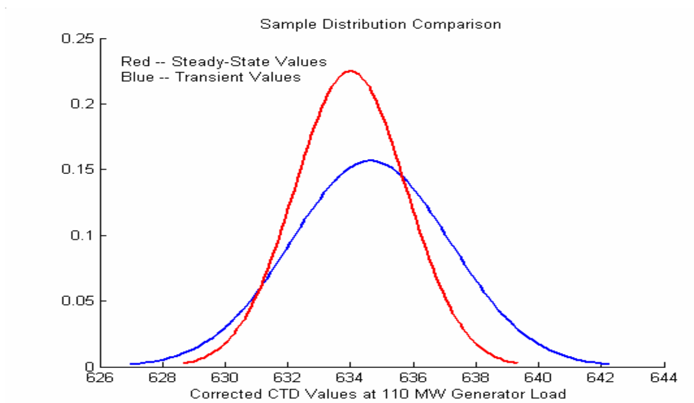


Figure 2-4
Distribution of Corrected CTD Data Corresponding to 110 MW Generator Load

Ambient Condition Correction

In an effort to increase the accuracy of the diagnostics modules, variations due to ambient conditions must be accounted for. These corrections include not only accounting for the effects of ambient temperature and pressure but also the effects due to humidity.

The ambient temperature and pressure are first order effects on the gas path parameters, and as such correcting for these influences is of critical importance. The temperature and pressure effects are accounted for by the standard delta and theta correction factors shown in equations (1) and (2).

$$\delta = \frac{P_{Ambient}}{P_{ISO}} \tag{1}$$

$$\theta = \frac{T_{Ambient}}{T_{ISO}} \tag{2}$$

These factors are then utilized to correct the gas path parameters as follows:

$$P_{Station\_Corr} = \frac{P_{Station}}{\delta} \tag{3}$$

$$T_{Station\_Corr} = \frac{T_{Station}}{\theta} \tag{4}$$

$$W_{f\_Corr} = \frac{W_f}{\delta\sqrt{\theta}} \tag{5}$$

The following figures (Figure 2-5 and 2-6) are included to illustrate the effect of accounting for these first order influences on the gas path parameters. The data shown in blue are the original data obtained from the data archive. The points illustrated in red show the correction effect when accounting for the first order influences of ambient pressure and temperature. The points illustrated in green depict the correction for the second order effects of ambient humidity.

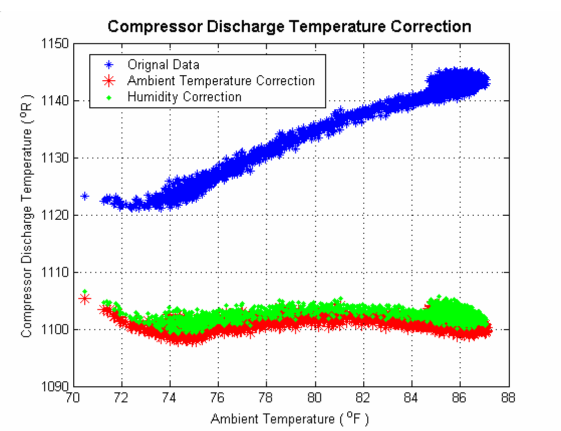


Figure 2-5
Results Obtained from Ambient Condition Corrections Made to CTD Values

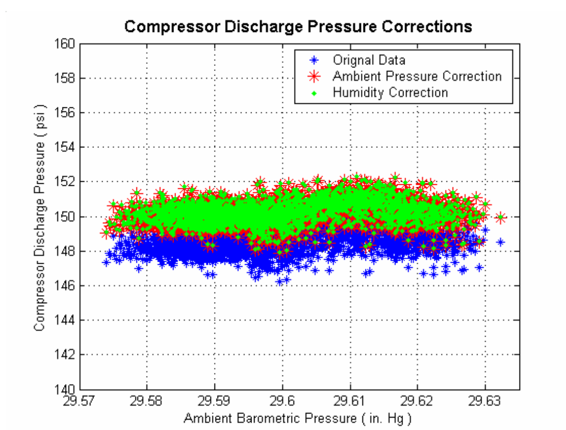


Figure 2-6
Results Obtained from Ambient Condition Corrections Made to CPD Values

The effects of humidity are a second order effect and as such have less of an impact on the data. However, in an effort to remove all possible variations due to the effects of atmospheric conditions, accounting for humidity is required. The presence of water vapor in dry air changes the values of the gas properties, namely, C_P (constant pressure specific heat), C_V (constant volume specific heat), R (gas constant), and γ (the ratio of C_P/C_V), primarily due to the molecular weight of water being far lower than that of dry air. Changing the gas properties can have a significant effect on thermodynamic processes throughout the CT. The correction algorithm utilizes generic exchange rates that are applied to the gas properties or specific gas path parameters, which may be utilized for first-order accuracy, to predict the effects of humidity on key performance parameters.[1]

The ambient humidity correction method used to adjust the gas properties and select gas path parameters to their corresponding values at 'standard day' relative humidity conditions employs the generic exchange rates given in Figure 2-7 and 2-8, respectively. The humidity correction process utilized first converts the desired value to its corresponding zero-moisture, 'dry-air' value if necessary by dividing the value by the exchange rate given for the current specific humidity. A subsequent step is taken to further modify the property or parameter value to its 'standard day' value by multiplying the value by the exchange rate resultant of a specific humidity value of 0.0064, corresponding to a relative humidity of 60 %.

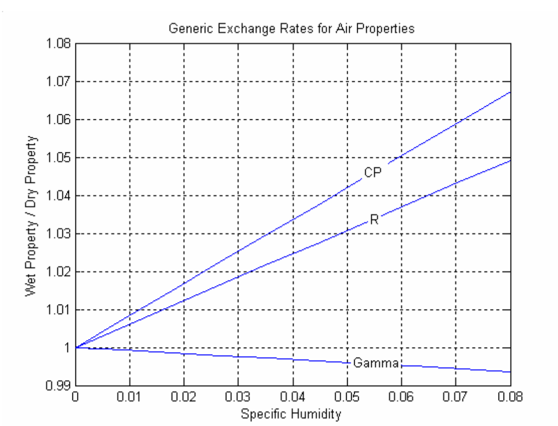


Figure 2-7
Exchange Rates for Ambient Humidity Correction of Gas Properties[1]

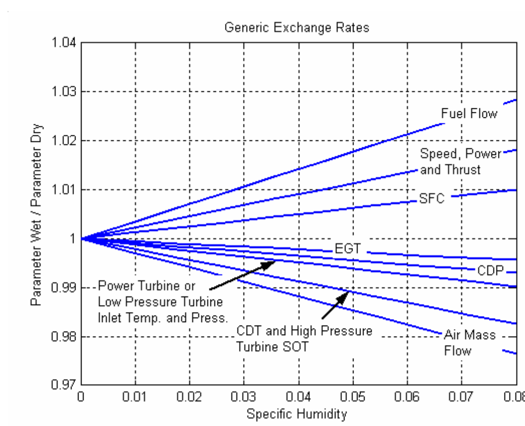


Figure 2-8
Exchange Rates for Ambient Humidity Correction of Select Gas Path Parameters[1]

Sensor Validation

The SVRM utilizes a suite of technically independent techniques to assess the overall health of the incoming signals. These independent methodologies have collaborative abilities in detecting various sensor failure modes. A final fusion process is used to combine results obtained from the different techniques to come up with a final overall health assessment. Table 2-2 outlines the validation techniques utilized by the respective sensors.

Table 2-2
Validation Technique by Sensor Type

Parameter Description	Generic Signal Processing	Model Based
AMBIENT_BAROMETRIC_PRESSURE	X	
AMBIENT_TEMPERATURE	X	
COMPRESSOR_DISCHARGE_PRESSURE	X	X
COMPRESSOR_DISCHARGE_TEMPERATURE	X	X
COMPRESSOR_INLET_DUCT_DIFFERENTIAL_PRESSURE	X	
COMPRESSOR_INLET_TEMPERATURE	X	
DEWPOINT_SENSOR	X	
GAS_FUEL_FLOW	X	X
LIQUID FUEL FLOW	X	X
GENERATOR_LOAD	X	
INLET_GUIDE_VANE_DEGREES	X	
RELATIVE_HUMIDITY	X	
EXHAUST_THERMOCOUPLE_1_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_10_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_11_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_12_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_13_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_14_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_15_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_16_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_17_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_18_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_19_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_2_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_20_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_21_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_22_COMPENSATED	X	X

Parameter Description	Generic Signal Processing	Model Based
EXHAUST_THERMOCOUPLE_23_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_24_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_25_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_26_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_27_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_3_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_4_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_5_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_6_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_7_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_8_COMPENSATED	X	X
EXHAUST_THERMOCOUPLE_9_COMPENSATED	X	X
WATER INJECTION FLOW	X	X

Sensor Validation Architecture

The architecture of the *Sensor Validation and Recovery Module* (SVRM), illustrated in Figure 2-9, has been developed to employ parallel signal validation methods. As presented in Table 2-2, there is a high degree of overlap in the sensors validated and also the failure modes detected by the two methods. This repetition in sensor fault detection capabilities helps to insure that a minimal number of "false alarms" are declared. The architecture first employs a low level check, which detects if the sensor values fall within their expected range of operation. This check will detect sensor saturation, as well as possible cross-talk and erroneous sensor connections. Failing this check results in an immediate zero confidence level in the sensor's integrity. Subsequent to the initial low level check, parameter values are further evaluated by the generic signal processing and model-based validation techniques. The output from these methods is a zero to one confidence level where zero corresponds to no confidence and one corresponds to one hundred percent confidence in the integrity of the signal. The final step in the process is the combination of results to yield a final determination of the confidence in the sensor's output. This culminating step utilizes the Dempster-Schafer method of data fusion to ascertain the ultimate determination of overall sensor health. In the event that an anomalous signal is detected from a sensor which is validated utilizing the model-based techniques, the output from the corresponding neural network is obtained for submission as a replacement for the erroneous data.

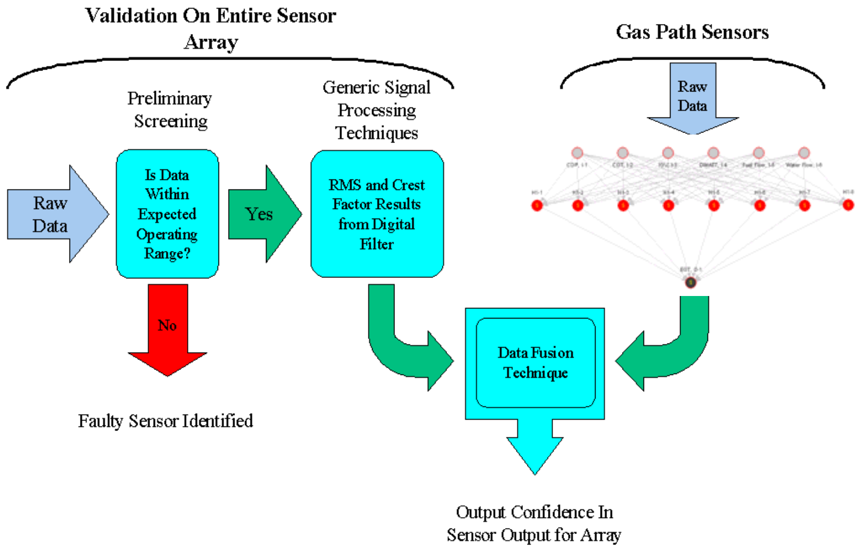


Figure 2-9
Architecture Utilized by the Sensor Validation Process

Generic Signal Processing Techniques

The motivation behind the development of generic signal processing techniques as a means of validating sensor output lies in the adaptability of the approach. The thought is to develop techniques that hold no regard for the type of parameter the sensor in question is monitoring. The signal processing based, sensor validation schema employs generic approaches that require minimal a priori information about the performance of the underlying system. Consequently, these techniques can be applied to virtually any sensor with minimal recurring design effort.

The initial check performed on the data is a basic saturation check. Exploiting the fact that each parameter has an expected range of operation determined by the physics involved, the incoming data is checked to determine if the values screened are physically possible. Though this is a very low level check, it is extremely useful in detecting sensor anomalies such as drop-outs and spikes.

A subsequent check of the data is made utilizing a digital high-pass filter. The engine signal digital filtering serves to screen the low frequency component of the sensor's signals (containing the relevant engine information), and allows any highly transient signal components that are greater than the highest transient expected from the CT to be passed through and isolated. The digital filtering algorithms are used to detect faults such as spikes, noise, intermittent signal loss, cross talk, clipping, and other anomalies, which manifest themselves by a rapid change in signal magnitude. These jump-discontinuities are passed by the filter and are the key metric utilized in detecting the failure modes mentioned.

The metric used to determine the presence of an anomaly in the signal is the standard deviation of the signal segment being examined. After filtering, the noisy signal will contain a standard deviation, which is an order of magnitude greater than that of the clean signal. This provides a clear distinction for detection of signal anomalies, which manifest themselves by a rapid change in magnitude.

Neural Network Model Based Technique

The model-based technique employs neural networks to capture inter-parameter relationships of the combustion turbine units throughout their range of operation. This methodology is highly data-driven and requires a sufficient supply of data to adequately capture all operating modes. Input data for training and subsequently during operation must be corrected to “ISO standard day” conditions before being supplied to the networks. This is done to remove variability in the resultant output due to fluctuations in ambient conditions. Results obtained from the neural networks are then utilized to calculate the residuals relative to the data from the sensors. The residuals are then analyzed by a fuzzy logic system to obtain the respective confidence level of the sensed data.

The artificial intelligence component of the sensor validation module utilizes a back-propagating *Artificial Neural Network* (ANN). Neural networks are adaptive systems, which can be trained to expect a particular outcome given certain conditions or inputs. To summarize, they “learn” from example. In this application, the neural network is taught to recognize the relationships that occur among the gas path parameters throughout the range of normal operation. As such, if one of the parameters deviates significantly from its expected value, without affecting any of the other sensors, the network is able to recognize this as a possible sensor fault.

Operation

Two distinct phases of neural nets are “training” and “operation.” The operation phase is simply "running" or "using" the trained network. The architecture utilized in back-propagation of the error is discarded and only the forward propagation of input data is needed. After the network converges on a training set, it is true that the particular architecture has learned the training set. But how well the network performs on new, unseen data depends on (i) whether the training data was a good representative sample of the universe of discourse for each variable, and (ii) whether the network structure is sufficiently compact for generalization. (If the neural net has excessive degrees of freedom (weights), it will "memorize" the training data set well, but generalize poorly on new data).

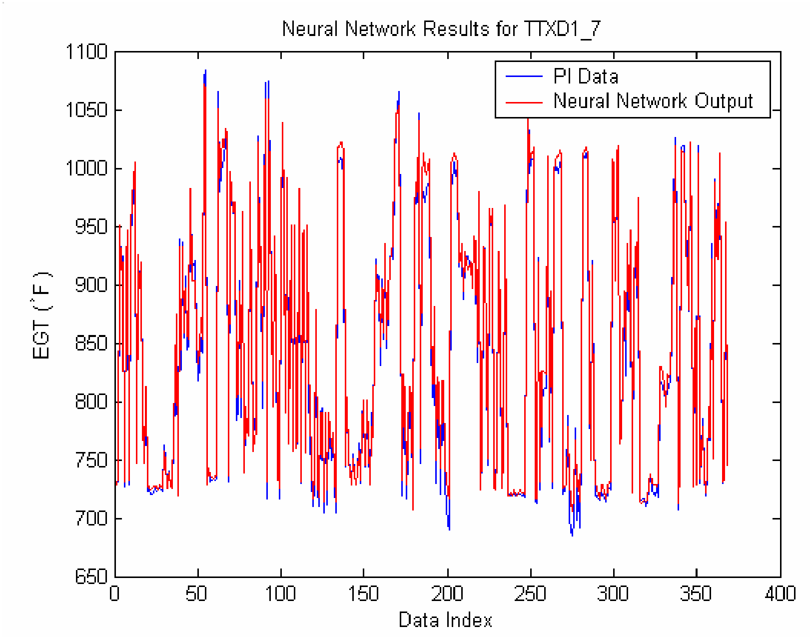


Figure 2-10
Neural Network Results for TTXD1_7 (Exhaust Gas Temperature)

Figure 2-10 illustrates the output results from the example network. The data illustrated is test data extracted from the PI Historian in the same manner as the training data and not a temporally sequential series.

As previously stated, implementation of the model-based techniques is also independent of the operating mode of the CT unit within the expected operating range, i.e. turbine running at full speed and the generator outputting a load between 65 MW and 170 MW. Again this goes back to the underlying assumption that the hysteretic effects encountered by the CT unit due to transients have little impact on the network's ability to determine the correct output. The neural networks have been developed to encompass the full range of reasonable operating values and conditions. Once the generalization is made that hysteretic effects can be ignored, the assumption can be made that each instant in time can be considered a pseudo steady-state condition. Now we are allowed to utilize the model-based techniques for all points whether the unit is at partial load or full load. Results obtained from analysis of the neural network's prediction compared to the actual data show consistent variation regardless of the operating model. Figure 2-11 illustrates neural network results obtained for a sample set of data. The data sample reflects the actual operational modes experienced by the CT unit. Figures 2-12 and 2-13 illustrate magnified views of two transient events encountered during operation. Figure 2-12 shows a long steady transient. The neural network does a very good job of tracking the actual compressor discharge temperature values through the transition. The results presented in Figure 2-13 illustrate a sharp transient. Again, the neural network does an excellent job of approximating the desired compressor discharge temperature values.

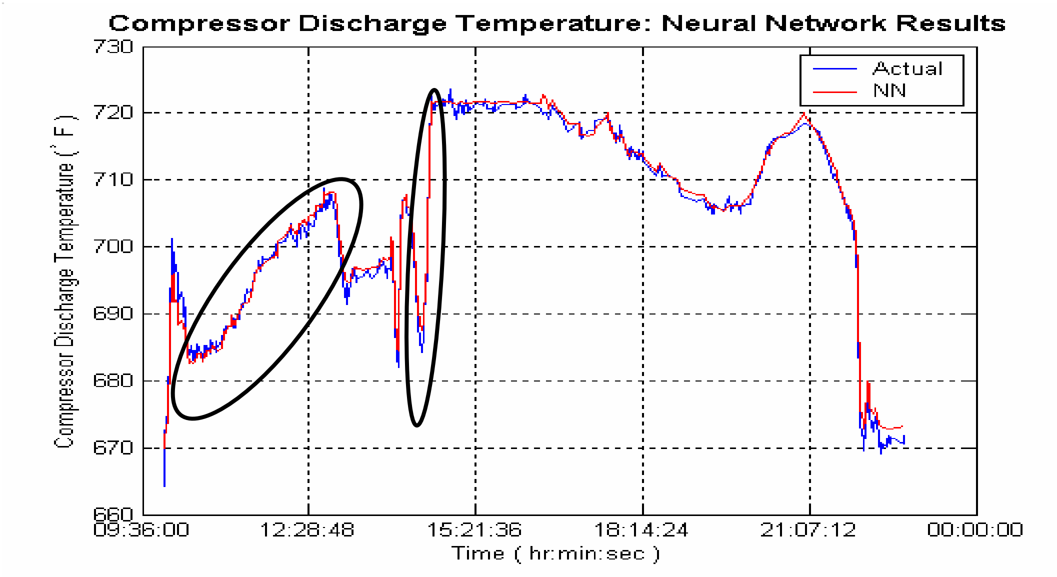


Figure 2-11
Sample Neural Network Results for Compressor Discharge Temperature

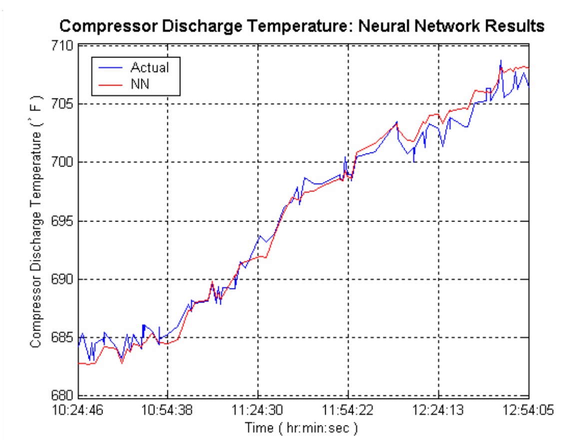


Figure 2-12
Neural Network Results Tracking a Gradual Transient

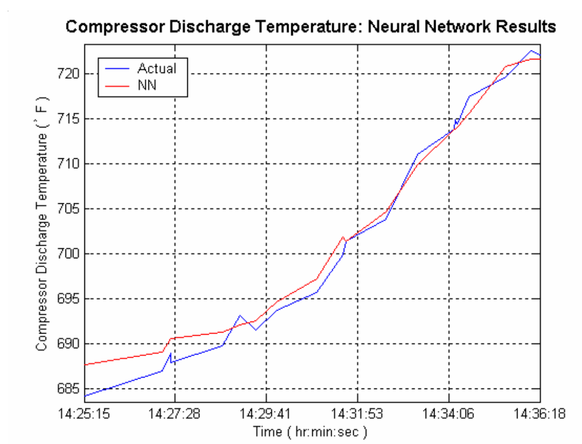


Figure 2-13
Neural Network Results Tracking a Steep Transient

One final consideration with respect to operating modes lies in the type of fuel being burned by the CT unit. We know that the Asheville units are required to burn liquid fuel during the winter months due to the drain they place on the gas pipeline when they are in operation. Analysis has shown that at low load conditions the characteristic response of the gas path parameters differs between the two fuel types. To compensate for this distinction two neural networks have been developed for each parameter, one for each fuel type. We should note that there is significantly less data available for periods of liquid fuel usage than for natural gas usage in the ten months of data available. This is due to the nature of the operation of the Asheville CT units. Recall the units there are 'peakers' and as such only come on line when the demand on the power grid is sufficient to warrant help in sustaining adequate supply. During the summer months the units will run from late morning through mid-evening with regularity. In contrast, during the winter months the CT units are generally only called upon for short durations, two to six hours.

Table 2-3 below lists the networks employed within the *Sensor Validation and Recovery Module* (SVRM). Recall that the input values presented to the networks have all been corrected to 'ISO standard day' conditions in an effort to remove the effects of ambient conditions on the networks' results. Each parameter has two underlying networks ready to evaluate based on the type of fuel being utilized. Note: During transitional periods when both types of fuel are being used simultaneously, no model-based evaluation can be completed.

Table 2-3
List of Neural Networks Employed by the SVRM

Output	Inputs
Compressor Discharge Pressure	Compressor Discharge Temperature Generator Output Power Gas or Liquid Fuel Flow Exhaust Gas Temperature Water Flow
Inlet Guide Vane Angle	Insufficient data is currently available to properly develop this neural network.
Compressor Discharge Temperature	Compressor Discharge Temperature Generator Output Power Gas or Liquid Fuel Flow Exhaust Gas Temperature Water Flow
Generator Output Power	Compressor Discharge Pressure Compressor Discharge Temperature Gas or Liquid Fuel Flow Exhaust Gas Temperature Water Flow
Gas Fuel Flow	Compressor Discharge Pressure Compressor Discharge Temperature Generator Output Power Exhaust Gas Temperature Water Flow
Liquid Fuel Flow	Compressor Discharge Pressure Compressor Discharge Temperature Generator Output Power Exhaust Gas Temperature Water Flow

Output	Inputs
Gas Fuel Temperature	Insufficient data is currently available to properly develop this neural network.
Exhaust Gas Temperature	Compressor Discharge Pressure Compressor Discharge Temperature Generator Output Power Gas or Liquid Fuel Flow Inlet Guide Vane Angle Water Flow
Water Flow	Compressor Discharge Pressure Generator Output Power Gas or Liquid Fuel Flow Exhaust Gas Temperature

Each parameter requires two networks be developed since the characteristic behavior of the parameters varies depending on the fuel used, natural gas or liquid. The 'Output' from the neural networks can be used to validate and recover either the voted value or the values output from the individual sensors used to monitor the parameters if they are available.

Fuzzy Logic System

As previously stated, the residuals obtained from the comparison of the neural network outputs to the original, corrected parameter values are evaluated by a fuzzy logic system in determining the associated confidence level in the sensor's integrity.

A fundamental concept of fuzzy sets is that its elements can belong to a set to varying degrees -- i.e. every element is characterized by a degree of membership within the set. A mapping of the domain interval to its degree of membership defines a membership function. The number of membership functions assigned to input/output variables and their shapes comprise an essential part of the "knowledge" embodied in a fuzzy logic system. This information is supplied by the domain expert, and when combined with the rule base, forms a complete knowledge base for a particular application.

This system utilizes a pre-processing step, which determines the "hard input." Here, the hard input is the difference between the measured value and the expected value in a normalized format. The fuzzy logic system then "fuzzifies" the hard input by utilizing the *max-min inference method* (see Appendix B) for assessing the appropriate rules from the rulebase utilizing the values obtained from the "membership functions." The "membership functions" determine the degree of membership of the associated input into the three fuzzy classifications, "Low", "Medium" and "High." Developing the membership function requires determining the "Universe of Discourse" which defines the range of hard input values expected by the fuzzy system. Figure 2-14 and 2-15 illustrate levels of displacement used to develop the membership function shown in Figure 2-16. Clearly, the one percent and two percent levels fall within the three-sigma boundary of expected values; therefore, these levels will be used to define the "Low" region. The five percent to ten percent displacement range, while a substantial amount in the realm of performance evaluation, is a "Medium" offset within sensor validation. Twenty percent offset will bound the upper limit of the "High" region.

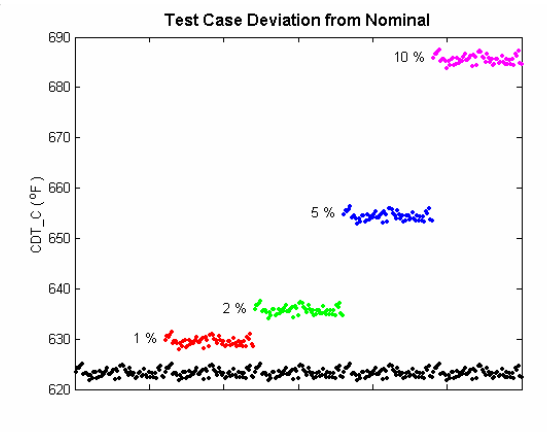


Figure 2-14
Levels of Displacement from Expected Values

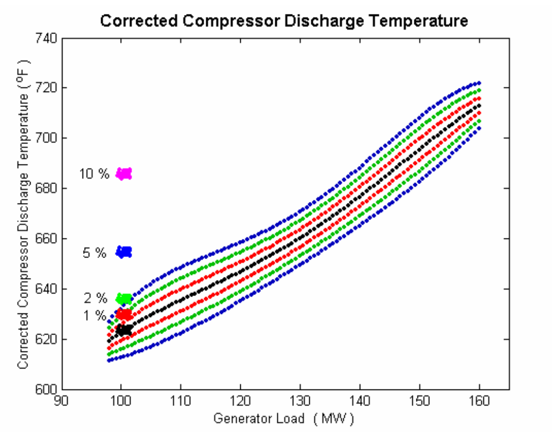


Figure 2-15
Levels of Displacement Shown on Operating Signature Curve

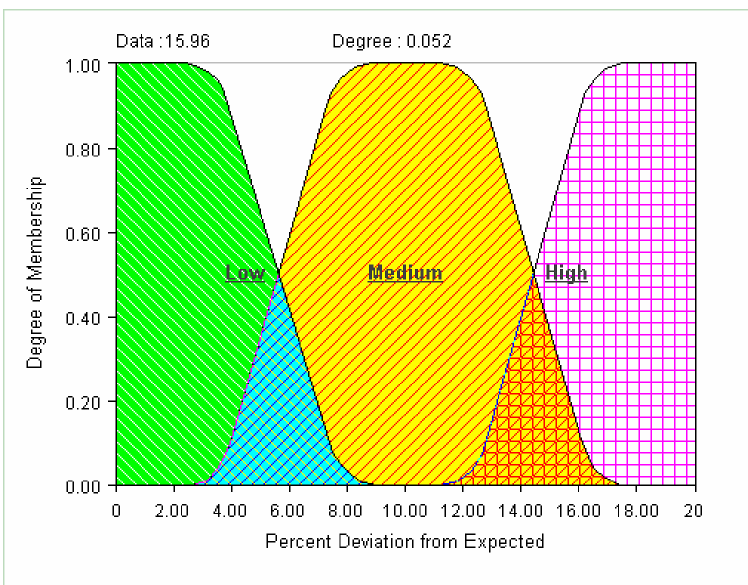


Figure 2-16
Fuzzy System Input "Fuzzification" Membership Function

The end result of the fuzzification step is the determination of the "fuzzy set." The "fuzzy set" is a geometric subset of the original membership functions. The shape of the "fuzzy set" is determined by the degree of membership of the hard inputs in the membership functions based on the applicable rules encountered in the expert rulebase. This fuzzy set is subsequently converted back into a hard output by a "de-fuzzification" process. The de-fuzzification process employed here utilizes the *centroid method*. Intuitively, the centroid method can be viewed as a "compromise" among the output actions recommended by different rules. The output value obtained as a result of the de-fuzzification process can now be interpreted as the signal confidence level obtained from the model-based validation technique.

Results Fusion

The results fusion process consists of the synergistic combination of collaborative information from the sensor validation techniques in order to provide an accurate and effective assessment of the observed sensor's past and present integrity. The result obtained from the Dempster-Shafer fusion process possesses greater certainty than the individual confidence with uncertainty levels when evaluating collaborative evidence.

An example of the Dempster-Shafer fusion process is shown in Figure 2-17. Here, Method #1 can represent the generic signal processing technique results and Method #2, the data driven model based results. The net result of the fusion process is a diagnostic confidence that is more accurate and robust than could be obtained by any single information source.

Example of Dempster-Shafer Belief Method

Sensor Confidence from Method #1 = 80% +/- 15%

Sensor Confidence from Method #2 = 30% +/- 10%

Therefor: m1(A) = 0.65 m1(A') = 0.05 m1(A,A') = 0.30
m2(A) = 0.20 m2(A') = 0.60 m2(A,A') = 0.20

	m2(A)	m2(A')	m2(A,A')
m1(A)	0.13 {A}	0.39 {0}	0.13 {A}
m1(A')	0.01 {0}	0.03 {A'}	0.01 {A'}
m1(A,A')	0.06 {A}	0.18 {A'}	0.06 {A,A'}

$$Belief\,(Hn) = \frac{\sum_{A\cap B=Hn} m_i(A)\cdot m_j(B)}{1-\sum_{A\cap B=0} m_i(A)\cdot m_j(B)}$$

m1(A) + m2(A) {True} = (0.13 + 0.13 +0.06)/(1-(0.01 + 0.39)) = 0.53

The uncertainty in this result is:

m(A,A') + m(B,B') = 0.06 / (1-(0.01 + 0.39)) = 0.10

Hence, the probability of Fault A having actually occurred given the diagnostic classification is **0.58 +/- 0.05**

Figure 2-17
Dempster-Shafer Fusion Process

Sensor Recovery

"Recovery" of signals from failed sensors has been identified as a highly valuable feature for enabling robust diagnostics on combustion turbines. "Sensor recovery" refers to the capability of the *Sensor Validation and Recovery Module* (SVRM) to substitute reasonable parameter values for data obtained from malfunctioning sensors. In the event that an anomalous value is detected a replacement, value can be provided to the performance worksheet and the assessment can continue.

The addition of the sensor recovery feature will enable the health diagnostics modules being developed to utilize suggested substitute parameter values upon identification of an anomalous sensed value. To this end, the artificial intelligence networks necessary to predict parameter values given the current operating state are called upon to serve dual duty. Initially, the neural networks are vehicles for supplying the model-based expected parameter values. As a subsequent duty, upon identification of anomalous sensor values, the output from the neural network is supplied to the performance algorithms as replacement values for the erroneous data. Each individual parameter requiring recoverability must have two corresponding neural networks developed, one for each type of fuel used. The neural networks developed utilize four to six inputs as specified in Table 2-3 that are used to define the current level of operation and predict the appropriate output. These inputs are primarily sensed gas path parameters, which are already being used in the sensor validation and performance analysis modules. Output from the network is a reasonable approximation of the expected output value, based on the inputs, which can be used to replace anomalous sensor output if necessary.

The architecture of the SVRM needed to be augmented to accommodate the functionality of parameter recovery as shown in Figure 2-18. The output from the neural networks needs to be retained until final results are obtained from the data fusion process. Should an anomalous sensed value be identified, the corresponding replacement value must be obtained from the appropriate neural network output. The modifications are highlighted in red in Figure 2-18. Feedback from the final sensor health assessment step is utilized to obtain any required replacement values from the original neural network output. This output is then post-processed to reintroduce the effects of the ambient conditions at the corresponding instance in time, i.e. revert back from ISO standard day conditions, to obtain an approximation of the original data for replacement in subsequent performance calculations.

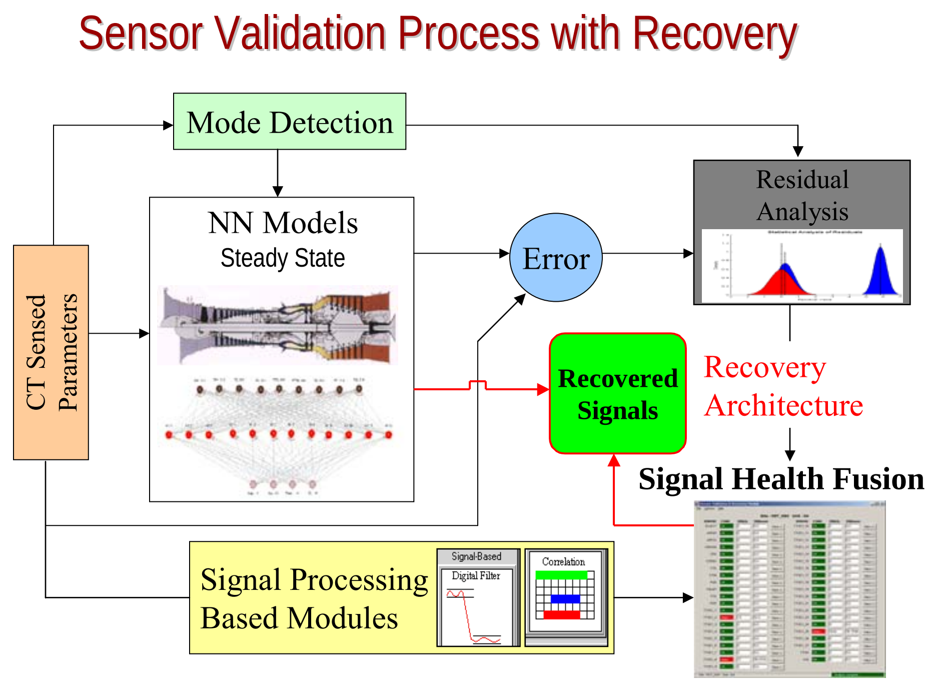


Figure 2-18
Sensor Validation Architecture with Recovery Capabilities

Neural Network Based Approach

The absence of rigorously matured empirical models necessitates the development of low cost, easy to develop alternatives, which can be developed reasonably quickly for varying CT unit types. These alternative methods are usually data driven requiring extensive amounts of data, sufficient to capture all modes of operation experienced by the combustion turbine unit. The *Sensor Validation and Recovery Module* (SRVRM) utilizes this data driven approach in developing the neural networks utilized in the model-based validation technique and subsequently in the value recovery process. Neural networks lend themselves very well to this type of application due to their ability to "learn" inter-parameter relationships which exist and generalize these learned relationships to adapt to "unseen," during training, inputs.

SVRM Features

Features of the SVRM Interface

The main *Graphical User Interface* (GUI) has been developed to present plant personnel with key information required for validation and subsequent performance assessment. The GUI, written in Tcl/Tk, provides an organized and aesthetically appealing way of presenting the information concerning sensor anomalies found in the data set being scrutinized, as shown in Figure 2-19. The SVRM GUI contains four fields for each sensor listed. The four fields are: '*SENSOR:*', '*COND:*', '*ERR(#):*', and '*ERR(sev):*'. Also included for each sensor is a '*View >>*' pushbutton, which calls a new window for viewing the underlying time series. An in-depth discussion of this functionality is forthcoming. Other features of the main SVRM graphical user interface include display of the site and unit currently being accessed by the data querying utility. Finally, a color-coded status field is presented in the lower right corner to allow easy recognition of the status of the current analysis.

Field Descriptions

The '*SENSOR:*' field is a static field that contains the name of the sensor. The sensor name coincides with the tag name utilized within the PI Historian. The '*COND:*' field is a dynamic Boolean field. This field is updated by the SVRM, is color-coded, and contains text. The response to a sensor with no anomalies detected will be a green field with 'OK' text. A red field with 'Alarm' text will signify an anomalous sensor. The '*ERR(#):*' field is also a dynamic field updated by the SVRM. This field acts as a counter for the number of anomalous points found. The final field is '*ERR(sev):*'. This field is utilized to rate the severity of the faults identified. Within the sensor validation module, the algorithms assign a confidence level to each sensor's output. This determination reflects the level of confidence that the output of each sensor reflects the actual parameter value. Calculating one hundred minus this confidence level gives the *error severity level*, which can be interpreted as the certainty, expressed as a percentage, that the sensor's output is erroneous. A sensor fault is identified when the error severity level crosses a pre-determined threshold. When numerous sensor faults have been identified, the error severity values are totaled and averaged by the number of faults found. This figure may be interpreted as an indication of the overall health of the sensor and the ability to use the data given to assess performance measures. Finally, a pushbutton is available for each sensor marked '*View >>*'. Selection of the pushbutton opens a new window, which contains a 'notebook' to view the time series data which has just been evaluated by the SVRM. Each 'notebook' contains at least one 'tab' or 'sheet' that contains the time series plot on it. In the event that multiple time series have been evaluated a separate 'tab' is created for each individual time series and the user may view the individual time series by selecting the different tabs.

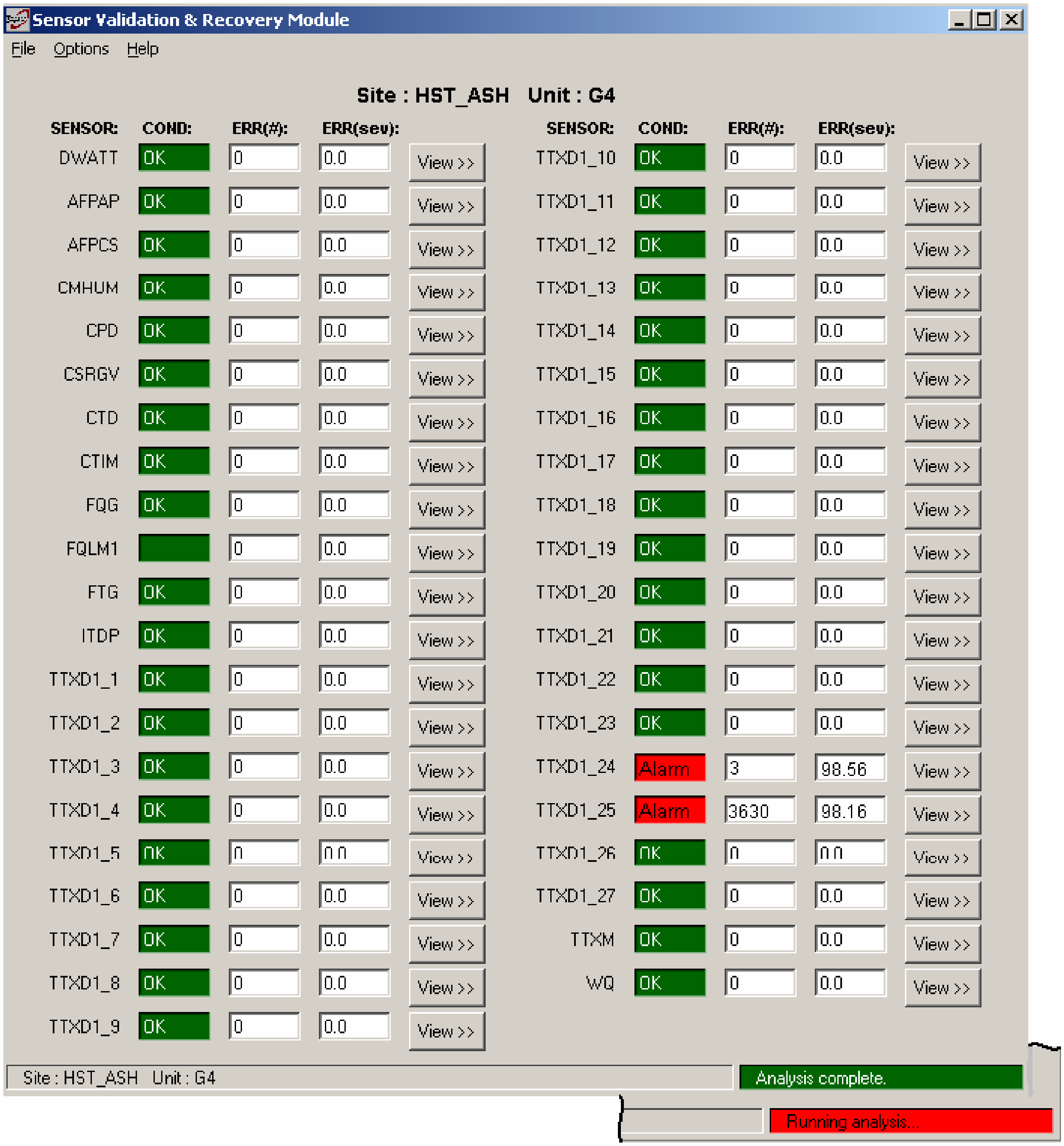


Figure 2-19
Sensor Validation and Recovery Module's Graphical User Interface

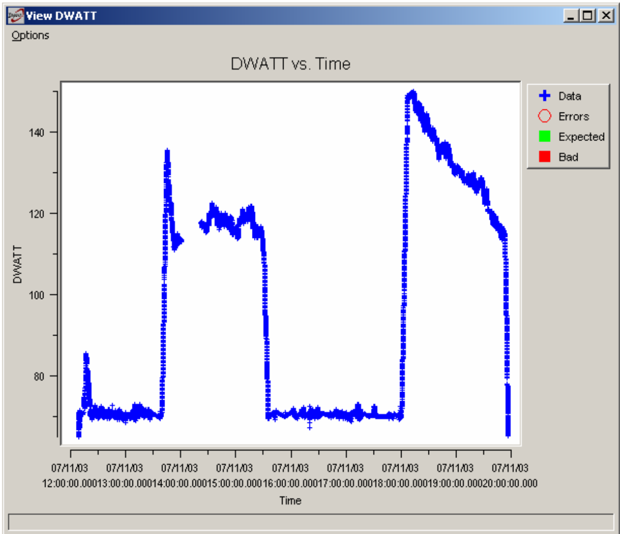


Figure 2-20
Generator Output Power for July 24, 2003

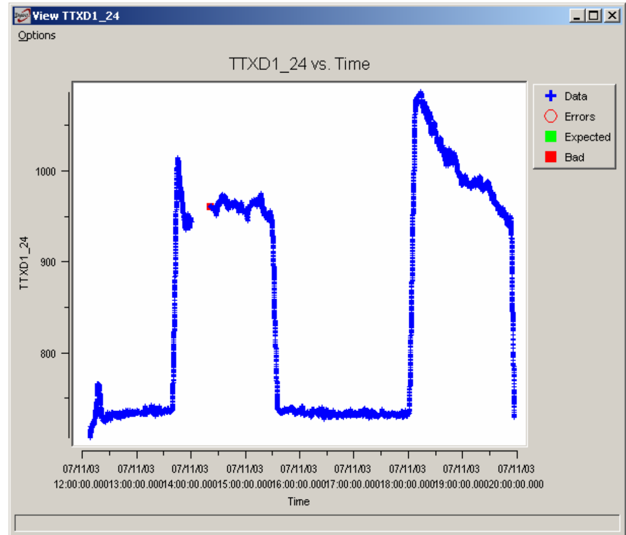


Figure 2-21
Exhaust Gas Temperature Output, Thermocouple Array -- #24

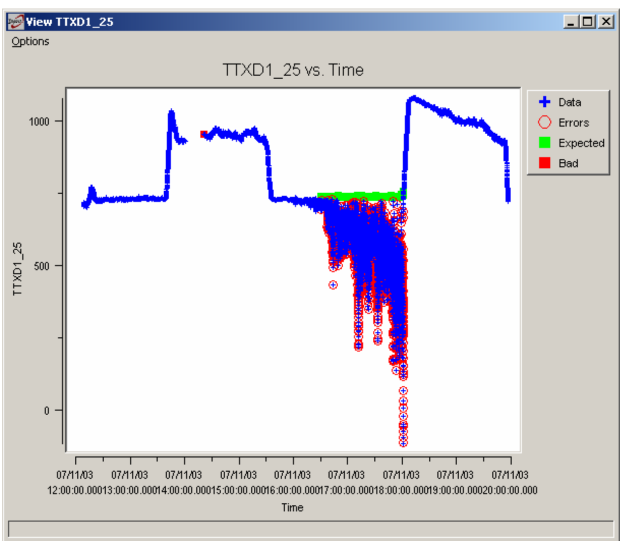


Figure 2-22
Exhaust Gas Temperature Output, Thermocouple Array -- #25

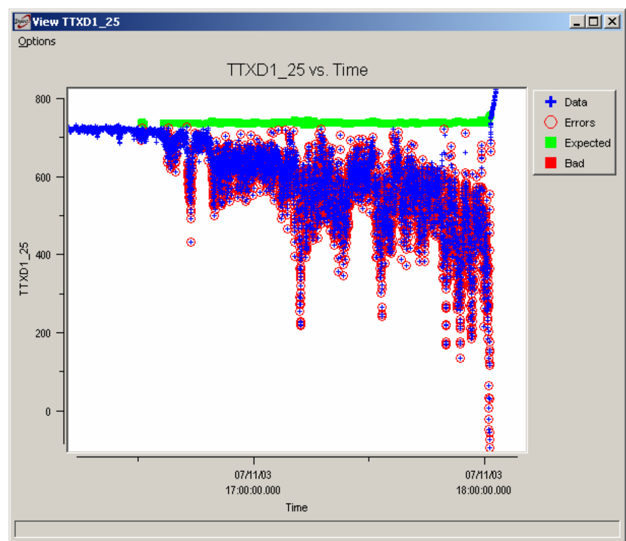


Figure 2-23
Magnified View of Region Around Thermocouple Drop-Out

Figure 2-20 through Figure 2-23 are screen shots illustrating the viewing capabilities of the GUI. Figures 2-20 and 2-21 are presented for comparison purposes to illustrate "normal" sensor output for the period of the analysis. Figures 2-22 and 2-23 illustrate anomalous output from a thermocouple monitoring exhaust gas temperature. A *ZOOM* feature is available utilizing a user specified *click and drag* box to define the region to be magnified, shown in Figure 2-23. Looking at the results for the *TTXD1_25* sensor it is clear that anomalous points were detected. The results shown in Figure 2-19 depict the results of the validation analysis, 'ERR(#):' equal to

3630 erroneous points were detected, resulting in an error severity level, 'ERR(sev):', of 98.16 %,.

E-Mailing Capabilities

File → Email Analysis Results…

The SVRM batch analysis operating mode was set up to enable the SVRM to operate as a behind the scenes application which would run unnoticed by CT operators unless a problem was detected. In the event that an anomalous signal is detected, specified e-mail recipients will receive a report detailing the exceptions found. The desired e-mail addresses are entered in the configuration file. Beta testing revealed that this functionality would also be a desirable feature when utilizing the SVRM module in its interactive operating mode. To this end a dialogue box, shown below, has been made available during all modes of operation that allows the user to enter an e-mail address and send the recipient results from the current analysis.

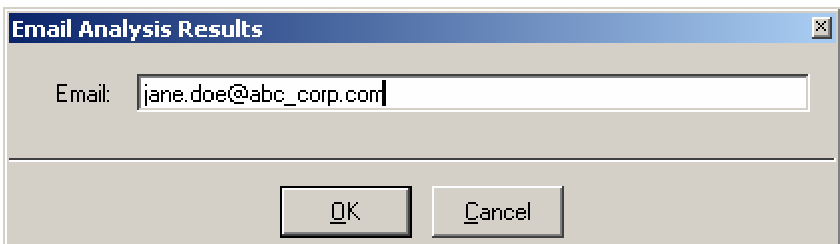


Figure 2-24
Dialogue Box Enabling Entry of E-mail Recipient's Address

Configuration Capabilities

The configuration capabilities are driven by the desire to make the Sensor Validation and Recovery Module as easy to use and as adaptable as possible. To this end the options made available to the user through the three tabs, which make up the *Configuration* window allow the user to tailor the capabilities of the SVRM to suit their requirements.

Options → Configuration…

The *Configuration* dialogue box has been modified to contain three tabs. The first tab, *Program*, is primarily used to select and enter information required by the DataLink Add-In utility pertaining to the desired CT unit to be analyzed. Here, the user can also now specify whether or not the SCAMP module is run.

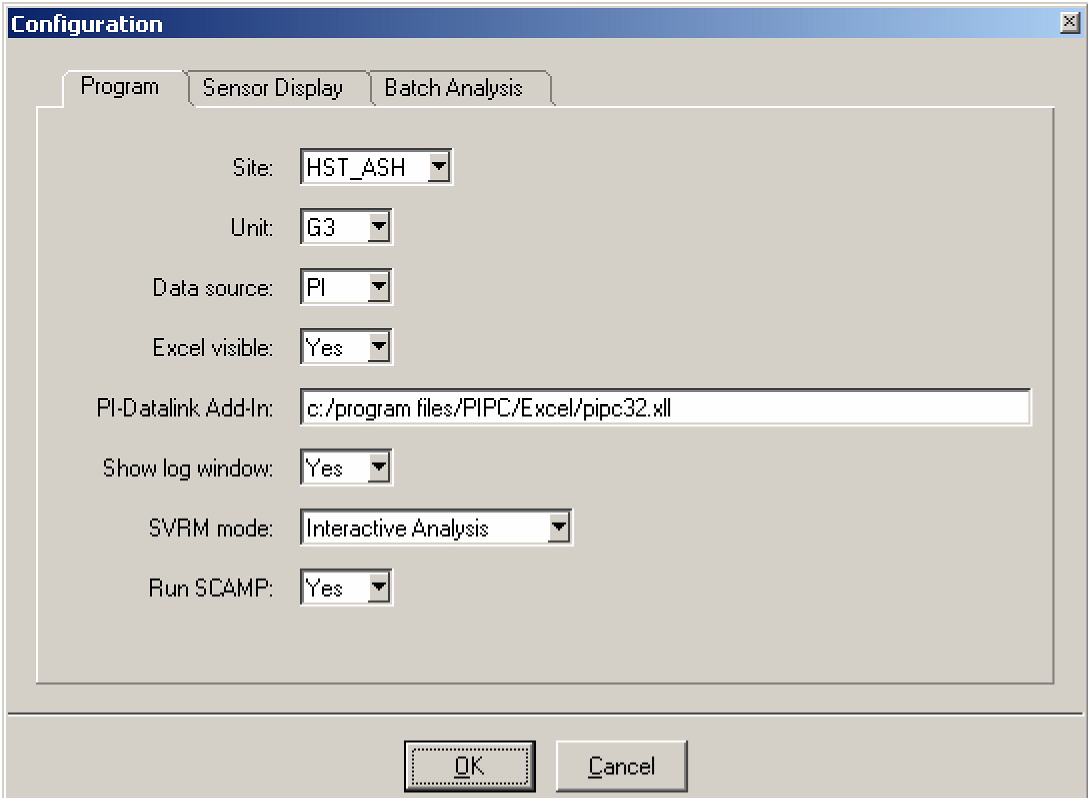


Figure 2-25
***Program* Tab of the *Configuration* Dialogue Box**

Feedback from beta testing revealed that an added benefit would be attained if the user could specify which parameters were displayed on the main SVRM window. Certain sensors may be thought of as extraneous to the current scope of interest when the user sits down to use the SVRM and as such can now be "turned off." The second tab of the *Configuration* dialogue box, *Sensor Display*, configures which parameters are displayed on the main SVRM screen. The user simply checks which parameters to be viewed.

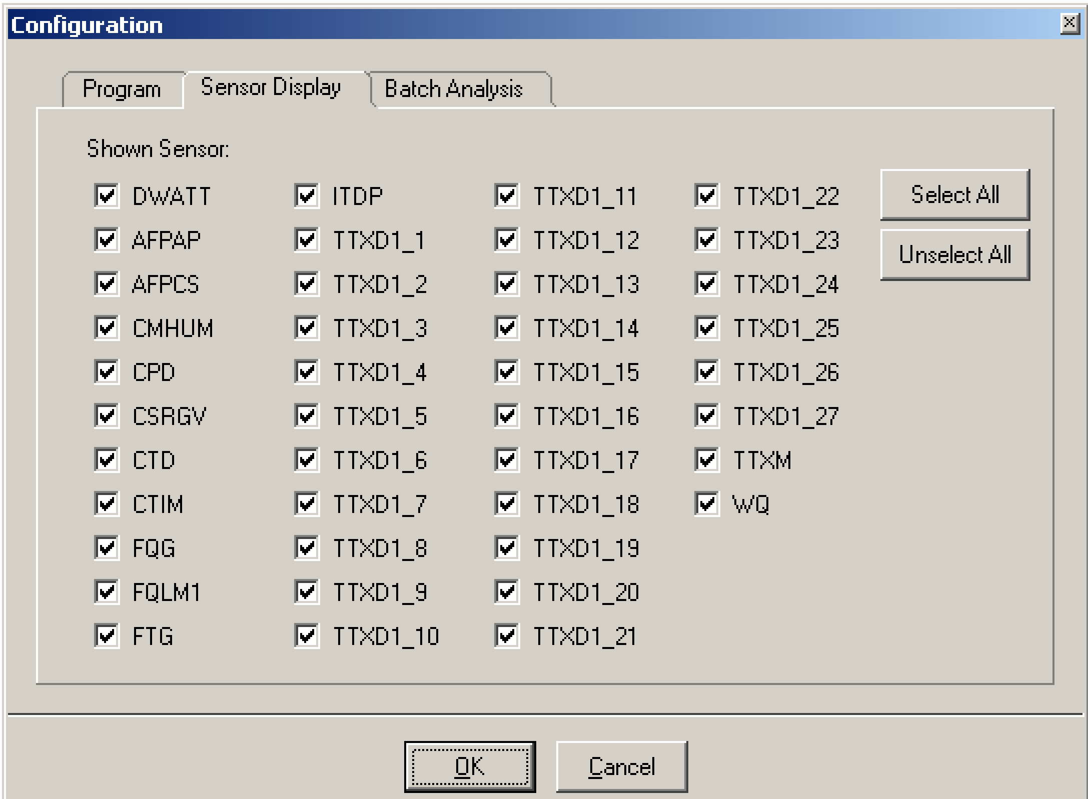


Figure 2-26
***Sensor Display* of the *Configuration* Dialogue Box**

The final tab, *Batch Analysis*, facilitates configuration of the SVRM when in batch analysis mode. Respondents to beta testing thought the original set-up of querying the previous twenty-four hours of data for analysis at or near mid-night, when network traffic is low, too constrictive. Utilizing this dialogue box the user can now dictate the duration of the window of time being analyzed and specify when the analysis takes place. For example, with the settings as they appear in Figure 2-27 an analysis would be initiated at mid-night and query the previous hour's data. Subsequent analyses would then start each hour after that on the respective previous hour's data.

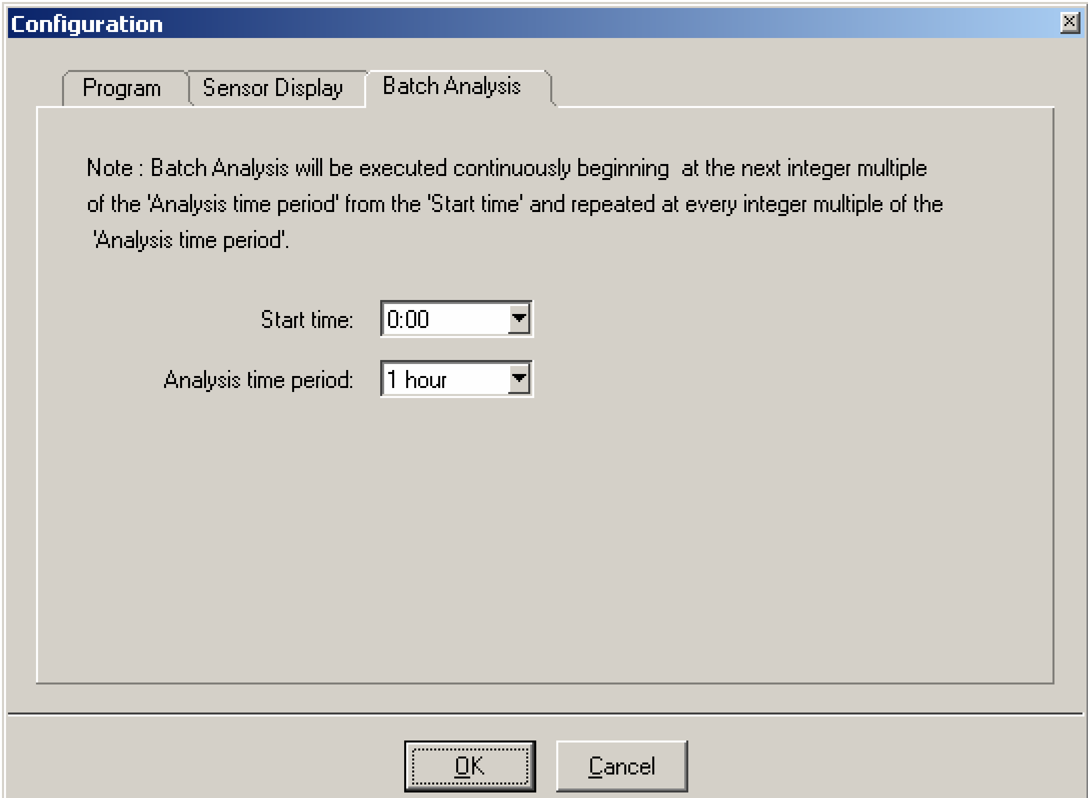


Figure 2-27
***Batch Analysis* Tab of the *Configuration* Dialogue Box**

Options → Run Sensor Validation (User Defined Time Period)…

Further key feature improvements included as a result of testing is an improved dialogue box for defining the time period of the analysis when using the SVRM in its interactive analysis mode. The addition of the new dialogue box allows the user to quickly and easily specify the date and time of interest. Figure 2-28 illustrates the dialogue box. Clicking the arrows at the top of the calendar will scroll through the months. A date is selected and subsequently highlighted by the click of the mouse. Finally, the hours of interest can be highlighted in the pane at the right to specify the hours of data being analyzed.

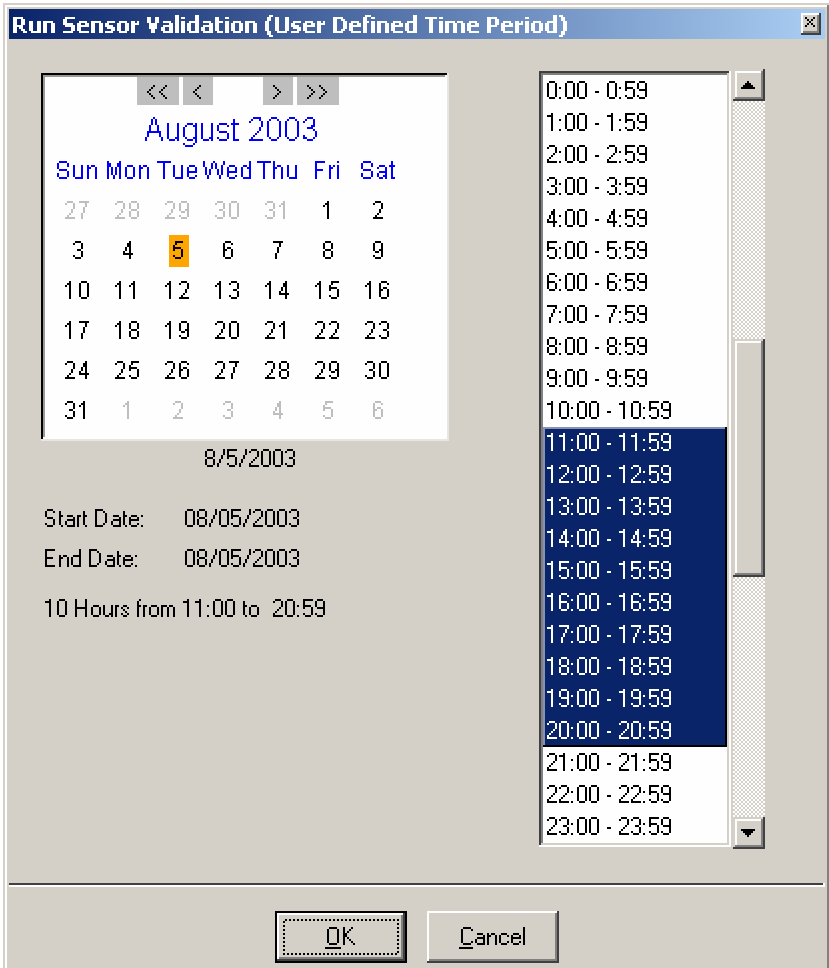


Figure 2-28
Dynamic Dialogue Box for Specifying *Interactive Analysis* Time Periods

Monitoring Multiple Units

Development concerning the issue of monitoring multiple CT units at the same time is in progress. At this time it is possible to monitor multiple units concurrently by launching multiple instances of the SVRM in batch mode and initiating their respective queries in non-coincident hours, e.g. the module monitoring G3 initiates on even hours for an analysis duration of two hours while the module monitoring G4 initiates on the odd hours for an analysis duration of two hours. This scenario has been difficult to test since the two units have not run at the same time very often.

Recommendations for Future Development

Virtual sensing of currently unmonitored parameters has been discussed as a possible avenue of future development. Certain gas path parameters, such as station total pressures and combustor discharge temperature, are very beneficial in calculating hot section performance. They are, however, impractical to monitor on all units. Virtual sensing of the parameters entails the development of predictive tools that assess the current state of operation of the unit and then map that state to a probable value of the virtually sensed parameter. Neural networks, like those currently utilized in the SVRM, are well suited to this type of application.

Another possible area of development would be to mature the ability to write recovered values back to the PI Historian. In the event that erroneous data values are detected as the result of analysis by the *Sensor Validation and Recovery Module* (SVRM), the recovered values could be written back to an appropriate place in the PI Historian. Having these values available could be advantageous for use in any subsequent analysis, which may take place or if verification/duplication of already completed analysis is ever required.

References

1. Walsch, Fletcher, *Gas Turbine Performance*, (pp. 113, 115, 565 & 585) Blackwell Science Ltd., ASME Press, 1998.

2. *Strategic Capacity Axial-Compressor Maintenance Program (SCAMP) Version 2*: *Spreadsheet User's Manua*l, EPRI, Palo Alto, CA: 2000. 1000939.

3. *O'INCA Design Framework for MS-Windows*. Vers. 1.1. Computer Software. Intelligent Machines, Inc., 1995.

Appendix A: Neural Networks

Artificial Neural Networks (ANN's) utilize a network of simple processing units ("*neurons*"), each having a small amount of local memory. These units are connected by "communication" channels ("*connections*"), which usually carry numeric data. The units operate only on their local data, which is received as input to the units via the connections. Most ANN's have some sort of *training* rule by which the weights of connections are adjusted based on some optimization criterion. Hence, ANN's learn from examples and exhibit certain capability for generalization beyond the training data (examples). ANN's represent a branch of the artificial intelligence techniques that have been increasingly accepted for data fusion and automated diagnostics in a wide range of applications. Their abilities to recognize patterns, and to learn from samples have made ANN's attractive for use with large data sets from complex systems.

The ANN *structure* is sometimes called *architecture*, or *topology*, which is an expression of the number of processing units and of the connections among these units; this is illustrated in Figure 2-29 below. Most processing units are arranged in *layers* (a layer is a collection of the units aligned for the same computational sequence), and the ANN is often referenced by the number of layers and the number of units in each layer.

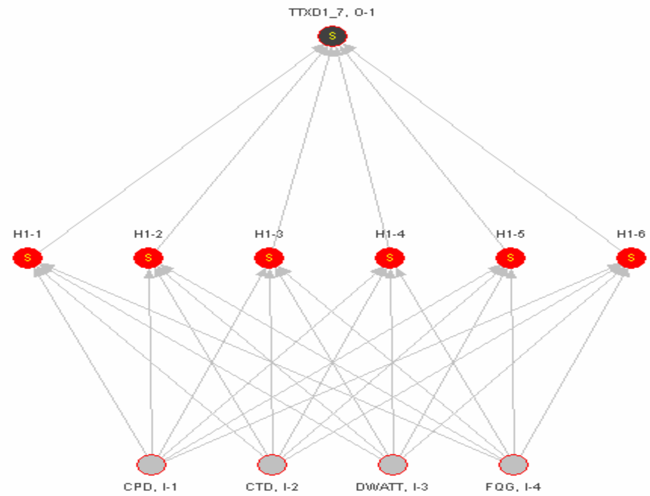


Figure 2-29
Neural Network Architecture Utilized in the Sensor Validation/Recovery Module

Each solid connection line in Figure 2-29 represents a numerical value called the *weight,* representing the connecting strength between the two inter-connected units. Each circle is a unit and it performs three sequential computations: the first is to multiply the weight by the output of the unit on the other end of the connection; the second is to sum the *weighted outputs* from all connections; and the third is to apply the *weighted sum* to a function (usually nonlinear and bounded) called an *activation* function. One of the most common activation functions is called the sigmoid function and the binary *f(x)* and bipolar *g(x)* versions are given below.

$$f(x) = \frac{1}{1+e^{-\sigma x}};\, g(x) = \frac{1-e^{-\sigma x}}{1+e^{-\sigma x}}$$

The functional value of the weighted sum is called the *output* (or *threshold*) of the unit. This sequence of computation is carried out for each unit and for each layer until the outputs layer of the ANN is reached.

Training

The ANN's utilized within the SVRM for the sensor recovery are multi-layered, feed forward neural networks, often referred to as "back-prop" neural networks. The back-prop designation comes from the training algorithm used in the learning phase. Networks of this type require a supervised learning process. Supervised training means that every "set" of data presented to the neural network for training is accompanied by a corresponding desired result that is also presented. Here, "set" implies an instantaneous snapshot of the input and output parameters, which form a "training pattern." Complete and proper training requires that a sufficient number of patterns be presented to the network to represent the entire range of operation of the parameters. However, presenting too many patterns causes "overtraining," which limits the networks' ability to generalize and interpret the inputs. In the supervised training mode, error for the output units can be determined from the difference between the actual output value and the target (desired) value. Back-prop minimizes the mean squared error for the training set by modifying the weights according the negative of the partial derivative of the error term with respect to the weight space.

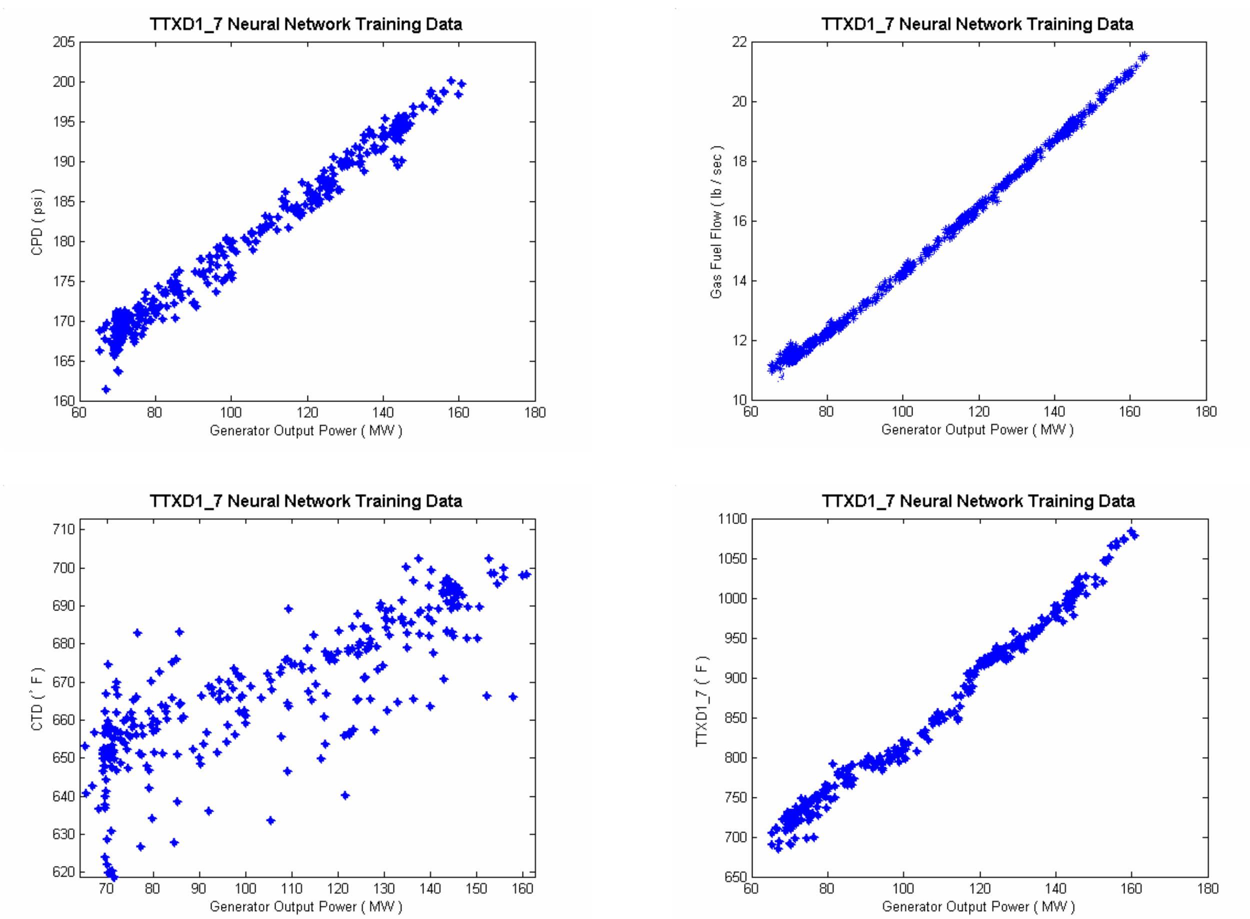


Figure 2-30
Training Data Sample for the TTXD1_7 Neural Network

Training data has been obtained from the PI Historian. Query results, similar to those utilized in the development of the operating signature curves, are first referred (corrected) to *International Standard Atmosphere* (ISA) sea level ('ISO standard day') static inlet conditions to account for the changing environmental conditions that occur over the course of operation. Sub-sets, as shown in Figure 2-30, are then extracted from the referred data to be presented to the neural networks as training patterns. The neural network used for illustration is for the TTXD1_7 sensor, a thermocouple in the array measuring exhaust gas temperature. *Compressor Discharge Pressure and Temperature* (CDP and CDT respectively), *gas fuel flow* (FQG) and *generator* *output power* (DWATT) are utilized as inputs for this network. Sixteen points have been selected from each period the CT unit, G3 in this case, was in service. The operating range of generator output power (DWATT) encompassing 65 MW to 165 MW was divided into four sub-ranges and four points extracted from each sub-range. Corresponding points were taken from CDP, CDT, FQG and TTXD1_7 based on the time stamp accompanying the DWATT data selected.

Appendix B: Fuzzy Logic Systems[3]

Overview of Fuzzy Logic Systems:

Fuzzy logic refers to a mode of reasoning based on imprecise/ambiguous information. Fuzzy logic technology enables machines to perform "approximate reasoning" and improves their performance through (i) efficient numerical representation of vague terms and concepts [such as 'dirty', 'slow', 'tall', 'heavy'], (ii) increasing their range of operation in ill-defined environments and (iii) decreasing their sensitivity to noisy data. Fuzzy logic also offers useful solutions to complex problems where mathematical models are neither available nor cost-effective to develop. Contrary to its nomenclature, fuzzy logic (or "fuzzy") systems operate based on precise, rigorous arithmetic of fuzzy sets. A fuzzy set that relates a domain interval to their "degree of membership" to a specific label (category) describes a membership function of the corresponding variable. After membership functions are defined over a variable's universe of discourse, relations between input and output fuzzy sets can be defined through a list of rules in the form: IF <condition> THEN <conclusion>. Sequence of operations in a fuzzy system can be described by three phases named fuzzification, inference, and defuzzification.

Many implementations of fuzzy systems are in the form of knowledge-based expert systems. Applications suitable for fuzzy logic range from systems modeling in science and economics, natural language man-machine interfaces, emulation of human decision making processes, to controlling nonlinear dynamic systems.

Max-Min Inference:

Suppose the membership function sets for T1, T2 and V are as shown below. If T1 and T2 use the same membership function set, and the following three rules are applied:

Rule 1: IF T1 IS warm OR T2 IS warm, THEN V is fast
Rule 2: IF T1 IS normal AND T2 IS warm, THEN V is fast
Rule 3: IF T1 IS normal AND T2 IS hot, THEN V is medium

Assume that fuzzification results are:

T1: cold=0.0, cool=0.0, normal=0.3, warm=0.7, hot=0.0
T2: cold=0.0, cool=0.0, normal=0.0, warm=0.4, hot=0.6

In the max-min inference method,

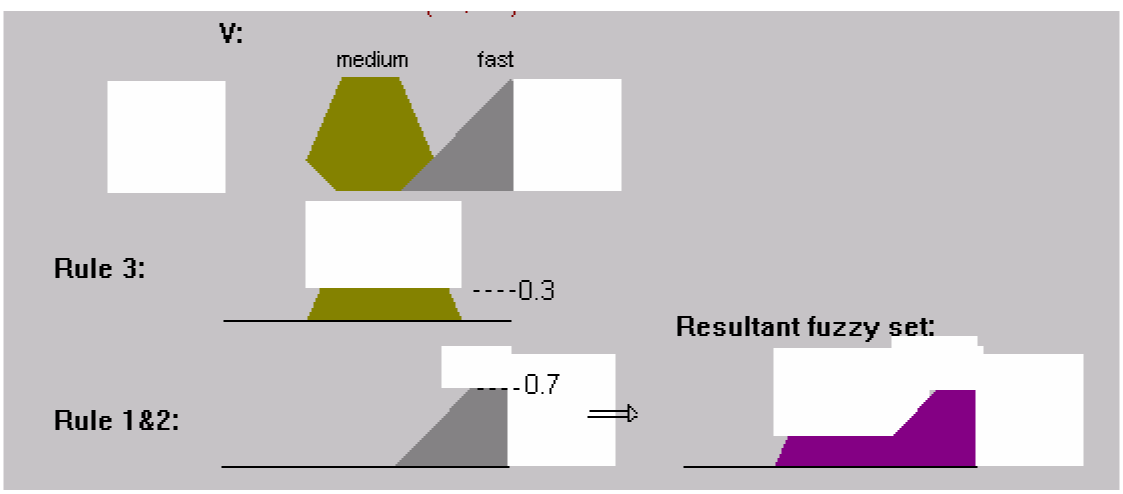
min operation $[\mu_A \cap \mu_B]$ is used for the AND conjunction (set intersection) and
max operation $[\mu_A \cup \mu_B]$ is used for the OR disjunction (set union)

to evaluate the grade ("strength") of the antecedent clause in each rule:

Rule 1: max(0.7, 0.4) = 0.7 fast
Rule 2: min(0.3, 0.4) = 0.3 fast
Rule 3: min(0.3, 0.6) = 0.3 medium

These values are used to clip the corresponding output membership function shapes. If multiple rules have the same consequent label, max operation is used to resolve conflicts. Since Rule 1 and Rule 2 have the same consequence label (fast), max operation is used:

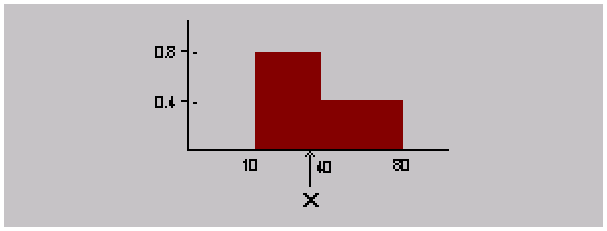
Rule 1 & Rule 2: max(0.7, 0.3) = 0.7 fast



The clipped membership functions are then merged to produce one final fuzzy set. The max operation is used to merge overlapping regions.

Centroid Defuzzification:

Referred to as the "center-of gravity" method, this process produces crisp data by computing the horizontal-axis (abscissa) component of the geometric centroid of the fuzzy set. Intuitively, the centroid method can be viewed as a "compromise" among the output actions recommended by different rules. For each output using this defuzzification method, the resultant fuzzy sets from all contributed rules are merged into a final aggregate shape. For example, the defuzzified result of the following shape is x=39:



The operation to use when merging overlapping shapes depends on the inference algorithm: (maximum for max-min and sum for max-dot and product-sum).

3

COMBUSTION TURBINE PERFORMANCE AND FAULT DIAGNOSTIC MODULE (CTPFDM), VERSION 3.2

Introduction

A performance degradation program has been developed for *Combustion Turbines* (CTs) and *Combined Cycles* (CCs). This Section describes the *Combustion Turbine Performance and Fault Diagnostic Module* (CTPFDM.) The following Section describes the *Combined Cycle Performance and Fault Diagnostic Module* (CCPFDM). CTPFDM is a spreadsheet which provides CT operators with a low-cost, easy-to-install, easy-to-use program for monitoring CT performance both on an overall basis and on a component by component basis. It can be used to diagnose the condition of a CT and to determine the benefits of maintenance actions such as an off-line compressor wash.

The CTPFDM spreadsheet can be used in either an "off-line" fashion through manual entry of data or "on-line" through automatic real-time data input using links to the PI data historian supplied by OSI Software, Inc.

Important features of the CTPFDM spreadsheet include:

- Operates as a spreadsheet with macros in Microsoft's Excel (version 97 or later)
- Runs under the Windows NT/95/98/2000 operating systems
- Comes with an installation routine developed using InstallShield
- Capable of monitoring multiple combustion turbines simultaneously
- Capable of monitoring combustion turbines of multiple makes and models
- Initial set-up includes built-in models of the GE 7FA and Siemens Westinghouse 501F combustion turbines
- The user has access to and may change data in the combustion turbine model file that defines the expected performance of the engine and can create new model files
- The familiar Excel "Chart" feature is used to trend the CTPFDM output
- Capable of detecting fault conditions in critical components of the combustion turbine
- Capable of handling English or metric (SI) units
- Capable of importing CT data from and results to a PI database via OSI's PI DataLink Excel Add-In

Background

Monitoring the performance of the components of a CT allows a user to determine which portion of the engine may be responsible for an observed decrease in output or efficiency. Through regular monitoring, an operator will know when to execute maintenance actions, such as an off-line wash, that can serve to restore machine performance back to its baseline.

Monitoring the condition of the axial compressor in a CT is an essential task in improving the overall performance of the engine. Fouling of the axial compressor of a CT will result in a decrease in both compressor efficiency and air flow. As noted in the *Axial Compressor Performance and Maintenance Guide* (EPRI TR-111038), a decrease in compressor efficiency of one percentage point will typically cause a drop in CT power of 1 to 1.5% and an increase in CT heat rate of 1 to 1.5%. Similarly, a 1% decrease in inlet air flow will typically result in a 1.1% drop in power output and a 0.2% increase in heat rate.

CTPFDM calculates both the actual and expected values of compressor efficiency and air flow to provide an indication of how well the compressor is performing. Built-in charts allow the user to trend these values over time, which facilitates rapid evaluation the compressor condition and of the effectiveness of on-line and off-line washes.

Compressor fouling also causes the compressor discharge temperature to increase due to the lower compressor efficiency. Most modern CTs use compressor discharge air to cool the combustor liner, transition pieces, and the first several rows of nozzles and blades in the expander section. Consequently, increased compressor fouling means hotter air is used to cool the hot section parts, which results in hotter metal temperatures and reduced parts life.

CTPFDM calculates the actual CT firing temperature (also know as first turbine rotor inlet temperature). By keeping a log of the amount of time spent at a given firing temperature, a CT operator can track the service history of an engine. In addition, EPRI envisions integrating CTPFDM with EPRI's hot section lifing software in the future to provide an automatic evaluation of remaining life of the hot section parts.

The turbine or expander section of a CT is another critical component in determining the overall performance of the engine. CTPFDM calculates both the actual and expected turbine section efficiency and trends it over time. While techniques for quick recovery of turbine section efficiency do not exist, knowing how much degradation has occurred can help a CT owner decide when a major overhaul needs to be scheduled.

The CTPFDM performance calculation output includes parameters which indicate the magnitude of degradation of critical CT components such as the compressor, combustion system, and turbine section. These diagnostic parameters are displayed in an easy-to-read table that allows the user to see at a glance potential problems, or faults, in critical CT components as they develop.

CTPFDM Development Philosophy

Several software packages are already commercially available for the on-line monitoring of CT performance. In fact, EPRI sponsored the development of the initial version of one of the first on-line CT performance monitoring packages, EfficiencyMap [1]. Rights to EfficiencyMap were later obtained by a commercial software firm and EfficiencyMap has subsequently been installed on more than 100 power plants. While commercially available on-line monitoring programs provide in-depth analysis of CT performance on a component-by-component basis, they are expensive to buy and expensive to implement in the field. For many CT operators, such an investment cannot be justified, particularly if their turbines are being used for peak-load operation only.

One of the goals for *CT Performance and Fault Diagnostic Module* (CTPFDM) was to produce a package that would be both easy to set up and inexpensive. To achieve these goals, several compromises or cost-benefit trade-offs were made during the initial design phase of CTPFDM. These included:

- Display of the results would be limited to a series of Excel charts and a one-page report screen. The ability to export results to PI will allow users to develop customized reports and displays.
- The mathematical model of CT performance would simply be based on a curve-fit of the manufacturer's expected performance rather than aero-thermal model of the physical behavior of the machine.

What's New in Version 3.2

This version of CTPFDM has been upgraded to include diagnostic algorithms to detect several combustion turbine faults. As part of this upgrade, two new worksheets have been added to the CTPFDM spreadsheet – one for user input of diagnostic parameter threshold values and another for display of diagnostic results. In addition, several new CT model parameters have been added to the GT model worksheet and there are several new measured input parameters on the Inputs worksheet.

Program Overview

CTPFDM carries out six main functions when it is called by another program: data checking, measured (or actual) performance, expected performance, transpose (or corrected) performance, evaporative cooling performance, and fault diagnostics.

The data checking function entails an evaluation of whether a complete set of input data is available and, if so, whether the data values make physical sense. (For example, if the compressor discharge temperature is colder than the compressor inlet temperature, an error message is issued and the calculation is not carried out.)

The actual performance calculations are based on key measurements from the plant instrumentation. Standard thermodynamic engineering formulas are used to derive key performance parameters such as heat rate and compressor isentropic efficiency. Curve fits to the thermodynamic properties of nitrogen, oxygen, argon, carbon dioxide and water vapor [2] are used to account for mixtures of dry air, water vapor and combustion products.

The expected performance calculations are based on the manufacturer's expected performance data that has been entered by the user (or from the two built-in CT models).

The corrected performance calculations transpose the actual performance results to "Standard Day" results by factoring out the effects of ambient conditions on CT performance.

If the program detects that some form of inlet cooling system is in operation, CTPFDM calculates what the actual performance of the CT would be if the cooling system was not in operation. In this way, the user can see the benefits that are obtained by using inlet cooling.

Fault diagnostics are based on rules developed by Dr. Meherwan Boyce. The diagnostic calculations result in logical "flags" which are evaluated for several combustion turbine parameters and used to alert the user to potentially excessive CT performance degradation.

The CTPFDM DLL requires two types of inputs: CT model data files and measured data files. The CT model data define the expected performance of the machine including the impact of changes in ambient conditions. The files containing these data are termed "static data files", as they will be changed infrequently, if ever. The files containing the measured data are called "dynamic data files" as they are updated each time performance calculations are requested and describe the operating condition of the machine at one moment in time.

All of the data files, static and dynamic, are accessed by the CTPFDM spreadsheet and displayed in the various worksheets of the spreadsheet.

The flowchart shown in Figure 3-1 depicts the interactions of the CTPFDM DLL with the CTPFDM spreadsheet (CTPFDM.xls). Measurements from the plant instrumentation are sent to the DCS (arrow 1). The user takes the data from the DCS and enters it in CTPFDM.xls (arrow 2). Then the user starts the calculation macro and the CTPFDM.xls writes the input data to ASCII files (arrow 3), then calls the CTPFDM DLL (arrow 4). The CTPFDM DLL reads the ASCII input files (arrow 5), performs the calculations, and then writes the results to ASCII output files (arrow 6). The CTPFDM.xls then reads the output files and stores the data for display and trending (arrow 7).

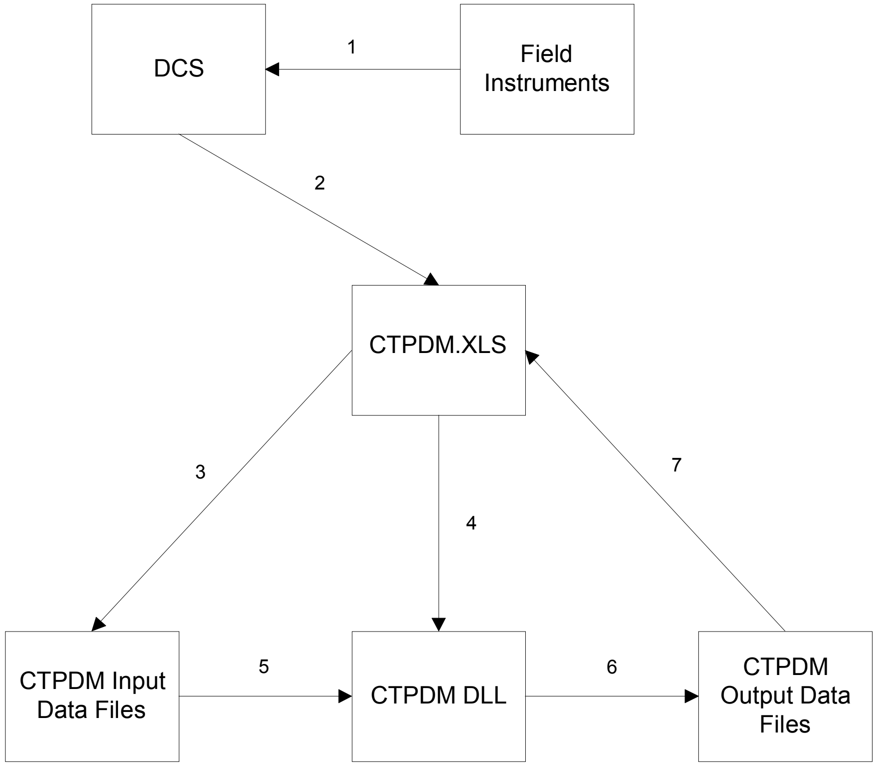


Figure 3-1
CTPFDM Software Functional Flowchart Showing Interaction between the CTPFDM DLL, the CTPFDM.xls Excel Spreadsheet, and the Combustion Turbine Instrumentation

Installation

Hardware & Software Requirements

Table 3-1 lists the minimum hardware requirements for running the CTPFDM spreadsheet. In addition, the PC must have Microsoft Excel 97 (or later) installed. Finally, if the user wishes to view an electronic version of this Users Manual, Acrobat Reader software from Adobe Systems, Inc. must be installed on the PC. Acrobat Reader is available free of charge on the Adobe Systems Web site at http://www.adobe.com.

Table 3-1
Minimum Hardware Requirements

Hardware	Minimum Requirement	Recommended
Processor	333 MHz Pentium III	Same
Operating System	Windows 95/98/2000/NT 4.0	Same
RAM	256 MB	512 MB
Available Hard Disk Space	10 MB	>20 MB

How to Install

1. Start Windows 95, 98, 2000 or NT. Make sure that no other application is running while CTPFDM is being installed.

2. The CTPFDM installation disk(s) may consist of either a single CD or multiple 3½-inch diskettes. Insert the CTPFDM installation CD or 1st diskette into the appropriate disk drive of your computer. For diskettes, this is usually drive A:\.

3. Select the "**Start**" button from the taskbar at the bottom of the screen and then "**Run**…". The "**Run**" dialog box appears.

4. For diskettes, type "A:\Setup.exe" in the Command Line text box. If installing from a CD or diskette drive other than A:\, substitute the appropriate letter for that source drive.

5. Select "**OK**". A welcome dialog box appears.

6. Select "**Next**" to go to the next screen.

7. The setup routine will then search for the path name of the Microsoft Excel executable file, Excel.exe. If it finds it, a message box appears and asks where to install the CTPFDM files (C:\Program Files\CTPFDM is the default path). If desired, change the default name and destination of the CTPFDM directory (folder).

   If the setup routine does not find the path to Excel.exe, a message box will appear stating that "Setup could not find an installed version of Excel." If you are certain that Excel is available on your PC, click the "**OK**" button and continue with the setup (the message box asking where to install the CTPFDM files will appear). After the setup routine is completed, it will be necessary to modify the "shortcut" to CTPFDM (see details at the end of this sub-section).

   The installation program will then install the program in the specified directory. If installing from diskettes, you will be prompted to change disks. The installation program will also add CTPFDM to the "**Programs**" menu option found under the "**Start**" button in the taskbar at the bottom of the screen. When you receive an on-screen message that the installation is complete, remove the final diskette from the drive.

8. To start the CTPFDM program, select the "**Start**" button from the taskbar, select the "**Programs**" submenu, click on **CTPFDM,** then click on the Excel spreadsheet icon labeled **CTPFDM**. Excel will start and load the CTPFDM.xls spreadsheet. A dialog box will appear stating that the spreadsheet contains macros and asking if you want to enable or disable the macros (see Figure 3-2). Click "**Enable Macros**" and the spreadsheet will finish loading.

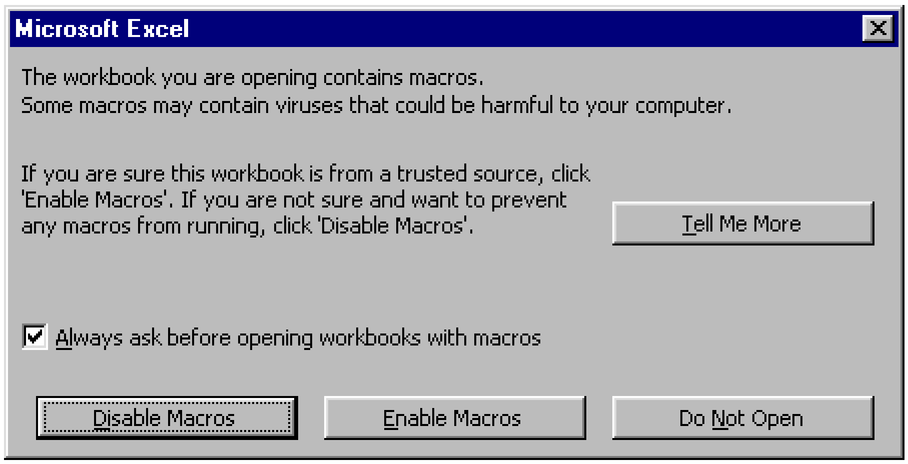


Figure 3-2
Example of Dialog Box that Appears Each Time the CTPFDM.xls Spreadsheet Is Loaded

Setup Cannot Find Excel

If you encountered the message during the installation that the setup routine could not find an installed version of Excel, but you know Excel is installed, you will have to modify the shortcut to CTPFDM to include the path to the Excel.exe file. To do this, first find the path to Excel.exe. Select the "**Start**" button from the taskbar, select the "**Programs**" submenu, then highlight **Microsoft Excel** and right-click with the mouse. A menu will appear and you should click on **Properties**. The **Excel Properties** window will appear. Highlight all of the text contained in the **Target** field under the **Shortcut** tab. The highlighted text is the path to Excel.exe. Copy it by simultaneously hitting the Control and C keys (**Ctrl+C**). Now close the Excel Properties window by clicking the "**Cancel**" button.

Now open the CTPFDM properties window by doing the following: select the "**Start**" button from the taskbar, select the "**Programs**" submenu, click on **CTPFDM,** then highlight the Excel spreadsheet icon labeled **CTPFDM** and right-click with the mouse. A menu will appear and you should click on **Properties**. The **CTPFDM Properties** window will appear. Place the cursor at the beginning of the **Target** field under the **Shortcut** tab by first clicking anywhere within the field and then hitting the Home key. Now paste in the Excel.exe path information by simultaneously hitting the Control and V keys (**Ctrl+V**). Next make sure there is a space between the end of the Excel.exe path and the beginning of the CTPFDM.xls path information by hitting the space key once. The text in the field should now look something like this:

"C:\Program Files\Microsoft Office\Office\EXCEL.EXE" "C:\Program Files\CTPFDM\CTPFDM.xls" /p "C:\Program Files\CTPFDM" /e

(The above text assumes the default directory was chosen for the CTPFDM files.)

Save the changes and close the CTPFDM Properties window by clicking the "**OK**" button. You are now ready to start CTPFDM (see step 8 above).

How to Uninstall

1. From the Windows 95, 98, 2000 or NT desktop, click on the "**My Computer**" icon to open the "My Computer" window.

2. From the "My Computer" window, click on the "**Control Panel**" icon to open the "Control Panel" window.

3. From the "Control Panel" window, click on the "**Add/Remove Programs**" icon to open the "Add/Remove Programs" window.

4. Select the CTPFDM software from the list of currently installed programs, then click the "**Add/Remove**" button ("Change/Remove" button in Windows 2000).

5. A message box will appear asking for confirmation of the removal of the program and its components. If you are certain that you want to uninstall CTPFDM, click the "**Yes**" button and CTPFDM will be removed.

CTPFDM File Structure

The CTPFDM.xls spreadsheet is automatically installed in the directory (folder) specified by the user during the InstallShield installation routine (the default directory is C:\Program Files\CTPFDM). In addition to the spreadsheet file, the installation program creates several other files and sub-directories. These files and sub-directories are described in this sub-section.

Main CTPFDM Directory

The files installed in the main CTPFDM directory (i.e., "C:\Program Files\CTPFDM" or the user-specified replacement) are:

- CTPFDM.xls, the CTPFDM Excel spreadsheet
- CTPFDM.dll, the CTPFDM dynamic link library
- Perfunit.dat, a text file containing the path of the data files for the CT unit to be monitored
- README.TXT, a text file directing the user to find help in either the CTPFDM Quick Guide to Getting Started or the CTPFDM Spreadsheet User's Manual.

- Status.sys, a text file containing basic technical information for the DLL
- Uninst.isu, a reference file used if CTPFDM is uninstalled via the Windows Control Panel "Add/Remove Programs" routine

Files for Monitoring Multiple Combustion Turbines

The CTPFDM.xls spreadsheet is capable of tracking the performance of multiple CTs. In CTPFDM.xls, each CT is called a "unit". Using the CTPFDM spreadsheet as it is installed from the installation disk(s), only one unit can be monitored at a time, but the user can switch from one unit to another with the click of a button. It is possible to simultaneously monitor multiple CTs, but this requires that the user set up multiple instances of the CTPFDM software. Details of how to accomplish this are provided later in this sub-section.

Since each CT may be a different make or model, each unit must have its own CT model data files, which define the expected performance of the engine. Similarly, each CT will have different operating results, so each unit must have its own results files.

To organize the various data and results files, each CT unit is given its own sub-directory under the main CTPFDM directory. The name of the sub-directory corresponds to the name of the unit as defined by the user when the unit is created (see sub-section heading "Tutorial") for an example of how to create a new unit). The names and structure of the files in each of the unit sub-directories are identical, but the contents of the files will vary from unit to unit. The names of the files in each unit sub-directory are listed in Table 3-2.

Table 3-2
List of Files in Each CT Unit Sub-Directory

CT Model Files	Performance Data Input Files	CTPFDM DLL Output Files	CTPFDM.xls Results File
Gtmodel.dat	Measinp.dat	Gtpdata.dat	Results.csv
Transpos.dat		Gtpsave.dat	
Washcrit.dat		Perferr.dat (only generated if errors are encountered)	
Unitsop.dat		Perfdone.inf	
Measdflt.dat			
Massfrac.dat			
Molepct.dat			
Perfops.dat			
Missinp.dat			
Partload.dat			
Turbine.dat			
Dpthresh.dat			

CT Reference Model Files

In addition to the individual unit sub-directories, the CTPFDM file system also has a separate "Reference Models" sub-directory, which contains the CT model data files that can be copied to create new units. The CTPFDM spreadsheet comes with built-in CT models for the General Electric 7FA and Siemens Westinghouse Power Corporation 501F engines. Models based in both English and SI units are available as shown in Table 3-3. In addition to the built-in models, any CT models that the user creates or copies will also be stored in the Reference Models sub-directory. Note that the reference CT model files are named according to the name supplied by the user when creating or copying a CT model. See sub-section heading "Using the Spreadsheet" for an example of how to create a new CT model.

Table 3-3
List of CT Model Files Pre-Installed with CTPFDM.xls

Model File Name	Units	CT Manufacturer Name
GE7FA.dat	English	General Electric PG7231(FA)
GE7FASI.dat	SI	General Electric PG7231(FA)
W501F.dat	English	SWPC 501F
W501FSI.dat	SI	SWPC 501F

Users Manual

This Users Manual, in the form of an Adobe Acrobat portable document format (PDF) file, is also installed in the Help sub-directory of the main CTPFDM directory.

File Directory Diagram

Figure 3-3 contains a schematic diagram of the CTPFDM spreadsheet file directory structure. It assumes that "C:\Program Files\CTPFDM" was specified as the "install to" directory for CTPFDM.

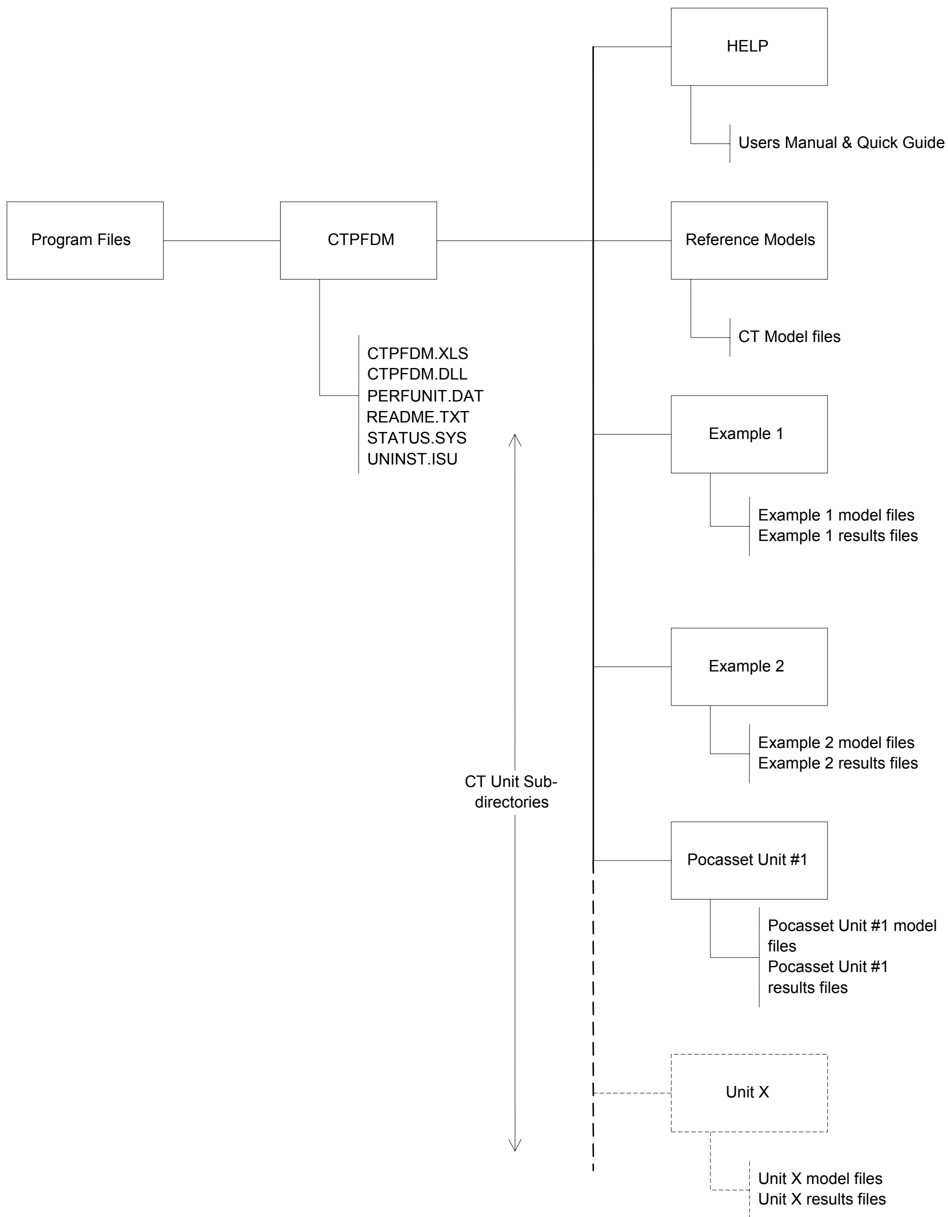


Figure 3-3
Schematic Diagram of the File Directory of CTPFDM

Monitoring Multiple Combustion Turbines Simultaneously

As stated at the beginning of this sub-section, using the CTPFDM spreadsheet as it is initially installed from the installation disks allows the monitoring of only one unit at a time. However, it is possible to simultaneously monitor multiple CTs by setting up multiple instances of the CTPFDM software. This can be accomplished either by installing the software multiple times or by simply making multiple copies of the software that was initially installed. As Microsoft Windows requires unique directory (folder) and file names, each additional copy of the software requires a different name. For example, there could be two copies of the software, one installed to a "C:\Program Files\CTPFDM Unit 1" directory and another copied to a "C:\Program Files\CTPFDM Unit 2" directory. Further details on simultaneous monitoring of multiple units can be found in the following sub-section under the heading “Using the Spreadsheet”.

Using the Spreadsheet

The CTPFDM.xls spreadsheet consists of a series of worksheets that the user can access by clicking on the tabs located at the bottom of the Excel screen. This sub-section describes the contents of each of the worksheets and explains how to execute the various macros that are built into the spreadsheet. The descriptions assume that the user is already familiar with Excel. If the user is not familiar with Excel, it is recommended that they first refer to the Excel User's Guide or the Excel On-Line Help function accessible via the "Help" menu at the top of the Excel screen.

Launching a CTPFDM Spreadsheet

Whenever a CTPFDM spreadsheet is launched, the menus containing the gas turbine units and combustion turbine models will be updated if the workbook was not saved after creating or removing units or models. In addition, the spin button for the "Display Previous CTPFDM Results" feature explained below will be updated to include any new results that were saved into the Results.csv file if the workbook was not saved after saving new results in Result.csv.

If the spreadsheet data is different from the saved data (this could occur if a unit is deleted without saving the spreadsheet), there will be a message box asking the user if they want to import saved data or leave the spreadsheet data as it is. Normally, you should choose to import the saved data.

Main Menu Worksheet

In this worksheet, the user can create a new unit, switch to another unit, remove a unit, or add/delete GT models. The currently existing units and models, and their respective units of measurement, are displayed at the right-hand side of the spreadsheet.

It is important to remember that all units referred to and operated on in the Main Menu worksheet can only be monitored one at a time *in the active workbook* (i.e., the currently-displayed CTPFDM spreadsheet*)*. Dealing with multiple units simultaneously requires that multiple instances of the CTPFDM spreadsheet are installed and running. More information on the simultaneous running of CTPFDM for multiple units is provided in later sub-sections.

Current Unit

The current unit is displayed at the top left-hand corner of the worksheet. It is also displayed at the top of several other worksheets. To change the current unit, select the "Switch Unit" option explained below.

CTPFDM Directory

The directory where the CTPFDM.xls, CTPFDM.dll, etc. files are located (i.e., the directory into which the software was installed or copied) is displayed at the top of the Main Menu worksheet. The name of the directory displayed will always conform to the current directory of the active workbook, so the user does not have to change it.

Switch Unit

To switch from the current unit to another unit, first select the name of the unit you want to switch to in the pull-down menu. Then click the button labeled "Switch Unit". A macro will then be executed that copies all of the data files associated with the new unit into the appropriate places in the spreadsheet. A message appears when the macro is finished. The user can then move to the other worksheets and either modify the data used to predict the expected performance of the CT or enter new operating data and execute the CTPFDM performance calculation routine.

Create Unit

To create a new unit, first select the GT model from the pull-down menu directly below the button. Then click the button labeled "Create Unit". The user will then be prompted to enter the name of the unit to be created. Click the "OK" button to create the unit.

Copy Unit

To copy a unit to another unit, first select the source unit and the units of measurement (Current or Switch) option. If you select the "Current" option, the source unit will have the same units of measurement (English or SI) as the target unit. Choose the "Switch" option to use the opposite units of measurement (i.e., English instead of SI) for the target unit. Then enter the name of the target unit. (You cannot use the same name as the source unit for the target unit, but you can overwrite a different unit or you can enter a completely new unit name.) A macro will then copy all of the data files from the sub-directory of the source unit to the sub-directory of the target unit (with the exception of the Results.csv file, which is not copied), and any units of measurement conversions will be carried out.

This function is useful when you want to add a new unit that is identical or nearly identical to an existing unit.

Save Current Data

Click on this button to save the data for the GT model, measured defaults, standard day conditions, units of measurement, performance option, mass fractions, mole percents, and saved results into the current files of the current unit. The Results.csv file will not be affected by the use of this button.

This feature can also be used to restore a unit that has just been removed accidentally, provided that "Current Unit" is still the one that was removed. In this case, the Results.csv file will conform to what the Data vs. Time charts, explained below, are displaying.

Save Unit As…

Click on this button to save the current unit's data for the GT model, measured defaults, standard day conditions, units of measurement, and wash criteria into another specified unit. The user will be prompted to enter the name of the unit to save to. The user has the option of overwriting an existing unit. If any of the values for any of the files are out of range, no data will be saved. The Results.csv file in the target unit sub-directory will be deleted when overwriting an existing unit.

This function is similar to the Copy Unit function, except that it uses the data displayed in the spreadsheet rather than the data saved to the data files to create (or overwrite) the data files of another unit.

Remove Unit

To remove an existing unit, first select the unit to be removed from the pull-down menu. Then click the button labeled "Remove Unit". There will be a message box asking the user if they really want to delete the specified unit. Click the "OK" button to delete it or click "Cancel" to cancel the delete operation. If "OK" is specified, a macro will be executed that will delete the sub-directory in which the unit is located and will remove all files in that sub-directory.

Display CT Model

First select the combustion turbine model from the menu directly below the button. Then click on the button. The data will be imported into the Gtmodel worksheet.

Add CT Model

First select the option of English or SI units of measurement. Then click the button to add a combustion turbine model to the Reference Models folder. The data currently on the spreadsheet will be saved in the units of measurement selected.

Copy CT Model

This button allows the user to copy a combustion turbine model from an external data source, such as a floppy disk or a directory other than the default CTPFDM directory. It is assumed that the user knows the units of measurement (English or SI) of the source file. First, select the units of measurement of the source file and the model to copy to in the Reference Models sub-directory. The user will then be prompted to enter the source directory and to enter the source file name. Then, the user will be prompted to enter the name of the model to copy to.

Remove CT Model

To remove an existing model, first select the model to be removed in the pull-down menu. Then click the button labeled "Remove CT Model". There will be a message box asking the user if they really want to delete the specified model. Click the "OK" button to delete it or click "Cancel" to cancel the delete operation. If "OK" is specified, a macro will be executed that will delete the sub-directory in which the model is located and will remove all files in that sub-directory.

Display Previous CTPFDM Results

With this button, you can display the results of saved previous runs of CTPFDM for the current unit. Use the spin button to select which results to display. The run number, date, and time will be displayed in the cells just above the spin button. To see the results, click the button labeled "Display Previous CTPFDM Results" and the results (and errors if they exist) will be displayed on the Report worksheet. If there are no saved results, "No Saved Results" will be displayed in the cell just below the button and this feature cannot be used.

Default Data Worksheet

This worksheet contains the data for measured defaults, standard day conditions, and wash criteria.

Default Data

This portion of the worksheet is used to import or modify the data for the Measdflt.dat file.

Get Defaults

To import the data from the measured defaults file, click the button labeled "Get Defaults". The data and the units of measurement of the data (depending on the units used, English or SI) will be displayed in the respective cells and pull-down menus.

Save Defaults

To save new data into the measured defaults file, first input the data into the appropriate cells and select the units of measurement in the pull-down menus, then click the button labeled "Save Defaults". The values contained in the cells will be converted to the units expected by CTPFDM, depending on which options are selected from the unit pull-down menus and whether English or SI units are used. If any values are out of range, an error message will be displayed, the out-of-range cell(s) will be selected, and no data will be saved. If all values are within the expected range, then the values (in the standard CTPFDM units of measurement) will be exported to the file. Note that no changes will be made to the actual file until the "Save Defaults" button is clicked.

If the user makes changes to the data and wishes to reset the values to what they were previously, this can be done using the "Get Defaults" button as long as the "Save Defaults" button has not been clicked.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter:

Inlet Pressure Drop	0-20 in. H2O, 0-50 mbar, 0-0.723 psid, 0-5000 Pa
Exhaust Pressure Drop	0-30 in. H2O, 0-75 mbar, 0-1.09 psid, 0-7500 Pa
Relative Humidity	0-100 %
Barometric Pressure	24-32 in. Hga, 0.81-1.08 bara, 610-812 mm Hga, 11.7-15.7 psia
Natural Gas Fuel LHV	0-45000 Btu/lb, 0-100000 kJ/kg
Liquid Fuel LHV	0-45000 Btu/lb, 0-100000 kJ/kg, 834500/S.G.* Btu/gal, 35049000/S.G.* Btu/bbl
Water/Fuel Ratio	0-2
Steam/Fuel Ratio	0-2
Injected Water Temperature	44-212 °F or 4.5-100 °C
Injected Steam Temperature	212-1000 °F or 100-500 °C
Natural Gas Fuel Temperature	0-600 °F or –18-350 °C
Natural Gas Fuel Pressure	100-1000 psig, 7-100 barg, 700000-7000000 Pa, 7-100 atm
Liquid Fuel Specific Gravity	0.6-1.1
Liquid Fuel Specific Heat	0-1
External Cooler Air Exit Temp.	0-500 °F or –18-350 °C
Atomization Air Temperature	0-1000 °F or –18-500 °C
Generator and Mech. Efficiency	0.8-1

*S.G.—Liquid Fuel Specific Gravity (value saved in Measdflt.dat)

Standard Day Conditions

This portion of the worksheet contains the data in the Transpos.dat file.

Get Conditions

To import the data from the transpose data file, click the button labeled "Get Values". The data and the units of measurement of the data (depending on the units used, English or SI), as well as the firing mode (base or peak) and the fuel used (gas or liquid), will be displayed in the respective cells and pull-down menus.

Get ISO Conditions

This button, when clicked, will put standard ISO conditions data into the respective cells and pull-down menus (including the units of measurement, firing, and fuel modes).

Save Conditions

To save new data into the file, first input the data into the cells and input the units of measurement, firing, and fuel options into the pull-down menus, then click the button labeled "Save Conditions". The values contained in the cells will be converted to the proper units, depending on which options are selected from the unit pull-down menus and whether English or SI units are used. If any values are out of range, an error message will be displayed, the out-of-range cell(s) will be selected, and no data will be saved. If all values are within the expected range, then the values (in the proper units of measurement) will be exported to the file. Note that no changes will be made to the actual file until the "Save Conditions" button is clicked.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter:

Barometric Pressure	24-32 in. Hga, 0.81-1.08 bara, 0.94-1.26 mm Hga, 11.7-15.7 psia
Compressor Inlet Temperature	Minimum GT model value-Maximum GT model value °F or °C
Relative Humidity	0-100 %
Inlet Pressure Drop	0-20 in. H2O, 0-50 mbar, 0-0.723 psid, 0-5000 Pa
Exhaust Pressure Drop	0-30 in. H2O, 0-75 mbar, 0-1.09 psid, 0-7500 Pa
Water/Fuel Ratio	0-1
Steam/Fuel Ratio	0-1

Compressor Wash Criteria

This portion of the worksheet contains the data in the Washcrit.dat file.

Get Criteria

To import the data from the transpose data file, click the button labeled "Get Values". The data will be displayed in the respective cells.

Save Criteria

To save new data into the file, first input the data into the cells then click the button labeled "Save Criteria". The values contained in the cells will be exported to the file. If either of the values is out of range, an error message will be displayed, the out-of-range cell(s) will be selected, and no data will be saved. Note that no changes will be made to the actual file until the "Save Criteria" button is clicked.

Acceptable Ranges

The acceptable range for both values is 0-100 %.

Performance Option

Get Option

To import the option from the performance option file, click the button labeled "Get Option". The data will be displayed in the pull-down menu.

Save Option

To save a different option to the file, first select "Inlet Air Flow" or "Heat Balance" from the pull-down menu at the bottom of the worksheet. Then click the button labeled "Save Option". The value of the selected option will be exported to the file. Note that no changes will be made to the actual file until the "Save Option" button.

Help on Inputs

For help on the specific sections of the Default Data worksheet, click the button labeled "Click for Help on Inputs". To return to the Default Data worksheet from the help screen, click the button labeled "Return to Defaults".

Diag. Thresh. Data Worksheet

This worksheet contains the data for the diagnostic parameter threshold values (Dpthresh.dat).

Get Diagnostics

To import the data from the diagnostic parameter threshold file, click the button labeled "Get Diagnostics". The data will be displayed in the respective cells along with the units of measurement based on the units of measurement (English or SI) being used for the current unit.

Save Diagnostics

To save new data into the file, first input the data into the appropriate cells, then click the button labeled "Save Diagnostics". The values contained in the cells will be exported to the file. Note that no changes will be made to the actual file until the "Save Diagnostics" button is clicked.

If the user makes changes to the data and wishes to reset the values to what they were previously, this can be done using the "Get Diagnostics" button as long as the "Save Diagnostics" button has not been clicked.

Number of Wheelspace Temperatures

These will change the values for the number of parameters for the Total Number of Wheelspace Temperatures Used, Minimum Number of Wheelspace Temperatures Needed for Alert, and Minimum Number of Wheelspace Temperatures Needed for Action Required. Do not change the numbers themselves, but use the spin buttons next to each one to change the number of parameters. Changing the numbers themselves will have no effect on the rows or columns. When the spin button is clicked, a row will be inserted or deleted in the correct location, depending on whether the up or down part of the button was clicked. The user can then enter new values into a new row if a row was added. A maximum of 12 temperatures may be used for each parameter.

If the user directly changes the numbers next to the spin buttons, these numbers can be reset by clicking the button labeled "Get Diagnostics". Using the spin buttons themselves will also reset these values.

Help on Inputs

For help on the specific sections of the Diag. Thresh. Data worksheet, click the button labeled "Click for Help on Inputs". To return to the Diag. Thresh. Data worksheet from the help screen, click the button labeled "Return to Diag. Thresh. Data".

Fuel Properties Worksheet

This worksheet contains the mass fraction data (Massfrac.dat) and mole percent data (Molepct.dat).

Mass Fractions

This portion of the worksheet contains the data for mass fractions.

Get Mass Fractions

To import the data from the mass fraction file, click the button labeled "Get Mass Fractions". The data will be displayed in the respective cells.

Save Mass Fractions

To save new data into the file, first input the data into the cells then click the button labeled "Save Mass Fractions". The values contained in the cells will be exported to the file. If the sum of the values is not equal to 1, an error message will be displayed and no data will be saved. Note that no changes will be made to the actual file until the "Save Mass Fractions" button is clicked.

Acceptable Range

The sum of all mass fractions must be equal to 1. The value of the sum is displayed in the cell directly below the last mass fraction entry. (The actual value of the sum will not be saved into the file.)

Mole Percents

Get Mole Percents

To import the data from the mole percent file, click the button labeled "Get Mass Fractions". The data will be displayed in the respective cells.

Save Mole Percents

To save new data into the file, first input the data into the cells then click the button labeled "Save Mole Percents". The values contained in the cells will be exported to the file. If the sum of the values is not equal to 100, an error message will be displayed and no data will be saved. Note that no changes will be made to the actual file until the "Save Mole Percents" button is clicked.

Acceptable Range

The sum of all mole percents must be equal to 100. The value of the sum is displayed in the cell directly below the last mole percent entry. (The actual value of the sum will not be saved into the file.)

Gtmodel Worksheet

This worksheet usually contains the data in the Gtmodel.dat file for the current unit. It also can contain data for a different GT model if the "Display Model" or "Add Model" buttons on the Main Menu worksheet are used. If a different model is displayed on this worksheet, you can click the button "Get Gtmodel Values from Unit" (explained below) to import the saved data for the current unit.

Reference Conditions for Rating

Enter Data

Enter the data and units into the respective cells and pull-down menus. Note that no data will be saved into the actual file until the "Save Gtmodel Values to Unit" button is clicked. This button is explained below.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter:

Barometric Pressure	24-31 in. Hga, 0.81-1.07 bara, 610-787 mm Hga, 11.7-15.6 psia
Compressor Inlet Temperature	–40-140 °F or –40-60 °C
Relative Humidity	0-100 %
Inlet Pressure Drop	0-20 in. H2O, 0-50 mbar, 0-0.723 psid, 0-5000 Pa
Exhaust Pressure Drop	0-30 in. H2O, 0-75 mbar, 0-1.09 psid, 0-7500 Pa
Inlet Guide Vane Position	–20-180 °

Reference Data for Inlet Flow Calculations

Enter Data

Enter the data and units into the respective cell and pull-down menu. Note that no data will be saved into the actual file until the "Save Gtmodel Values to Unit" button is clicked.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter:

Inlet Area at IGVs	0-20000 sq. in. or 0-13000000 sq. mm
Flow Coefficient	0-1

Number of Parameters for Correction Factors

These will change the values for the number of parameters for the Temperature Inlet, Water Injection, Steam Injection, and Specific Humidity Correction Factors. Do not change the numbers themselves, but use the spin buttons next to each one to change the number of parameters. Changing the numbers themselves will have no effect on the rows or columns. When the spin button is clicked, a row will be inserted or deleted in the correct location, depending on whether the up or down part of the button was clicked. The user can then enter new values into a new row if a row was added. A maximum of 20 parameters may be used.

If the user directly changes the numbers next to the spin buttons, these numbers can be reset by clicking the button labeled "Get Gtmodel Values from Unit". Using the spin buttons themselves will also reset these values.

Inlet/Exhaust Pressure Drop Effects

Enter the data into the respective cells. Note that no data will be saved into the actual file until the "Save Gtmodel" button is clicked. The range for Power and Heat Rate effects is 0 - 0.1. The range for the Exhaust Temperature effect is 0 - 10 °F or 0 - 5.6 °C

Rated Performance at Reference Conditions

Enter Data

Enter the data and units into the respective cells and pull-down menus. You can also select the flow option (air or exhaust). For help on this topic, select the "Click for Help on Gtmodel" button explained below. Note that no data will be saved into the actual file until the "Save Gtmodel Values to Unit" button is clicked.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter:

Power	0-500000 kW
Heat Rate	3412-20000 Btu/kW-hr, 3600-20000 kJ/kW-hr
Flow	0-10000000 lb/hr, 0-6000000 kg/hr, 0-2780 lb/sec, 0-1260 kg/sec

Compressor Inlet Temperature Correction Factors

Enter Data

First, change the number of parameters, if necessary, using the spin buttons described above. Then, make any necessary changes to the data. A pull-down menu is available to select the unit of temperature (Fahrenheit or Celsius). The temperatures will be converted depending on whether English or SI units are used. Again, no data will be saved until the "Save Gtmodel values to Unit" button is clicked.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter:

Compressor Inlet Temperature	–40-140 °F or –40-60 °C
Power	0.1-2

Heat Rate	0.1-2
Flow	0.1-2
Compressor Efficiency	0-100 %
Pressure Ratio (P-ratio)	1-100 %
Exhaust Temperature	400-1400 °F or 204.4-760 °C

Correction Factor Charts

Four charts will be displayed on separate worksheets graphing the correction factors vs. temperature. The first chart contains temperature vs. power, heat rate, and air flow for base mode. The second contains this data for peak mode. The third contains temperature vs. compressor efficiency and pressure ratio for base mode. The fourth contains this data for peak mode. These charts will be automatically adjusted whenever the Gtmodel.dat file is imported to display the range properly.

Combustor Water Injection Correction Factors

Enter Data

First, change the number of parameters, if necessary, using the spin buttons described above. Then, make any necessary changes to the data. A pull-down menu is available to select the unit of temperature (Fahrenheit or Celsius). The temperatures will be converted depending on whether English or SI units are used. Again, no data will be saved until the "Save Gtmodel Values to Unit" button is clicked.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter:

Compressor Inlet Temperature	–40-140 °F or –40-60 °C
MW-wtr	0-1
HR-wtr	0-1
AF-wtr	0-1

Combustor Steam Injection Correction Factors

Enter Data

First, change the number of parameters, if necessary, using the spin buttons described above. Then, make any necessary changes to the data. A pull-down menu is available to select the unit of temperature (Fahrenheit or Celsius). The temperatures will be converted depending on whether English or SI units are used. Again, no data will be saved until the "Save Gtmodel Values to Unit" button is clicked.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter:

Compressor Inlet Temperature	–40-140 °F or –40-60 °C
MW-wtr	0-1
HR-wtr	0-1
AF-wtr	–1-1

Humidity Correction Factors

Enter Data

First, change the number of parameters, if necessary, using the spin buttons described above. Then, make any necessary changes to the data. A pull-down menu is available to select the unit of temperature (Fahrenheit or Celsius). The temperatures will be converted depending on whether English or SI units are used. Again, no data will be saved until the "Save Gtmodel Values to Unit" button is clicked.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter:

Specific Humidity	0-0.1
Power	0.9-1.1
Heat Rate	0.9-1.1

Cooling Air Factors

Enter Data

Enter the data into the respective cells and pull-down menus. Also, select the External Cooler Option (yes or no) from the pull-down menu. Note that no data will be saved into the actual file until the "Save Gtmodel Values to Unit" button is clicked. This button is explained below.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter:

Total Cooling Air	0-0.33
Liquid Fuel Atomization Air	0-0.025
Rotor Cooling Air	0-0.33

First Nozzle Cooling Air	0-0.33
Combustor Efficiency	0.98-1
Number of Compressor Stages	0-25
Compressor Stage for Wheelspace Cooling Air	0-# of compressor stages

Get GTmodel Values from Unit

To import the saved data for the current unit, click this button. The correction factor charts will be adjusted to conform to the saved data. The pull-down menus containing the units of measurement will also be adjusted. (Note that the data will be imported from the current unit and not the current CT model if there is a different model displayed using the "Display Model" or "Add Model" buttons on the Main Menu worksheet.)

Save GTmodel Values to Unit

When this button is clicked, the data will be exported to the Gtmodel.dat file. If any values are out of range, an error message will be displayed, the out-of-range cell(s) will be selected, and no data will be saved. (Note that the data will be saved to the current unit and not the current CT model if there is a different model displayed using the "Display Model" or "Add Model" buttons on the Main Menu worksheet. Also, if a different model is displayed, it is possible to export the data into the current unit, but it is not recommended if there are previously saved results. In this case, a warning message will be issued before saving the data.)

Help on Inputs

For details on all of the sections of the Gtmodel worksheet, click the button labeled "Click for Help on Inputs". To return to the Gtmodel worksheet from the help screen, click the button labeled "Return to Gtmodel".

Inputs Worksheet

This worksheet allows the user to define and control the measured input data that will be processed in the CTPFDM.dll file. The user can either enter data manually or use on-line, real-time data via links to third-party data historians such as OSI's PI database. (The user should consult the documentation on the third-party data historian software for instructions on how to link an Excel cell to a specific data point.) In addition to entering the input values, the user can specify the units of measurement and data quality flag to be used for each of the inputs.

Enter Data

Value

In the cells, the user enters the values for the CTPFDM data into the respective cells.

Units of Measurement

The user can select the units of measurement of the input data for each cell. Depending on the unit option selected, the values will be converted into the standard CTPFDM units (English or SI) before the measured inputs are exported.

Data Quality Flag (Use Input, Use Default, or Ignore Input)

The user can select the data quality flag for some of the input options. For some inputs, not all of these options will be available. For help on these flags, select the "Help on Inputs" button explained below.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter. Many of these range values are dependent on the saved GT model data.

Ambient Temperature*	Minimum GT model value-Maximum GT model value °F or °C
Barometric Pressure	24-31 in. Hga, 0.81-1.07 bara, 610-787 mm Hga, 11.7-15.6 psia
Relative Humidity	0-100 %
Compressor Inlet Temperature*	same as Ambient Temperature
Inlet Filter Pressure Drop	0-20 in. H2O, 0-50 mbar, 0-0.723 psid, 0-5000 Pa
Inlet Total Pressure Drop	0-20 in. H2O, 0-50 mbar, 0-0.723 psid, 0-5000 Pa
Bellmouth Static Pressure Drop	0-432 in. H2O, 0-1080 mbar, 0-15.7 psid, 0-108000 Pa
For Future Use	no range check
Compressor Discharge Pressure	14.7-614 psig, 1-42 barg, 101000-4230000 Pa, 1-41 atm
Compressor Discharge Temp.*	Comp. Inlet Temp. value °F or °C-1300 °F or 700 °C
Inlet Guide Vane Position	GT model value - 3-GT model value + 3
Generator Power	0.67 * GT model value/1000-1.25 * GT model value/1000 MW
Gas Fuel Flow	0.1-49.5 lb/sec, 0.01-22 kg/sec, 360-178200 lb/hr, 160-80800 kg/hr, 6-2950 lb/min, 2.5-1300 kg/min
Liquid Fuel Flow	0.1-49.5 lb/sec, 0.01-22 kg/sec, 360-178200 lb/hr, 160-80800 kg/hr, 6-2950 lb/min, 2.5-1300 kg/min, 0.72/S.G.**-356/S.G.** gpm, 2.72/S.G.**-1347 S.G.** liter/min
Inlet Air Flow*	0.67 * GT Model value-1.25 * GT Model value lb/sec, kg/sec, lb/hr, kg/hr, lb/min, or kg/min
Water Injection Flow	0-2*Gas or Liquid Fuel Flow*** lb/sec, kg/sec, lb/hr, kg/hr, lb/min, kg/min, gpm, or liter/min*
Steam Injection Flow	0-2*Gas or Liquid Fuel Flow*** lb/sec, kg/sec, lb/hr, kg/hr, lb/min, or kg/min*
Dew Point Temperature	–20-120 °F or –29-49 °C
Injected Water Temperature	40-212 °F or 4.5-100 °C
Injected Steam Temperature	212-1000 °F or 100-1000 °C
Gas Fuel Temperature	0-600 °F or –18-350 °C
Gas Fuel Pressure	100-1000 psig, 7-100 barg, 700000-7000000 Pa, 7-100 atm
Liquid Fuel Temperature	0-600 °F or –18-350 °C
Exhaust Temperature	Comp. Disch. Temp.*-2000 °F or –Comp. Disch. Temp.-1093 °C
Cold End Vibration – A	0-2 in./sec or 0-50.8 mm/sec
Cold End Vibration – B	0-2 in./sec or 0-50.8 mm/sec

Hot End Vibration – A	0-2 in./sec or 0-50.8 mm/sec
Hot End Vibration – B	0-2 in./sec or 0-50.8 mm/sec
Exhaust Temperature Spread	0-250 °F or 0-121 °C
Hot End Bearing Metal Temperature	0-300 °F or 0-149 °C
Hot End Bearing Drain Temperature	0-250 °F or 0-121 °C
Wheelspace Temperature(s)	0-1200 °F or 0-649 °C

*The minimum and maximum values will be converted to the proper units depending on the option selected in the pull-down menu.

**S.G.—Liquid Fuel Specific Gravity (value saved in Measdflt.dat file).

***Value used depends on the fuel mode (Gas or Liquid).

Help on Inputs

For the specific details on the impact of the "ignore input" flag, click the button labeled "Click for Help on Inputs". From the help screen, click the button labeled "Return to Inputs" to return to the Inputs worksheet.

Run CTPFDM

Click the button labeled "Click to Run CTPFDM" to execute the CTPFDM.dll calculation engine in "off-line" (manual) mode. First, all measured input data currently shown on the worksheet will be exported to the measured input data file. If any of the values are out of range, an error message will be displayed, the out-of-range cell(s) will be selected, no data will be saved, and CTPFDM will not run. If all values are within the expected range, then the CTPFDM DLL will be executed. After the DLL terminates, the results will be imported into the workbook and a Report worksheet will be updated. When operating in off-line mode, the user is automatically taken to the Report worksheet.

Note that an error message will be generated if the user attempts to manually run the CTPFDM DLL while the software is in "on-line" mode.

Enable On-Line Operation

Click the toggle button labeled "Click to Enable Online Operation" to place the software in "on-line" (automatic) mode. The toggle button label will immediately change to "Click to Disable Online Operation" and the software will initiate a timer based on the "Online Update Interval" specified in cell "K15" of the worksheet. This timer is specified in the standard time format of hours-minutes-seconds (HH:MM:SS). In cell "K16" will be displayed the next CTPFDM run time. When the specified period of time has elapsed, the real-time data will be retrieved from the OSI PI database and placed into the appropriate cells on the worksheet. Then the worksheet data will be exported to the measured input data file and the CTPFDM DLL will be executed. Note that, while in on-line mode, no range checking is done in the spreadsheet prior to running the

CTPFDM DLL (as is done in off-line operation). Full error checking is, however, always performed in the DLL calculations. After the DLL terminates, the results will be imported into the workbook, saved to the Results.csv file, and all worksheets related to performance results will be updated. When operating in on-line mode, the user is not automatically taken to the Report worksheet. Rather, the current worksheet (i.e., that being displayed when the DLL is executed) remains displayed.

To disable on-line operation, click the toggle button again (now labeled "Click to Disable Online Operation"). The toggle button label will immediately change back to "Click to Enable Online Operation" and the software will deactivate the on-line timer and return to off-line mode.

See the Detailed Information on Worksheets section later in this sub-section for more details on on-line operation.

Report Worksheet

This worksheet displays all of the results calculated by running the CTPFDM DLL, with the exception of fault diagnostics, which are shown on a separate worksheet. If there are error messages, these will be displayed at the bottom of this worksheet. Depending on the difference between the ambient temperature and inlet temperature, the "Effect of Evaporative Cooling" section may or may not be displayed. If the ambient and inlet temperatures are the same, this section will not be displayed.

Save Results

Like the "Save Results" button on the Diagnostics worksheet, when this button is clicked, the current results are saved to the Results.csv file. Also, the charts explained below are adjusted to display the new results. Results will be saved only if the data date and time are later than the last saved results.

Print Report

When this button is clicked, the report will be printed to the default printer.

Diagnostics Worksheet

This worksheet displays the fault diagnostics calculated by running the CTPFDM DLL. The potential faults are listed in the left-most column of a table, or "matrix", followed on the right by the status of each fault and the individual degradation parameter flag values used to determine each fault condition. The status of each fault and degradation parameter flag is denoted in color-coded text.

Save Results

Like the "Save Results" button on the Report worksheet, when this button is clicked, the current results are saved to the Results.csv file. Also, the charts explained below are adjusted to display the new results. Results will be saved only if the data date and time are later than the last saved results.

Print Diagnostics

When this button is clicked, the fault diagnostics table will be printed to the default printer.

Chart Worksheets

These charts graph time vs. air flow, compressor efficiency, overall efficiency, heat rate, and power. Each chart can be printed by clicking the Print button in the Excel toolbar.

Air Flow Worksheet

This chart contains data for time vs. air flow. It is adjusted whenever new results are saved or the current unit is switched.

Comp. Effcy. Worksheet

This chart contains data for time vs. compressor efficiency. It is adjusted whenever new results are saved or the current unit is switched.

Efficiency Worksheet

This chart contains data for time vs. overall efficiency. It is adjusted whenever new results are saved or the current unit is switched.

Heat Rate Worksheet

This chart contains data for time vs. heat rate. It is adjusted whenever new results are saved or the current unit is switched.

Power Worksheet

This chart contains data for time vs. power. It is adjusted whenever new results are saved or the current unit is switched.

Detailed Information on Worksheets

Combustion Turbine Model (Gtmodel Worksheet)

The combustion turbine model data are supplied by the turbine manufacturer or owner. The purpose of the data is to provide a model to be used in calculating expected performance at either base- or peak-load over the anticipated range of ambient conditions.

The CT model data include the design rating, the rated conditions, and the compressor inlet temperature effects. The rated conditions are the operating conditions cited by the manufacturer as the basis for the manufacturer's design rating. This is often ISO conditions, but in some cases may be the average expected site conditions or some other standard.

The design rating data are the power, heat rate, and inlet air or exhaust flow that is expected at the rated conditions. Design rating data can be input for each operating mode (base and peak) and each fuel type (natural gas and liquid) accommodated by CTPFDM.

The following effects on CT performance are required by CTPFDM:

- The effect of compressor inlet temperature on power, heat rate, compressor isentropic efficiency, compressor pressure ratio, inlet air (or exhaust) flow, and exhaust temperature
- The effect of inlet and exhaust pressure drop on power, heat rate, and exhaust temperature
- The effect of specific humidity (i.e., mass-water/mass-dry air) on power
- The effect of combustor water injection on power, heat rate, and flow
- The effect of combustor steam injection on power, heat rate, and flow

Example model curves for a typical combustion turbine are shown below. An example of inlet temperature correction factor curves is shown in Figure 3-4, while Figure 3-5 shows an example of compressor inlet temperature versus exhaust temperature, and Figure 3-6 shows typical inlet temperature versus pressure ratio and compressor efficiency curves.

With the exception of the effect of compressor inlet temperature on compressor efficiency and compressor pressure ratio, most of the data should be readily available from the CT manufacturer. If the compressor efficiency and compressor pressure data are not available, it is recommended to just enter constant values of reasonable magnitudes for the entire temperature range (e.g., 85% for compressor efficiency and 15 for pressure ratio). These can always be adjusted later once you have more operating data from the compressor.

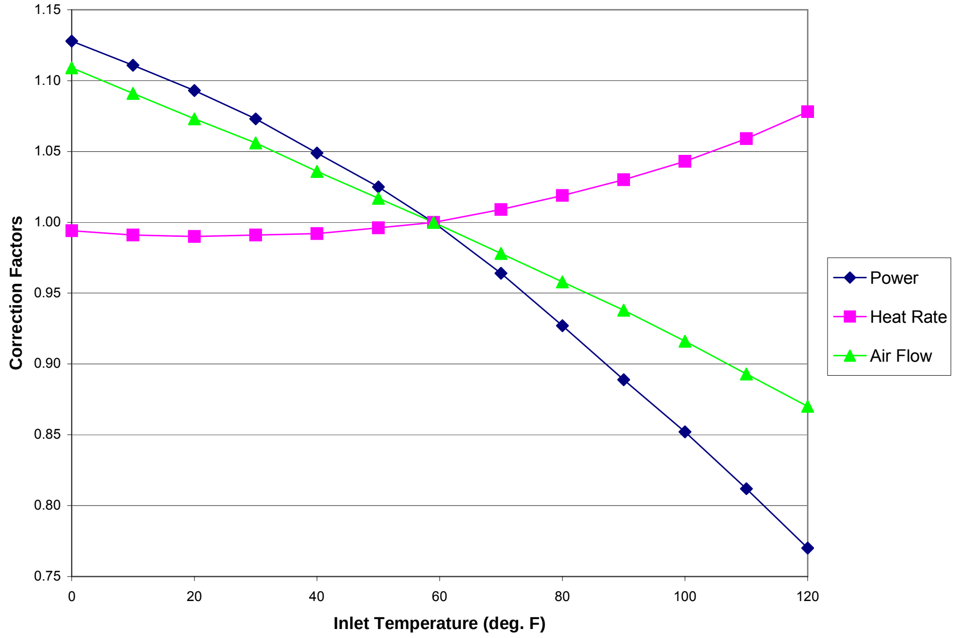


Figure 3-4
Example of Inlet Temperature Correction Factors for a GE 7FA Combustion Turbine

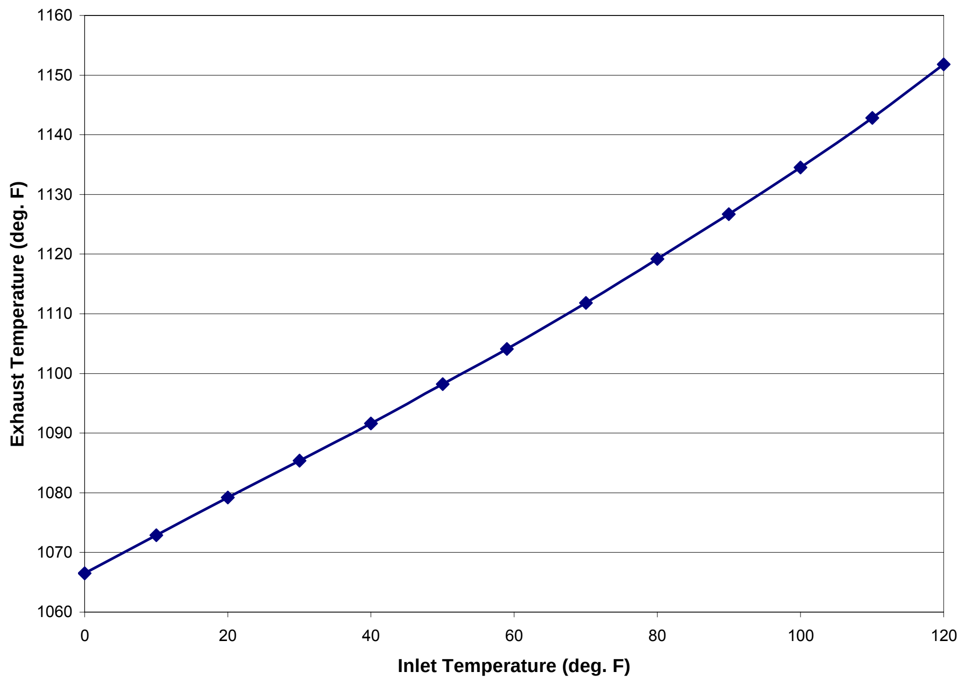


Figure 3-5
Example of Inlet Temperature vs. Exhaust Temperature Effects for a GE 7FA Combustion Turbine

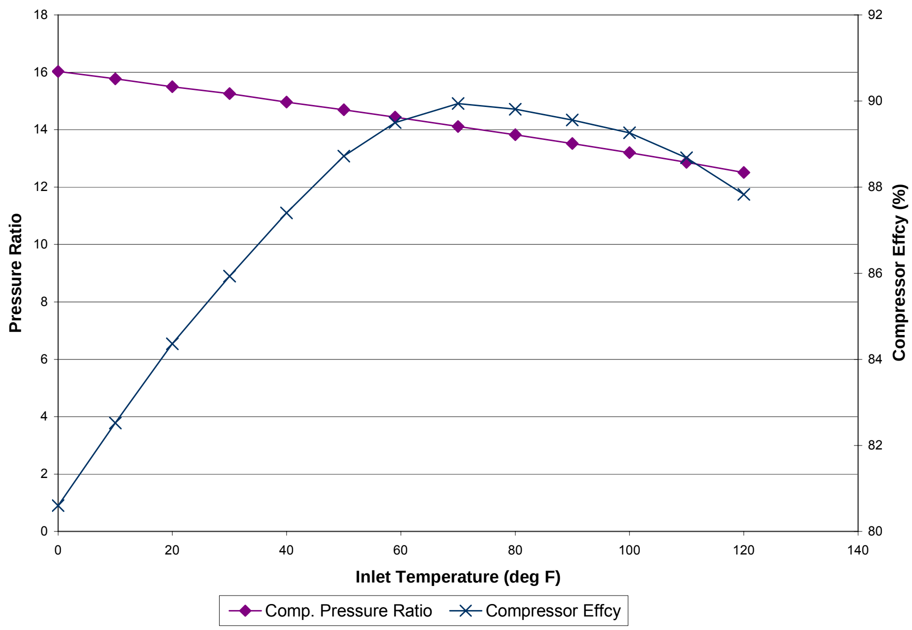


Figure 3-6
Example of Inlet Temperature vs. Compressor Pressure Ratio and Isentropic Efficiency for a GE 7FA Combustion Turbine

Original Equipment Manufacturer (OEM) data for the impact of combustor water or steam injection are often expressed as a function of both compressor inlet temperature and the flow rate of water or steam or the ratio of water to fuel flow. A typical example is shown in Figure 3-7. In CTPFDM, these corrections are approximated by a straight line with the slope of the line being a function of compressor inlet temperature, according to the following formula:

$$\text{Correction Factor} = 1 + (\text{Slope}(T_{inlet})) * (\text{Injected Water or Steam Mass Flow / Fuel Energy Flow})$$

The fuel flow is stated in terms of energy (i.e., LHV × mass flow) so that the same correction factors can be used for both natural gas and liquid fuel.

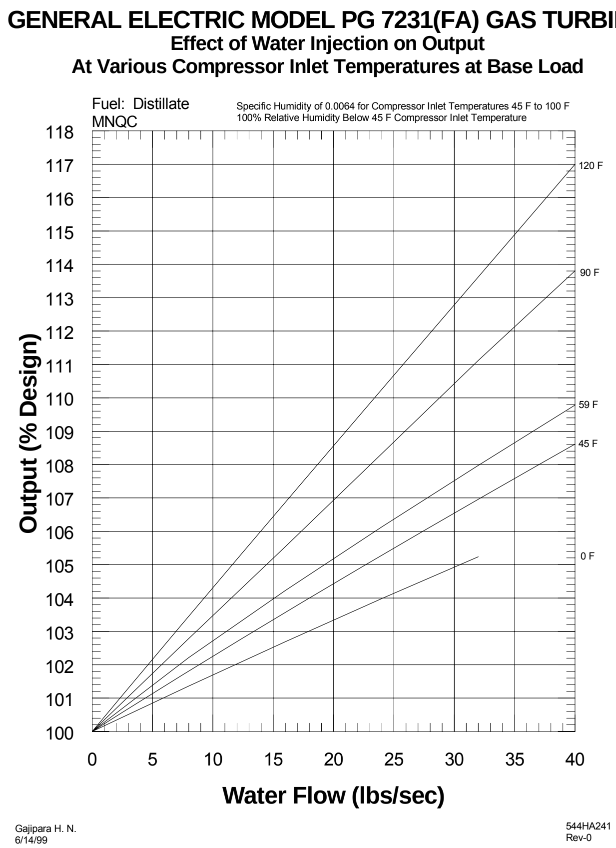


Figure 3-7
Typical Example of Power Output Correction Factor for the Effect of Combustor Water Injection

Modifying the OEM Data

While the manufacturer's data may be the best choice for predicting the performance of a relatively new CT, as time goes on, the capability of a turbine will naturally decline. A user may want to "de-rate" the engine by modifying the data in the CT model files. Conversely, if a CT is upgraded to allow higher firing temperatures and/or increased air flow, a user will also want to modify the rating data to reflect the turbine's increased capability.

Measured Input Data (Inputs Worksheet)

The measured inputs to CTPFDM include up to 43 instrument signals, plus two signals from the control system indicating the firing mode (base or peak) and fuel type (gas or liquid), and three inputs generated by the user which specify the name of the CT unit and the date and time that the instrument data was captured. Table 3-4 contains a complete list of the measured input data including the "standard" CTPFDM units of measurement. CTPFDM can handle a variety of SI and English units for the inputs, but if the units of measurement do not match the "standard"

CTPFDM units, they will be converted internally when the CTPFDM DLL is called. All results will be reported in the standard CTPFDM units.

Figure 3-8 shows the locations of some of the 43 instruments on a schematic diagram of a combustion turbine. It should be noted that not all 43 instruments are required in order to obtain results from CTPFDM. This is discussed in more detail in the following section.

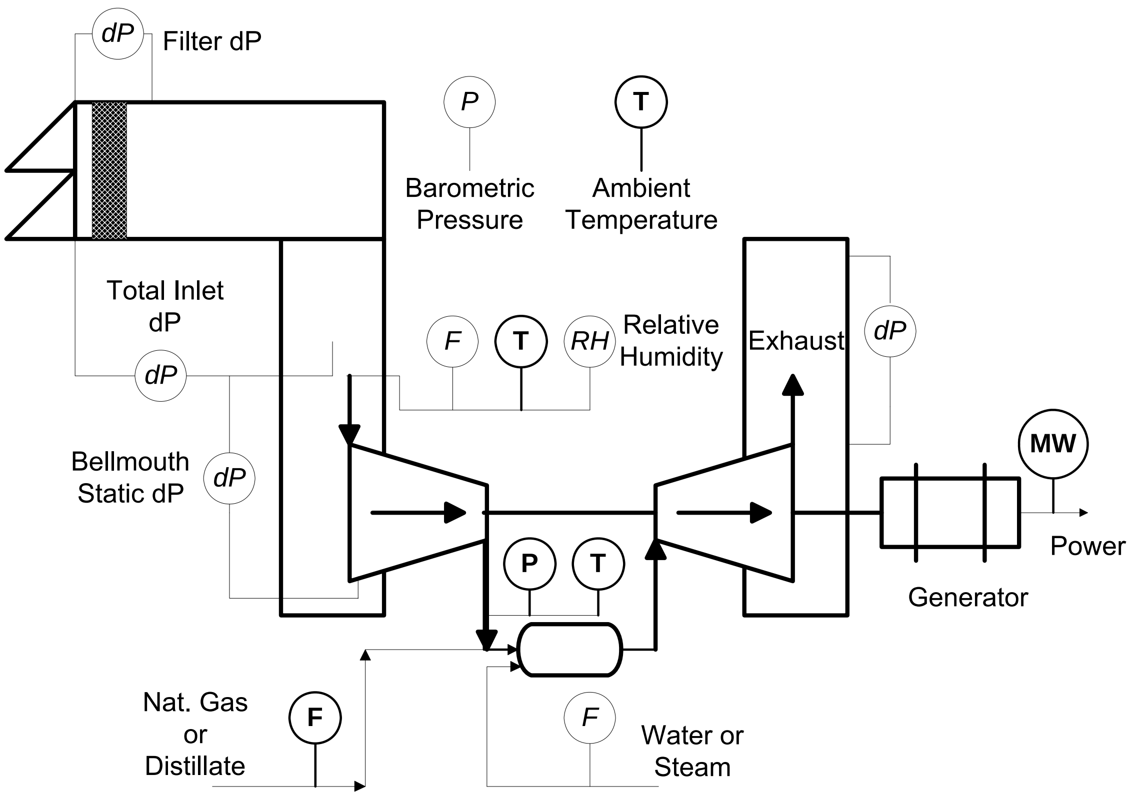


Figure 3-8
Schematic Diagram of a Combustion Turbine Showing Some of the Instruments Used as Inputs to CTPFDM

Table 3-4
Measured Input Data List

Inputs Row #	Description	English Units	SI Units	Comments
3	Unit Name	N/A	N/A	Maximum of 40 characters
4	Date of Data Capture	N/A	N/A	MM-DD-YYYY
5	Time of Data Capture	N/A	N/A	HH:MM:SS
6	Firing Mode Option	N/A	N/A	0 = base, 1 = peak
7	Fuel Type Option	N/A	N/A	0 = natural gas fuel, 1 = liquid fuel
8	Ambient Temperature	°F	°C	
9	Barometric Pressure	" Hga	bara	Default value available
10	Relative Humidity	%	%	Default value available
11	Compressor Inlet Temperature	°F	°C	
12	Inlet Filter Pressure Drop	" H_2O	mbar	Optional
13	Total Inlet Pressure Drop	" H_2O	mbar	Default value available
14	Exhaust Pressure Drop	" H_2O	mbar	Default value available
15	Bellmouth Static Pressure Drop	" H_2O	mbar	Optional, used in air flow formula
16	Reserved for Future Use	N/A	N/A	
17	Compressor Discharge Press.	psig	barg	
18	Compressor Discharge Temp.	°F	°C	
19	Inlet Guide Vane Position	degrees	degrees	
20	Power	MW	MW	
21	Natural Gas Fuel Flow	lb/sec	kg/sec	
22	Liquid Fuel Flow	lb/sec	kg/sec	
23	Inlet Air Flow	lb/sec	kg/sec	
24	Water Injection Flow	lb/sec	kg/sec	Default available
25	Steam Injection Flow	lb/sec	kg/sec	Default available
26	Dew Point Temperature	°F	°C	Used if Rel. Humidity not available
27	Injected Water Temperature	°F	°C	Default available

Table 3-4 Continued

Inputs Row #	Description	English Units	SI Units	Comments
28	Injected Steam Temperature	°F	°C	Default available
29	Gas Fuel Temperature	°F	°C	Default available
30	Gas Fuel Pressure	°F	°C	Default available
31	Liquid Fuel Temperature	°F	°C	Default available
32	Exhaust Temperature	°F	°C	Used in firing temp. and air flow by heat balance calculations
33	Cold End Vibration – A	in./sec	mm/sec	Used in fault diagnostics
34	Cold End Vibration – B	in./sec	mm/sec	Used in fault diagnostics
35	Hot End Vibration – A	in./sec	mm/sec	Used in fault diagnostics
36	Hot End Vibration – B	in./sec	mm/sec	Used in fault diagnostics
37	Exhaust Temperature Spread	°F	°C	Used in fault diagnostics
38	Hot End Bearing Metal Temp.	°F	°C	Used in fault diagnostics
39	Hot End Bearing Drain Temp.	°F	°C	Used in fault diagnostics
40	Wheelspace Temperature #1*	°F	°C	Used in fault diagnostics
41	Wheelspace Temperature #2*	°F	°C	Used in fault diagnostics
42	Wheelspace Temperature #3*	°F	°C	Used in fault diagnostics
43	Wheelspace Temperature #4*	°F	°C	Used in fault diagnostics
44	Wheelspace Temperature #5*	°F	°C	Used in fault diagnostics
45	Wheelspace Temperature #6*	°F	°C	Used in fault diagnostics
46	Wheelspace Temperature #7*	°F	°C	Used in fault diagnostics
47	Wheelspace Temperature #8*	°F	°C	Used in fault diagnostics
48	Wheelspace Temperature #9*	°F	°C	Used in fault diagnostics
49	Wheelspace Temperature #10*	°F	°C	Used in fault diagnostics
50	Wheelspace Temperature #11*	°F	°C	Used in fault diagnostics
51	Wheelspace Temperature #12*	°F	°C	Used in fault diagnostics

*Can be assigned a more meaningful description using the optional input cells on "Diag. Thresh. Data" worksheet.

Discussion on Measured Input Data Requirements

As the axial compressor becomes fouled, the flow of air through the compressor will decline from its expected value. Hence, inlet air flow is a key parameter for detecting compressor performance degradation. A direct measurement of the inlet air flow measurement is the most accurate method of monitoring air flow, but few CTs are fitted with such a measurement. If direct measurement of air flow is not available, it can be estimated using the bellmouth static pressure drop and information about the inlet geometry. If the bellmouth static pressure drop is also not measured, the performance calculations will still go forward, but no comparison to the expected inlet air flow will be made. Compressor performance can then only be evaluated based on isentropic efficiency and the CT power output.

CTPFDM assumes that bellmouth static pressure drop is defined as the difference between the compressor inlet total pressure and the bellmouth static pressure. Some manufacturers may provide a measurement of the bellmouth static pressure as an absolute pressure. For such cases, the bellmouth static pressure drop, ΔP_{bell}, can be calculated as:

$$\Delta P_{bell} = P_{baro} - \Delta P_{inlet} - P_{bell}$$

where ΔP_{inlet} is the pressure drop across the inlet duct (total pressure in minus total pressure out), P_{bell} is the absolute static pressure at the bellmouth, and P_{baro} is the barometric pressure.

Relative humidity, which has a minor effect on performance, can either be entered as an on-line measurement, calculated from an on-line measurement of the dewpoint temperature, or defaulted to the value in the measured default data (see Defaults worksheet).

The inlet filter pressure drop is optional. Currently it is not used in any performance calculation; however, it may be useful to trend this value over time to get an indication of when the filters should be replaced. In addition, it is anticipated that in future versions of CTPFDM, the effect of inlet filter pressure drop on performance will be calculated. Hence, the option is given to include it as an input now.

The absolute total, or stagnation, pressure at the inlet to the axial compressor is used in the calculation of compressor efficiency. It will be calculated from the measured barometric pressure and the overall pressure drop from the air intake to the compressor inlet. The overall inlet pressure drop measurement must be based on a total pressure measurement at the compressor inlet and not a static (i.e., flush with the wall) pressure measurement. If the inlet does not include a filter house, the total pressure drop will probably not vary much over time at full-load. In that case, using a default value for the pressure drop should not adversely affect the accuracy of the results.

CTPFDM's expected performance model is only valid for full-load (base or peak) operation. As a check for full-load conditions, CTPFDM will compare the measured *Inlet Guide Vane* (IGV) position to the reference value for full-load. If these differ by more than 6 degrees, CTPFDM will issue an error message and not go forward with the expected performance calculations. If the IGV measurement is not available (i.e., data quality set to "ignore input"), CTPFDM will skip this check.

CTPFDM can handle dual fuel operation on an "either-or" basis, but it can not handle simultaneous operation on a mixture of gas and liquid fuel. The program will first look at the flag defining the type of fuel in use, and then read the value for flow for that fuel. The other fuel flow signal will be ignored.

Default Measured Input Data (Default Data Worksheet)

For some inputs, CTPFDM allows the substitution of "default" values in case on-line measurements are not available. Default values can be entered for the following measurements:

- Relative Humidity
- Barometric Pressure
- Inlet Pressure Drop
- Exhaust Pressure Drop
- Water-to-Fuel Ratio
- Steam-to-Fuel Ratio
- Injected Water Temperature
- Injected Steam Temperature
- Gas Fuel Temperature
- Gas Fuel Pressure
- Liquid Fuel Temperature

In addition to these default measurements, data are supplied for several other parameters that may or may not be applicable for a particular CT unit:

- Natural Gas *Lower Heating Value* (LHV)
- Liquid Fuel LHV
- Liquid Fuel Specific Gravity
- Liquid Fuel Specific Heat
- External Cooler Air Exit Temperature (for CTs with external cooling of the rotor cooling air)
- Atomizing Air Temperature
- Combined Generator and Mechanical Efficiency

The last parameter is used to convert the measured generator power into the CT output shaft power. The shaft power is then used in the energy balance calculations. CTPFDM comes with pre-set values for all of the default parameters, but the user should update them if better data are available (e.g., in the case of fuel data, whenever fuel sample lab reports are received). In addition, if either the gas or liquid fuel LHV is set to zero, the LHV will be calculated from the fuel composition data (see Fuel Properties worksheet).

Standard Day Data (Default Data Worksheet)

A "standard day condition" should be specified by the user, which defines the "standard operating condition" to which the measured results will be corrected or "transposed". This condition can be base load at ISO conditions or some other values that represent an approximate average operating condition. It need not be the same as the OEM's rated conditions, which are the basis for the OEM's rated performance data discussed earlier in this sub-section.

The software uses the standard day condition data to factor out the influences on turbine and axial compressor performance that are external to the machine, such as ambient temperature, barometric pressure and relative humidity. The corrected values will be the most meaningful for trending purposes, since any change in them will indicate a true change in the condition of the machine, rather than a change in the weather or operating strategy (e.g., distillate vs. natural gas firing).

The standard day condition data include:

- Compressor Inlet Temperature
- Relative Humidity
- Barometric Pressure
- Inlet Pressure Drop
- Exhaust Pressure Drop
- Water-to-Fuel Ratio
- Steam-to-Fuel Ratio
- Mode of Operation (base or peak)
- Type of Fuel (natural gas or liquid)

Axial Compressor Wash Criteria Data (Default Data Worksheet)

If the degradation in axial compressor performance exceeds certain user-specified criteria, CTPFDM will set an indicator flag that a compressor wash is needed. The flag appears in the performance report. The axial compressor wash criteria data consist of the following parameters:

- Power-Based Wash Criterion
- Inlet Air Flow-Based Wash Criterion

These two items are used to specify the level of degradation in power and inlet air flow below which the software is to trigger the wash indicator flag. If either of the criteria is met, the wash indicator flag will be set to "yes". Both items are expressed as percentages and are assumed to be negative. In other words, if the user wishes the wash indicator flag to appear whenever the generator power drops below 96% of the OEM's expected value, then the power-based wash criterion should be set to 4.

Performance Options Data (Default Data Worksheet)

If the air flow is either directly measured or can be calculated from the bellmouth static pressure drop, then the user may choose whether to use that air flow value in the firing temperature calculation or use the value for air flow that is determined via a heat balance around the CT. This can be specified by setting the "firing temperature calculation option" flag. It is recommended that the measured air flow be used if it is available, but if the user suspects that the air flow measurement may be inaccurate, it will be useful to run the performance calculations twice: once using the air flow as measured and once using the air flow from the heat balance. If both cases yield approximately the same values for the firing temperature, this is an indication that the measured air flow is still reasonably accurate. If there is a wide deviation, then the user must make a judgment as to which case makes the most sense.

Diagnostic Threshold Data (Diagnostic Thresh. Data Worksheet)

The diagnostic threshold data is used to make comparisons to the calculated degradation parameters to determine the current state of the inlet filter, compressor, combustion system, and turbine section, that is, whether the equipment is operating within normal parameters or whether action should be taken to correct an impending fault condition in the equipment.

"Alert" and "Action Required" threshold values should be specified for each of the following:

- Inlet Filter Pressure Drop
- Compressor Efficiency
- Inlet Air Flow
- Cold End Vibration
- Fuel Consumption
- Hot Average Exhaust Temperature
- Cold Average Exhaust Temperature
- Exhaust Temperature Spread Approach to Maximum
- Turbine Section Efficiency
- Hot End Vibration
- Hot End Bearing Metal Temperature
- Hot End Bearing Drain Temperature
- Wheelspace Temperatures (up to 12)

The "Alert" (A) and "Action Required" (AR) threshold values specified for the Exhaust Temperature Spread Approach to Maximum parameter are not used directly as threshold values, but are used to calculate the threshold values shown below. The calculation of the Maximum Exhaust Temperature Spread used in the equations below is discussed later in this section.

Exhst. Temp. Spread "Alert" Threshold = Max. Exhst. Temp. Spread – A

Exhst. Temp. Spread "Action Required" Threshold = Max. Exhst. Temp. Spread – AR

In determining fault conditions, some calculated degradation parameters must be greater than their threshold values to indicate a problem, while others must be less than their threshold values. These various relationships are detailed in the section below.

Conditions Indicating a Fault (Alert or Action Required):

Inlet Filter dP > Threshold Value

Compressor Efficiency < Threshold Value

Inlet Air Flow < Threshold Value

Cold End Vibration > Threshold Value

Fuel Consumption > Threshold Value

Hot Average Exhaust Temperature > Threshold Value

Cold Average Exhaust Temperature < Threshold Value*

Exhaust Temperature Spread > Threshold Value

Turbine Section Efficiency < Threshold Value

Hot End Vibration > Threshold Value

Hot End Bearing Metal Temperature > Threshold Value

Hot End Bearing Drain Temperature > Threshold Value

*Note that for the Cold Average Exhaust Temperature, the threshold values should be entered as negative values.

In addition to threshold values, the data entered on the "Diag. Thresh. Data" worksheet includes the coefficients A, B and C for the equation below which defines the maximum allowable Exhaust Temperature Spread.

$$\text{Max. Exhst. Temp. Spread} = A * (\text{Avg. Exhst. Temp.}) - B * (\text{Comp. Disch. Temp.}) + C$$

Also appearing on this worksheet is the Minimum Number of Wheelspace Temperatures Needed for Alert, which specifies how many temperatures are required to meet or exceed their threshold values before an "Alert" fault is indicated. Likewise, the Minimum Number of Wheelspace Temperatures Needed for Action Required specifies how many temperatures are required to meet or exceed their threshold values before an "Action Required" fault is indicated.

Note that the Total Number of Wheelspace Temperatures Used should match the number of temperatures being measured.

Wheelspace Temperatures may also be assigned an optional Name to Associate with Input to provide a more descriptive name for each numbered temperature. Any optional names specified will appear on the Inputs worksheet in place of the corresponding numbered temperature.

Fuel Properties Data (Fuel Properties Worksheet)

Natural Gas Composition

The user can specify the composition of the natural gas by entering the mole percentage for each of the twenty-one components commonly found in natural gas. The sum of the values must equal 100%. The composition is used to determine the composition of the exhaust gas, which in turn is used in the firing temperature and energy balance calculations. In addition, if the LHV for natural gas has been set to zero in the Defaults worksheet, the composition will be used to calculate the LHV of the natural gas.

Liquid Fuel Composition

The user can specify the composition of the liquid fuel by entering the mass fraction for each of the seven components commonly found in liquid fuel. The sum of the values must equal 1. The composition is used to determine the composition of the exhaust gas, which in turn is used in the firing temperature and energy balance calculations. In addition, if the LHV for liquid fuel has been set to zero in the Defaults worksheet, the composition along with the liquid fuel specific gravity will be used to calculate the LHV of the fuel.

Report Worksheet

The Report worksheet is divided into eight sections. Each section is described in detail in the following sections.

Measured Site Conditions

The first section, labeled "Measured Site Conditions" lists the input data that were used to generate the results. (However, if the data quality flag for a certain input was set to "ignore data", the value entered for that input is still displayed even though it was not used in the calculation. An error will appear at the bottom of the page indicating that the input value was invalid.)

Actual Performance

The second section, labeled "Actual Performance", shows measured (or calculated), expected, and relative difference (measured minus expected) values of key indicators of the turbine's performance. The measured values represent the actual performance of the machine. The expected values represent the performance that would be expected by the OEM at the current operating condition. In other words, the expected values represent the performance expected for the current firing mode and fuel type at the measured inlet and exhaust conditions accounting for the measured water or steam injection rate. Measured, expected, and difference values for the following parameters are included in the output:

- Power
- Heat Rate
- Overall (Thermal) Efficiency
- Natural Gas Fuel Flow
- Liquid Fuel Flow
- Inlet Air Flow
- Inlet Air flow by Heat Balance
- Axial Compressor Isentropic Efficiency

In addition, the calculated firing temperature is listed for the measured conditions only. The firing temperature is calculated via two different methods (see Appendix A for a full description), one based on an energy balance around the combustor and first stage nozzle, the other based on an energy balance around the expander (turbine) section. The part load level (in percent) is also reported in this section. If the turbine is being operated in part load mode, then the calculated load level is shown. Otherwise, the part load level is reported as 100%.

Effect of Evaporative Cooling

For gas turbines with an inlet cooling system, the third section of the report, labeled "Effect of Evaporative Cooling", includes measured, predicted, and difference values comparing actual performance to the performance predicted if there was no evaporative cooling, taking into account the current level of degradation in performance. Measured, expected, and difference values for the following parameters are included:

- Power
- Heat Rate
- Overall (Thermal) Efficiency
- Inlet Air Flow
- Inlet Air flow by Heat Balance

The measured compressor inlet temperature must be at least one degree less than the measured ambient temperature for the effects of inlet cooling to be reported. Otherwise, the program assumes that the inlet cooling system is not operating and the relevant calculations are skipped.

Corrected Site Conditions

The fourth section of the results report is labeled "Corrected Site Conditions". It contains the "Standard Day" conditions to which the actual results are corrected. These are the conditions the user has entered in the Default Data worksheet to represent the "standard operating condition" of the unit.

Corrected Performance

The fifth section of the results report, labeled "Corrected Performance", shows results that factor out the influences on turbine and axial compressor performance that are external to the machine, such as ambient temperature, barometric pressure, and relative humidity. The corrected values will be the most meaningful for trending purposes, since any change in them will indicate a true change in the condition of the machine, rather than a change in the weather or operating strategy (e.g., distillate vs. natural gas firing).

The corrected performance data include measured, expected, and relative difference values pertaining to the calculated corrected performance of the CT. The measured results represent the actual performance of the machine corrected to the standard day conditions. The expected results represent the performance expected by the OEM at the standard day conditions. The expected values should not change over time, as long as the standard day conditions are not changed. Measured, expected, and difference values for the following parameters are included:

- Power
- Heat Rate
- Overall (Thermal) Efficiency
- Natural Gas Fuel Flow
- Liquid Fuel Flow
- Inlet Air Flow
- Inlet Air Flow by Heat Balance
- Axial Compressor Isentropic Efficiency

(Axial Compressor) Wash Indicator

The sixth section of the results report is the axial compressor wash indicator. CTPFDM compares the calculated degradation (measured minus expected) in power and inlet air flow to the input values of the corresponding wash criteria data. If either of the calculated differences exceeds the corresponding input value, the software sets the wash indicator to "yes" to indicate the need to wash the axial compressor. When the calculated differences in power and inlet air flow are both below their corresponding wash criteria values, the wash indicator is set to "no".

If air flow is not measured directly or calculated from the bellmouth static pressure drop, then the wash indicator is based only on the degradation in power.

While compressor isentropic efficiency is also a key indicator of compressor efficiency, the difference between actual and expected compressor efficiency is not used as a wash criteria. This is because the expected value of compressor efficiency is normally not readily available to the CT operator. In addition, the absolute accuracy of the calculated efficiency is subject to errors due to inherent biases in the measurement of the compressor discharge temperature and pressure, as discussed later in this sub-section.

Mission Heat Rate Results

The seventh section of the results report is labeled "Mission Heat Rate Results". "Mission heat rate" is defined as the total fuel consumed by the turbine divided by the total power output of the turbine over the course of one "mission" (i.e., a complete operating run of a turbine from start-up to shutdown). Therefore, the mission heat rate takes into account the fuel needed to bring the turbine to its "full-speed, no-load" condition, as well as the fuel used during lower efficiency part-load operation as the turbine comes up to full output. Mission heat rate should provide the user with a more accurate indication of a turbine's variable operating cost than simply looking at the heat rate at full load.

Mission heat rate results include the following parameters:

- Fuel Consumption
- Power Production
- Heat Rate

Note that the mission heat rate calculations are optional. The user can configure the calculations by editing the Missinp.dat file (located in each unit sub-directory) using any text editor such as Microsoft's Notepad. Missinp.dat contains an option flag which specifies whether or not the mission heat rate calculations are to be performed. Also included in this file is an option flag which specifies whether or not the mission heat rate values are to be reset, as well as the update interval to be used in the calculations (i.e., the time (in seconds) elapsed since the last mission heat rate calculations were performed).

An example Missinp.dat file is shown below.

```
2
0
60
```

Table 3-5 shows the format of the Missinp.dat file (using the example data values shown above).

Table 3-5
Format of Missinp.dat File

Line #	Example Value	Variable Name	Description	Units
1	2	MissionOp	Mission Heat Rate Calculation Option	0, 1, or 2[1]
2	0	ResetOp	Mission Heat Rate Reset Option	0 or 1[2]
3	60	Interval	Mission Heat Rate Update Interval	seconds[3]

[1]0 = no mission heat rate calculations (performance only),
1 = mission heat rate calculations only (no performance),
2 = both mission heat rate and performance calculations
[2]0 = no reset of mission heat rate,
1 = reset mission heat rate
[3]Maximum of 600 seconds (10 minutes). Warning is issued for intervals exceeding 600 seconds (mission heat rate calculations proceed).

Warning: As the mission heat rate is based on a constant update interval, it is meant for use only in "on-line" applications where the CTPFDM DLL is being called at a regular interval. In such cases, it is up to the user to ensure that the update interval specified in the Missinp.dat file matches the update interval of the CTPFDM DLL. **Failure to match the mission heat rate update interval with the "Online Update Interval" specified in cell "K15" of the Inputs worksheet will produce erroneous mission heat rate results.**

Error Messages

The eighth and final section of the report lists any error messages that were generated during the execution of the CTPFDM DLL.

Compressor Efficiency Calculation - Sources of Error

The calculation of compressor isentropic efficiency is sensitive to the value of the compressor discharge temperature (CDT). A change in the CDT of 1% is sufficient to change the calculated compressor efficiency by one percentage point.

Experience during beta testing of CTPFDM has shown that CDT values can fluctuate by more than 1% from scan to scan. Consequently, it is recommended that a time-averaged value for the CDT be used as input rather than an instantaneous one.

If the calculated compressor efficiency appears to be too high, it may be due to the compressor discharge temperature and pressure measurements not reflecting the true average thermodynamic condition at the discharge of the compressor. For example, while a GE 7FA has three thermocouples for measuring CDT, these thermocouples together may not be positioned to measure the bulk mean stagnation temperature of the discharge flow upon which the compressor efficiency calculation is based. Similarly, the three compressor discharge pressure measurements may not measure the exact bulk mean stagnation pressure of the flow. However, they should accurately detect *changes* in compressor discharge pressure and temperature, and therefore trending the value of the calculated compressor efficiency should provide an indication of changes in compressor condition.

Diagnostics Worksheet

The Diagnostics worksheet contains a table, or "matrix", showing the status of nine potential CT fault conditions. The following fault condition parameters are included:

- Clogged Inlet Filter
- Compressor Fouling
- Compressor Blade Damage
- Clogged Fuel Nozzles
- Cracked Combustor Liner
- Crossover Tube Failure
- Bowed Nozzle
- Turbine Blade Damage
- High Turbine Blade Temperature
- Turbine Section Fouling

The nine faults are listed in the left-most column of the diagnostics table, followed on the right by the status of each fault and the twelve individual degradation parameter flag values used to determine each fault condition. The individual degradation parameter flags can have values of 0, 1, 2, or 3. A value of zero (0) represents an "Undetermined" condition caused by a lack of valid input data. A value of one (1) represents a "Normal", or no-fault, condition. A value of two (2) represents an "Alert" condition in which the operator should be prepared to take action or seek collaborating evidence. A value of three (3) represents an "Action Required", or fault, condition that should be immediately investigated. Similarly, each fault is assigned a status of "Undetermined", "Normal", "Alert", or "Action Required" based on an evaluation of the highlighted individual degradation parameter flags in the right-hand columns of the table. Cells containing status and degradation parameter flags are highlighted using the following color scheme: 0 or "Undetermined" - gray, 1 or "Normal" - green, 2 or "Alert" - yellow, 3 or "Action Required" - red.

An example diagnostics worksheet is shown in Figure 3-9.

CTPDM Version 3.2
Gas Turbine Performance Results for Pocasset Unit #1

Data Time: 14:26:18
Data Date: September 23, 2003

Print Diagnostics | Save Results

DIAGNOSTICS:

			DEGRADATION PARAMETER FLAG VALUE											
FAULT	STATUS		COMP. EFFCY.	INLET AIR FLOW	COLD END VIBRATN.	INLET PRESS. DROP	EXHAUST TEMP. SPREAD	FUEL CONS.	HOT EXHAUST TEMP.	COLD EXHAUST TEMP.	TURBINE SECTION EFFCY.	WHLSPC. TEMPS.	HOT END VIBRATN.	HOT END BEARING TEMPS.
Clogged Inlet Filter	Normal					1								
Compressor Fouling	Normal		3	1	1									
Compressor Blade Damage	Normal		3	1	1									
Clogged Fuel Nozzles	Normal						1	1	1					
Cracked Combustor Liner	Normal						1	1		3				
Crossover Tube Failure	Normal						1	1		3				
Bowed Nozzle	Normal										1	1	1	3
Turbine Blade Damage	Normal										1	1	1	3
High Turbine Blade Temp.	Normal										1	1		
Turbine Section Fouling	Normal										1		1	3

Figure 3-9
Example Diagnostics Worksheet

On-Line vs. Off-Line Operation (Inputs Worksheet)

The CTPFDM spreadsheet, by default, operates in the off-line mode of operation. That is, the user must enter measured input data by hand and manually run the CTPFDM DLL performance calculations for each record (set) of data by clicking on the "Click to Run CTPFDM" button. When the DLL calculations have been completed, control is returned to the spreadsheet, where the user can review the results and decide whether to save the record to the Results.csv file.

Before on-line calculations can be implemented, the user must set up the links to the data historian so that the current values of the various input parameters can be displayed in the spreadsheet in real time. If OSI's PI data historian is being used, and OSI's DataLink software has been installed, the parameters in PI can be displayed in an Excel cell using the "=GetPiVal()" function. The user should consult's OSI's DataLink documentation for more details.

When set up for use with OSI's PI (or another) data historian, the user can initiate on-line operation by clicking the toggle button labeled "Click to Enable Online Operation" which is found on the Inputs worksheet. Doing so initiates a user-specified timer that controls how often the CTPFDM DLL is executed. Then, whenever the specified period of time has elapsed, the current values of the input data are exported to the measured input data file and the CTPFDM DLL is executed. After termination of the DLL, the results are imported into the workbook, saved to the Results.csv file, and all worksheets related to performance results are updated.

While in on-line mode, all worksheets other than the Inputs worksheet, Report worksheet, and chart worksheets are hidden from the user. This is done to prevent the current unit, model data, or default data from being changed while in the middle of an on-line monitoring session.

Table 3-6 shows the important differences between off-line and on-line modes of operation.

Table 3-6
Differences between Off-Line and On-Line Modes of Operation

Item	Off-Line Operation	On-Line Operation
All Worksheets Available to User	Yes	No
Spreadsheet Range Check Prior to DLL Execution	Yes	No
Worksheet Displayed after DLL Execution	Report	Same as Worksheet Displayed Prior to DLL Execution
Results Saved to Results.csv File	Manually by the User	Automatically by CTPFDM

Simultaneous On-Line Monitoring of Multiple Units

As stated earlier under sub-section heading "CTPFDM File Structure", it is possible to simultaneously monitor multiple CTs by setting up multiple instances of the CTPFDM software. This can be accomplished either by installing the software multiple times or by simply making multiple copies of the software that was initially installed. As Microsoft Windows requires unique directory (folder) and file names, each additional copy of the software requires a different name. For example, there could be two copies of the software, one installed to a "C:\Program Files\CTPFDM Unit 1" directory and another copied to a "C:\Program Files\CTPFDM Unit 2" directory.

After installing and setting up the software for the desired number of units, simply launch the CTPFDM spreadsheet for each unit to be monitored and enable on-line operation for each one. Once started, the user should not use the computer for any tasks other than those related to CTPFDM. See the warning below.

Remember to verify the on-line update interval for each unit (located in cell "K15" of the Inputs worksheet) before enabling on-line operation. If the user wishes to change the update interval, on-line operation must first be disabled. Attempting to change the update interval while in on-line operation will result in the display of a warning message when the next scheduled process time is encountered. Upon confirmation of the warning by the user, the update interval will be reset to its previous value.

Warning: When simultaneously monitoring multiple units in on-line mode, it is important that no other programs be running on the computer at the same time. This is especially true of programs which may scan the system disk, such as virus scanning software. **Running other programs during on-line operation may cause CTPFDM data file corruption and/or cause the CTPFDM software to crash!** If CTPFDM should happen to crash during on-line operation, exit the affected spreadsheet and restart. When exiting, you may be prompted whether you want to save the changes you made to the spreadsheet. Click on the "**No**" button.

Tutorial

Lesson 1 - Create a New Unit

CTPFDM can be used to track the performance of multiple combustion turbines. Each combustion turbine (CT) that is to be tracked is called a **Unit** in CTPFDM and each **Unit** must have a unique **Unit Name** such as "Pocasset Unit #1". CTPFDM comes with two units pre-installed. The two units are named "Example 1" and "Example 2". Example 1 is based on a General Electric 7FA (GE 7FA) and Example 2 is based on a Siemens Westinghouse Power Corporation 501F (W501F). This lesson shows how you can create a new unit.

1. Switch to the worksheet labeled "Main Menu" (refer to Microsoft Excel Help menu for information on how to switch from one worksheet to another within an Excel workbook).

2. In cell "B7" (just under the button labeled "Create Unit:"), use the pull-down menu to select the type of combustion turbine (CT) you want to monitor. CTPFDM comes with two CT models built-in: a W501F and a GE 7FA. The user may also create new models. Information how to do this will be covered in Case 3. For this case, you should select either the GE 7FA or the W501F in the pull-down menu.
3. Now click the button in cell "B6" labeled "Create Unit:". A box will appear that says "Enter name of unit:". Type in the following name in the entry box: **Pocasset Unit #1**. Then click the "**OK**" button. Excel will now execute a macro that creates a sub-directory named "Pocasset Unit #1" and copy the appropriate files to that sub-directory. When the macro is finished, a message box will appear that reads: "Unit Pocasset Unit #1 created".
4. Click the "OK" button on the message box to make it disappear.
5. If you now select the pull-down menu located in cell "B4" (just under the button labeled "Switch Unit:"), you will see that Pocasset Unit #1 now appears as one of the available units.

Lesson 2 - Switching to Another Unit and Getting Results

The act of creating a new Unit (Lesson 1) does not make the new Unit the "active" or "current" unit. In other words, if you move to other worksheets in the workbook, the data they show will not be from Pocasset Unit #1. By default, the first time you start CTPFDM, the program is set to monitor the unit named "Example 1". You can see this by looking at cell "B1" in the worksheet (just to the left of the label "Current Unit:"). The current unit should be "Example 1" (unless you've previously used the "Switch Unit:" button to switch to another Unit). This lesson will show you how to switch to the Pocasset Unit #1 unit created in Lesson 1 above and then how to calculate the performance of this unit.

1. In the pull-down menu located in cell "B4" (just under the button labeled "Switch Unit:"), select **Pocasset Unit #1** and then click the "**Switch Unit:**" button in cell "B3". An Excel macro will now import all of the data related to Pocasset Unit #1. This will take several seconds and you will see many different worksheets appear and disappear as the macro moves through all the worksheets. When the macro is finished, a message box will appear that reads "Switched to unit Pocasset Unit #1". Click the "**OK**" button to make the box disappear.
2. To calculate performance, first move to the worksheet labeled "Inputs".
3. Assume that you have received a print-out of the operations overview screen of your unit with the data as shown in Figure 3-10. You now have to enter the data into the Inputs worksheet in the appropriate places. For inputs that are not measured, you can either estimate values, tell the program to use the default value, or tell it to ignore that input (which could result in the program skipping some of the calculations). Enter the data into the **Inputs** worksheet as shown in Table 3-7.

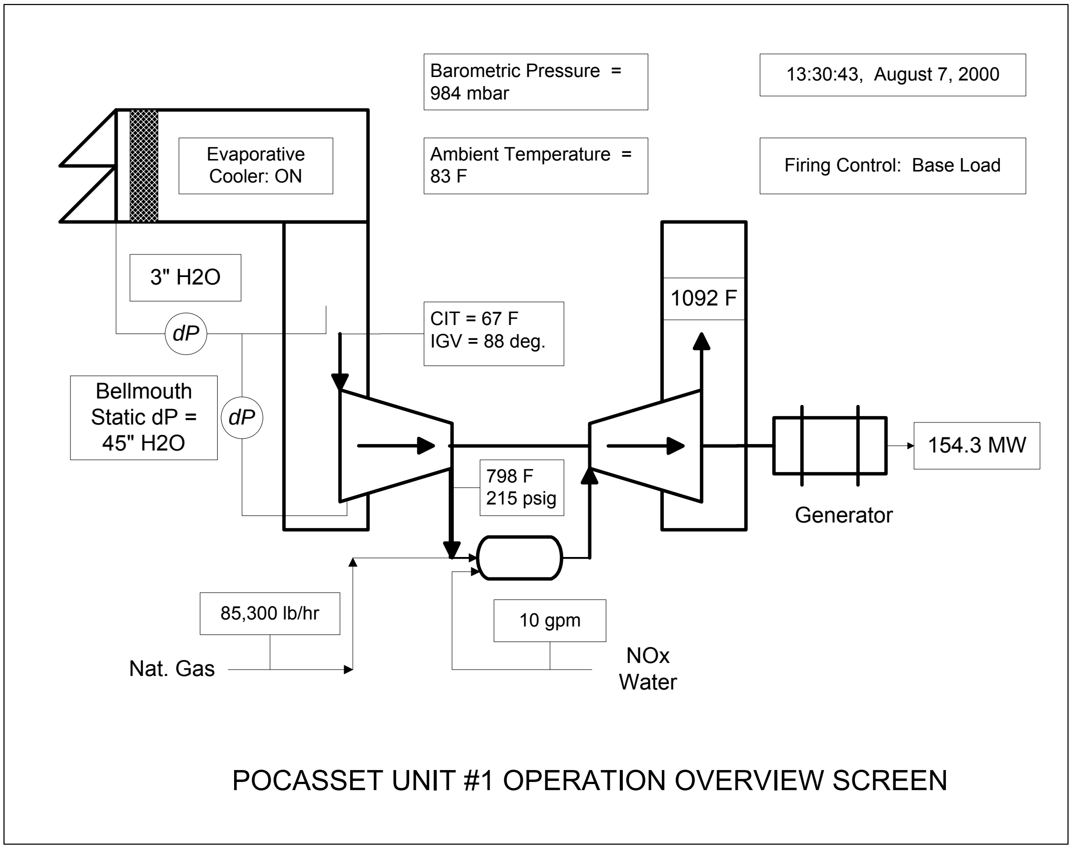


Figure 3-10
Example #1 of CT Operation Overview Screen

Table 3-7 Data to Be Entered in "Inputs" Worksheet

Entry Label	Entered Value	Comments
Unit Name	Pocasset Unit #1	
Date Data Taken	8/7/2000	Will be converted to display "August 7, 2000" after it is entered.
Time Data Taken	1:30:43 PM	Will be converted to display "13:30:43" after it is entered.
Firing Mode	(Click the "Base" bullet.)	
Fuel Type	(Click the "Gas" bullet.)	
Ambient Temperature	83	Set the units pull-down menu option to "deg. F", and set "data quality" pull-down menu to "use input".
Barometric Pressure	0.984	Set units pull-down menu option to bara, note mbar not available on menu, so have to convert instrument reading in mbar to bara by dividing by 1000. Set data quality option to "use input".
Relative Humidity	95	This is an estimated value based on the fact that the evaporative cooler is in operation. Set data quality option to "use input".
Comp. Inlet Temp.	67	Set units pull-down menu option to "deg. F".
Inlet Filter dP	Leave as is.	Since the filter dP is not measured, set data quality option to "use default".
Inlet Total dP	3	Set units pull-down menu option to "in. H_2O" and the data quality option to "use input".
Exhaust dP	Leave as is.	Since the exhaust dP is not measured, set data quality option to "use default".
Bellmouth Static dP	45	Set units pull-down menu option to "in. H_2O" and the data quality option to "use input".
For Future Use	Leave as is.	Set data quality to "ignore input".
Comp. Discharge Pr.	215	Set units pull-down menu option to "psig" and data quality option to "use input".
Comp. Discharge T.	798	Set units pull-down menu option to "deg. F" and data quality option to "use input".
IGV Position	88	Set data quality option to "use input".
Generator Power	154.3	
Gas Fuel Flow	85300	Set units to "lb/hr".
Liquid Fuel Flow	Leave as is.	
Inlet Air Flow	Leave as is.	Set data quality option to "ignore input" since there is not direct measurement of inlet air flow (it will be calculated from the bellmouth dP).
Water Injection Flow	10	Set units pull-down menu option to "lb/s" and data quality option to "use input".
Steam Injection Flow	0	Zero is entered since we assume there is no steam injection. Set data quality option to "use input".
Dew Point Temp.	Leave as is.	Set data quality option to "ignore input".
Injected Water Temp.	Leave as is.	Set data quality option to "use default".
Injected Steam Temp.	Leave as is.	Set data quality option to "use default".
Gas Fuel Temp.	Leave as is.	Set data quality option to "use default".
Gas Fuel Pressure	Leave as is.	Set data quality option to "use default".
Liquid Fuel Temp.	Leave as is.	Set data quality option to "use default".
Exhaust Temp.	1092	Set units pull-down menu option to "deg. F" and data quality option to "use input".

4. Once the data in the **Inputs** worksheet match the values shown in, the performance calculations can be initiated by clicking on the button labeled "Click to Run CTPFDM". The input data will be sent to the calculation subroutine and once the calculations are complete, the results will be displayed in the worksheet labeled "Report". When the macro is finished, the display will automatically be switched to the **Report** worksheet.

5. Print the contents of the **Report** worksheet by clicking the button labeled "Print Report". The printed report should be identical to that shown in Figure 3-11.

SCAMP Version 3.0

Gas Turbine Performance Results for Pocasset Unit #1

Data Time:	13:30:43	Data Date:	August 7, 2000

MEASURED SITE CONDITIONS:

Mode: Peak		Fuel: Natural Gas	
Dew Point Temperature	50.00 deg. F	Relative Humidity	95.00 %
Ambient Temperature	83.00 deg. F	Barometric Pressure	29.14 in. Hga
Inlet Temperature	67.00 deg. F	Total Inlet Pressure Drop	3.00 in. H2O
Total Inlet Pressure	14.20 psia	Exhaust Pressure Drop	5.00 in. H2O
Bellmouth Static Pressure	45.00 in. H2O	Water Injection Flow	10.00 lb/sec
Discharge Temperature	798.00 deg. F	Steam Injection Flow	0.00 lb/sec
Discharge Pressure	215.00 psig	Water Injection Temp.	60.00 deg. F
Natural Gas Fuel Temperature	60.00 deg. F	Steam Injection Temp.	600.00 deg. F
Natural Gas Fuel Pressure	600.00 psig	Exhaust Temperature	1092.00 deg. F
Liquid Fuel Temperature	59.00 deg. F	Inlet Guide Vane Pos.	88.00 deg.

ACTUAL PERFORMANCE:	MEASURED	EXPECTED	DIFFERENCE (M-E)
Gas Turbine Gen. Power (kW)	154300.00	166198.90	-7.1595 %
Heat Rate (Btu/kW-hr)	9950.75	9610.59	3.5394 %
Overall Efficiency (%)	34.29	35.50	-1.2136 pts.
Gas Fuel Flow (lb/hr)	85300.00	88737.18	-3.8734 %
Liquid Fuel Flow (lb/hr)	0.00	0.00	0.0000 %
Inlet Air Flow (lb/hr)	3002778.00	3220934.00	-6.7731 %
Inlet Air Flow by Heat Bal. (lb/hr)	3294861.00	3220934.00	2.2952 %
Axial Comp. Isen. Efficiency (%)	84.78	88.75	-3.9703 pts.
Firing Temperature (Comb.) (deg. F)	2506.63		
Firing Temperature (Turb.) (deg. F)	2419.09		
Part Load Level (%)	100.00		

EFFECT OF EVAPORATIVE COOLING:

	MEASURED (with cooling)	PREDICTED (w/o cooling)	DIFFERENCE (M-P)
Gas Turbine Gen. Power (kW)	154300.00	145075.40	6.3585
Heat Rate (Btu/kW-hr)	9950.75	10106.50	-1.5411
Overall Efficiency (%)	34.29	33.76	0.5284
Inlet Air Flow (lb/hr)	3002778.00	2905127.00	3.3613
Inlet Air Flow by Heat Bal. (lb/hr)	3294861.00	3187711.00	3.3613

CORRECTED SITE CONDITIONS:

Mode: Base		Fuel: Natural Gas	
Barometric Pressure	29.93 in. Hga	Relative Humidity	0.00 %
Inlet Temperature	59.00 deg. F	Water In./Fuel Ratio	0.00
Total Inlet Pressure Drop	3.00 in. H2O	Steam In./Fuel Ratio	0.00
Exhaust Pressure Drop	5.00 in. H2O		

CORRECTED PERFORMANCE:	MEASURED	EXPECTED	DIFFERENCE (M-E)
Gas Turbine Gen. Power (kW)	157971.00	170153.00	-7.1595 %
Heat Rate (Btu/kW-hr)	9647.37	9317.58	3.5394 %
Overall Efficiency (%)	35.37	36.62	-1.2518 pts.
Gas Fuel Flow (lb/hr)	84666.94	88078.60	-3.8734 %
Liquid Fuel Flow (lb/hr)	0.00	0.00	0.0000 %
Inlet Air Flow (lb/hr)	3219861.00	3453789.00	-6.7731 %
Inlet Air Flow by Heat Bal. (lb/hr)	3533060.00	3453789.00	2.2952 %
Axial Comp. Isen. Efficiency (%)	85.55	89.52	-3.9703 pts.

WASH INDICATOR: Yes

MISSION HEAT RATE RESULTS:

Fuel Consumption (MMBtu)	0.00
Power Production (kW-hr)	0.00
Heat Rate (Btu/kW-hr)	0.00

ERROR MESSAGES:

None

Figure 3-11 Report Output from CTPFDM Using Inputs of Table 3-7

6. When CTPFDM executes performance calculations, the results are displayed in the **Report** worksheet, but they are not saved to the results database file, Results.csv, until the user clicks the button labeled "Save Results". This is to guard against adding bogus results caused by mis-entry of the input data. Once the user has reviewed the report and verified that the results make sense, they can be saved. Do that now by clicking on the "**Save Results**" button. An Excel macro will execute that writes the results to Results.csv and updates the performance trend charts to include the current results. Once the macro is finished, a box appears displaying the message "Results saved to Results.csv." Click the "**OK**" button to make the box disappear.

7. Now switch to the worksheet labeled "Air Flow Chart". You will see a chart that looks similar to Figure 3-12. The chart displays only one point for each of the three trended parameters: measured, expected, and corrected inlet air flow. The range of the x-axis is also extremely broad; covering more than 100 years. This will change once a second set of performance results is added. You can begin to do that by returning to the **Inputs** worksheet.

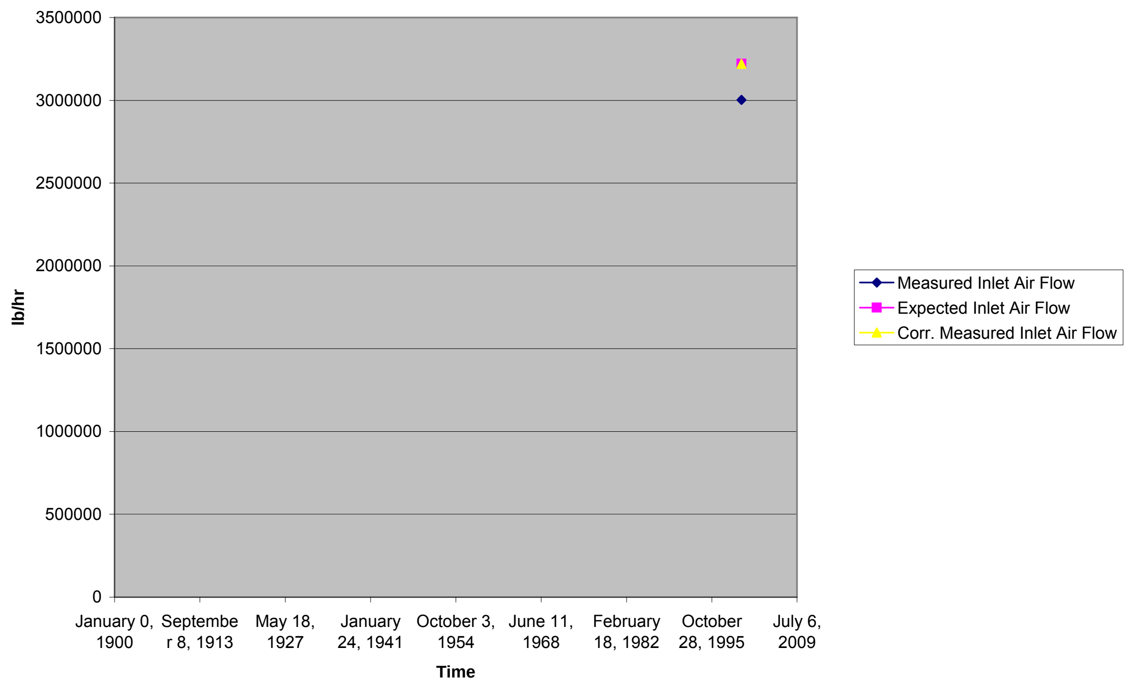


Figure 3-12
"Air Flow Chart" Worksheet after One Performance Results Case Has Been Saved

8. Now assume that you have a printout of the Pocasset Unit #1 operations overview screen for the next day (August 8, 2000) that is similar to that shown in Figure 3-13.

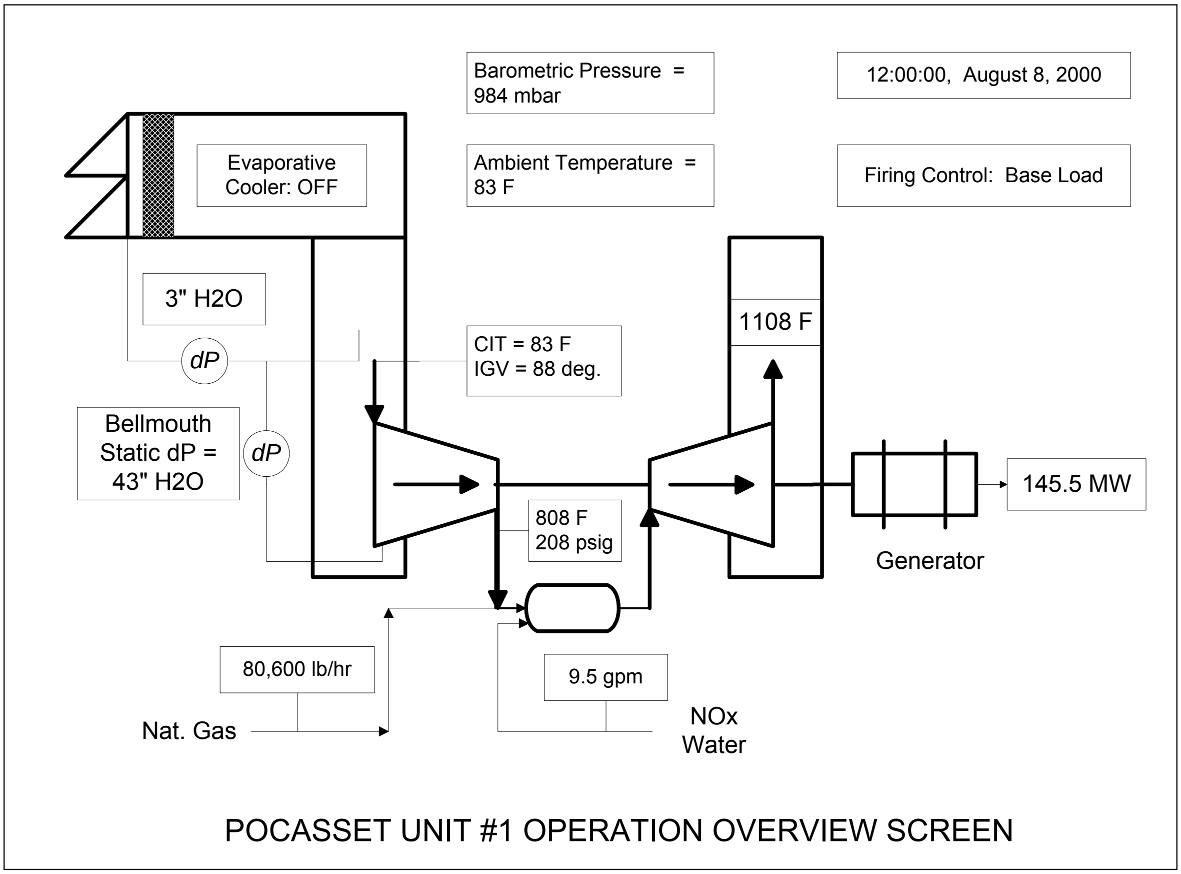


Figure 3-13
Example #2 of CT Operation Overview Screen

Table 3-8
Data to Be Entered in "Inputs" Worksheet for Second Run

Entry Label	Entered Value	Comments
Unit Name	Pocasset Unit #1	
Date Data Taken	8/8/2000	Will be converted to display "August 8, 2000" after it is entered.
Time Data Taken	12:00:00 PM	Will be converted to display "12:00:00" after it is entered.
Firing Mode	No changes.	
Fuel Type	No changes.	
Ambient Temperature	No changes.	
Barometric Pressure	No changes.	
Relative Humidity	Leave as is.	Since Evap. Cooler is not in use, we cannot assume 95% relative humidity at the compressor inlet. Set data quality flag to "use default", and the default value (60%) will be used.
Comp. Inlet Temp.	83	
Inlet Filter Dp	No changes.	
Inlet Total dP	No changes.	
Exhaust dP	No changes.	
Bellmouth Static dP	43	
For Future Use	No changes.	
Comp. Discharge Pr.	208	
Comp. Discharge T.	808	
IGV Position	No changes.	
Generator Power	145.5	
Gas Fuel Flow	80600	
Liquid Fuel Flow	No changes.	
Inlet Air Flow	No changes.	
Water Injection Flow	9.5	
Steam Injection Flow	No changes.	
Dew Point Temp.	No changes.	
Injected Water Temp.	No changes.	
Injected Steam Temp.	No changes.	
Gas Fuel Temp.	No changes.	
Gas Fuel Pressure	No changes.	
Liquid Fuel Temp.	No changes.	
Exhaust Temp.	1108	

9. Enter the data from Figure 3-13 into the **Inputs** worksheet. Follow the instructions given in Table 3-8. Note that far less time is required to enter the data for the second run, as the units of measurement and data quality flags have already been set up. Once the data in the **Inputs** worksheet matches that shown in Table 3-8, start the performance calculations by clicking the "**Click to Run CTPFDM**" button. The results in the **Report** worksheet should be identical to that shown in Figure 3-14.

SCAMP Version 3.10
Gas Turbine Performance Results for Example 1

Data Time:	16:29:00	Data Date:	September 15, 2003

MEASURED SITE CONDITIONS:

Mode: Peak		Fuel: Natural Gas	
Dew Point Temperature	50.00 deg. F	Relative Humidity	95.00 %
Ambient Temperature	83.00 deg. F	Barometric Pressure	29.14 in. Hga
Inlet Temperature	67.00 deg. F	Total Inlet Pressure Drop	3.00 in. H2O
Total Inlet Pressure	14.20 psia	Exhaust Pressure Drop	5.00 in. H2O
Bellmouth Static Pressure	45.00 in. H2O	Water Injection Flow	10.00 lb/sec
Discharge Temperature	798.00 deg. F	Steam Injection Flow	0.00 lb/sec
Discharge Pressure	215.00 psig	Water Injection Temp.	60.00 deg. F
Natural Gas Fuel Temperature	60.00 deg. F	Steam Injection Temp.	600.00 deg. F
Natural Gas Fuel Pressure	600.00 psig	Exhaust Temperature	1092.00 deg. F
Liquid Fuel Temperature	59.00 deg. F	Inlet Guide Vane Pos.	80.00 deg.

ACTUAL PERFORMANCE:	MEASURED	EXPECTED	DIFFERENCE (M-E)
Gas Turbine Gen. Power (kW)	154300.00	154300.00	0.0000 %
Heat Rate (Btu/kW-hr)	9950.75	9737.48	2.1902 %
Overall Efficiency (%)	34.29	35.04	-0.7510 pts.
Gas Fuel Flow (lb/hr)	85300.00	83471.82	2.1902 %
Liquid Fuel Flow (lb/hr)	0.00	0.00	0.0000 %
Inlet Air Flow (lb/hr)	3002778.00	3019733.00	-0.5615 %
Inlet Air Flow by Heat Bal. (lb/hr)	3294861.00	3019733.00	9.1110 %
Axial Comp. Isen. Efficiency (%)	84.78	89.89	-5.1115 pts.
Turbine Section Efficiency (%)	94.3	91.3	3.04 pts.
Firing Temperature (Comb.) (deg. F)	2506.63		
Firing Temperature (Turb.) (deg. F)	2419.09		
Part Load Level (%)	100.00		

EFFECT OF EVAPORATIVE COOLING:

	MEASURED (with cooling)	PREDICTED (w/o cooling)	DIFFERENCE (M-P)
Gas Turbine Gen. Power (kW)	154300.00	145075.40	6.3585
Heat Rate (Btu/kW-hr)	9950.75	10106.50	-1.5411
Overall Efficiency (%)	34.29	33.76	0.5284
Inlet Air Flow (lb/hr)	3002778.00	2905127.00	3.3613
Inlet Air Flow by Heat Bal. (lb/hr)	3294861.00	3187711.00	3.3613

CORRECTED SITE CONDITIONS:

Mode: Base		Fuel: Natural Gas	
Barometric Pressure	29.93 in. Hga	Relative Humidity	0.00 %
Inlet Temperature	59.00 deg. F	Water In./Fuel Ratio	0.00
Total Inlet Pressure Drop	3.00 in. H2O	Steam In./Fuel Ratio	0.00
Exhaust Pressure Drop	5.00 in. H2O		

CORRECTED PERFORMANCE:	MEASURED	EXPECTED	DIFFERENCE (M-E)
Gas Turbine Gen. Power (kW)	170153.00	170153.00	0.0000 %
Heat Rate (Btu/kW-hr)	9521.66	9317.58	2.1902 %
Overall Efficiency (%)	35.83	36.62	-0.7848 pts.
Gas Fuel Flow (lb/hr)	90007.68	88078.60	2.1902 %
Liquid Fuel Flow (lb/hr)	0.00	0.00	0.0000 %
Inlet Air Flow (lb/hr)	3434397.00	3453789.00	-0.5615 %
Inlet Air Flow by Heat Bal. (lb/hr)	3768464.00	3453789.00	9.1110 %
Axial Comp. Isen. Efficiency (%)	84.41	89.52	-5.1115 pts.

WASH INDICATOR: No

MISSION HEAT RATE RESULTS:

Fuel Consumption (MMBtu)	25.59
Power Production (kW-hr)	2571.67
Heat Rate (Btu/kW-hr)	9950.75

ERROR MESSAGES:
Error 8 in PERFORM : Meas. IGV angle < full open value; part load assumed

Figure 3-14 Report Output from CTPFDM Based on Inputs in Table 3-8

10. Click the "**Save Results**" button, then click the "**OK**" button when the message box pops up indicating that the results have been saved. Now move to the "Air Flow Chart". Each of the three trended parameters should have two data points with a line connecting them. In addition, the x-axis range should cover only the two-day period from August 7 to August 8 as shown in Figure 3-15. Note that both the measured and expected inlet flows have dropped significantly due to the hotter compressor inlet temperature on August 8, but the "corrected" measured inlet air flow (i.e., the actual flow corrected to standard day conditions) has dropped only slightly. This indicates that only a minor amount of compressor fouling has occurred during the past 23 hours.

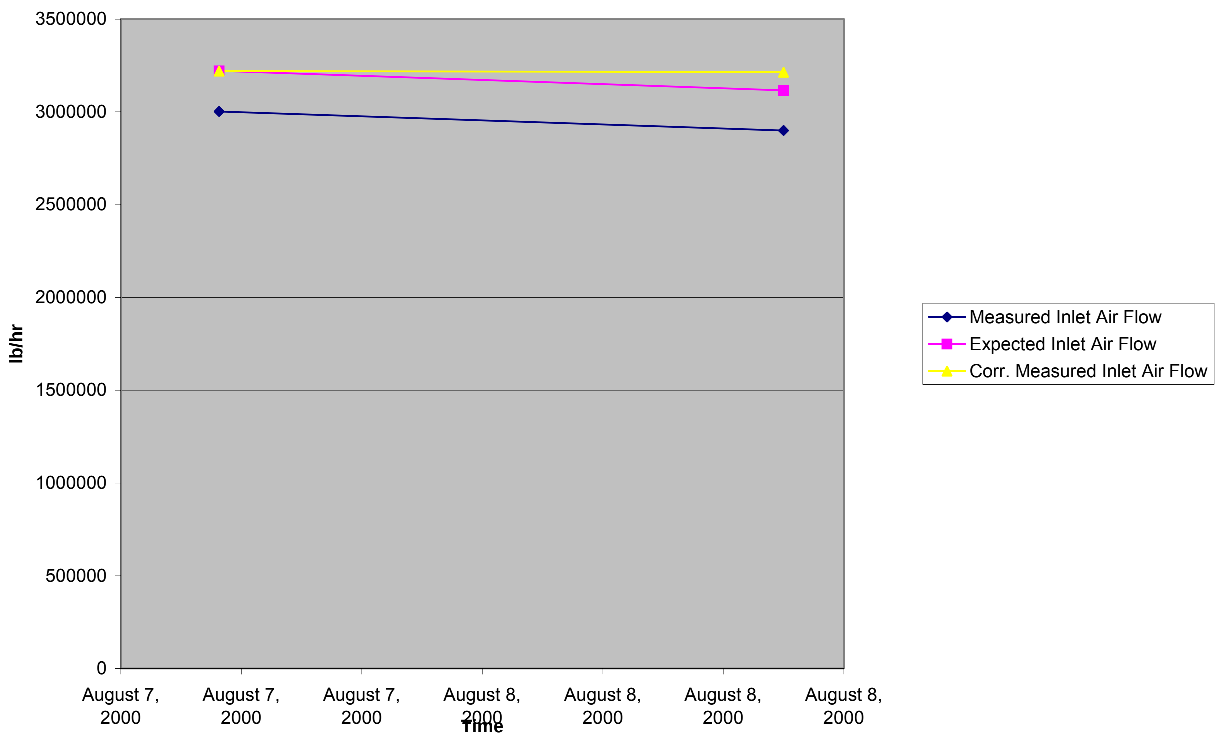


Figure 3-15
"Air Flow Chart" Worksheet after Two Performance Results Cases Have Been Saved

Lesson 3 - Add a New CT Model

If your CT is not a GE 7FA or a W501F, then you will have to modify one of those two CT models to match the characteristics of your turbine. This lesson shows how to modify an existing model and save it as a new CT "reference model".

1. Make sure "Pocasset Unit #1" is the "Current Unit". If not, go to the **Main Menu** worksheet and set the pull-down menu in cell "B4" to "Pocasset Unit #1" and click the "**Switch Unit:**" button.
2. Go to the worksheet labeled "Gtmodel". This is where all of the data that defines the expected performance of the CT is displayed. Let's assume that your CT is a upgraded version of the GE 7FA, called a 7FAA, and that its ISO rating is given in Table 3-10. These

data should now be entered in the appropriate cells in the **Gtmodel** worksheet, starting with the base-load power rating on natural gas (175,000) in cell "B36".

Table 3-9
ISO Rating for a GE 7FAA

Fuel	**Natural Gas**	**Distillate**
Base Power	175,000	173,000
Base Heat Rate	9280	9320
Base Exhaust Flow	3,460,000	3,460,000
Peak Power	180,000	177,500
Peak Heat Rate	9190	9250
Peak Exhaust Flow	3,460,000	3,460,000

3. Once all of the data from Table 3-10 have been entered into the **Gtmodel** worksheet, move up and click the button at cell "H24" labeled "Save GTmodel Values to Unit". The data you just entered will be written to the file "Gtmodel.dat" in the Pocasset Unit #1 sub-directory. If you run the performance calculations, the expected performance values will now be based on the "GE 7FAA" rating.

4. Saving the changes using the "Save GTmodel Values to Unit" button only impacts the expected performance calculations of the current unit. To make the GE 7FAA model data available for other units, you must create a new "model file". To do so, first move to the **Main Menu** worksheet.

5. Go to the "Add CT Model" at cell "B22", and set the Units of Measurement pull-down menu in cell "B23" to "Current". Then click on the "**Add CT Model:**" button.

6. An input box will appear asking for the name of the new CT model. Type in "GE 7FAA" and click the "**OK**" button. An Excel macro will be executed which copies the currently displayed data from the **Gtmodel** worksheet into a file named **GE 7FAA.dat** in the **CTPFDM\Reference Models** sub-directory. Once the macro has finished, a message box will appear reading "Model GE 7FAA saved to Reference Models.". Click the "**OK**" button to make the message box disappear.

7. If you check the pull-down menu under the "Create Unit:" button in cell "B7", you will see that the GE 7FAA model now appears along with the W501F and the GE 7FA.

8. To make the GE 7FAA model data available for new units that use SI measurements, you could either re-run the "Add CT Model" macro with the Units of Measurement menu set to "SI" rather than "Current", or you could use the "Copy CT Model" macro. We will do the latter. First make sure the "Units of Source" pull-down menu in cell "B26" is set to "English" and that the "Units of Target" pull-down menu below it in cell "B27" is set to "SI". Now click the "**Copy CT Model:**" button.

9. An input box will appear asking for the drive and path of the CT model source file. By default, the drive and path for the **CTPFDM\Reference Models** sub-directory is displayed. Click the "**OK**" button to proceed.

10. The new input box asks for the name of the source model. Type in **GE 7FAA** and click the "**OK**" button. A box then appears telling you to make sure there is a floppy disk in the diskette drive if you have specified that as the location of the source file. Since you have specified a hard disk as the source location, you don't have to worry about the diskette drive, so just click the "**OK**" button to move on.

11. An input box now appears asking for the name of the new model. Type in **GE 7FAA-SI** and click the "**OK**" button. The GE 7FAA.dat file in the **CTPFDM\Reference Models** sub-directory will now be copied into a file named GE 7FAA-SI.dat in the **CTPFDM\Reference Models** sub-directory. When the file has been copied, a message box will appear reading "Copied Model to GE 7FAA-SI". Click the "**OK**" button to make the box disappear.

12. If you look in the pull-down menu in cell "B7" for the list of available CT models, you will see that **GE 7FAA-SI** is now in the list.

Lesson 4 - Deleting Units and Models

In order to prevent cluttering up your CTPFDM sub-directories with unneeded units and CT models, you should delete the units and models that were created in Lessons 1 through 3. That will be done in this lesson.

1. On the **Main Menu** worksheet, move to cell "B30" and select "**GE 7FAA-SI**" from the pull-down menu.
2. Now click on the button in cell "B29" labeled "**Remove CT Model:".** A message box will appear asking you to confirm that you want to delete the model **GE 7FAA-SI**. Click the "**OK**" button to continue.
3. A macro will be executed that deletes the **GE 7FAA-SI.dat** file. When the macro is completed, a message box will appear telling you so. Click the "**OK**" button to make the box disappear.
4. Now select the model "**GE 7FAA**" from the "B30" pull-down menu and then click the "**Remove CT Model**" button and click the "**OK**" button twice to delete the **GE 7FAA.dat** file.
5. Note that removing the CT reference model does not effect the CT model data files that are stored in the individual unit sub-directories. You can confirm this by looking at the **Gtmodel** worksheet of the Pocasset Unit #1 unit. If Pocasset Unit #1 is not the current unit, make it so by using the "**Switch Unit**" button in cell "B3" of the **Main Menu**. Now move to the **Gtmodel** worksheet.
6. To confirm that the CT model data file with data matching the rating data shown in Table 3-10 still exists, click the "**Get Gtmodel Values from Unit**" button in cell "F24". A macro will execute which imports in the data stored in the Gtmodel.dat file located in the

CTPFDM\Pocasset Unit #1 sub-directory. When the macro is finished, a message box will appear telling you "Import of Gtmodel.dat completed." Click the "**OK**" button to make the box disappear.

7. Now that we've verified that removing the CT reference model files did not effect the files in the individual unit sub-directories, we now will remove the **Pocasset Unit #1** unit. First return to the **Main Menu** worksheet.
8. In cell "B17", select **Pocasset Unit #1** from the pull-down menu. Then click the "**Remove Unit**" button just above the menu.
9. A message box will appear asking you if you are sure you want to remove the unit Pocasset Unit #1. Click the "**OK**" button to continue. A macro will now delete the **CTPFDM\Pocasset Unit #1** sub-directory and all of the files in it. When it is finished, a message box will appear telling you so. Click the "**OK**" button to make the box disappear.
10. Note that the entries in Row A still indicate that Pocasset Unit #1 is the current unit. However, if you try to run performance calculations in Pocasset Unit #1, you will get a message that it doesn't exist. To verify this, switch to the Inputs worksheet and click the "**Click to Run CTPFDM**" button. A message box appears telling you "Pocasset Unit #1 has been removed. Switch to a different unit." Click the "**OK**" button to make the box disappear.
11. Return to the **Main Menu** worksheet and switch to the unit Example 1 by selecting **Example 1** in the pull-down menu of cell "B3" and clicking the Switch Unit button above it. Once the macro has finished, click the "**OK**" button and then close the CTPFDM worksheet using the Excel "File" menu. When you are prompted "Do you want to save the changes you made to CTPFDM.xls", click "**Yes**".

References

1. Levine, P., E. Dougherty, and C. Dohner, *Software for the Performance Monitoring of Combined Cycles*, ASME 86-JPGC-GT-3, 1986.
2. Documentation of the Benedict-Webb-Rubin Mark 2 Program, Engineering & Operations Analysis, 72-T-16A, 1972.

Appendix A: Detailed Description of Performance Calculations

Overview

When the CTPFDM DLL is called, it carries out six main functions: data checking, measured (or actual) performance, expected performance, transpose (or corrected) performance, evaporative cooling performance, and fault diagnostics. In addition, CTPFDM may calculate optional mission heat rate results, if the software has been configured to do so. Each of these functions will be described in detail in this appendix.

Data Checking

CTPFDM performs several internal checks to verify the quality of the measured data. The first aspect that is checked is the reasonableness of the data. Each of the numerical inputs is checked to see if it falls within an expected range of values (see Table 3-11). If any are outside the expected range, and the data quality flag is set to "use input", then an error message is issued and the calculations do not proceed.

Table 3-10
Expected Range Check for Key Input Measurements

Parameter	Lower Limit	Upper Limit
Barometric Pressure	24" Hg (0.786 bara)	32" Hg (1.08 bara)
Compressor Inlet Temperature	Min. temp. in model correction factor data	Max. temp. in model correction factor data
Generator Power	67% of design rating	125% of design rating

If all of the inputs fall within the expected range of values, then CTPFDM reviews the available data to determine what calculations should be carried out.

CTPFDM checks whether a valid value (i.e., data quality set to "use input") for relative humidity is present. If it is not, it looks for a valid value of dew point temperature and, if that is present, CTPFDM calculates a value of relative humidity. Otherwise, the default value for relative humidity is used.

CTPFDM then checks for a valid value of inlet air flow. If this is not present, it checks for a valid value of bellmouth static pressure drop, ΔP_{bell}. If this is present, it first calculates the absolute static pressure at the bellmouth, P_{bell} and then estimates the inlet air flow based on the following formulas:

$$M_{in} = \sqrt{\frac{2}{k-1}\left[\left(\frac{P_{in}}{P_{bell}}\right)^{\frac{k-1}{k}} - 1\right]}$$

$$W_{air} = \frac{C_{air} A_{air} P_{in} M_{in}}{\left[1 + \left(\frac{k-1}{2}\right) M_{in}^2\right]^{\frac{k+1}{2(k-1)}}} \sqrt{\frac{k}{RT_{in}}}$$

where P_{in} and T_{in} are the total pressure and temperature at the compressor inlet, C_{air} is the bellmouth air flow coefficient and A_{air} is the cross-sectional area at the inlet guide vanes that is entered in the model data file (see sub-section heading "Installation").

If bellmouth static pressure is also not available, then the program will calculate a "measured" air flow using an energy balance around the CT. This calculation procedure is described later in this sub-section under the heading "Heat Balance Calculations".

If the measured inlet pressure drop is flagged as "ignore input", then the pressure drop is assumed to be equal to the design rating value, an error message is issued, and no correction will be made for inlet pressure drop. The performance calculations, however, will move forward. Similarly, if the exhaust pressure drop is flagged as "ignore input", then the pressure drop is assumed to be equal to the design rating value, an error message is issued, and the performance calculations go forward with no correction made for exhaust pressure drop.

If the values for water or steam injection are greater than two times the fuel mass flow rate, then an error message is issued and the water or steam flow is set to zero.

If the measured value for inlet guide vane angle differs from the design full-load value by more than 3 degrees, an error message is issued, but the performance calculations will move forward based on the assumption that the IGV angle is correct and the CT is operating at part-load.

If the exhaust temperature is flagged as "ignore input", then CTPFDM does not calculate the air flow via a heat balance, nor does it calculate the firing temperature.

Finally, CTPFDM checks to determine whether sufficient data are present to calculate the axial compressor efficiency by verifying the presence of valid data for the compressor discharge temperature and pressure. If either of these two measurements is missing (i.e., have "ignore input" flags), then an error message is issued to that effect and the measured compressor efficiency is not calculated.

Measured Performance Analysis

Once the data checking functions have been completed, CTPFDM will carry out the measured performance analysis function, provided sufficient data are available. The measured performance analysis determines the actual performance of the machine based on the measured data and various thermodynamic calculations described below.

Heat Rate

The heat rate, HR, is calculated from the measured fuel flow, w_{fuel}, and measured generator power, MW, and the default value for the lower heating value of the fuel, LHV:

$$HR = \frac{w_{fuel} * 3600 * LHV}{MW * 1000}$$

Overall Efficiency

The overall efficiency of the combustion turbine, η_{CT}, is calculated from the heat rate. For the English units option the formula is:

$$\eta_{CT} = 3412 / HR$$

For the SI units option the formula is:

$$\eta_{CT} = 3600 / HR$$

Axial Compressor Isentropic Efficiency

The axial compressor isentropic efficiency is calculated from the formula:

$$\eta_{comp} = \frac{h_d - h_{in}}{h_{ds} - h_{in}}$$

where h_d and h_{in} are the enthalpies of the air flow at the compressor discharge and inlet. They are calculated using the Benedict-Webb-Rubin (BWR) equation of state and are based on the measured temperature and pressure at the respective location and the composition of the air accounting for the measured relative humidity. The other enthalpy, h_{ds}, corresponds to the isentropic discharge condition and is calculated using the compressor discharge pressure and the entropy corresponding to the compressor inlet conditions. The BWR equation is used to calculate both h_{ds} and the inlet entropy.

Firing Temperature

The firing temperature calculations are based on General Electric's definition of combustion turbine firing temperature: the mass flow mean total temperature at the plane of the first stage nozzle trailing edge. The calculation procedure for the firing temperature is described later in this sub-section under the heading "Heat Balance Calculations".

Turbine Section Efficiency

The turbine section efficiency is calculated by the formula:

$$\text{Teff-m} = \text{TPW} / \text{TPWs} * 100$$

Where TPW is the turbine section power and TPWs is the isentropic turbine section power. TPW is defined by Equation A-8 found in the "Heat Balance Calculations". TPWs is calculated from:

$$TPWs = WFIRE * (HFIRE - Hs1) + WCOOL * (HCOOL - Hs2) + WWC * (HEXC - Hs3)$$

Hs1, Hs2, and Hs3 represent the endpoint enthalpies of the isentropic expansion of the WFIRE, WCOOL, and WWC flows. Those three flows are also defined in the "Heat Balance Caluculations" section of this appendix.

Expected Performance Analysis

The expected performance analysis functions calculate the performance that would be expected from the combustion turbine based on the model data for the measured operating conditions.

Expected Generator Power

The expected generator power, MW_{exp}, is calculated by the following formula:

$$MW_{exp} = MW_{rated} * CF_{MW-T} * CF_{MW-P} * CF_{MW-dPin} * CF_{MW-dPexh} * CF_{MW-hum} * CF_{MW-stm} * CF_{MW-wtr}$$

where MW_{rated} is the generator power at the design rating for the current firing mode (base or peak) and current fuel option (natural gas or liquid). This value is adjusted by a series of correction factors (CF):

- CF_{MW-T} is the power correction factor for inlet temperature.
- CF_{MW-P} is the power correction factor for ambient pressure ($CF_{MW-P} = P_{baro} / P_{baro-rated}$).
- $CF_{MW-dPin}$ is the power correction factor for inlet total pressure drop.
- $CF_{MW-dPexh}$ is the power correction factor for exhaust pressure drop.
- CF_{MW-hum} is the power correction factor for specific humidity.
- CF_{MW-stm} is the power correction factor for steam injection.
- CF_{MW-wtr} is the power correction factor for water injection.

The values of the correction factors are set by the data entered into the turbine model data file (See sub-section heading “Using the Spreadsheet”). However, all of the correction factors are equal to 1.0 at the design rating conditions. Consequently, at the design rating conditions, the expected power, MW_{exp}, is equal to the rated power MW_{rated}.

If the measured operating conditions fall in between two points in the correction factor tables, the value for the correction factor is based on a linear extrapolation between the two points.

Expected Heat Rate

The expected heat rate, HR_{exp}, is calculated in an approach similar to that of the calculation of the expected power:

$$HR_{exp} = HR_{rated} * CF_{HR-T} * CF_{HR-dPin} * CF_{HR-dPexh} * CF_{HR-hum} * CF_{HR-stm} * CF_{HR-wtr}$$

where HR_{rated} is the generator power at the design rating for the current firing mode and current fuel option. This value is adjusted by a series of correction factors (CF):

- $CF_{HR\text{-}T}$ is the heat rate correction factor for inlet temperature.
- $CF_{HR\text{-}dPin}$ is the heat rate correction factor for inlet total pressure drop.
- $CF_{HR\text{-}dPexh}$ is the heat rate correction factor for exhaust pressure drop.
- $CF_{HR\text{-}hum}$ is the heat rate correction factor for relative humidity.
- $CF_{HR\text{-}stm}$ is the heat rate correction factor for steam injection.
- $CF_{HR\text{-}wtr}$ is the heat rate correction factor for water injection.

The value of each of the correction factors is equal to 1.0 at the design rating conditions and varies at off-design conditions according to the data entered into the combustion turbine model file.

Expected Overall Efficiency

The expected overall efficiency of the combustion turbine, $\eta_{CT\text{-}exp}$, is calculated from the expected heat rate. For the English units option, the formula is:

$$\eta_{CT\text{-}exp} = 3412 \,/\, HR_{exp}$$

For the SI units option, the formula is:

$$\eta_{CT\text{-}exp} = 3600 \,/\, HR_{exp}$$

Expected Fuel Flow

The expected fuel flow is calculated from the expected heat rate, the expected generator power, and the LHV of the fuel for the specified fuel option:

$$w_{fuel} = HR_{exp} * MW_{exp} / LHV_{fuel}$$

Expected Inlet Air Flow

The expected inlet air flow, AF_{exp}, is calculated based on the following formula:

$$AF_{exp} = AF_{rated} * CF_{AF-T} * CF_{AF-stm} * CF_{AF-wtr} * \frac{P_{inlet}}{P_{inlet-rated}}$$

where AF_{rated} is the generator power at the design rating for the current firing mode and current fuel option. This value is adjusted by a series of correction factors (CF):

- $CF_{AF\text{-}T}$ is the air flow correction factor for inlet temperature.
- $CF_{AF\text{-}stm}$ is the air flow correction factor for steam injection.

- $CF_{AF\text{-}wtr}$ is the air flow correction factor for water injection.
- $P_{inlet}/P_{inlet\text{-}rated}$ is the ratio of the measured inlet total pressure to its value at the rated conditions. Both pressures are absolute (i.e., psia or bara).

The value of each of the correction factors is equal to 1.0 at the design rating conditions and varies at off-design conditions according to the data entered into the combustion turbine model file. Note that the impacts of exhaust pressure drop and specific humidity on air flow are assumed to be small enough that they can be ignored.

Expected Axial Compressor Efficiency

Axial compressor efficiency is normally a function of several parameters. Figure 3-16 shows a typical performance "map" for an axial compressor. The map shows the lines of constant efficiency as a function of pressure ratio, corrected speed (N_{corr}) and corrected air flow (W_{corr}).

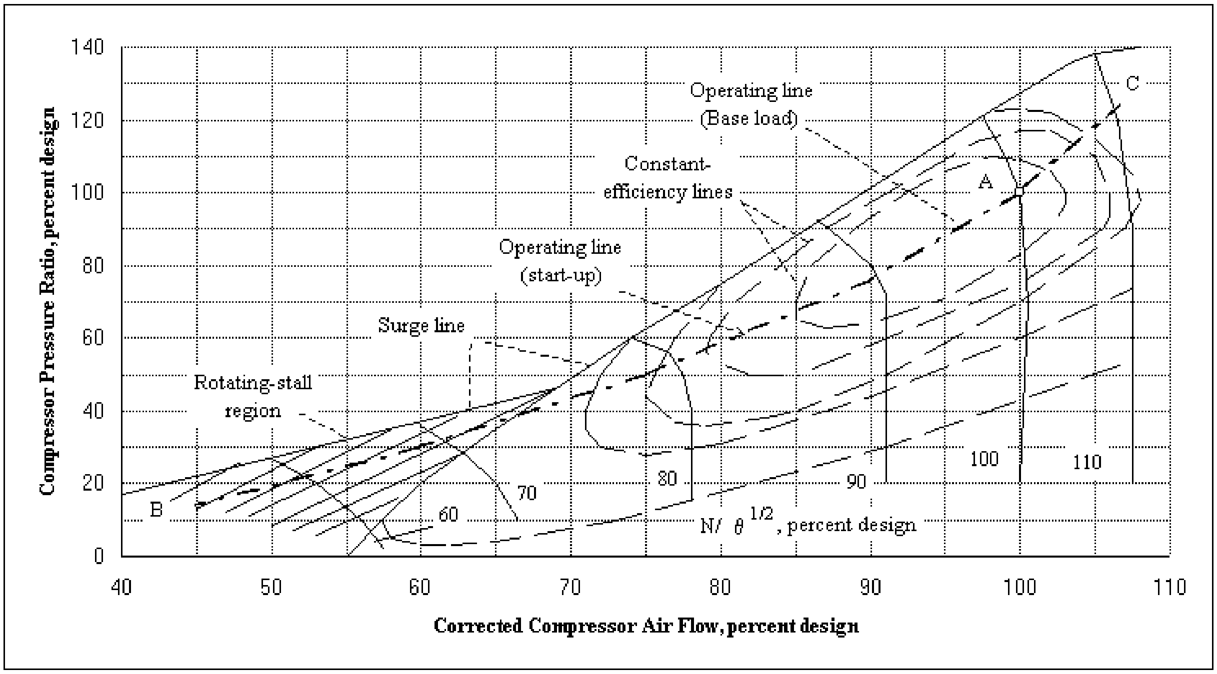


Figure 3-16
Typical Multi-Stage Axial Compressor Operating Map
(from NASA Aerodynamic Design of Axial-Flow Compressors, 1965)

Corrected air flow is defined as:

$$W_{corr} = W_{meas}\sqrt{\theta}/\delta$$

And corrected speed is defined as:

$$N_{corr} = N_{meas}/\sqrt{\theta}$$

where:

$$\theta = \frac{T_{Inlet-meas}}{T_{Inlet-rated}} \frac{MW_{rated}}{MW_{meas}}$$

and:

$$\delta = \frac{P_{Inlet-meas}}{P_{Inlet-rated}}$$

The map also shows the normal baseload operating line for the compressor (dashed line running from point B to point A to point C). This operating line is dictated by the pressure drop versus characteristic of the machine downstream of the compressor discharge. It would be changed if operating mode of the turbine were changed. For example, if the firing temperature was raised to the peak value, then more pressure would be needed to push the same amount of mass flow through the first stage turbine nozzle. The operating line of the compressor would therefore move upward.

If the firing temperature is held constant, the operating point of the compressor is then only a function of the corrected speed. Because corrected speed is a function of θ, even if the rotor speed of the compressor is held constant (e.g., a single-shaft combustion turbine), the operating point of the compressor will still move as inlet conditions change.

An increase in inlet temperature will lead to an increase in θ. This will cause the corrected speed to decrease. From Figure 3-16, we can see that a lower corrected speed will move the compressor to the left and downward along the operating line, which will result in a lower compressor pressure ratio. Note that in Figure 3-6, the pressure ratio is shown to fall as inlet temperature increases.

Drier air has a higher molecular weight. Thus, a decrease in relative humidity (while holding inlet temperature constant) will result in a smaller value for θ, and an increase in corrected speed. This would move the operating point to the right and upward along the operating line.

A change in the inlet pressure, however, will not cause a change in the corrected speed. (It does, however, cause the actual mass flow to change.)

At a given operating mode (i.e., base or peak), compressor efficiency is only a function of the compressor pressure ratio. Consequently, if the compressor inlet and discharge pressures are known, one can predict the expected compressor efficiency. This is the approach used in CTPFDM. The expected isentropic efficiency of the axial compressor is found by using the temperature correction model data as a "look-up" table that provides the compressor efficiency as a function of pressure ratio. The measured pressure ratio is used as the input and the compressor efficiency is found by extrapolating between pressure ratio points in the table.

Figure 3-17 is a plot of the compressor pressure ratio versus compressor efficiency at base load operation for a typical combustion turbine. The data displayed is the same as that used in Figure 3-6. Note that the compressor is generally designed to operate near its maximum efficiency point at the rated conditions, and that the efficiency curves remain relatively flat on either side of the design point. Only when compressor ratio deviates significantly from the design point does the efficiency fall off.

It should be noted that water or steam injection can cause the operating line of the compressor to change just as a varying the firing temperature does. If water or steam is injected into the combustor and the firing temperature is held constant, this will require the discharge pressure of the compressor to increase in order to push the extra mass through the first stage nozzle of the turbine. This also cause the compressor to operate closer to its surge line, so many OEMs lower the firing temperature of their turbines when water or steam is injected in order to maintain the same surge margin as in dry (i.e., no water or steam injection) operation. If this is the case, then no adjustment in the expected compressor efficiency needs to be made when steam or water injection is used. However, if firing temperature is held constant and the surge margin is reduced, then the compressor efficiency versus pressure ratio data in the model file should be adjusted to reflect this new operating line for the compressor.

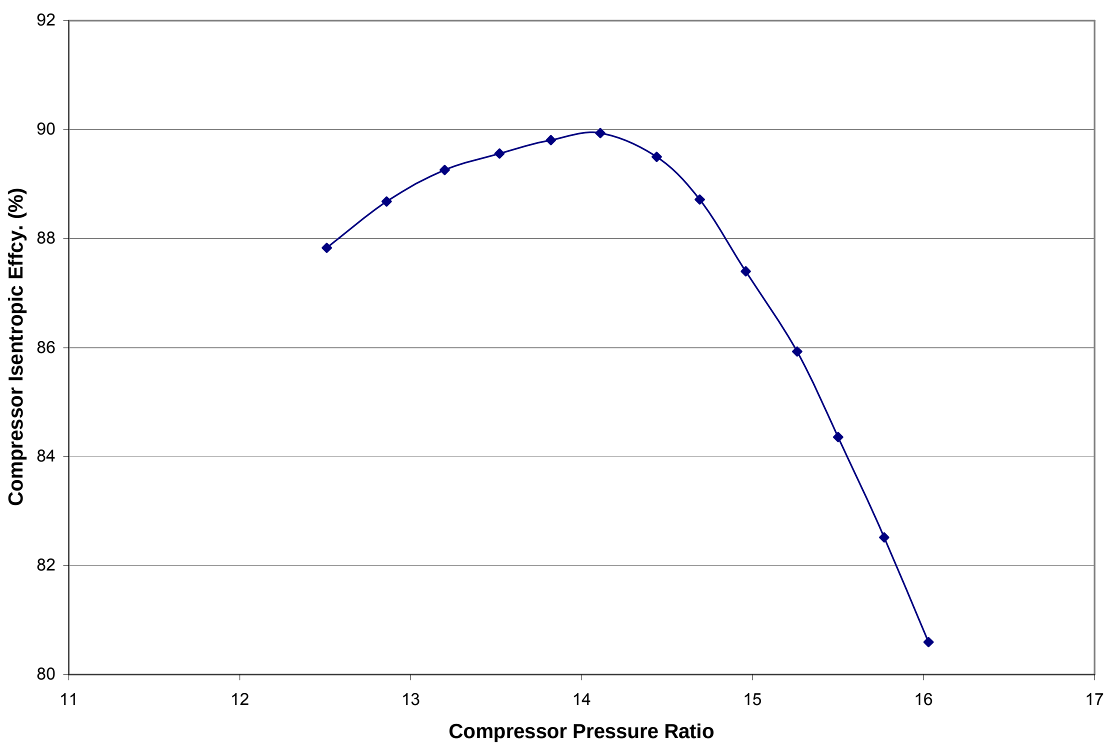


Figure 3-17
Plot of Compressor Isentropic Efficiency as a Function of Compressor Pressure Ratio for a Typical Combustion Turbine

Expected Turbine Section Efficiency

The expected turbine section efficiency is based on a correlation developed from actual GE 7FA performance data collected by Dr. Meherwan Boyce:

$$\text{Teff-exp} = A * X^2 + B * X + C$$

where X = U/V and A, B, and C are engine specific correlation coefficients. U is the tip speed of the 1st stage turbine blade. This can be calculated from:

$$U = \pi * RPM * d_{blade} / 60$$

RPM is the design speed of the turbine and d_{blade} is the tip-to-tip diameter of the first stage blades.

V is the "jet velocity" and can be calculated from:

$$V = \left[(h_{fire} - h_{exh}) * 2 * 32.2 * 778 \big/ NTS \right]^{0.5}$$

where NTS is the number of turbine section stage and h_{fire} and h_{exh} are the enthalpies (in btu/lb) at the turbine inlet and exhaust corresponding the measured conditions.

Based on Dr. Boyce's analysis, the turbine efficiency parameters for a GE 7FA:

A = -228.35

B = 256.32

C = 19.61

RPM = 3600

d_{blade} = 7.271 ft

NTS = 3

Evaporative Cooling Analysis

Many combustion turbines are equipped with an evaporative cooler in the air intake system. The cooler allows the turbine to produce more power by feeding it higher density air. There is also typically some heat rate benefit to operating with a cooler inlet temperature (refer to Figure 3-4). CTPFDM analyzes the performance benefit of an operating inlet cooling system by calculating the power and heat rate that would be expected if the inlet cooler were not present and comparing those values to the actual measured results.

Impact of Cooler on Power

The generator power that the turbine would produce if the inlet cooler were not present, $MW_{no-cool}$, is predicted based on the following formula:

$$MW_{no-cool} = MW_{meas} \frac{MW_{exp-Tamb}}{MW_{exp-Tinlet}}$$

where $MW_{exp-Tamb}$ is the expected power at the measured ambient temperature and $MW_{exp-Tinlet}$ is the expected power at the measured inlet temperature (i.e., after the cooler). This latter value has already been calculated as part of the expected performance analysis. $MW_{exp-Tamb}$ is calculated using the expected power formula described earlier in this sub-section, except the temperature correction factor is based on the ambient temperature rather than the inlet temperature.

The difference between the measured power and $MW_{no-cool}$ is then calculated on a percentage basis to provide an indication of the impact of the cooler on power production:

$$\text{Difference} = 100\left(MW_{meas} - MW_{no-cool}\right)/MW_{no-cool}$$

Impact of Cooler on Heat Rate and Overall Efficiency

The heat rate of the turbine if the inlet cooler were not present, $HR_{no-cool}$, is predicted based on the following formula:

$$HR_{no-cool} = HR_{meas} \frac{HR_{exp-Tamb}}{HR_{exp-Tinlet}}$$

where $HR_{exp-Tamb}$ is the expected heat rate at the measured ambient temperature and $HR_{exp-Tinlet}$ is the expected heat rate at the measured inlet temperature, which has already been calculated as part of the expected performance analysis. $HR_{exp-Tamb}$ is calculated using the expected heat rate formula described earlier in this sub-section, except that the temperature correction factor is based on the ambient temperature rather than the inlet temperature.

The difference between the measured heat rate and $HR_{no-cool}$ is then calculated on a percentage basis to provide an indication of the impact of the cooler on heat rate.

Also, the overall efficiency of the combustion turbine without inlet cooling is derived from the $HR_{no-cool}$ by dividing into the appropriate conversion constant (3412 Btu/kW-hr or 3600 kJ/kW-hr). The absolute difference between the measured and predicted no-cooling efficiency is then calculated.

Impact of Cooler on Air Flow

The air flow into the compressor if the inlet cooler were not present, $AF_{no\text{-}cool}$, is predicted based on the following formula:

$$AF_{no-cool} = AF_{meas} \frac{AF_{exp-Tamb}}{AF_{exp-Tinlet}}$$

Where $Af_{exp\text{-}Tamb}$ is the expected air flow at the measured ambient temperature and $AF_{exp\text{-}Tinlet}$ is the expected air flow at the measured inlet temperature, which has already been calculated as part of the expected performance analysis. $AF_{exp\text{-}Tamb}$ is calculated using the expected air flow formula described earlier in this sub-section except that the temperature correction factor is based on the ambient temperature rather than the inlet temperature.

The difference between the measured air flow and $AF_{no\text{-}cool}$ is then calculated on a percentage basis to provide an indication of the impact of the cooler on air flow.

Corrected Performance Analysis

The final analysis that is executed by CTPFDM is corrected performance analysis in which the measured performance is transposed back to the reference transpose, or standard day, conditions. This is done in a manner similar to that of the inlet cooler impact analysis.

Corrected Generator Power

The measured generator power is transposed to the corrected value, $MW_{corr,}$ using the following formula:

$$MW_{corr} = MW_{meas} \frac{MW_{SD}}{MW_{exp}}$$

where MW_{SD} is the expected power at the standard day conditions. This value will remain constant as long as the transpose reference conditions remain unchanged by the user. From the above equation, one can see that if the measured power is equal to the expected power (i.e., no degradation in performance), then the corrected power will be equal to MW_{SD}. However, if the measured power is less than the expected power, the corrected power will be less than MW_{SD} by a similar ratio. By monitoring the trend of corrected power, the user will see clearly whether the machine is degrading in performance and by how much.

Corrected Heat Rate and Overall Efficiency

The corrected heat rate, HR_{corr}, is calculated base on the following formula:

$$HR_{corr} = HR_{meas} \frac{HR_{SD}}{HR_{exp}}$$

where HR_{SD} is the expected heat rate at the standard day conditions.

The corrected overall efficiency of the combustion turbine is then derived from the HR_{corr} by dividing into the appropriate conversion constant (3412 Btu/kW-hr or 3600 kJ/kW-hr).

Corrected Fuel Flow

The corrected fuel flow is derived from the corrected heat rate, the corrected generator power and the LHV of the fuel for the specified fuel option:

Corrected Air Flow

The corrected inlet air flow, AF_{corr}, is calculated base on the following formula:

$$AF_{corr} = AF_{meas} \frac{AF_{SD}}{AF_{exp}}$$

where AF_{SD} is the expected air flow at the standard day conditions.

Corrected Axial Compressor Efficiency

The corrected axial compressor efficiency is calculated based on the assumption that the difference between the actual and expected efficiency at the standard day conditions would be the same as the difference between the actual and expected efficiency at the measured conditions. Hence:

$$\eta_{corr} = \eta_{SD} - (\eta_{exp} - \eta_{meas})$$

Fault Diagnostics

CTPFDM calculates fault diagnostics based on rules developed by Dr. Meherwan Boyce. The diagnostic calculations compare both user-input and calculated threshold values for up to 24 measured inputs with degradation parameter values. As a result of the comparisons, logical "flags" are set for the up to 24 degradation parameters. These degradation parameter flags are then evaluated and in some cases, combined (e.g., those for hot end bearing temperatures and wheelspace temperatures), to produce a subset of 12 degradation parameter flags. Finally, these 12 flags are evaluated and used to determine the status of 9 potential fault conditions relating to the inlet filter, compressor, combustion system, and turbine section.

The degradation parameter flag values used as the criteria for setting each fault condition are given in Tables 3-12 and 3-13 below. The four status conditions and associated flag values of the degradation parameters are as follows:

0 = "Undetermined"

1 = "Normal"

2 = "Alert"

3 = "Action Required"

Table 3-11 Criteria for "Alert" Fault Status

	Degradation Parameter Flag Value											
Fault	**Comp. Effcy.**	**Inlet Air Flow**	**Cold End Vibr.**	**Inlet Press. Drop**	**Exhst. Temp. Spread**	**Fuel Cons.**	**Hot Exhst. Temp.**	**Cold Exhst. Temp.**	**Turb. Section Effcy.**	**Wheel-space Temps.**	**Hot End Vibr.**	**Hot End Bearing Temps.**
Clogged Inlet Filter				2								
Compressor Fouling	2 or 3*	2 or 3*	1									
Compressor Blade Damage	2 or 3*	2 or 3*	2 or 3*									
Clogged Fuel Nozzles					2 or 3*	2 or 3*	2 or 3*					
Cracked Comb. Liner					2 or 3*	1		2 or 3*				
Crossover Tube Failure					2 or 3*	2 or 3*		2 or 3*				
Bowed Nozzle									2 or 3*	1	1	1
Turbine Blade Damage									2 or 3*	2 or 3*	2 or 3*	2 or 3*
High Turbine Blade Temp.									1	2 or 3*		
Turbine Section Fouling									2 or 3*		2 or 3*	1

*Note that for "Alert" faults that are determined by multiple degradation parameters that can have a flag value of 2 or 3, all flags must be 2s or there must be a mix of 2s and 3s. Otherwise, if all flags are 3s, an "Action Required" fault is indicated as shown below.

Table 3-12 Criteria for "Action Required" Fault Status

	Degradation Parameter Flag Value											
Fault	**Comp. Effcy.**	**Inlet Air Flow**	**Cold End Vibr.**	**Inlet Press. Drop**	**Exhst. Temp. Spread**	**Fuel Cons.**	**Hot Exhst. Temp.**	**Cold Exhst. Temp.**	**Turb. Section Effcy.**	**Wheel-space Temps.**	**Hot End Vibr.**	**Hot End Bearing Temps.**
Clogged Inlet Filter				3								
Compressor Fouling	3	3	1									
Compressor Blade Damage	3	3	3									
Clogged Fuel Nozzles					3	3	3					
Cracked Comb. Liner					3	1		3				
Crossover Tube Failure					3	3		3				
Bowed Nozzle									3	1	1	1
Turbine Blade Damage									3	3	3	3
High Turbine Blade Temp.									1	3		
Turbine Section Fouling									3		3	1

Some fault diagnostics are based on comparisons between threshold values and calculated degradation parameters which have already been detailed in the performance analyses sections above. These calculated degradation parameters include the differences between measured and expected values of compressor efficiency, inlet air flow, fuel consumption (heat rate), and overall (turbine section) efficiency. Other degradation parameters, such as those for vibrations, are based on threshold comparisons to measured input data values. There are, however, some degradation parameters which require additional calculations described below.

Expected Inlet Pressure Drop

Using the formulas below, the expected inlet pressure drop must be calculated for use in determining the status of the "Clogged Inlet Filter" fault. First, the measured volumetric air flow ($V_{dot\text{-}meas}$) is calculated using:

$$V_{dot\text{-}meas} = W_{inlet\text{-}meas} / MX_{air} * 19.31 * (T_{inlet} + RKN) / P_{inlet}$$

where MX_{air} is the molecular weight of air and RKN is the conversion factor to convert degrees F to degrees R (459.67).

Next, the rated inlet pressure must be calculated using:

$$P_{inlet\text{-}rated} = P_{baro\text{-}rated} - dP_{inlet\text{-}rated})$$

Then, the rated volumetric air flow ($V_{dot\text{-}rated}$) is calculated using:

$$V_{dot\text{-}rated} = W_{inlet\text{-}rated} / MX_{air} * 19.31 * (T_{rated} + RKN) / P_{inlet\text{-}rated}$$

Finally, the expected inlet pressure drop ($dP_{inlet\text{-}exp}$) can be calculated using:

$$dP_{inlet\text{-}exp} = dP_{inlet\text{-}rated} * V_{dot\text{-}meas} / V_{dot\text{-}rated}$$

Expected Exhaust Temperature

The expected exhaust temperature ($T_{exhst\text{-}exp}$) must be calculated for use in determining the status of the "Clogged Fuel Nozzles", "Cracked Combustor Liner", and "Crossover Tube Failure" faults. For full- or peak-load, an initial value of $T_{exhst\text{-}exp}$ is interpolated using the data entered into the turbine model data file (See sub-section heading “Using the Spreadsheet”). For part-load, the initial value of $T_{exhst\text{-}exp}$ is interpolated using the part-load curves of exhaust temperature versus percent load at different compressor inlet temperatures found in the Partload.dat file. Once an initial value has been found, adjustments are made based on the measured inlet and exhaust pressure drops using the following formula:

$$T_{exhst\text{-}exp} = T_{exhst\text{-}exp} + CFexhstT_{dPinlet} + CFexhstT_{dPexhst}$$

$CFexhstT_{dPinlet}$ and $CFexhstT_{dPexhst}$ are the inlet and exhaust pressure drop effects of exhaust temperature which are entered into the turbine model data file (See sub-section heading "Using the Spreadsheet").

Mission Heat Rate Calculations

If configured to do so, CTPFDM will calculate optional mission heat rate results. Mission heat rate is the total fuel consumed by the turbine divided by the total power output of the turbine over the course of one "mission" (i.e., a complete operating run of a turbine from start-up to shutdown). See sub-section heading "Using the Spreadsheet" for more details.

The running total of fuel consumption for the current mission, MFUEL, is based on the following formula:

$$MFUEL = MFUEL + (((W_{fuel} / 3600) * LHV) * Interval) / 1000000$$

where W_{fuel} is the measured fuel flow, LHV is the default value for the lower heating value of the fuel, and Interval is the user-specified time interval between the CTPFDM calculations (i.e., how often the CTPFDM DLL is called).

The running total of power production for the current mission, MKWH, is based on the following formula:

$$MKWH = MKWH + (KWM * Interval) / 3600$$

where KWM is the measured power and Interval is the user-specified time interval between the CTPFDM calculations.

Once MFUEL and MKWH have been calculated, the mission heat rate, MHR, can be found based on the following formula:

$$MHR = (MFUEL / MKWH) * 1000000$$

Heat Balance Calculations

Gas Turbine Model Definitions

A schematic of the combustion turbine model used in the CT performance calculations is shown in Figure 3-18. The model, based on the original version of EPRI's EfficiencyMap software, is an approximate characterization to the complex details of an actual CT. Nevertheless, the model contains the features of cooling flows (air splits), generator losses, compressor extractions, and atomization air for liquid fuels. The first stage turbine nozzle is shown separately in Figure 3-18 because of its importance to the firing temperature calculations.

The air splits are treated as a fraction of the compressor inlet air flow. They are the atomization air or liquid fuel units (B3), rotor cooling air (B4), first stage nozzle cooling air (B5), and wheelspace cooling air (B6). The total combustor by-pass air fraction is B1 where:

$$B1 = B4 + B5 + B6$$ **Equation A-1**

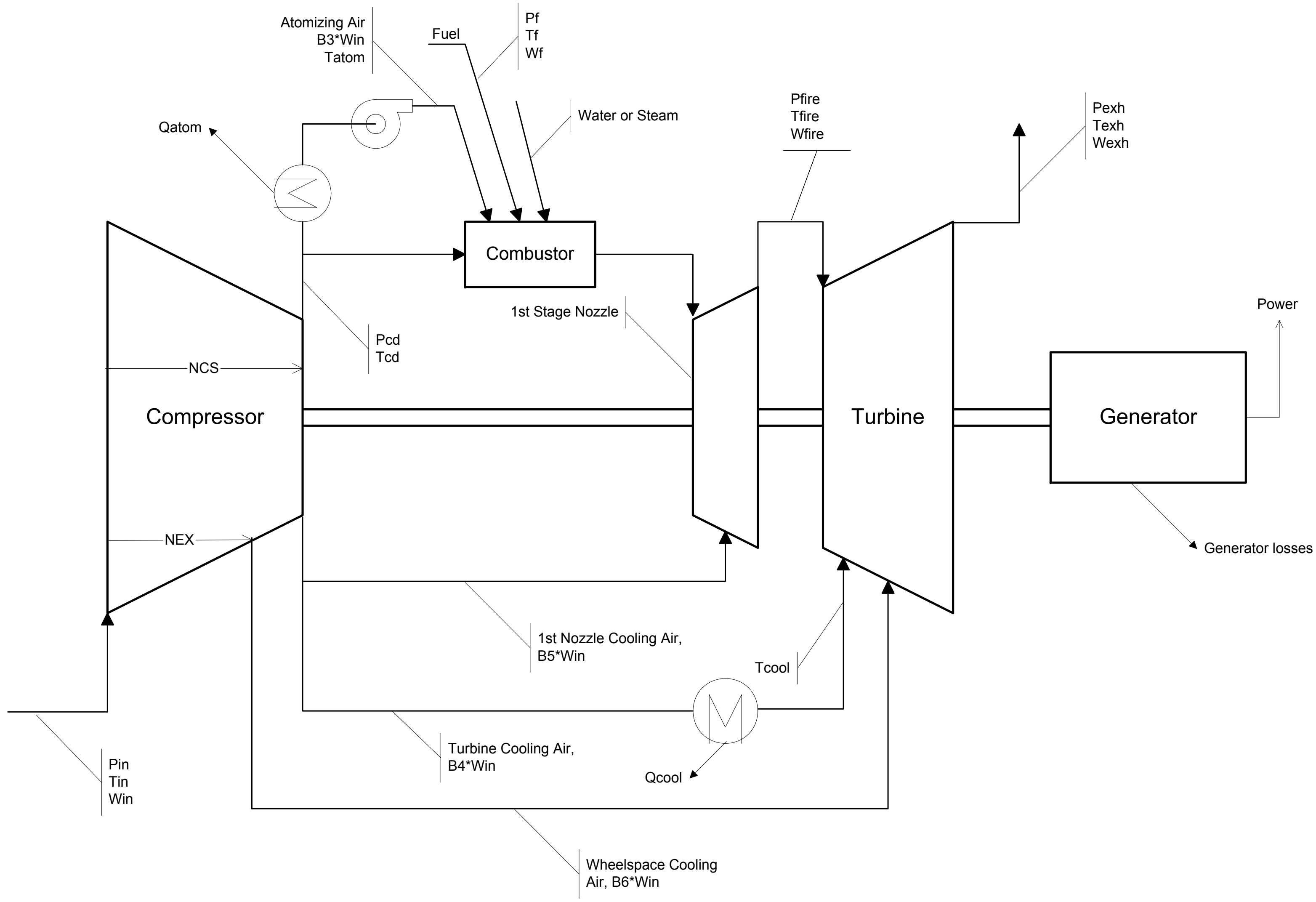


Figure 3-18
Schematic Diagram of Combustion Turbine Model Flow Definitions

The following definitions are used in the heat balance and firing temperature calculations:

Flows

- WIN - Compressor inlet air flow
- WF - Fuel flow
- WATOM - Atomization air flow: WATOM = B3 ∗ WIN
- WWC - Wheelspace cooling air flow: WWC = B6 ∗ WIN
- WCOOL - Rotor cooling air flow: WCOOL = B4 ∗ WIN
- WNOZ – 1st nozzle cooling air flow: WNOZ = B5 * WIN
- WCI - Combustor inlet air flow: WCI = (1 − B1 − B3) ∗ WIN
- WW - Water injection flow
- WS - Steam injection flow
- WCO - Combustor outlet flow: WCO = WCI + WF + WATOM + WW + WS
- WFIRE - Turbine inlet flow: WFIRE = WCO + WNOZ
- WEX - Exhaust flow: WEX = WIN + WF + WW + WS

Pressures

- PATM - Ambient pressure
- PIN - Compressor inlet pressure
- IPD - Inlet pressure drop: IPD = PATM − PIN
- PCD - Compressor discharge pressure
- DPCOMB - Pressure drop from compressor discharge to turbine
- PFIRE - Turbine inlet pressure: PFIRE = PCD ∗ (1 − DPCOMB)
- EPD - Exhaust duct pressure drop
- PEX - Exhaust pressure: PEX = PATM + EPD

Temperatures

- TIN - Compressor inlet air temperature
- TCD - Compressor discharge air temperature
- TCI - Combustor inlet air temperature: TCI = TCD
- TCO - Combustor outlet gas temperature
- TFIRE - Turbine inlet temperature

- TATOM - Atomization air temperature
- TCOOL - Rotor cooling air temperature when externally cool, TCOOL = TCD if not externally cooled
- TEX - Exhaust temperature
- TF - Fuel temperature
- TREF - Fuel reference temperature for LHV
- TWI - Temperature of water at injection
- TSI - Temperature of steam at injection

Enthalpies

- HIN - Compressor inlet air enthalpy
- HCD - Compressor discharge air enthalpy
- HWC - Wheelspace cooling air enthalpy: $HWC = HIN + NEXC / NCS * (HCD - HIN)$
- HCI - Combustor inlet enthalpy: $HCI = HCD$
- HCO - Combustor outlet enthalpy
- HATOM - Atomization air enthalpy
- HEX - Exhaust gas enthalpy
- H1REF - Enthalpy of air at TREF
- H2REF - Enthalpy of combustion products at TREF
- HF - Enthalpy of fuel
- HFR - Enthalpy of fuel at TREF
- HWI - Enthalpy of injection water
- HSI - Enthalpy of injection steam
- HWR - Enthalpy of injection water at TREF
- HSR - Enthalpy of injection steam at TREF
- HWV - Heat of vaporization of injection water

Combustor Heat Balance

Before calculating an energy balance around the entire CT, it is useful to calculate a heat balance around the combustor and use that to define the net heat input to the gas stream, QC.

The combustor heat balance is:

$$WCI * (HCD - H1REF) + WF * (HF - HFR) + WF * LHV * NCOMB + WW * (HWI - HWV - HWR) + WS * (HIS - HWR) + WATOM * (HATOM - H1REF) = (WCI + WATOM + WF + WW + WS) * (HCO - H2REF)$$ **Equation A-2**

The net heat input to the gas stream is:

$$QC = WCI * (HCO - HCD) + WF * (HCO - HF) + WATOM * (HCO - HATOM) + WS * (HCO - HSI) + WW * (HCO - HWI + HWV)$$ **Equation A-3**

Combining Equations A-2 and A-3 gives:

$$QC = (WCI + WATOM) * (H2REF - H1REF) + WF * (H2REF - HFR) + WF * LHV * NCOMB + WW * (H2REF - HWR) + WS * (H2REF - HWR)$$ **Equation A-4**

The net heat release provides an adjustment to account for the reference temperature at which the LHV is determined.

Using Equation A-4, the heat input, QC, to the cycle is readily calculated from the fuel flow and the cycle model parameters.

Combustion Turbine Heat Balance

The overall CT heat balance is:

$$WIN * HIN + QC + WF * HF + WW * (HWI - HWV) + WS * (HSI) = WEX * HEX + POWER / NGEN + WCOOL * (HCD - HCOOL) + WATOM * (HCD - HATOM)$$ **Equation A-5**

Generator cooling, lubrication cooling, and convective and radiative cooling losses are treated by means of a combined generator and mechanical efficiency, NGEN, where NGEN is defined such that the output shaft power is equal to the electrical power at the generator terminals divided by NGEN. NGEN is specified in the Measured Defaults section of the **Default Data** worksheet.

Recognizing that WEX = WIN + WW + WS + WF, Equation A-5 can be rewritten as:

$$QC + WF * HF + WW * (HWI - HWV) + WS * (HSI) - (WW + WS + WF) * HEX - POWER / NGEN - WCOOL * (HCD - HCOOL) - WATOM * (HCD - HATOM) = WIN * (HEX - HIN)$$ **Equation A-6**

Equation A-6 has to be solved by iteration because HEX is a function of the composition of the exhaust gas, which in turn is a function of WIN. The approach taken in CTPFDM is to use the expected inlet air flow value as the first guess for WIN and then iterate until Equation A-6 is solved.

Firing Temperature via Combustor Energy Balance

Once WIN is known, the enthalpy of the combustor outlet flow, HCO, can be found from Equation A-3. The enthalpy HFIRE is then found by the dilution calculation, mixing the gas exiting the combustor with the first stage nozzle cooling air:

$$WCO * HCO + WNOZ*HCD = WFIRE * HFIRE \quad \textbf{Equation A-7}$$

The firing temperature, TFIRE, is then found using thermodynamic property functions that determining enthalpy as function of temperature, pressure and gas composition and iterating on temperature until the enthalpy matches HFIRE.

Firing Temperature via Turbine Section Energy Balance

The energy balance on the turbine section is:

$$\text{Turbine Power} = \text{Compressor Power} + \text{Output Shaft Power}$$

or:

$$TPW = CPW + PW / NGEN \quad \textbf{Equation A-8}$$

The turbine power is:

$$TPW = WFIRE * HFIRE + WCOOL * HCOOL + WWC * HEXC - WEX * HEX \quad \textbf{Equation A-9}$$

The compressor power is:

$$CPW = WIN * (HCD - HIN) * FC \quad \textbf{Equation A-10}$$

where FC accounts for the extraction flow:

$$FC = 1 - B6 * (HCD - HEXC) / (HCD - HIN) \quad \textbf{Equation A-11}$$

Combining Equations A-9, A-10, and A-11 yields the following expression for HFIRE:

$$HFIRE = [WIN * (HCD - HIN) * FC + PW / NGEN - WCOOL * HCOOL - WWC * HEXC + WEX * HEX] / WFIRE \quad \textbf{Equation A-12}$$

The firing temperature, TFIRE, can then be found from HFIRE using the thermodynamic gas property functions.

In theory, the value for TFIRE found via the turbine section energy balance should be the same as the firing temperature determined via the combustor energy balance. However, since the two methods rely on different measurements to calculate TFIRE, the results may differ due to inaccuracies in the measurements. In particular, the combustor energy balance method is quite sensitive to the fuel flow and fuel LHV. Errors in those two measurements will have a bigger impact on TFIRE calculated via the combustor energy balance than the TFIRE calculated by the turbine section energy balance.

4

COMBINED CYCLE PERFORMANCE AND FAULT DIAGNOSTIC MODULE (CCPFDM), VERSION 1.2

Introduction

The *Combined Cycle Performance and Fault Diagnostic Module* (CCPFDM) spreadsheet provides *Combined Cycle* (CC) plant operators with a low-cost, easy-to-install, easy-to-use program for monitoring and diagnosing the condition of the plant and determining the benefits of maintenance actions. It was developed to be a simple, add-on program to the *Combustion Turbine Performance and Fault Diagnostic Module* (CTPFDM) spreadsheet (Ref. 1), which does not provide any information on the performance of combined cycle power plants other than that of the gas turbine(s). This Section describes the CCPFDM.

The CCPFDM spreadsheet can be used in either an "off-line" fashion through manual entry of data or "on-line" through automatic real-time data input using links to the PI data historian supplied by OSI Software, Inc.

Important features of the CCPFDM spreadsheet include:

- Operates as a spreadsheet with macros in Microsoft's Excel (version 97 or later)
- Runs under the Windows NT/95/98/2000 operating systems
- Comes with an installation routine developed using InstallShield
- Capable of monitoring combined cycle units while simultaneously monitoring multiple combustion turbines with CTPDM
- Capable of monitoring one *Combustion Turbine* (CT)/one *Steam Turbine* (ST) and two CT/one ST combined cycle configurations (for two CT configurations, both CTs must be identical)
- Capable of predicting performance at base-load and part-load operation
- Capable of detecting fault conditions in critical components of a combined cycle plant
- Capable of handling English or metric (SI) units
- Capable of importing CC data from and results to a PI database via OSI's PI DataLink Excel Add-In

Background

When examining the performance of a combined cycle, there are four major pieces of the plant that could impact performance: the combustion turbine (CT), the *Heat Recovery Steam Generator* (HRSG), the steam turbine (ST), and the *condenser cooling water system* (COND). Degradation in the performance of any one of these pieces will result in a decrease in the output of the steam turbine. Consequently, a drop in the expected output of the ST may not indicate a problem with the physical condition of the steam turbine. A comprehensive performance monitoring program for a combined cycle would be able to determine the ultimate source of the decrease in steam turbine output, whether it be due to HRSG or condenser fouling or CT compressor performance, or damage to the ST blades. This is the type of information one can obtain from GE's EfficiencyMap™ or one of its competitors.

On the other hand, the performance of a combined cycle is also influenced by factors external to the equipment, such as the ambient temperature and the condenser cooling water temperature. If an operator could compare actual plant performance to the plant performance expected for the current set of external conditions, he or she would then at least know whether the plant was operating near its expected performance on an overall basis (i.e., overall output and overall heat rate). If it was not, then more detailed analysis could be performed off-line to determine the source of the degradation. This is the approach EPRI has used for CCPFDM.

To obtain the overall expected performance, CCPFDM uses the approach used by Siemens Westinghouse for predicting the expected performance of a combined cycle power plant (Ref. 2). An overview of this approach is attached as an appendix to this manual. In general, Siemens Westinghouse uses a series of correction curves to account for the change in total plant output, heat rate, and steam turbine exhaust flow. The latter is then used to determine what the steam turbine exhaust pressure should be for the measured dry bulb or wet bulb conditions. A final correction is then made for any deviation between the calculated expected steam turbine exhaust pressure and the design assumption (typically, 2" Hga).

If correction curves from the OEM similar to those in Ref. 2 are not available, the plant owner (or others) could derive the correction curves by creating a model of the plant using combined cycle simulation software such as GE's GateCycle™ and executing a series of runs to simulate the impact of changes in ambient conditions. Development of such a model could cost $10,000 to $20,000, depending on the complexity of the plant.

The CCPFDM performance calculation output includes parameters which indicate the magnitude of degradation of the CT(s), HRSG, ST, and COND components of the plant. These diagnostic parameters are displayed in an easy-to-read table that allows the user to see at a glance potential problems, or faults, in critical CC components as they develop.

What's New in Version 1.2

This version of CCPFDM has been upgraded to include diagnostic algorithms to detect several combined cycle plant faults. As part of this upgrade, a new worksheet has been added to the

CCPFDM spreadsheet for user input of diagnostic parameter threshold values. Also, the existing Report worksheet has been modified to include a new diagnostics section.

Program Overview

CCPFDM carries out four main functions when a performance calculation is requested: data checking, measured performance, expected performance, and fault diagnostics.

The data checking function entails an evaluation of whether a complete set of input data is available and, if so, whether the data values make physical sense.

The actual performance calculations are based on key measurements from the plant instrumentation. Standard thermodynamic engineering formulas are used to derive key performance parameters such as heat rate.

The expected performance calculations are based on the manufacturer's expected performance data.

Fault diagnostics are based on rules developed by Dr. Meherwan Boyce. The diagnostic calculations result in logical "flags" which are evaluated for the four major pieces of the plant and used to alert the user to potentially excessive CC performance degradation.

The CCPFDM DLL requires two types of inputs: CC model data files and measured data files. The CC model data define the expected performance of the plant including the impact of changes in ambient conditions. The files containing these data are termed "static data files", as they will be changed infrequently, if ever. The files containing the measured data are called "dynamic data files" as they are updated each time performance calculations are requested and describe the operating condition of the plant at one moment in time.

All of the dynamic data files and some of the static files are accessed by the CCPFDM spreadsheet and displayed in the various worksheets of the spreadsheet.

The flowchart shown in Figure 4-1 depicts the interactions of the CCPFDM DLL with the CCPFDM spreadsheet (CCPFDM.xls). Measurements from the plant instrumentation are sent to the DCS (arrow 1). The user takes the data from the DCS and enters it in CCPFDM.xls (arrow 2). Then the user starts the calculation macro and the CCPFDM.xls writes the input data to ASCII files (arrow 3), then calls the CCPFDM DLL (arrow 4). The CCPFDM DLL reads the ASCII input files (arrow 5), performs the calculations, and then writes the results to ASCII output files (arrow 6). The CCPFDM.xls then reads the output files and stores the data for display and trending (arrow 7).

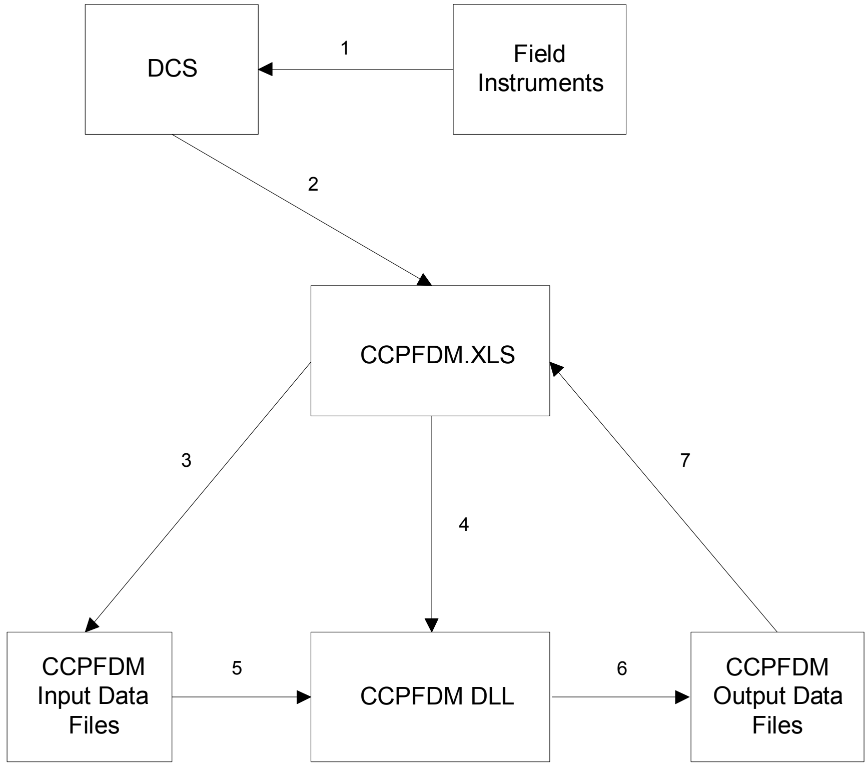


Figure 4-1
CCPFDM Software Functional Flowchart Showing Interaction Between the CCPFDM DLL, the CCPFDM.xls Excel Spreadsheet, and the Plant Instrumentation

Installation

Hardware and Software Requirements

Table 4-1 lists the minimum hardware requirements for running the CCPFDM spreadsheet. In addition, the PC must have Microsoft Excel 97 (or later) installed. Finally, if the user wishes to view an electronic version of this Users Manual, Microsoft Word 97 (or later) must be installed on the PC. Acrobat Reader is available free of charge on the Adobe Systems Web site at http://www.adobe.com.

Table 4-1
Minimum Hardware Requirements

Hardware	Minimum Requirement	Recommended
Processor	333 MHz Pentium III	Same
Operating System	Windows 95/98/2000/NT 4.0	Same
RAM	256 MB	512 MB
Available Hard Disk Space	10 MB	>20 MB

How to Install

1. Start Windows 95, 98, 2000 or NT. Make sure that no other application is running while CCPFDM is being installed.
2. The CCPFDM installation disk(s) may consist of either a single CD or multiple 3½-inch diskettes. Insert the CCPFDM installation CD or 1st diskette into the appropriate disk drive of your computer. For diskettes, this is usually drive A:\.
3. Select the "**Start**" button from the taskbar at the bottom of the screen and then "**Run**…". The "**Run**" dialog box appears.
4. For diskettes, type "A:\Setup.exe" in the Command Line text box. If installing from a CD or diskette drive other than A:\, substitute the appropriate letter for that source drive.
5. Select "**OK**". A welcome dialog box appears.
6. Select "**Next**" to go to the next screen.
7. The setup routine will then search for the path name of the Microsoft Excel executable file, Excel.exe. If it finds it, a message box appears and asks where to install the CCPFDM files (C:\Program Files\CCPFDM is the default path). If desired, change the default name and destination of the CCPFDM directory (folder).
8. If the setup routine does not find the path to Excel.exe, a message box will appear stating that "Setup could not find an installed version of Excel." If you are certain that Excel is available on your PC, click the "**OK**" button and continue with the setup (the message box asking where to install the CCPFDM files will appear). After the setup routine is completed, it will be necessary to modify the "shortcut" to CCPFDM (see details at the end of this sub-section).

   The installation program will then install the program in the specified directory. If installing from diskettes, you will be prompted to change disks. The installation program will also add CCPFDM to the "**Programs**" menu option found under the "**Start**" button in the taskbar at the bottom of the screen. When you receive an on-screen message that the installation is complete, remove the CD or final diskette from its drive.

9. To start the CCPFDM program, select the "**Start**" button from the taskbar, select the "**Programs**" submenu, click on **CCPFDM,** then click on the Excel spreadsheet icon labeled **CCPFDM**. Excel will start and load the CCPFDM.xls spreadsheet. A dialog box will appear stating that the spreadsheet contains macros and asking if you want to enable or disable the macros (see Figure 4-2). Click "**Enable Macros**" and the spreadsheet will finish loading.

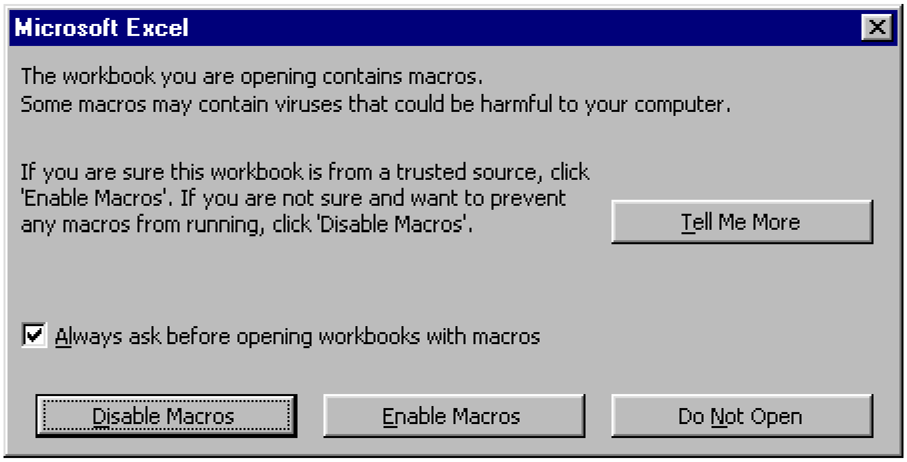


Figure 4-2
Example of Dialog Box that Appears Each Time the CCPFDM.xls Spreadsheet Is Loaded

Setup Cannot Find Excel

If you encountered the message during the installation that the setup routine could not find an installed version of Excel, but you know Excel is installed, you will have to modify the shortcut to CCPFDM to include the path to the Excel.exe file. To do this, first find the path to Excel.exe. Select the "Start" button from the taskbar, select the "Programs" submenu, then highlight Microsoft Excel and right-click with the mouse. A menu will appear and you should click on Properties. The Excel Properties window will appear. Highlight all of the text contained in the Target field under the Shortcut tab. The highlighted text is the path to Excel.exe. Copy it by simultaneously hitting the Control and C keys (Ctrl+C). Now close the Excel Properties window by clicking the "Cancel" button.

Now open the CCPFDM properties window by doing the following: select the "Start" button from the taskbar, select the "Programs" submenu, click on CCPFDM, then highlight the Excel spreadsheet icon labeled CCPFDM and right-click with the mouse. A menu will appear and you should click on Properties. The CCPFDM Properties window will appear. Place the cursor at the beginning of the Target field under the Shortcut tab by first clicking anywhere within the field and then hitting the Home key. Now paste in the Excel.exe path information by simultaneously hitting the Control and V keys (Ctrl+V). Next make sure there is a space between the end of the Excel.exe path and the beginning of the CCPFDM.xls path information by hitting the space key once. The text in the field should now look something like this:

"C:\Program Files\Microsoft Office\Office\EXCEL.EXE" "C:\Program Files\CCPFDM\CCPFDM.xls" /p "C:\Program Files\CCPFDM" /e

(The above text assumes the default directory was chosen for the CCPFDM files.)

Save the changes and close the CCPFDM Properties window by clicking the "OK" button. You are now ready to start CCPFDM (see step 8 above).

How to Uninstall

1. From the Windows 95, 98, 2000 or NT desktop, click on the "**My Computer**" icon to open the "My Computer" window.
2. From the "My Computer" window, click on the "**Control Panel**" icon to open the "Control Panel" window.
3. From the "Control Panel" window, click on the "**Add/Remove Programs**" icon to open the "Add/Remove Programs" window.
4. Select the CCPFDM software from the list of currently installed programs, then click the "**Add/Remove**" button ("**Change/Remove**" button in Windows 2000).
5. A message box will appear asking for confirmation of the removal of the program and its components. If you are certain that you want to uninstall CCPFDM, click the "**Yes**" button and CCPFDM will be removed.

CCPFDM File Structure

The CCPFDM.xls spreadsheet is automatically installed in the directory (folder) specified by the user during the InstallShield installation routine (the default directory is C:\Program Files\CCPFDM). In addition to the spreadsheet file, the installation program creates several other files and sub-directories. These files and sub-directories are described in this sub-section.

Main CCPFDM Directory

The files installed in the main CCPFDM directory (i.e., "C:\Program Files\CCPFDM" or the user-specified replacement) are:

- CCPFDM.xls, the CCPFDM Excel spreadsheet
- CCPFDM.dll, the CCPFDM dynamic link library
- Perfunit.dat, a text file containing the path of the data files for the combined cycle unit to be monitored
- README.TXT, a text file directing the user to find help in either the *CCPFDM Quick Guide to Getting Started* or the *CCPFDM Spreadsheet User's Manual*
- Uninst.isu, a reference file used if CCPFDM is uninstalled via the Windows Control Panel "Add/Remove Programs" routine

Files for Monitoring Multiple Combined Cycle Plants

The CCPFDM.xls spreadsheet is capable of tracking the performance of multiple combined cycle (CC) plants. In CCPFDM.xls, each CC is called a "unit". Using the CCPFDM spreadsheet as it is installed from the installation disks, only one unit can be monitored at a time, but the user can switch from one unit to another with the click of a button. It is possible to simultaneously monitor multiple CCs, but this requires that the user set up multiple instances of the CCPFDM software. Details of how to accomplish this are provided later in this sub-section.

Since each CC may be a different make or model, each unit must have its own CC model data files, which define the expected performance of the engine. Similarly, each CC will have different operating results, so each unit must have its own results files.

To organize the various data and results files, each CC unit is given its own sub-directory under the main CCPFDM directory. The name of the sub-directory corresponds to the name of the unit as defined by the user when the unit is created (see sub-section heading “Tutorial” for an example of how to create a new unit). The names and structure of the files in each of the unit sub-directories are identical, but the contents of the files will vary from unit to unit. The names of the files in each unit sub-directory are listed in Table 4-2.

Table 4-2
List of Files in Each CC Unit Sub-Directory

CC Model Files	Performance Data Input Files	CCPFDM DLL Output Files	CCPFDM.xls Results File
CCmodel.dat Unitsop.dat Scmpdflt.dat Dpthresh.dat	Scmpinp.dat	Scmppout.dat Scmpprep.dat Spperr.inf (only generated if errors are encountered) Sppdone.inf	Results.csv

CC Reference Model Files

In addition to the individual unit sub-directories, the CCPFDM file system also has a separate "Reference Models" sub-directory, which contains CC model data files that can be copied to create new units. The CCPFDM spreadsheet comes with a built-in CC model for a "2-on-1" combined cycle plant with two Siemens Westinghouse Power Corp. (SWPC) 501F engines. In addition to the built-in model, any CC models that the user copies will also be stored in the Reference Models sub-directory. Note that the reference CC model files are named according to the name supplied by the user when copying a CC model.

Users Manual

This Users Manual, in the form of an Adobe Acrobat portable document format (PDF) file, is also installed in the Help sub-directory of the main CCPFDM directory.File Directory Diagram

Figure 4-3 contains a schematic diagram of the CCPFDM spreadsheet file directory structure. It assumes that "C:\Program Files\CCPFDM" was specified as the "install to" directory for CCPFDM.

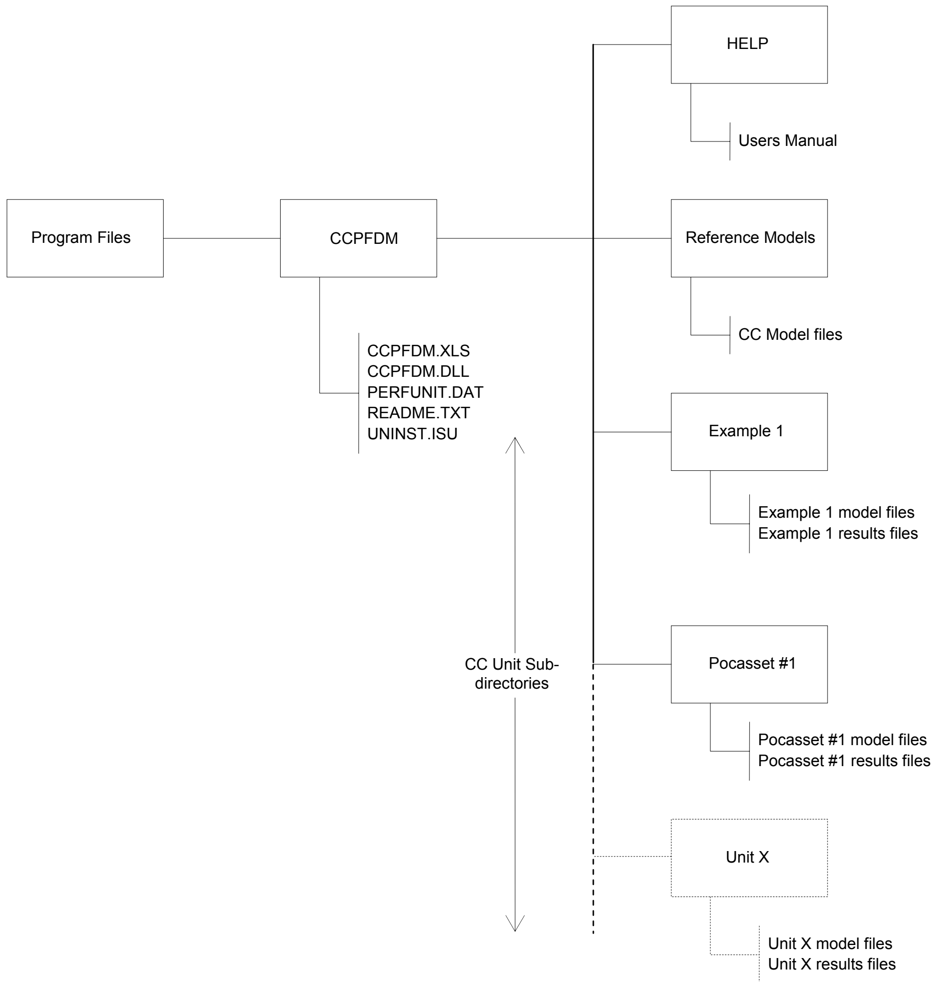


Figure 4-3
Schematic Diagram of the File Directory of CCPFDM

Monitoring Multiple Combined Cycle Plants Simultaneously

As stated at the beginning of this sub-section, using the CCPFDM spreadsheet as it is initially installed from the installation disks allows the monitoring of only one unit at a time. However, it is possible to simultaneously monitor multiple CCs by setting up multiple instances of the CCPFDM software. This can be accomplished either by installing the software multiple times or by simply making multiple copies of the software that was initially installed. As Microsoft Windows requires unique directory (folder) and file names, each additional copy of the software requires a different name. For example, there could be two copies of the software, one installed to a "C:\Program Files\CCPFDM Unit 1" directory and another copied to a "C:\Program Files\CCPFDM Unit 2" directory. Further details on simultaneous monitoring of multiple units can be found in sub-section heading “Using the Spreadsheet”.

Using the Spreadsheet

The CCPFDM.xls spreadsheet consists of a series of worksheets that the user can access by clicking on the tabs located at the bottom of the Excel screen. This sub-section describes the contents of each of the worksheets and explains how to execute the various macros that are built into the spreadsheet. The descriptions assume that the user is already familiar with Excel. If the user is not familiar with Excel, it is recommended that they first refer to the Excel User's Guide or the Excel On-Line Help function accessible via the "Help" menu at the top of the Excel screen.

Launching a CCPFDM Spreadsheet

Whenever a CCPFDM spreadsheet is launched, the menus containing the combined cycle units and reference models will be updated if the workbook was not saved before creating or removing units or models. In addition, the spin button for the "Display Previous CCPFDM Results" feature explained below will be updated to include any new results that were saved into the Results.csv file if the workbook was not saved after saving new results.

If the spreadsheet data is different from the saved data (this could occur if a unit is deleted without saving the spreadsheet), there will be a message box asking the user if they want to import saved data or leave the spreadsheet data as it is. Normally, you should choose to import the saved data.

Main Menu Worksheet

In this worksheet, the user can create a new unit, switch to another unit, remove a unit, or copy/delete CC models. The currently existing units and models, and their respective units of measurement, are displayed at the right-hand side of the spreadsheet.

It is important to remember that all units referred to and operated on in the Main Menu worksheet can only be monitored one at a time in the active workbook (i.e., the currently-displayed CCPFDM spreadsheet). Dealing with multiple units simultaneously requires that multiple instances of the CCPFDM spreadsheet are installed and running. More information on the simultaneous running of CCPFDM for multiple units is provided in later sub-sections.

Current Unit

The current unit is displayed at the top left-hand corner of the worksheet. It is also displayed at the top of several other worksheets. To change the current unit, select the "Switch Unit" option explained below.

CCPFDM Directory

The directory where the CCPFDM.xls, CCPFDM.dll, etc. files are located (i.e., the directory into which the software was installed or copied) is displayed at the top of the Main Menu worksheet. The name of the directory displayed will always conform to the current directory of the active workbook, so the user does not have to change it.

Switch Unit

To switch from the current unit to another unit, first select the name of the unit you want to switch to in the pull-down menu. Then click the button labeled "Switch Unit". A macro will then be executed that copies all of the data files associated with the new unit into the appropriate places in the spreadsheet. A message appears when the macro is finished. The user can then move to the other worksheets and enter new operating data and execute the CCPFDM performance calculation routine.

Create Unit

To create a new unit, first select the CC model from the pull-down menu directly below the button. Then click the button labeled "Create Unit". The user will then be prompted to enter the name of the unit to be created. Click the "OK" button to create the unit.

Copy Unit

To copy a unit to another unit, first select the source unit and the units of measurement (Current or Switch) option. If you select the "Current" option, the source unit will have the same units of measurement (English or SI) as the target unit. Choose the "Switch" option to use the opposite units of measurement (i.e., English instead of SI) for the target unit. Then enter the name of the target unit. (You cannot use the same name as the source unit for the target unit, but you can overwrite a different unit or you can enter a completely new unit name.) A macro will then copy all of the data files from the sub-directory of the source unit to the sub-directory of the target unit (with the exception of the Results.csv file, which is not copied), and any units of measurement conversions will be carried out.

This function is useful when you want to add a new unit that is identical or nearly identical to an existing unit.

Save Current Data

Click on this button to save the data for the measured defaults, units of measurement, and saved results into the current files of the current unit. The Results.csv file will not be affected by the use of this button.

This feature can also be used to restore a unit that has just been removed accidentally, provided that "Current Unit" is still the one that was removed.

Save Unit As…

Click on this button to save the current unit's data for the CC model, measured defaults and units of measurement into another specified unit. The user will be prompted to enter the name of the unit to save to. The user has the option of overwriting an existing unit. If any of the values for any of the files are out of range, no data will be saved. The Results.csv file in the target unit sub-directory will be deleted when overwriting an existing unit.

This function is similar to the Copy Unit function, except that it uses the data displayed in the spreadsheet rather than the data saved to the data files to create (or overwrite) the data files of another unit.

Remove Unit

To remove an existing unit, first select the unit to be removed from the pull-down menu. Then click the button labeled "Remove Unit". There will be a message box asking the user if they really want to delete the specified unit. Click the "OK" button to delete it or click "Cancel" to cancel the delete operation. If "OK" is specified, a macro will be executed that will delete the sub-directory in which the unit is located and will remove all files in that sub-directory.

Copy CC Model

This button allows the user to copy a CC model from an external data source, such as a floppy disk or a directory other than the default CCPFDM directory. It is assumed that the user knows the units of measurement (English or SI) of the source file. First, select the units of measurement of the source file and the units of the target file, which will be copied to the Reference Models sub-directory. The user will then be prompted to enter the source directory and to enter the source file name. Then, the user will be prompted to enter the name the model will be given in the Reference Model sub-directory.

Remove CC Model

To remove an existing model, first select the model to be removed in the pull-down menu. Then click the button labeled "Remove CC Model". There will be a message box asking the user if they really want to delete the specified model. Click the "OK" button to delete it or click "Cancel" to cancel the delete operation. If "OK" is specified, a macro will be executed that will delete the sub-directory in which the model is located and will remove all files in that sub-directory.

Display Previous CCPFDM Results

With this button, you can display the results of saved previous runs of CCPFDM for the current unit. Use the spin button to select which results to display. The run number, date, and time will be displayed in the cells just above the spin button. To see the results, click the button labeled "Display Previous CCPFDM Results" and the results (and errors if they exist) will be displayed on the Report worksheet. If there are no saved results, "No Saved Results" will be displayed in the cell just below the button and this feature cannot be used.

Default Data Worksheet

This worksheet is used to import or modify the measured default data contained in the Scmpdflt.dat file.

Get Defaults

To import the data from the measured defaults file, click the button labeled "Get Defaults". The data and the units of measurement of the data (depending on the units used, English or SI) will be displayed in the respective cells and pull-down menus.

Save Defaults

To save new data into the measured defaults file, first input the data into the appropriate cells and select the units of measurement in the pull-down menus, then click the button labeled "Save Defaults". The values contained in the cells will be converted to the units expected by CCPFDM, depending on which options are selected from the unit pull-down menus and whether English or SI units are used. If any values are out of range, an error message will be displayed, the out-of-range cell(s) will be selected, and no data will be saved. If all values are within the expected range, then the values (in the standard CCPFDM units of measurement) will be exported to the file. Note that no changes will be made to the actual file until the "Save Defaults" button is clicked.

If the user makes changes to the data and wishes to reset the values to what they were previously, this can be done using the "Get Defaults" button as long as the "Save Defaults" button has not been clicked.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter:

Barometric Pressure	24-32 in. Hga, 0.81-1.08 bara, 610-812 mm Hga, 11.7-15.7 psia
Ambient Relative Humidity	0-100 %
CT Inlet Pressure Drop	0-20 in. H2O, 0-50 mbar, 0-0.723 psid, 0-5000 Pa
CT Exhaust Pressure Drop	0-30 in. H2O, 0-75 mbar, 0-1.09 psid, 0-7500 Pa
Natural Gas Fuel LHV	1000-35000 Btu/lb, 2326-81420 kJ/kg
Liquid Fuel LHV	1000-35000 Btu/lb, 2326-81420 kJ/kg
ST Exhaust Quality	0.75-1
Measured Plant Auxiliary Load	0-0.1

Help on Inputs

For help on the Default Data worksheet, click the button labeled "Click for Help on Inputs". To return to the Default Data worksheet from the help screen, click the button labeled "Return to Defaults".

Diag. Thresh. Data Worksheet

This worksheet contains the data for the diagnostic parameter threshold values (Dpthresh.dat).

Get Diagnostics

To import the data from the diagnostic parameter threshold file, click the button labeled "Get Diagnostics". The data will be displayed in the respective cells.

Save Diagnostics

To save new data into the file, first input the data into the appropriate cells, then click the button labeled "Save Diagnostics". The values contained in the cells will be exported to the file. Note that no changes will be made to the actual file until the "Save Diagnostics" button is clicked.

If the user makes changes to the data and wishes to reset the values to what they were previously, this can be done using the "Get Diagnostics" button as long as the "Save Diagnostics" button has not been clicked.

Help on Inputs

For help on the Diag. Thresh. Data worksheet inputs, click the button labeled "Click for Help on Inputs". To return to the Diag. Thresh. Data worksheet from the help screen, click the button labeled "Return to Diag. Thresh. Data".

Inputs Worksheet

This worksheet allows the user to define and control the measured input data that will be processed in the CCPFDM.dll file. The user can either enter data manually or use on-line, real-time data via links to third-party data historians such as OSI's PI database. (The user should consult the documentation on the third-party data historian software for instructions on how to link an Excel cell to a specific data point.) In addition to entering the input values, the user can specify the units of measurement to be used for each of the inputs.

Enter Data

Value

In the cells, the user enters the values for the CCPFDM data into the respective cells.

Units of Measurement

The user can select the units of measurement of the input data for each cell. Depending on the unit option selected, the values will be converted into the standard CCPFDM units (English or SI) before the measured inputs are exported.

Acceptable Ranges

The following table shows the acceptable range values that the user can enter for each parameter. Many of these range values are dependent on the saved CC model data.

Barometric Pressure	24-32 in. Hga, 0.81-1.08 bara, 610-812 mm Hga, 11.7-15.7 psia, 810-1105 mbara
Ambient Temperature	−40-140 °F or −40-60 °C
Net Plant Power	0-1.5 * CC model value/1000 MW
Steam Turbine Generator Power	0-CC model value/1000 MW
Steam Turbine Exhaust Flow	0-Maximum CC model value in condenser pressure vs. temperature array
Steam Turbine Exhaust Pressure	0-10 in. Hga, 0-0.34516 bara, 0-254 mm Hga, 0-5.03 psia, 0-345.16 mbara
ST Extraction Steam Flow Rate	0-CC model design ST exhaust flow

ST Extraction Steam Pressure	0-Maximum CC model value in correction factor array
Steam Turbine Exhaust Quality	0.75-1
Measured Plant Auxiliary Load	0-0.1 x CC model value
Comp. Inlet Temp. (CTs 1 & 2)*	Minimum CC model value-Maximum CC model value °F or °C
Inlet Pressure Drop (CTs 1 & 2)	0-Maximum CC model value in correction factor array
Exhaust Press. Drop (CTs 1 & 2)	0-Maximum CC model value in correction factor array
Meas. Generator Power (CTs 1 & 2)	0-CC model value/number of CTs
Part-Load Level (CTs 1 & 2)	0-110 % of full load
Gas Fuel Flow (CTs 1 & 2)	0-500 lb/sec, 0-226.8 kg/sec, 0-1800000 lb/hr, 0-816466 kg/hr, 0-30000 lb/min, 0-13608 kg/min
Liquid Fuel Flow (CTs 1 & 2)	0-500 lb/sec, 0-226.8 kg/sec, 0-1800000 lb/hr, 0-816466 kg/hr, 0-30000 lb/min, 0-13608 kg/min
NOx Stm. Inj. Flow Rate (CTs 1 & 2)	0-Gas or Liquid Fuel Flow x maximum CC model steam/fuel ratio
Duct Burn. Gas Fuel Flow (CTs 1 & 2)	0-(CC model Net Plant Heat Rate x 1000000)/(N.G. LHV** x 3600)
Duct Burn. Liq. Fuel Flow (CTs 1 & 2)	0-(CC model Net Plant Heat Rate x 1000000)/(Liquid LHV*** x 3600)
Exp. Generator Power (CTs 1 & 2)	0-CC model value/number of CTs
Condenser Cooling Water Temp.	32-140 °F or 0-60 °C
Ambient Wet Bulb Temperature*	–10 °F or –23 °C-Ambient Dry Bulb Temperature
Relative Humidity	0-100 %

*The minimum and maximum values will be converted to the proper units depending on the option selected in the pull-down menu.

**N.G. LHV—Natural Gas Fuel Lower Heating Value (value saved in Scmpdflt.dat file).

***Liquid LHV—Liquid Fuel Lower Heating Value (value saved in Scmpdflt.dat file).

Since the CCPFDM spreadsheet does not allow the user to create or modify CC model data, individual CC model parameters are not input and are therefore unknown to the spreadsheet. This, in turn, means that any of the range checks listed above, which are dependent on model values, are not performed within the CCPFDM spreadsheet. Instead, those range checks are performed in the CCPFDM DLL calculations.

Help on Inputs

For information on the inputs, click the button labeled "Click for Help on Inputs". From the help screen, click the button labeled "Return to Inputs" to return to the Inputs worksheet.

Run CCPFDM

Click the button labeled "Click to Run CCPFDM" to execute the CCPFDM.dll calculation engine in "off-line" (manual) mode. First, all measured input data currently shown on the worksheet will be exported to the measured input data file. If any of the values are out of range, an error message will be displayed, the out-of-range cell(s) will be selected, no data will be saved, and CCPFDM will not run. If all values are within the expected range, then the CCPFDM DLL will be executed. After the DLL terminates, the results will be imported into the workbook and a Report worksheet will be created. When operating in off-line mode, the user is automatically taken to the Report worksheet.

Note that an error message will be generated if the user attempts to manually run the CCPFDM DLL while the software is in "on-line" mode.

Enable On-Line Operation

Click the toggle button labeled "Click to Enable Online Operation" to place the software in "on-line" (automatic) mode. The toggle button label will immediately change to "Click to Disable Online Operation" and the software will initiate a timer based on the "Online Update Interval" specified in cell "K15" of the worksheet. This timer is specified in the standard time format of hours-minutes-seconds (HH:MM:SS). In cell "K16" will be displayed the next CCPFDM run time. When the specified period of time has elapsed, the real-time data will be retrieved from the OSI PI database and placed into the appropriate cells on the worksheet. Then the worksheet data will be exported to the measured input data file and the CCPFDM DLL will be executed. Note that, while in on-line mode, no range checking is done in the spreadsheet prior to running the DLL. Full error checking is, however, always performed in the DLL calculations. After the DLL terminates, the results will be imported into the workbook, saved to the Results.csv file, and all worksheets related to performance results will be updated. When operating in on-line mode, the user is not automatically taken to the Report worksheet. Rather, the current worksheet (i.e., that being displayed when the DLL is executed) remains displayed.

To disable on-line operation, click the toggle button again (now labeled "Click to Disable Online Operation"). The toggle button label will immediately change back to "Click to Enable Online Operation" and the software will deactivate the on-line timer and return to off-line mode.

See the Detailed Information on Worksheets section later in this sub-section for more details on on-line operation.

Report Worksheet

This worksheet displays all of the results calculated by running the CCPFDM DLL. If there are error messages, these will be displayed at the bottom of the worksheet. If the current unit is modeled for two combustion turbines, the Report worksheet will contain two "Conditions" sections (one for each CT) and performance results for both CTs. Otherwise, the report will display only data for a single CT.

Save Results

When this button is clicked, the results are saved into the Results.csv file. Results will be saved only if the data date and time are later than the last saved results.

Print Report

When this button is clicked, the report will be printed to the default printer.

Chart Worksheets

These charts graph time vs. net plant power, net plant heat rate, steam turbine power, steam turbine exhaust flow, and condenser pressure. Each chart can be printed by clicking the Print button in the Excel toolbar.

Net Plant Power Chart Worksheet

This chart contains data for time vs. net plant power. It is adjusted whenever new results are saved or the current unit is switched.

Net Plant HR Chart Worksheet

This chart contains data for time vs. net plant heat rate. It is adjusted whenever new results are saved or the current unit is switched.

ST Power Chart Worksheet

This chart contains data for time vs. steam turbine power. It is adjusted whenever new results are saved or the current unit is switched.

ST Ex. Flow Chart Worksheet

This chart contains data for time vs. steam turbine exhaust flow. It is adjusted whenever new results are saved or the current unit is switched.

Cond. Press. Chart Worksheet

This chart contains data for time vs. condenser pressure. It is adjusted whenever new results are saved or the current unit is switched.

Detailed Information on Worksheets

Measured Input Data (Inputs Worksheet)

The measured inputs to CCPFDM include up to 35 instrument signals (24 for one CT), plus four signals (two for one CT) from the control system indicating the CT and duct burner fuel type (gas or liquid), and three inputs generated by the user which specify the name of the CT unit and the date and time that the instrument data was captured. Table 4-3 contains a complete list of the measured input data including the "standard" CCPFDM units of measurement. CCPFDM can handle a variety of SI and English units for the inputs, but if the units of measurement do not match the "standard" CCPFDM units, they will be converted internally when the CCPFDM DLL is called. All results will be reported in the standard CCPFDM units.

Table 4-3
Measured Input Data List

Inputs Row #	Description	English Units	SI Units	Comments
3	Unit Name	N/A	N/A	Maximum of 40 characters
4	Date of Data Capture	N/A	N/A	MM-DD-YYYY
5	Time of Data Capture	N/A	N/A	HH:MM:SS
6	Barometric Pressure	" Hga	bara	Default value available
7	Ambient Temperature	°F	°C	
8	Net Plant Power	MW	MW	Optional[1]
9	Steam Turbine Generator Power	MW	MW	Optional[2]
10	Steam Turbine Exhaust Flow	lb/sec	kg/sec	
11	Steam Turbine Exhaust Pressure	“ Hga	mbara	
12	ST Extract. Steam Flow Rate	lb/sec	kg/sec	Required only for extraction STs
13	ST Extraction Steam Pressure	psig	barg	Required only for extraction STs
14	Steam Turbine Exhaust Quality	fraction	fraction	Default value available
15	Measured Plant Auxiliary Load	MW	MW	Optional[3]
16	CT #1 Compressor Inlet Temp.	°F	°C	
17	CT #1 Inlet Pressure Drop	" H_2O	mbar	Default value available
18	CT #1 Exhaust Pressure Drop	" H_2O	mbar	Default value available
19	CT #1 Meas. Generator Power	MW	MW	
20	CT #1 Fuel Type Option	N/A	N/A	0 = natural gas fuel, 1 = liquid fuel
21	CT #1 Duct Burn. Fuel Type Op.	N/A	N/A	0 = natural gas fuel, 1 = liquid fuel

Inputs Row #	Description	English Units	SI Units	Comments
22	CT #1 Part-Load Level	%	%	Percent of full load
23	CT #1 Natural Gas Fuel Flow	lb/sec	kg/sec	
24	CT #1 Liquid Fuel Flow	lb/sec	kg/sec	
25	CT #1 NOx Steam Inj. Flow Rate	lb/sec	kg/sec	Required only if steam inj. used
26	CT #1 Duct Burn. N.G. Fuel Flow	lb/sec	kg/sec	
27	CT #1 Duct Burn. Liq. Fuel Flow	lb/sec	kg/sec	
28	CT #1 Expected Generator Power	MW	MW	
29	Condenser Cooling Water Temp.	°F	°C	Requirement depends on condenser cooling option[4]
30	Ambient Wet Bulb Temperature	°F	°C	Requirement depends on condenser cooling option[4]
31	Relative Humidity	%	%	Default value available[5]
32	CT #2 Compressor Inlet Temp.	°F	°C	
33	CT #2 Inlet Pressure Drop	" H_2O	mbar	Default value available
34	CT #2 Exhaust Pressure Drop	" H_2O	mbar	Default value available
35	CT #2 Meas. Generator Power	MW	MW	
36	CT #2 Fuel Type Option	N/A	N/A	0 = natural gas fuel, 1 = liquid fuel
37	CT #2 Duct Burn. Fuel Type Op.	N/A	N/A	0 = natural gas fuel, 1 = liquid fuel
38	CT #2 Part-Load Level	%	%	Percent of full load
39	CT #2 Natural Gas Fuel Flow	lb/sec	kg/sec	
40	CT #2 Liquid Fuel Flow	lb/sec	kg/sec	
41	CT #2 NOx Steam Inj. Flow Rate	lb/sec	kg/sec	
42	CT #2 Duct Burn. N.G. Fuel Flow	lb/sec	kg/sec	
43	CT #2 Duct Burn. Liq. Fuel Flow	lb/sec	kg/sec	
44	CT #2 Expected Generator Power	MW	MW	

[1]If not available (out of range), CCPFDM will calculate net plant power as:

Net Plant Power = CT #1 Measured Generator Power + CT #2 Measured Generator Power + Steam Turbine Generator Power – Measured Plant Auxiliary Load

[2]If not available (out of range), CCPFDM will calculate steam turbine generator power as:

Steam Turbine Generator Power = Net Plant Power – CT #1 Measured Generator Power – CT #2 Measured Generator Power + Measured Plant Auxiliary Load

[3]If not available (out of range), CCPFDM will calculate measured plant auxiliary load as:

Measured Plant Auxiliary Load = Net Plant Power ∗ Measured Plant Auxiliary Load Default Factor

[4]Condenser cooling water temperature is only required if condenser is cooled by once-through water flow from river, lake or ocean (rCFlag = 3 in Ccmodel.dat). Wet bulb temperature is only required if the condenser cooling water is supplied by an evaporative cooling tower is present (rCFlag = 1 in Ccmodel.dat).

[5]Only required if evaporative cooling tower is present (rCFlag = 1 in Ccmodel.dat) and wet bulb temperature is not available.

Discussion on Measured Input Data Requirements

If the plant has a wet condenser which is cooled by water supplied by an evaporative cooling tower, then the program needs the ambient wet bulb temperature to predict what the condenser back pressure will be. If a wet bulb temperature is not available, the program will calculate the wet bulb temperature based on the relative humidity and the ambient dry bulb temperature. If values for both the wet bulb temperature and the relative humidity are supplied, the program will use the wet bulb value and ignore the relative humidity value.

CCPFDM can handle dual fuel operation on an "either-or" basis, but it can not handle simultaneous operation on a mixture of gas and liquid fuel. The program will first look at the flag defining the type of fuel in use, and then read the value for flow for that fuel. The other fuel flow signal will be ignored.

Default Measured Input Data (Default Data Worksheet)

For some inputs, CCPFDM allows the substitution of "default" values in case on-line measurements are not available. Default values can be entered for the following measurements:

- Barometric Pressure
- Ambient Relative Humidity
- CT Inlet Pressure Drop
- CT Exhaust Pressure Drop
- Steam Turbine Exhaust Quality
- Measured Plant Auxiliary Load

In addition to these default measurements, data are supplied for several other parameters that may or may not be applicable for a particular CT unit:

- Natural Gas Lower Heating Value (LHV)
- Liquid Fuel LHV

CCPFDM comes with pre-set values for all of the default parameters, but the user should update them if better data are available (e.g., in the case of fuel data, whenever fuel sample lab reports are received).

Diagnostic Threshold Data (Diag. Thresh. Data Worksheet)

The diagnostic threshold data is used to make comparisons to the calculated degradation parameters to determine the current state of the CT(s), HRSG, condenser, and steam turbine, that is, whether the equipment is operating within normal parameters or whether action should be taken to correct an impending fault condition in the equipment.

"Alert" and "Action Required" threshold values should be specified for each of the following:

- Combustion Turbine #1
- Combustion Turbine #2 (if applicable)
- *Heat Recovery Steam Generator* (HRSG)
- Condenser
- Steam Turbine

The diagnostic threshold data values on this worksheet are input as percents. The more negative the value of the calculated parameter, the greater the indicated degradation of the particular piece of equipment. That is, the calculated degradation parameters must be less than or equal to their threshold values to indicate a problem. Logic used in the comparison of user-specified threshold values to calculated values is shown below.

Normal	Calc. Value > User-Spec. "Alert" Thresh. Value
Alert	Calc. Value <= User-Spec. "Alert" Thresh. Value but > User-Spec. "Action Req." Thresh. Value
Action Req.	Calc. Value <= User-Spec. "Action Req." Thresh. Value

Report Worksheet

The Report worksheet is divided into either seven or eight sections, depending upon whether the current unit is comprised of one or two CTs. Each section is described in detail in the following sections.

Ambient Conditions

The first section, labeled "Ambient Conditions" shows the measured input data values for the following ambient parameters:

- Wet Bulb Temperature

- Ambient Temperature
- Relative Humidity
- Barometric Pressure

Combustion Turbine #1 Conditions

The second section, labeled "Combustion Turbine #1 Conditions" shows the measured input data for the first CT which was used in the CCPFDM DLL calculations. The parameters displayed in this section include:

- Compressor Inlet Temperature
- Inlet Pressure Drop
- Exhaust Pressure Drop
- Part-Load Level
- NO_x Steam Injection Flow Rate
- CT Fuel Type
- CT Fuel Flow
- CT Fuel LHV
- Duct Burner Fuel Type
- Duct Burner Fuel Flow
- Duct Burner Fuel LHV

Note that the LHV values displayed are default values.

Combustion Turbine #2 Conditions

The third section, labeled "Combustion Turbine #2 Conditions" shows the measured input data for the second CT (if applicable) which was used in the CCPFDM DLL calculations. If the current unit has only a single CT, this section will not be displayed. When applicable, the parameters displayed in this section include the same parameters shown above for the first CT.

Steam Turbine Conditions

The next section, labeled "Steam Turbine Conditions" shows the measured input data for the steam turbine which was used in the CCPFDM DLL calculations. If the current unit has only a single CT, this section will not be displayed. The parameters displayed in this section include:

- Extraction Steam Flow
- Extraction Steam Pressure

- Exhaust Quality
- Condenser Cooling Water Temperature

Performance

The next section, labeled "Performance", shows measured (or calculated), expected, and relative difference (measured minus expected) values of key indicators of the combine cycle plant's performance. The measured values represent actual performance. The expected values represent the performance that would be expected by the OEM at the current operating condition. In other words, the expected values represent the performance expected for the current fuel type at the measured inlet and exhaust conditions accounting for the measured steam injection rate. Measured, expected, and difference values for the following parameters are included in the output:

- Net Plant Power
- Combustion Turbine #1 Power
- Combustion Turbine #2 Power (if applicable)
- Steam Turbine Power
- Auxiliary Load Power
- Net Plant Heat Rate

Thermal Efficiency

- Steam Turbine Exhaust Flow
- Condenser Pressure

See Appendix A for more information about the performance calculations.

Correction Factors

The next section, labeled "Correction Factors", shows the correction factors for various parameters which were interpolated by the CCPFDM DLL and used to calculate expected power, heat rate, and steam turbine exhaust flow. Correction factors for the following parameters are displayed:

- Compressor Inlet Temperature
- Barometric Pressure
- CT Inlet Pressure Drop
- CT Exhaust Pressure Drop
- Part-Load

- CT Steam Injection
- Duct Burner
- Steam Extraction
- Condenser Pressure

In addition, the steam extraction power loss and condenser pressure power loss are shown (expressed as kW) in this section. See Appendix A for more information about the correction factor calculations.

Diagnostics

The next-to-last section of the report, labeled "Diagnostics", shows the status of either four or five potential CC fault conditions, depending on the plant configuration. The following fault condition parameters are included:

- Combustion Turbine #1
- Combustion Turbine #2 (if applicable)
- *Heat Recovery Steam Generator* (HRSG)
- Condenser
- Steam Turbine

Each fault is listed with its status and the degradation parameter value used to determine each fault condition. The status conditions of "Undetermined", "Normal", "Alert", or "Action Required" are the result of a comparison of the degradation parameter values to the user-specified diagnostic threshold data values. An "Undetermined" status indicates a condition caused by a lack of valid data, that is, there is insufficient data to determine the fault status. A "Normal" status indicates that the particular piece of equipment is operating normally, that is, in a no-fault condition. An "Alert" status indicates a condition which should prompt the operator to be prepared to take action or seek collaborating evidence. An "Action Required" status indicates a condition which should be immediately investigated by the operator. The following color scheme is used to highlight the status of each fault: "Undetermined" - gray, "Normal" - green, "Alert" - yellow, "Action Required" - red.

Error Messages

The final section of the report lists any error messages that were generated during the execution of the CCPFDM DLL.

On-Line vs. Off-Line Operation (Inputs Worksheet)

The CCPFDM spreadsheet, by default, operates in the off-line mode of operation. That is, the user must enter measured input data by hand and manually run the CCPFDM DLL performance calculations for each record (set) of data by clicking on the "Click to Run CCPFDM" button. When the DLL calculations have been completed, control is returned to the spreadsheet, where the user can review the results and decide whether to save the record to the Results.csv file.

Before on-line calculations can be implemented, the user must set up the links to the data historian so that the current values of the various input parameters can be displayed in the spreadsheet in real time. If OSI's PI data historian is being used, and OSI's DataLink software has been installed, the parameters in PI can be displayed in an Excel cell using the "=GetPiVal()" function. The user should consult's OSI's DataLink documentation for more details.

When set up for use with OSI's PI (or another) data historian, the user can initiate on-line operation by clicking the toggle button labeled "Click to Enable Online Operation" which is found on the Inputs worksheet. Doing so initiates a user-specified timer that controls how often the CCPFDM DLL is executed. Then, whenever the specified period of time has elapsed, the current values of the input data are exported to the measured input data file and the CCPFDM DLL is executed. After termination of the DLL, the results are imported into the workbook, saved to the Results.csv file, and all worksheets related to performance results are updated.

While in on-line mode, all worksheets other than the Inputs worksheet and Report worksheet are hidden from the user. This is done to prevent the current unit or default data from being changed while in the middle of an on-line monitoring session.

Table 4-4 shows the important differences between off-line and on-line modes of operation.

Table 4-4
Differences Between Off-Line and On-Line Modes of Operation

Item	Off-Line Operation	On-Line Operation
All Worksheets Available to User	Yes	No
Spreadsheet Range Check Prior to DLL Execution	Yes	No
Worksheet Displayed after DLL Execution	Report	Same as Worksheet Displayed Prior to DLL Execution
Results Saved to Results.csv File	Manually by the User	Automatically by CCPFDM

Simultaneous On-Line Monitoring of Multiple Units

As stated under sub-section heading "Installation", it is possible to simultaneously monitor multiple CTs by setting up multiple instances of the CCPFDM software. This can be accomplished either by installing the software multiple times or by simply making multiple copies of the software that was initially installed. As Microsoft Windows requires unique directory (folder) and file names, each additional copy of the software requires a different name. For example, there could be two copies of the software, one installed to a "C:\Program Files\CCPFDM Unit 1" directory and another copied to a "C:\Program Files\CCPFDM Unit 2" directory.

After installing and setting up the software for the desired number of units, simply launch the CCPFDM spreadsheet for each unit to be monitored and enable on-line operation for each one. Once started, the user should not use the computer for any tasks other than those related to CCPFDM. See the warning below.

Remember to verify the on-line update interval for each unit (located in cell "K15" of the Inputs worksheet) before enabling on-line operation. If the user wishes to change the update interval, on-line operation must first be disabled. Attempting to change the update interval while in on-line operation will result in the display of a warning message when the next scheduled process time is encountered. Upon confirmation of the warning by the user, the update interval will be reset to its previous value.

Warning: When simultaneously monitoring multiple units in on-line mode, it is important that no other programs are running on the computer at the same time. This is especially true of programs which may scan the system disk, such as virus scanning software. **Running other programs during on-line operation may cause CCPFDM data file corruption and/or cause the CCPFDM software to crash!** If CCPFDM should happen to crash during on-line operation, exit the affected spreadsheet and restart. When exiting, you may be prompted whether you want to save the changes you made to the spreadsheet. Click on the "**No**" button.

Tutorial

Lesson 1 - Create a New Unit

CCPFDM can be used to track the performance of multiple combined cycle plants. Each combined cycle (CC) that is to be tracked is called a **Unit** in CCPFDM and each **Unit** must have a unique **Unit Name** such as "Pocasset Unit #1". CCPFDM comes with one pre-installed unit. The unit is named "Example 1" and is based on a "2-on-1" CC plant with two Siemens Westinghouse Power Corporation 501F (W501F) combustion turbines (CTs). This lesson shows how you can create a new unit.

1. Switch to the worksheet labeled "Main Menu" (refer to Microsoft Excel Help menu for information on how to switch from one worksheet to another within an Excel workbook).
2. In cell "B7" (just under the button labeled "Create Unit:"), use the pull-down menu to select the type of unit you want to create. CCPFDM comes with the single W501F CT model. The user may also create new models. Information on how to do this will be covered in Case 3. For this case, you should select the W501F in the pull-down menu.
3. Now click the button in cell "B6" labeled "Create Unit:". A box will appear that says "Enter name of unit:". Type in the following name in the entry box: Pocasset Unit #1. Then click the "OK" button. Excel will now execute a macro that creates a sub-directory named "Pocasset Unit #1" and copy the appropriate files to that sub-directory. When the macro is finished, a message box will appear that reads: "Unit Pocasset Unit #1 created".
4. Click the "OK" button on the message box to make it disappear.

5. If you now select the pull-down menu located in cell "B4" (just under the button labeled "Switch Unit:"), you will see that Pocasset Unit #1 now appears as one of the available units.

Lesson 2 - Switching to another Unit and Getting Results

The act of creating a new Unit (Lesson 1) does not make the new Unit the "active" or "current" unit. In other words, if you move to other worksheets in the workbook, the data they show will not be from Pocasset Unit #1. By default, the first time you start CCPFDM, the program is set to monitor the unit named "Example 1". You can see this by looking at cell "B1" in the worksheet (just to the left of the label "Current Unit:"). The current unit should be "Example 1" (unless you've previously used the "Switch Unit:" button to switch to another Unit). This lesson will show you how to switch to the Pocasset Unit #1 created in Lesson 1 above and then how to calculate the performance of this unit.

1. In the pull-down menu located in cell "B4" (just under the button labeled "Switch Unit:"), select **Pocasset Unit #1** and then click the "Switch Unit:" button in cell "B3". An Excel macro will now import all of the data related to Pocasset Unit #1. This will take several seconds and you will see many different worksheets appear and disappear as the macro moves through all the worksheets. When the macro is finished, a message box will appear that reads "Switched to unit Pocasset Unit #1". Click the "**OK**" button to make the box disappear.
2. To calculate performance, first move to the worksheet labeled "Inputs".
3. You now have to enter the input data into the **Inputs** worksheet in the appropriate places. For inputs that are not measured, you can either estimate values or let the program attempt to use default values, if applicable. Enter the data into the **Inputs** worksheet as shown in Table 4-5.

Table 4-5
Data to Be Entered in "Inputs" Worksheet

Entry Label	Entered Value	Comments
CC Unit Name	Pocasset Unit #1	
Date Data Taken	11/12/2002	Will be converted to display "November 12, 2002" after it is entered.
Time Data Taken	2:28:15 PM	Will be converted to display "14:28:15" after it is entered.
Barometric Pressure	29.9	Set units pull-down menu option to "in. Hga".
Ambient Temperature	43	Set units pull-down menu option to "deg. F".
Net Plant Power	506	
Steam Turbine Gen. Power	170.2	
Steam Turb. Exhaust Flow	306	Set units pull-down menu option to "lb/sec".
Steam Turb. Exhaust Press.	1.41	Set units pull-down menu option to "in. Hga".
ST Extract. Stm. Flow Rate	45	Set units pull-down menu option to "lb/sec".
ST Extract. Steam Press.	450	Set units pull-down menu option to "psig".
ST Exhaust Quality	0.98	
Meas. Plant Auxiliary Load	6.4	
CT #1 Comp. Inlet Temp.	43	Set units pull-down menu option to "deg. F".
CT #1 Inlet Pressure Drop	3	Set units pull-down menu option to "in. H_2O".
CT #1 Exhaust Press. Drop	10	Set units pull-down menu option to "in. H_2O".
CT #1 Meas. Gen. Power	172.8	
CT #1 Fuel Type	(Click the "Gas" bullet.)	
CT #1 Duct Burn. Fuel Type	(Click the "Gas" bullet.)	
CT #1 Part-Load Level	100	
CT #1 Gas Fuel Flow	21.4	Set units pull-down menu option to "lb/sec".
CT #1 Liquid Fuel Flow	0	
CT #1 NOx Stm. Inj. Fl. Rate	0	
CT #1 D. Burn. Gas Fuel Fl.	0.3	Set units pull-down menu option to "lb/sec".
CT #1 D. Burn. Liq. Fuel Fl.	0	
CT #1 Exp. Generator Power	182.6	
Cond. Cooling Water Temp.	40	Set units pull-down menu option to "deg. F".
Ambient Wet Bulb Temp.	21	Set units pull-down menu option to "deg. F".
Relative Humidity	100	
CT #2 Comp. Inlet Temp.	43	Set units pull-down menu option to "deg. F".
CT #2 Inlet Pressure Drop	2.9	Set units pull-down menu option to "in. H_2O".
CT #2 Exhaust Press. Drop	10.4	Set units pull-down menu option to "in. H_2O".
CT #2 Meas. Gen. Power	169.4	
CT #2 Fuel Type	(Click the "Gas" bullet.)	
CT #2 Duct Burn. Fuel Type	(Click the "Gas" bullet.)	
CT #2 Part-Load Level	100	
CT #2 Gas Fuel Flow	20.7	Set units pull-down menu option to "lb/sec".
CT #2 Liquid Fuel Flow	0	
CT #2 NOx Stm. Inj. Fl. Rate	0	
CT #2 D. Burn. Gas Fuel Fl.	0.3	Set units pull-down menu option to "lb/sec".
CT #2 D. Burn. Liq. Fuel Fl.	0	
CT #2 Exp. Generator Power	182.6	

4. Once the data in the **Inputs** worksheet match the values shown in Table 4-5, the performance calculations can be initiated by clicking on the button labeled "Click to Run CCPFDM". The input data will be sent to the calculation subroutine and once the calculations are complete, the results will be displayed in the worksheet labeled "Report".

When the macro is finished, the display will automatically be switched to the **Report** worksheet.

5. Print the contents of the **Report** worksheet by clicking the button labeled "Print Report". The printed report should be identical to that shown in Figure 4-4.

SCAMP+CC Version 1.1

Combined Cycle Performance Results for Pocasset Unit #1

Data Time:	14:28:15	Data Date:	November 12, 2002

AMBIENT CONDITIONS:

Wet-Bulb Temperature	21.00 deg. F	Relative Humidity	100.00 %
Ambient Temperature	43.00 deg. F	Barometric Pressure	29.90 in. Hga

COMBUSTION TURBINE #1 CONDITIONS:

Inlet Temperature	43.00 deg. F	CT Fuel Type	Natural Gas
Inlet Pressure Drop	3.00 in. H2O	CT Fuel Flow	21.40 lb/sec
Exhaust Pressure Drop	10.00 in. H2O	CT Fuel LHV	21000.00 Btu/lb
Part-Load Level	100.00 %	Duct Burner Fuel Type	Natural Gas
NOx Steam Flow	0.00 lb/sec	Duct Burner Fuel Flow	0.30 lb/sec
		Duct Burner Fuel LHV	21000.00 Btu/lb

COMBUSTION TURBINE #2 CONDITIONS:

Inlet Temperature	43.00 deg. F	CT Fuel Type	Natural Gas
Inlet Pressure Drop	2.90 in. H2O	CT Fuel Flow	20.70 lb/sec
Exhaust Pressure Drop	10.40 in. H2O	CT Fuel LHV	21000.00 Btu/lb
Part-Load Level	100.00 %	Duct Burner Fuel Type	Natural Gas
NOx Steam Flow	0.00 lb/sec	Duct Burner Fuel Flow	0.30 lb/sec
		Duct Burner Fuel LHV	21000.00 Btu/lb

STEAM TURBINE CONDITIONS:

Extraction Flow	45.00 lb/sec	Extraction Pressure	450.00 psig
Exhaust Quality	0.98 fraction	Cooling Water Temp.	40.00 deg. F

PERFORMANCE:	MEASURED	EXPECTED	DIFFERENCE (M-E)
Net Plant Power (MW)	506.00	527.11	-4.0046 %
Comb. Turbine #1 Power (MW)	172.80	182.60	-5.3669 %
Comb. Turbine #2 Power (MW)	169.40	182.60	-7.2289 %
Steam Turbine Power (MW)	170.20	168.31	1.1238 %
Auxiliary Load Power (MW)	6.40	6.40	0.0000 %
Net Plant HR (Btu/kW-hr)	6379.68	6290.86	1.4119 %
Thermal Efficiency (%)	53.48	54.24	-0.7551 pts.
Steam Turb. Exh. Flow (lb/sec)	306.00	304.54	0.4783 %
Condenser Pressure (in. Hga)	1.41	1.50	-6.2383 %

CORRECTION FACTORS:	POWER	HEAT RATE	STM. EXH. FLOW
Compressor Inlet Temperature	1.0476	0.9976	1.0221
Barometric Pressure	0.9990	1.0000	0.9990
CT Inlet Pressure Drop	1.0027	0.9989	1.0012
CT Exhaust Pressure Drop	0.9998	1.0003	1.0002
Part-Load	1.0000	1.0000	1.0000
CT Steam Injection	0.0000	1.0000	1.0000
Duct Burner	1.0113	1.0057	1.0340
Steam Extraction (kW)	-6997.5000		
Condenser Pressure (kW)	1353.5660		

ERROR MESSAGES:

None

Figure 4-4
Report Output from CCPFDM Using Inputs of Table 4-5

6. When CCPFDM executes performance calculations, the results are displayed in the **Report** worksheet, but they are not saved to the results database file, Results.csv, until the user clicks the button labeled "Save Results". This is to guard against adding bogus results caused by mis-entry of the input data. Once the user has reviewed the report and verified that the results make sense, they can be saved. Do that now by clicking on the "Save Results" button. An Excel macro will execute that writes the results to Results.csv and updates the performance trend charts to include the current results. Once the macro is finished, a box appears displaying the message "Results saved to Results.csv." Click the "**OK**" button to make the box disappear.

Lesson 3 - Add (or Copy) a New CC Model

Though it's not possible to directly create and edit a new CC model using the CCPFDM spreadsheet, you can copy an existing CC model to a new model. Then, using any text editor, you can edit the data contained in the CCmodel.dat file to accurately reflect the characteristics of the new model. See Appendix B for details on the contents and format of CCmodel.dat. This lesson shows how to copy an existing model and save it as a new CC "reference model".

1. Switch to the worksheet labeled "Main Menu" (refer to Microsoft Excel Help menu for information on how to switch from one worksheet to another within an Excel workbook).
2. In cell "B20" (just under the button labeled "Copy CC Model:"), use the pull-down menu to select the data units (English or SI) to be used for the model which will serve as the source of the copy procedure.
3. In cell "B21", use the pull-down menu to select the data units (English or SI) to be used for the model which will serve as the target of the copy procedure.
4. Now click the button in cell "B21" labeled "Copy CC Model:". A box will appear that says "Enter drive/path of source model:". The default drive/path which appears in the input box is the Reference Models subdirectory **CCPFDM\Reference Models**. For this exercise, we'll use the default drive/path as shown. However, it is possible to specify an external data source, such as a floppy disk.
5. Click the "**OK**" button and a new box will appear that says "Enter name of source model:". In the input box, type "W501F", the name of the model that comes pre-installed with CCPFDM.
6. Click the "**OK**" button and a message box will appear reminding you to make sure a floppy disk is inserted, if using that as the source drive.
7. Click the "**OK**" button and a new box will appears that says "Enter name of target model (up to 20 characters) "". In the input box, type "Test Model".
8. Once again, click the "**OK**" button. An Excel macro will be executed which copies the model data from the **W501F.dat** file in the **CCPFDM\Reference Models** sub-directory to the **Test Model.dat** file in the same location. Once the macro has finished, a message box will appear reading "Model copied to Test Model. ". Click the "**OK**" button to make the message box disappear.

9. If you check the pull-down menu under the "Create Unit:" button in cell "B7", you will see that Test Model now appears along with the W501F model.

Lesson 4 - Deleting Units and Models

In order to prevent cluttering up your CCPFDM sub-directories with unneeded units and CC models, you should delete the unit and model that were created in Lessons 1 through 3. That will be done in this lesson.

1. On the **Main Menu** worksheet, move to cell "B24" and select "Test Model" from the pull-down menu.
2. Now click on the button in cell "B23" labeled "Remove CC Model:". A message box will appear asking you to confirm that you want to delete the model **Test Model**. Click the "**OK**" button to continue.
3. A macro will be executed that deletes the **Test Model.dat** file. When the macro is completed, a message box will appear telling you so. Click the "**OK**" button to make the box disappear.
4. Note that removing the CC reference model does not effect the CC model data files that are stored in the individual unit sub-directories. You can confirm this by using Windows Explorer to look in the **CCPFDM\Pocasset Unit #1** sub-directory. You will see that the **CCmodel.dat** file still exists.
5. Now that we've verified that removing a CC reference model file does not effect the files in an individual unit sub-directory, we now will remove the **Pocasset Unit #1** unit.
6. In cell "B17" of the **Main Menu** worksheet, select **Pocasset Unit #1** from the pull-down menu. Then click the "**Remove Unit:**" button just above the menu.
7. A message box will appear asking you if you are sure you want to remove the unit **Pocasset Unit #1**. Click the "**OK**" button to continue. A macro will now delete the **CCPFDM\Pocasset Unit #1** sub-directory and all of the files in it. When it is finished, a message box will appear telling you so. Click the "**OK**" button to make the box disappear.
8. Note that the entries in Row A still indicate that **Pocasset Unit #1** is the current unit. However, if you try to run performance calculations in Pocasset Unit #1, you will get a message that it doesn't exist. To verify this, switch to the Inputs worksheet and click the "**Click to Run CCPFDM**" button. A message box appears telling you "Pocasset Unit #1 has been removed. Switch to a different unit." Click the "**OK**" button to make the box disappear.
9. Return to the **Main Menu** worksheet and switch to the unit Example 1 by selecting **Example 1** in the pull-down menu of cell "B4" and clicking the "**Switch Unit:**" button above it. Once the macro has finished, click the "**OK**" button and then close the CCPFDM worksheet using the Excel "File" menu. When you are prompted "Do you want to save the changes you made to CCPFDM.xls", click "**Yes**".

References

1. Volume 1, Combustion Turbine Performance and Fault Diagnostic Module Version 3.2, EPRI, Palo Alto, CA: 2003. CM-1000939.

2. Anon., "Correction Curves Overview and Instructions", Combined Cycle 60Hz Application Handbook, Westinghouse Electric Corp., 1996.

Appendix A: Detailed Description of Performance Calculations

Overview

When the CCPFDM DLL is called, it carries out four main functions: data checking, measured performance calculations, expected performance calculations, and fault diagnostics. Each of these functions will be described in detail in this appendix.

Data Checking

CCPFDM performs several internal checks to verify the quality of the measured data. The first aspect that is checked is the reasonableness of the data. Each of the numerical inputs is checked to see if it falls within an expected range of values (see Table 4-6). If any are outside the expected range, then an error message is issued and the calculations do not proceed (except where noted).

Table 4-6
Expected Range Check for Key Input Measurements

Parameter	Lower Limit	Upper Limit
Ambient Temperature	-40 °F (-40 °C)	140 °F (60 °C)
CT Meas. Generator Power	0 MW[1]	Rated Value / No. of CTs
CT Fuel Flow	0 lbs/sec (0 kg/sec)[2]	500 lbs/sec (226.8 kg/sec)
CT Duct Burner Fuel Flow	0 lbs/sec (0 kg/sec)[2]	(Rated Plant Heat Rate ∗ 1000000) / (Default Fuel LHV ∗ 3600)
CT NOx Steam Injection Flow Rate	0 lbs/sec (0 kg/sec)[2]	Fuel Flow * Maximum CC Model Steam/Fuel Ratio
ST Exhaust Flow	0 lbs/sec (0 kg/sec)	Maximum CC model value in condenser pressure vs. temperature array
ST Exhaust Pressure	0" Hga (0 bara)	10" Hga (0.33864 bara)
ST Extraction Steam Flow	0 lbs/sec (0 kg/sec)[2]	CC model design ST exhaust flow
ST Extraction Steam Pressure	0 psig (0 barg)	Maximum CC model value in correction factor array

[1]If the input value is less than 0, the value is reset to 0, the CT part-load level is (re)set to 0, an error message is generated, and the performance calculations are allowed to continue.
[2]If the input value is less than 0, the value is reset to 0, an error message is generated, and the performance calculations are allowed to continue.

In addition to the parameters shown in the table above, the input flag values of fuel type are checked. If any fuel type flag is not equal to either 0 (gas fuel) or 1 (liquid fuel), an error message is generated and the calculations are not allowed to proceed.

If all of the inputs above fall within the expected range of values, then CCPFDM reviews the rest of the available data to determine what calculations should be carried out.

CCPFDM checks whether a valid value of steam turbine generator power is present. If not, an error message is generated warning the user that the steam turbine generator power is out of range and that an alternate calculation is being used. Steam turbine generator power is then calculated using the following equation:

Steam Turbine Generator Power = Net Plant Power – CT #1 Measured Generator Power – CT #2 Measured Generator Power + Measured Plant Auxiliary Load

CCPFDM checks whether a valid value of measured plant auxiliary load is present. If not, an error message is generated warning the user that the measured plant auxiliary load is out of range and that an alternate calculation is being used. Measured plant auxiliary load is then calculated using the following equation:

Measured Plant Auxiliary Load = Net Plant Power ∗ Measured Plant Auxiliary Load Default Factor

If the measured plant auxiliary load is calculated as shown above, but the measured plant auxiliary load default factor is out of range (less than 0 or greater than 1), the calculations are not allowed to proceed.

CCPFDM also checks whether a valid value of expected plant auxiliary load is present. If the expected plant auxiliary load is less than 0, the value is reset to 0, the CT part-load level is (re)set to 0, an error message is generated, and the performance calculations are allowed to continue. If the input value is greater than the upper limit, an error message is generated and the performance calculations are allowed to continue, but the expected performance calculations are skipped.

If the barometric pressure is determined to be out of range, the input value is reset to the default value of barometric pressure drop, an error message is generated, and the performance calculations are allowed to continue. However, if the default value of barometric pressure is also out of range, the calculations are not allowed to proceed.

If the CT inlet pressure drop is determined to be out of range, the input value is reset to the default value of CT inlet pressure drop, an error message is generated, and the performance calculations are allowed to continue. Similarly, if the CT exhaust pressure drop is out of range, the input value is reset to the default value of CT exhaust pressure drop, an error message is generated, and the performance calculations are allowed to continue. However, if the either of the pressure drops are reset to the default value and that value is also out of range, the calculations are not allowed to proceed.

If the CT compressor inlet temperature is determined to be out of range, an error message is generated and the performance calculations are allowed to continue, but the expected performance calculations are skipped.

If the CT part-load level is less than 0, the value is reset to 0, an error message is generated, and the performance calculations are allowed to continue. If the input value is greater than the upper limit, an error message is generated and the performance calculations are allowed to continue, but the expected performance calculations are skipped.

If the ST exhaust quality is determined to be out of range, the input value is reset to the default value of ST exhaust quality, an error message is generated, and the performance calculations are allowed to continue. However, if the default value of ST exhaust quality is also out of range, the calculations are not allowed to proceed.

If an evaporative cooling tower is present (rCFlag = 1 in Ccmodel.dat) and the ambient wet bulb temperature is out of range, CCPFDM attempts to calculate ambient wet bulb temperature using the inputs of relative humidity, ambient temperature, and barometric pressure. If the relative humidity input is out of range, the input value is reset to the default value, and that value is used in the calculation of ambient wet bulb temperature.

If the condenser is cooled by a once-through water flow from river, lake or ocean (rCFlag = 3 in Ccmodel.dat), the condenser cooling water temperature is checked. If the condenser cooling water temperature is out of range, an error message is generated, and the performance calculations are allowed to continue, but the expected performance calculations are skipped.

In addition to the measured input data checks described above, CCPFDM checks the default values of lower heating value for gas and liquid fuels. If either one is out of range (less than 0 or greater than 100000), the performance calculations are not allowed to proceed.

Measured Performance Analysis

Once the data checking functions have been completed, CCPFDM will carry out the measured performance analysis functions, provided sufficient data are available. The measured performance analysis determines the actual performance of the combined cycle plant based on the measured data and various thermodynamic calculations described below.

Measured Net Plant Heat Rate

The measured net plant heat rate, HR, is calculated from the measured fuel flow, w_{fuel}, and measured net power, MW, and the default value for the lower heating value of the fuel, LHV:

$$HR = \frac{w_{fuel} * 3600 * LHV}{MW * 1000}$$

where w_{fuel} is equal to the sum of the fuel flow to CT1 and CT2, plus the sum of the fuel flow to the duct burners.

Measured Overall Plant Efficiency

The measured overall efficiency of the combined cycle plant, EFFCC, is calculated from the heat rate. For the English units option the formula is:

$$EFFCC = 3412 * 100 / HR$$

For the SI units option the formula is:

$$EFFCC = 3600 * 100 / HR$$

Expected Performance Analysis

When the measured performance functions have been completed, CCPFDM will carry out the expected performance analysis functions, provided sufficient data are available. The expected performance analysis functions calculate the performance that would be expected from the combined cycle plant based on the model data for the measured operating conditions. The various correction factors used in the expected calculations are calculated from linear interpolations of the design data. For the part-load correction factors in the case of two CTs, the correction factors are based on the average value of the CT load levels. If one CT load level is zero, then it is assumed that only one CT is operating, and the single CT part-load correction factor curves are used instead of using the average CT load level.

Expected Net Plant Power

The expected net plant power, MW_{exp}, is calculated by the following formula:

MWexp = rPlPw ∗ CFMWCIT ∗ CFPbaro ∗ CFMWdPin ∗ CFMWdPexh ∗ CFMWCTPL ∗ CFMWstinj ∗ CFMWDB

where rPlPw is the rated net plant power (in MW). This value is adjusted by a series of correction factors (CF):

- $CFMW_{CIT}$ = CT compressor inlet temperature correction factor
- CF_{Pbaro} = barometric pressure correction factor
- $CFMW_{dPin}$ = CT inlet pressure drop correction factor
- $CFMW_{dPexh}$ = CT exhaust pressure drop correction factor
- $CFMW_{CTPL}$ = CT part-load correction factor
- $CFMW_{stinj}$ = CT steam injection correction factor

- $CFMW_{DB}$ = duct burner correction factor

and:

$$CFMWDB = CFMWDB1 + CFMWDB2 - 1$$

Note that in order to interpolate the duct burner correction factor curve, the duct burner fuel flow has to be converted into energy consumption (MMBtu/hr or GJ/hr) by multiplying by the fuel LHV. The LHV is obtained from the default data file and the duct burner fuel type flag will indicate which LHV (gas or liquid) to use.

MW_{exp} then has to be adjusted by two additional factors: steam turbine back-pressure, MW_{stbp}, and steam turbine extraction flow, StExtPw:

StExtPw = mStExtF ∗ MWLost / 1000000

where:

- mStExtF = measured extraction steam flow rate in lb/hr
- MWLost = lost steam turbine power in kW per 1000 lb/hr of extraction steam

MWLost is found from a correction curve which plots LostMW as a function of extraction pressure.

The calculation of MW_{stbp} is a multi-step process:

First calculate the expected steam turbine exhaust flow from:

eStExF = rPlExF ∗ CFSECIT ∗ CFPbaro ∗ CFSEdPin ∗ CFSEdPexh ∗ CFSECTPL ∗ CFSEstinj ∗ CFSEDB – (mStExtF – rStExtF)

where:

- RPlExF = rated steam turbine exhaust flow (in lb/hr)
- $CFSE_{CIT}$ = CT compressor inlet temperature correction factor
- CF_{Pbaro} = barometric pressure correction factor
- $CFSE_{dPin}$ = CT inlet pressure drop correction factor
- $CFSE_{dPexh}$ = CT exhaust pressure drop correction factor
- $CFSE_{CTPL}$ = CT part-load correction factor
- $CFSE_{stinj}$ = CT steam injection correction factor

- $CFSE_{DB}$ = DB correction factor
- RStExtF = rated steam turbine extraction flow

$$CFSEDB = CFSEDB1 + CFSEDB2 – 1$$

eStExF is then multipled by the measured steam exhaust quality, mStExQ, to get the total flow of steam vapor into the condenser:

$$STMcond = eStExF * mStExQ$$

STM_{cond} and the applicable condenser cooling mechanism temperature (wet bulb temperature + cooling tower approach if Cflag = 1, dry bulb temperature if Cflag = 2, or Triver if Cflag = 3) are then used to look up the expected condenser operating pressure (eStExP) in the condenser expected performance table.

eStExP and eStExF are then used to look up the expected change in steam turbine output due to condenser back-pressure, MW_{stbp}, from the ST back-pressure performance table.

Now the final value of MW_{exp} can be calculated from:

$$MW_{exp} = (MW_{exp} + MW_{stbp} - StExtPw) / 1000$$

Expected Steam Turbine Power

The expected steam turbine power, $STMW_{exp}$, is calculated by the following formula:

$$STMW_{exp} = MW_{exp} – eTPw1 – eTPw2 + mPLAuxLd$$

where:

- ETPw1 = CT #1 expected power (in MW)
- ETPw2 = CT #2 expected power (in MW)
- mPlAuxLd = plant auxiliary power load (in MW)

The expected CT powers are calculated in CTPDM and then passed to CCPFDM as a "measured" input.

Expected Net Plant Heat Rate

The expected heat rate, HR_{exp}, is calculated in an approach similar to that of the calculation of the expected net plant power:

HRexp = rPlHtRt * CFHRCIT * CFHRPbaro * CFHRdPin * CFHRdPexh * CFHRptLd * CFHRstinj * CFHRDB where:

- rPlHtRt = rated net plant heat rate (in Btu/kW-hr)
- $CFHR_{CIT}$ = CT compressor inlet temperature correction factor
- CF_{Pbaro} = barometric pressure correction factor
- $CFHR_{dPin}$ = CT inlet pressure drop correction factor
- $CFHR_{dPexh}$ = CT exhaust pressure drop correction factor
- CFHRptld = CT part-load correction factor
- $CFHR_{stinj}$ = CT steam injection correction factor
- $CFHR_{DB}$ = Duct Burner correction factor

and:

$$CFHRDB = CFHRDB1 + CFHRDB2 - 1$$

HR_{exp} then has to be adjusted by two additional factors: steam turbine back-pressure, MW_{stbp}, and steam turbine extraction flow, StExtF.

$$HR_{exp} = HR_{exp} * (MW_{exp} - MW_{stbp} / 1000 + StExtPw / 1000) / MW_{exp}$$

Expected Overall Plant Efficiency

The expected overall efficiency of the combined cycle plant, $EFFCC_{exp}$, is calculated from the expected heat rate. For the English units option the formula is:

$$EFFCC_{exp} = 3412 * 100 / HR_{exp}$$

For the SI units option the formula is:

$$EFFCC_{exp} = 3600 * 100 / HR_{exp}$$

Fault Diagnostics

CCPFDM calculates fault diagnostics based on rules developed by Dr. Meherwan Boyce. The diagnostic calculations compare user-input threshold values with degradation parameter values. As a result of the comparisons, logical "flags" are set for the degradation parameters. These degradation parameter flags are then evaluated to determine the status of potential fault conditions in the combustion turbine(s), HRSG, condenser, and steam turbine.

The four status conditions and associated flag values of the degradation parameters are as follows:

0 = "Undetermined"

1 = "Normal"

2 = "Alert"

3 = "Action Required"

The HRSG fault diagnostic is based on a comparison between its threshold values and the measured-expected difference in steam turbine exhaust flow. The calculation for expected steam turbine exhaust flow has already been detailed in the expected performance analysis section above. For the CT fault diagnostic(s), threshold values are compared to a measured-expected difference calculated from measured input data values. The two remaining degradation parameters for the condenser and steam turbine require additional calculations described below.

Condenser Fouling Parameter

Using the formula below, the condenser fouling parameter (Condfp) is calculated for use in determining the status of the "Condenser" fault.

$$\text{Condfp} = ((\text{kWStBp}_{mm} - \text{kWStBp}_{em}) / 1000) / \text{STMW}_{exp} * 100$$

where kWStBp_{mm} is the interpolated expected change in steam turbine output due to condenser back pressure (using measured values of ST exhaust pressure and ST exhaust flow), kWStBp_{em} is the interpolated expected change in steam turbine output due to condenser back pressure (using an expected value of ST exhaust pressure and measured ST exhaust flow), and STMW_{exp} is the calculated expected ST power previously described.

Steam Turbine Degradation Parameter

Using the formulas below, the steam turbine degradation parameter (STdp) is calculated for use in determining the "Steam Turbine" fault. First to be calculated is the measured ST power per unit of steam flow after factoring out the impact of condenser fouling (ST_{meas}) using:

$$\text{ST}_{meas} = (\text{mSTPw} - (\text{kWStBp}_{mm} - \text{kWStBp}_{em}) / 1000) / \text{mStExF}$$

where mSTPw is the measured ST power and mStExF is the measured ST exhaust flow.

Then, the expected ST power per unit of steam flow (ST_{exp}) can be calculated using:

$$\text{ST}_{exp} = \text{STMW}_{exp} / \text{eStExF}$$

Finally, the ST degradation parameter (STdp) based on the ST power per unit of steam flow can be calculated using:

$$STdp = (ST_{meas} - ST_{exp}) / ST_{exp} * 100$$

Appendix B: Detailed Description of CCmodel.dat File

The CCmodel.dat file contains the data for the expected performance of a combined cycle plant based on the performance curves provided by the manufacturer. A typical example of manufacturer-supplied performance curves is shown in Figure 4-5.

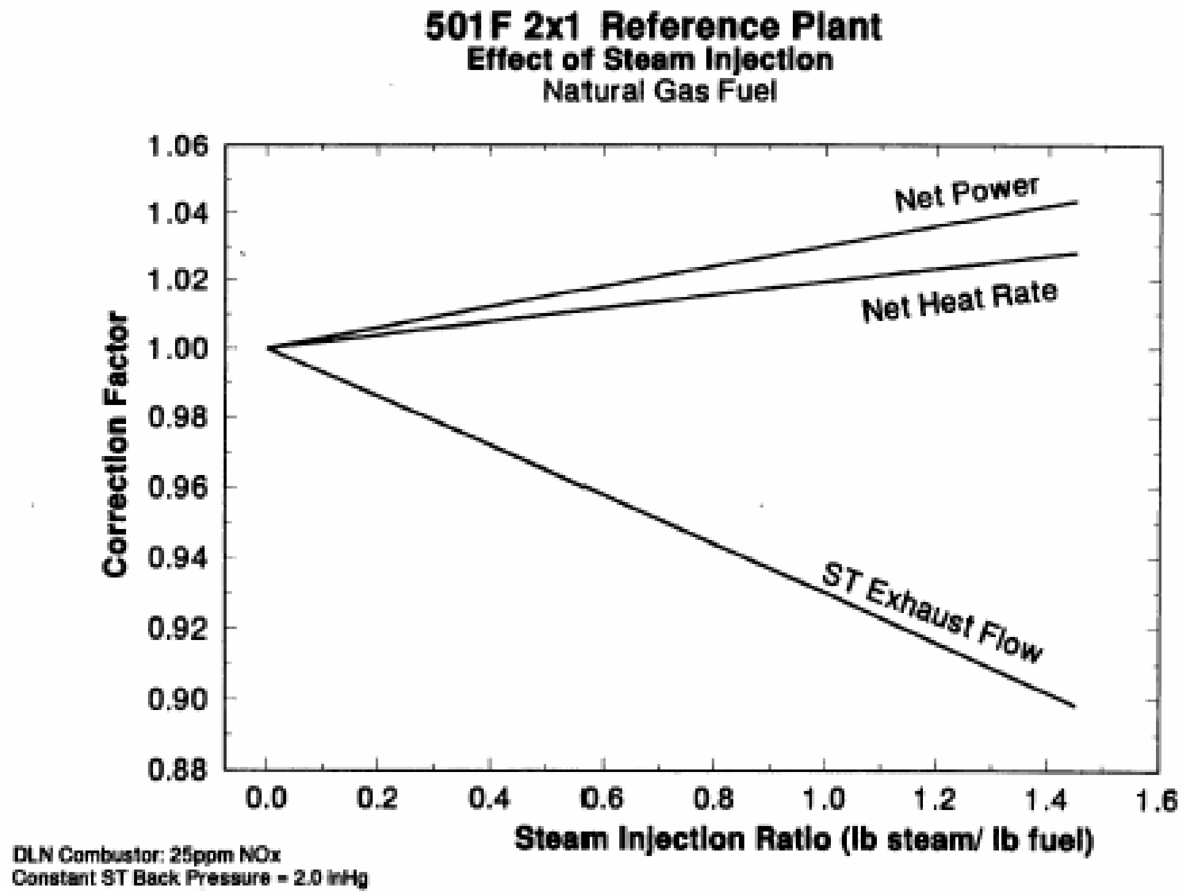


Figure 4-5
Example of a Combustion Turbine Steam Injection Correction Curve for a Siemens Westinghouse 501F Combined Cycle Power Plant

Each unit that is monitored by CCPFDM has its own CCmodel.dat file which is located in the unit sub-directory. In addition, CCPFDM maintains a separate "Reference Models" sub-directory in which a copy of each unit's CCmodel.dat file resides. Of course, in the Reference Models sub-directory, each of the CC model data files must be given a unique name. For example, the CCPFDM spreadsheet comes with a built-in CC model for a "2-on-1" combined cycle plant with two Siemens Westinghouse Power Corp. (SWPC) 501F engines. During the installation process, a unit named "Example 1" is created. The CCPFDM\Example 1 unit sub-directory contains the W501F CC model data file named CCmodel.dat. That same model data is also stored in the Reference Models sub-directory, this time with the name W501F.dat.

Since a user cannot directly create and edit a new CC model using the CCPFDM spreadsheet, detailed information on the contents and format of the CCmodel.dat file is provided in this appendix. Using any text editor and this appendix as a reference, a user can edit the data contained in the CCmodel.dat file (and the corresponding file stored in the Reference Models sub-directory) to accurately reflect the characteristics of a new or changed model.

Contents of the CCmodel.dat File

Each CCmodel.dat file (and corresponding file stored in the Reference Models sub-directory) contains the following information:

Rated Conditions

- Number of CTs
- Barometric Pressure ("Hg abs. or bara)
- CT Compressor Inlet Temperature (°F or °C)
- CT Inlet Pressure Drop ("H_2O or mbar)
- CT Exhaust Pressure Drop ("H_2O or mbar)
- CT Steam Injection Ratio (lb steam/lb fuel)
- Ambient Dry-Bulb Temperature (°F or °C)
- Ambient Wet-Bulb Temperature (°F or °C)
- Process Steam Extraction Flow from ST (lb/hr or kg/hr)
- Steam Turbine Back-Pressure ("Hg or mbar)
- Condenser Cooling Flag, CFlag (1 = evaporative cooling tower, 2 = air cooled, 3 = river water)
- Cooling Tower Approach Temperature (for Cflag = 1 only)

Design Rating

The following four values are needed for each of two operating conditions: base-natural gas, base-distillate:

- Design Net Plant Power (kW)
- Design Net Plant Heat Rate (LHV basis) (Btu/kW-hr or kJ/kW-hr)
- Design Steam Turbine Exhaust Flow (lb/hr or kg/hr)
- Design Steam Exhaust Quality (fraction)

Total Plant Correction Curves

A table of data is needed showing the values of expected ST exhaust flow, net plant heat rate, and net plant power versus:

- CT Compressor Inlet Temperature
- CT Inlet Pressure Drop
- CT Exhaust Pressure Drop
- CT Steam Injection Ratio
- CT Part-Load Operation with Two CTs on (as % of single CT full-load power, both CTs operating at same load level) – for 2×1 combined cycles only
- CT Part-Load Operation with One CT on (as % of single CT full-load power) – for 2×1 or 1×1 combined cycles
- HRSG Duct Firing Rate (fraction of design power value vs. MMBtu/hr or GJ/hr of duct firing)

The flow, heat rate, and power are entered as a fraction of the design rating value. It is assumed that natural gas and distillate operation will follow the same curves.

Steam Turbine Correction Curves

The following curves, which describe steam turbine expected performance, must be entered as tables of data:

- Decrease in ST Power per 1000 lb/hr (or 1000 kg/hr) of Extraction Steam Flow vs Extraction Steam Pressure (psig or barg)
- Change in ST Power vs ST Exhaust Flow at Various Values of Constant Condenser Pressure, and:
- ST Exhaust Flow vs Ambient Wet Bulb Temperature at Various Values of Constant Condenser Pressure (if Cflag = 1), or:
- ST Exhaust Flow vs Ambient Dry Bulb Temperature at Various Values of Constant Condenser Pressure (if Cflag = 2), or:
- ST Exhaust Flow vs River Water Temperature at Various Values of Constant Condenser Pressure (if Cflag = 3)

Format of the CCmodel.dat File

An example CCmodel.dat file is shown below, followed by Table 4−7 showing the exact format of the file.

Example File:

2

29.92915,59.0,4.0,10.0,0.0,59.0,51.0

0.0,2.0,1,15

502100,6209,1079450,0.95

10

6

10

5

11

11

3

3

20,1.113,0.991,1.054

30,1.085,0.993,1.04

40,1.056,0.997,1.026

50,1.028,0.999,1.013

59,1.0,1.0,1.0

70,0.97,1.005,0.99

80,0.942,1.008,0.979

90,0.913,1.011,0.968

100,0.884,1.014,0.96

110,0.855,1.016,0.951

0,1.0101,0.9958,1.0047

2,1.0051,0.9979,1.0023

4,1.0,1.0,1.0

6,0.9951,1.0031,0.9976

8,0.99,1.0042,0.9952

10,0.9849,1.0062,0.9929

0,1.0107,0.9842,0.9893

2,1.0085,0.9873,0.9912

4,1.0064,0.9906,0.9932

6,1.0042,0.9936,0.9953

8,1.0021,0.9968,0.9976

10,1.0,1.0,1.0

12,0.9978,1.003,1.0022

14,0.9957,1.0062,1.0048

16,0.9934,1.0092,1.0073

18,0.9913,1.0123,1.01

0,1.0,1.0,1.0

0.4,1.012,1.008,0.972

0.8,1.024,1.016,0.944

1.2,1.036,1.023,0.916

1.6,1.048,1.031,0.888

50,0.265,1.18,0.356

55,0.293,1.152,0.375

60,0.319,1.126,0.393

65,0.345,1.103,0.41

70,0.37,1.082,0.427

75,0.395,1.065,0.444

80,0.417,1.052,0.461

85,0.44,1.04,0.478

90,0.46,1.03,0.495

95,0.48,1.025,0.512

100,0.5,1.023,0.529

50,0.554,1.124,0.704

55,0.604,1.104,0.744

60,0.655,1.084,0.78

65,0.704,1.066,0.816

70,0.75,1.052,0.848

75,0.796,1.039,0.878

80,0.842,1.029,0.908

85,0.884,1.02,0.936

90,0.924,1.012,0.962

95,0.964,1.005,0.984

100,1.0,1.0,1.0

0.0,1.0,1.0,1.0

10.0,1.01,1.005,1.03

20.0,1.02,1.01,1.06

0.0,1.0,1.0,1.0

20.0,1.01,1.005,1.03

40.0,1.02,1.01,1.06

19

0,20

100,105

200,131

300,143.5

400,152

500,159

600,164.5

700,169.5

800,174

900,178

1000,182

1100,185

1200,188

1300,191

1400,193.5

1500,196

1600,198

1700,200

1800,202

7,13

1

450,5880

750,5880

850,4780

900,4220

950,3700

1000,3200

1050,2760

1100,2320

1150,1920

1200,1520

1250,1160

1300,880

1350,620

2

450,0

750,0

850,0

900,0

950,0

1000,0

1050,0

1100,0

1150,0

1200,0

1250,0

1300,0

1350,0

3

750,-5720

800,-6020

850,-6280

900,-6480

950,-6620

1000,-6680

1050,-6660

1100,-6560

1150,-6410

1200,-6200

1250,-5940

1300,-5600

1350,-5220

4

750,-10440

800,-10960

850,-11440

900,-11860

950,-12200

1000,-12460

1050,-12640

1100,-12740

1150,-12760

1200,-12680

1250,-12520

1300,-12320

1350,-12080

5

750,-14920

800,-15480

850,-15980

900,-16440

950,-16830

1000,-17160

1050,-17440

1100,-17660

1150,-17860

1200,-18000

1250,-18040

1300,-18050

1350,-18050

6

750,-19400

800,-19880

850,-20340

900,-20800

950,-21220

1000,-21580

1050,-21890

1100,-22160

1150,-22390

1200,-22600

1250,-22790

1300,-22940

1350,-23040

7

750,-22080

800,-23280

850,-24200

900,-24940

950,-25600

1000,-26110

1050,-26560

1100,-26920

1150,-27100

1200,-27200

1250,-27240

1300,-27200

1350,-27010

4,7

1

20,894000

30,864000

40,790000

50,642000

60,440000

70,180000

76.07,0

2

30.43,1494000

40,1438000

49.64,1320000

60,1130000

71.43,840000

81.43,518000

88.64,234000

3

36.71,1846000

46.43,1778000

56.43,1648000

66.79,1450000

80,1118000

90.71,760000

100,410000

4

40,2036000

50,1958000

60,1846000

72.64,1660000

87.29,1346000

100,1024000

113.29,636000

Table 4-7
CCmodel.dat File Format

Line #	Example Value	Variable Name	Description	Units
1	2	NumCTs	Number of CTs	
2:1	29.92915	rBPHg	Barometric Pressure	bara or "Hga
2:2	59.00000	rTcit	CT Compressor Inlet Temp.	deg.C or deg.F
2:3	4.00000	rInPD	CT Inlet Pressure Drop	mbar or "H2O
2:4	10.00000	rExPD	CT Exhaust Press. Drop	mbar or "H2O
2:5	0.00000	rStInjRat	CT Steam Injection Ratio	lb steam/lb fuel
2:6	59.00000	rTamb	Ambient Dry Bulb Temperature	deg.C or deg.F
2:7	51.00000	rTwet	Ambient Wet Bulb Temperature	deg.C or deg.F
3:1	0.00000	rStExtF	Process Steam Extraction Flow	kg/hr or lb/hr
3:2	2.00000	rStBkP	Steam Turbine Back-Pressure	mbar or "Hga
3:3	1	rCflag	Condenser Cooling Flag	1, 2 or 3[1]
3:4	15	rCTower	Cooling Tower Approach Tmp.[2]	deg.C or deg.F
4:1	502100.00000	rPlPw	Design Net Plant Power	Kw
4:2	6209.00000	rPlHtRt	Design Net Plant Heat Rate	kJ/kW-hr or Btu/kW-hr
4:3	1079450.00000	rPlExF	Design ST Exhaust Flow	kg/hr or lb/hr
4:4	0.95000	rPlExQ	Design Steam Exhaust Quality	fraction
5	10	NumCmpT	Num. of C. Inlet. Tmp. CF Pts.[3]	
6	6	NumInPD	Num. of In. Pr. Drop CF Pts.[3]	
7	10	NumExPD	Num. of Ex. Pr. Drop CF Pts.[3]	
8	5	NumStInj	Num. of St. Inj. Ratio CF Pts.[3]	
9	11	NumPtLd2	Num. of Part-Ld. 2-CT CF Pts.[3]	
10	11	NumPtLd1	Num. of Part-Ld. 1-CT CF Pts.[3]	
11	3	NumDB1	Num. of DB 1-CT CF Pts.[3]	
12	3	NumDB2	Num. of DB 2-CT CF Pts.[3]	
13:1	20.00000	CfTcit(1, 1)	Comp. Inlet Temp. (CIT) #1	deg.C or deg.F
13:2	1.11300	CfTcit(1, 2)	CIT Power Corr. Factor Pt. #1	fraction
13:3	0.99100	CfTcit(1, 3)	CIT Heat Rate Corr. Fact. Pt. #1	fraction
13:4	1.05400	CfTcit(1, 4)	CIT Stm. Exhst. Flow CF Pt. #1	fraction
14:1	30.00000	CfTcit(2, 1)	Comp. Inlet Temp. (CIT) #2	deg.C or deg.F
14:2	1.08500	CfTcit(2, 2)	CIT Power Corr. Factor Pt. #2	fraction
14:3	0.99300	CfTcit(2, 3)	CIT Heat Rate Corr. Fact. Pt. #2	fraction
14:4	1.04000	CfTcit(2, 4)	CIT Stm. Exhst. Flow CF Pt. #2	fraction
↓ etc. ↓				
22:1	110.00000	CfTcit(10, 1)	Comp. Inlet Temp. (CIT) #10	deg.C or deg.F
22:2	0.85500	CfTcit(10, 2)	CIT Power Corr. Factor Pt. #10	fraction
22:3	1.01600	CfTcit(10, 3)	CIT HR Corr. Factor Pt. #10	fraction
22:4	0.95100	CfTcit(10, 4)	CIT Stm. Exhst. Flow CF Pt. #10	fraction
23:1	0.00000	CfInPD(1, 1)	Inlet Pressure Drop (IPD) #1	mbar or "H2O
23:2	1.01010	CfInPD(1, 2)	IPD Power Corr. Factor Pt. #1	fraction
23:3	0.99580	CfInPD(1, 3)	IPD HR Corr. Factor Pt. #1	fraction

Line #	Example Value	Variable Name	Description	Units
23:4	1.00470	CfInPD(1, 4)	IPD Stm. Exhst. Flow CF Pt. #1	fraction
24:1	2.00000	CfInPD(2, 1)	Inlet Pressure Drop (IPD) #2	mbar or "H2O
24:2	1.00510	CfInPD(2, 2)	IPD Power Corr. Factor Pt. #2	fraction
24:3	0.99790	CfInPD(2, 3)	IPD HR Corr. Factor Pt. #2	fraction
24:4	1.00230	CfInPD(2, 4)	IPD Stm. Exhst. Flow CF Pt. #2	fraction
↓				
etc.				
↓				
28:1	10.00000	CfInPD(6, 1)	Inlet Pressure Drop (IPD) #6	mbar or "H2O
28:2	0.98490	CfInPD(6, 2)	IPD Power Corr. Factor Pt. #6	fraction
28:3	1.00620	CfInPD(6, 3)	IPD HR Corr. Factor Pt. #6	fraction
28:4	0.99290	CfInPD(6, 4)	IPD Stm. Exhst. Flow CF Pt. #6	fraction
29:1	0.00000	CfExPD(1, 1)	Exhaust Pressure Drop (EPD) #1	mbar or "H2O
29:2	1.01070	CfExPD(1, 2)	EPD Power Corr. Factor Pt. #1	fraction
29:3	0.98420	CfExPD(1, 3)	EPD HR Corr. Factor Pt. #1	fraction
29:4	0.98930	CfExPD(1, 4)	EPD Stm. Exhst. Flow CF Pt. #1	fraction
30:1	2.00000	CfExPD(2, 1)	Exhaust Pressure Drop (EPD) #2	mbar or "H2O
30:2	1.00850	CfExPD(2, 2)	EPD Power Corr. Factor Pt. #2	fraction
30:3	0.98730	CfExPD(2, 3)	EPD HR Corr. Factor Pt. #2	fraction
30:4	0.99120	CfExPD(2, 4)	EPD Stm. Exhst. Flow CF Pt. #2	fraction
↓				
etc.				
↓				
38:1	18.00000	CfExPD(10, 1)	Exhaust Pressure Drop (EPD) #6	mbar or "H2O
38:2	0.99130	CfExPD(10, 2)	EPD Power Corr. Factor Pt. #6	fraction
38:3	1.01230	CfExPD(10, 3)	EPD HR Corr. Factor Pt. #6	fraction
38:4	1.01000	CfExPD(10, 4)	EPD Stm. Exhst. Flow CF Pt. #6	fraction
39:1	0.00000	CfStInj(1, 1)	Steam Injection Ratio (SIR) #1	fraction
39:2	1.00000	CfStInj(1, 2)	SIR Power Corr. Factor Pt. #1	fraction
39:3	1.00000	CfStInj(1, 3)	SIR HR Corr. Factor Pt. #1	fraction
39:4	1.00000	CfStInj(1, 4)	SIR Stm. Exhst. Flow CF Pt. #1	fraction
40:1	0.40000	CfStInj(2, 1)	Steam Injection Ratio (SIR) #2	fraction
40:2	1.01200	CfStInj(2, 2)	SIR Power Corr. Factor Pt. #2	fraction
40:3	1.00800	CfStInj(2, 3)	SIR HR Corr. Factor Pt. #2	fraction
40:4	0.97200	CfStInj(2, 4)	SIR Stm. Exhst. Flow CF Pt. #2	fraction
↓				
etc.				
↓				
43:1	1.60000	CfStInj(5, 1)	Steam Injection Ratio (SIR) #5	fraction
43:2	1.04800	CfStInj(5, 2)	SIR Power Corr. Factor Pt. #5	fraction
43:3	1.03100	CfStInj(5, 3)	SIR HR Corr. Factor Pt. #5	fraction
43:4	0.88800	CfStInj(5, 4)	SIR Stm. Exhst. Flow CF Pt. #5	fraction
44:1	50.00000	CfPtLd1(1, 1)	Part Ld. Level w/1 CT (PLL1) #1	%
44:2	0.26500	CfPtLd1(1, 2)	PLL1 Power Corr. Factor Pt. #1	fraction
44:3	1.18000	CfPtLd1(1, 3)	PLL1 HR Corr. Factor Pt. #1	fraction

Line #	Example Value	Variable Name	Description	Units
44:4	0.35600	CfPtLd1(1, 4)	PLL1 Stm. Exhst. Flow CF Pt. #1	fraction
45:1	55.00000	CfPtLd1(2, 1)	Part Ld. Level w/1 CT (PLL1) #2	%
45:2	0.29300	CfPtLd1(2, 2)	PLL1 Power Corr. Factor Pt. #2	fraction
45:3	1.15200	CfPtLd1(2, 3)	PLL1 HR Corr. Factor Pt. #2	fraction
45:4	0.37500	CfPtLd1(2, 4)	PLL1 Stm. Exhst. Flow CF Pt. #2	fraction
↓				
etc.				
↓				
54:1	100.00000	CfPtLd1(11, 1)	Part Ld. Lev. w/1 CT (PLL1) #11	%
54:2	0.50000	CfPtLd1(11, 2)	PLL1 Power Corr. Factor Pt. #11	fraction
54:3	1.02300	CfPtLd1(11, 3)	PLL1 HR Corr. Factor Pt. #11	fraction
54:4	0.52900	CfPtLd1(11, 4)	PLL1 Stm. Exhst. Fl. CF Pt. #11	fraction
55:1	50.00000	CfPtLd2(1, 1)	Part Ld. Level w/2 CTs (PLL2) #1	%
55:2	0.55400	CfPtLd2(1, 2)	PLL2 Power Corr. Factor Pt. #1	fraction
55:3	1.12400	CfPtLd2(1, 3)	PLL2 HR Corr. Factor Pt. #1	fraction
55:4	0.70400	CfPtLd2(1, 4)	PLL2 Stm. Exhst. Flow CF Pt. #1	fraction
56:1	55.00000	CfPtLd2(2, 1)	Part Ld. Level w/2 CTs (PLL2) #2	%
56:2	0.60400	CfPtLd2(2, 2)	PLL2 Power Corr. Factor Pt. #2	fraction
56:3	1.10400	CfPtLd2(2, 3)	PLL2 HR Corr. Factor Pt. #2	fraction
56:4	0.74400	CfPtLd2(2, 4)	PLL2 Stm. Exhst. Flow CF Pt. #2	fraction
↓				
etc.				
↓				
65:1	100.00000	CfPtLd2(11, 1)	Part Ld. Lev. w/2 CTs (PLL2) #11	%
65:2	1.00000	CfPtLd2(11, 2)	PLL2 Power Corr. Factor Pt. #11	fraction
65:3	1.00000	CfPtLd2(11, 3)	PLL2 HR Corr. Factor Pt. #11	fraction
65:4	1.00000	CfPtLd2(11, 4)	PLL2 Stm. Exhst. Fl. CF Pt. #11	fraction
66:1	0.00000	CfDB1(1, 1)	DB Firing Rate w/1 CT (DB1) #1	GJ/hr or MMBtu/hr
66:2	1.00000	CfDB1(1, 2)	DB1 Power Corr. Factor Pt. #1	fraction
66:3	1.00000	CfDB1(1, 3)	DB1 HR Corr. Factor Pt. #1	fraction
66:4	1.00000	CfDB1(1, 4)	DB1 Stm. Exhst. Fl. CF Pt. #1	fraction
67:1	10.00000	CfDB1(2, 1)	DB Firing Rate w/1 CT (DB1) #2	GJ/hr or MMBtu/hr
67:2	1.01000	CfDB1(2, 2)	DB1 Power Corr. Factor Pt. #2	fraction
67:3	1.00500	CfDB1(2, 3)	DB1 HR Corr. Factor Pt. #2	fraction
67:4	1.03000	CfDB1(2, 4)	DB1 Stm. Exhst. Fl. CF Pt. #2	fraction
68:1	20.00000	CfDB1(3, 1)	DB Firing Rate w/1 CT (DB1) #3	GJ/hr or MMBtu/hr
68:2	1.02000	CfDB1(3, 2)	DB1 Power Corr. Factor Pt. #3	fraction
68:3	1.01000	CfDB1(3, 3)	DB1 HR Corr. Factor Pt. #3	fraction
68:4	1.06000	CfDB1(3, 4)	DB1 Stm. Exhst. Fl. CF Pt. #3	fraction
69:1	0.00000	CfDB2(1, 1)	DB Firing Rate w/2 CTs (DB2) #1	GJ/hr or MMBtu/hr
69:2	1.00000	CfDB2(1, 2)	DB2 Power Corr. Factor Pt. #1	fraction

Line #	Example Value	Variable Name	Description	Units
69:3	1.00000	CfDB2(1, 3)	DB2 HR Corr. Factor Pt. #1	fraction
69:4	1.00000	CfDB2(1, 4)	DB2 Stm. Exhst. Fl. CF Pt. #1	fraction
70:1	20.00000	CfDB2(2, 1)	DB Firing Rate w/2 CTs (DB2) #2	GJ/hr or MMBtu/hr
70:2	1.01000	CfDB2(2, 2)	DB2 Power Corr. Factor Pt. #2	fraction
70:3	1.00500	CfDB2(2, 3)	DB2 HR Corr. Factor Pt. #2	fraction
70:4	1.03000	CfDB2(2, 4)	DB2 Stm. Exhst. Fl. CF Pt. #2	fraction
71:1	40.00000	CfDB2(3, 1)	DB Firing Rate w/2 CTs (DB2) #3	GJ/hr or MMBtu/hr
71:2	1.02000	CfDB2(3, 2)	DB2 Power Corr. Factor Pt. #3	fraction
71:3	1.01000	CfDB2(3, 3)	DB2 HR Corr. Factor Pt. #3	fraction
71:4	1.06000	CfDB2(3, 4)	DB2 Stm. Exhst. Fl. CF Pt. #3	fraction
72	19	NStLost	Num. of ST Ext. Power Loss Pts.[4]	
73:1	0.00000	CfMwLst(1, 1)	Extraction Steam Pressure #1	bara or psia
73:2	20.00000	CfMwLst(1, 2)	Ex. St. Press. Power Loss Point #1	kW per 1000 kg/hr or lb/hr
74:1	100.00000	CfMwLst(2, 1)	Extraction Steam Pressure #2	bara or psia
74:2	105.00000	CfMwLst(2, 2)	Ex. St. Press. Power Loss Point #2	kW per 1000 kg/hr or lb/hr
↓ etc. ↓				
91:1	1800.00000	CfMwLst(19, 1)	Extraction Steam Pressure #19	bara or psia
91:2	202.00000	CfMwLst(19, 2)	Ex. St. Press. Power Loss Pt. #19	kW per 1000 kg/hr or lb/hr
92:1	7	NExConP	Num. of Const. Cond. Pr. Lines[5]	
92:2	13	NStPwVEx	Num. of Exhst. Fl. Δ Pwr. Pts.[3]	
93	1.00000	StPwvF(1, 1, 1)	Constant Cond. Press. (CCP) #1	bara or "Hga
94:1	450.00000	StPwvF(1, 1, 2)	ST Exhst. Flow Pt. #1 for CCP #1	1000 kg/hr or lb/hr
94:2	5880.00000	StPwvF(1, 1, 3)	Δ Power Point #1 for CCP #1	kW
95:1	750.00000	StPwvF(1, 2, 2)	ST Exhst. Flow Pt. #2 for CCP #1	1000 kg/hr or lb/hr
95:2	5880.00000	StPwvF(1, 2, 3)	Δ Power Point #2 for CCP #1	kW
↓ etc. ↓				
106:1	1350.00000	StPwvF(1, 13, 2)	ST Exhst. Fl. Pt. #13 for CCP #1	1000 kg/hr or lb/hr
106:2	620.00000	StPwvF(1, 13, 3)	Δ Power Point #13 for CCP #1	kW
107	2.00000	StPwvF(2, 1, 1)	Constant Cond. Press. (CCP) #2	bara or "Hga
108:1	450.00000	StPwvF(2, 1, 2)	ST Exhst. Flow Pt. #1 for CCP #2	1000 kg/hr or lb/hr
108:2	0.00000	StPwvF(2, 1, 3)	Δ Power Point #1 for CCP #2	kW
109:1	750.00000	StPwvF(2, 2, 2)	ST Exhst. Flow Pt. #2 for CCP #2	1000 kg/hr or

Line #	Example Value	Variable Name	Description	Units
				lb/hr
109:2	0.00000	StPwvF(2, 3, 3)	Δ Power Point #2 for CCP #2	kW
↓				
etc.				
↓				
120:1	1350.00000	StPwvF(2, 13, 2)	ST Exhst. Fl. Pt. #13 for CCP #2	1000 kg/hr or lb/hr
120:2	0.00000	StPwvF(2, 13, 3)	Δ Power Point #13 for CCP #2	kW
121	3.00000	StPwvF(3, 1, 1)	Constant Cond. Press. (CCP) #3	bara or "Hga
122:1	750.00000	StPwvF(3, 1, 2)	ST Exhst. Flow Pt. #1 for CCP #3	1000 kg/hr or lb/hr
122:2	-5720.00000	StPwvF(3, 1, 3)	Δ Power Point #1 for CCP #3	kW
123:1	800.00000	StPwvF(3, 2, 2)	ST Exhst. Flow Pt. #2 for CCP #3	1000 kg/hr or lb/hr
123:2	-6020.00000	StPwvF(3, 3, 3)	Δ Power Point #2 for CCP #3	kW
↓				
etc.				
↓				
190:1	1350.00000	StPwvF(7, 13, 2)	ST Exhst. Fl. Pt. #13 for CCP #7	1000 kg/hr or lb/hr
190:2	-27010.00000	StPwvF(7, 13, 3)	Δ Power Point #13 for CCP #7	kW
191:1	4	NTConP	Num. of Const. Cond. Pr. Lines[5]	
191:2	7	NTLines	Num. of Temperature Points[3, 6]	
192	1.00000	ExFvT(1, 1, 1)	Constant Cond. Press. (CCP) #1	
193:1	20.00000	ExFvT(1, 1, 2)	Temp. Point #1 for CCP #1[6]	deg.C or deg.F
193:2	894000.00000	ExFvT(1, 1, 3)	ST Exhst. Flow Pt. #1 for CCP #1	kg/hr or lb/hr
194:1	30.00000	ExFvT(1, 2, 2)	Temp. Point #2 for CCP #1[6]	deg.C or deg.F
194:2	864000.00000	ExFvT(1, 2, 3)	ST Exhst. Flow Pt. #2 for CCP #1	kg/hr or lb/hr
↓				
etc.				
↓				
199:1	76.00000	ExFvT(1, 7, 2)	Temp. Point #7 for CCP #1[6]	deg.C or deg.F
199:2	0.00000	ExFvT(1, 7, 3)	ST Exhst. Flow Pt. #7 for CCP #1	kg/hr or lb/hr
200	2.00000	ExFvT(2, 1, 1)	Constant Cond. Press. (CCP) #2	
201:1	30.43000	ExFvT(2, 1, 2)	Temp. Point #1 for CCP #2[6]	deg.C or deg.F
201:2	1494000.00000	ExFvT(2, 1, 3)	ST Exhst. Flow Pt. #1 for CCP #2	kg/hr or lb/hr
202:1	40.00000	ExFvT(2, 2, 2)	Temp. Point #2 for CCP #2[6]	deg.C or deg.F
202:2	1438000.00000	ExFvT(2, 2, 3)	ST Exhst. Flow Pt. #2 for CCP #2	kg/hr or lb/hr
↓				
etc.				
↓				
207:1	88.64000	ExFvT(2, 7, 2)	Temp. Point #7 for CCP #2[6]	deg.C or deg.F
207:2	234000.00000	ExFvT(2, 7, 3)	ST Exhst. Flow Pt. #7 for CCP #2	kg/hr or lb/hr

Line #	Example Value	Variable Name	Description	Units
208	3.00000	ExFvT(3, 1, 1)	Constant Cond. Press. (CCP) #3	
209:1	36.71000	ExFvT(3, 1, 2)	Temp. Point #1 for CCP #3[6]	deg.C or deg.F
209:2	1846000.00000	ExFvT(3, 1, 3)	ST Exhst. Flow Pt. #1 for CCP #3	kg/hr or lb/hr
210:1	46.43000	ExFvT(3, 2, 2)	Temp. Point #2 for CCP #3[6]	deg.C or deg.F
210:2	1778000.00000	ExFvT(3, 2, 3)	ST Exhst. Flow Pt. #2 for CCP #3	kg/hr or lb/hr
↓				
etc.				
↓				
215:1	100.00000	ExFvT(3, 7, 2)	Temp. Point #7 for CCP #3[6]	deg.C or deg.F
215:2	410000.00000	ExFvT(3, 7, 3)	ST Exhst. Flow Pt. #7 for CCP #3	kg/hr or lb/hr
↓				
etc.				
↓				
223:1	113.29000	ExFvT(4, 7, 2)	Temp. Point #7 for CCP #4[6]	deg.C or deg.F
223:2	636000.00000	ExFvT(4, 7, 3)	ST Exhst. Flow Pt. #7 for CCP #4	kg/hr or lb/hr

[1] 1 = evaporative cooling tower,
2 = air cooled,
3 = river water

[2] Applicable only if rCflag = 1

[3] Maximum of 20.

[4] Maximum of 25.

[5] Maximum of 10.

[6] Temperature depends on value of rCflag (see note #1 above).
If rCflag = 1: wet bulb temperature
If rCflag = 2: ambient dry bulb temperature
If rCflag = 3: river water temperature

Note that the part load correction factor table for two CTs, CfPtLd2(), and the duct burner firing correction factor table for two CTs, CfDB2(), are only read if NumCTs = 2.

Total number of lines = 15 + NumCmpT + NumInPD + NumExPD + NumStInj + NumPtLd2 + NumPtLd1 + NumDB1 + NumDB2 + NStLost + NExConP + (NExConP ∗ NStPwVEx) + NTConP + (NTConP ∗ NTLines)

5

START-UP DIAGNOSTICS MODULE (SUDM), VERSION 1.0

Introduction

The *Start-Up Diagnostics Module* (SUDM) is a computer program that facilitates the comparison of trends from one CT start to another. Start trends such as those shown in Figure 5-1 can be compared to trends from a different start-up on the same CT or from a start-up on a different CT. Trends can be plotted against time or against other important turbine parameters such as rotor speed or fuel flow.

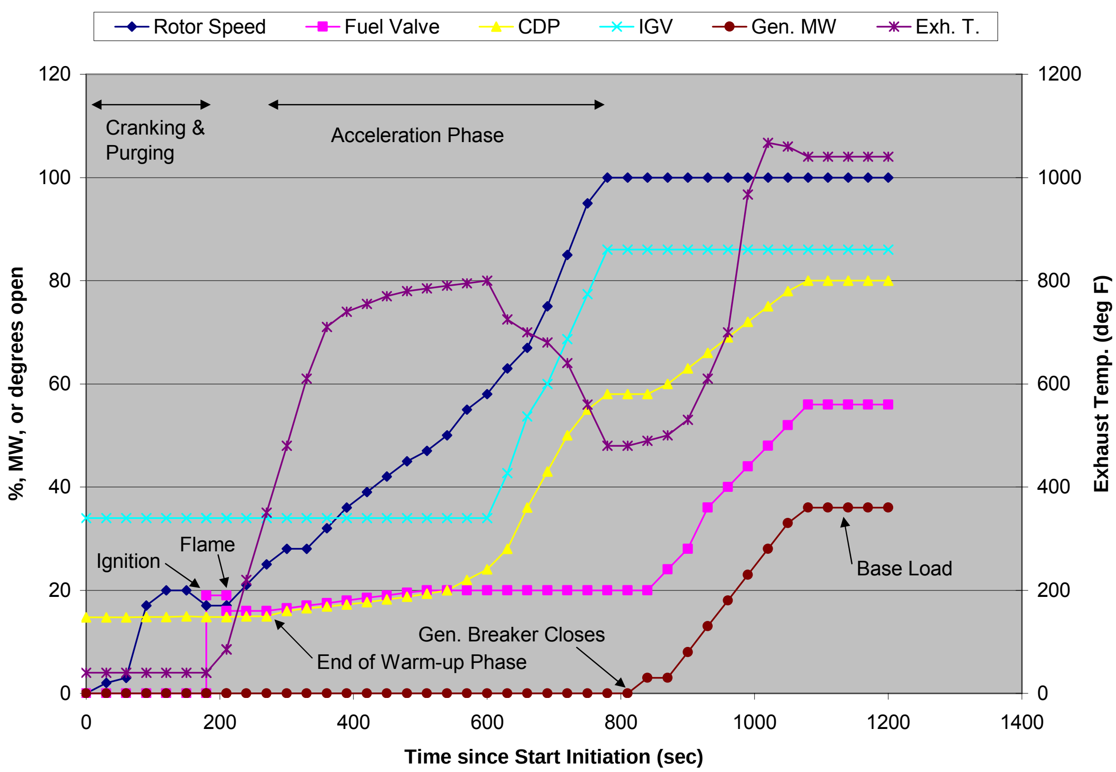


Figure 5-1
A Representative Time History Trend Chart for a CT Start-up

The SUDM can maintain a database of trends of key parameters collected during the various start-ups of a CT. A user can then compare the trends of the most recent start-up or start-ups to a baseline trend that was obtained when the CT started successfully. A user has the ability to define different baselines for different types of operation (e.g., fast starts and normal starts, natural gas starts and distillate starts, cold weather starts and warm weather starts, cold CT starts and warm CT starts, etc.).

The SUDM will work in a “look back” mode after a start-up is completed rather than in “real time” during a start-up. The reason for this is that most start-up sequences are completely automated leaving very few actions for the operator to take which can influence the success of a start. In addition, many of the sequences during a start-up take place so quickly that there would be no time to react.

Instead, the strategy for using the SUDM will be to examine a start after it has happened and compare it to a “reference” start in an effort to detect changes that have occurred in the engine or control system that could impact the reliability of future starts.

Program Design

SUDM operates in Windows 2000 and Windows XP using Microsoft Office 2000 or 2002 applications.

SUDM, with two exceptions, is “self-contained” software meaning no other software programs will need to be installed on the user’s PC in order to use SUDM. The two exceptions are the PC will also require:

- Excel 2000 or 2002
- OSI’s PI DataLink 2.0

PI Datalink is an Excel add-in for accessing data from a PI database. It is assumed that the PI database server will be installed on a separate computer.

SUDM has been developed using Microsoft’s Access 2003 with royalty-free runtime license provided with Microsoft Visual Tools for Office 2003.

Program Overview

SUDM has five basic functions:

- Start-up data retrieval via PI DataLink to an Excel spreadsheet
- Start-up data import from an Excel spreadsheet into a Microsoft Access Database file
- Ploting trend charts for a single start-up
- Creating “overlay” trends charts for comparing trends from two start-ups
- Database adminstration functions (e.g., deleting starts, remaining starts, etc.)

Detailed descriptions of these five functions can be found in sub-section heading "SUDM Description & Users Manual".

Vision and Module Development

Vision

By comparing trends from recent start-ups against trends from a start when a CT was known to be in good condition, it is possible to detect and diagnose problems before they impact starting reliability.

In many deregulated markets there is an added financial incentive for maintaining high starting reliability. If a CT owner makes a bid to deliver power at a certain time and at a certain price and that CT fails to start at the appointed time, the CT owner must purchase the amount of power it agreed to provide from the spot market. If the spot price is higher than the CT owner's bid price, the difference must be absorbed by the CT owner. Concerns about getting "caught with their plants down" have actually caused some CT owners in marginal power markets to decline to bid into the market even when it would appear to be attractive to do so.

EPRI's SUDM is meant to be a simple tool that can assist CT engineers in diagnosing start-up related problems. The simple premise is that a CT engineer can identify at least one "good start" which can serve as the "gold standard" by which all other starts are judged. In this report, such a start is referred to as a "reference start".

To facilitate a comparison between starts, SUDM allows the user to "overlay" the trend lines of the start of interest (the "analyzed start") on top of the trend lines of the reference start. In many cases, the trend lines will plot time in the x-axis, but there are situations in which other parameters may be plotted such as rotor rpm that will provide additional insight. For example, vibrations are typically a function of rotor speed. Consequently, when comparing the vibrations from an analyzed start to the vibrations of the reference start, it would make sense to base the overlay plot on rotor rpm. That way the user can compare the vibration levels at the same rpm levels.

Problems to Look For During Start-Ups

A typical gas turbine starting sequence can be grouped into the following phases:

- Cranking & Purge
- Ignition
- Warm-Up
- Acceleration
- Synchronization

The starting sequence begins with the Cranking & Purge phase. During this phase the turbine rotor is turned entirely by a starter motor of some type - usually an electric or diesel motor. Once the rotor reaches a pre-determined speed (well below the rated speed of the engine) a purge timer begins. The purpose of the purge time is to ensure that sufficient volumes of fresh air have passed through the turbine and its exhaust system in order to lower the concentration of any combustible gases to well below their lower flammability limits. This will prevent an explosion in the exhaust system when the CT lights off.

Once the purge timer has expired, the starting sequence enters the Ignition phase. In this phase the CT control system adjusts the fuel control valve to a pre-determined percent open position, while the fuel stop valve remains closed. The control sequencer then energizes the spark plug or igniter in the combustion section of the CT and opens the fuel stop valve to allow fuel to begin flowing to the combustion section. The sequencer starts an ignition timer. The flame "eyes" within the combustion section must report back with a positive flame signal before the ignition timer expires or the start will be tripped (i.e., fuel stop valve closed, igniter de-energized, trip purge sequence started).

If the flame eyes do report back a positive signal before the ignition timer expires, then the starting sequence enters the Warm-Up phase. The purpose of the Warm-Up phase is to minimize the thermal shock of a start on the hot section of a gas turbine and the downstream equipment. Typically the Warm-Up phase will last on the order of 60 seconds. Because heat is being released in the combustor, the CT is exerting some work on the rotor and the rotor will speed up. To limit the rate of acceleration during the Warm-Up stage, the fuel control valve will actually close off some compared to its value during ignition. In Figure 5-1 the change in fuel control valve position is seen as a step function at the end of the Ignition phase.

Once the Warm-Up timer has expired, the starting sequence enters the Acceleration phase. During this phase the turbine rotor speeds up until it approaches the rated speed of the engine. Fuel flow is increased with a ramping function. The rate of acceleration is monitored and the fuel ramp can be temporarily halted if the acceleration rate reaches the OEM's limit. As seen in Figure 5-1, the exhaust temperature increases rapidly during this phase and then falls as air flow through the turbine increases. The starter motor also disengages during the Acceleration phase when the rotor speed reaches a pre-set level.

Once the rotor speed reaches its rated 100% value, the starting sequence enters the Synchronization phase. During this phase, the control system adjusts the turbine speed and generator exciter current to match the frequency, phase, and voltage of the grid. Once all three parameters are synchronized, the generator breaker closes and the generator is connected to the grid. At that point the CT is operating at its "*Full Speed, No Load*" (FSNL) condition. This is usually defined as the end of the starting sequence; however, the CT then has to be ramped up to the load level that is desired

Potential problems can appear in each phase, and the SUDM reference start overlay technique can be used to identify those problems. Some examples are provided in this sub-section.

Slow to Reach Purge Speed

As a starter motor degrades, the time it takes for the rotor to come up to purge speed will increase. If the overlay chart of rotor speed versus time shows a slower rate of increase for the analyzed start compared to the reference start, this could be an indication of problems with the starter motor. For example, in Figure 5-2, "Start3" took 90 seconds longer to reach the purge speed when compared to the other two starts examined. This could be a sign that the starter motor on this turbine has degraded and needs maintenance.

However, it could also be an indication of increased friction within the CT itself. If a CT is slow to reach its purge speed, the user should also examine an overlay chart of vibrations versus rotor speed over the range from 0 rpm to the purge speed. If the vibrations from the analyzed start are significantly higher, this is an indication that the fault lies within the CT and not with the starter motor.

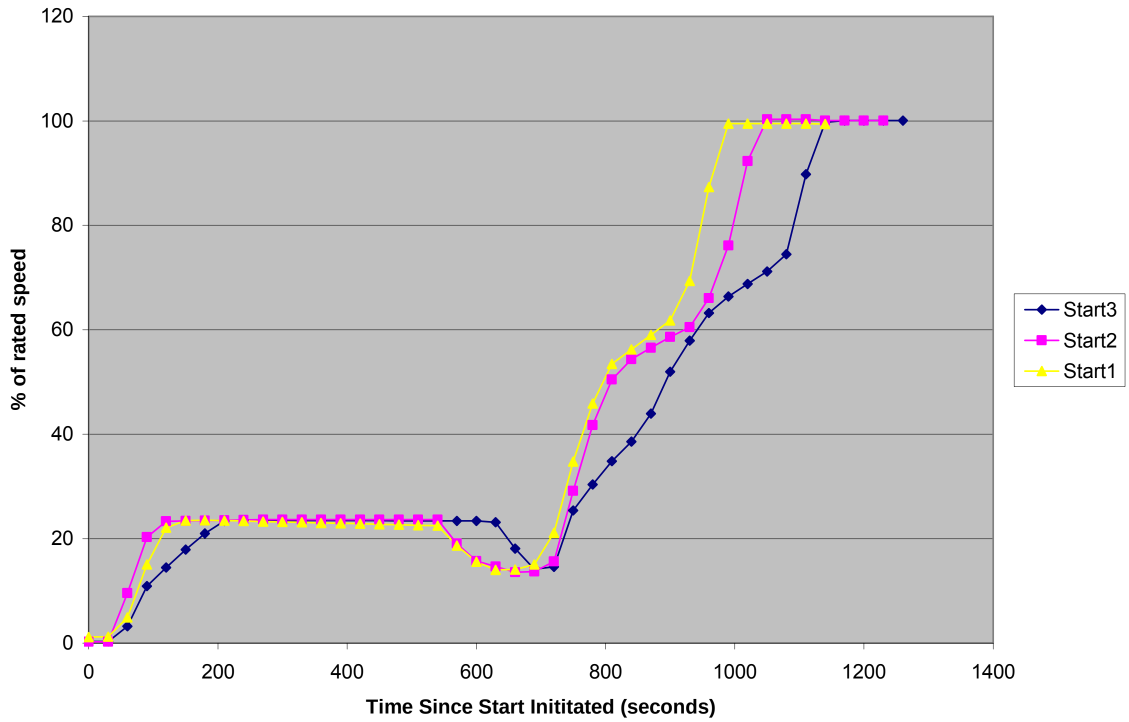


Figure 5-2
Overlay Trend Chart showing Rotor Speed versus Time for Three Starts on the Same Machine

Failure to Light-off

At least two possible scenarios could lead to a tripped start caused by a failure to light-off during the Ignition phase. The first scenario is a failure of the flame eye to detect an actual flame. The second scenario is an actual failure to light-off.

The difference between the two scenarios can easily be determined by examining an overlay chart of the trends of the fuel valve position (FSR) and exhaust gas temperature (EGT) versus time. If EGT ramps up as quickly in the analyzed start as it did in the reference start, then the problem lies in the flame detector. On the other hand, if the EGT does not ramp up at all or the ramp is delayed or slower than the reference, this is an indication of a true failure to light-off. The root cause of the problem could be the ignitor or the fuel nozzles, or the fuel supply system.

There is no need to wait until a CT has a tripped start to detect an imminent failure to light-off. Since the FSR value drops as soon as a positive flame is detected, one can use the time between the point that the FSR reaches its ignition value and the point that it is reset to the warm-up value as an indicator of the length of time to reach a positive flame signal. If this time in an analyzed start is significantly longer than the reference start, the user should examine the EGT trends and determine whether the flame eye is slow to detect a real flame or a real flame is slow to appear. Maintenance actions can be determined accordingly.

Slow to Accelerate

If a longer acceleration phase is needed to get the CT up to 100% speed, this could be a sign of several potential problems. Among these are:

- Degraded starter motor
- Rubbing
- Fouled Compressor
- Faulty Compressor Bleed Valve

The first two problems can be evaluated in the same manner as outlined earlier in under sub-section heading “Problems to Look for During Start-Ups”. A fouled compressor can be detected with an overlay chart of compressor discharge temperature (CDT) versus compressor discharge pressure (CDP). Ideally the ambient temperature should be similar for both the reference start and the analyzed start, but even if it is not, if the slope of the CDT line for the analyzed start is steeper than the slope of the reference start, this is an indication of reduced compressor efficiency.

A faulty compressor bleed valve could result in the valve not fully closing. If this happens, some of the turbine’s power, which would be accelerating the rotor, will be wasted by compressing air that is bled off. Detection of this problem may be difficult unless the bleed valve has a position sensor with feedback to the control system that can be trended. Typically the bleed valve is adjusted based on rotor speed, so a trend chart of valve position versus speed would be the best choice for detecting deviations from the reference start.

A second method for detecting a leaking bleed valve is to monitor the air temperature downstream of the valve. Some CTs have a thermocouple in the air bleed line specifically for this purpose. In other CTs the bleed air is routed back to the inlet duct of the turbine. For CTs with that set-up, the deviation between ambient temperature and compressor inlet temperature can be used as an indicator of bleed valve leakage.

High Exhaust Gas Temperature Spread

If the difference between the hottest and coldest thermocouple in the CT exhaust exceeds the OEMs guidelines, the protection system will trip the unit to avoid damaging the engine. High exhaust gas temperature spreads are caused by a variety of problems, but the two most common are fouled fuel nozzles and unequal combustion liner air flow (caused by cracks in the liner or out-of-spec manufacturing). For CTs burning liquid fuel, sticky check valves in the liquid fuel lines are also a frequent cause of high spreads.

In order to prevent a start from being tripped by high EGT spread, it is important to monitor the EGT spread from each start. Since the trip value for EGT spread is typically a function of the average exhaust gas temperature, the most meaningful overlay chart would plot EGT spread versus average EGT. If the trend line for the analyzed start is getting close to the trip values, maintenance should be planned for the fuel nozzles. If switching out the fuel nozzles does not cure the problem, the combustion liners should be inspected.

Degraded DLN Fuel Nozzles

Start-up operation is very taxing on dry, low NO_x fuel nozzles. Often the nozzles operate in non-premixed mode or with a pre-mixed flame very close to the tips of the nozzles during start-up. This can damage the fuel nozzles and cause the orifices of the nozzles to be enlarged.

An enlarged orifice will allow more fuel flow at a given supply pressure. Consequently, an overlay plot of fuel manifold pressures versus fuel flow can reveal a damaged fuel nozzle (this is also true for non-DLN fuel nozzles).

Detecting an enlarged fuel nozzle orifice is also a safety issue. The fuel valve position at ignition is set to provide the proper amount of fuel to allow a combustible fuel-air mixture to be present in the combustor. If the nozzle orifices are enlarged, more fuel will flow at the ignition setting and could result in a fuel-air mixture that is too rich for light-off. However, once cooling air flows are added to the mixture, it could fall back within the fuel's flammability limits and pose a danger of explosion if it finds a hot spot.

Module Development

Several potential options were considered for the structure of the SUDM. First, building the module in an Excel spreadsheet was considered. This is the platform that was used for the *Remaining Life Module* (RLM) and *Combustion Turbine Performance Fault Diagnostic Module* (CTPFDM). However, because of the large number of start-up data sets that could potentially be used in SUDM, it was determined that Microsoft's database software package, Access, would be a better choice for SUDM.

Since many users will not necessarily have Access already installed on their PCs and since they may not be familiar with Access' commands, it was decided to develop a self-contained executable program that contained the capabilities of Access, but had simplified commands and options. The program was developed using Microsoft's Visual Tools for Office 2003. The executable automatically opens a specific Access 2003 database file named SUDM.mdb.

While the ideal design would have allowed the user to extract data directly from a PI database into the SUDM database, it was learned that the PI database supplied with most GE turbines does not allow any third-party program to query it. Consequently, PI data must be extracted using

Excel and the PI DataLink Add-In. Once the data is saved as an Excel file, it can be imported into SUDM.mdb. To make this process easier, a macro was built into SUDM that starts Excel and imports a pre-defined set of tags into Excel. More information on this macro is provided later under the sub-section heading "Retrieve Start Data from PI Database".

An unexpected issue arose once development of the program was started. The charting capabilities of Access are different (and less sophisticated) from those in Excel. It proved impossible to create meaningful overlay charts using the Access charting package. To overcome this drawback, a macro was created in SUDM that causes overlay charts to be created in a new Excel spreadsheet using the Excel X-Y chart type. While this is again less than ideal, it does provide the important overlay charting tool, and it is hoped that future versions of SUDM will be able to generate overlay charts within Access.

SUDM Description & Users Manual

Installation

INCLUDE THE INSTALLATION STEPS HERE AND HOW TO START THE APPLICATION.

Main Program Functions

SUDM has four main program functions:

- Importing data into the SUDM.mdb Access file
- Extracting data from PI via Excel and PI DataLink
- Graphing data from a single start
- Producing overlay charts using data from two starts

Each of these four functions is invoked by clicking on the appropriate button displayed in the main SUDM screen (see Figure 5-3).

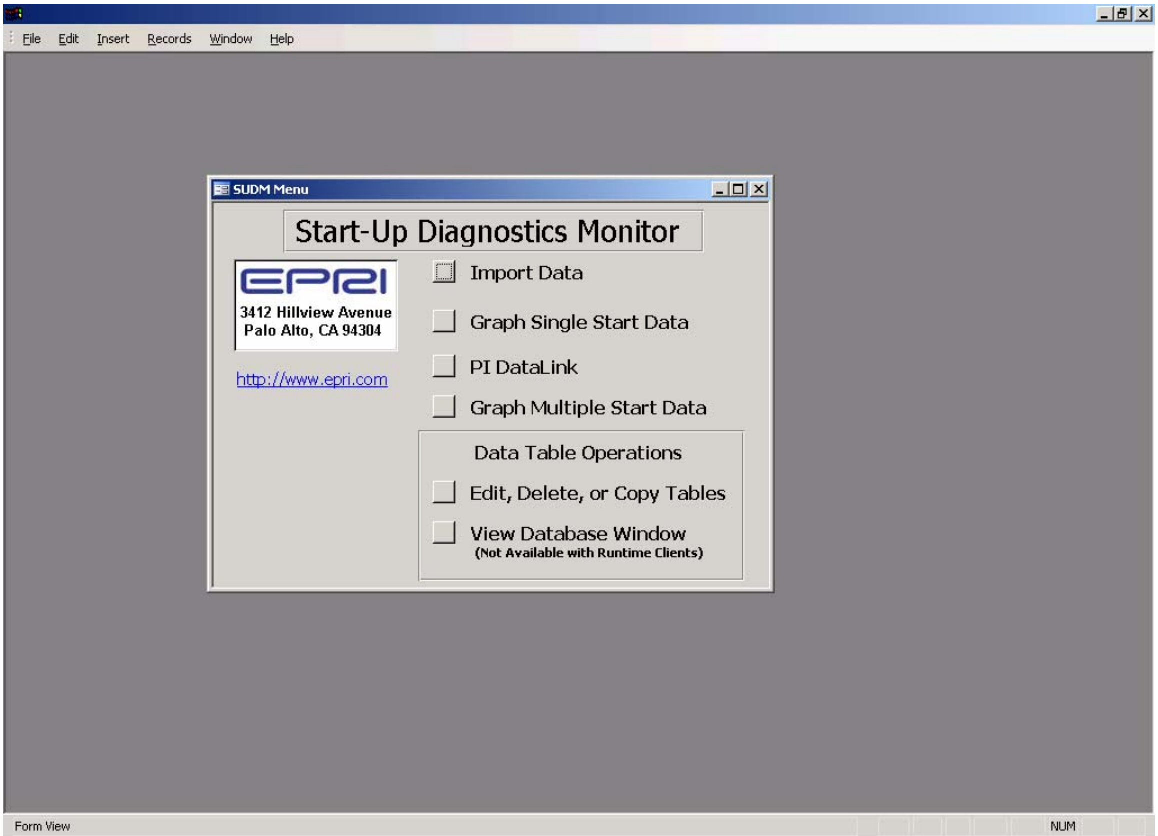


Figure 5-3
Main Screen of SUDM showing the Four Main Functions

In addition to the four main functions, SUDM has two data table administration functions, which allow the user to modify or delete the tables that contain the start-up data.

Import Data into Access Database

Since it was developed with a run-time version of Microsoft Access, SUDM can import any type of data file that has a format recognizable by Access. These file types include: Access databases (*.mdb), Excel spreadsheets (*.xls), Text files (*.txt, *.csv), and dBase databases (*.dbf).

When the button labeled "Import Data" is clicked, the "Import" form is displayed (see Figure 5-4). The user should first click on the "Step 1" button labeled "Import Data". This will cause the familiar "file explorer" window to open, and the user can search for the file that is to be imported (see Figure 5-5). By default the file explorer displays only Access files, but the user can change the type of files that is displayed by selecting a different type in the "Files of Type" scroll-down menu.

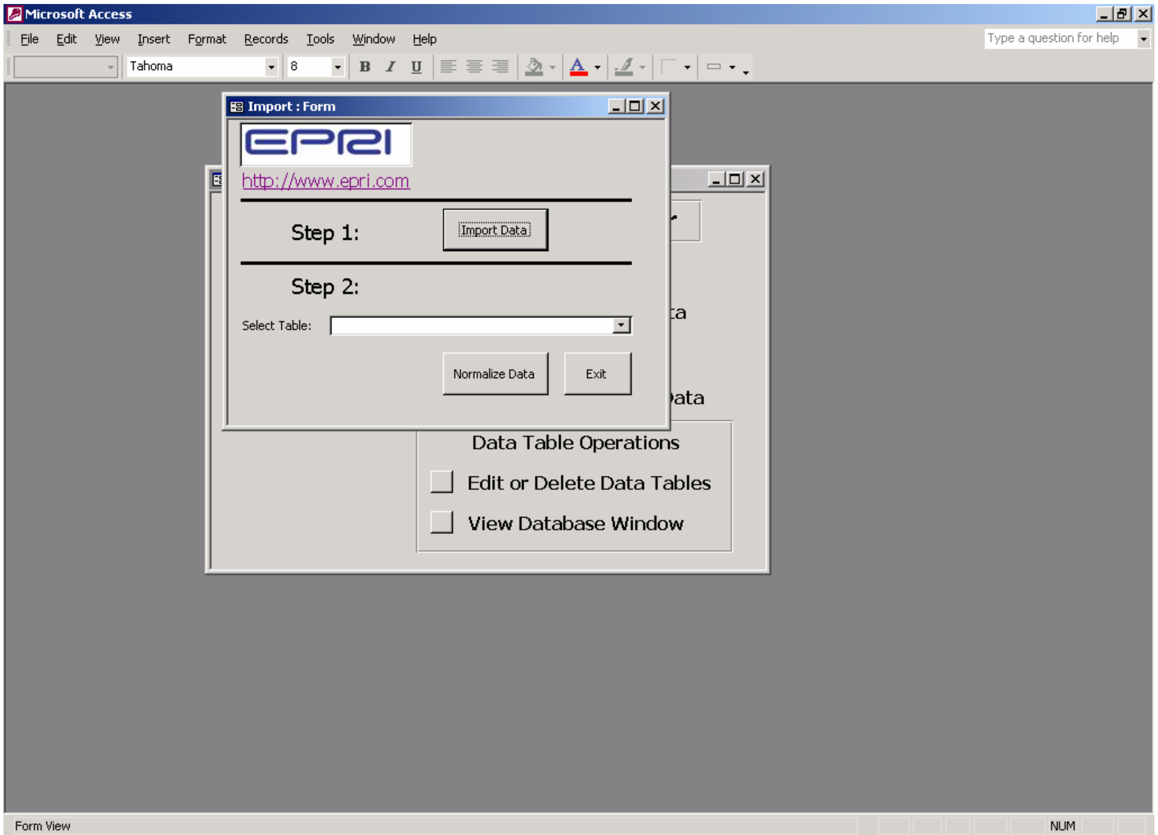


Figure 5-4
Two-step "Import" Form that appears when "Import Data" Function is selected from SUDM Main Menu

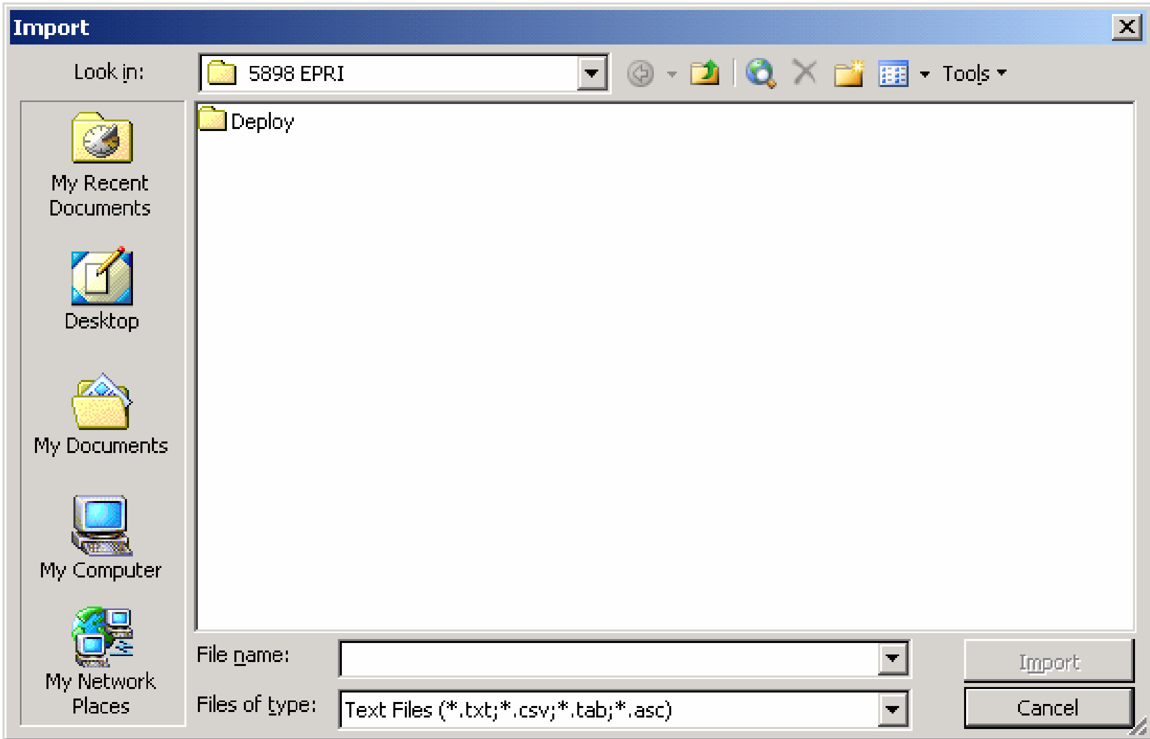


Figure 5-5
"File Explorer" Window that Appears when "Import Data" is Selected by User

Once a specific file is selected, the "Import" button on the "file explorer' window will be highlighted and the user should click on it. This will start a built-in Access "wizard" which will walk the user through the process of importing the contents of the file into an Access database table. During this process the user will type a name for the new Access table that will store the imported data. (Note: if the user is importing a file with a list of PI tagnames that will be used for retrieving start data via PI DataLink, the option "no index" must be selected.)

If the imported data was process data from a start, then the data must be "normalized" to allow proper display of the data in overlay charts. The normalizing process is initiated by clicking on the Step 2 "Normalize Data" button in the Import form (Figure 5-4). This will start a macro which will generate a new column of data in the process data which will show the amount of time since the beginning of the start. The beginning is arbitarily defined as the timestamp of the first data in the data set. If this is not the appropriate start time, the data can be edited later (see subsequent sub-section heading "Data Table Administrative Functions").

Retrieve Start Data from PI Database

A macro has been created in SUDM to help automate the retrieval of data from PI via Excel and PI DataLink. Before this macro can be used, the user must first import a list of PI database tag names. This list will then form the group of tags, which will be extracted from PI. The user may also import multiple tag name lists and then chose among those lists for the set of tags wanted for a specific query. For example, the user might have one set of tags for one CT and another set for a different CT.

Once at least one list of PI tag names has been imported into SUDM, the user can start the PI DataLink macro by clicking on the "PI DataLink" button in the SUDM main menu. A new form labeled "AcquireData" will appear as shown in Figure 5-6.

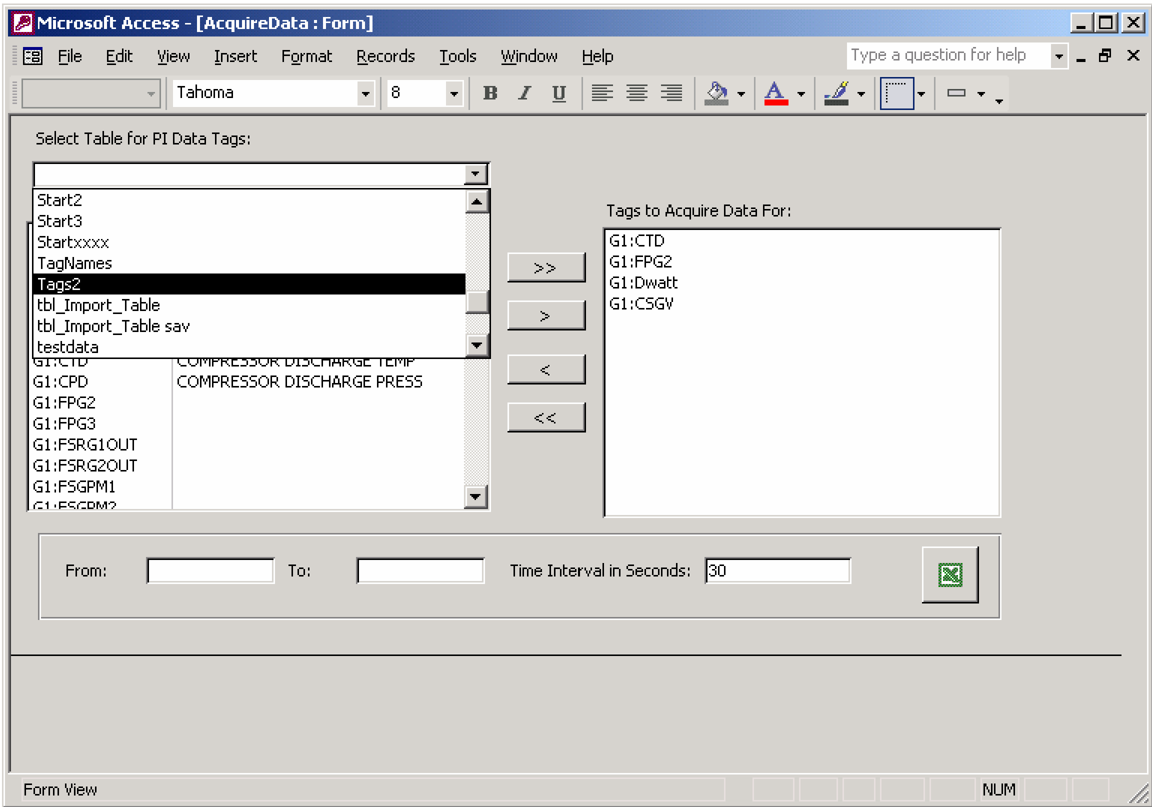


Figure 5-6
PI DataLink Setup Form showing Scroll-Down Menu with the Names of all the Tables in the SUDM.mdb Database

The user must then select the Access table that contains the list of PI tag names he or she wishes to import. Once one of the tables is selected, the list of tags in that table will be displayed in the left-hand window of the AcquireData form (see Figure 5-7). If the user then determines that the wrong table has been selected, a different table can be selected again using the pull-down menu labeled "Select Table for PI Data Tags:".

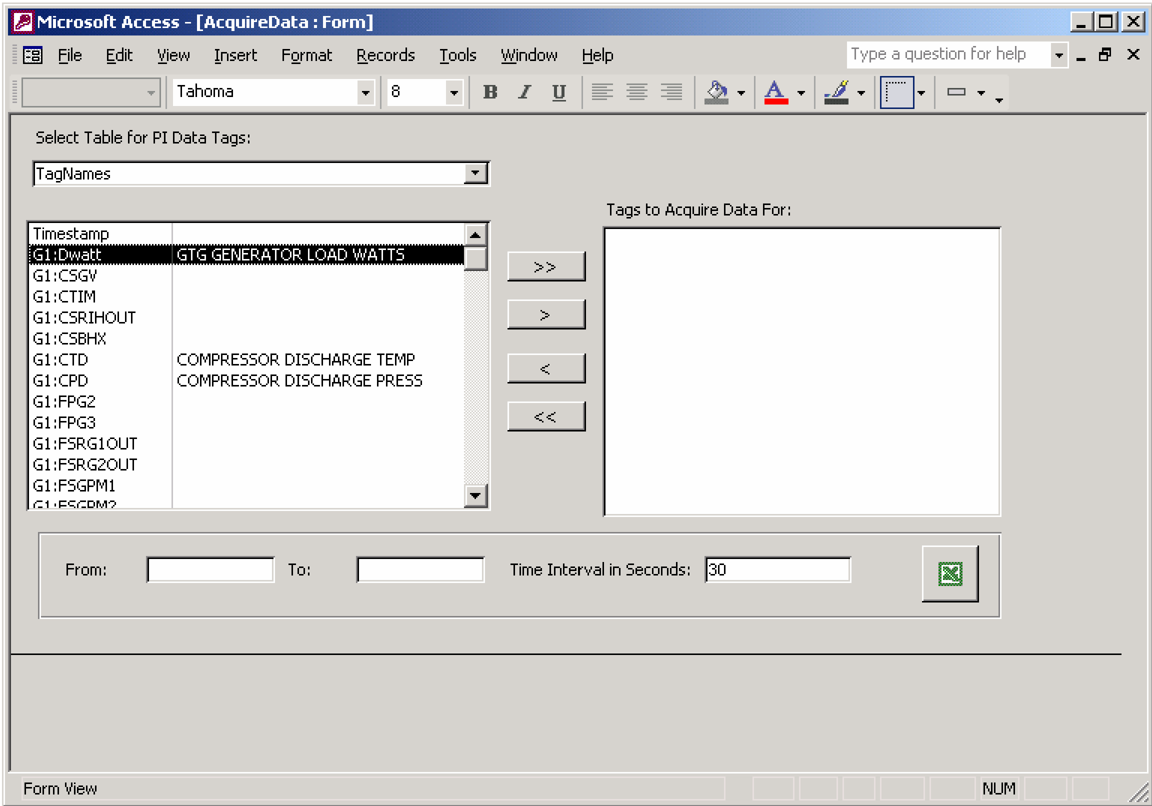


Figure 5-7
PI DataLink Setup Form Showing Contents of File Selected from Scroll-Down List

Once the user has selected the correct list of tag names, the user must then select which tag names should be used in the current query of the PI database. If the user wants to retrieve data for each tag in the list, the ">>" button in the middle of the AcquireData form should be selected. The user will then see the entire list in the right-hand window of the form.

Individual tags can be added to or removed from the selected tag list by clicking on the tag of interest and using either the ">" (add) or "<" (remove) button. The entire list of selected tags can be cleared by clicking on the "<<" button.

The user must then enter the start date and time and end date and time of the start interval of interest (expected format is MM/DD/YEAR HR:MN:SC) and also enter in the data frequency interval for the PI query. These settings are entered in the three boxes on the lower portion of the form.

Once the user has specified all the settings, the button with the Excel symbol in the lower-right of the AcquireData form should be clicked. This will open up a new Excel spreadsheet and paste the list of selected tag names across the first row of the worksheet and then fill each column with the PI data via DataLink queries.

Once the PI data query has been completed, the macro will save the Excel file as AcquireMMDDYYHRMN.xls where MMDDYYHRMN are the numbers corresponding to current date and time. The contents of the spreadsheet can then be imported into SUDM using the "Import Data" function.

Single Run Trend Charts

After data from a particular start has been imported into SUDM, trend charts of that data can be easily generated using the "Graph Single Start Data" button in the SUDM main menu. When that button is selected, the "graph" form appears as shown in Figure 5-8.

To produce a graph, the user must first select the Access table that contains the start data of interest using the pull-down menu labeled "Select Table". Once a table is selected, a list of the variables in the table will be displayed in the left-hand window labeled "Select Y-axis Variables". The user should select the variable to appear in the trend chart by clicking on the variable and then clicking on the ">" button in the middle of the form. All of the selected variables will then appear in the right-hand window labeled "Y-Axis Variables". The user must then select the variable to be plotted as the x-axis in the chart. If time-based trend is desired, the user should select the "timestamp" variable for the start.

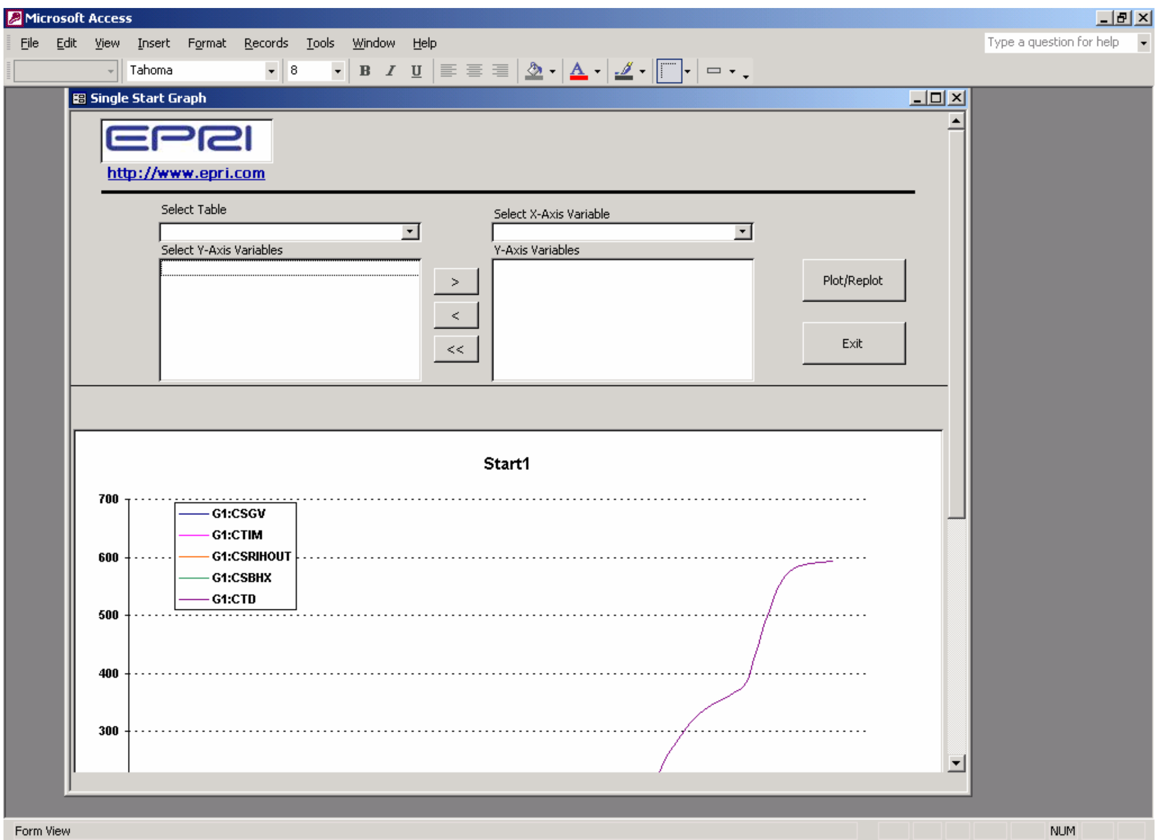


Figure 5-8
Set-up Screen for Single Start Graphs

Once all of the chart parameters have been selected, the new chart will be generated and displayed in the lower half of the form when the "Plot/Replot" button is clicked. An example of a chart with all of the parameters set is shown in Figure 5-9.

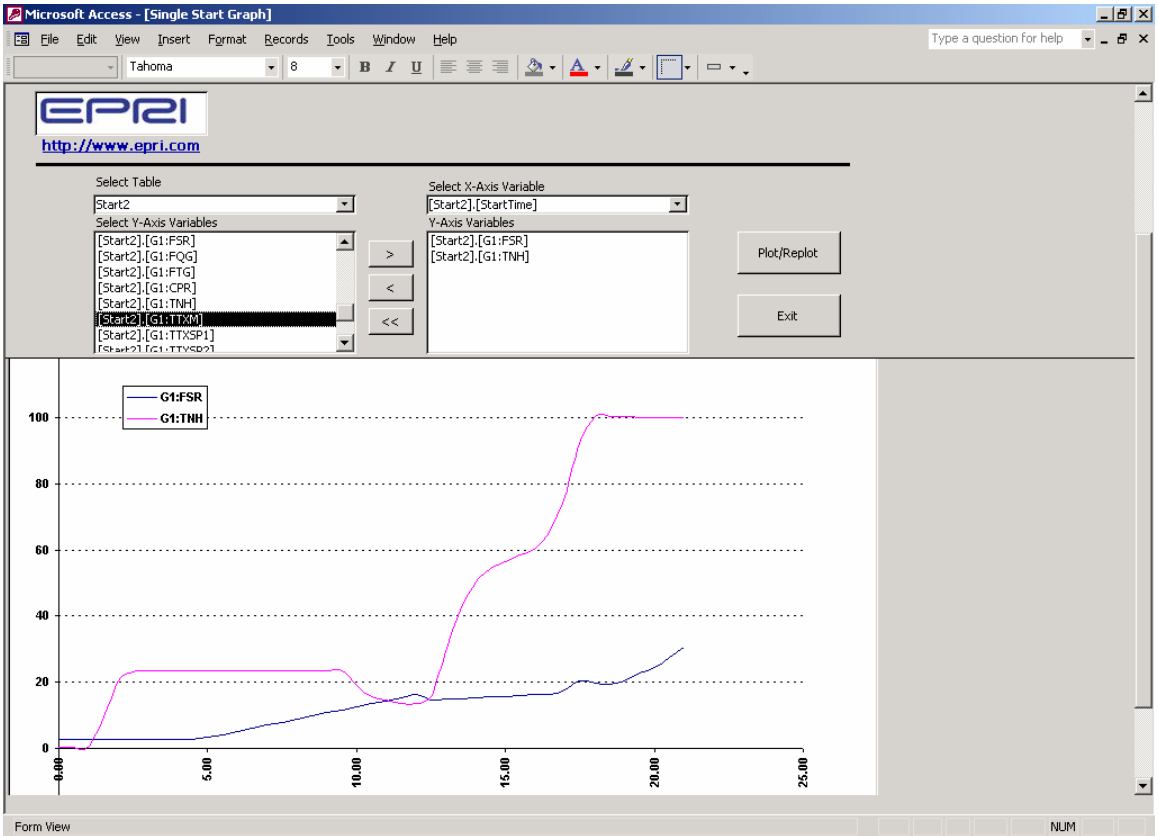


Figure 5-9
Example of a Single Start Trend Chart

A trend chart can be printed by selecting "File/Print" from the title bar menu of SUDM. A "print preview" function is also available.

Start Comparison Charts

Trends from two starts can be compared by clicking the "Graph Multiple Start Data" button on the SUDM main menu. When that button is clicked, the form "GraphMulti" appears (see Figure 5-10).

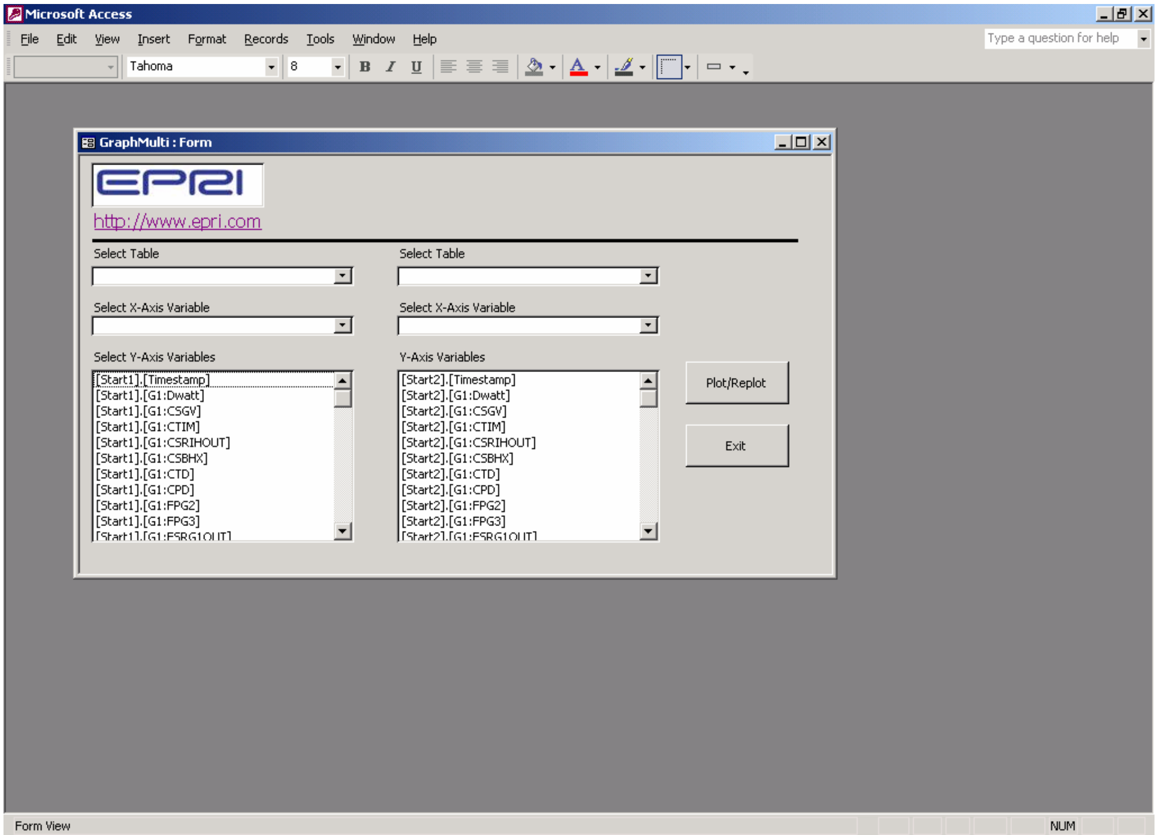


Figure 5-10
Multi-Start Chart Set-up Form

The user must select the two tables that contain the data from the two starts of interest using the pull-down menus labeled “Select Table”. The desired X-axis variable for each start should be selected from the pull-down menus labeled “Select X-axis Variable”. If the user wants an overlay time trend chart, the variable “StartTime” should be selected rather than Timestamp. StartTime is the time-since-beginning-of-start variable, which was generated using the “Normalize Data” button shown in Figure 5-4.

The user should then select the variable or variables to be plotted in the trend charts by clicking on the variable names in the windows labeled “Select Y-axis Variables”. Multiple Y-Axis Variables can be selected by simply clicking on more than one variable, while holding either the Shift or Ctrl key.

Once the user is has made all of the desired selections, the Plot/Replot button should be clicked. This will cause a new Excel spreadsheet to be opened up and the selected data will be written to the spreadsheet and plotted in an Excel X-Y chart (see Figure 5-11). Once the chart has been created, the user can manipulate it using the standard Excel chart commands.

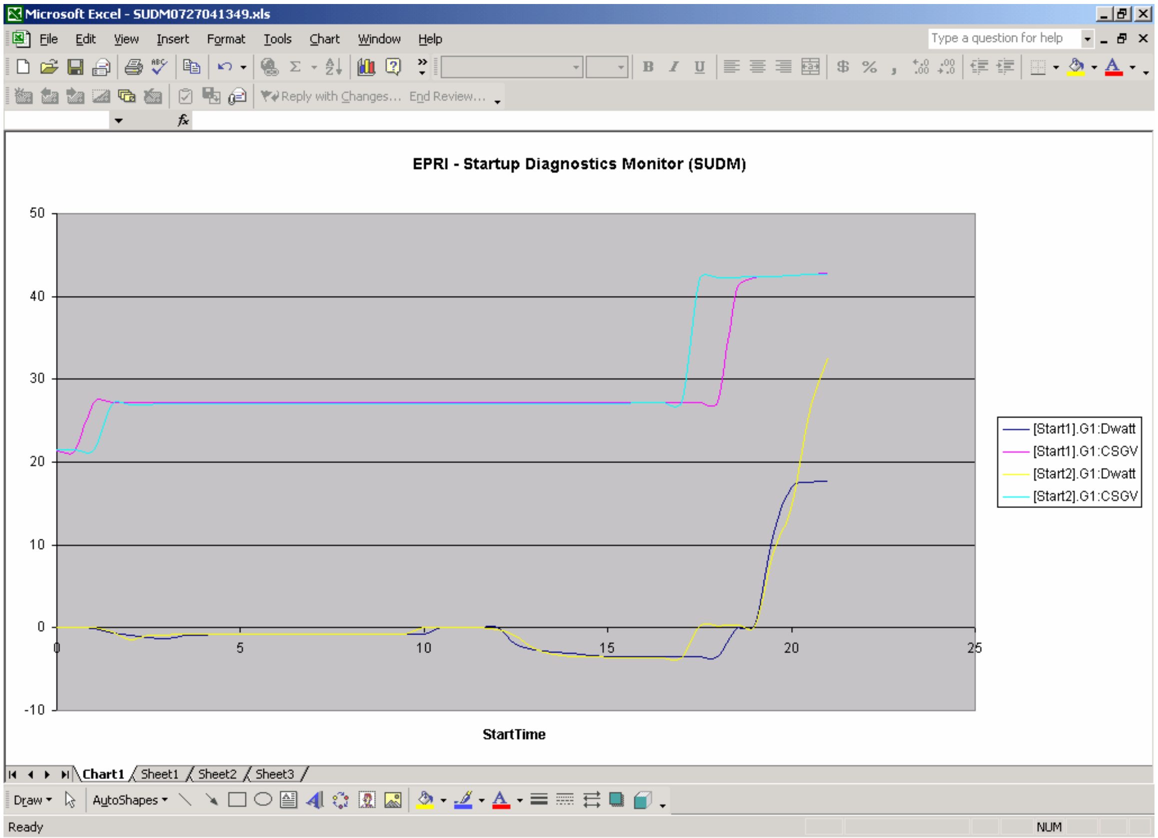


Figure 5-11
Multiple Start Trend Chart Generated in Excel Spreadsheet via an SUDM Macro

Data Table Administrative Functions

SUDM allows a user to edit or delete tables via the "edit or delete data tables" button in the main menu. That action causes a new form to appear in which the user is prompted for the name of the table of interest (Figure 5-12). The user can then select either the "Delete Table" button or the "Edit Table" button.

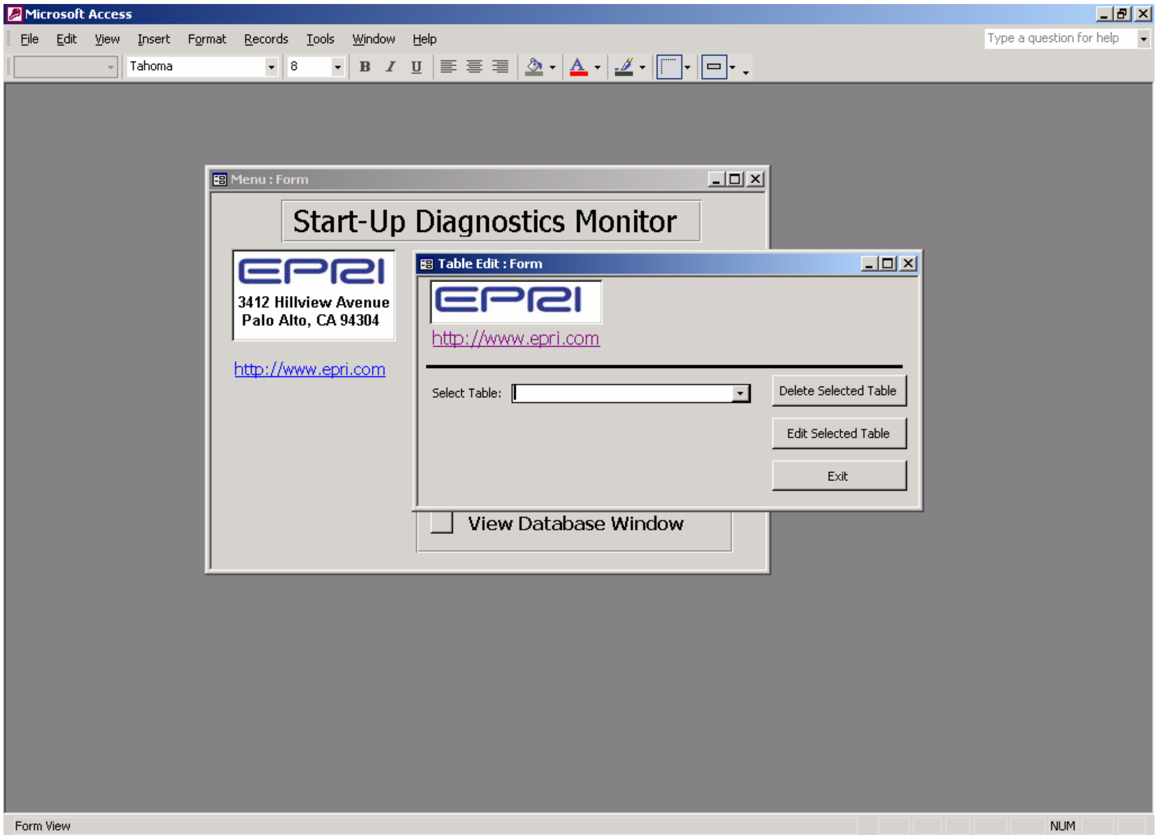


Figure 5-12
Delete or Edit Data Table Screen

If the edit table button is selected, the table is opened in the standard Access view (see Figure 5-13), where the entries can be modified or new lines (called "records" in Access) can be added or existing records can be deleted.

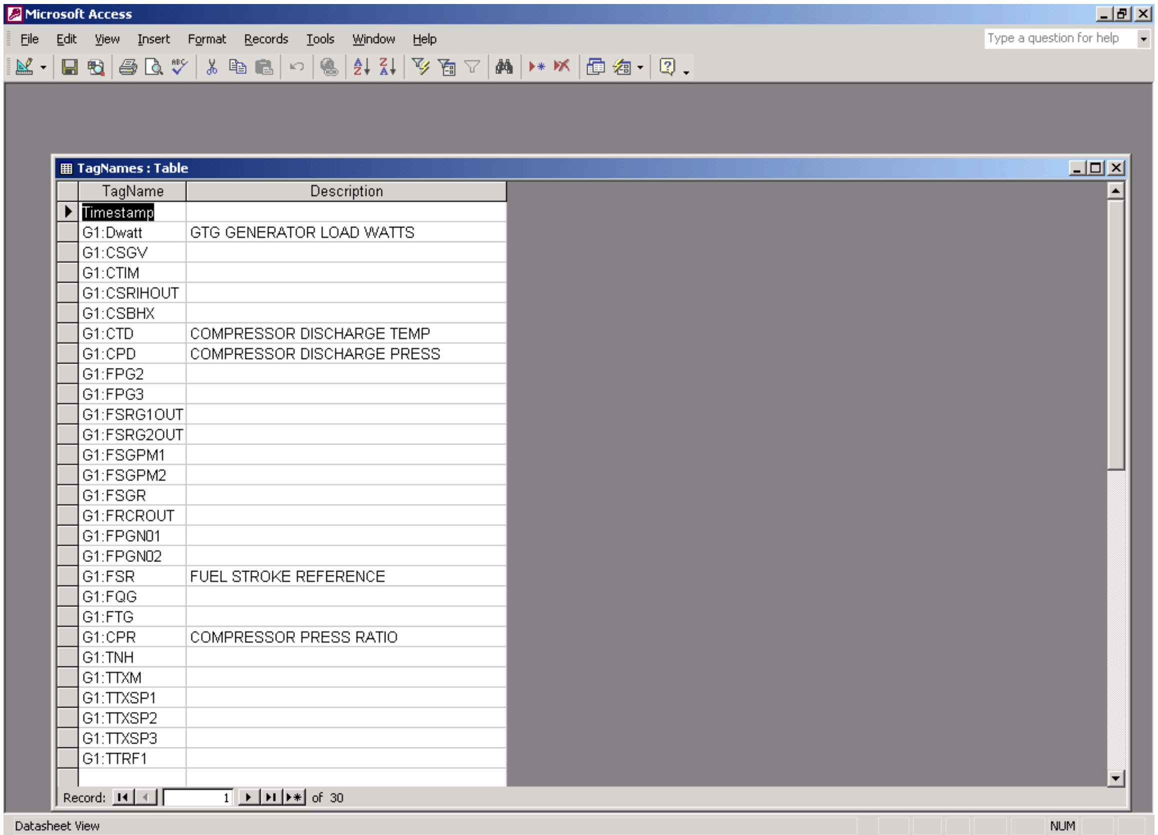


Figure 5-13
Data Table Open for Editing

For users with a full license of Access installed on their computer, the SUDM main menu button labeled "View Database Window" will allow the user to open the SUDM.mdb database with the standard Access user interface (see Figure 5-14). The user should refer to Microsoft's user manual for Access for an explanation of the various functions available in the Access user interface.

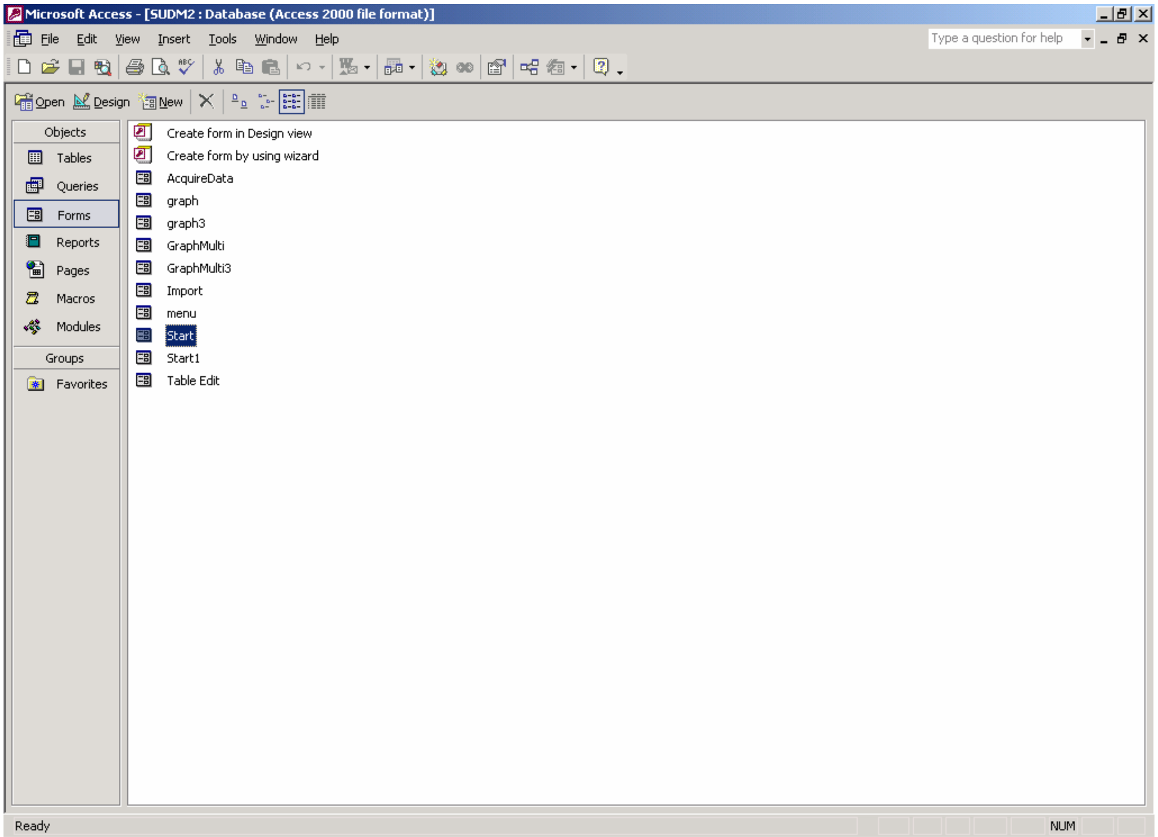


Figure 5-14
Standard Access user interface (accessible via View Database Window button)

Example Results

To facilitate initial testing during the development phase, Progress Energy supplied example start-up data from three starts from one GE 7FA (PG 7241) combustion turbine in its fleet. The data from the three starts was imported into SUDM.

Table 5-1 lists the parameters that were included in the data sets. This sub-section provides an overview of the results that were obtained from SUDM when viewing the example data.

Table 5-1
List of Parameters Included in 7FA Start-Up Data Tables

TagNames	Description
Timestamp	
G1:Dwatt	Generator Output
G1:CSGV	INLET_GUIDE_VANE_DEGREES
G1:CTIM	COMPRESSOR_INLET_TEMPERATURE
G1:CSRIHOUT	Compressor Bleed Valve Position
G1:CSBHX	Inlet Heating Control Valve Position
G1:CTD	COMPRESSOR_DISCHARGE_PRESSURE
G1:CPD	COMPRESSOR_DISCHARGE_TEMPERATURE
G1:FPG2	GAS FUEL INNERVALVE PRESSURE
G1:FPG3	GAS FUEL PRESSURE (ABSOLUTE)
G1:FSRG1OUT	PM1 Gas Control Valve Servo Command
G1:FSRG2OUT	PM2 Gas Control Valve Servo Command
G1:FSGPM1	PM1 GCV Position Feedback
G1:FSGPM2	PM2 GCV Position Feedback
G1:FSGR	SPEED RATIO VALVE CALIBR POS
G1:FRCROUT	Fuel Gas Speed Ratio Servo Command
G1:FPGN01	PM1 Fuel Manifold Press - CPD
G1:FPGN02	PM2 Fuel Manifold Press - CPD
G1:FSR	Gas Fuel Valve Setpoint
G1:FQG	Gas Fuel Flow Rate
G1:FTG	FUEL GAS TEMPERATURE
G1:CPR	COMPRESSOR PRESSURE RATIO
G1:TNH	Rotor speed
G1:TTXM	Average Exhaust Temp.
G1:TTXSP1	Exhaust Temp Spread 1
G1:TTXSP2	Exhaust Temp Spread 2
G1:TTXSP3	Exhaust Temp Spread 3
G1:TTRF1	Reference Firing Temp

Start-Up Trends

The time trends of six principal parameters for the three starts are shown in Figures 5-15, 5-16, and 5-17. The charts show data from the beginning of the start until shortly after the generator breaker closed and power (DWATT) was starting to ramp up.

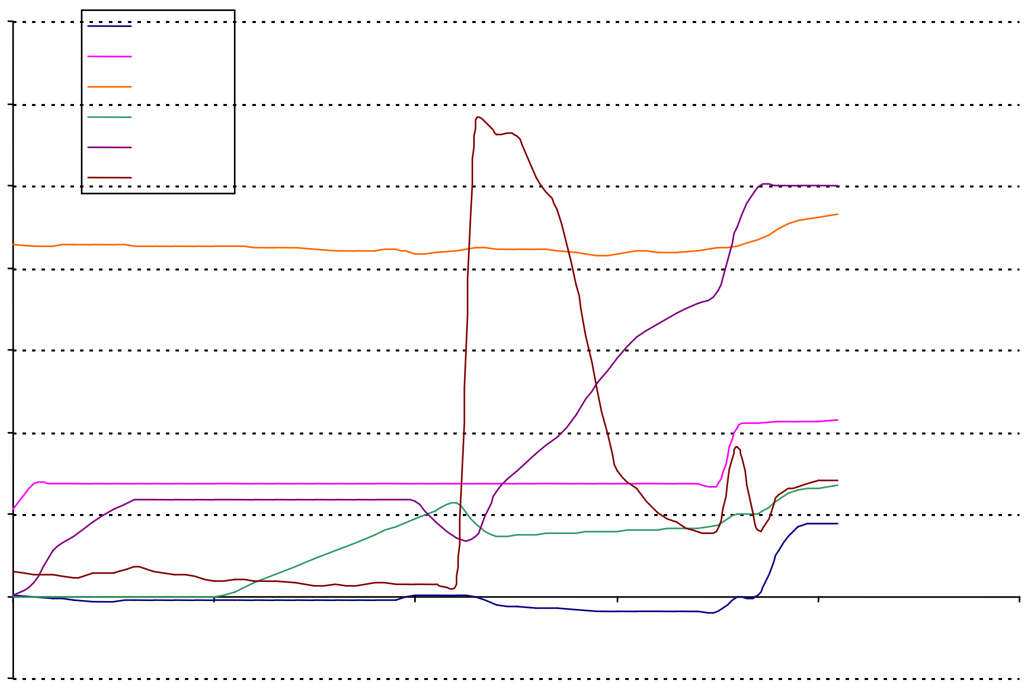


Figure 5-15
Trend Chart for "Start1" (x-axis is time since start began in minutes) (For consistency, enclose Start1 with brackets, i.e. [Start1])

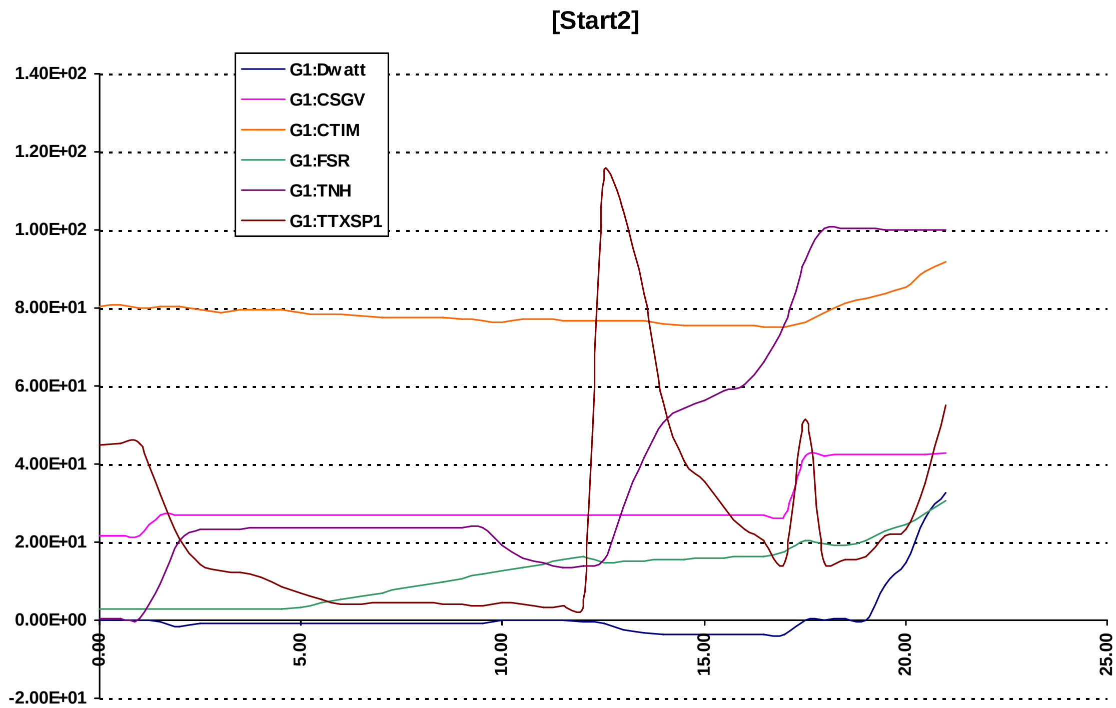


Figure 5-16
Trend Chart for "Start2" (x-axis is time since start began in minutes)

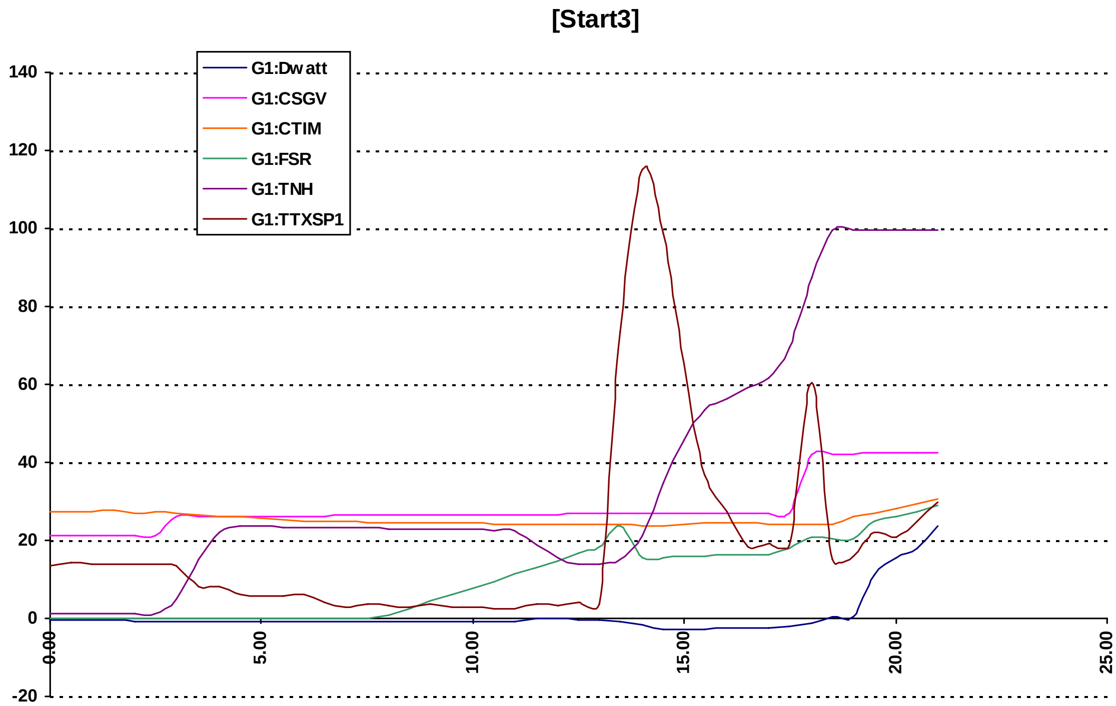


Figure 5-17
Trend Chart for "Start3" (x-axis is time since start began in minutes)

Both "Start1" and "Start2" took place during warm weather, while "Start3" occurred when the ambient temperate was less than 30ºF.

Several observations can be made based on the three charts:

- The inlet guide vanes were held at approximately 25º open until the rotor speed reached 75% of its rated value. Then the IGVs opened to slightly more than 40º.
- The exhaust gas temperature spread parameter TTXSP1 is an excellent indicator of the start of firing. It shot up rapidly to more than 100ºF in each run when ignition occurred.
- The ignition value of FSR was slightly over 20% for two starts, but was less than 20% for "Start2". This could be an artifact of the 30 second sample time in the data missing the peak value FSR in Start2.
- The warm-up value for FSR was approximately 15% in all three starts.

Influence of Compressor Bleed on Inlet Temperature

As was discussed earlier under sub-section heading "Slow to Accelerate", if the discharge flow from a compressor bleed valve is sent to mix with the inlet air, it will cause the *Compressor Inlet Temperature* (CIT) to rise. This connection between CIT and bleed flow can be used as a means of detecting a leaking bleed valve.

While the bleed valves in the three example starts were not leaking, the impact of compressor bleed flow on CIT can be seen in Figure 5-18, where the compressor inlet temperature is plotted along with the *compressor bleed valve position* (CSBHX). In the last phase of the start, the bleed valve is opened (presumably to adjust the fuel/air ratio in the pre-mixed combustor) and the CIT starts to climb. [Label the axes on the chart.]

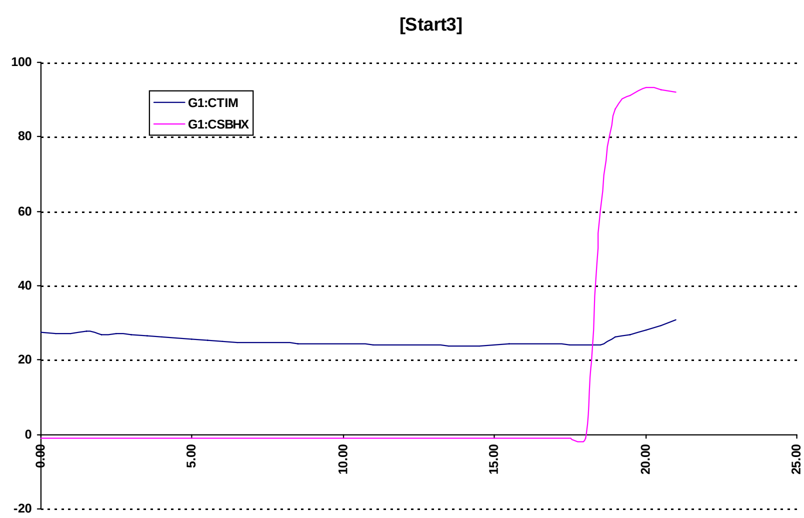


Figure 5-18
Influence of Compressor Bleed on Compressor Inlet Temperature

Fuel Manifold Pressure versus Fuel Flow

The Progress Energy 7FA has a DLN combustion system. The start-up tables included data on the total *fuel flow rate* (FQG) and the pressure differential between the two main fuel manifolds and the compressor discharge pressure (FPGN01 and FPGN02). As Figure 5-19 indicates, the pressure versus flow trends from Starts 1 and 2 were quite similar. This is an indication that the flow area of the fuel nozzle orifices did not change between the two starts.

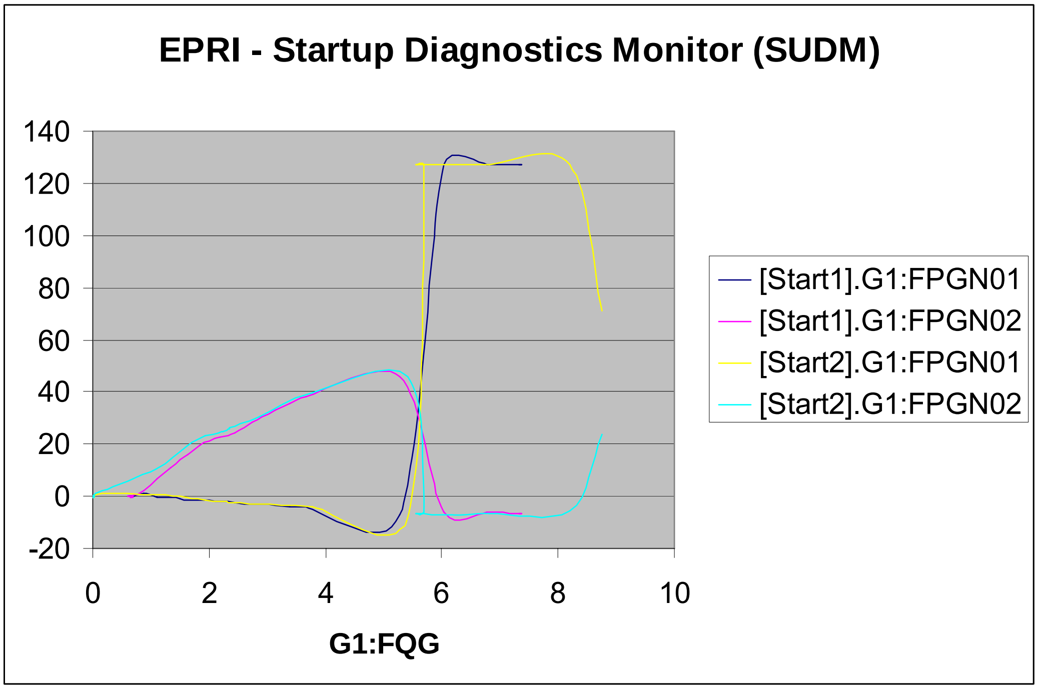


Figure 5-19
Overlay Chart of Fuel Manifold Pressures versus Fuel Flow Rate

Slow to Reach Purge Speed

The overlay trends of rotor speed versus time were quite similar for two starts (see Figure 5-20), but the trend for “Start1” showed it was slow to reach its purge speed (Figure 5-21). This caused the overall time to reach the full speed no load condition to be almost 2 minutes longer in “Start1” than in the other two example starts. Since vibration data were not supplied, it is not possible to eliminate a rotor rub as the cause of the slow start. However, if vibrations were similar to those in “Start2” and “start3”, one would have to suspect that degradation of the start motor was the cause of the slow start.

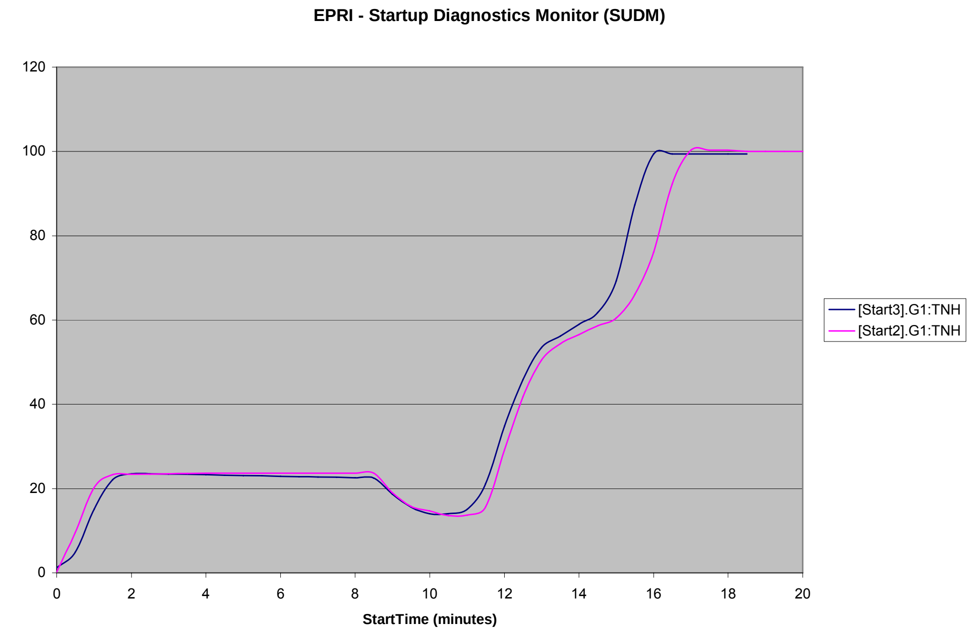


Figure 5-20
Overlay Plot for Two GE 7FA Starts showing Similar Trends for Rotor Speed versus Time

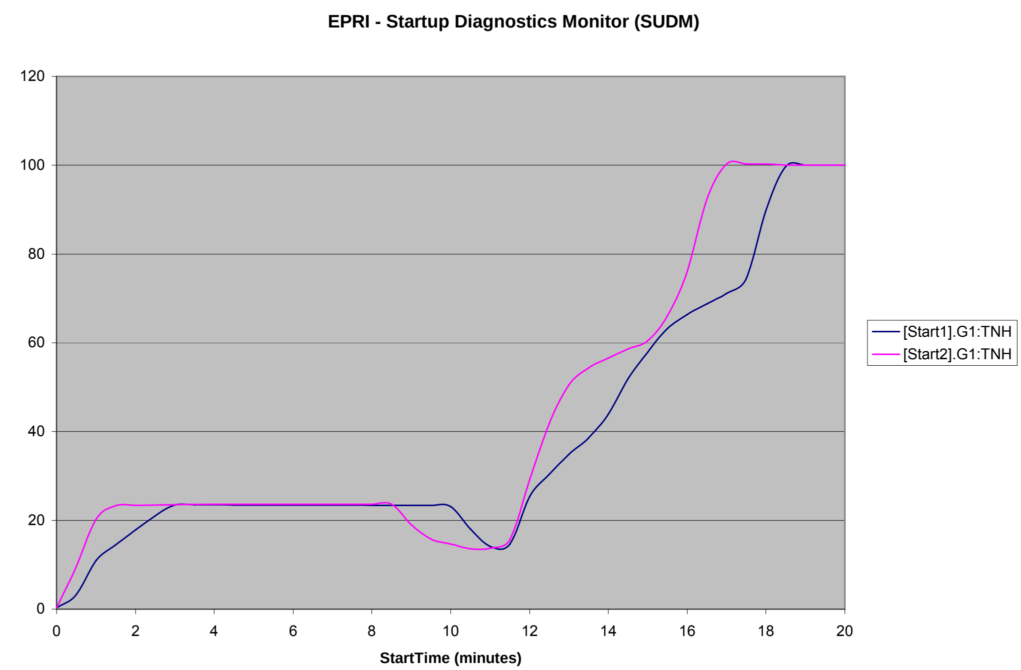


Figure 5-21
Overlay Plot of Rotor Speed for Two GE 7FA Starts

6
REMAINING LIFE MODULE REPORT (RLM), VERSION 1.0

Introduction

The *Remaining Life Module* (RLM) is a spreadsheet that predicts the remaining hot section life of a GE heavy-duty gas turbine via two methods: EPRI's *Hot Section Life Management Platform* (HSLMP) algorithms [1] and GE's standard algorithms [2] described in GER-3620J. The HSLMP algorithms are currently only applicable to the first stage rotating blade of the GE 7FA+ (MS7231) combustion turbine. The GER-3620J algorithms can be used for all of GE's heavy duty combustion turbines.

Important features of the RLM spreadsheet include:

- Operates as a spreadsheet with macros in Microsoft's Excel (version 97 or later)
- Runs under the Windows NT/98/2000 operating systems
- Comes with an installation routine developed using InstallShield
- Uses data calculated by the CTPFDM spreadsheet for performance monitoring of combustion turbines
- The familiar Excel "Chart" feature can be used to trend the RLM output
- Capable of predicting the remaining hot section life of GE heavy-duty gas turbines using GE's GER-3620J algorithms
- Capable of predicting the remaining hot section life of GE 7FA+ gas turbines using EPRI's HSLMP algorithms

Program Overview

The RLM calculations can be carried out in two different modes: initialization and run-by-run. In the initialization mode, the user manually enters the current operating history of an engine in terms of fired hours, number of starts, number of trips, etc. Where necessary, the user will input estimates to characterize the nature of the operating history (e.g., percentage of total hours operated in part-load, base-load and peak-load). The GER-3620J calculations are carried out to define the current equivalent (a.k.a. factored) run hours and starts for the hot section, the rotor, and the combustor. This will then form the basis for future calculations on a run-by-run basis using either the 3620J algorithms or the EPRI algorithms.

The run-by-run mode can be used after the initialization calculations have been executed. When a run (i.e., a complete start-stop cycle) has ended, the user can enter the approximate start and stop times and a macro will extract the specified data from a PI data historian supplied by OSI Software, Inc. The macro then "marches" through the run data on an hour-by-hour basis to calculate the equivalent operating hours and starts incurred during the run. If the run-by-run calculations are carried out on a GE 7FA+, the HSLMP algorithms will also be calculated.

Note that it is possible for a user to forego the initialization calculation if an on-line PI database contains information on each run that the turbine has executed. In such a case, the user can enter the start and stop times for each run, one-by-one, and calculate the contribution of each run to the cumulative factored hours and starts total.

Theory and Module Development

GER-3620J Algorithms

The GER-3620J algorithms provide an hours-based maintenance interval and a starts-based maintenance interval for inspection and replacement of the hot section parts of a CT. Typically starts may be related to the accumulated damage caused from thermal mechanical fatigue (TMF) cycles, and hours may be related to coating degradation and/or creep damage accumulated over time.

The 3620J algorithms assume there is no interaction between the starts-based and hours-based intervals. The maintenance action should be carried out if either interval is exceeded. This philosophy is shown visually in Figure 6-1.

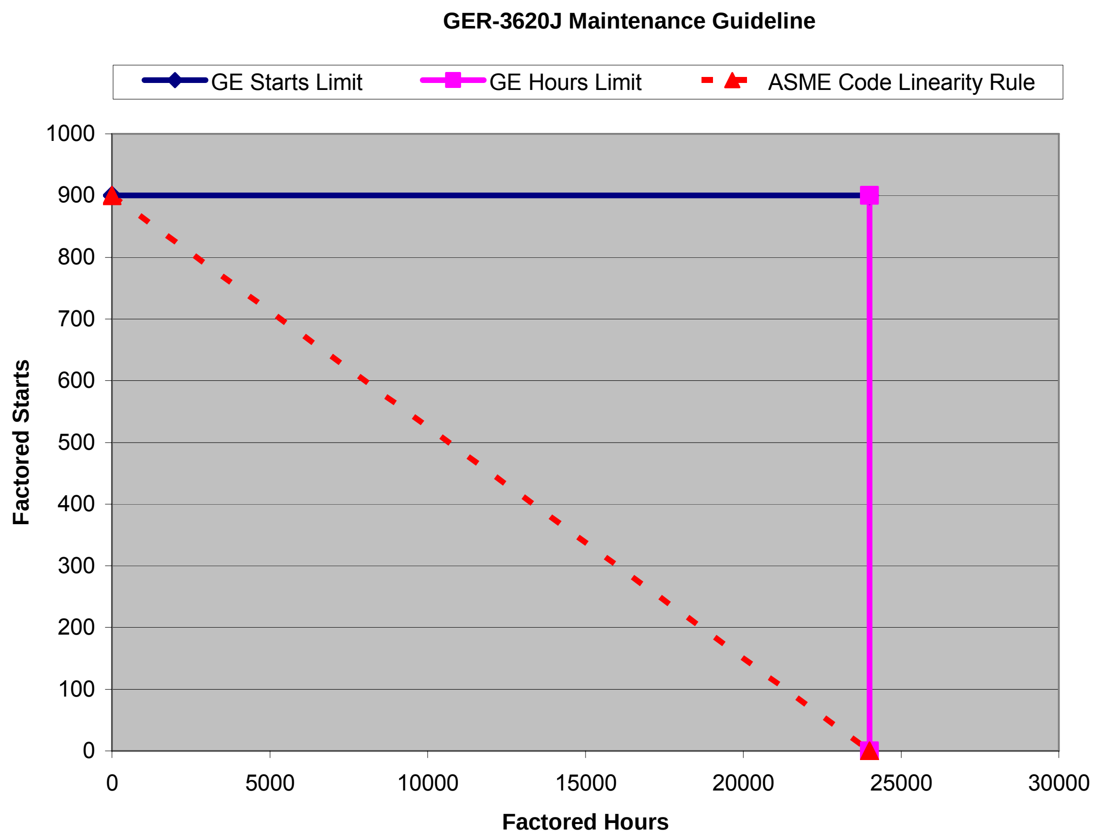


Figure 6-1
Hot Gas Path Maintenance Interval Criteria for a GE "F" Class Turbines based on GER-3620J

The term "factored starts" used in the figure means that actual starts are referenced to a baseline start referred to as a normal base load start or NB in the starts-based portion of the GER-3620J formula. To account for damage accumulated for different types of starts or trips, factors are applied to the normal base-load start-stop cycle (NB), reflecting GE's opinion of their relative severity. For example, a "fast load start" is given a severity factor of two, meaning one fast load start counts as two factored starts. Similarly, the term "factored hours" means actual operating hours are referenced to a baseline of base-load operation with natural gas and no water or steam injection. Note that based on the GE criteria, an F class CT could have 899 normal starts and 23,999 base load fired hours and not need a hot section overhaul, but if it had one normal start and 24,001 baseload fired hours it would need a hot section overhaul.

Creep Fatigue Interaction

The assumption that there is no interaction between starts (fatigue) and operating hours (creep) is not supported by experts outside of GE. There is a large body of evidence that shows creep-induced damage will reduce the fatigue life of a metal and that fatigue-induced damage will reduce the metal's creep life. The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section III, Case N-47 addresses the interaction between fatigue and creep. It recommends using a linear combination of remaining creep life and remaining fatigue life to determine a materials remaining life. The least conservative assumption is that:

% Remaining Life = (% Remaining Fatigue + % Remaining Creep Life) – 100%

This is known as the "linearity rule". It is also shown in Figure 6-1. Actual tests on different metals have shown that the interaction between fatigue and creep is often stronger than that described by the linearity rule [3].

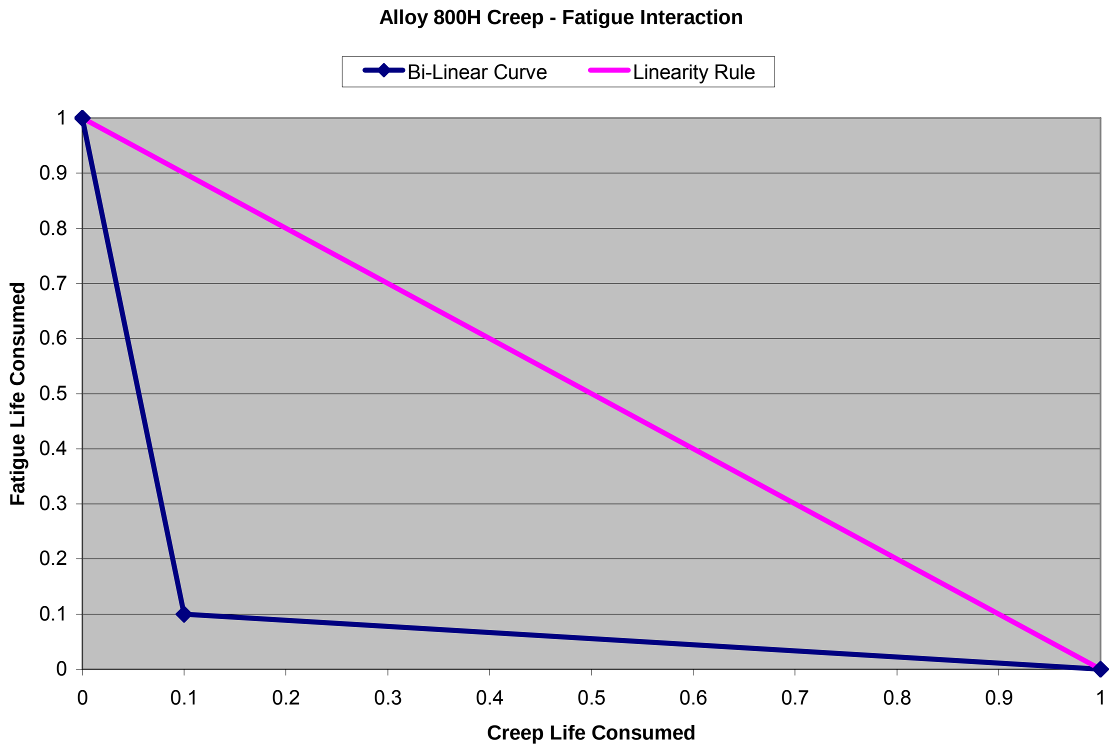


Figure 6-2
Bi-Linear Creep-Fatigue Interaction Curve for Alloy 800H from Ref. 3 compared to ASME Section II Code Case N-47 Linearity Rule

An example of a stronger creep-fatigue interaction is shown in the "bi-linear" curve of Figure 6-2 that was derived from experimental data for Alloy 800H. It shows that when 10% of the creep life of 800H has been consumed, the material will fail if more than 10% of its fatigue life is expended.

Even GE's own published data indicate there is a strong interaction between starts and hours, at least for the combustion liner and transition piece of the PGT10 [4]. An example of that data is shown in Figure 6-3, which shows the "maintenance line" for the transition piece. The maintenance line represents the locus of points at which 2/3rds of the engines surveyed had experienced transition piece failures. The data in Figure 6-3 strongly suggest a linear relationship between fatigue and creep. This directly contradicts the assertion made in GER-3620J.

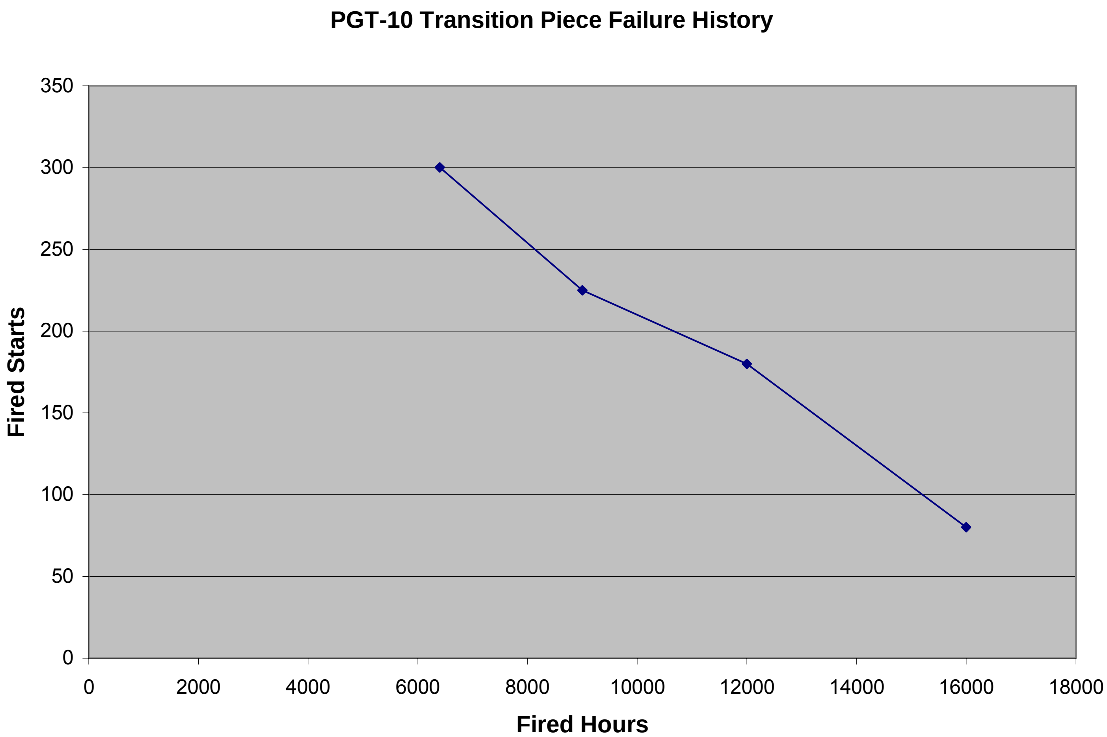


Figure 6-3
GE PGT-10 Transition Piece "Maintenance Line" based on the failure history of multiple engines surveyed by GE.4

Without additional data it is not known if the maintenance intervals recommended for an F class CT in GER-3620J represent a conservative simplification of the creep-fatigue linearity rule or an unconservative simplification. The unconservative possibility is represented by Figure 6-1. It would suggest that hot section failures could occur in CTs that accumulate a combination of hours and start cycles which fall within GE's 24,000 hour and 900 starts limit.

The conservative possibility is represented by Figure 6-4. If that figure represents the actual situation, then it implies that CTs that operate many hours with few cycles could go far beyond GE's 24,000 factored hour limit. Also, turbines that experience many cycles but few hours could withstand more than 900 factored starts before encountering hot section failures.

Whether the GE criteria are conservative or unconservative, either scenario represents a potential for unnecessary maintenance expenses. If the criteria are overly conservative, CT owners will be replacing parts too soon and therefore spending too much money on hot section spares. In addition, the units will be shutdown for overhauls more frequently than necessary which represents a loss in revenue.

If the GE criteria are unconservative, CT owners will experience hot section failures that could cause additional damage to downstream parts. In addition the unplanned outages caused by the failures may mean that replacement parts will not be available right away, which will extend the length of the outage and cause additional revenue loss.

Clearly there is an incentive to improve upon the GER-3620J remaining life algorithms. That was the motivation for the EPRI *Hot Section Life Management Platform* (HSLMP).

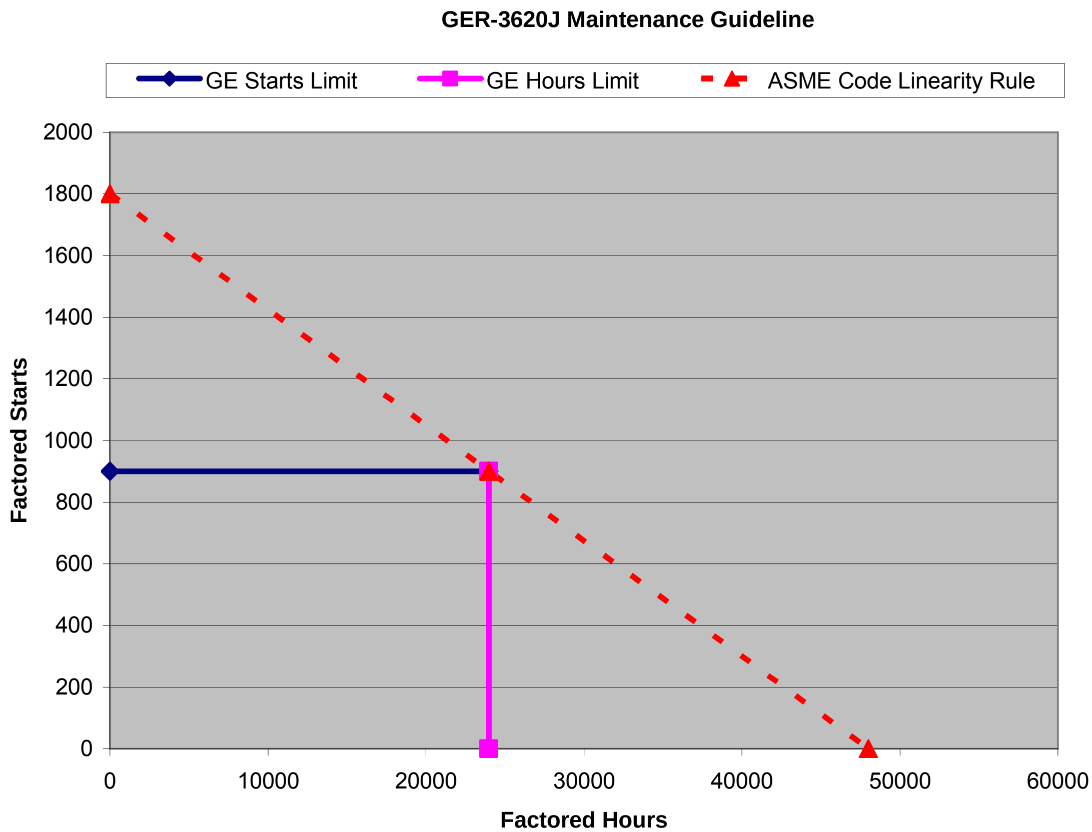


Figure 6-4
"Conservative" Simplification of Creep-Fatigue Linearity Rule

EPRI's Hot Section Life Management Platform

Unlike the GER-3620J approach, EPRI's *Hot Section Life Management Platform* (HSLMP) algorithms do assume there is interaction between the various damage mechanisms that occur in a CT hot section. The algorithms consolidate the damage caused for different types of events as a basis to establish when the equivalent maintenance interval is reached. The algorithms are based on aerothermal modeling and tests carried out to estimate the strain induced at specific locations by specific operating conditions such as an emergency trip from full-load. This information is then used to calculate a severity factor for each condition or event.

In the initial version of RLM, HSLMP algorithms for only the GE 7FA+ series 1st stage bucket (i.e., rotating airfoils) are incorporated. The current OEM inspection limits for the 7FA+ 1st stage bucket are set at 900 starts maximum and/or 24,000 hours, whichever comes first. Replacement limits are 1800 factored starts and 48,000 factored hours.

Results of a hypothetical calculation of an interval using both the OEM approach (GER-3620J) and the HSLMP approach are presented in Figure 6-5. In the example, on a 7FA+ 1st stage bucket, a trip at 40% load is considered by GER-3620J to be 4.2 times as damaging as a normal base load start-stop cycle. As reflected in the figure, the HSLMP factor would produce 50% less life consumption (2.1 times an NB start-stop cycle). It should be noted that the actual factors used in HSLMP are different from those shown in Figure 6-5.

Factored Starts	Annual Starts	OEM Factor	HSLMP Adjusted
Normal Base Load S-S	**90**	**1.0**	**1.0**
Part Load S-S (<60%)	0	0.5	0.3
Peak Load S-S	0	1.3	0.7
Fast Load Starts	2	2.0	1.0
Trip Severity @ 25%	0	2.6	1.3
Trip Severity @ 40%	4	4.2	2.1
Trip Severity @ 60%	0	6.0	3.0
Trip Severity @ 80-100%	0	8.0	4.0
Emergency Start	1	20.0	10.0

Actual Starts	97	97
Factored Starts	131	110.4
Maximum Specified Starts	900	900
Maintenance Interval =	**667**	**791**
Maintenance Factor	**1.35**	**1.14**

Life Consumed	14.5%	12.3%
Life Remaining	85.5%	87.7%

Note: HSLMP factors in example are hypothetical, used for illustration purposes only

The adjusted factors reflect the relative damage at specific locations based on the equivalent strain ranges produced from the aero thermal analysis.

- They reflect the relative severity of each additional type of cycle as predicted by the HSLMP.

In this example, the maximum specified NB type starts used to establish the proportion of life consumption is kept at 900.

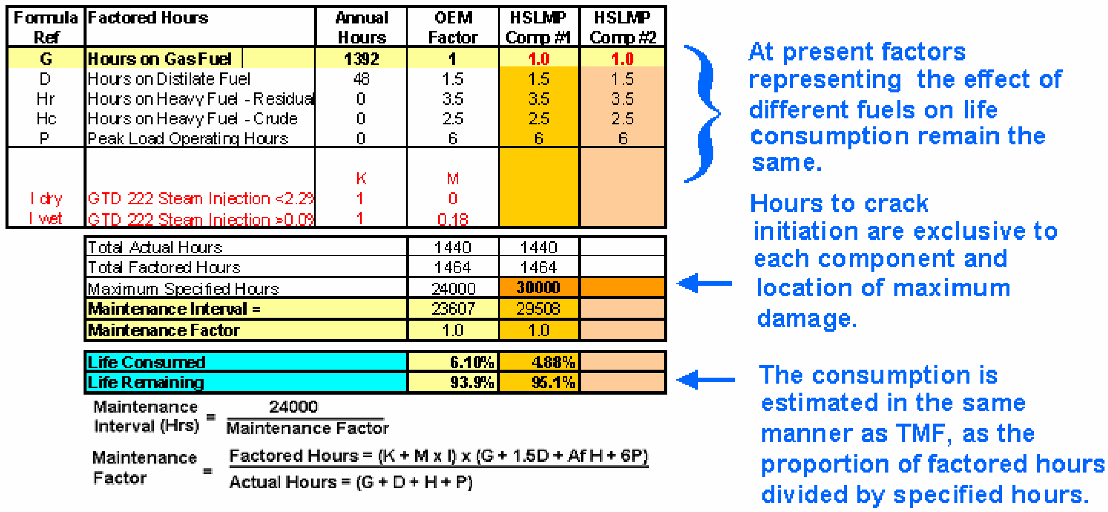
As a consequence, the lower factors produce a slightly lower rate of life consumption.

Figure 6-5
Formulation of Life Consumption for Start-Based Criterion

As reflected in Figure 6-5, the HSLMP provides an opportunity to independently compare and assess the OEM interval estimates. In the calculation using the OEM factors, the starts are reflected as a portion of the total life consumed to date and proportion of life remaining. From the hypothetical record of 131 factored starts, it infers that nearly 14.5% of the total life has been consumed. The independent calculation produced from factors that are adjusted to reflect proportional damage accumulation for each of the referenced events provided by the HSLMP reflects a life consumption of 12.3%. However, this is based on the damage caused to a specific location on the 1st stage bucket, attributable to TMF only.

The treatment of life consumption due to creep and/or coating life in the HSLMP is treated in a similar fashion, as shown in Figure 2-6. Note that in this example a different baseline interval assumed in the HSLMP calculations (30000 vs. 24000 hours).

The linear damage rule is used to take into account the interaction between creep and fatigue damage and the result is reported as a "combined" remaining life parameter.



Formula Ref	Factored Hours	Annual Hours	OEM Factor	HSLMP Comp #1	HSLMP Comp #2
G	Hours on Gas Fuel	1392	1	1.0	1.0
D	Hours on Distilate Fuel	48	1.5	1.5	1.5
Hr	Hours on Heavy Fuel - Residua	0	3.5	3.5	3.5
Hc	Hours on Heavy Fuel - Crude	0	2.5	2.5	2.5
P	Peak Load Operating Hours	0	6	6	6
		K	M		
I dry	GTD 222 Steam Injection <2.2%	1	0		
I wet	GTD 222 Steam Injection >0.0%	1	0.18		
	Total Actual Hours		1440	1440	
	Total Factored Hours		1464	1464	
	Maximum Specified Hours		24000	30000	
	Maintenance Interval =		23607	29508	
	Maintenance Factor		1.0	1.0	
	Life Consumed		6.10%	4.88%	
	Life Remaining		93.9%	95.1%	

Figure 6-6
Formulation of Life Consumption for Hours-Based Criterion

The principal distinction between the HSLMP results and the OEM approach is that the HSLMP derives its estimates of proportional damage directly for each of the respective locations where maximum temperatures, stresses and strains are predicted to occur. Rate of damage for each principal mechanism is based on the properties obtained by controlled tests of materials and coating samples independently performed by EPRI. This means that the final result is specific to:

a. the part (and/or the particular design iteration that is installed),
b. the operating conditions of the unit (whether in a heat recovery scheme or as a stand alone unit),
c. the location on the part (where it is most susceptible to a particular type of damage) and
d. the operating record (reflected in measurements by the units' automated data tracking system).

Comparisons made with factors obtained from the HSLMP have indicated in certain situations that the OEM life formulation produced a more conservative interval for inspection and replacement because it lacks the specificity provided by the HSLMP. Conversely, damage caused by certain modes of operation is apparently being underestimated by the OEM's formulas. In this regard, the appearance of cracks in regions such as the trailing edge cooling hole of the 1st stage bucket was predicted by HSLMP for start intervals below the OEM factored allowable, based on the stresses and temperatures that were being calculated in this region. These predictions were subsequently confirmed by examples obtained from the field. A recent TIL (1186-2r1) has reduced the inspection interval for 7FA+ parts to 350 starts, with guidance as to what maximum crack sizes are allowable.

Module Development

EPRI's developer for the HSLMP was Turbine Technology, Inc. (TTI) of Rochester, NY. As part of the RLM project, TTI created a *Dynamic Link Library* (DLL), which contained the HSLMP algorithms for the 7FA+ 1st stage buckets. A DLL can be thought of as a compiled subroutine that can be called by a Windows-based program.

It was determined that the best way to implement the HSLMP calculation was in a "batch-wise" fashion at the end of each CT run (start-stop cycle). The HSLMP algorithms account for events that occur over the complete course of a start-stop cycle and therefore are not conducive to being used in a real-time mode during a CT run.

Instead, the DLL was designed to be called at the end of each CT run. Input parameters to the DLL included the three % remaining life values (TMF-based, Creep-based, and combined) before the run started and various parameters that describe the severity of the run such as fuel type, peak firing temperature, and whether an emergency trip occurred. A full description of the inputs can be found later under sub-section heading "Individual Run Calculations". The outputs from the DLL were the three remaining life parameters, updated to reflect the impact of the run.

A simple Excel spreadsheet was initially developed to allow testing of the HSLMP DLL. The spreadsheet required all of the DLL inputs to be manually entered in cells of the spreadsheet. The DLL was called by a macro, which was invoked by clicking a button in the spreadsheet. TTI tested this simple spreadsheet and confirmed that the DLL was operating correctly.

This simple spreadsheet was then expanded to include the GER-3620J calculations and automatic retrieval of CT operating data to support both the 3620J calculations and the HSLMP calculations. In addition, the macro that called the HSLMP DLL was automatically linked to the macro that implemented the run-by-run 3620J calculations.

As described earlier under sub-section heading "Program Overview", the RLM calculations can be carried out in either an initialization mode or a run-by-run mode. The initialization calculations use only the GER-3620J calculations to determine the remaining life of the hot section. Details of how these calculations are carried out are provided later under sub-section heading "Initialization Calculations".

The run-by-run calculations always follow the GER-3620J algorithms and also use the HSLMP DLL if the CT type is a 7FA+. A description of how the run-by-run calculations are implemented is found in Reference [4].

Initialization Calculations

Inputs

The initialization calculations are set up on the RLM.xls worksheet named "Initialization Inputs". The user must specify information on the combustion turbine being evaluated. This information includes:

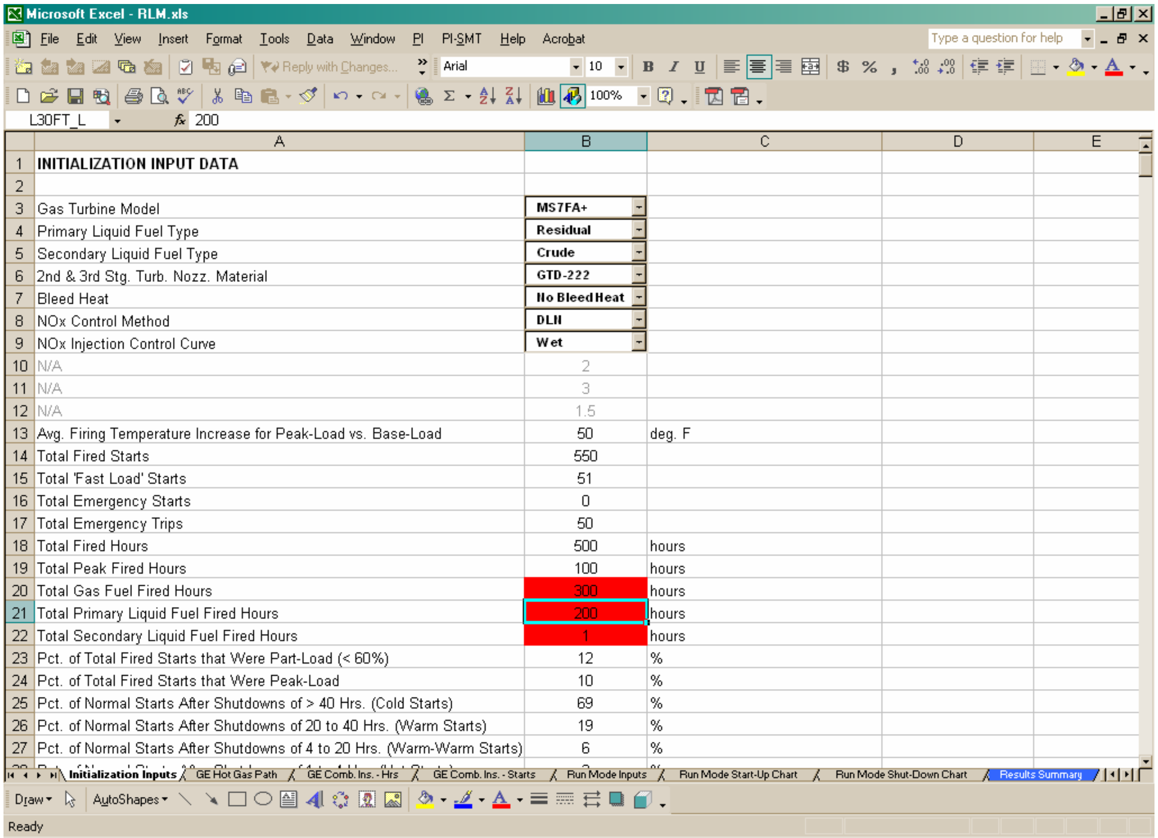
- CT model type (e.g., MS6B, MS7FA+, etc.)
- Fuel type corresponding to the primary and secondary liquid fuel flow meters
- 2nd and 3rd stage turbine nozzle material (GTD-222 or FSX-414)
- Whether compressor bleed heating is used to pre-heat inlet air
- What NO_x control method is used (e.g., DLN combustor, water injection, steam injection)

Also, the user must enter the values of the following counters from the CT's operating history or can optionally define formulas in the cells to extract the values from a PI database (using the Excel add-in PI DataLink):

- Total Fired Starts, L30CFS
- Total Fast Starts, L30CFLS
- Total Emergency Trips, L30CES
- Total Fired Hours, L30FT_T
- Total Peak Hours, L30FT_P
- Total Gas Fuel Fired Hours, L30FT_G
- Total Primary Liquid Fuel Fired Hours, L30FT_L
- Total Secondary Liquid Fuel Fired Hours, L30FT_L2

In addition to the counters, the user must also enter estimates that describe the operating history of the CT. For example, the user is asked to estimate the percentage of total starts that were part-load (i.e., <60% load) starts and the percentages of starts that were fired on gas fuel, on the primary liquid fuel and on the secondary liquid fuel.

The spreadsheet has some built-in error-checking to ensure that the user enters a consistent set of data. For example, if the sum of the gas fired, primary liquid fired, and secondary liquid fired hours does not equal the total fired hours, the cells for the three fuel-based hours counters will be highlighted in red (see Figure 6-7).



	A	B	C
1	INITIALIZATION INPUT DATA		
2			
3	Gas Turbine Model	MS7FA+	
4	Primary Liquid Fuel Type	Residual	
5	Secondary Liquid Fuel Type	Crude	
6	2nd & 3rd Stg. Turb. Nozz. Material	GTD-222	
7	Bleed Heat	No Bleed Heat	
8	NOx Control Method	DLN	
9	NOx Injection Control Curve	Wet	
10	N/A	2	
11	N/A	3	
12	N/A	1.5	
13	Avg. Firing Temperature Increase for Peak-Load vs. Base-Load	50	deg. F
14	Total Fired Starts	550	
15	Total 'Fast Load' Starts	51	
16	Total Emergency Starts	0	
17	Total Emergency Trips	50	
18	Total Fired Hours	500	hours
19	Total Peak Fired Hours	100	hours
20	Total Gas Fuel Fired Hours	300	hours
21	Total Primary Liquid Fuel Fired Hours	200	hours
22	Total Secondary Liquid Fuel Fired Hours	1	hours
23	Pct. of Total Fired Starts that Were Part-Load (< 60%)	12	%
24	Pct. of Total Fired Starts that Were Peak-Load	10	%
25	Pct. of Normal Starts After Shutdowns of > 40 Hrs. (Cold Starts)	69	%
26	Pct. of Normal Starts After Shutdowns of 20 to 40 Hrs. (Warm Starts)	19	%
27	Pct. of Normal Starts After Shutdowns of 4 to 20 Hrs. (Warm-Warm Starts)	6	%

Figure 6-7
Example of Error Checking on Initialization Inputs Worksheet

Results

Using the user-entered inputs, the following parameters are calculated based on the GER-3620J formulas:

- Hot Gas Path Inspection
  - Factored Starts
  - Maintenance Factor – Starts Based
  - Maintenance Interval – Starts Based
  - % of Starts Based Maintenance Interval Remaining
  - Factored Hours
  - Maintenance Factor – Hours Based
  - Maintenance Interval – Hours Based
  - % of Hours Based Maintenance Interval Remaining
- Rotor Life
  - Factored Hours
  - Maintenance Factor – Hours Based

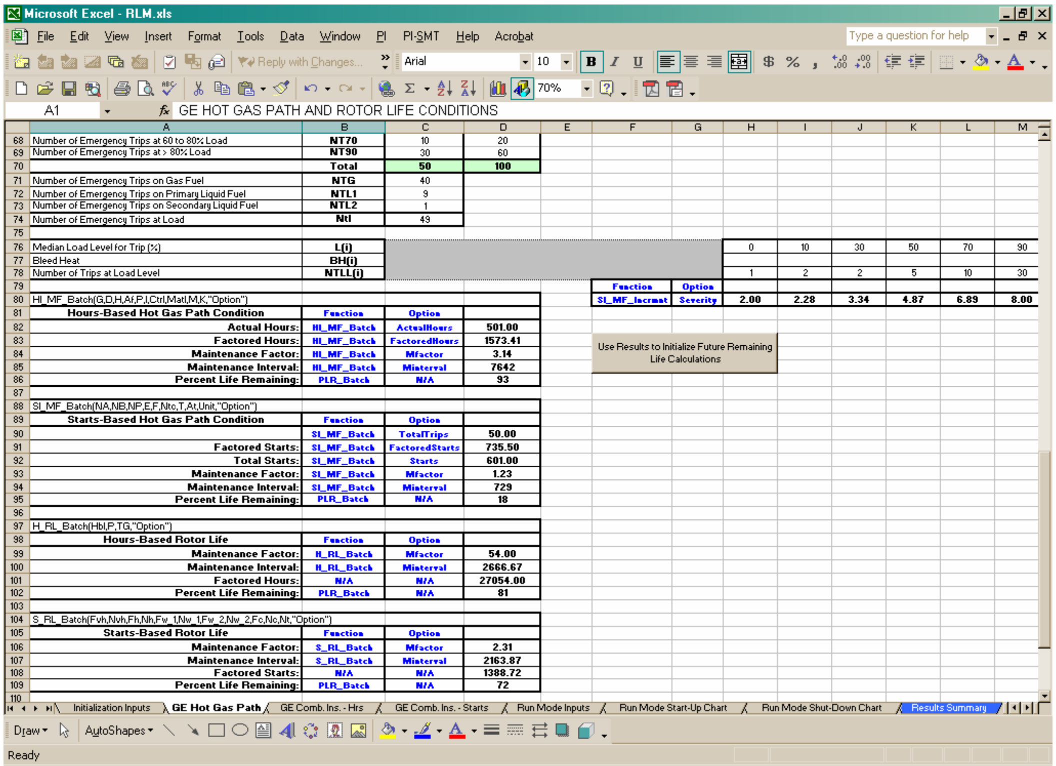
  - Maintenance Interval – Hours Based
  - % of Hours Based Maintenance Interval Remaining
  - Factored Starts
  - Maintenance Factor – Starts Based
  - Maintenance Interval – Starts Based
  - % of Starts Based Maintenance Interval Remaining
- Combustion Inspection
  - Factored Hours
  - Maintenance Factor – Hours Based
  - Maintenance Interval – Hours Based
  - % of Hours Based Maintenance Interval Remaining
  - Factored Starts
  - Maintenance Factor – Starts Based
  - Maintenance Interval – Starts Based
  - % of Starts Based Maintenance Interval Remaining

These results, along with details of the calculation, are displayed on three results worksheets: GE Hot Gas Path, GE Comb. Ins. – Hrs, and GE Comb. Ins. – Starts (see Figures 6-8, 6-9, and 6-10). These three worksheets are automatically updated whenever a change is made to the initialization inputs. If the user wants to save the results shown on these sheets and use them as the starting point for subsequent run-by-run calculations, the button labeled "Use Results to Initialize Future Remaining Life Calculations" should be clicked. Note that even though this button exists on all three worksheets, it is not necessary to click all three buttons. Clicking the button on any of one of the worksheets will save the complete set of results from all three worksheets.

After the results are saved, the Results Summary worksheet is displayed and the user should again check the results reported there. If satisfied with the results, initialization of the current gas turbine can be considered complete and further runs for the turbine can be analyzed using the individual run calculations discussed later under sub-section heading "Individual Run Calculations". Otherwise, the user may return to the Initialization Inputs worksheet to modify the data there, then re-initialize the gas turbine, overwriting the previous results.

Whenever the user attempts to re-initialize a gas turbine, a warning message will be displayed informing the user of 1 or 2 existing files. If the gas turbine being re-initialized is a GE 7FA+, the first warning message to be displayed will inform the user that an existing Results.csv (HSLMP results) file has been detected. If the user is certain that they want to overwrite the previous HSLMP initialization results, they should click on the "Yes" button. If unsure about re-initializing, the user should click on the "No" button to abort the initialization. The second warning message to be displayed (or first, in the case of non-GE 7FA+ gas turbines) will inform the user that an existing 3620J.csv (GER-3620J results) file has been detected. If the user is certain that they want to overwrite the previous GER-3620J initialization results, they should click on the "Yes" button. If unsure about re-initializing, the user should click on the "No" button to abort the initialization.

The user must be careful when re-initializing. Completing the re-initialization process, (i.e., saving the results to file) results not only in the loss of all previous initialization results, but also the loss of all previous run results if the turbine has already been analyzed for individual runs.



Microsoft Excel - RLM.xls

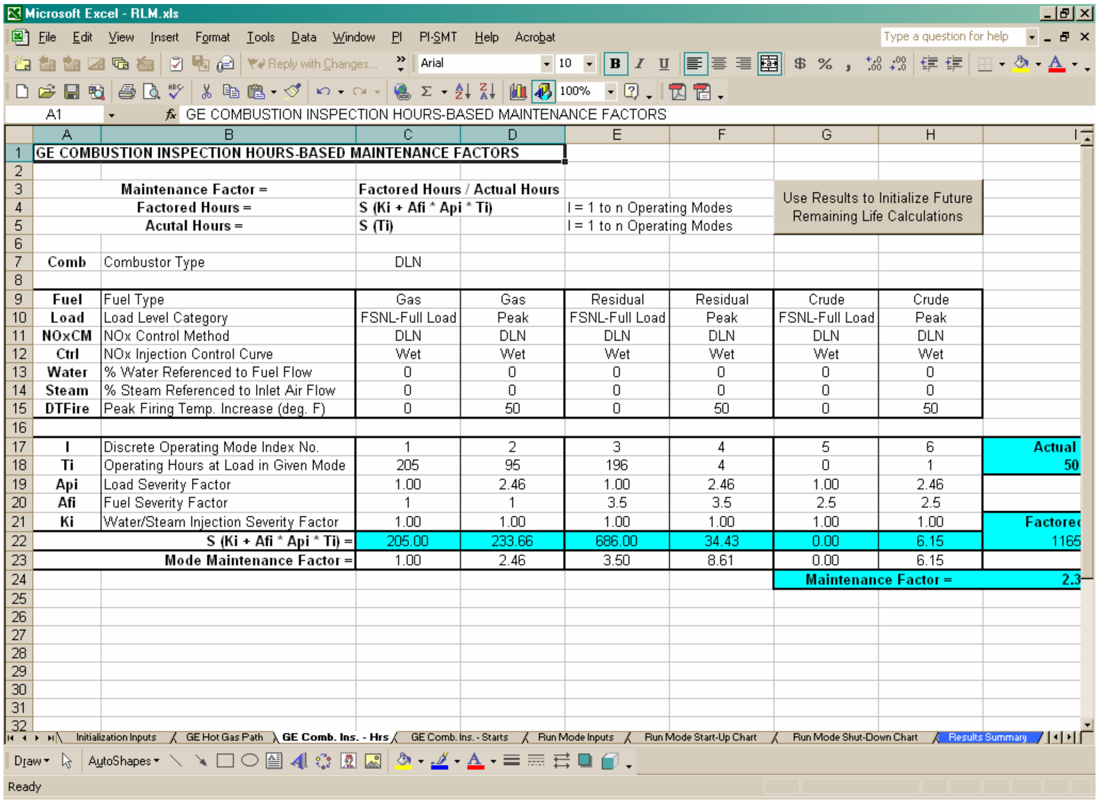
A1 — GE HOT GAS PATH AND ROTOR LIFE CONDITIONS

	A	B	C	D	E	F	G	H	I	J	K	L	M
68	Number of Emergency Trips at 60 to 80% Load	NT70	10	20									
69	Number of Emergency Trips at > 80% Load	NT90	30	60									
70		Total	50	100									
71	Number of Emergency Trips on Gas Fuel	NTG	40										
72	Number of Emergency Trips on Primary Liquid Fuel	NTL1	9										
73	Number of Emergency Trips on Secondary Liquid Fuel	NTL2	1										
74	Number of Emergency Trips at Load	Ntl	49										
75													
76	Median Load Level for Trip (%)	L(i)						0	10	30	50	70	90
77	Bleed Heat	BH(i)											
78	Number of Trips at Load Level	NTLL(i)						1	2	2	5	10	30
79						Function	Option						
80	HI_MF_Batch(G,D,H,Af,P,I,Ctrl,Matl,M,K,"Option")					SI_MF_Incrmnt	Severity	2.00	2.28	3.34	4.87	6.89	8.00
81	Hours-Based Hot Gas Path Condition	Function	Option										
82	Actual Hours:	HI_MF_Batch	ActualHours	501.00									
83	Factored Hours:	HI_MF_Batch	FactoredHours	1573.41		Use Results to Initialize Future Remaining Life Calculations							
84	Maintenance Factor:	HI_MF_Batch	Mfactor	3.14									
85	Maintenance Interval:	HI_MF_Batch	Minterval	7642									
86	Percent Life Remaining:	PLR_Batch	N/A	93									
87													
88	SI_MF_Batch(NA,NB,NP,E,F,Ntc,T,At,Unit,"Option")												
89	Starts-Based Hot Gas Path Condition	Function	Option										
90		SI_MF_Batch	TotalTrips	50.00									
91	Factored Starts:	SI_MF_Batch	FactoredStarts	735.50									
92	Total Starts:	SI_MF_Batch	Starts	601.00									
93	Maintenance Factor:	SI_MF_Batch	Mfactor	1.23									
94	Maintenance Interval:	SI_MF_Batch	Minterval	729									
95	Percent Life Remaining:	PLR_Batch	N/A	18									
96													
97	H_RL_Batch(Hbl,P,TG,"Option")												
98	Hours-Based Rotor Life	Function	Option										
99	Maintenance Factor:	H_RL_Batch	Mfactor	54.00									
100	Maintenance Interval:	H_RL_Batch	Minterval	2666.67									
101	Factored Hours:	N/A	N/A	27054.00									
102	Percent Life Remaining:	PLR_Batch	N/A	81									
103													
104	S_RL_Batch(Fvh,Nvh,Fh,Nh,Fw_1,Nw_1,Fw_2,Nw_2,Fc,Nc,Nt,"Option")												
105	Starts-Based Rotor Life	Function	Option										
106	Maintenance Factor:	S_RL_Batch	Mfactor	2.31									
107	Maintenance Interval:	S_RL_Batch	Minterval	2163.87									
108	Factored Starts:	N/A	N/A	1388.72									
109	Percent Life Remaining:	PLR_Batch	N/A	72									
110													

Initialization Inputs / GE Hot Gas Path / GE Comb. Ins. - Hrs / GE Comb. Ins. - Starts / Run Mode Inputs / Run Mode Start-Up Chart / Run Mode Shut-Down Chart / Results Summary

Ready

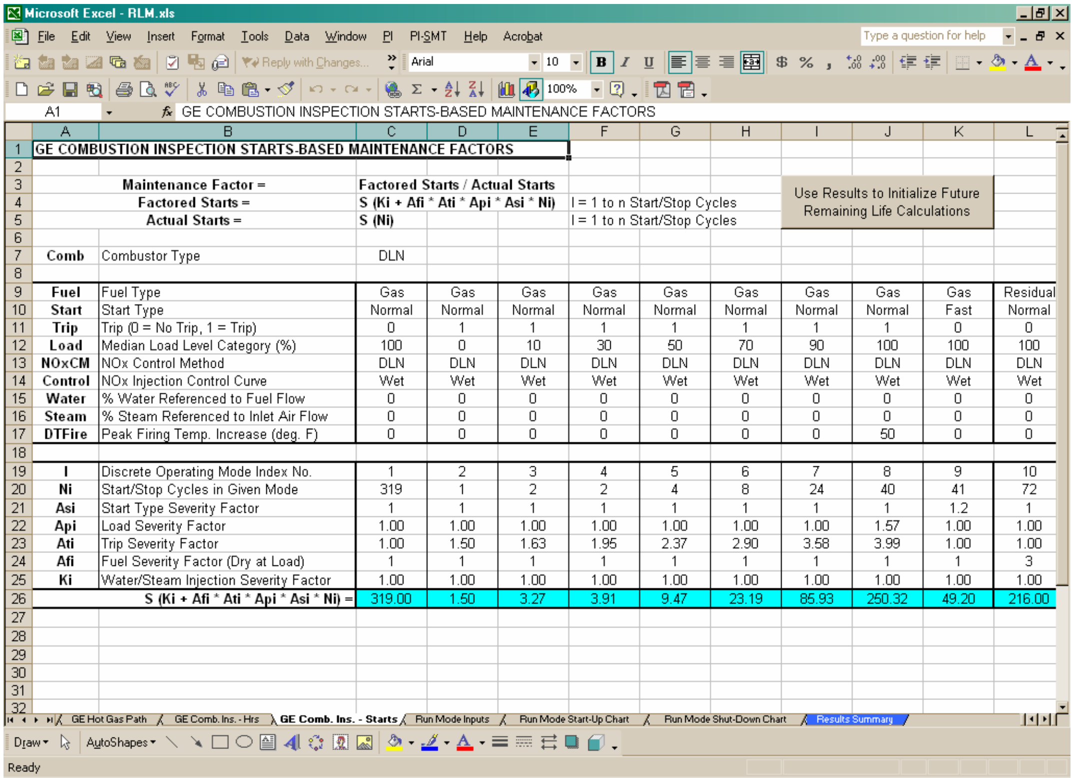
Figure 6-8
Example of Initialization Results for Hot Gas Path and Rotor Life Calculations



GE COMBUSTION INSPECTION HOURS-BASED MAINTENANCE FACTORS

A	B	C	D	E	F	G	H	I
	Maintenance Factor =	Factored Hours / Actual Hours				Use Results to Initialize Future Remaining Life Calculations		
	Factored Hours =	S (Ki + Afi * Api * Ti)		I = 1 to n Operating Modes				
	Acutal Hours =	S (Ti)		I = 1 to n Operating Modes				
Comb	Combustor Type	DLN						
Fuel	Fuel Type	Gas	Gas	Residual	Residual	Crude	Crude	
Load	Load Level Category	FSNL-Full Load	Peak	FSNL-Full Load	Peak	FSNL-Full Load	Peak	
NOxCM	NOx Control Method	DLN	DLN	DLN	DLN	DLN	DLN	
Ctrl	NOx Injection Control Curve	Wet	Wet	Wet	Wet	Wet	Wet	
Water	% Water Referenced to Fuel Flow	0	0	0	0	0	0	
Steam	% Steam Referenced to Inlet Air Flow	0	0	0	0	0	0	
DTFire	Peak Firing Temp. Increase (deg. F)	0	50	0	50	0	50	
I	Discrete Operating Mode Index No.	1	2	3	4	5	6	Actual
Ti	Operating Hours at Load in Given Mode	205	95	196	4	0	1	50
Api	Load Severity Factor	1.00	2.46	1.00	2.46	1.00	2.46	
Afi	Fuel Severity Factor	1	1	3.5	3.5	2.5	2.5	
Ki	Water/Steam Injection Severity Factor	1.00	1.00	1.00	1.00	1.00	1.00	Factored
	S (Ki + Afi * Api * Ti) =	205.00	233.66	686.00	34.43	0.00	6.15	1165
	Mode Maintenance Factor =	1.00	2.46	3.50	8.61	0.00	6.15	
						Maintenance Factor =		2.3

Figure 6-9
Example of Initialization Results for Hours-Based Combustion Inspection Interval



GE COMBUSTION INSPECTION STARTS-BASED MAINTENANCE FACTORS

Maintenance Factor = Factored Starts / Actual Starts

Factored Starts = S (Ki + Afi * Ati * Api * Asi * Ni) I = 1 to n Start/Stop Cycles

Actual Starts = S (Ni) I = 1 to n Start/Stop Cycles

Use Results to Initialize Future Remaining Life Calculations

Comb	Combustor Type	DLN									
Fuel	Fuel Type	Gas	Gas	Gas	Gas	Gas	Gas	Gas	Gas	Gas	Residual
Start	Start Type	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Fast	Normal
Trip	Trip (0 = No Trip, 1 = Trip)	0	1	1	1	1	1	1	1	0	0
Load	Median Load Level Category (%)	100	0	10	30	50	70	90	100	100	100
NOxCM	NOx Control Method	DLN	DLN	DLN	DLN	DLN	DLN	DLN	DLN	DLN	DLN
Control	NOx Injection Control Curve	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Wet
Water	% Water Referenced to Fuel Flow	0	0	0	0	0	0	0	0	0	0
Steam	% Steam Referenced to Inlet Air Flow	0	0	0	0	0	0	0	0	0	0
DTFire	Peak Firing Temp. Increase (deg. F)	0	0	0	0	0	0	0	50	0	0
I	Discrete Operating Mode Index No.	1	2	3	4	5	6	7	8	9	10
Ni	Start/Stop Cycles in Given Mode	319	1	2	2	4	8	24	40	41	72
Asi	Start Type Severity Factor	1	1	1	1	1	1	1	1	1.2	1
Api	Load Severity Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.57	1.00	1.00
Ati	Trip Severity Factor	1.00	1.50	1.63	1.95	2.37	2.90	3.58	3.99	1.00	1.00
Afi	Fuel Severity Factor (Dry at Load)	1	1	1	1	1	1	1	1	1	3
Ki	Water/Steam Injection Severity Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	S (Ki + Afi * Ati * Api * Asi * Ni) =	319.00	1.50	3.27	3.91	9.47	23.19	85.93	250.32	49.20	216.00

Figure 6-10
Example of Initialization Results for Starts-Based Combustion Inspection Interval

Details on the calculation algorithms for each maintenance interval are provided in the following sub-sections.

Hours-Based Hot Section Calculation

Since the GE fuel-based run hour counters do not distinguish between base and peak load operation, RLM uses the following modified version of the GER-3620J formula for factored hours:

Factored Hours – Gas = (K + M * I)g * (G + 6 * Pg)

Factored Hours – Distillate = (K + M * I)d * (1.5 * D + 6 * Pd)

Factored Hours – Residual = (K + M * I)r * (3.5 * H + 6 * Pr)

Factored Hours – Crude = (K + M * I)c * (2.5 * H + 6 * Pc)

Total Factored Hours = Sum of the four fuel-based factored hours where the subscripted Ps indicate the number of peak run hours on the various fuel types: gas, distillate, residual, and crude. This breakdown is found by multiplying the total peak hours by the user-entered percentages. The base-load hours (G, D, and H) are calculated from:

G = L30FT_G – Pg

D = L30FT_L – Pd, etc.

The subscripted (K + M * I)s represent the water/steam injection factors corresponding to operation on the various fuel types.

Starts-Based Hot Section Calculation

First, the number of normal starts is calculated:

NN = L30CFS – L30CFLS

Then the normal starts are broken down into part-load, base-load and peak-load starts using the user-entered percentages.

Next, the number of trips that occurred at the various load ranges is calculated based on the user-entered percentages. The trip severity factor for each of the load ranges is then calculated using the median value of each range as the load level (e.g., 30% for the range 20% to 40%).

Hours-Based Rotor Life

First, total base-load hours is calculated:

Hrl = L30FT_T – L30FT_P

Total time on turning gear is estimated by the formula:

TG = K62CD ∗ L30CFS

where K62CD is the cool-down sequence timer length

Then the maintenance factor is calculated based on the formula in GER-3620J.

Starts-Based Rotor Life

Using the number of normal starts, NN, calculated for the Hot Section Interval, the normal starts are broken down into the various shutdown length categories based on the user-entered percentages.

Then the fast starts are broken down into the various shutdown lengths based on the user-entered percentages for fast starts. The formula for maintenance factor (MF) is:

$$MF = [(Fh * Nh + Fw1 * Nw1 + Fw2 * Nw2 + Fc * Nc)normal + (Fh * Nh + Fw1 * Nw1 + Fw2 * Nw2 + Fc * Nc)fast + Ft * Nt] / [(Nh + Nw1 + Nw2 + Nc)normal +(Nh + Nw1 + Nw2 + Nc)fast]$$

$$Nhnormal = NN * \%Hotnormal / 100$$

$$Nhfast = NN * \%Hotfast / 100$$

where %Hotnormal is the user-entered percentage of normal starts that were considered hot starts and %Hotfast is the user-entered percentage of fast starts that were considered hot starts. Similar formulas are used for the "w1", "w2", and "c" start categories.

The "F" factors can be found in the table in Figure 45 of GER-3620J.

Hours-Based Combustion Inspection

The following operating modes are considered:

- Gas-Fired, FSNL to Full Load
- Gas-Fired, Peak
- Primary Liquid-Fired, FSNL to Full Load
- Primary Liquid-Fired, Peak
- Secondary Liquid-Fired, FSNL to Full Load
- Secondary Liquid -Fired, Peak

The water/steam injection severity factors are calculated for each operating mode based on the user-entered values for average steam or water injection flows for each fuel type.

The fuel severity factors are based on the values in GER-3620J and the user-entered information on whether a DLN combustor is present.

The peak load severity factors are based on the user-entered value for the peak firing temperature increase.

The number of operating hours in each mode has previously been calculated for the hot section maintenance factor evaluation (G, Pg, etc.).

Starts-Based Combustion Inspection

A total of 27 types of start/stop cycles are considered:

- Gas-Fired
    - Normal Start
        - Up to Base Load
            - No Trip
            - Trip
                - FSNL
                - FSNL to 20% Load
                - 20 to 40%
                - 40 to 60%
                - 60 to 80%
                - >80%
        - Peak Load
    - Fast Start
- Primary Liquid-Fired
    - Normal Start
        - Up to Base Load
            - No Trip
            - Trip
                - FSNL
                - FSNL to 20% Load
                - 20 to 40%
                - 40 to 60%
                - 60 to 80%
                - >80%
        - Peak Load
    - Fast Start
- Secondary Liquid-Fired
    - Normal Start
        - Up to Base Load
            - No Trip
            - Trip
                - FSNL
                - FSNL to 20% Load
                - 20 to 40%
                - 40 to 60%
                - 60 to 80%
                - >80%
        - Peak Load
    - Fast Start

For each fuel type, it is assumed that the water/steam injection severity factor will be identical for all start types. The value is based on the user-entered values for average steam or water injection flow and control curve type.

The fuel severity factor is based on the GER-3620J values and the user-entered specification of DLN or non-DLN.

The trip severity factor for each of the load ranges is based on the median value of the range (e.g., 30% for the range 20% to 40%).

The load severity factor for peak starts is based on the user-entered value for the peak firing temperature adder.

Individual Run Calculations

User Inputs

The inputs for individual run calculations are entered on the Run Mode Inputs worksheet.

The user should manually enter or select the following information:

- Run Number
- Date and Hour that Run Started
- Date and Hour that Run Ended
- Date and Hour that Previous Run Ended (normally will automatically be filled with the date and hour from a previous run calculation)
- CT Engine Model
- Primary Liquid Fuel Type (distillate, residual, or crude)
- Secondary Liquid Fuel Type (distillate, residual, or crude)
- 2^{nd} & 3^{rd} Stage Nozzle Material
- NO_x Control Method (water, steam, DLN, or none)
- If water or steam, then NO_x Control Curve Type (wet or dry)
- Base Load Firing Temperature (deg. F)

Also, the user must enter the PI database tag names for the parameters listed in the lower-left section of the worksheet beginning in cell "C17" (see Figure 6-11). Note that some of the parameters are normally not available from the Mark V (or Mark VI), but are calculated by the *Combustion Turbine Performance and Fault Diagnostics Module* (CTPFDM.xls). Therefore, CTPFDM should be set up to execute calculations during a run and to export the required parameters to the PI database. This assumes the user has available, unused PI tagnames, which CTPFDM will use to store parameter values.

Once all the inputs have been set, the user should click the button labeled "Retrieve Run Data and Run Remaining Life Calculations". That button initiates a macro that retrieves, via PI DataLink function calls, one minute data for the HP turbine shaft speed (TNH) from 30 minutes before the user-entered starting time to 30 minutes after the start and from 30 minutes before the user-entered ending time to 30 minutes after the end. For example if the user entered:

Date & Time that Run Started: 2/2/04 13:30
Date & Time that Run Ended: 2/4/04 23:05

The data would be retrieved for every minute from 13:00 to 14:00 on 2/2/04 and from 22:35 to 23:35 on 2/4/04.

Table 6-1
Parameters Required from PI Database

Parameter Description	Mark V Tag
Peak Fired Time Counter	L30FT_P
Total Fired Time Counter	L30FT_T
Time Unit Fired on Gas Fuel	L30FT_G
Time Unit Fired on Liquid Fuel	L30FT_L
Steam Injection Flow, lbs/sec	WQJA
NOx Injection Water Flow, lbs/sec	WQJ
Compressor Inlet Air Flow, lbs/sec	AFQ
Gas Fuel Flow, lbs/sec	FQG
Primary Liquid Fuel Mass Flow, lbs/sec	FQLM1
Second. Liquid Fuel Mass Flow, lbs/sec	FQLM2
Fired Starts Counter	L30CFS
Total Starts Counter	L30CTS
‘Fast Load’ Starts Counter	L30CFLS
Emergency Trips Counter	L30CES
Firing Temperature (from CTPFDM.xls), deg. F	Tfire
% Load (from CTPFDM.xls)	Load
HP Turbine Shaft Speed, rpm	TNH
Bleed Heat (On/Off)	CSRIHOUT
GT Inlet Air Flow (from Mark VI or CTPFDM.xls), lbs/sec	WIN

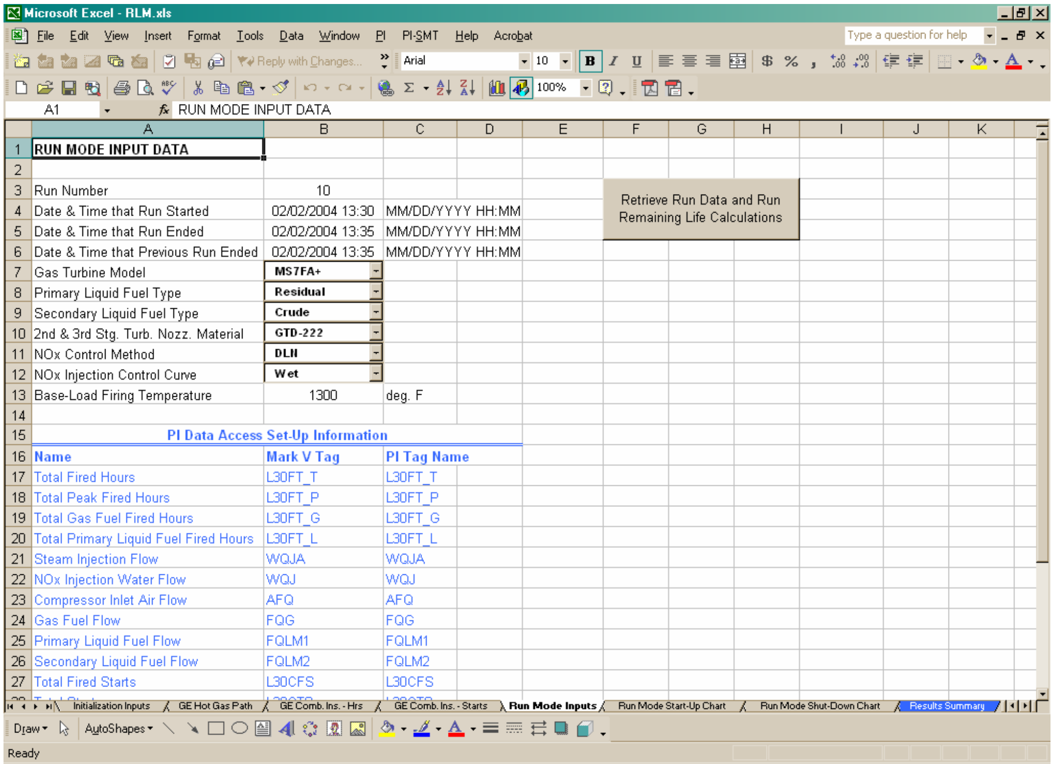


Figure 6-11
Example Run Mode Inputs Worksheet

The macro also creates a trend chart of HP turbine speed versus time for the retrieved data around the starting time. A message box pops up asking the user, "Do you wish to modify the date and/or hour that the run started?" If the user selects the button labeled "Yes", then the view switches back to the Run Mode Inputs worksheet and the macro ends. The user can then modify the start date or time and re-run the retrieve data macro. This feature is included as an aid for determining the exact starting time of a run. In the example shown in Figure6-12, it is clear from the plotted data that the turbine was not running during the specified period, and the user should click "Yes" and enter a new starting time.

If the user selects the button labeled "No" when viewing the TNH plot around the starting time, the macro then creates a trend chart of TNH versus time from the retrieved data around the ending time. Another message box pops up asking the user "Do you wish to modify the date and/or hour that the run ended?" If "Yes" is selected, then the macro returns the user to the Run Mode Inputs worksheet. Otherwise, if the user selects "No", the macro continues with the main data extraction via PI DataLink for each hour of the run, and performs the GER-3620J calculations (and the EPRI HSLMP calculations if the CT model is a 7FA+).

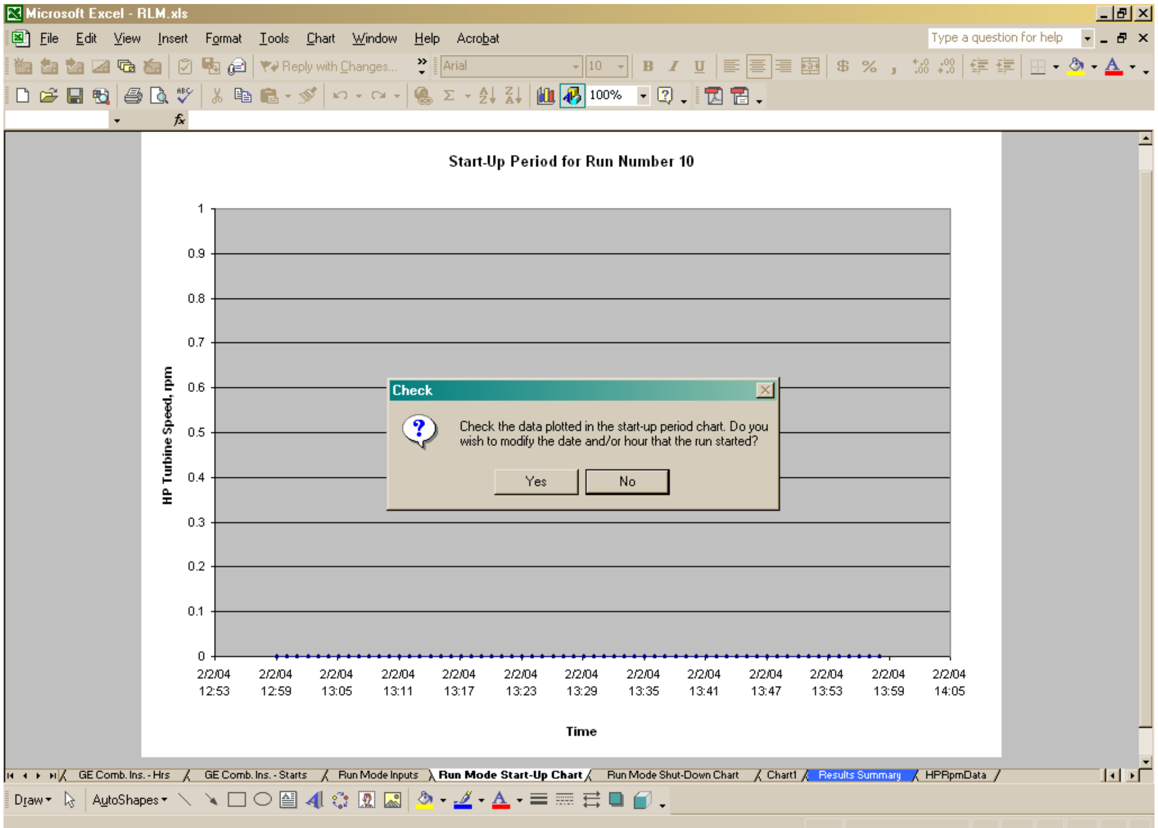


Figure 6-12
Trend Chart of HP Turbine Speed (TNH) around the Period of the User-Specified Run Start Time

Results

Once the user has accepted the starting and ending times for the run mode input data, RLM begins analyzing each hour of retrieved run period data using the GER-3620J algorithms. If the CT model is a GE MS7FA+, the macro also uses the HSLMP algorithms for the first stage rotating blades to calculate the % of maintenance interval remaining based on creep (comparable to GER-3620J hours-based calculation), TMF (comparable to GER starts-based calculation), and the % of maintenance interval remaining based on the combined effects of creep and TMF (no comparable GER-3620J calculation). Then, after RLM has completed processing all run period hours, a message box will pop up displaying a brief summary of the calculated results: Hot Gas Path Factored Hours and Factored Starts, Rotor Life Factored Hours and Factored Starts, and Combustion Inspection Factored Hours and Factored Starts for the run (see Figure 6-13). If the CT model is a 7FA+, Remaining Creep Life, Remaining Thermal Mechanical Fatigue, and Remaining Combined Life percentages are also displayed.

In the pop-up message box, the user is given the option to either accept or reject the results. If the user accepts the results by clicking the "Yes" button, the GER-3620J results are written to a new line in a separate comma separated value (CSV) format file named 3620J.csv. Each line in 3620J.csv represents an individual turbine run (start/stop cycle). The data in the CSV file is also imported to the 3620J.csv worksheet where it can be used for generating trend charts. (Charts can be created by the user.) The end date and time for the current run is also written to the input cell for "Date & Time that Previous Run Ended" (cell "B6") to prepare for the next run calculation.

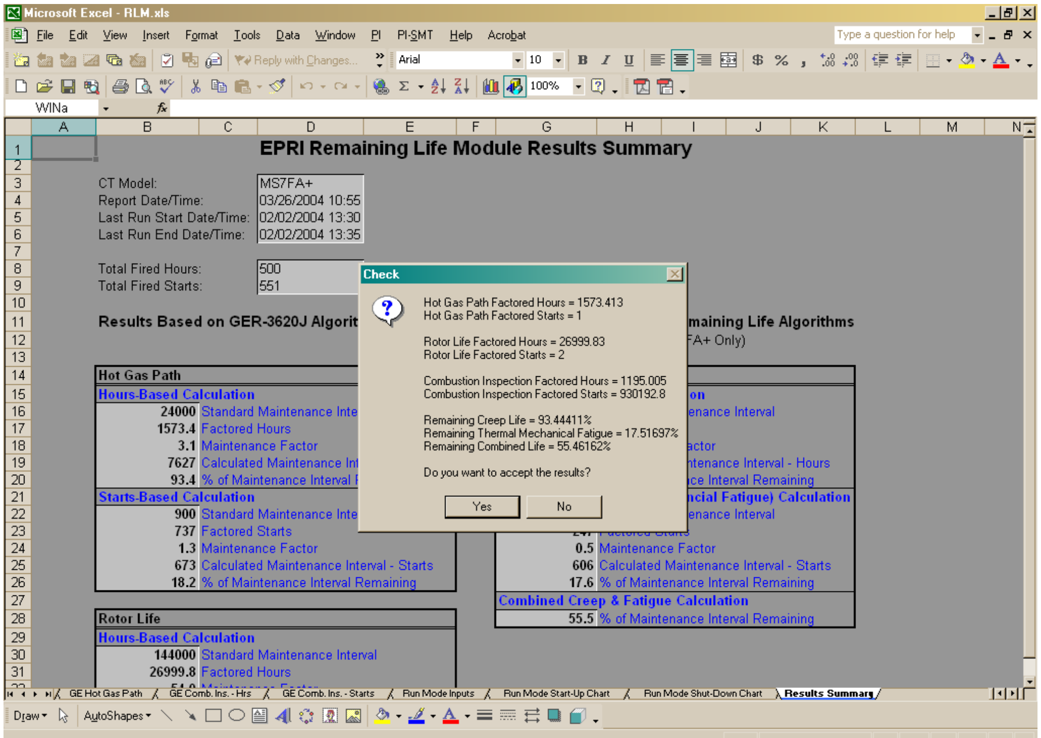


Figure 6-13
Pop-Up Window on Results Summary Worksheet that Appears after Run Mode Calculations are Completed

The data written to 3620J.csv includes:

- Run Number
- Date & Time that Run Started (stored in days since 1/1/1900 format)
- Date & Time that Run Ended (stored in days since 1/1/1900 format)
- Total Cumulative Hours on Turning Gear
- Actual Hours for the Run
- Hot Gas Path Hours-Based Results
  - Factored Hours for Run
  - Maintenance Factor for the Run
  - Cumulative Factored Hours
  - Cumulative Maintenance Factor
  - Maintenance Interval

  - % of Maintenance Interval Remaining
- Hot Gas Path Starts-Based Results
  - Factored Starts for Run
  - Cumulative Factored Starts
  - Cumulative Maintenance Factor
  - Maintenance Interval
  - % of Maintenance Interval Remaining
- Rotor Life Hours-Based Results
  - Factored Hours for Run
  - Maintenance Factor for the Run
  - Cumulative Factored Hours
  - Cumulative Maintenance Factor
  - Maintenance Interval
  - % of Maintenance Interval Remaining
- Rotor Life Starts-Based Results
  - Factored Starts for Run
  - Cumulative Factored Starts
  - Cumulative Maintenance Factor
  - Maintenance Interval
  - % of Maintenance Interval Remaining
- Combustion Inspection Hours-Based Results
  - Factored Hours for Run
  - Maintenance Factor for the Run
  - Cumulative Factored Hours
  - Cumulative Maintenance Factor
  - Maintenance Interval
  - % of Maintenance Interval Remaining
- Combustion Inspection Starts-Based Results
  - Factored Starts for Run
  - Cumulative Factored Starts
  - Cumulative Maintenance Factor
  - Maintenance Interval
  - % of Maintenance Interval Remaining

If the user accepts the results by clicking the "Yes" button in the pop-up message box and the CT being analyzed is a GE 7FA+, the HSLMP results will also be saved to a separate CSV file named Results.csv and to a Results.csv worksheet. The worksheet data can then be used to generate charts showing the historical trend in % life remaining. (Charts can be created by the user.)

After the "Yes" button in the pop-up message box has been clicked to accept the results and the data has been saved to the CSV file(s) and worksheet(s), the message box is closed and the calculated results are displayed on the Results Summary worksheet.

If the user chooses to reject the results by clicking the "No" button in the message box, the results are neither saved to file(s) nor saved to worksheet(s), but the results are displayed on the Results Summary worksheet. The user can then review the results and/or return to the Run Mode Inputs worksheet where the input data can be modified before retrieving the run data and running the remaining life calculations once again.

Results Summary

A summary of all of the life calculations is displayed in the Results Summary worksheet. An example of a portion of the summary screen is shown in Figure 6-14.

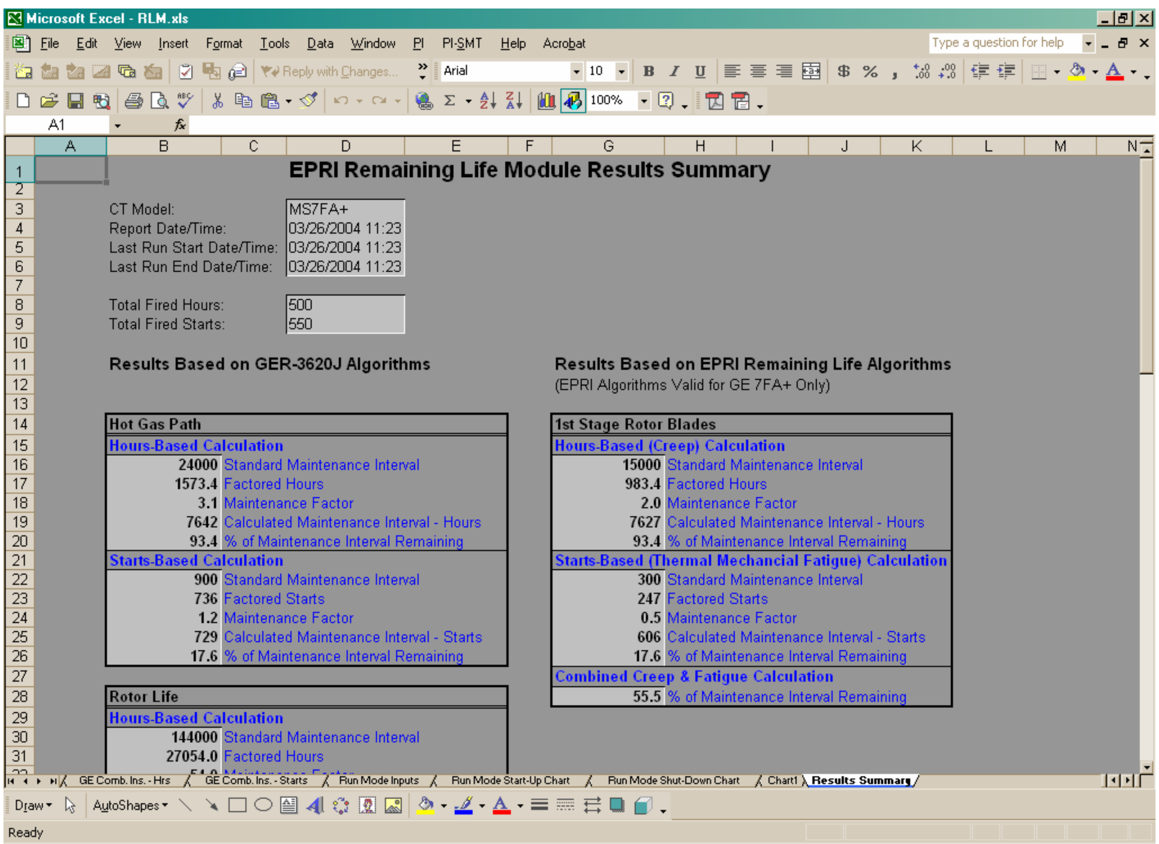


Figure 6-14
Example of Results Summary Worksheet

References

1. Robert Dewey, "Combustion Turbine F Class Life Management: Maintenance Life Tracking", EPRI Report 1004364, Dec. 2002.
2. Robert Hoeft, Jamison Janawitz, and Richard Keck, "Heavy-Duty Gas Turbine Operating and Maintenance Considerations", GE Power Systems Report GER-3620J, Atlanta, GA, Jan. 2003.
3. "Specialists' meeting on heat exchanging components of gas-cooled reactors Duesseldorf (Germany) 16-19 Apr 1984", International Atomic Energy Agency, International Working Group on Gas-Cooled Reactors, Vienna (Austria) IWGGCR--9, pp:377-388
4. Fabio, G., and F. Carlevaro, "Gas Turbine Maintenance Policy: A Statistical Methodology to Prove Interdependency between Number of Starts and Running Hours", ASME Technical Paper GT2002-30281, presented at Turbo Expo 2002, Amsterdam, June 2002.

Appendix A

Installation

Hardware & Software Requirements

Table 6-2 lists the minimum hardware requirements for running the RLM spreadsheet. In addition, the PC must have Microsoft Excel 97 (or later) and OSI Software PI DataLink 2.0 (or later) installed. Finally, if the user wishes to view an electronic version of this User's Guide, Adobe Acrobat Reader 5.0 (or later) must be installed on the PC. Acrobat Reader is available free of charge on the Adobe Systems Web site at http://www.adobe.com.

Table 6-2
Minimum Hardware Requirements

Hardware	Minimum Requirement	Recommended
Processor	333 MHz Pentium III	Same
Operating System	Windows 95/98/2000/NT 4.0/XP	Same
RAM	256 MB	512 MB
Available Hard Disk Space	10 MB	>20 MB

How to Install

1. Start Windows 95, 98, 2000, NT, or XP. Make sure that no other application is running while RLM is being installed.
2. The RLM installation disk(s) may consist of either a single CD or multiple 3½-inch diskettes. Insert the RLM installation CD or 1st diskette into the appropriate disk drive of your computer. For diskettes, this is usually drive A:\.

3. Select the "**Start**" button from the taskbar at the bottom of the screen and then "**Run**…". The "**Run**" dialog box appears.
4. For diskettes, type "A:\Setup.exe" in the Command Line text box. If installing from a CD or diskette drive other than A:\, substitute the appropriate letter for that source drive.
5. Select "**OK**". A welcome dialog box appears.
6. Select "**Next**" to go to the next screen.
7. A message box appears and asks where to install the RLM files (C:\Program Files\RLM is the default path). If desired, change the default name and destination of the RLM directory (folder).
8. The installation program will then install the program in the specified directory. If installing from diskettes, you will be prompted to change disks. The installation program will also add RLM to the "**Programs**" menu option found under the "**Start**" button in the taskbar at the bottom of the screen. When you receive an on-screen message that the installation is complete, remove the CD or final diskette from its drive.
9. To start the RLM program, select the "**Start**" button from the taskbar, select the "**Programs**" submenu, click on **RLM,** then click on the Excel spreadsheet icon labeled **RLM**. Excel will start and load the RLM.xls spreadsheet. A dialog box will appear stating that the spreadsheet contains macros and asking if you want to enable or disable the macros (see Figure 6-15). Click "**Enable Macros**" and the spreadsheet will finish loading.

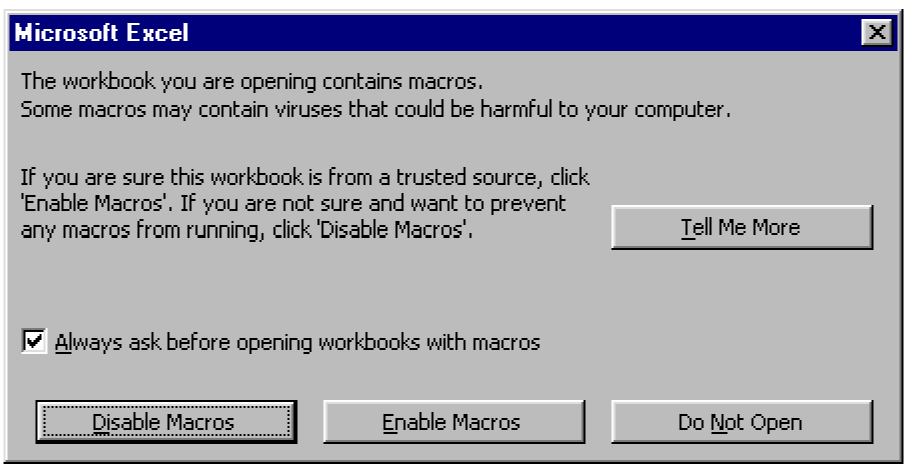


Figure 6-15
Example of Dialog Box that Appears Each Time the RLM.xls Spreadsheet Is Loaded

How to Uninstall

1. From the Windows 95, 98, 2000, NT, or XP desktop, click on the "**My Computer**" icon to open the "My Computer" window.
2. From the "My Computer" window, click on the "**Control Panel**" icon to open the "Control Panel" window.
3. From the "Control Panel" window, click on the "**Add/Remove Programs**" icon to open the "Add/Remove Programs" window.

4. Select the RLM software from the list of currently installed programs, then click the "**Add/Remove**" button ("**Change/Remove**" button in Windows 2000).
5. A message box will appear asking for confirmation of the removal of the program and its components. If you are certain that you want to uninstall RLM, click the "**Yes**" button and RLM will be removed.

7
VIBRATION FAULT DIAGNOSTIC SYSTEM MODULE

Introduction

The success of a condition-based maintenance strategy is dependent on the performance of the process and the costs associated with condition monitoring. Development of a sophisticated, automated condition assessment tool promotes the success of the program by becoming a value – added asset integral to the operation by providing real-time anomaly detection and diagnostics of performance and mechanical faults. This information can then be utilized to predict critical component remaining useful life and turbine degradation. Through proper utilization of these health management technologies, timely decisions can be made regarding unit operation and maintenance practices.

Mechanical faults (i.e. bearing, rotordynamic, and structural) can be detected and classified from vibration sensors placed at specified locations on the engine using feature-based diagnostic techniques. Domain knowledge associated with particular vibration fault frequencies, fixed frequency ranges, per-rev excitations, and structural resonances can be extracted from the vibration spectrums acquired from sensors monitoring the combustion turbine's operation. For a particular engine type, these spectrums are used to develop a knowledge base from which reasoners are adapted for diagnosing mechanical faults.

The *Vibration Fault Diagnostics System* (VFDS) described herein has been designed to aide personnel in detecting incipient mechanical fault conditions and planning appropriate maintenance actions. The system utilizes high bandwidth data to extract narrow bandwidth feature data. This narrow bandwidth feature data, in addition to being posted to the PI Historian, is utilized by the diagnostic reasoner to determine actionable failure modes. The software resides on a dedicated computer and interacts with the existing vibration monitoring system. Once started, the diagnostic system will remain on at all times thus eliminating the necessity of operator interaction to control operation. Upon detection of CT operation and the availability of useful data, analyses are initiated every second. The narrow bandwidth feature data, output from these analyses, reflect the current diagnostic assessment from the analyzed data snapshot. All outputs from the analyses can be displayed on the user interface, viewable on the host computer's monitor (if equipped). A subset of the results attained, low bandwidth results, are posted to the PI Historian system where they can be viewed and analyzed from any computer with access to the data archive. The interaction with the PI Historian allows the system to be run completely unattended while providing the relevant condition assessment information to personnel in the control room.

The VFDS module has been developed to primarily operate as an independent node on the network, passively processing the available data in real-time. It can also be utilized as a very capable interactive diagnostic tool in the hands of vibration specialist. Processed vibration data can be displayed in a multitude of formats which can prove useful in an active condition monitoring program.

An in depth discussion is presented in this report covering the components of the VFDS. This will include topics covering; the architecture of the VFDS hardware and software, the diagnostic tools available during the passive and interactive modes, and the technique utilized to fuse the processed data into a likely fault.

Hardware Overview

The *Vibration Fault Diagnostics System* (VFDS) is a standalone autonomous device consisting of the computer running the developed software and data acquisition cards collecting the data. This configuration offers the most flexible solution, allowing communication with the Bently-Nevada system and PI Historian. In addition, using a standalone fully operational desktop computer affords flexibility in the system placement. The diagnostic computer can be placed in any convenient location including outside of the control room. A schematic is shown in Figure 7-1.

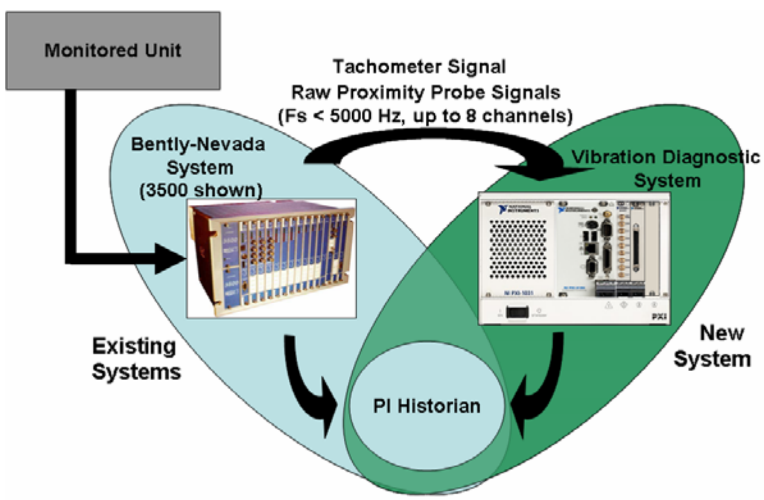


Figure 7-1
Vibration Diagnostic Module Hardware Schematic

The host computer is a standalone, fully operational, ruggedized computer, a PXI (PCI eXtension for Instrumentation) form factor that affords flexibility in the system placement. The following discussion on installation and configuration requires an understanding of the components utilized in the VFDS. As such, an overview is provided here to introduce the hardware components, as seen in Figure 7-2, utilized in creating the monitoring system. The system is comprised entirely of *Commercially available Off-the-Shelf* (COTS) components from National Instruments™.

There are three primary hardware components: the host computer, data acquisition cards, and a common chassis.

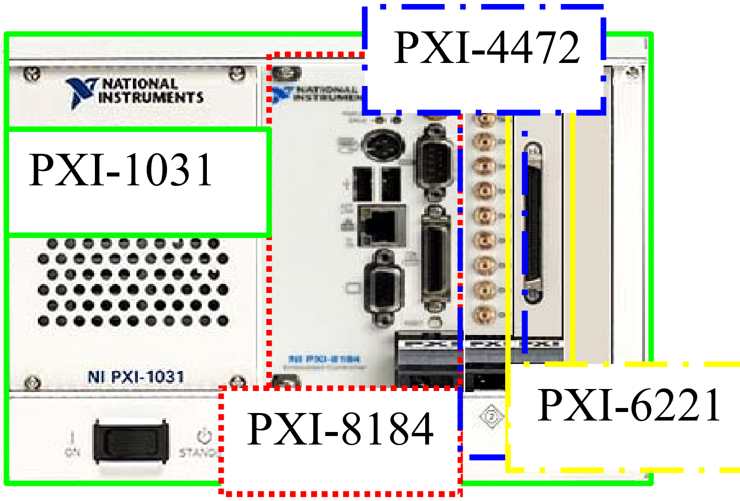


Figure 7-2
Vibration Fault Diagnostics System Dedicated Computer

1. **Host Computer:** A National Instruments^{TM} PXI-8184 embedded controller has been selected as the host computer. The developed software is deployed and run on this standalone computer. This Windows-based fully functional, ruggedized computer is capable of communication with the Bently Nevada system and with PI Historian.

2. **Data Acquisition Card:** A National Instruments^{TM} PXI-4472 dynamic signal acquisition board was selected as the data acquisition board for this project. This card is capable of simultaneously sampling eight channels with a dynamic range of 110 decibels and a 45kHz alias-free bandwidth and is well suited for vibration measurements. All eight channels are used to acquire proximity probe data from the four probes on the turbine and the four probes on the generator.

3. **Tachometer Data Acquisition Card:** Since all eight channels on the PXI-4472 are used, an additional card was required for the tachometer signal. A National Instruments^{TM} PXI-6221 multifunction data acquisition card was selected to acquire the tachometer signal. This 16-bit card is capable of acquiring up to 16 channels at rates up to 250,000 samples per second. The current configuration utilizes only one of the 16 channels, leaving up to 15 channels for further expansion (depending on the input configuration). One drawback of this card is that there is no built-in antialiasing filter (as the PXI-4472 has), though this should not effect the tachometer signal acquisition.

4. **Common Chassis:** A National Instruments^{TM} PXI-1031 is a rugged and compact chassis that encloses and powers the above host computer and data acquisition cards. Its dimensions are 10.12 x 7.50 x 8.38 (W x H x D in inches). The chassis has an available slot for further expansion if a need develops for acquiring additional channels, or an alternative bus technology is required.

Installation and Configuration

The *Vibration Fault Diagnostics System* (VFDS) has been developed to reside on the dedicated computer described above which houses the data acquisition, vibration analysis and diagnostic capabilities. Installation of the system is completed by establishing the connections with a power source, *Local Area Network* (LAN) and the sensors monitoring operation of the turbine and generator.

1. 110 volt AC power source is supplied to the system via the PXI-1031.

2. Data from the eight proximity probes monitoring the turbine/generator system are supplied to the PXI-4472 via the Bently Nevada vibration monitoring system. Data is passed through the Bently Nevada system and the connection is completed via the eight SubMiniture B (SMB) connectors located on the card.

3. The tachometer signal is input into the system via the PXI-6221. The signal is routed through a shielded connector block, National Instruments™ SCB-68, supplied with the system. The connection is made utilizing a BNC connector at the connector block where minor analog signal conditioning is performed to coerce the tachometer signal into the ±10V signal range of the PXI-6221.

4. The capability of writing data to the PI Historian is dependent upon the ability to access the destination PI Server over a LAN. This connection is made through the PXI-8184 via an Ethernet cable.

5. The VFDS has been developed to operate autonomously, however, should configuration be required, or use of the vibration analysis interface, a mouse, keyboard and monitor can be connected to the PXI-8184 utilizing the standard connections.

6. An external hard drive is provided to record raw, time domain data. A USB1.1 connection is utilized between the hard drive and the PXI-8184.

Signals

The vibration diagnostic module will accept up to eight channels of raw high bandwidth proximity and seismic probe signals. These signals are the signal conditioned outputs from the Bently-Nevada system, thus eliminating the need for another signal conditioning system. The default connections are shown in Table 7-1.

Table 7-1
Default Signal Connections

Channel	Connection	Description
CT Bearing 1 V	PXI1Slot2/ai0	Eddy Current Displacement Probe
CT Bearing 1 H	PXI1Slot2/ai1	Eddy Current Displacement Probe
CT Bearing 2 V	PXI1Slot2/ai2	Eddy Current Displacement Probe
CT Bearing 2 H	PXI1Slot2/ai3	Eddy Current Displacement Probe
Gen Bearing 1 V	PXI1Slot2/ai4	Eddy Current Displacement Probe
Gen Bearing 1 H	PXI1Slot2/ai5	Eddy Current Displacement Probe
Gen Bearing 2 V	PXI1Slot2/ai6	Eddy Current Displacement Probe
Gen Bearing 2 H	PXI1Slot2/ai7	Eddy Current Displacement Probe
Tachometer	PXI1Slot3/ai0	Eddy Current Displacement Probe

The tachometer channel is of critical importance. It is preferable to have a "raw" tachometer signal, such as a TTL square wave, but other indicators of the current shaft speed are acceptable. A requirement of the tachometer signal is that it be in phase with the vibration data. It is of critical importance that there is no lag between the speed indication and the sensor data. Accurate order analysis depends on having the correct speed value for a given sensor data. Any lag will result in erroneous order extraction. Please refer to Appendix __ for further sensor details.

Software Architecture

Here we will discuss the considerations that went into laying out the architecture of the VFDS software. Software development was completed using National Instruments LabVIEW integrated development environment. LabVIEW is a data acquisition, data analysis, and graphical user interface development tool. Currently LabVIEW has over 450 built-in data analysis tools and techniques. This extensive library of tools greatly reduces software development time by reducing time required to "reinvent the wheel." Included are tools that allow software developed in LabVIEW to take advantage of other Microsoft Windows components such as AxtiveX™ that provide a means of communication with OSIsoft's PI Historian. Development of the software was focused around integration of the various preexisting techniques and tools.

Software Components

A common approach in software development is to divide an application into task oriented components. The VFDS has been decomposed into the following distinct modules:

- *Graphical User Interface* (GUI)
- Data Acquisition

- Analysis
- Communication with PI

It is critical that each module perform its tasks in a deterministic fashion to prevent buffer memory overflow or an interruption in the time sensitive portions of the code. When in use, the GUI must provide feedback to the operator and allow for control of the program without interference from action “behind the scenes.” The Data Acquisition module is the most time sensitive; if data is not removed from the acquisition buffer at an average rate equal to the acquisition rate, memory will overflow and the application will stop. The Analysis module is responsible for pulling the data out of the acquisition buffer and performing a series of processes which result in the low bandwidth feature data. Communication with PI has been relegated to an independent module because the communication is dependent on network availability and bandwidth. A slow down in network communication can not be allowed to interfere with the time-critical acquisition of data.

Each module runs independently, but also must communicate with the others. A software architecture traditionally called a producer/consumer model was selected to permit independent operation of the modules and allow for data exchanges between them. Memory stacks called queues are utilized to allow each module to run at a different rate. For example, the Data Acquisition module runs at a fixed rate of one second per iteration determined by the sampling rate (5000 samples acquired and read per second) and then places the data into a queue for consumption by the Analysis module. If the Analysis module is running at a slower rate for a short period of time, data will accumulate in the queue. The Analysis module will continue to pull the oldest data out of the queue and process it; in this way, no data is overlooked. Similarly, the Analysis module produces data for the PI Communication module’s consumption; however, in this case the queue is limited to one packet of data. The PI Communication module runs as quickly as possible given the network connection. In the ideal situation, the PI Communication module will be capable of running faster than the other modules, so it will always be waiting for data. If this is the case, no data will be dropped. If the communication is slower, the most recent data will be delivered to the PI Historian as often as possible, but at a slower rate than the data is locally processed. This architecture allows data to be continuously acquired, processed, and locally saved to disk (when appropriate) to prevent an event from being missed. The communication with the PI Historian is entirely network dependent, and incapable of interfering with the other components.

Operational Modes

The internal operation of the software is largely transparent to the user; however, the operational modes are relevant to the operation at all levels. The VFDS makes a distinction, based on shaft speed, between operational modes of the monitored unit. The four operational modes are:

- Idle
- Startup
- Steady State (SS)

- Shutdown

There are a few parameters in the configuration file that relate specifically to identifying operational modes and to how raw data is stored in a mode. Descriptions of the related configuration parameters and their default values are listed below in Table 7-2.

Table 7-2
Configuration Parameters Related to Operational Modes

Configuration Parameter	Default Value	Description
Transient Speed Limit	150 RPM	The threshold speed between Idle/Startup and Shutdown/Idle. 120 RPM is theoretically the minimum speed measurable by the VFDS utilizing a 1 second window and 1 pulse per revolution tachometer signal.
SS Speed Low Bound	3590 RPM	The threshold speed between Startup/SS and SS/Shutdown. This may be set as close to the steady state speed of 3600 as desired as long as measured variations in speed at steady speed do not fluctuate under this value.
SS Save Period	60 seconds	The frequency that raw time series data will be saved to disk during SS. A discussion below under **Data Storage** explains the effect of SS Save Period and Acq Duration on disk usage for raw data.
Acq Duration	5 seconds	The amount of data to save to disk during SS for each Save Period.

The analysis of the signals and calculation of the results will be the same for each mode, except the Idle mode where no features are calculated. The Bode and Polar Plot can only be calculated on transient data, while the frequency and order waterfalls can be displayed at all times, but have less significance outside of transient conditions.

Mode Selection Logic

Once a test has been started, the software constantly acquires data and determines the shaft speed. The mode of the unit is determined based on the configuration parameters and the knowledge of the current mode. When the unit is idle, that is, when the shaft speed is less then the *Transient Speed Limit* (TSL), no data is saved and no features are calculated. When the shaft speed exceeds the TSL, the software identifies the operating mode as Startup and begins acquiring and saving data continuously, as well as calculating and posting features to the PI Historian. From the Startup mode, the unit can only transition back to Idle, or to Steady State. Recognizing that the unit may spend extended amounts of time at Steady State, the software scales back the amount of data saved. The SS Save Period, and SS Acq Duration parameters control the amount of data saved while the unit is in Steady State. Based on the default parameters, the software will save 5 seconds of data every 60 seconds. This minimizes the storage requirements for data that is unlikely to change significantly. While the amount of data saved is scaled back, the data processing and analysis is continuous as well as the posting of data to the PI Historian. For this reason, it is suggested that the PI Historian is configured to compress the points to minimize the storage requirements for the PI server. If a feature is determined to be out of limits at any point, the VFDS software immediately triggers a dump of the buffer to disk. This feature is discussed more in the Data Storage section. Once the software determines that the unit is running in Steady State mode, it can only transition to Shutdown or remain in Steady State. The Shutdown mode is treated identically to the Startup mode as far as the software is concerned.

Startup/Shutdown Mode

As discussed above, the unit is determined to be in Startup/Shutdown mode when the shaft speed is between the *Transient Speed Limit* (TSL) and the SS Speed Low Bound. The entire suite of features and results will be calculated and posted to PI Historian. Waterfall, Tracked Order, and Orbit plots are most useful during transients to skilled vibration specialists. Again, these plots will only be available on the diagnostic system's host computer and not via PI Historian.

Only the most recent two startup/shutdown events' data is saved. An operator could compare successive startup/shutdown events by renaming the saved data or by plotting it and saving an image of the processed data. As always, the data stored in the PI archive is available for analysis.

Steady State Mode

During steady state operation, when shaft speed is at or above the SS Speed Low Bound, the software will operate in the Steady State operational mode. Like the transient mode, the entire suite of features and results will be calculated and posted to the PI Historian. Also, like the other mode the Steady State mode will post data to the PI Historian as often as every second. PI Historian can then compress and archive the results according to its schedule. Unlike in the Startup/Shutdown operational mode, raw data is not continuously being streamed to disk.

Data Storage

To facilitate analysis of diagnostic events, the software will automatically record a configurable amount of raw data for each significant detected event. By default, raw data is held in an internal buffer in memory for ten minutes. In the event of an out-of-limit event, raw data with a duration equal to the buffer size before, and one half the buffer size afterward will be written to disk. For instance, after an over limit of RMS the software will save the preceding ten minutes and the following five minutes of raw data. In addition the software will automatically archive a snapshot of data periodically during Steady State operation and a total of four transient events are kept on disk (two Startup, two Shutdown for each test). Disk space is conserved by only saving data while the monitored unit is running, but the amount of data generated could potentially be significant.

Although a large external hard drive is utilized, storage space can quickly be filled. Archiving all nine channels (eight proximity probes and tachometer) of raw data for many minutes requires significant disk space. Figure 7-3 shows the method used to calculate the required disk space. The decision was made to store the data in binary format for this reason. The advantages of using binary format are size and speed of access. The disadvantage is the difficulty associated with reading the data; the file can not be read using a traditional piece of software like Window's Notepad or Microsoft Excel without converting it first to an ASCII format.

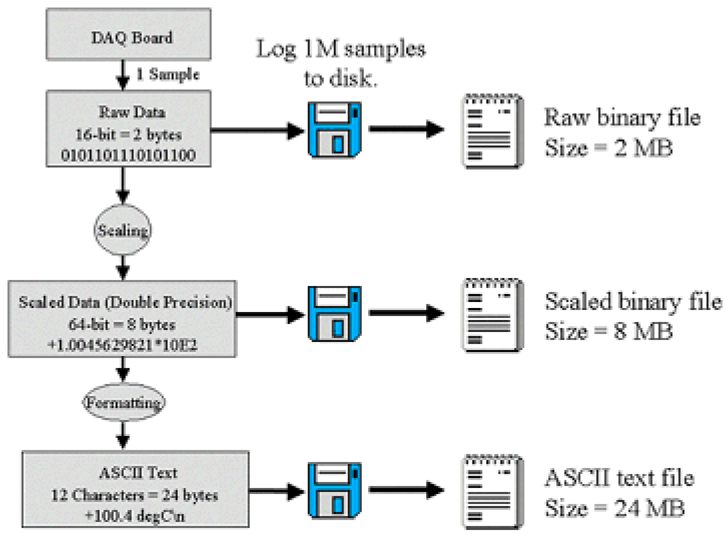


Figure 7-3
Example Disk Space Requirement[1]

Equation (1) can be used to determine the storage requirements for a day of Steady State operation given the parameters described in Figure 7-4. It can be seen that storage space will be consumed relatively quickly.

$$Storage[GB] = \frac{Fs \cdot C \cdot Sd \cdot \left(\dfrac{60 \cdot 60 \cdot 24}{Sp} \right) \cdot B}{1024^3} \qquad (1)$$

[1] National Instruments Corporation (www.ni.com)

Parameter	Variable	Units	Value
Sampling Rate	Fs	Hertz	5000
Number Channels	C	#	9
SS Acq. Duration	Sd	second	5
SS Save Period	Sp	second	60
Bytes per sample	B	bytes	4

Total **1.2** **Gigabytes per day**
Minimum (plus overhead)

Definitions:
Fs: sampling rate
Number Channels: number of channels acquired
SS Acq. Duration: lengfh of time data will be collected
SS Save Perio: time between acquisitions
Bytes per sample: data format size

DAQ Resolution	Bytes
12 bit	2
16 bit	2
24 bit	4

Figure 7-4
Required Disk Space for Archiving Steady State Data

Analysis Specification

Automatic Feature Calculations

The vibration diagnostics module provides many signal processing techniques to extract useful features from the monitored signals. Some of these features are extracted directly from the raw time domain signal and others are extracted after further analysis. Traditionally, there are two domains employed in vibration analysis: time and frequency. Time domain features are extracted directly from the time-based signal. Frequency domain features require a frequency analysis such as a *Fast Fourier Transform* (FFT) to be performed before the features calculation.

The analysis is conducted every second on one second blocks of data. In development, the sampling rate was set to 5000 Hz; therefore the amount of data to analyze every second is 5000 points per channel. The development unit's dynamic signal acquisition card is fully exploited with eight vibration channels monitoring four bearings (two on the combustion turbine and two on the generator). Additionally, the tachometer signal is acquired on the other data acquisition card at the same rate. That results in a total of 45000 analysis points per second. This amount of data can, on average, be processed for the following features in one second because of the computational power of the embedded computer and efficient programming. If the processing time exceeds one second for a period of time, the controller's memory is utilized to queue the data for analysis.

Time Domain Features

Time domain features are typically statistically based. They are derived from the raw time waveform of each acquired channel. Although there are many time domain features used in diagnostics, experience has shown the following features to be the most robust indicators of system health.

Maximum Amplitude

The maximum absolute vibration amplitude measured during the specified time interval can indicate the onset of unbalance, rubs, and bearing faults.

RMS

The *Root Mean Square* (RMS) value of a vibration signal is a time analysis feature that is the measure of the power content in the vibration signature. This feature is useful for tracking the broadband vibration level, but does not provide much information for fault isolation. It can also be very effective in detecting a major out-of-balance in a rotating system. Equation (2) is used to calculate the root mean square value of a data series, x_n over length N.

$$RMS = \sqrt{\frac{1}{N} \cdot \sum_{n=1}^{N} x_n{}^2} \qquad (2)$$

An example of the user interface on the host machine is shown below (Figure 7-5) displaying the RMS feature for each channel as it changes with time. The monitored unit shaft speed is also plotted on the chart (the thick black line).

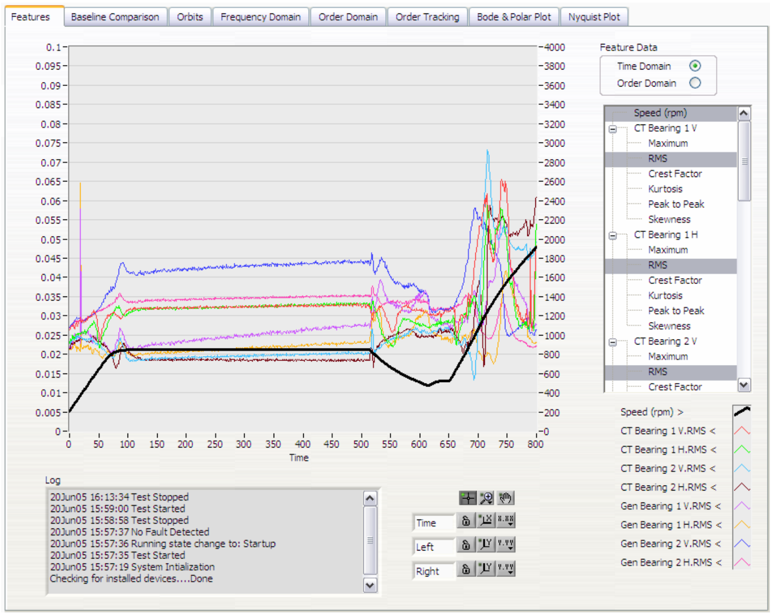


Figure 7-5
Feature Tracking with Time in the VFDS Interface

Crest Factor

The simplest approach to measuring defects in the time domain is using the RMS approach. However, the RMS level may not show appreciable changes in the early stages of mechanical failures. A better measure is to use the "Crest Factor" which is defined as the ratio of the peak level of the input signal to the RMS level; see Equation (3). Therefore, peaks in the time series signal will result in an increase in the crest factor value. For normal operations, crest factor may reach between 2 and 6. A value above 6 can mean that problems are developing. The Crest Factor is particularly useful in detecting transient events such as partial rubs and loose mechanical connections.

$$Crest\ Factor = \frac{PeakLevel}{RMS} \qquad (3)$$

Kurtosis

Kurtosis is the fourth statistical moment of the time domain vibration signal. A kurtosis value greater than three indicates that the frequency of large spikes is greater than would be expected for normally distributed noise. The equation for calculating Kurtosis is shown in Equation (4) below.

$$Kurtosis = \frac{\sum_{i=1}^{N}(x_i - \mu)^4}{N\sigma^4} \qquad (4)$$

x_i = Series value
μ = Mean of data series
N = Number of data points in series
σ = Standard deviation of data series

Peak to Peak

The peak-to-peak value of a signal is a measure from the signal's minimum to maximum value.

Skewness

The skewness is the third statistical moment of the time domain vibration signal. This statistic provides a characterization of the degree of asymmetry of the signal sample's distribution around its mean; see Equation (5).

$$Skewness = \frac{\sum_{i=1}^{N}\left(x_i - \mu\right)^3}{N\sigma^3} \qquad (5)$$

x_i = Series value
μ = Mean of data series
N = Number of data points in series
σ = Standard deviation of data series

Frequency Domain Features

Frequency domain features are useful in not only identifying the presence of a fault, but also identifying the type of fault. The magnitude of the monitored signal at specific frequencies related to the shaft speed can be used to determine resonances of the structure, unbalance, misalignment and many other mechanical faults.

The basis of frequency domain features is the *Fast Fourier Transform* (FFT), a frequency analysis technique. During the FFT calculation a window is applied to the data. Then the magnitudes of the specific frequencies of interest can be extracted from the FFT by a "peak-picking" algorithm. These peaks represent the magnitudes of the signal of interest. Frequencies of interest may include shaft speed and its harmonics, bearing frequencies, and many others.

In addition to the peaks at frequencies of interest, the sidebands of the peak can be used in diagnostics. Sidebands are peaks in the FFT magnitude that are near a larger peak. The existence and magnitude of sidebands can be used to diagnose and characterize faults.

The one second sampling period will allow one hertz resolution on the FFT based diagnostics. This is sufficient for diagnosing most faults.

Engine Order Tracking

Engine orders are the shaft speed and its harmonics. The signal magnitudes at these frequencies are extremely useful in diagnosing faults. By comparing and tracking the relative magnitude of twenty-one orders (1/4, 1/3, 1/2, 2/3, 1, 1-2/3, 2, 2-1/3, 3, 4, …, 15 times shaft speed) the software is capable of detecting many fault types.

However, extracting the engine orders can be difficult. The vibration signal needs to be sampled at constant angular positions during a revolution. Typically sampling is performed at constant times, not positions. If the shaft speed is changing the sampling will not be at constant angular positions. The difference is illustrated in Figure 7-6 as well as the impact on the frequency spectrum calculated from the signals.

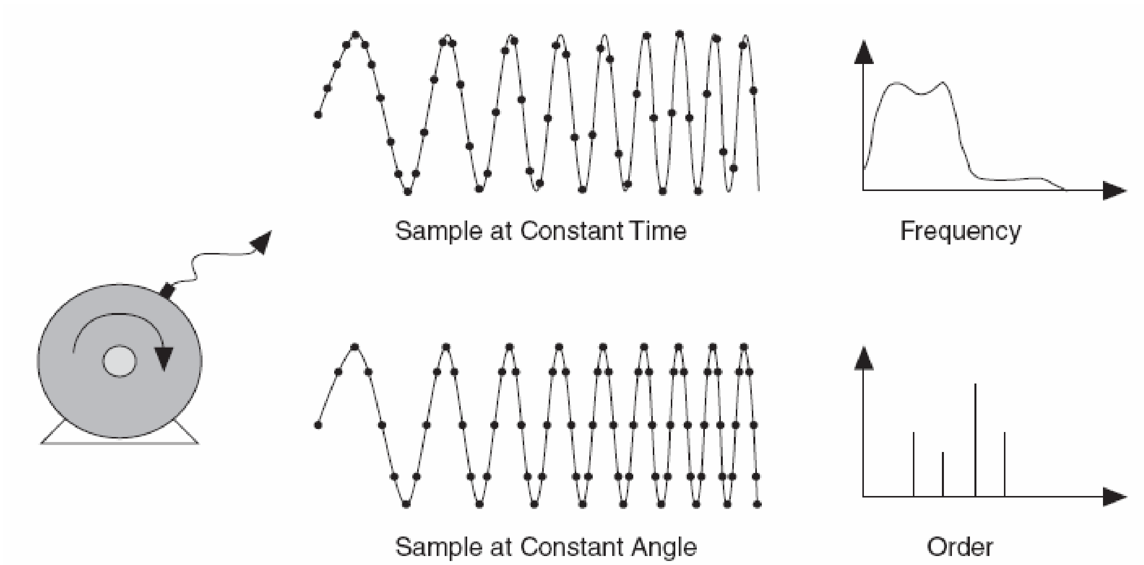


Figure 7-6
Resampling Technique and Effect on Frequency Spectrum

The resampling process performed by the VFDS software is broken down into four steps:

1. Acquire vibration and tachometer signal at constant sampling rate
2. Interpolate angular positions between tachometer pulses
3. Calculate the time at desired angular increments
4. Interpolate the vibration signal at the selected times to acquire new samples

Once the signal has been resampled, an FFT is performed and the engine orders are extracted by a "peak-picking" process. The process is displayed graphically in Figure 7-7.

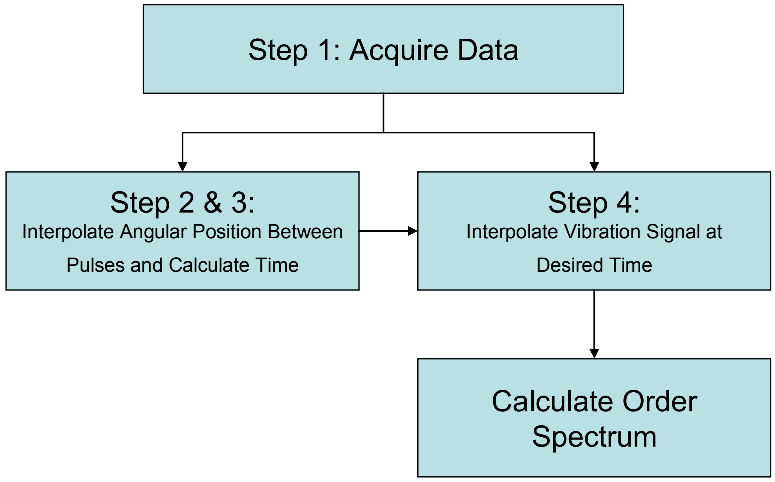


Figure 7-7
Resampling Process Performed in VFDS

Baseline Comparisons

Baseline comparisons are critical to the proper function of the *Vibration Fault Diagnostics System* (VFDS), and are what allow the system to be relevant to many different applications. Application generic absolute values are rarely available as guidelines to the difference between "good" and "bad" on individual features. The VFDS system has the ability to be taught to differentiate between the two by generating Baseline files to use for guidance.

A Baseline file is generated from "healthy" data that has been acquired and processed. The processing involves calculating over 45 features per channel from the data for each second acquired. Statistical principles are used to reduce the quantity of data to a manageable amount and the generated model is saved to disk for later use. During the startup of the software, the baseline files (one for each operating mode: Startup, Steady State, and Shutdown) are loaded into memory. During testing, feature values calculated in real-time are compared to the model limits to determine if a feature is out-of-the-ordinary. The *Baseline Comparison* pane has been included in the software interface to give users a means of examining the comparison process with a limited feature set. The expected baseline operation for the selected channel and feature is statically plotted on the axes shown in Figure 7-8. During operation, the current value of the target feature is superimposed as a cross-hair on the baseline plot to highlight the comparison of the feature to its expected value given the current operating mode.

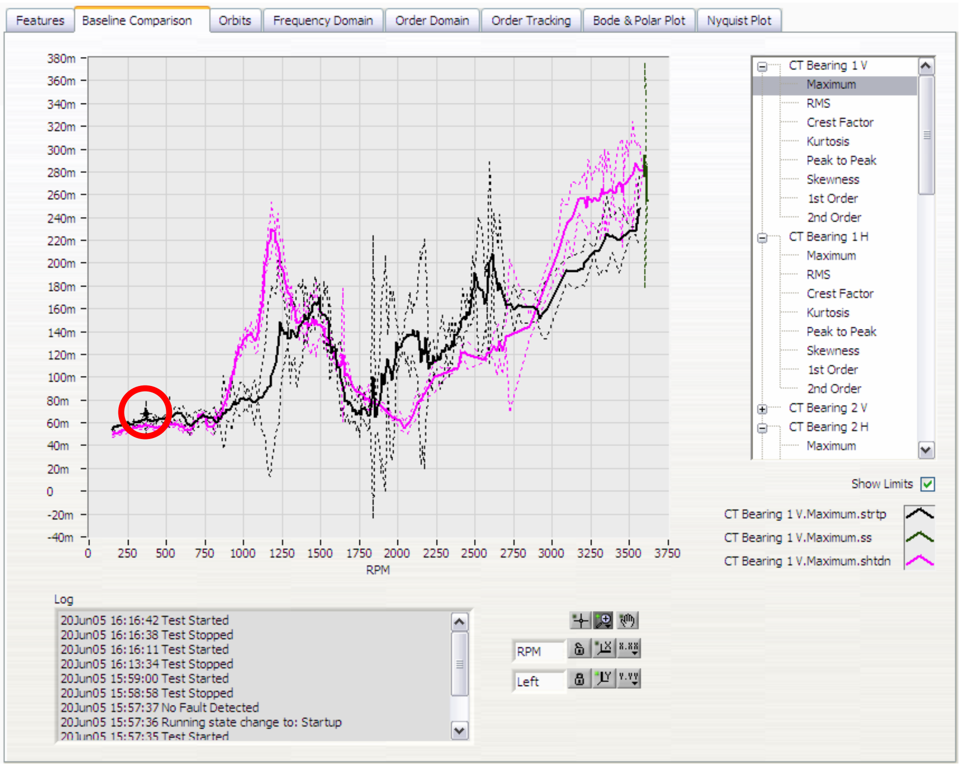


Figure 7-8
Baseline Comparison Pane of the Software Interface

The utilization of the Baseline files allow the VFDS module to be very flexible in operation. As long as an applicable set of Baseline files have been generated, the system can be used in many rotating machinery applications. The ability to generate Baseline files was included in a bundled application.

Manual Data Analysis Tools

In addition to the automatic data analysis functionality, a number of additional manual tools are provided to aid the vibration specialist extract meaning from the raw data. These tools are only available from the host machine, either used locally or remotely. Examples of the graphical user interfaces provided for the Bode Plot, Polar Plot, and Waterfall Plot tools are displayed in Figure 7-9 below.

Waterfall Plots

A waterfall is a three dimensional plot useful in vibration diagnostics. A waterfall illustrates the changes of the vibration spectrum with respect to time or shaft speed. As it is computationally and memory intensive, only the latest 60 seconds of waterfall data are available for display by the VFDS.

Shaft Orbits

An orbit plot can be analyzed for features indicative of faults. Ordinarily, two orthogonally oriented transducers are used to generate an orbit plot; however, here the resampled signal from a single channel is used to generate multiple orbits over speed. The change in the tachometer mark on the orbit plot over time shows the change in phase lag, and the shape of the plot can be used to identify resonances or balance problems during the transient operating modes.

Bode, Polar Plot, & Nyquist Plot

Bode plots are used to illustrate the relationship of the magnitude and phase lag to the unit's operating speed during transients. The Polar plot displays the same data in the transducer response plane, illuminating characteristics of the shaft when used to observe the 1st engine order magnitudes and phase lags. Due to the memory and computationally intensive nature of Bode analysis, these tools are only available when the VFDS unit is offline, or through a separately accessible application which does not need to reside on the host computer. The Nyquist plot displays the real and imaginary (not to be confused with the magnitudes and phase lags) parts of the frequency spectrum on the complex plane.

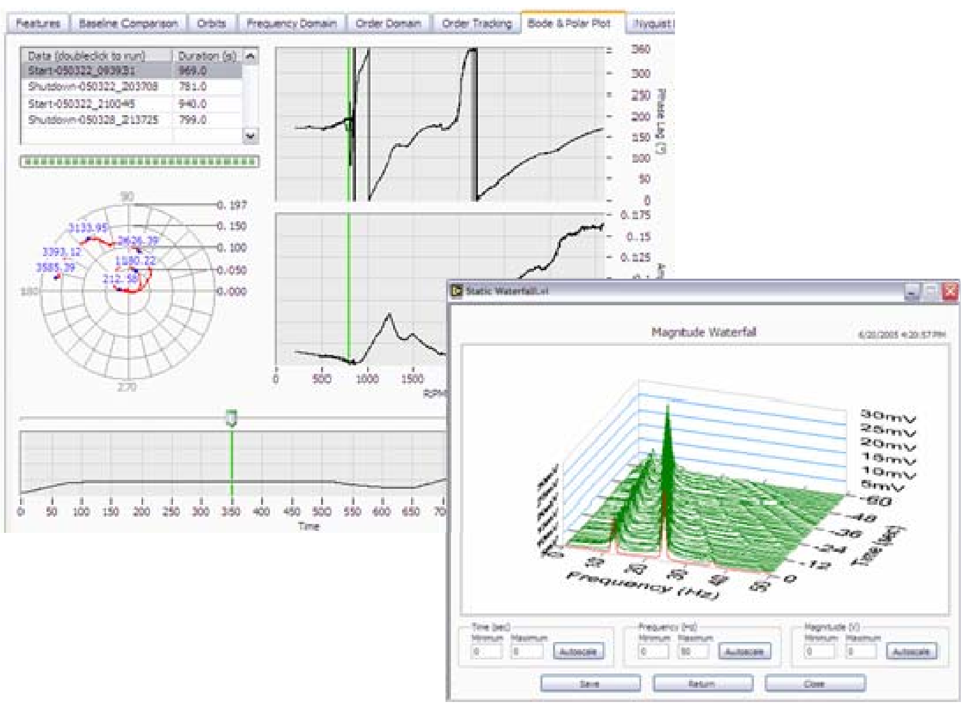


Figure 7-9
Manual Data Analysis Tools

Diagnostic Assessment

While any one of the above features can be used individually to diagnose a problem, health assessments based on a single feature may not detect a fault under all conditions and may lead to unacceptable false alarms. To provide a robust fault diagnosis it is necessary to intelligently fuse all of the above results in to a single robust and accurate diagnostic assessment.

The VFDS module uses a Dempster-Shafer type data fusion as opposed to the more widely used Bayesian Belief Network to combine the individual results into a fault diagnosis that is available to be posted to a networked data archival system and is viewable on the host machine's interface.

Bayesian Belief Network

When using a Bayesian Belief network for vibration diagnostics, the goal is to calculate the probability of one particular event occurring given that one or many other events have occurred. For example, the probability of event 'C' occurring given that 'A' and 'B' have occurred is represented by the following equation:

$$P(C/AB) = \frac{P(C/B)(P(A/CB)}{P(C/B)P(A/CB) + P(C'/B)P(A/C'B)} \qquad (6)$$

In Equation (6), event 'C' can be thought of as being a fault, imbalance for example, and events 'A' and 'B' can be thought of as being fault symptoms from the order tracking analysis such as presence of divergent side-bands and half engine orders. One can easily see that for multiple fault symptoms, equation [5] will grow to unmanageable proportions. That is, to compute the desired probability we need discrete values of all a priori probabilities and all joint probabilities. Additionally, in Bayesian networks, believing a hypothesis automatically implies disbelieving the remaining hypotheses. Further discussion of Bayes Theorem and Bayesian Belief Networks can be referenced in Appendix B.

Dempster-Shafer Theory

The basis of Dempster-Shafer is that it computes the probability that evidence supports a hypothesis rather than computing the probability of the hypothesis. This overcomes the obstacle of accurately estimating prior and conditional probabilities that are required by Bayes' theorem. Additionally there is no causal relationship between the hypothesis and its negation; therefore, lack of belief does not imply disbelief. It merely implies a state of uncertainty. To fuse the fault symptoms, the Dempster-Shafer algorithm is supplied with initial uncertainties. The process of narrowing down to a particular fault involves updating the uncertainties and beliefs as newer evidence is accumulated.

Example of Dempster-Shafer Results Fusion[2]

In this example, the results fusion process consists of the synergistic combination of collaborative information from sensor validation techniques in order to provide an accurate and effective assessment of the observed sensor's past and present integrity. The result obtained

[2] *Combustion Turbine Diagnostic Health Monitoring: Sensor Validation and Recovery Module,* EPRI, Palo Alto, CA: 2003.

from the Dempster-Shafer fusion process possesses greater certainty than the individual confidence with uncertainty levels when evaluating collaborative evidence.

In Figure 7-10, Method #1 can represent the generic signal processing technique results and Method #2, the data driven model based results. The net result of the fusion process is a diagnostic confidence that is more accurate and robust than could be obtained by any single information source.

Example of Dempster-Shafer Belief Method

Sensor Confidence from Method #1 = 80% +/- 15%

Sensor Confidence from Method #2 = 30% +/- 10%

Therefor: m1(A) = 0.65 m1(A') = 0.05 m1(A,A') = 0.30
m2(A) = 0.20 m2(A') = 0.60 m2(A,A') = 0.20

	m2(A)	m2(A')	m2(A,A')
m1(A)	0.13 {A}	0.39 {0}	0.13 {A}
m1(A')	0.01 {0}	0.03 {A'}	0.01 {A'}
m1(A,A')	0.06 {A}	0.18 {A'}	0.06 {A,A'}

$$Belief\,(Hn) = \frac{\sum_{A \cap B = Hn} m_i(A) \cdot m_j(B)}{1 - \sum_{A \cap B = 0} m_i(A) \cdot m_j(B)}$$

m1(A) + m2(A) {True} = (0.13 + 0.13 +0.06)/(1-(0.01 + 0.39)) = 0.53

The uncertainty in this result is:

m(A,A') + m(B,B') = 0.06 / (1-(0.01 + 0.39)) = 0.10

Hence, the probability of Fault A having actually occurred given the diagnostic classification is **0.58 +/- 0.05**

Figure 7-10
Dempster-Shafer Fusion Process

Fault Diagnosis

For the *Vibration Fault Diagnostics System* (VFDS), a fault matrix was created for fault symptoms that were identified as being critical to gauging turbine health (see Tables 7-3 and 7-4). The fault symptom beliefs were assigned using domain expertise. Twelve fault symptoms were used to diagnose eight commonly observed faults. Machinery vibration faults and their symptoms have been studied in great depth and are well documented (2, 3, 4, 5). For example, if a scan of the calculated FFTs indicates existence of elevated 1st and 2nd engine order magnitudes and a general increase in the harmonics of the 1st engine order, there is a high possibility of the fault being misalignment. Table 7-3 summarizes the fault symptoms and the beliefs assigned to corresponding faults. If one or more symptoms are detected, the beliefs in the table are fused to arrive at a fault that is most likely to exist. During the analysis, if none of these eight faults are detected, the Vibration Fault Diagnostics System module reports 'No Fault'.

Table 7-3
Table Engine Order Fault/Feature Matrix

	Faults							
Feature	Unbalance	Shaft Eccentricity	Misalignment	Partial rubs	Blade tip rub	Eccentric stator Loose iron	Variable Air Gap	Loose Connector
High 1st EO only	High	Low	Low	Low	Low	None	None	None
1st and 2nd EO	Low	Low	High	Low	None	None	None	None
Harmonics of 1 EO	Low	Low	Medium	None	Medium	None	None	None
1/2 EO	None	None	None	Medium	Low	None	None	None
1/3, 2/3, 1/4 EO	None	None	None	Medium	Medium	None	None	None
Constant 1 EO amplitude	Low	High	Low	None	None	None	None	None
High Spectral Density	None	None	Low	Medium	Medium	None	None	None
NonInteger x EO	None	None	None	Low	None	None	None	None
IEO step increase	None	None	None	Low	Low	None	None	None
2x Line Frequency (FL)	None	None	None	None	None	High	Medium	Low
2xFL w/ Pole Freq (FP) Sidebands	None	None	None	None	None	Low	High	Low
2xFL w/ 1/3FL Sidebands	None	None	None	None	None	Low	Low	High

Table 7-4
Fault-Symptom Correlation Key

Correlation	
None	(grey)
Low	(green)
Medium	(yellow)
High	(red)

Unbalance

Unbalance is a very common problem with rotating machinery. An unbalanced rotor may lead to higher dynamic bearing loads resulting in bearing fatigue. Symptoms of unbalance are primarily a high once per rev amplitude. In addition there may be a phase difference (90 degrees) between axial and radial measurements (5).

Shaft Eccentricity

Similar to unbalance, eccentricity of the shaft can lead to high once per revolution vibration amplitudes. A strong once per rev will occur at low speeds for an eccentric shaft whereas the magnitude of a once per rev caused by unbalance is directly related to speed (2).

Misalignment

Shaft misalignment is another very common problem with rotating machinery. As with unbalance, misalignment can lead to excessive bearing load. Symptoms of misalignment are high once and twice per revs. Distinguishing between unbalance and misalignment (and others) can be difficult. However misalignment, especially in severe cases, will have a strong twice per rev and often higher per revs. In addition a 180 degree phase difference may exist between radial positions or across a coupling (3).

Partial Rubs

A rub is contact between a rotating part and a stationary part. When this contact does not occur through an entire cycle, it is called a partial rub. There is a tendency for partial rubs to cause an increase in magnitude of non integer multiples of shaft speed (0.5x, 2.25x, etc) (2).

Blade Tip Rub

Like partial rub, blade tip rub is contact between a rotating part, in this case a blade tip, and a stationary part, such as the inner lining. Blade tip rub will have similar symptoms as partial rub, though it will have an increased once per rev amplitude (4, 5).

Eccentric Stator/ Loose Iron

An eccentric stator or loose iron (can be caused by loose supports) can lead to high vibration and ultimately failure in an electric generator. In addition lamination problems can cause similar symptoms as well as high temperatures (4).

Variable Air Gap

A variable air gap between the rotor and the stator in the generator can cause a modulating vibration and ultimately failure (4).

Loose Connector

A loose connector can cause very high vibration and very quickly lead to catastrophic failure of the generator (4).

Baseline Data Analysis

Baseline Data Overview

During the period beginning March 22, 2005 through March 28, 2005 two runs of the monitored unit occurred and were captured by the data acquisition system. Data was recorded continuously during both the startup and shutdown portions, and five second snapshots were recorded once per minute during the steady state portions of the runs. Some of the details about the two runs are displayed in Table 7-5

Table 7-5
Acquired Data

22-Mar-05	Run
3:02:26	Total Time
0:16:09	Startup Time
2:33:16	Steady State Time
0:13:01	Shutdown Time

28-Mar-05	Run
3:02:06	Total Time
0:15:43	Startup Time
2:35:35	Steady State Time
0:10:48	Shutdown Time

The VFDS module determines the "operational mode" of the run based on the RPM signal and some settings in the configuration file. During this acquisition, the beginning of a run is defined by the shaft speed exceeding 150 RPM. Steady State operation is achieved by the shaft speed exceeding 3590 RPM.

The baseline vibration features used by the VFDS module to detect incipient faults were calculated using this data. Every second of available data from each channel was read and processed to generate a set of more than twenty features composed of time domain statistics and order domain magnitudes associated with the shaft speed and monitored unit state (startup, steady state, or shutdown) during that second. The range of operating speeds was divided into a set of bins, and the mean and standard deviation of each feature were calculated to provide a baseline value and range for each bin, feature, channel, and state. The following data is the result of this process, and is assumed to be "normal" data. It is possible that the operation of the monitored unit during these two runs may not be representative of "normal" operating conditions.

Baseline Features

The vibration diagnostic module uses many signal processing techniques to extract diagnostic features from the monitored signals. Some of these features are extracted directly from the raw time domain signal and others are extracted after further signal processing. Traditionally, there are two domains: time and frequency. Time domain features are extracted directly from the time-based signal. Frequency domain features require a frequency analysis such as a Fast Fourier Transform (FFT) to be performed before the feature's calculation. The following baseline features are available for display in the software on each channel: Maximum, RMS, Crest Factor, Kurtosis, Peak to Peak, Skewness, 1st Order Magnitude, and 2nd Order Magnitude. Additional features are utilized by the diagnostic reasoner. In the interest in brevity, only a few representative features are presented here.

In the following plots the independent variable is the shaft speed and the dependent variable is the individual feature amplitude in mils. There are a number of traces on each plot: the three solid traces represent the mean value of the feature for each operational mode (startup, steady state, and shutdown), and the dotted traces represent the three sigma limits for that feature. The channel and feature displayed is labeled in the graph title.

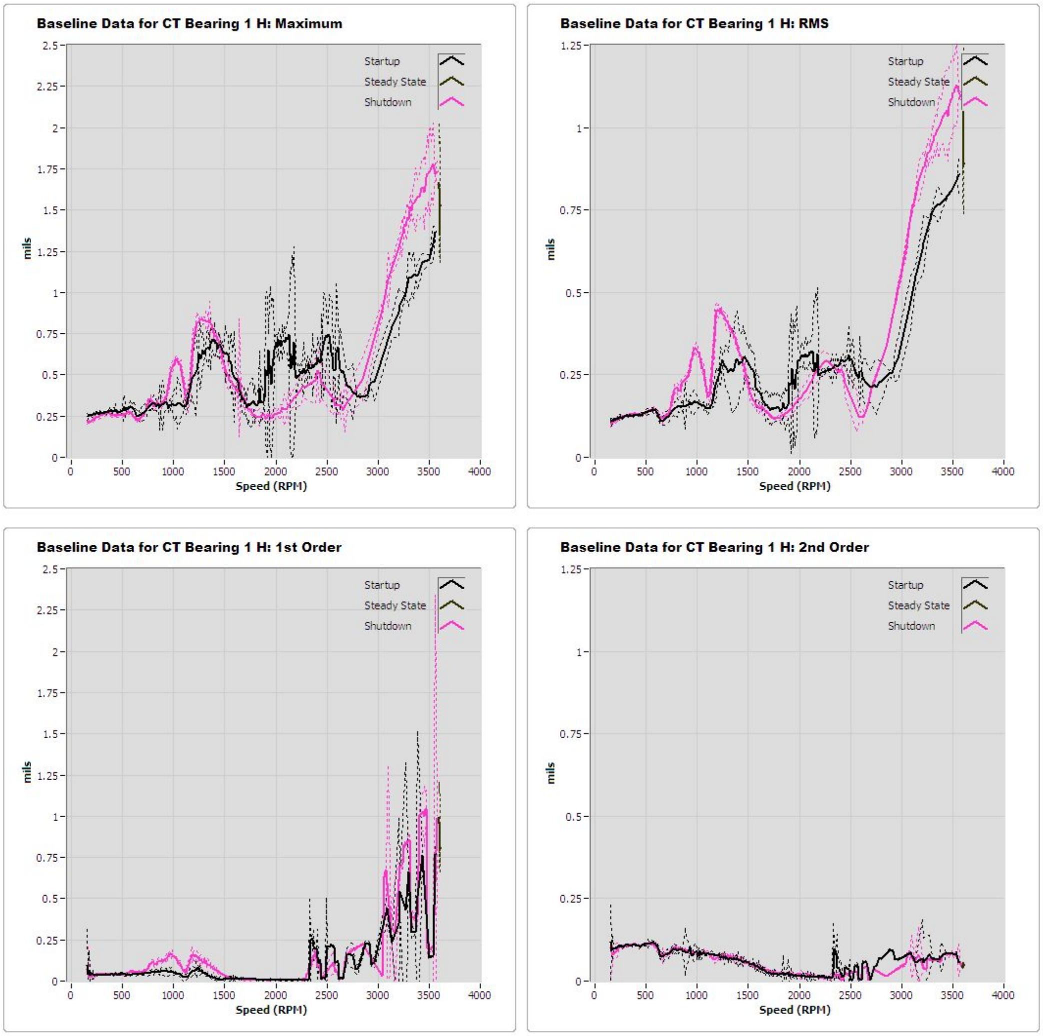


Figure 7-11
Sampling of CT Bearing 1H Baseline Features

The bin variance on the features tends to increase at higher speeds; this is partially because the unit accelerates fairly quickly at those speeds, and therefore comparably fewer samples were taken in that region leading to increased standard deviations of the binned features. This characteristic will make the system less capable of detecting faults in these regions because the limits serve as the threshold for determining "abnormal" data. The "smoothness" of the RMS feature as compared to the Maximum is to be expected based on the nature of the feature. Note the increase in amplitude of the Maximum, RMS, and 1st Order Magnitude features just below 1500 RPM. This result suggests a resonance in that region (it is fairly uniform across the CT channels). Also, the 2nd Order Magnitude is greater than the 1st Order Magnitude at speeds less than about 2400 RPM. This condition is pronounced only on CT Bearing 1.

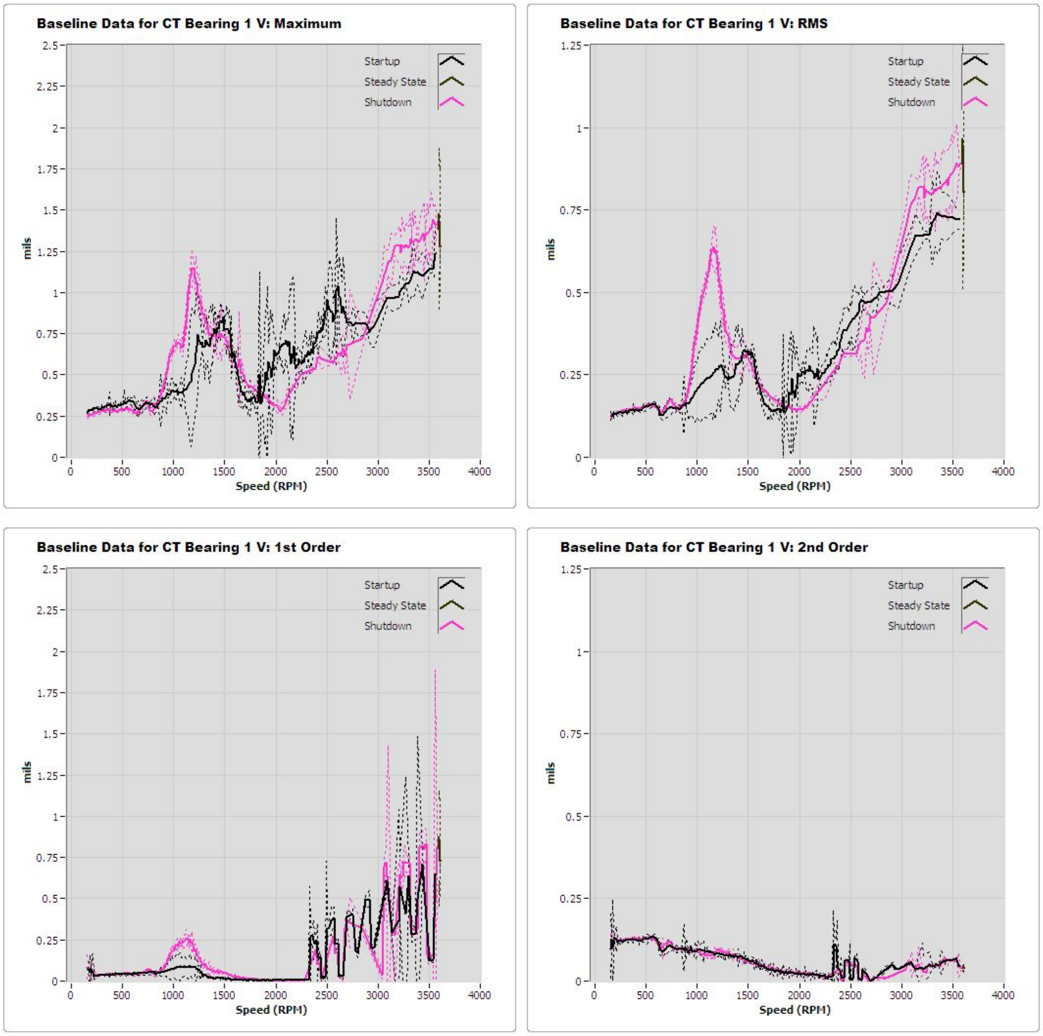


Figure 7-12
Sampling of CT Bearing 1V Baseline Features

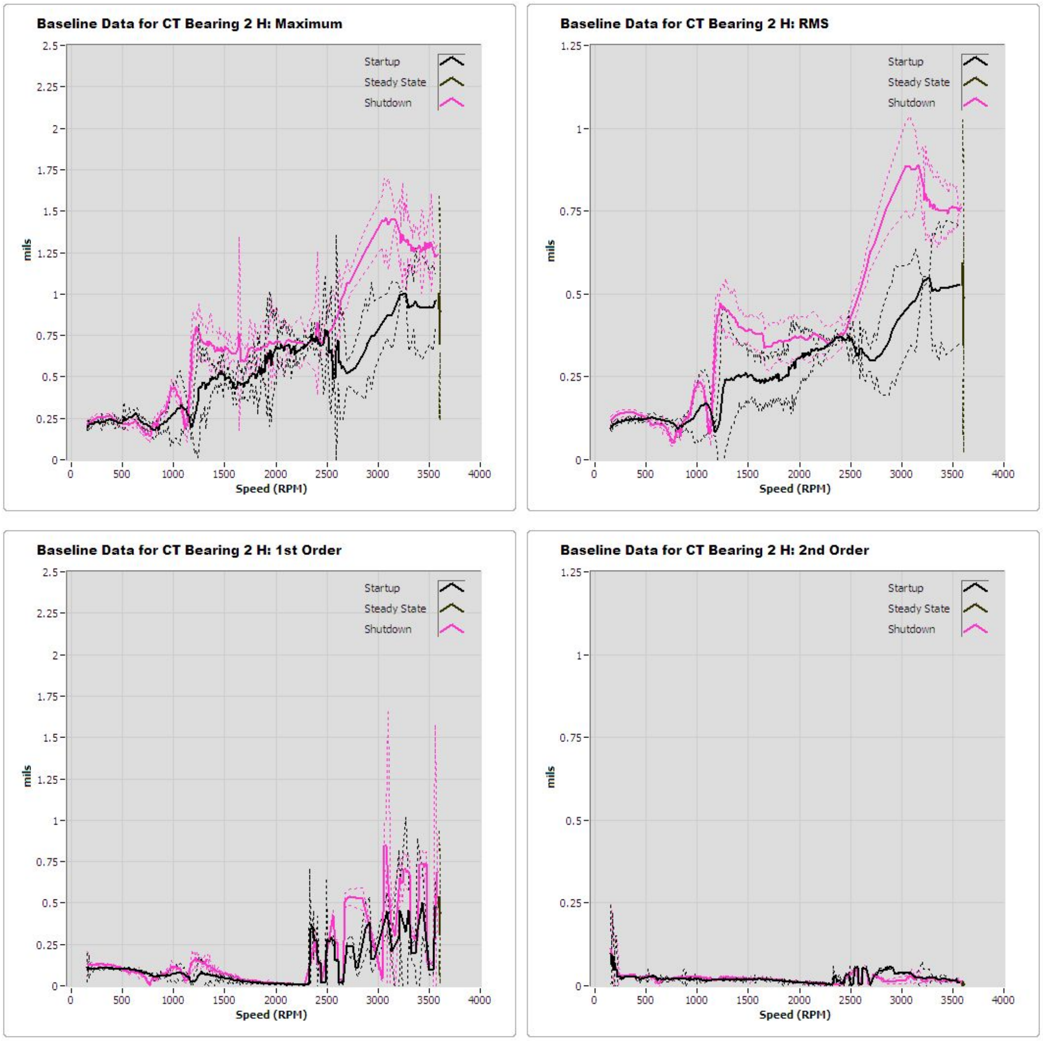


Figure 7-13
Sampling of CT Bearing 2H Baseline Features

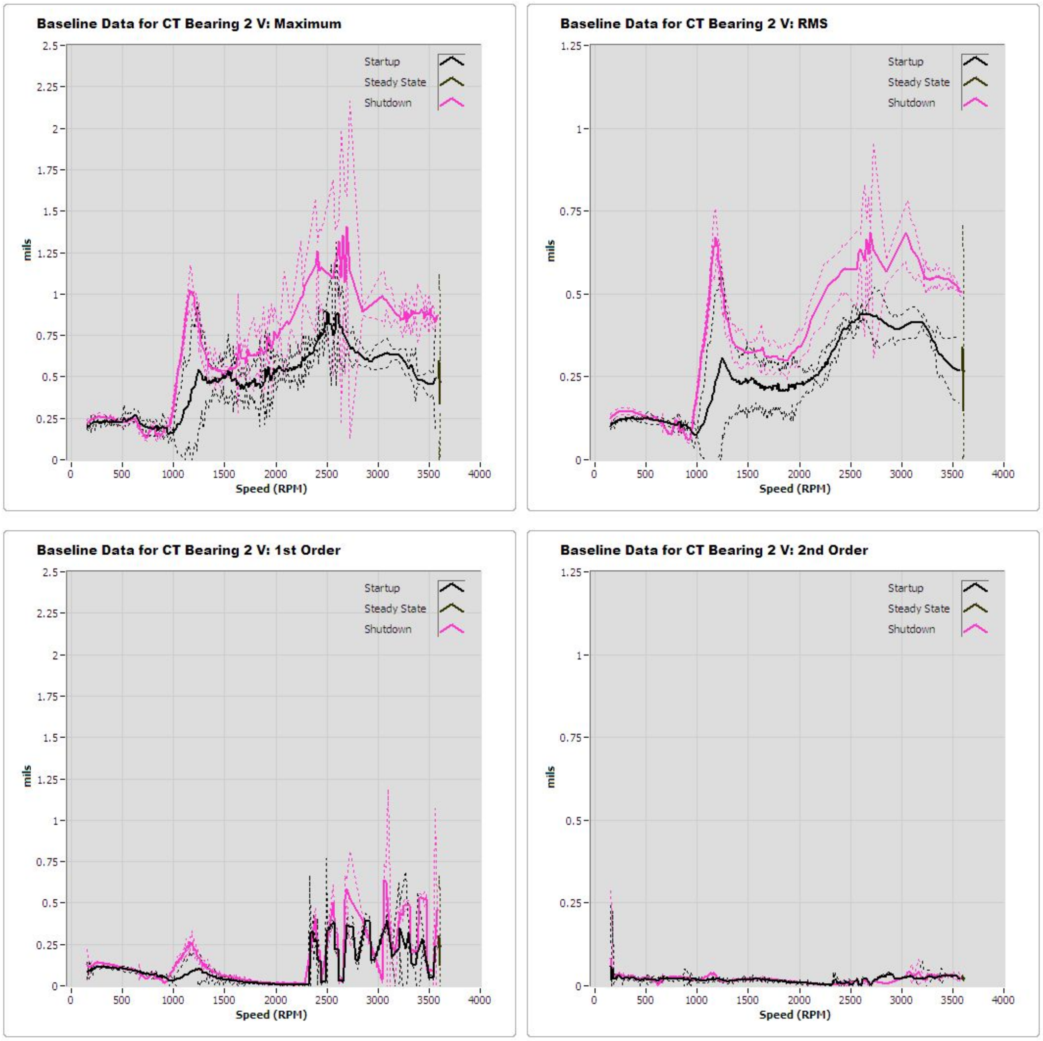


Figure 7-14
Sampling of CT Bearing 2V Baseline Features

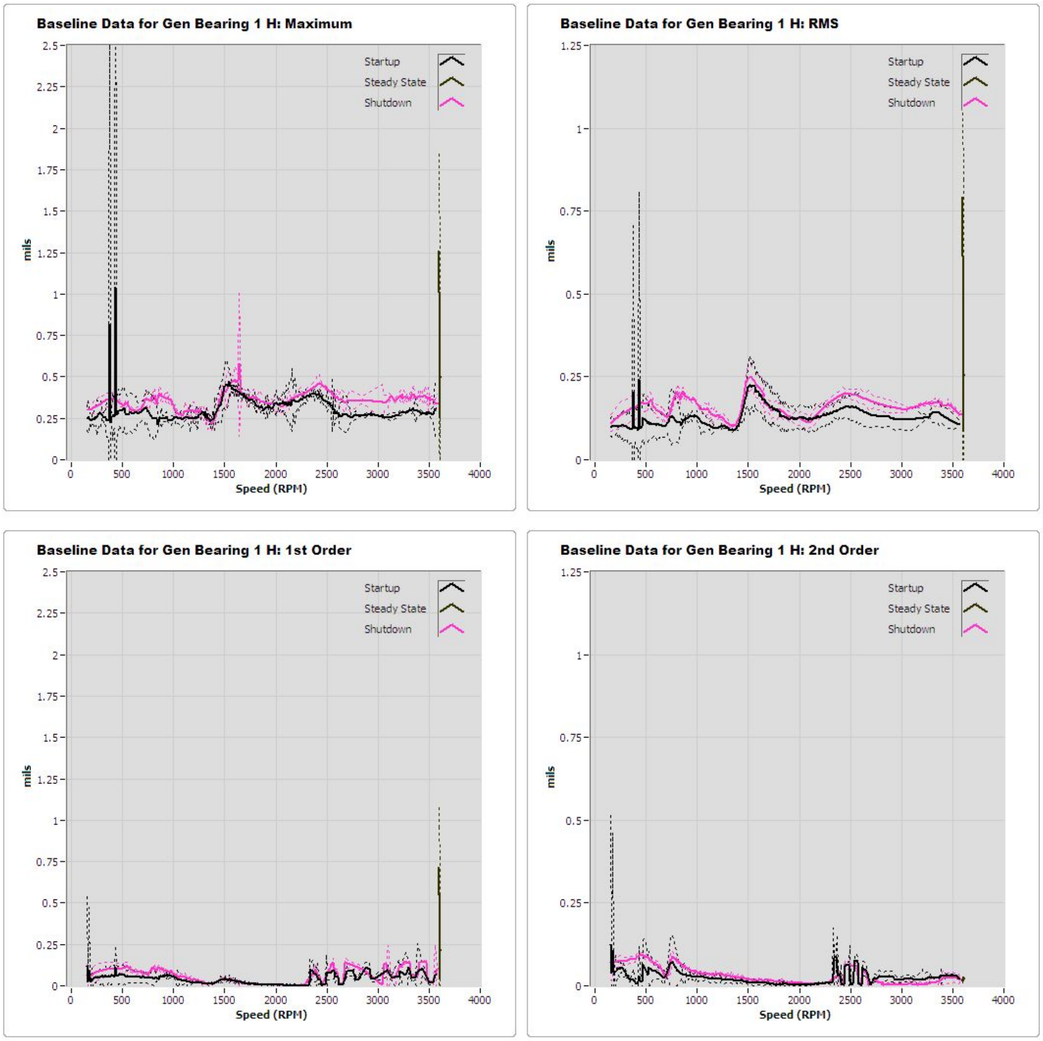


Figure 7-15
Sampling of Gen Bearing 1H Baseline Features

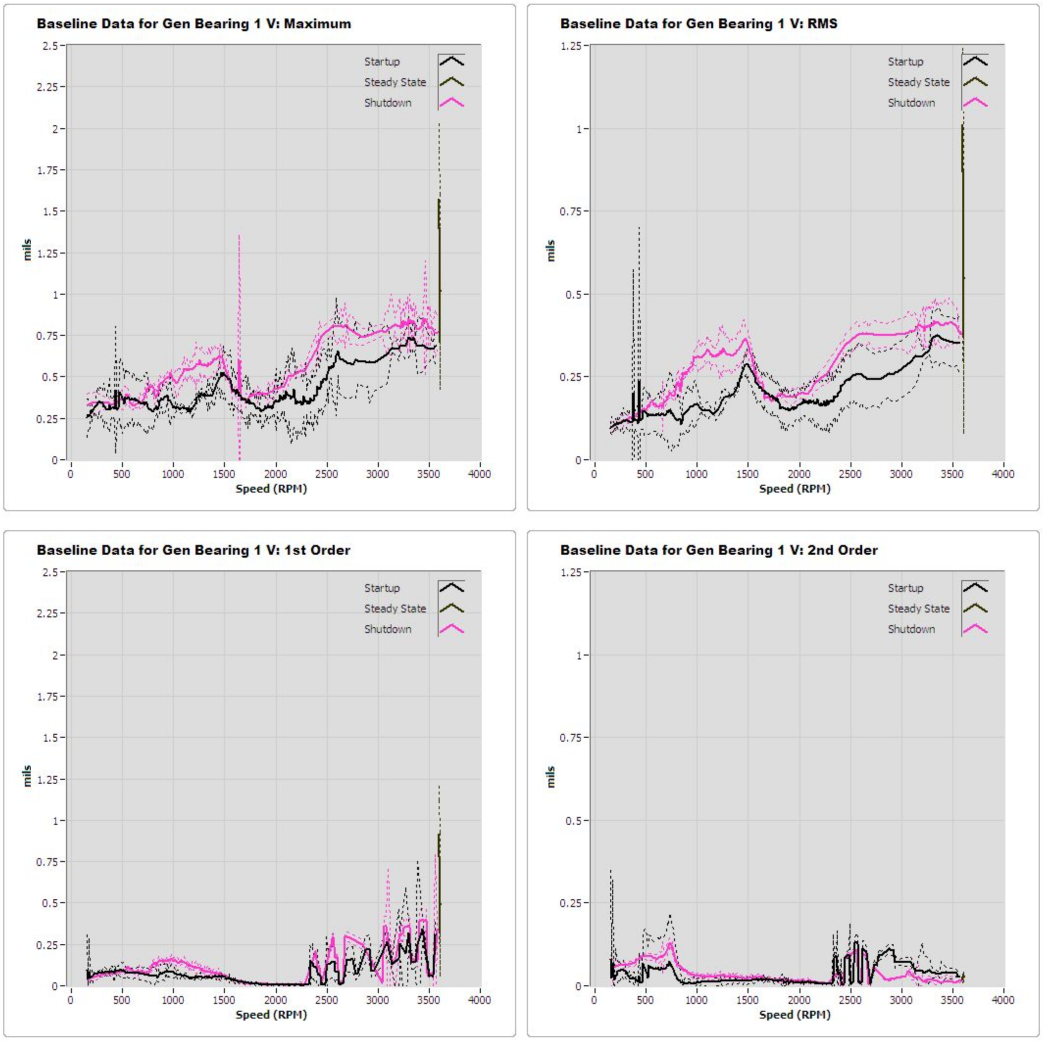


Figure 7-16
Sampling of Gen Bearing 1V Baseline Features

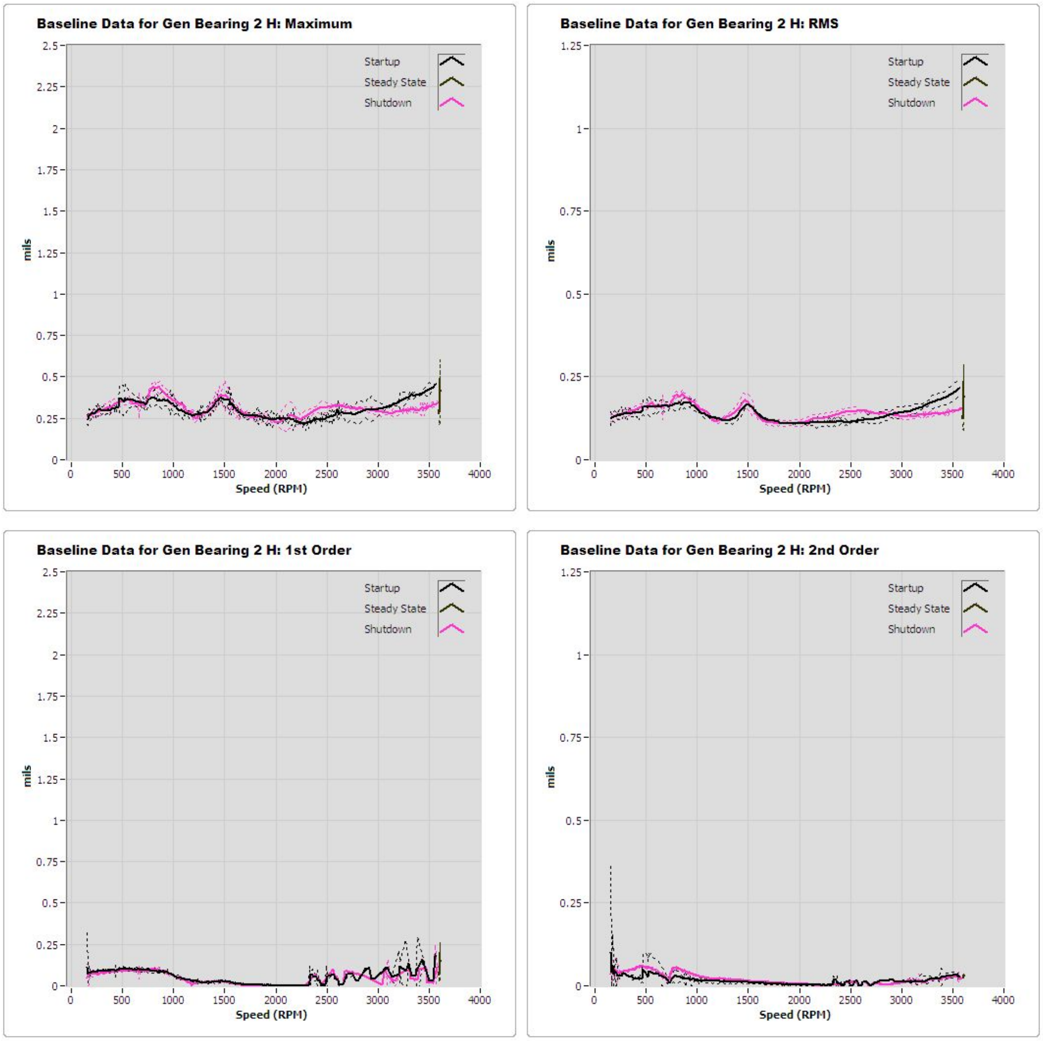


Figure 7-17
Sampling of Gen Bearing 2H Baseline Features

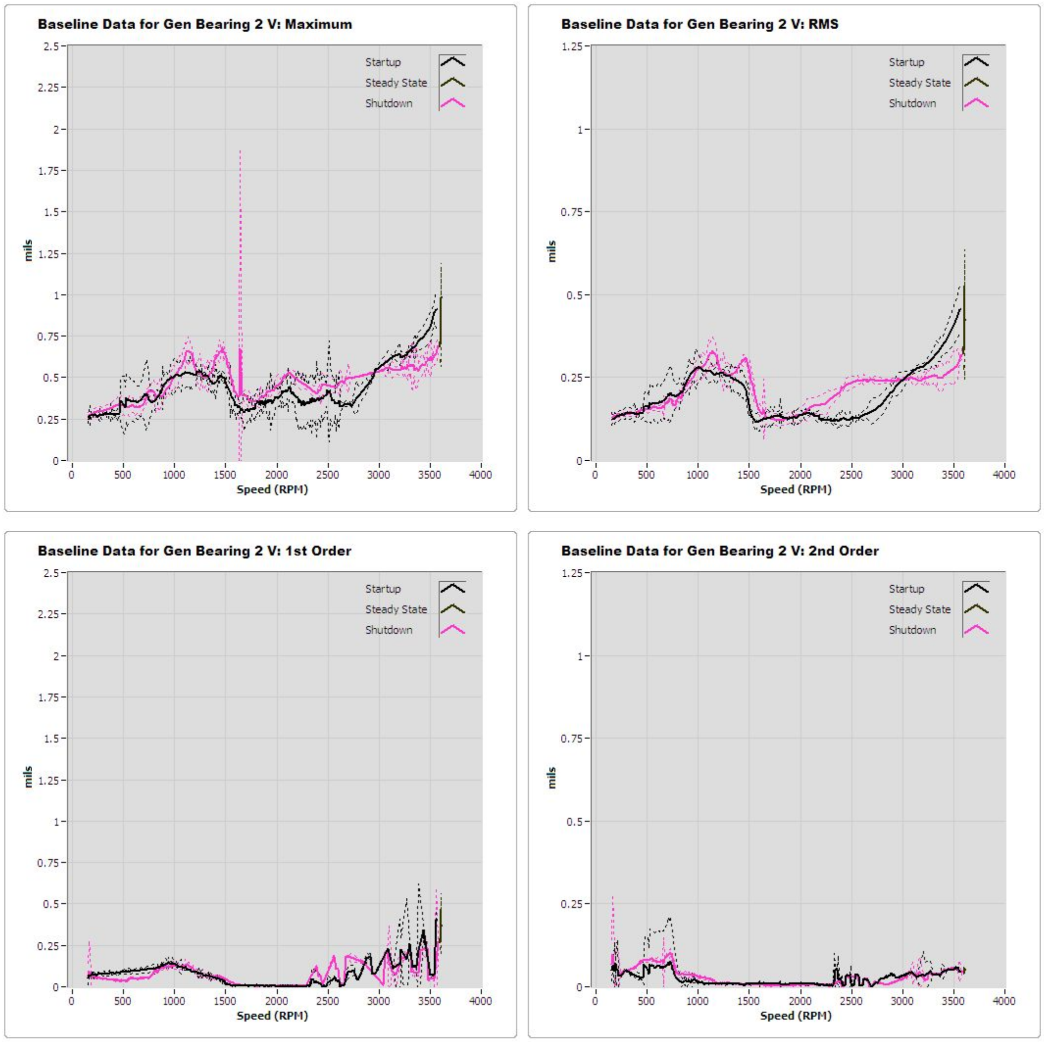


Figure 7-18
Sampling of Gen Bearing 2V Baseline Features

Bode & Polar Plot Representation of Baseline Data

Each of the following figures is composed of four graphical representations of the data. The two graphs stacked in the top right corner are a Bode Plot, and they represent the magnitude and the phase of the selected order as it changes with speed. To their left is a Polar Plot which displays the same information on a polar coordinate system. On the bottom is a simple plot of the speed against time during the selected transient. The analysis that produced the following plots utilized slow roll compensation to remove the non-dynamic action (i.e., shaft runout, bowed rotor, coupling issues, etc.) from the dynamic vibration magnitude. Note: vertical lines appear on the Bode Phase Lag plot when the lag changes from 360° to 0° and are expected. Representative results from every channel for the first Startup occurrence are displayed below using the 1st order data.

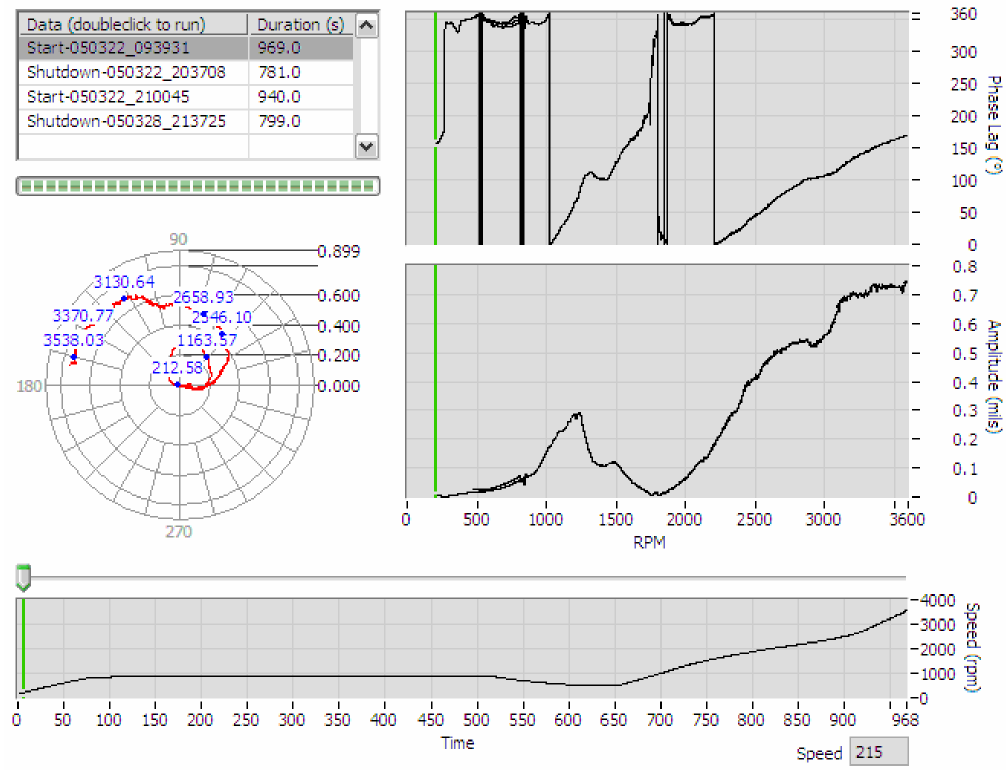


Figure 7-19
Startup-050322.CT Bearing 1V: 1st Order Transient Analysis

The suggestion of a resonance under 1500 RPM is re-enforced by the profile of the Bode Magnitude plot in Figure 7-19. It is also apparent that the shaft acceleration changes dramatically between 2500 and 3600 RPM as previously mentioned.

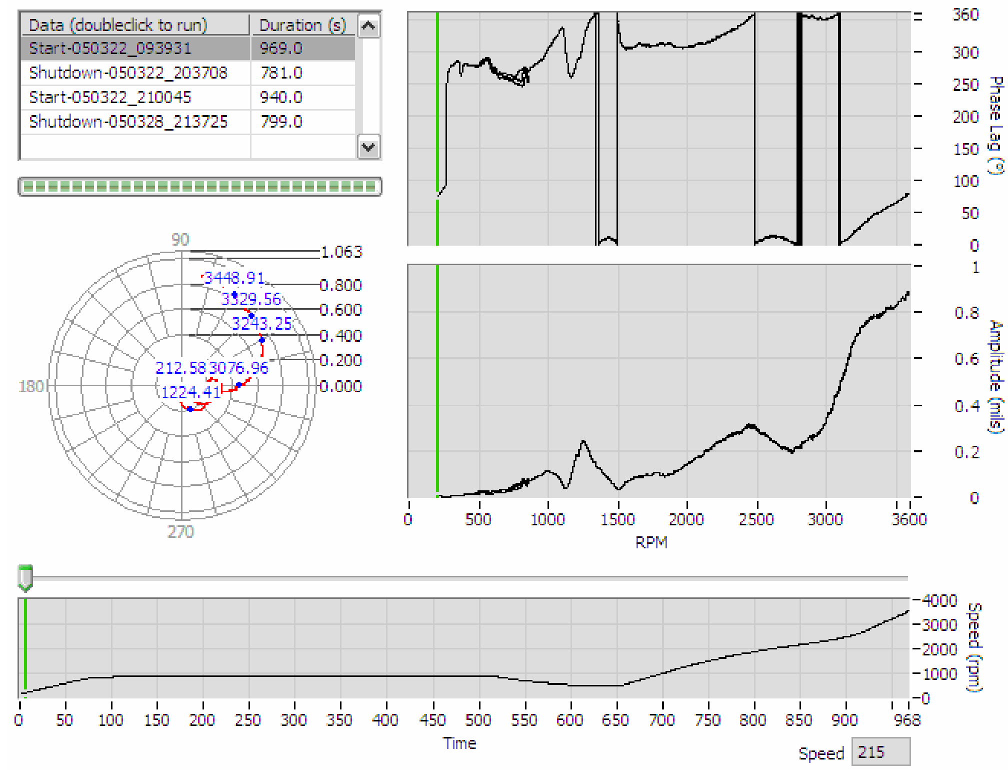


Figure 7-20
Startup-050322.CT Bearing 1H: 1st Order Transient Analysis

As expected, the CT Bearing 1H Transient analysis in Figure 7-20 is very similar to the CT Bearing 1V analysis shown in Figure 7-19, except for the Phase Lag being shifted by approximately 90° on both the Bode and Polar Plot. This is the expected behavior for perpendicularly mounted proximity probes.

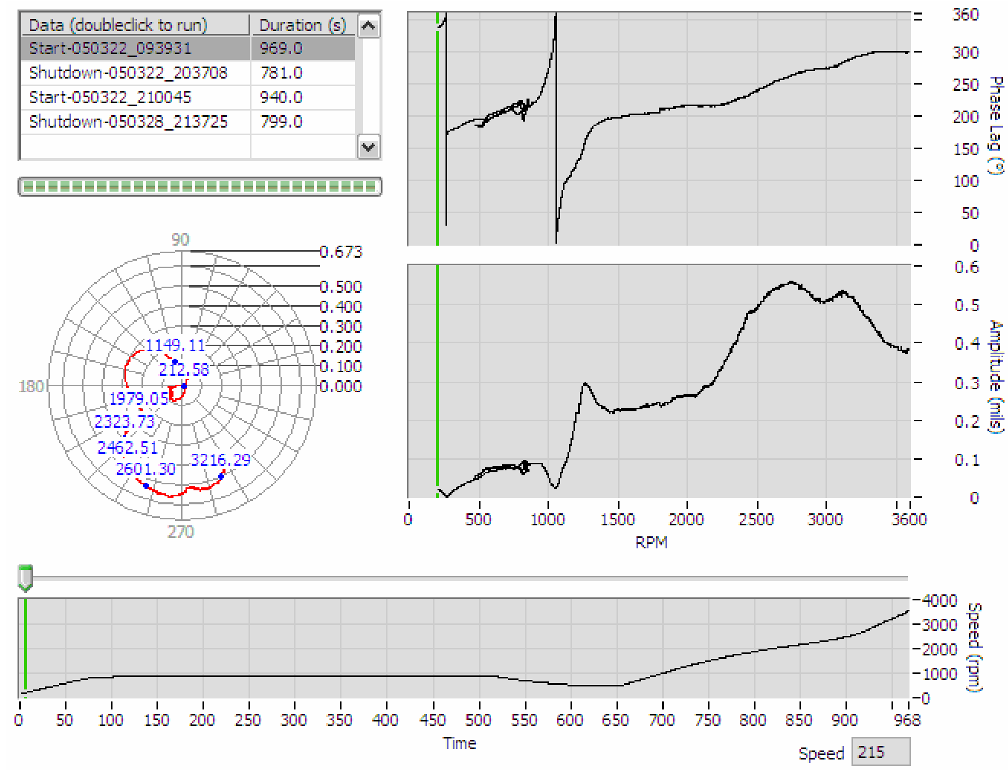


Figure 7-21
Startup-050322.CT Bearing 2V: 1st Order Transient Analysis

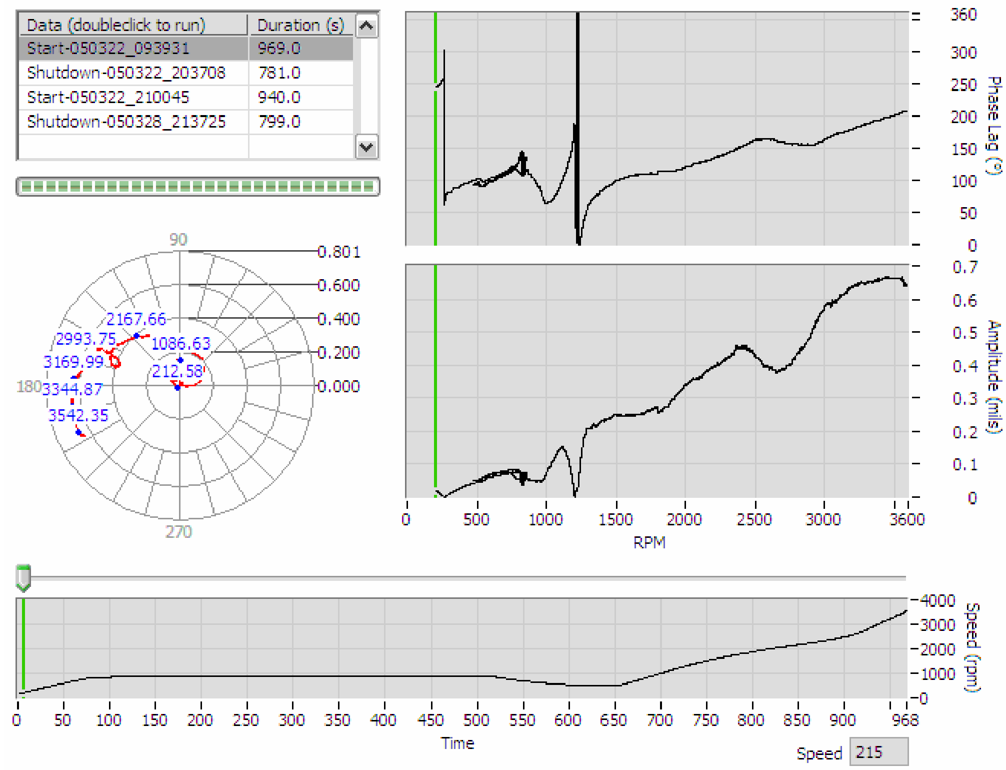


Figure 7-22
Startup-050322.CT Bearing 2H: 1st Order Transient Analysis

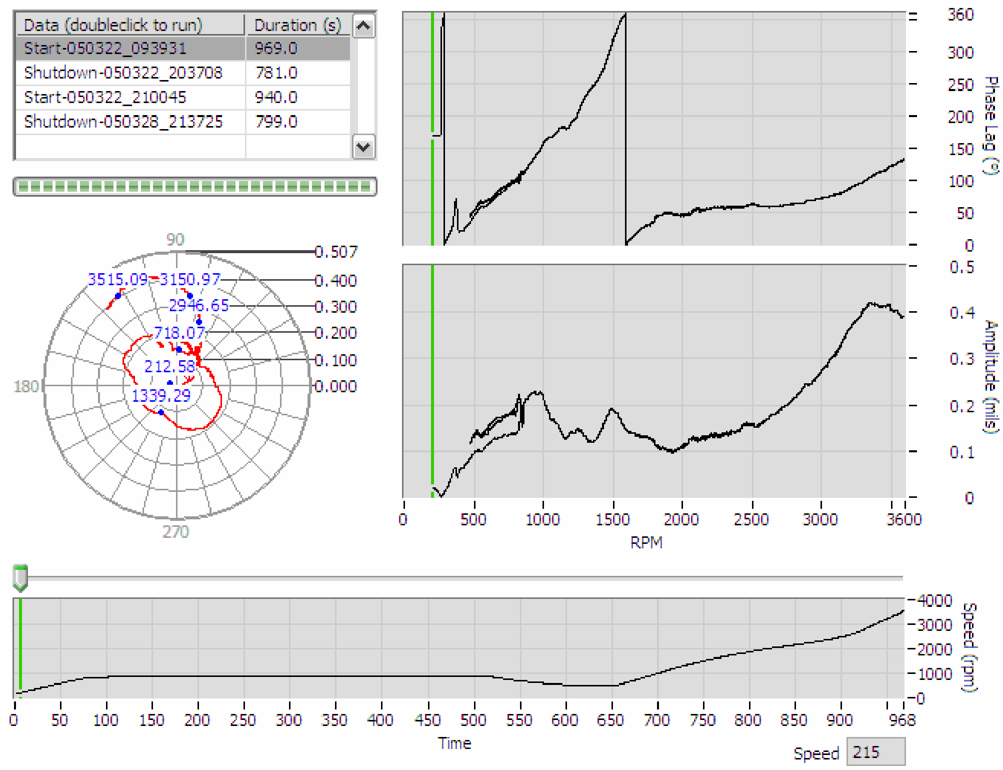


Figure 7-23
Startup-050322.Gen Bearing 1V: 1st Order Transient Analysis

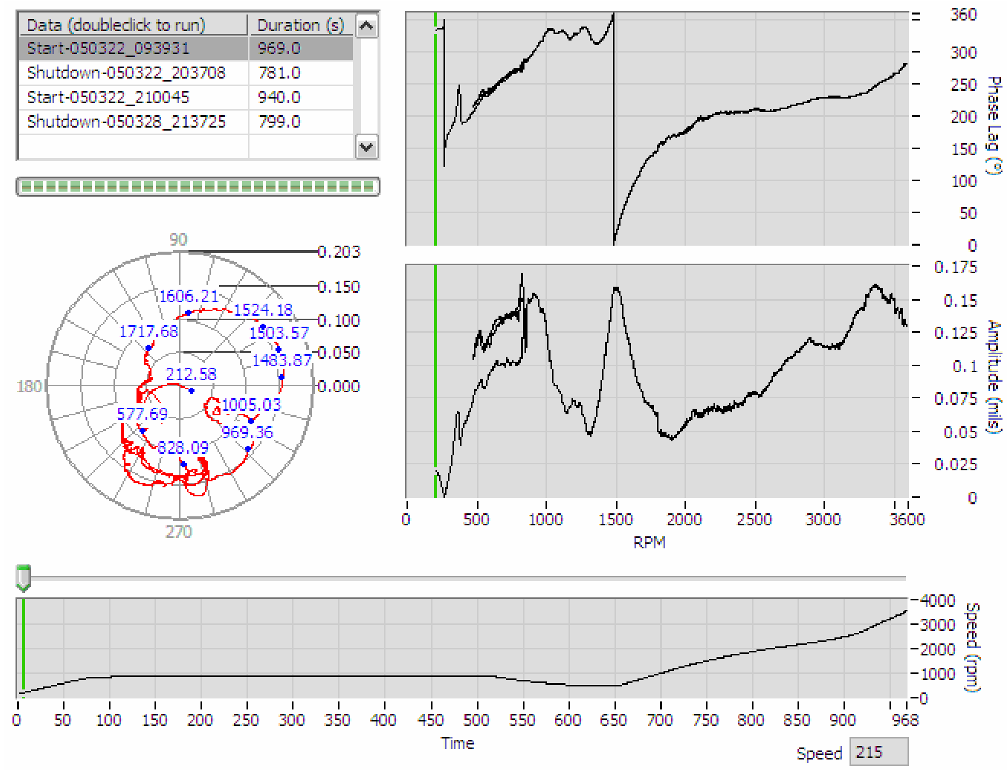


Figure 7-24
Startup-050322.Gen Bearing 1H: 1st Order Transient Analysis

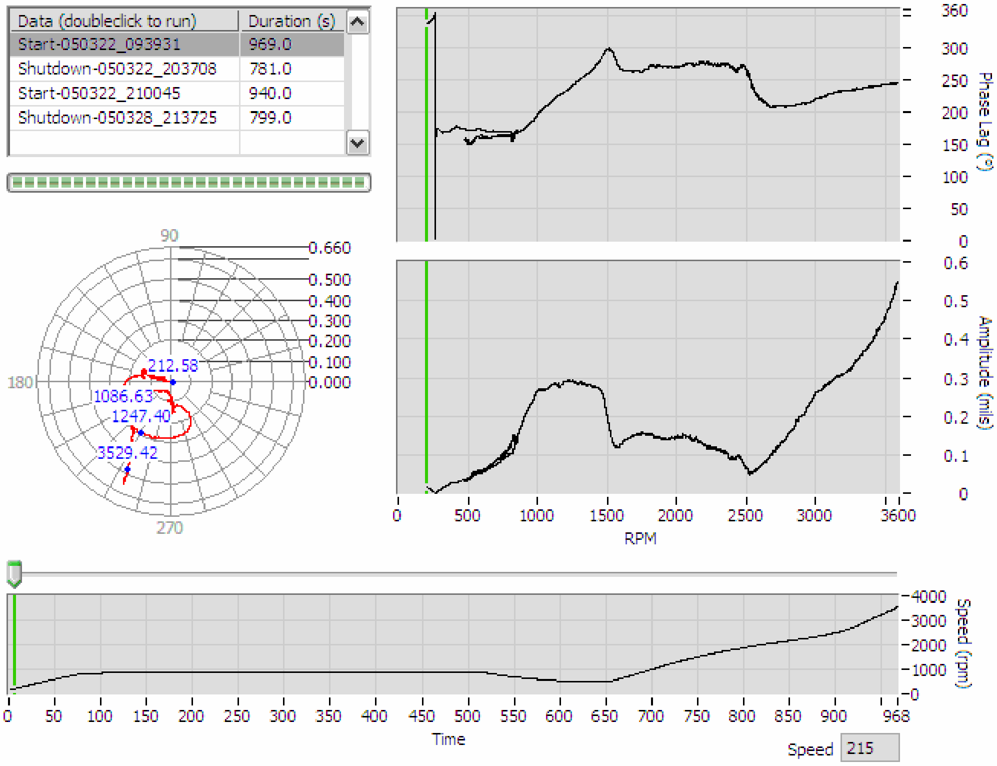


Figure 7-25
Startup-050322.Gen Bearing 2V: 1st Order Transient Analysis

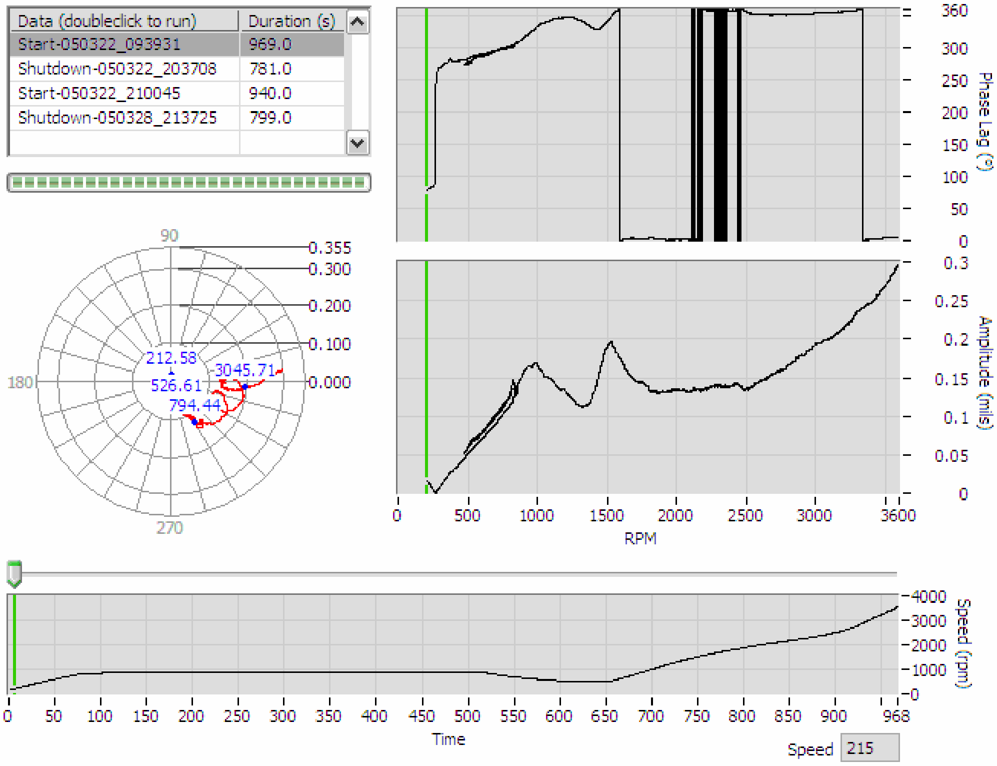


Figure 7-26
Startup-050322.Gen Bearing 2H: 1st Order Transient Analysis

For comparison to Figure 7-19, data from the 2nd order was also used to generate Bode and Polar Plots for CT Bearing 1V as seen in Figure 7-27 below.

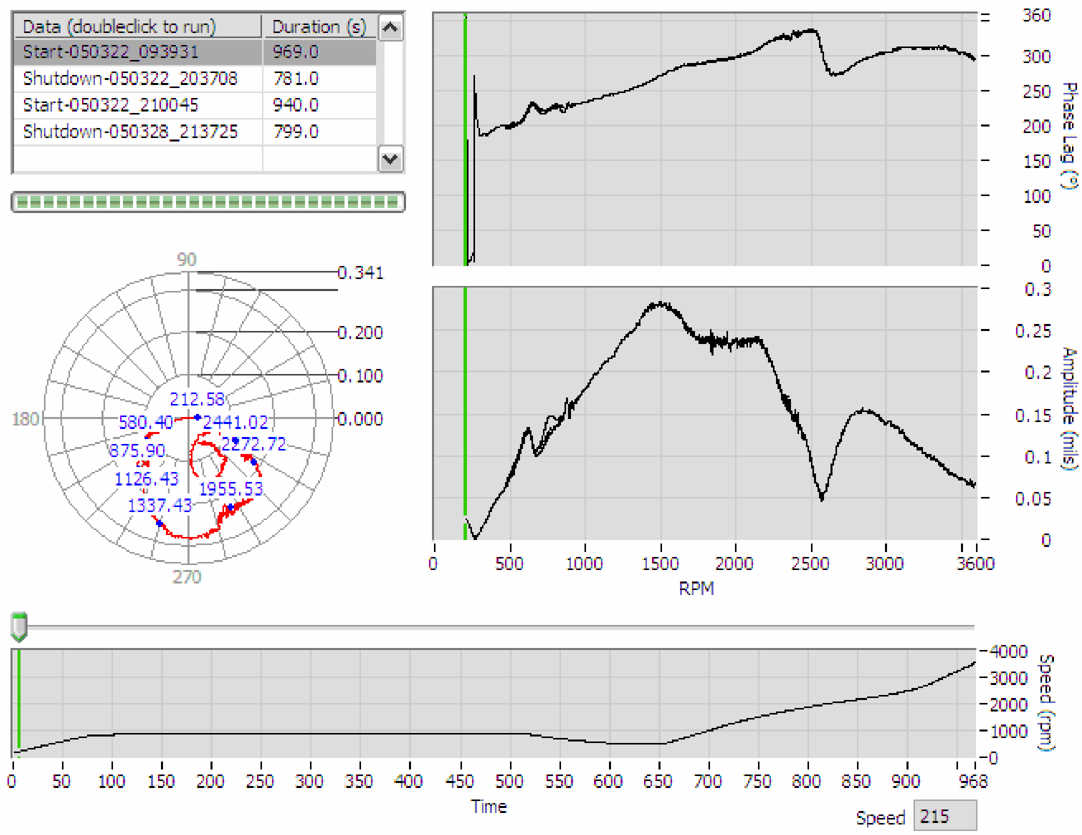


Figure 7-27
Startup-050322.CT Bearing 1V: 2nd Order Transient Analysis

This plot highlights the characteristic of CT Bearing 1 where the 2^{nd} order magnitude is relatively high compared to the 1^{st} order magnitude up to approximately 2500 RPM.

Analyses on the other acquired transients are similar and are excluded here for the sake of brevity.

VFDS Features

The Vibration Fault Diagnostics System's software has been developed to operate autonomously behind the scenes offering real-time diagnostic assessments of the health of the combustion turbine/generator set. The algorithms utilized in the system calculate a host of statistical and frequency based features which are utilized to capture and assess the current health state of the combustion turbine/generator unit. These features, derived from the raw, high bandwidth proximity probe data, are intelligently combined utilizing a diagnostic reasoner to arrive at the real time health state assessment. The resultant features and the final fault diagnosis can be viewed in their entirety from within the host computer. The low bandwidth features, as well as the diagnostic assessment, may then be stored on the PI Historian.

The software showcases an extensive graphical user interface (GUI) developed to display the analysis features in an efficient and intuitive manner. The main interface can be seen in Figure 7-28. A summary of the main interface elements are included here; for detailed explanation of the interface and operation of the software, please refer to the *Combustion Turbine Vibration Fault Diagnostics System User's Guide*.

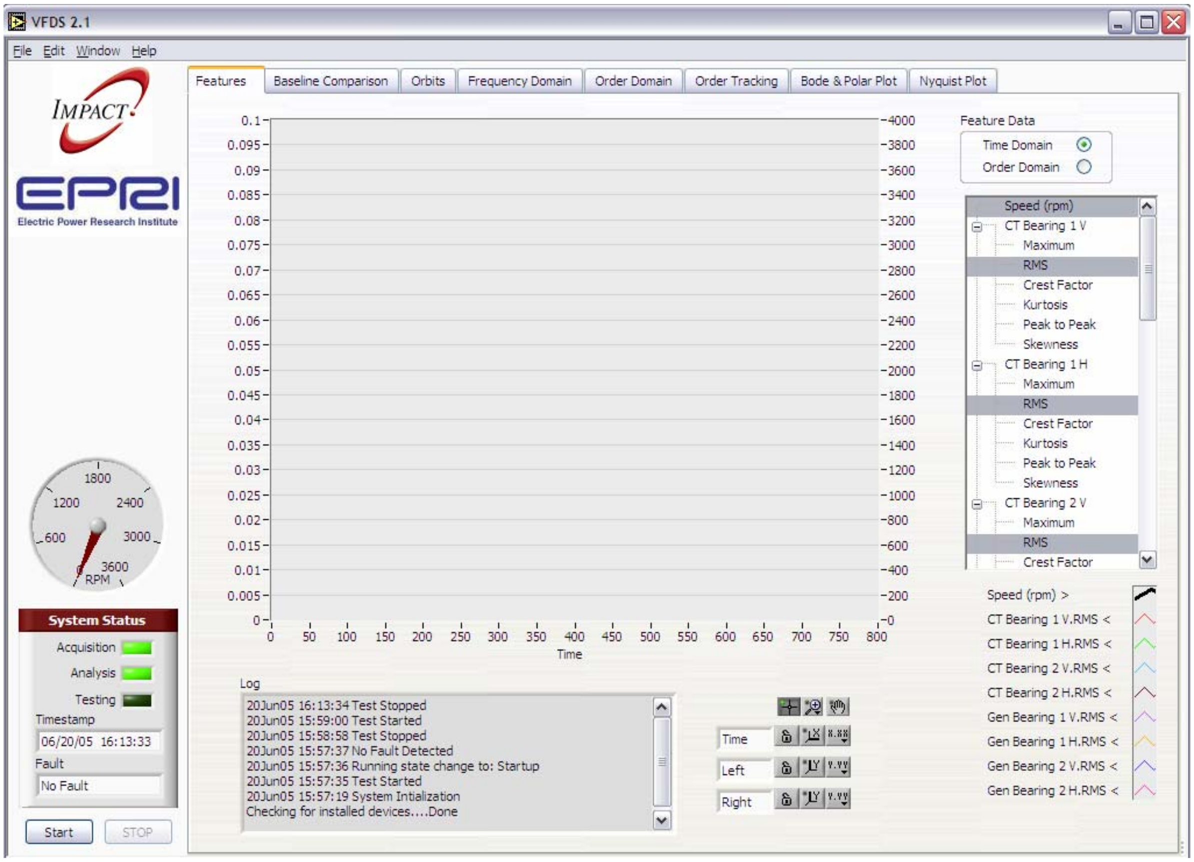


Figure 7-28
Vibration Fault Diagnostics System User Interface

VFDS System Status

The VFDS software is internally divided into several components or threads: GUI, Acquisition, Analysis, and PI Communication. The status indicators shown in Figure 7-29 display the current status of the critical portions of the software, and provide information about the current state of the machine.

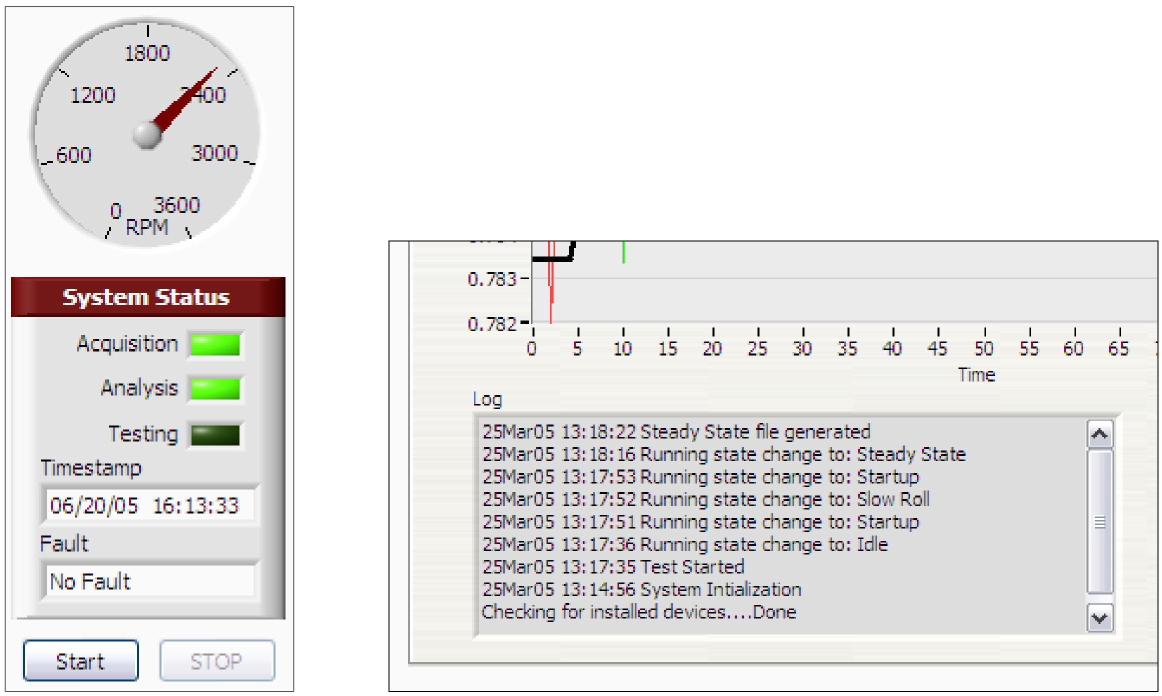


Figure 7-29
System Status Indicators, Controls and Log

Log

This dynamic text field displayed in Figure 7-29 is updated with relevant information about the current state of the system. The diagnostic assessment algorithms determine the current operating mode of the combustion turbine and display it here, along with information about files saved or deleted by the software and any errors that may occur. This information is also recorded in a text file on disk under the name VFDS Log.txt.

Features

The Vibration Fault Diagnostics System utilizes many signal processing techniques to extract useful diagnostic features from the monitored signals. Some of these features are extracted directly from the raw time domain signal; others are extracted from the frequency domain after an initial processing step. Time domain features are extracted directly from the time-based signal. Frequency domain features require a frequency analysis such as a Fast Fourier Transform

(FFT) to be performed before the features calculation. The *Features* pane (Figure 7-30) is dedicated exclusively to statistical features obtained from the time domain data.

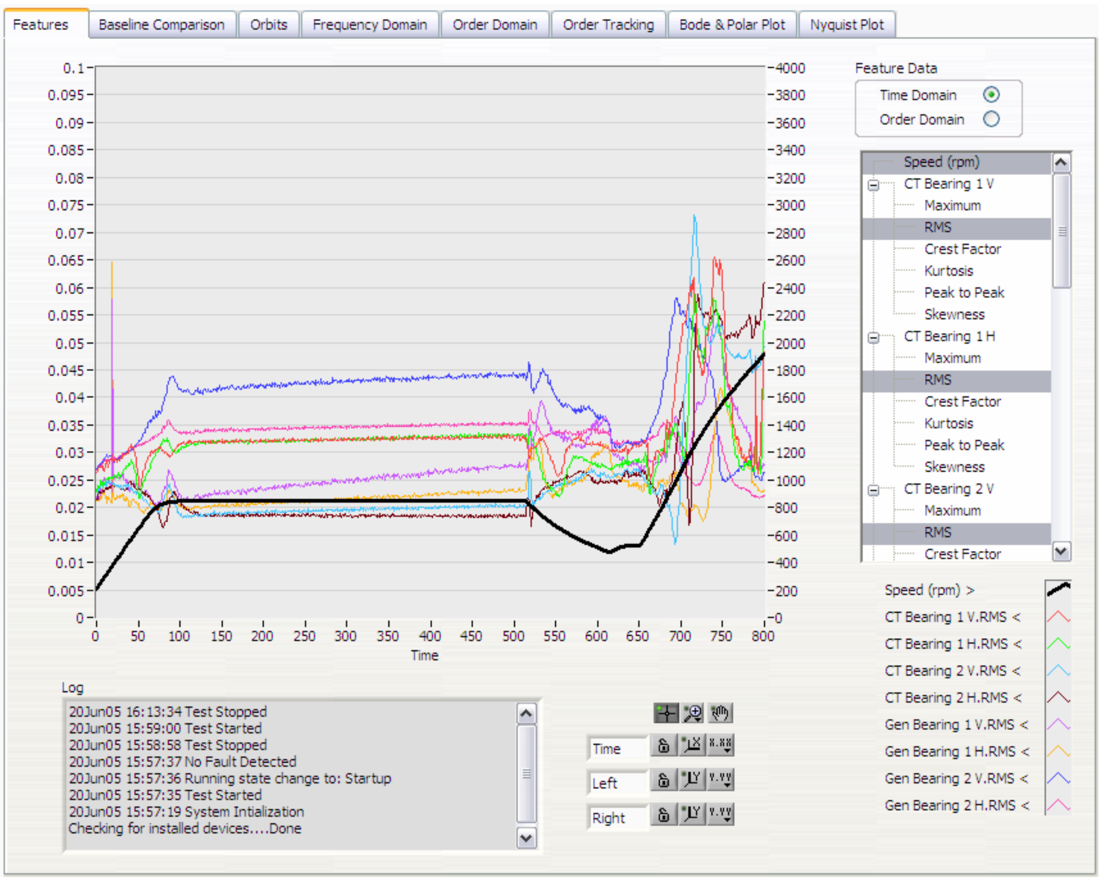


Figure 7-30
Main Viewing Area for Statistical Features

Baseline Comparison

The Baseline Comparison pane has been previously discussed under sub-section heading "Analysis Specification". It is included to give users a means of determining if the features being investigated are falling within expected ranges. Statistical models have been developed from “normal” data to characterize the expected behavior of many features across the range of operation experienced by the turbine/generator set. This range includes startup, shutdown and steady state operation at 3600 RPM. The abscissa has been relegated to the RPM domain and has been incremented in 10-RPM intervals. The expected baseline operation is statically plotted on the axes shown in Figure 7-31. The current value of the target feature (circled) is superimposed as a cross-hair on the baseline plot to highlight the comparison of the feature to its expected value given the current operating mode. The color of the cross-hair is set to match the current running state. The option of displaying tolerance bands is provided to gain a greater feel for the behavior of the current results. The tolerance range is defined in the configuration file as a multiple of the standard deviation.

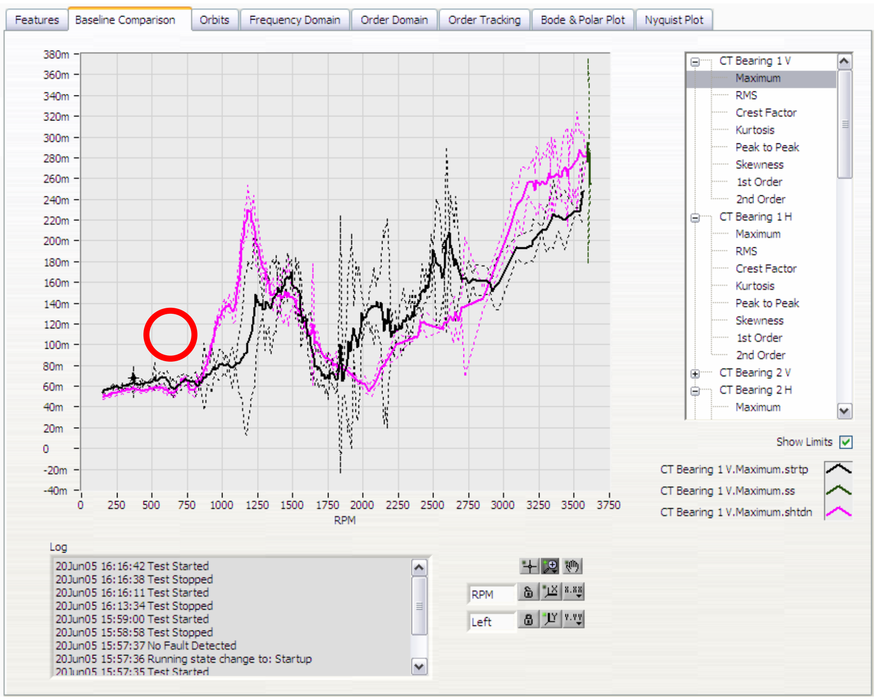


Figure 7-31
Main Viewing Area for Baseline Comparison of Features

Orbits

Although not a feature itself, an orbit plot can be analyzed for features indicative of faults. The time domain signal is resampled to the order domain, and then used to extract the selected engine order in order to generate a plot of the relative displacement of the shaft during one revolution or an average from many revolutions. An orbit plot would be expected to be circular for an anomaly free rotation. The shape of the orbit can be analyzed for indications of misalignment, unbalance, and other faults. The pane, shown in Figure 7-32, features one user control to define which channel to feature and a second series of user controls to control plot generation.

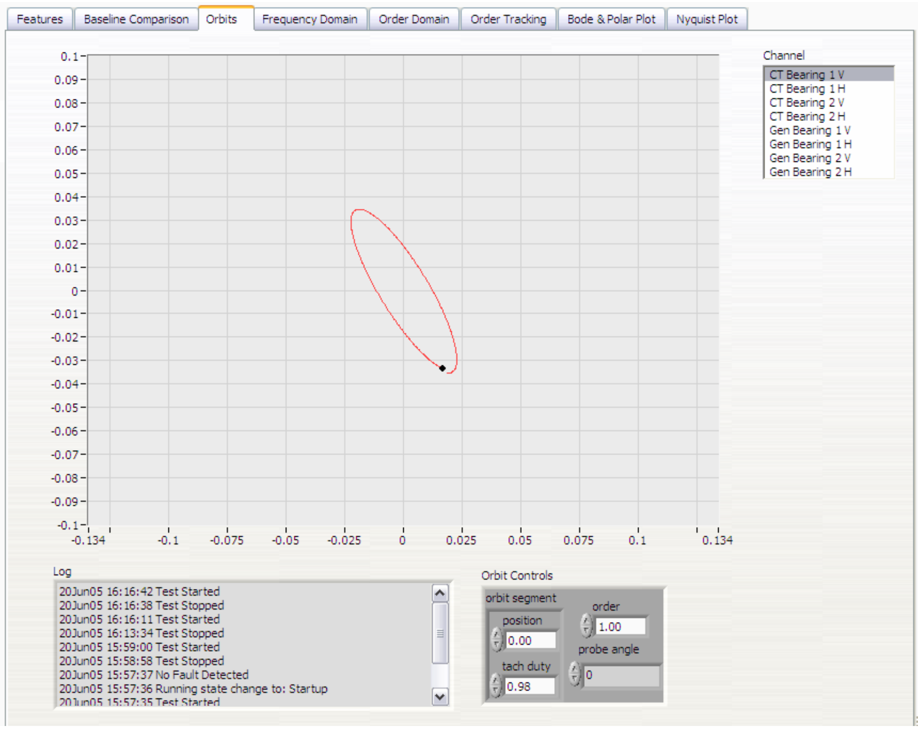


Figure 7-32
Main Viewing Area for Orbits Analysis Tool

Frequency Domain

Frequency domain features are useful in not only detecting faults but also diagnosing the type of fault. The magnitude of the frequency content of the raw time domain signal at specific frequencies can be used to determine resonances of the structure, unbalance, misalignment and many other mechanical faults.

An FFT is applied to one second's, windowed data to attain the frequency content of the raw signals. Applying the window insures periodicity of the signal, a requirement of the FFT calculation. Magnitudes corresponding to specific frequencies of interest can be extracted from the FFT by utilizing a "peak-picking" algorithm. These peaks represent the energy content of the signal at the frequencies of interest. These frequencies (and signals) include shaft speed and its harmonics, i.e. full and fractional engine orders.

In addition to the peaks at frequencies of interest, the sidebands of the peak are used in diagnostics. Sidebands are peaks in the FFT magnitude that are near a larger peak. The existence and magnitude of sidebands is used to diagnose and characterize faults.

The one-second sampling period provides a one hertz resolution on the FFT based diagnostics.

The graphical interface provided for the user is shown in Figure 7-33. The interface consists of three plotting regions and user controls for selecting the signal to highlight and capture a static representation of the waterfall plot.

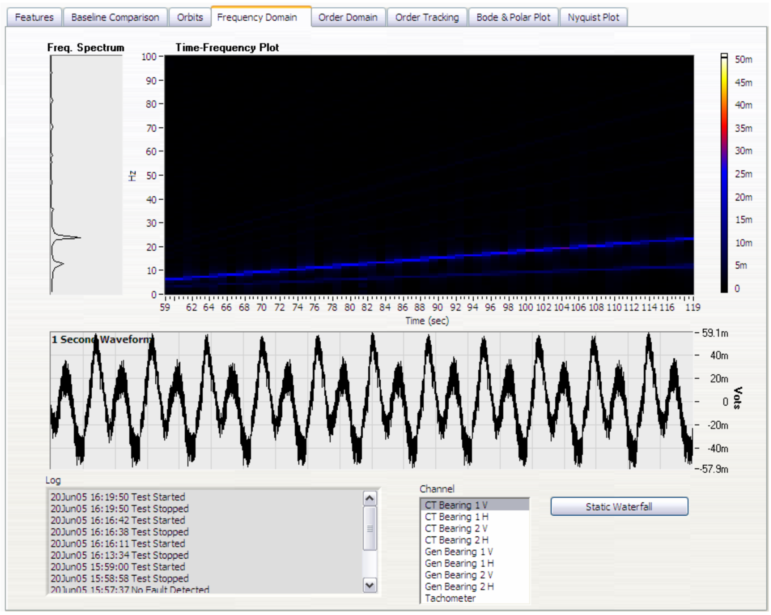


Figure 7-33
Main Viewing Area of Frequency Domain Analysis Tool

Order Domain

The *Order Domain* features are an alternative view of the frequency domain analysis described in the previous sub-section. The difference stems from a transformation process which takes place after conversion of the raw, time domain signal to the order domain. During this transformation the frequencies are expressed in terms of the rotational speed of the engine at the time of data acquisition. As an example, if the unit is rotating at 3600 RPM the frequency of 60 Hz is equal to 1 in the engine order domain.

Analysis in the *Order Domain* begins with the data being resampled to attain a constant sampling frequency based on the rotation of the shaft rather than time. As in the *Frequency Domain,* an FFT is applied to one second’s, resampled data to attain the order content of the raw signals. Applying a window to the data insures periodicity of the signal, a requirement of the FFT calculation. Magnitudes corresponding to specific orders of interest can be extracted from the FFT by utilizing a “peak-picking” algorithm. These peaks represent the energy content of the signal at the frequencies of interest with these frequencies now expressed in terms of engine orders. These frequencies (and signals) include shaft speed and its harmonics, i.e. full and fractional engine orders.

In addition to the peaks at orders of interest, the sidebands of the peak are used in diagnostics. Sidebands are peaks in the FFT magnitude that are near a larger peak. The existence and magnitude of sidebands is used to diagnose and characterize faults.

The graphical interface provided for the user is shown in Figure 7-34. The interface, like the one provided for the *Frequency Domain* analysis, consists of three plotting regions and user controls for selecting the signal to highlight and capture a static representation of the waterfall plot.

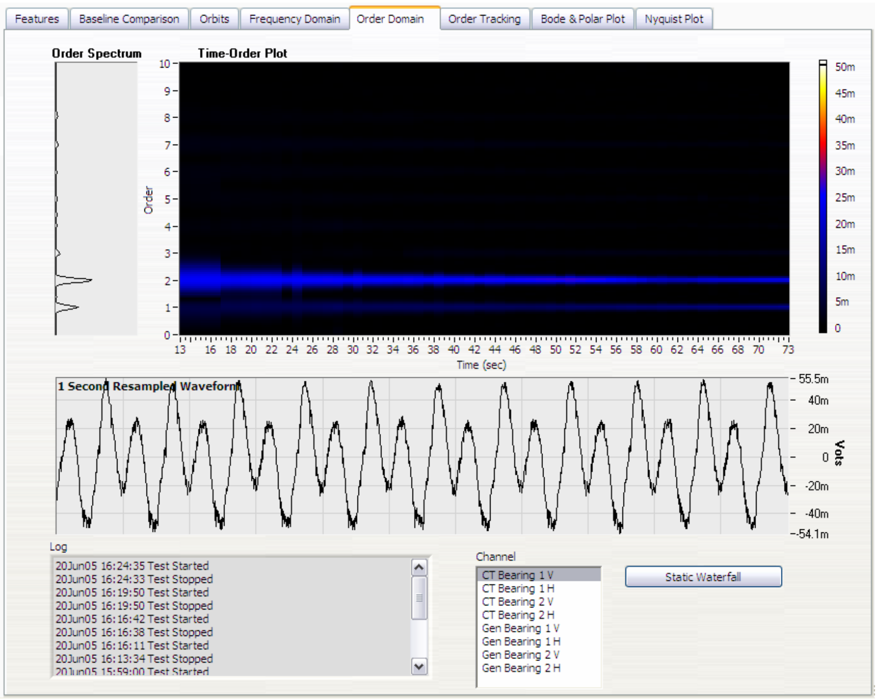


Figure 7-34
Main Viewing Area of Order Domain Analysis Tool

Static Waterfall Plots

The *Static Waterfall* plot is a compilation of the frequency or order spectra up to the time the control was pressed. Time and frequency/order are represented on the horizontal axes and spectra amplitude expressed in volts defines the vertical axis. The static view feature has been added to facilitate gathering screen captures for reports and analyses. User controls are included to customize the extent of the desired view.

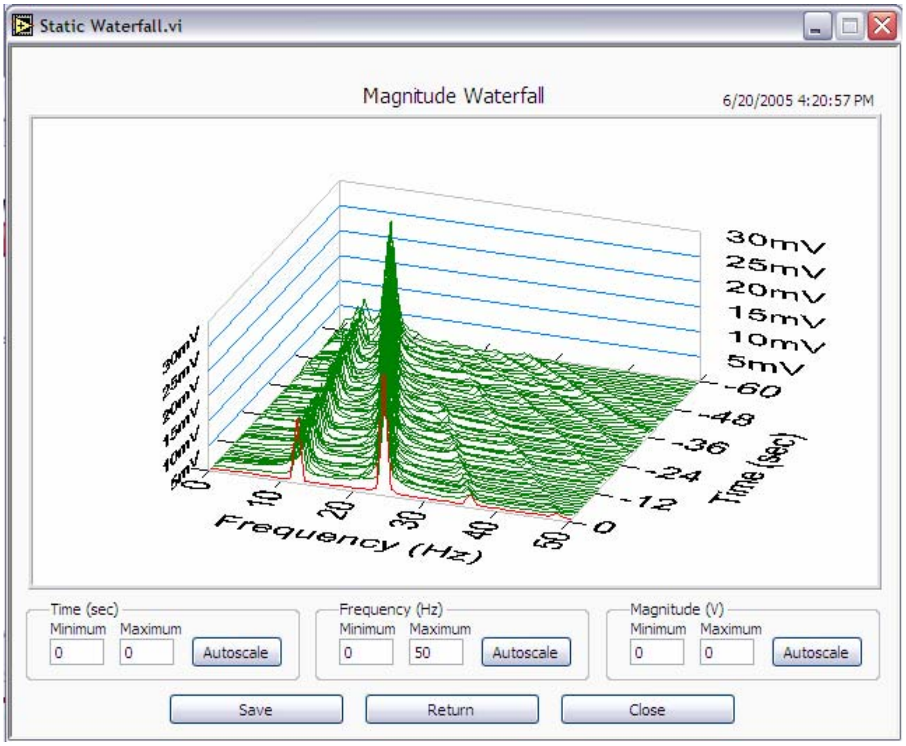


Figure 7-35
Static Waterfall Plot

Order Tracking

The *Order Tracking* showcases engine order magnitude information obtained from the frequency spectrum at frequencies corresponding to the shaft speed and their harmonics. The signal magnitudes at these frequencies are extremely useful in diagnosing faults. By comparing and tracking the relative magnitude of 21 engine orders the software has the ability to detect many fault types.

Extracting the engine orders is accomplished by first resampling the data to a sampling frequency corresponding to a constant angular displacement. Typically, sampling is performed at constant time intervals not angular positions. If the shaft is accelerating the sampling will not be at constant angular positions. Many methods can be used to resample the time-sampled signal into a position-sampled signal. LabVIEW has built in functions to perform the necessary resampling.

Once the signal has been resampled, an FFT is performed and several full and fractional engine orders are extracted. The 1st engine order through the 15th engine order are determined along with the 1/4, 1/3, 1/2, 2/3, 1-2/3, and 2-1/3 engine orders. These features are supplied from data from each of the proximity probes monitoring turbine/generator set operation.

The user interface developed to support this feature of the Vibration Fault Diagnostics System (Figure 7-36) utilizes two graphing utilities to monitor the engine order magnitudes and tracks.

One graph plots the real-time magnitude values determined from the current analysis. This graph plots all engine orders concurrently. The second utility facilitates monitoring selected engine order magnitudes through time. User controls are also provided to customize this view.

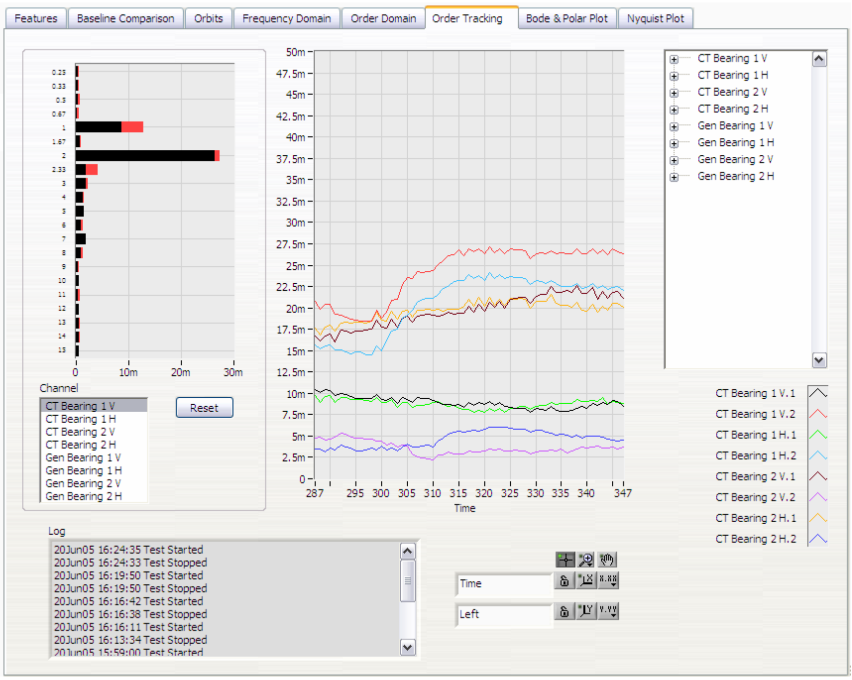


Figure 7-36
Main View of the *Order Tracking* Analysis Tool

Bode and Polar Plot

This portion of the application can be run by selecting the tab at the top of the VFDS application screen, or by running the independent executable *Offline Analysis.exe*. The Bode & Polar Plot tab is disabled while a test is running, but is available when the test is stopped. Bode plots are used to illustrate the relationship of the magnitude, phase and frequency response of a system during start-up or shutdown events. Slow roll compensation capabilities have been included to clarify the dynamic information contained in these plots. Slow roll compensation removes shaft runout from the vibration signature, leaving only the dynamic vibration feature. The plots are available on the host computer.

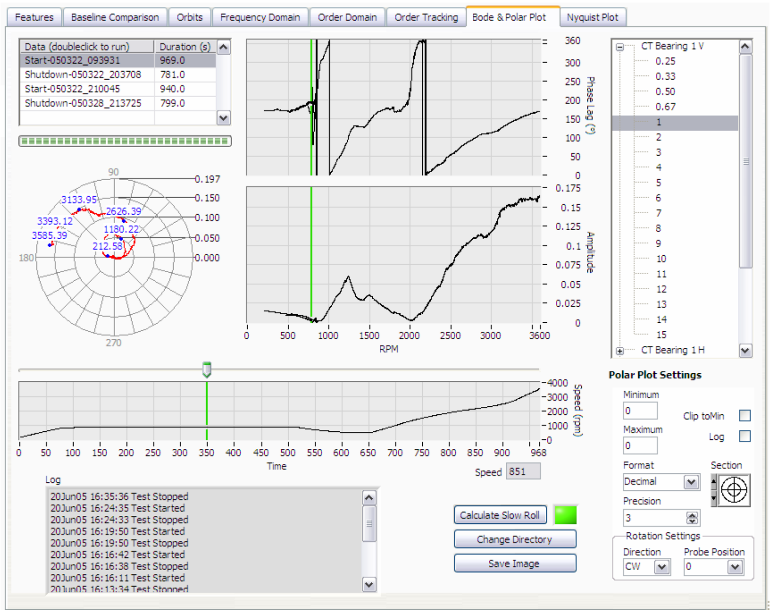


Figure 7-37
Main View of the *Bode and Polar Plot* Analysis Tool

Nyquist Plot

Nyquist plots represent the real and imaginary parts of the frequency spectrum of a signal shown on the complex plane, and can be useful identifying resonances. Again, the plot is available only on the host machine.

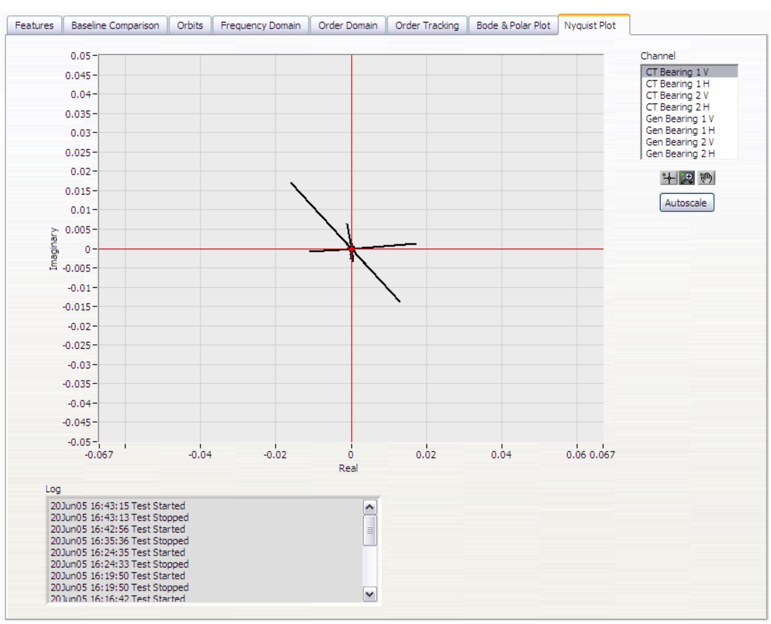


Figure 7-38
Main View of the *Nyquist Plot*

Utilities

Aside from VFDS v2.exe, there are three other included supporting applications:

- VFDS Config Control.exe
- Baseline Generator.exe
- Offline Analysis.exe

These applications are described in detail in the user manual. The *VFDS Config Control* application is a utility that allows the operator to change the configuration parameters used by the VFDS. *Baseline Generator* creates the files necessary to plot the baseline data, as well as providing the reference point for the diagnostics. The *Offline Analysis* application allows the data to be viewed external to the host machine, given the availability of data.

References

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Appendix A: The Proximity Probe[3]

One very common type of proximity probe is known commercially as a "Proximiter", which is a trademark of the Bentley Nevada Company.

The Proximity Probe, also called an "Eddy Current Probe" or "Displacement Transducer", is a permanently mounted unit, and requires a signal-conditioning amplifier to generate an output voltage proportional to the distance between the transducer end and the shaft. It operates on a magnetic principle, and is thus sensitive to magnetic anomalies in the shaft -- care should be taken that the shaft is not magnetized to assure the output signal is not contaminated. It is important to realize that the transducer measures relative displacement between the bearing and the journal, and does not measure total vibration level of the shaft or the housing. The displacement transducer is very commonly installed in large machines with journal bearings where it is used to detect bearing failure and to shut the machine down before catastrophic failure occurs.

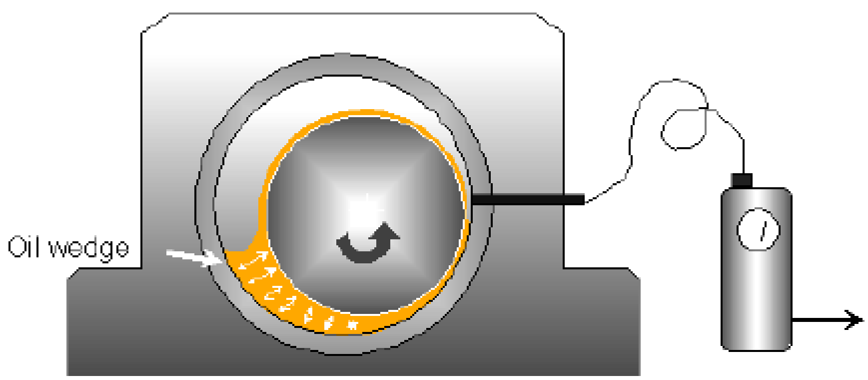

Figure 7-39
Schematic Usage of a Proximity Probe

These transducers are frequently used in pairs oriented 90 apart, and can be connected to the vertical and horizontal plates of an oscilloscope to display the "orbit", or path of the journal as it migrates around in the bearing. The frequency response of the displacement transducer extends from DC (0 Hz) to about 1000 Hz.

[3] http://www.dliengineering.com/vibman/theproximityprobe.htm

Appendix B: Bayes' Theorem and Bayesian Belief Networks

For dependent events 'A' and 'B', the product rule expresses the probability of both events 'A' and 'B' occurring.

$$P(A,B) = P(A)(P(B/A) \quad (1)$$

where $P(B/A)$ is the probability of 'B' given that 'A' has occurred. Also,

$$P(A,B) = P(B)(P(A/B) \quad (2)$$

Equating, (1) and (2) we have a simple version of Bayes' Theorem:

$$P(A/B) = \frac{P(A)(P(B/A)}{P(B)} \quad (3)$$

Using the total probability rule, we can expand the denominator in (3) to:

$$P(A/B) = \frac{P(A)(P(B/A)}{P(A)P(B/A) + P(A')P(B/A')} \quad (4)$$

where P(A') is the probability that event A has not occurred and is equivalent to 1-P(A)