Combustion Turbine Diagnostic Health Monitoring

Combustion Turbine Performance and Fault Diagnostic Module (CTPFDM)

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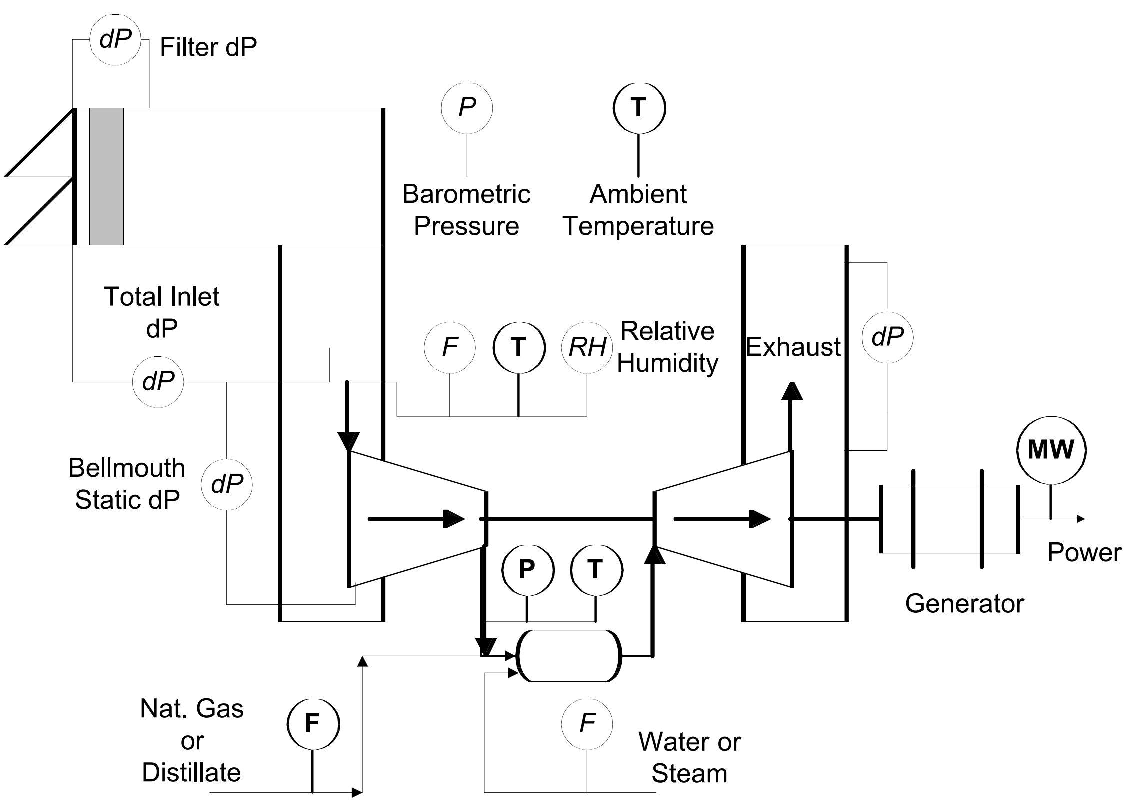

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Final Report, March 2004

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PRODUCT DESCRIPTION

The industrywide transition to condition-based maintenance strategies has prompted development of sophisticated, automated condition assessment tools. The Combustion Turbine Performance and Fault Diagnostic Module (CTPFDM) presented in this report is the second of a suite of intelligent software tools being developed by EPRI and the U.S. Department of Energy (DOE) National Energy Technology Laboratory as part of the Combustion Turbine Health Management (CTHM) System. The CTHM System will offer a significant improvement over currently available techniques for turbine monitoring and diagnostics, by providing a comprehensive array of intelligent tools for assessing the "total health" of a combustion turbine, both mechanically and thermodynamically.

Results & Findings

Monitoring the performance of combustion turbine (CT) components allows users 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. The CTPFDM carries out six main functions—data checking, measured (or actual) performance, expected performance, 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. The actual performance calculations are based on key measurements from plant instrumentation. Standard thermodynamic engineering formulas are used to derive key performance parameters such as heat rate and compressor isentropic efficiency. The expected performance calculations are based on the expected base load and part-load performance data for GE 7FA combustion turbines. 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 an inlet cooling system is in operation, the CTPFDM calculates what the CT actual performance would be if the cooling system were not in operation. In this way, the user can see the benefits obtained from inlet cooling. Fault diagnostics result in logical "flags," evaluated for several CT parameters and serve as alerts to potentially excessive CT performance degradation.

Challenges & Objective(s)

While commercially available on-line monitoring programs provide in-depth analysis of CT plant performance on a component-by-component basis, they are expensive to buy and implement in the field. One goal in development of the CTPFDM was to produce a package that would be both easy to set up and inexpensive to use in monitoring multiple combustion turbines simultaneously as well as ones of various makes and models.

Applications, Values & Use

This report should be of great interest to engineering personnel concerned with maintaining optimal performance in simple and combined cycle (CC) power generation systems. Version 3.2 of the CTPFDM has been upgraded to include part-load performance monitoring and fault diagnostic capabilities to detect key CT component faults. In the future, EPRI envisions integrating the CTPFDM with EPRI's hot section life assessment technology to provide an automatic evaluation of the remaining life of hot section parts. Technology such as this empowers personnel with the ability to make informed decisions through accurate detection of fault conditions in critical components of CT plants.

EPRI Perspective

Deregulation of the power generation industry has elevated the bar of marketplace competitiveness. Operators need to be more cautious and proactive in their maintenance programs in an effort to maximize output while minimizing unscheduled downtime. The CTPFDM is the second of the CTHM suite of intelligent software tools that offers customers an essential added level of confidence in the validity of results obtained from a performance diagnostic program. In addition to the CTPFDM, available software tools in this suite include the Sensor Validation and Recovery Module (EPRI report 1004969) for checking the integrity of sensed data before it is passed to the diagnostic and prognostic modules and the Combined Cycle Performance and Fault Diagnostic Module (CCPFDM; report 1009491), an add-on program for monitoring and diagnosing the condition of combined cycle plants and determining the benefits of maintenance actions. Both the CCPFDM and CTPFDM—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 CC units and multiple combustion turbines. Other modules in the CTHM suite to be completed include the CT/CC Life Limiting Component Prognostic Module, CT/CC Combustion Diagnostics Module, and CT/CC Rotor Dynamics/Mechanical Anomaly Module.

Keywords

Combustion Turbine Health Management (CTHM) System
Combustion Turbine Performance and Fault Diagnostic Module (CTPFDM)
Combined Cycle Performance and Fault Diagnostic Module (CCPFDM)
Combustion turbines
Performance diagnostics
Predictive maintenance
Fault diagnostics

ABSTRACT

Development of a comprehensive Combustion Turbine Health Management (CTHM) System will play a critical role in reducing the cost of electricity by improving reliability, availability, and maintainability. The real-time health management technologies under development use a combination of probabilistic and artificial-intelligence-based tools to assess both thermodynamic and mechanical health of combustion turbines. These technologies include sensor validation, performance diagnostics and prognostics, vibration diagnostics, and critical component remaining useful life assessments. EPRI and the Department of Energy (DOE) National Energy Technology Laboratory have developed a performance degradation program for combustion turbine (CT) plants. This volume 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. EPRI report 1009491 describes the Combined Cycle Performance and Fault Diagnostic Module (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.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

A performance degradation and fault diagnostic program has been developed for combustion turbines (CTs) and combined cycles (CCs). This report describes the Combustion Turbine Performance and Fault Diagnostic Module or CTPFDM. A companion report (EPRI Product 1009491) describes the Combined Cycle Performance and Fault Diagnostic Module or CCPFDM. CTPFDM is a spreadsheet which provides combustion turbine (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/98/2000 operating systems
- Comes with an installation routine developed using InstallShield
- Capable of monitoring combustion turbines of multiple makes and models
- Expected performance predicted for both base load and part load operations
- Initial set-up includes built-in model of the GE 7FA combustion turbine
- 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.

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 quickly see 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 Degradation Module 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 Gtmodel worksheet and there are several new measured input parameters on the Inputs worksheet.

This version also provides complete part-load performance monitoring. Previous versions of the spreadsheet could monitor either base load operations only (Version 2.0), or could provide expected performance results at base load only while giving measured results at base load or part load conditions (Version 3.0).

Actual and expected turbine section efficiency calculations have also been added to the performance monitoring module.

Finally, the spreadsheet macros have been modified to allow multiple copies of the spreadsheet to be running simultaneously. This makes it possible to monitoring more than one CT on-line from the same PC.

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 1-1 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).

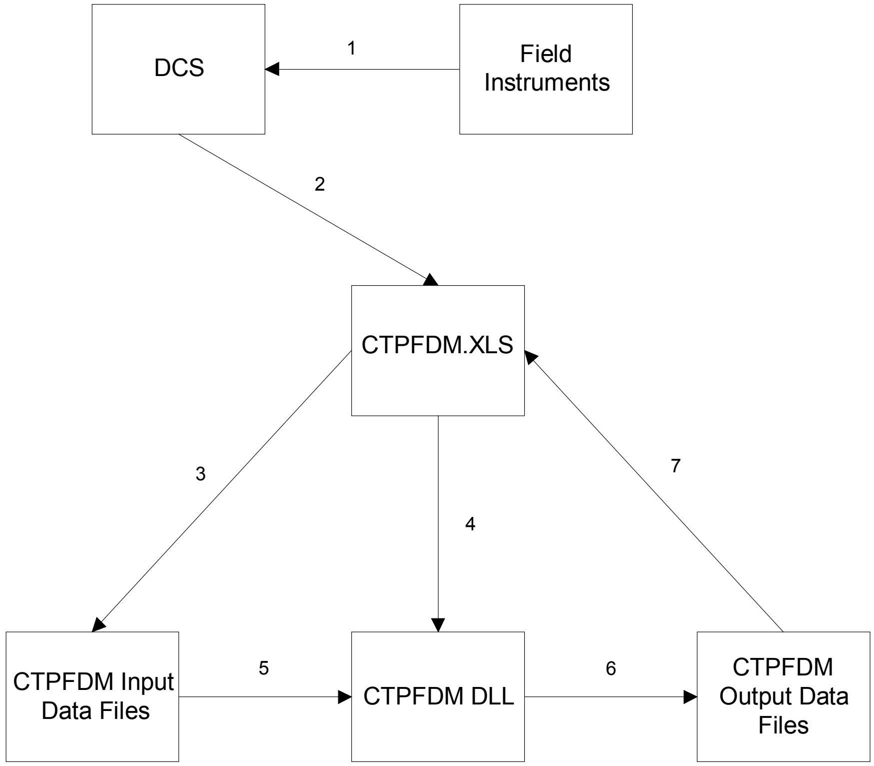

Figure 1-1
CTPFDM Software Functional Flowchart Showing Interaction Between the CTPFDM DLL, the CTPFDM.xls Excel Spreadsheet, and the Combustion Turbine Instrumentation

2
INSTALLATION

Hardware & Software Requirements

Table 2-1 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 2-1
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 chapter).

   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 2-1). Click "**Enable Macros**" and the spreadsheet will finish loading.

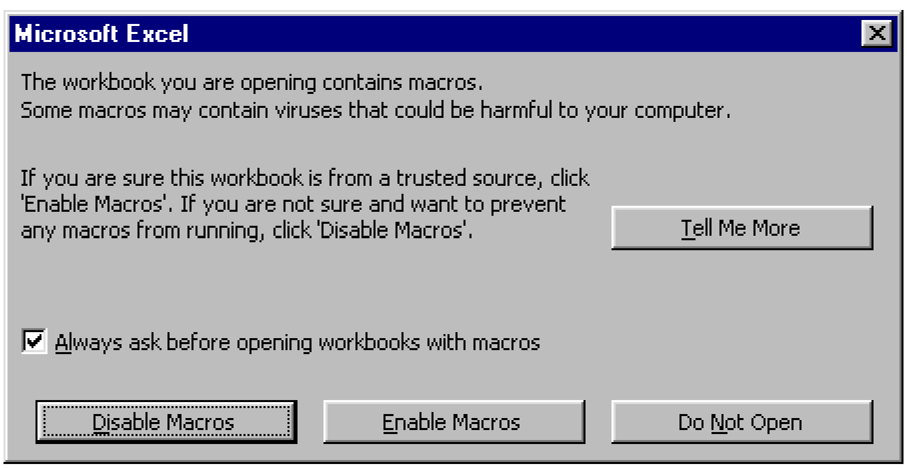

Figure 2-1
Example of Dialog Box that Appears Each Time the CTPFDM.xls Spreadsheet Is Loaded

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.

3
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 chapter.

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 chapter.

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 Chapter 5 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 3-1.

Table 3-1
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			
Measdflt.dat		Perfdone.inf	
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 3-2. 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 Chapter 4 for an example of how to create a new CT model.

Table 3-2
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 3-1 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.

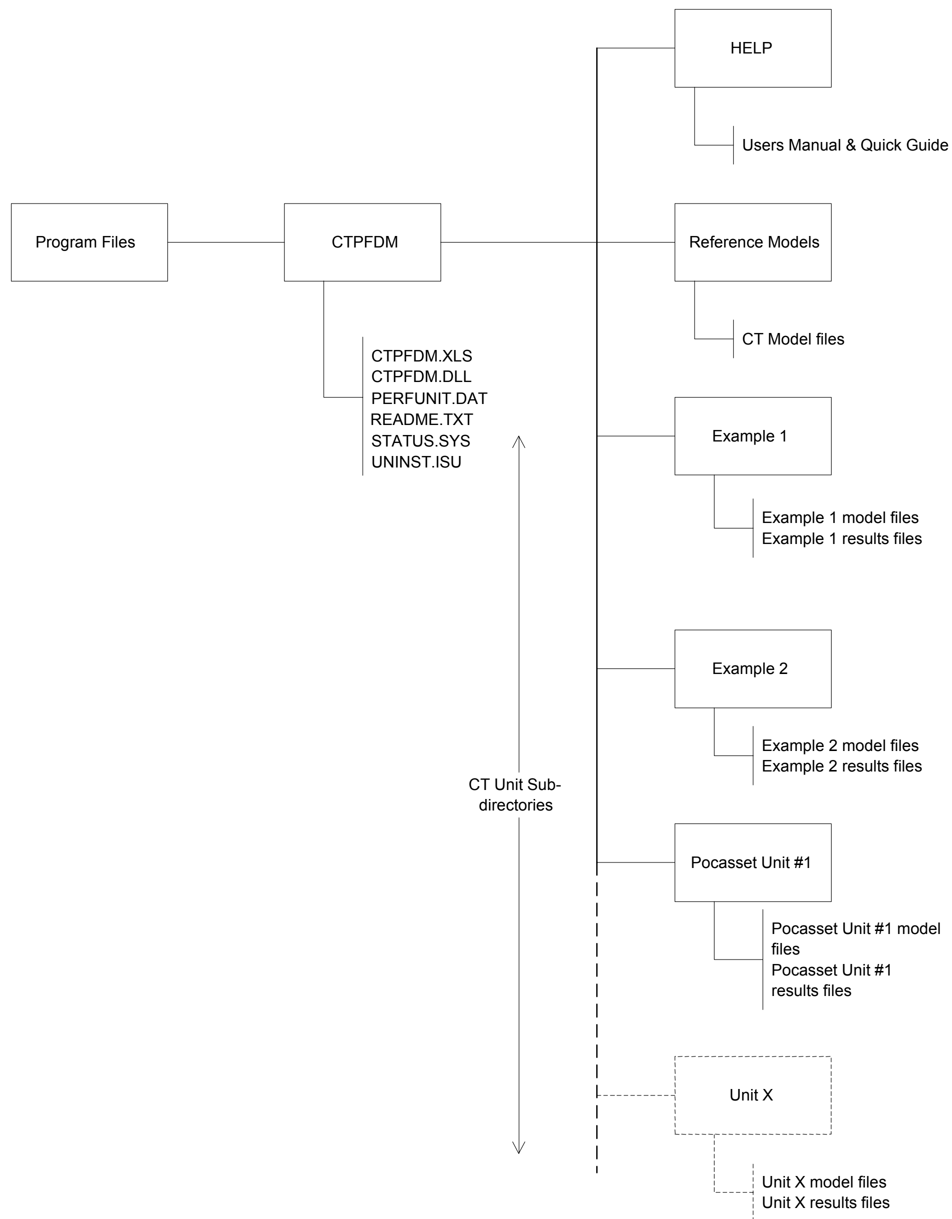

Figure 3-1
Schematic Diagram of the File Directory of CTPFDM

Monitoring Multiple Combustion Turbines Simultaneously

As stated at the beginning of this chapter, 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 Chapter 4.

4
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 chapter 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 sections of this chapter.

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. H_2O, 0-50 mbar, 0-0.723 psid, 0-5000 Pa
Exhaust Pressure Drop	0-30 in. H_2O, 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 chapter 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 4-1, while Figure 4-2 shows an example of compressor inlet temperature versus exhaust temperature, and Figure 4-3 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.

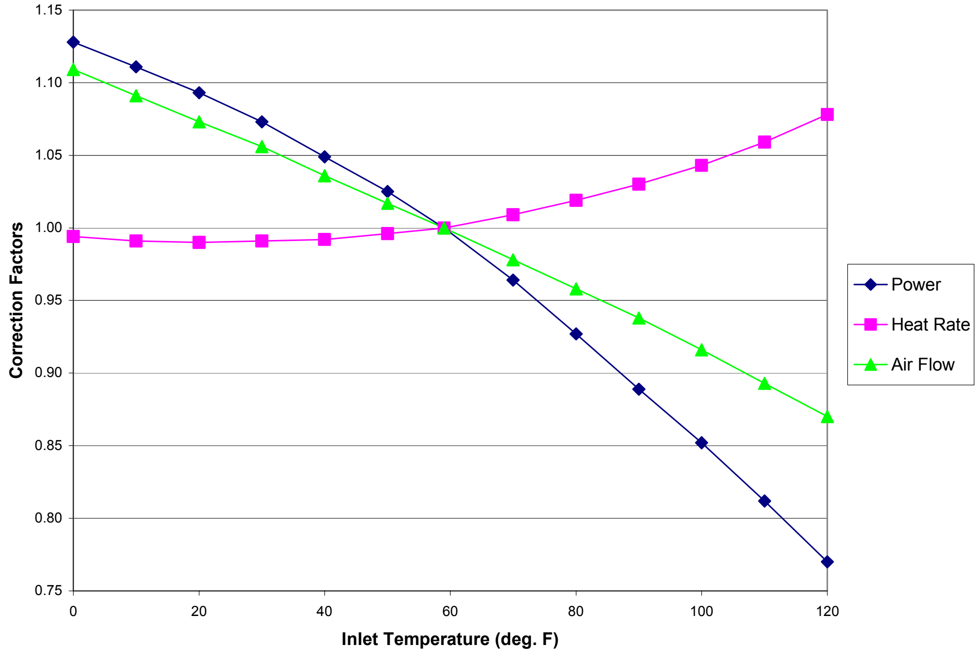

Figure 4-1
Example of Inlet Temperature Correction Factors for a GE 7FA Combustion Turbine

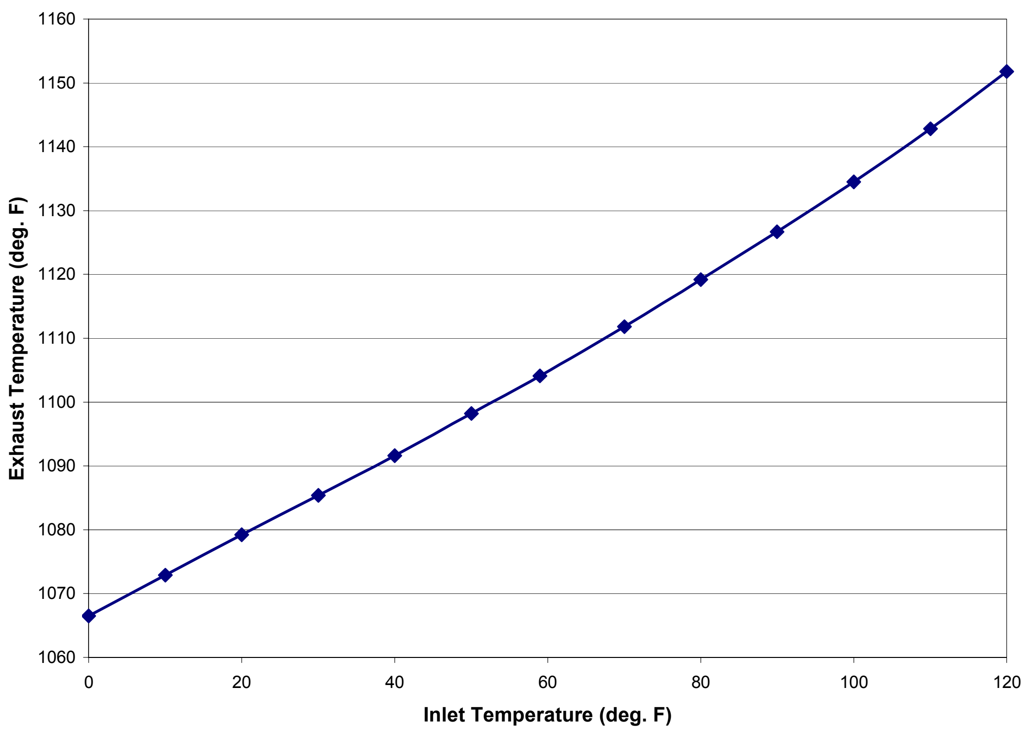

Figure 4-2
Example of Inlet Temperature vs. Exhaust Temperature Effects for a GE 7FA Combustion Turbine

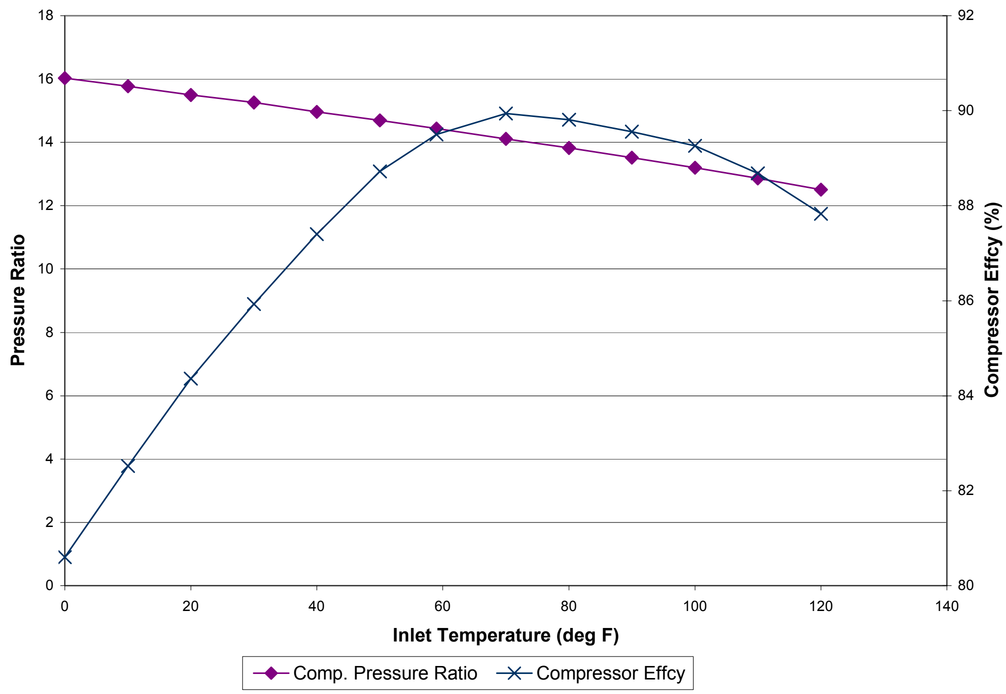

Figure 4-3
Example of Inlet Temperature vs. Compressor Pressure Ratio and Isentropic Efficiency for a GE 7FA Combustion Turbine

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 4-4. 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.

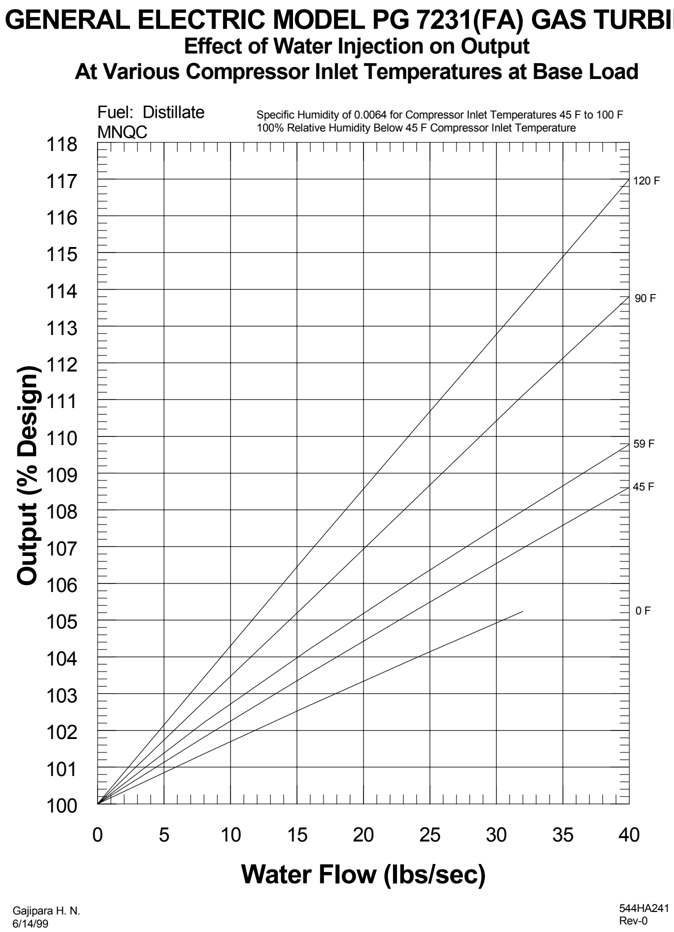

Figure 4-4
Typical Example of Power Output Correction Factor for the Effect of Combustor Water Injection

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 4-1 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 4-5 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.

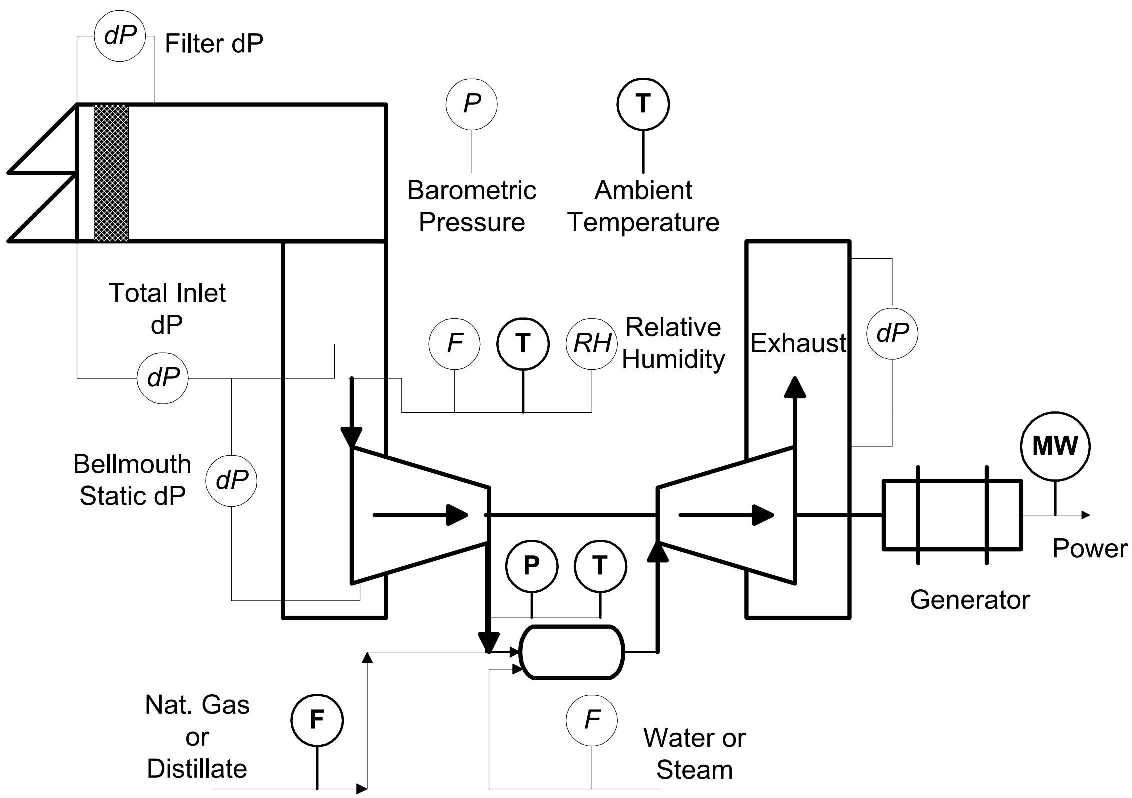

Figure 4-5
Schematic Diagram of a Combustion Turbine Showing Some of the Instruments Used as Inputs to CTPFDM

Table 4-1
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 4-1 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 chapter.

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 judgement as to which case makes the most sense.

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 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.

Max. Exhst. Temp. Spread = A ∗ (Avg. Exhst. Temp.) − B ∗ (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 chapter.

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 4-2 shows the format of the Missinp.dat file (using the example data values shown above).

Table 4-2
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 4-6.

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 4-6
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 4-3 shows the important differences between off-line and on-line modes of operation.

Table 4-3
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 in Chapter 3, 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.

5 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 5-1. 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 5-1.

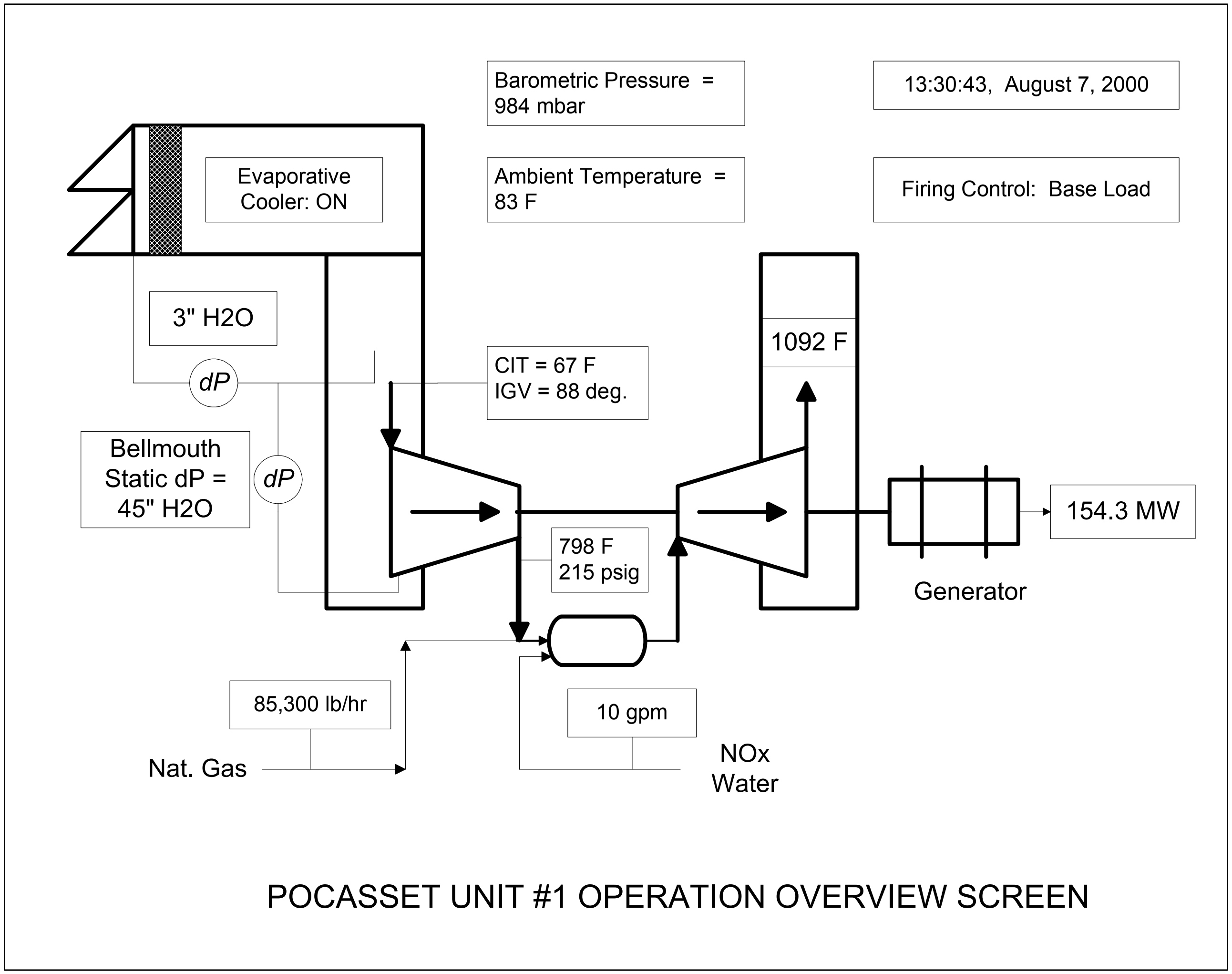

Figure 5-1
Example #1 of CT Operation Overview Screen

Table 5-1
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 Table 5-1, 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 5-2.

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 5-2
Report Output from CTPFDM Using Inputs of Table 5-1

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 5-3. 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.

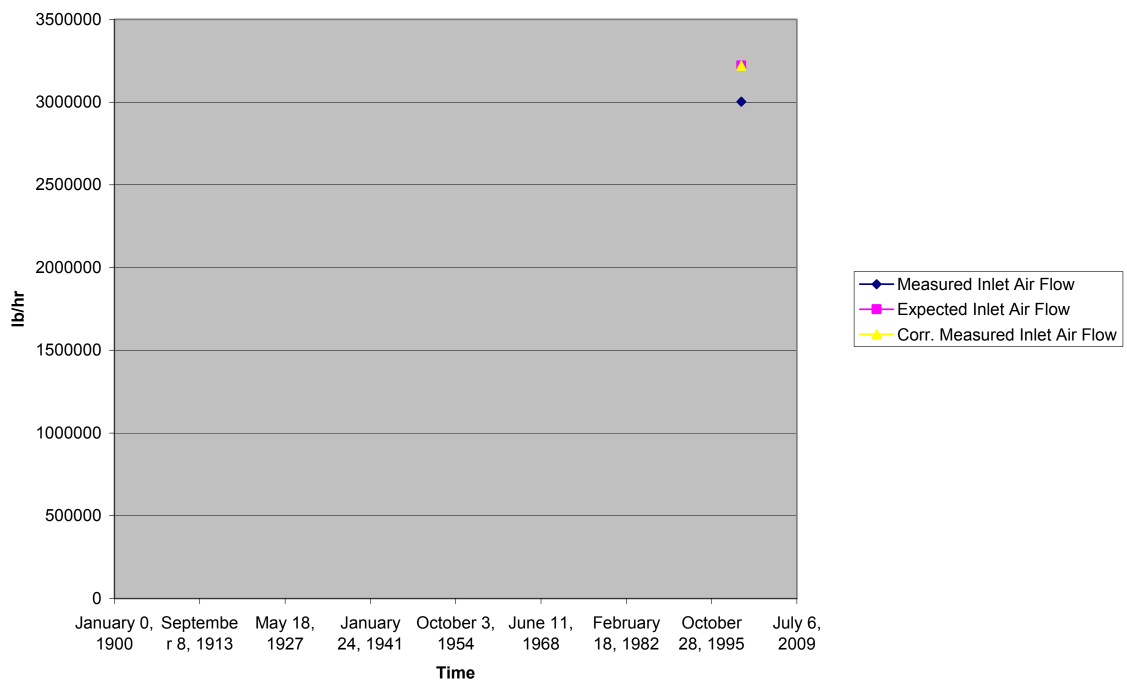

Figure 5-3
"Air Flow Chart" Worksheet after One Performance Results Case Has Been Saved

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 5-4.

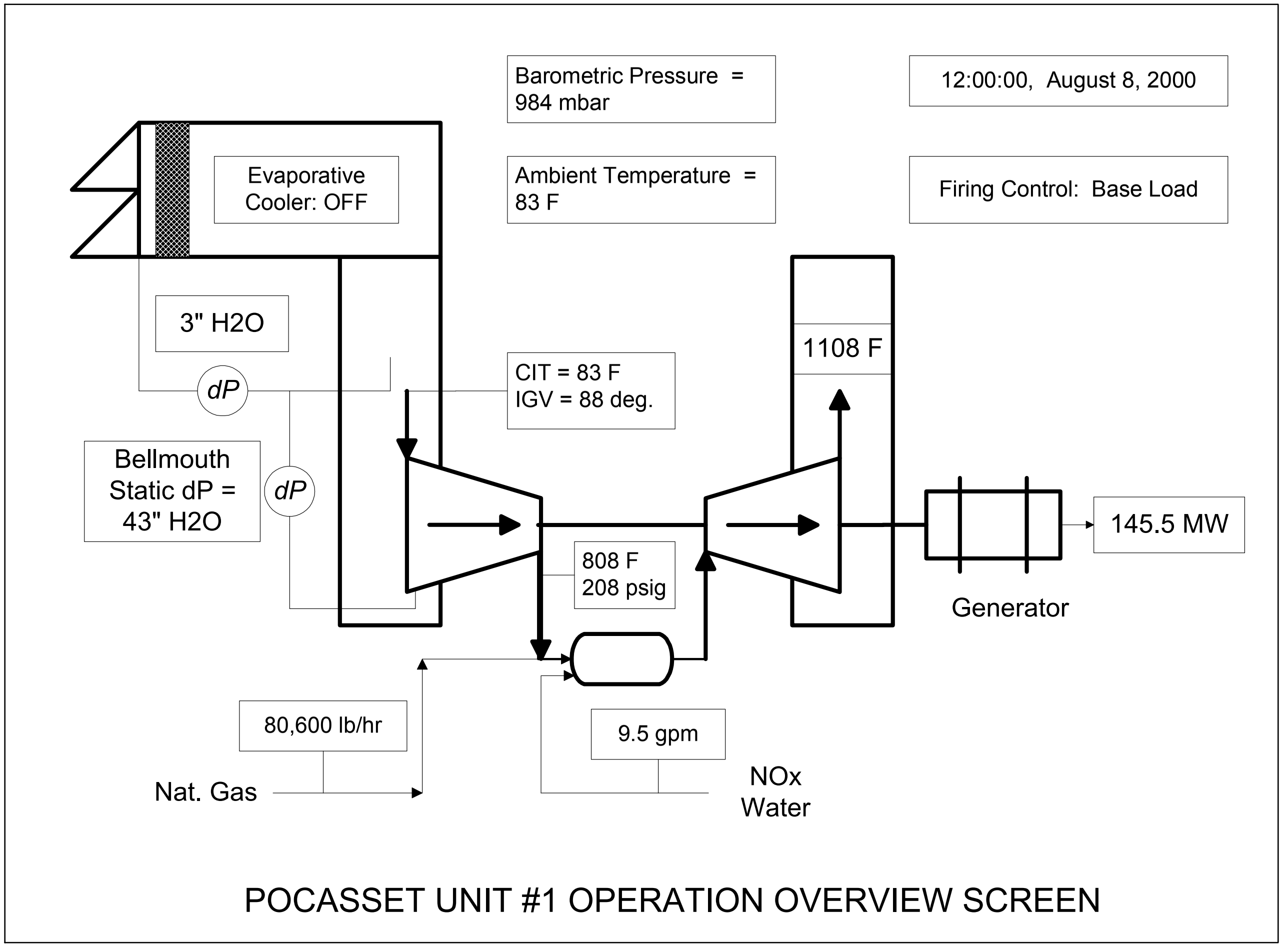

Figure 5-4
Example #2 of CT Operation Overview Screen

Table 5-2
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 5-4 into the **Inputs** worksheet. Follow the instructions given in Table Table 5-2. 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 5-2, 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 5-5.

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 5-5
Report Output from CTPFDM Based on Inputs in Table 5-2

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 5-6. 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.

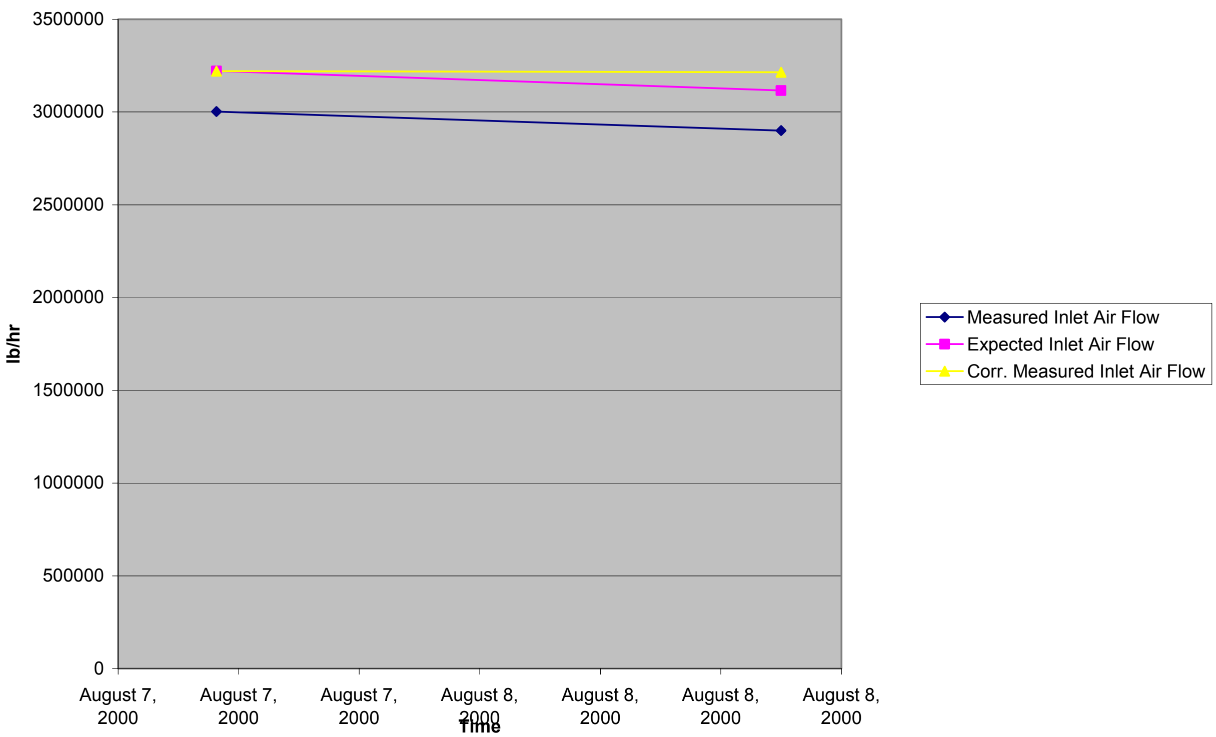

Figure 5-6
"Air Flow Chart" Worksheet after Two Performance Results Cases Have Been Saved

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 5-3. 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 5-3
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 5-3 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 5-3 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**".

6
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.

A
APPENDIX — 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 A-1). 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 A-1
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 Chapter 2).

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 chapter 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 chapter 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:

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

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.

- $CF_{MW\text{-}dPexh}$ is the power correction factor for exhaust pressure drop.
- $CF_{MW\text{-}hum}$ is the power correction factor for specific humidity.
- $CF_{MW\text{-}stm}$ is the power correction factor for steam injection.
- $CF_{MW\text{-}wtr}$ 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 (Chapter 4). 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-T} is the air flow correction factor for inlet temperature.
- CF_{AF-stm} is the air flow correction factor for steam injection.
- CF_{AF-wtr} is the air flow correction factor for water injection.
- $P_{inlet}/P_{inlet-rated}$ 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 A-1 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}).

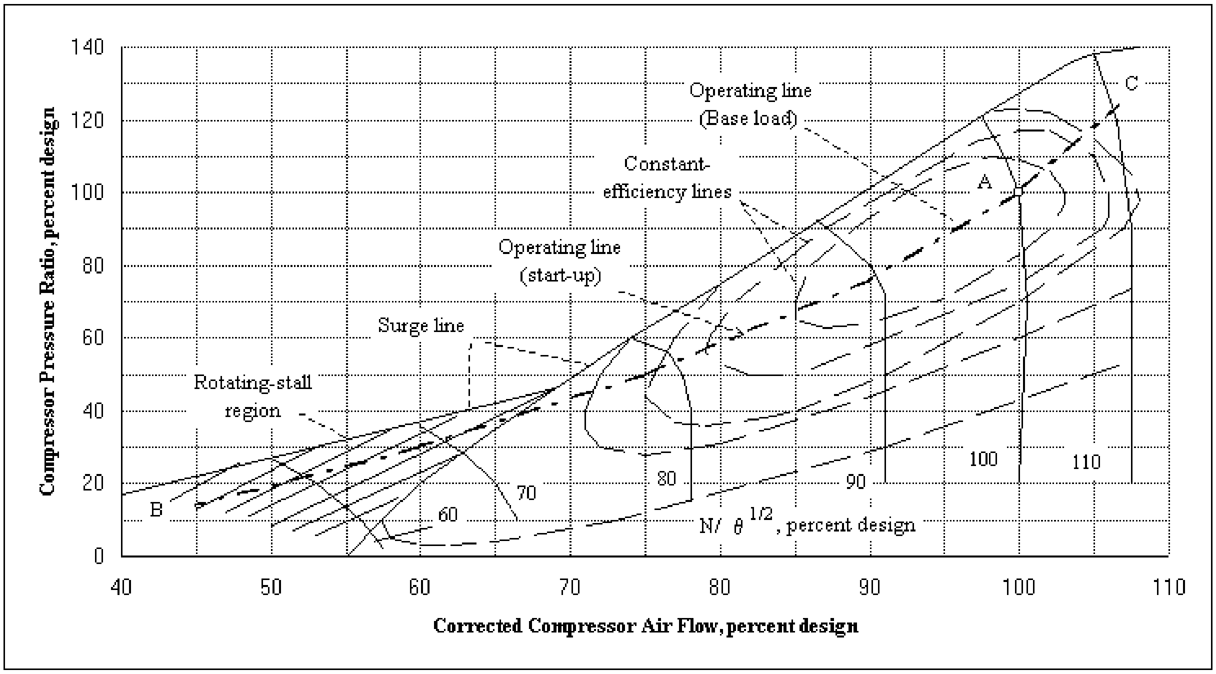

Figure A-1
Typical Multi-Stage Axial Compressor Operating Map (from NASA Aerodynamic Design of Axial-Flow Compressors, 1965)

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 A-1, 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 4-3, 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 A-2 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 4-3. 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.

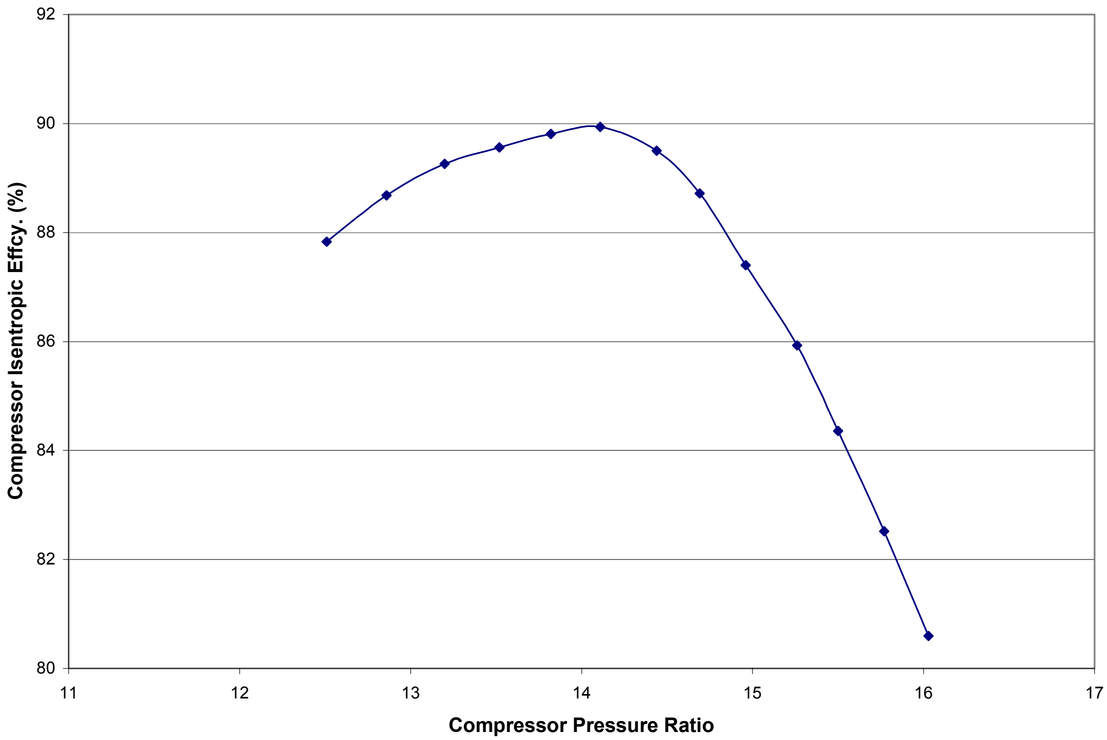

Figure A-2
Plot of Compressor Isentropic Efficiency as a Function of Compressor Pressure Ratio for a Typical Combustion Turbine

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:

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

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 4-1). 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, $MW_{no\text{-}cool}$, is predicted based on the following formula:

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

where $MW_{exp\text{-}Tamb}$ is the expected power at the measured ambient temperature and $MW_{exp\text{-}Tinlet}$ 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. $MW_{exp\text{-}Tamb}$ is calculated using the expected power formula described earlier in this chapter, except the temperature correction factor is based on the ambient temperature rather than the inlet temperature.

The difference between the measured power and $MW_{no\text{-}cool}$ 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, $HR_{no\text{-}cool}$, is predicted based on the following formula:

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

where $HR_{exp\text{-}Tamb}$ is the expected heat rate at the measured ambient temperature and $HR_{exp\text{-}Tinlet}$ is the expected heat rate at the measured inlet temperature, which has already been calculated as part of the expected performance analysis. $HR_{exp\text{-}Tamb}$ is calculated using the expected heat rate formula described earlier in this chapter, 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 $HR_{no\text{-}cool}$ 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 $HR_{no\text{-}cool}$ 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 chapter 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:

$$w_{fuel-corr} = HR_{corr} * MW_{corr} * 1000 / LHV$$

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 Table A-2 and Table A-3 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 A-2
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 A-3
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 (Chapter 4). 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 (Chapter 4).

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 Chapter 4 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 A-3. 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 A-3 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:

$$B1 = B4 + B5 + B6 \quad \textbf{Equation A-1}$$

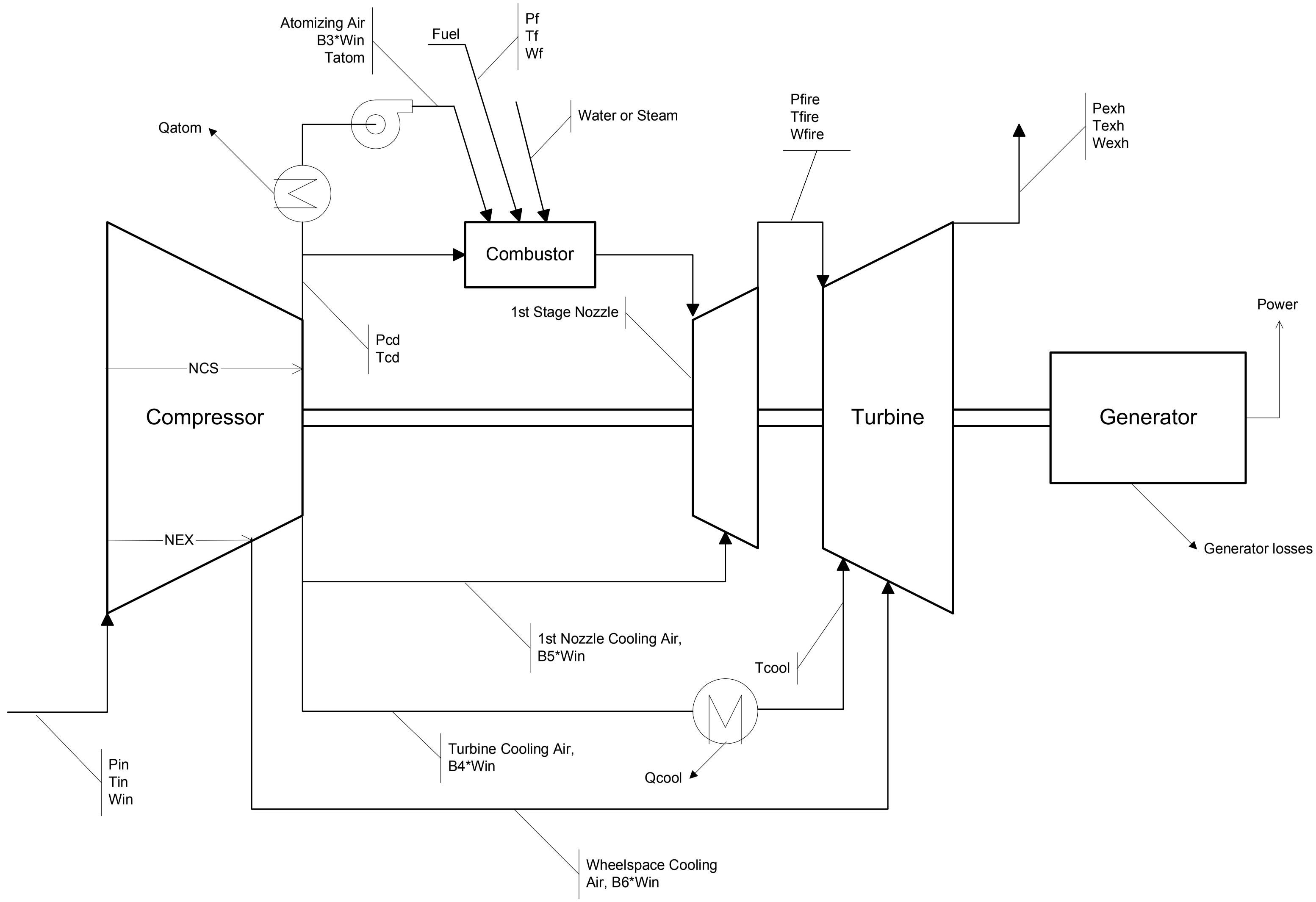

Figure A-3
Schematic Diagram of Combustion Turbine Model Flow Definitions

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:

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

The net heat input to the gas stream is:

$$\begin{aligned}QC = &WCI * (HCO - HCD) + WF * (HCO - HF) + WATOM * (HCO - HATOM) \\ &+ WS * (HCO - HSI) + WW * (HCO - HWI + HWV)\end{aligned}$$ **Equation A-3**

Combining Equations A-2 and A-3 gives:

$$\begin{aligned}QC = &(WCI + WATOM) * (H2REF - H1REF) + WF * (H2REF - HFR) \\ &+ WF * LHV * NCOMB + WW * (H2REF - HWR) \\ &+ WS * (H2REF - HWR\end{aligned}$$ **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:

$$\begin{aligned}&WIN * HIN + QC + WF * HF + WW * (HWI - HWV) + WS * (HSI) = \\ &WEX * HEX + POWER / NGEN + WCOOL * (HCD - HCOOL) \\ &+ WATOM * (HCD - HATOM)\end{aligned}$$ **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:

$$\begin{aligned}&QC + WF * HF + WW * (HWI - HWV) + WS * (HSI) - (WW + WS + WF) * HEX - \\ &POWER / NGEN - WCOOL * (HCD - HCOOL) - WATOM * (HCD - HATOM) = \\ &WIN * (HEX - HIN)\end{aligned}$$ **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:

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

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:

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

The turbine power is:

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

The compressor power is:

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

where FC accounts for the extraction flow:

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

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

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

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.

Program:

Combustion Turbine and Combined-Cycle O&M

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