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PRODUCT DESCRIPTION

This report provides a reference for nuclear power plant personnel involved in using and understanding thermal performance models. This report provides guidance for utilization, maintenance, considerations for troubleshooting, updating, and documentation of thermal performance heat balance modeling software inputs and results, by collecting and documenting industry best practices.

Background

Thermal modeling software is used throughout the nuclear industry to support the thermal performance programs at utilities. Thermal performance modeling software is a tool used throughout the nuclear power industry to maximize electrical output and identify problems that reduce electrical output and increase heat rate. Modeling software is also used to conduct studies of proposed modifications, different operating scenarios, or abnormal conditions effect on the performance of the rest of the cycle.

Due to a number of challenges, which may include employee turnover, increased or changing work scope for the thermal performance engineer, maintaining knowledgeable users of thermal performance models may become more challenging to utilities. Consequently, it is not uncommon for a thermal performance model to be updated solely by vendors during plant equipment replacements and modifications. Furthermore, a lack of internal knowledge at utilities results in ineffective and outdated thermal performance models. An effective thermal performance program, which includes the use of thermal performance modeling software, is beneficial to maintaining efficiency in the plant and troubleshooting off normal conditions.

Objective

- To provide general guidance to nuclear power plant personnel in using, maintaining and updating thermal performance heat balance models.

Approach

This report defines the attributes of the thermodynamic modeling process as well as the role of thermodynamic modeling in the troubleshooting process. The data gathered in this report was collected through investigation of existing best practices in the industry. The report identifies near term improvements; ascertaining the costs, method of implementation, and advantages for utilities. This report provides a list of the attributes of a good model, recommendations for qualified personal, propositions for maintaining design heat balance and as-built baseline models, recommendations for organizing and documenting models (configuration and control), and tips for performing input data validation.

Results

This report provides best practice general guidance for nuclear power plant personnel for using, maintaining, and updating thermal performance heat balance models.

Application, Value and Use

The guidance available in this report documents the important attributes of thermodynamic modeling process. It also describes the role of thermodynamic modeling in the troubleshooting process. The general guidance is intended to be independent of any particular thermal performance modeling software; rather it provides guidance generically applicable to thermal performance models. This report contains a list of the attributes of a good model and recommendations for qualified personal, maintaining design heat balance and as-built baseline models, organization and documentation of models (configuration and control), and strategies for validating input data. This report may be used as guidance for utilities to increase the modeling knowledge base of the utility thermal performance engineers and identify gaps in the current modeling software knowledgebase, documentation, and usage. These gaps may identify areas for individual training or programmatic improvement.

Keywords

Plant baseline and modeling
Performance goals
Monitoring and trending
Search and recovery
Thermal losses

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

1.1 Background

Thermal performance modeling software is a tool used throughout the electric power industry to maximize electrical output and identify problems that reduce electrical output and increase heat rate. High level industry guidance has not been available to help thermal performance engineers effectively utilize models. This report provides generic guidance on the use of Thermal Performance Modeling Software.

1.2 Report Purpose

The purpose of this report is to provide guidance to nuclear power plant personnel in using, maintaining and updating thermal performance heat balance modeling software. Use of the software by utilities is often ineffective due to a number of factors such as long time periods between software usage as well as retaining knowledgeable users of the software. Issues have been experienced where these software models were misplaced or out of date. It may be common for the models to only be updated by vendors during plant equipment replacement and modifications. This report documents best practices to help increase the overall effectiveness of the resulting models by users throughout the industry.

The documentation of best practices included in this report are intended to provide near term improvements to utilities. The main near term improvement is this report. No comprehensive guide has been available to thermal performance software users beyond the “Help” information included in the software. Specific near term improvements included in this report are a list of the attributes of a good model, recommendations for qualified personal, recommendations for maintaining design heat balance and as-built baseline models, recommendations for organizing and documenting models (configuration and control), and tips for performing input data validation.

1.3 Report Scope

This report is focused on software used in electrical power plants to model thermal cycle efficiency of steam turbines (Rankine cycle) in a nuclear steam cycle. These software packages can also be used for Fossil steam cycles, gas turbines (Brayton cycle) or combined cycles. Various versions of this type of software have been produced by a number of difference vendors, academia, and individual utilities. The issues associated with using, maintaining, and updating the software in the nuclear power industry are generic in nature and not based on a particular software package.

This report is intended to be used independent of any particular brand of software.

The report will document the important attributes of thermodynamic modeling process. It will also describe the role of thermodynamic modeling in the troubleshooting process.

The term “thermal performance software” and the term “thermal cycle software” are used interchangeably in this report. Essentially, the terms refer to software that can model any type of thermal cycle or power system such as the Rankine cycle or Brayton cycle or combination thereof. Thermal performance software may also be described as heat balance calculation software.

There are some software products used in the power industry that employ a combination of first principals and statistical methods to analyze plant performance; however, these types of packages are not discussed in this report even though some of the information in this report will apply to those products. More information about these products can be found in EPRI report 3002005345.

1.4 Intended Users

This report is focused on users of Thermal Performance software modeling the Rankine thermal cycle in a nuclear power plant. However, most of the information is applicable to thermal performance modeling software users in fossil power plants and the steam turbine section of a combined cycle power plant.

1.5 Future Work

Long term improvements are not part of this report but could be included in future reports. Possible long term improvements include the development of pre-configured models, use and development of an Excel based model interface, guidance for the modeling off-design conditions, modeling tuning techniques, and techniques for developing advanced sub-models for steam generators, moisture separator reheaters, and feedwater heaters.

2

ATTRIBUTES OF MODELING SOFTWARE

2.1 Software Attributes

Thermal performance cycle software was developed to predict electrical output of a thermal cycle given a set of interface conditions. Its first uses were mainly for design and design validation of steam turbines. It has evolved into a tool for monitoring and troubleshooting power plant performance as well as for the design of a thermal cycle.

The modeling of steam turbines is primarily based on first principles for expected turbine blade performance [Ref. Salisbury[1] and Bartlett[2]]. Some software includes expected performance of turbine sections based on publically available vendor publications from the 1960s and 1970s. [Ref. ASME[3]].

Nuclear thermal performance models are primarily concerned with the turbine cycle part of the unit but often include some interaction with a reactor, reactor systems such as control rod drive or reactor water clean-up, steam generator, and steam generator blowdown systems. The scope of any model depends on the envelope or control volume of the area of the plant being modeled. The control volume may include the heat or steam source (steam generator or reactor), electric generator, and go as far as the ultimate heat sink (condenser, circulating water supply, or cooling tower). Some models will include the primary side of the steam generator within the boundary.

Thermal cycle modeling software is available from commercial sources or a plant or utility may have developed their own. The software generally has the following attributes.

2.1.1 Standard Calculations

Typical thermal cycle modeling software provides standard calculations, for each type of equipment, that are the basis for most cycle modeling. Some software uses a simplified modeling approach where the user selects the number of primary equipment components and the software builds a model automatically assuming a typical component arrangement. This is good for an approximate absolute calculation and relative performance studies, but it may not accurately represent the actual cycle because some specific unit characteristics may be excluded in the automated design process.

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[1] *Steam Turbines and Their Cycles*, J. Kenneth Salisbury, 1950

[2] *Steam Turbine Performance and Economics*, Robert L. Bartlett, 1958

[3] A Method for Predicting the Performance of Steam Turbine-Generators…16,500 KW and Larger, ASME Paper No. 62-WA-209, R. C. Spencer, K. C. Cotton and C. N. Cannon, 1962

The user must be cognizant of the standard calculations of their particular software. The following are examples of some of the types of standard calculations:

- Throttle valve losses
- Throttle valve steam leakage
- Gland seal system leakoffs, demand and spillover flow rates
- Turbine design (number of stages, stage efficiency, moisture removal, stage power, impulse or reaction or a combination and blade design). It is helpful if the software can model the subtle difference between impulse and reaction turbines as it makes a difference in extraction pressures which in turn affect feedwater heater performance.
- Feedwater heaters and heat exchangers
- Condensers
- Cooling towers
- Total cycle thermal power input and heat rate
- Main generator losses

In addition to standard calculations, some software has built-in calculations with more specific applications that the user should be aware of as they use the model:

- New technology
- Proprietary turbine designs
- Pressure drops such as the extraction steam to feedwater heaters or reheat steam lines
- Unusual cycle arrangements

2.1.2 Flexibility

Flexibility is needed to configure the software model for different types of operation. Typically a plant will have a design or “baseline” model to match the design of the plant or normal operating point. A model that is flexible can be quickly modified to represent a different operating point or simulate a degraded component such as a feedwater heater. The flexibility of the model is a direct relation to the ability to “float” with changing conditions. This will be discussed in more detail in Section 3.2.

2.1.3 Configuration Control

Configuration control is always a concern when working with a software model. Thermodynamic modeling almost always involves the use of different configurations of the model and scenarios for comparison. The responsibility of configuration control always belongs to the user. Thermal performance modeling software that provides a visual model in addition to numerical results can make documenting some aspects of the model relatively easy. However, some model documentation systems are inadequate and may inhibit understanding by future model users. In these cases, a thorough report documenting model development is more useful. It is important not only to document what is in the model but the basis for what is in the model and the source of information used for model development.

2.1.4 Ease of Use

Software that is easy to use can be conveniently modified and run quickly. However, there is a tradeoff between ease of use and the ability of the model to accurately represent the physics of the process. The modeling technique and complexity should correspond with the proposed use of the model. The various modeling products available have different levels of complexity. The more complex the modeling product the more difficult it is to use. The need for constant review of a software manual and complexity of commands can lead to frustration and lack of use. Comments from industry meetings suggest this is a common problem for utility engineers who do not have the time to stay focused on modeling.

Easy on-line links to input requirements and descriptions help simplify access to seldom used information. Additionally, on-line help and tutorials may be available for quick access to modeling features. Comprehensive manuals provide easy to understand summaries and examples of modeling techniques and components in addition to more technical information. As discussed above, it is very important to reference the manual provided with the software to ensure proper model usage. Not understanding the actual way the model is performing its functions has led to inaccurate model results.

2.1.5 Availability of Training

Training availability is an important attribute to compensate for a limited number of qualified users, which may be challenged by personnel turnover or transfers. Training is available from the commercial software vendors and other contractors, but training for “in-house” software or software not widely used in the industry may be difficult to obtain. Each utility must consider their own situation and needs to determine how training will be provided.

Training classes may include instruction on how to:

- Build new models from scratch
- Revise existing models
- Run existing models to analyze plant problems, including tuning actual plant data

2.1.6 Industry Use

Some thermal software is in more wide spread use than other types due to its long history in the market, commercial considerations, or advantages in modeling a particular type of cycle. The choice of the software product selected by a utility must be balanced against the needs of the utility. The availability of help from industry peers and experts may be increased by participation in user group meetings; in particular, when commonality of modeling software exits.

As with any product available to the utility industry, consideration of available help from industry peers and experts is recommended. Participation in user group meetings, obtaining previous meeting proceedings, seeking help from peers on common modeling problems and use of industry experts are valuable tools that can improve the efficiency of modeling efforts especially where the engineer performs the task infrequently.

2.2 Model Attributes

2.2.1 Flexibility

A model is flexible if it can be easily utilized to simulate various operational modes and situations. Models that already contain most actual flow paths can be easily utilized or adapted so they require less time to revise and are more economical to maintain and run. For example, flow paths can be included during initial development to model equipment bypasses, dumps, and vents. Under normal conditions these flow paths are not in operation, but when simulating a bypass flow or leakage no geometry changes would be required.

2.2.2 Accuracy

The thermodynamic model for a unit must be accurate, i.e. it must produce results that reflect either ideal design conditions or actual operation. The definition of the accuracy of a model depends on the intent of the model. For example, if a model is being used for a design study to prepare for a replacement low pressure turbine the focus of accuracy is on MW output. If the model is being used to predict condenser pressure based on the number of circulating water pumps in-service the focus of accuracy is on the condenser. It is difficult to assign an actual accuracy value to the output of a model because of the large number of input variables.

The required accuracy of a model also depends on whether it will be used to produce an absolute value of unit performance or a relative change in performance. The results of a model used to evaluate a difference between two state points or conditions are typically more reliable than the absolute results of a single point.

2.2.3 Simplicity

Simplicity is a desirable trait because it aids in the understanding and maintenance of model. However, simplicity and flexibility are often a trade-off in a model. Thermodynamic models of the Rankine cycle do not lend themselves to simplicity due to the complexity of the actual plants. When a model is simplified it is usually done at the expense of flexibility. Accuracy can also be reduced for certain aspects of the model depending on the assumptions made in order to simplify the model.

2.2.4 Pertinence

A model must be pertinent to be useful. It must be up-to-date if used for accurate calculation of absolute results or it must reflect realistic changes in performance if used for a relative change in performance calculations. The model will not produce acceptable results if it is not relevant to the situation. For example, using the model of a sister unit may be useful for relative calculations but not be relevant for absolute value calculations due to minor differences in design, actual performance or different operating conditions between the units.

3
PRECAUTIONS AND LIMITATIONS

3.1 Initial Data

Thermal performance models are solved using an iterative process. The iteration process to a solution is commonly known as “running” a model. The process begins by using a set of initial assumptions for unknown values of flows, temperatures and pressures. As the process continues, flows are iterated until mass and energy is balanced around each component and the entire cycle according to the first principles and the model converges to a solution. The convergence criteria for the mass and energy balances may be set by the user or coded into the software.

The complexity of thermal performance software and models lend themselves to enabling errors that produce invalid results or will not allow a model to iterate to completion. Experience has demonstrated that a thermal performance (TP) model may not converge to a solution due to poor choices for initial values. Additionally, a model may not converge due to hard coding of equipment performance parameters that are not allowed to change (float) in the iterative solution process. Data entry errors can also cause a model to fail or produce misleading or incorrect results. The figure below shows how an error in a main steam pressure input can impact the predicted gross generation. A mix up over instrument location or failure to account for a pressure drop or water leg could easily introduce an input error, shown in Figure 3-1.

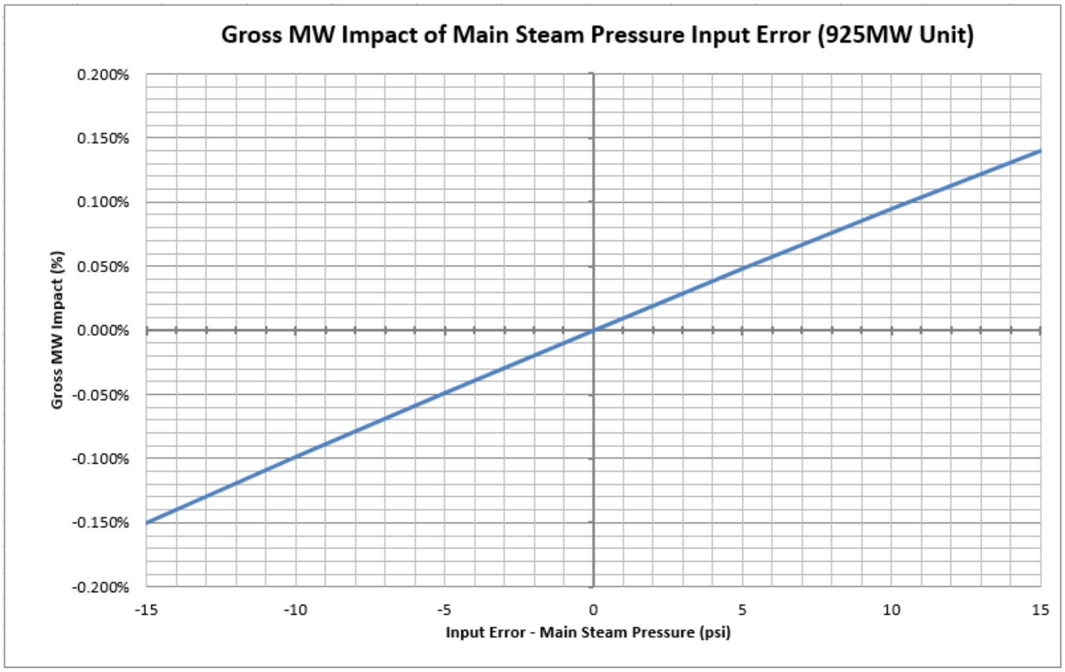

Figure 3-1
Example of a data entry error for main steam pressure and the effect on Gross MW Output

Commercially available supplied software will include documentation regarding the use of initial assumptions for unknown values. Initial assumptions are composed of an “educated guess” of a particular value as well as actual data values from the plant. These values may be used by the software as an initial state to be iterated upon or as boundary conditions. In a nuclear plant, full power models may use values from the full power heat balance as the initial assumption. For other models, initial data from a design heat balance near the load being simulated may provide better convergence.

3.2 “Floating” Conditions

When modeling a thermal cycle, base model inputs and outputs are usually set and validated (“hard coded”) at one particular heat balance condition or operating point. However, actual thermal performance varies with the quantity of energy entering the cycle. If the amount of energy entering a cycle (often referred to as unit load, plant power, system inlet energy, or reactor power) varies, the flows between components, temperature and pressures will vary accordingly. In order for the model to accurately simulate these changes base model inputs and conditions cannot be “hard coded” or “forced.” All components must be able to react to new cycle conditions and adjust its performance. This is often referred to a “floating” model.

Often a user will be interested in examining the results at multiple power levels. This can easily be accomplished by running the model at the various power levels. However, the input data and types of components used in the model must allow each component and the entire model itself to vary or “float” with plant power. This is done using different methods by various software packages. First principles models may calculate expected component performance at different conditions based on fundamental thermodynamic, heat transfer, or component design equations, while empirical models may use tables of values, interpolation between values or curve fitted equations.

If a user has “hard coded” inputs in the model, meaning the input values that are fixed and will not vary with a change in cycle conditions, the end results will be inaccurate. This inaccuracy may not be detected by the user because it may be masked by other changes in the model outputs that occurred due to the change in cycle conditions. Hard coded inputs may also prevent the model from converging to a solution.

Errors due to hard coding can also occur at the component level. For example, a user may be interested in studying the change in performance of a component such as a feedwater heater due to operational configuration changes elsewhere in the thermal cycle. If the drain temperature of the heater is hard coded, the model may not converge or it may converge to an incorrect answer.

A typical method to load generalize a model is to use interpolated performance curves for some input values instead of discrete values. Combined with components that respond to new conditions such as pressure drops based on volumetric flow, the model can accurately predict changes in performance and, depending on input quality and model complexity, absolute performance.

There may be situations where it is necessary to “hard code” certain parameters for a particular study. Care should be taken to adequately document the model so that future use of the model will not be subject to the problems described above.

3.3 Model Input Data

Models may contain alternate sets of input data intended for use at different loads or configurations. Multiple sets of input data, each with a minor change, may be grouped within a base model to run one after another to facilitate an examination of the results of a sequence of minor changes to a base model or changes in cycle operating conditions.

The use of alternate sets of input data can greatly reduce the amount of time the user spends analyzing a problem or proposed change in plant configuration. However, there is the danger of old input data and old modeling decisions being forgotten and left in place. This danger comes with older "inherited" models or models that have a long history. The best practice to handle this issue is to use caution and thoroughly review the content and run sequence of all sets of data in older models.

Documentation of model changes and model iterations help reduce the risk of old or unwanted data being left in an earlier data input set. Some software packages will have features that can aid the user in creating descriptions and notes.

The following are some of the problems that may arise from not understanding or knowing the changes contained in each set of input data:

- Input data left over from previous model studies may be incorrect or fixed
- Model configuration changes left over from previous studies may cause invalid results

3.4 Engineering Units

Use of consistent engineering units for temperatures, pressures, flows, and enthalpy is important for accurate results. Typically, TP software allows the user to select what engineering units the input and outputs will use. Errors are introduced into the model when the input data is in different engineering units than specified in the model set-up.

Unexpected results or suspicious results are often caused by incorrect use of engineering units. A common error is the input of pressure in the units of gage rather than absolute.

3.5 Transient Data

When plant data is used as the input data of a model it must be from a period of steady state operation. Users of TP software must always know the condition of the plant when data was collected. One of the pitfalls of automatic data collection is that data will be collected from periods when a plant may be in a transient condition. This can affect accuracy as thermal performance software calculates a heat balance at a single operation point and the assumption is that the data comes from a period of steady state operation. Additionally, taking an instantaneous snapshot of plant data instead of short-term averaged plant data can increase uncertainty in the model results.

3.6 Main Control Valve Throttle Losses

The simulation of main turbine control valve throttle losses varies between TP software vendors and between equipment manufacturers. The TP software user will need to be cognizant of how their model calculates these throttle losses. Actual throttle losses vary based on the size of the control valves, the volumetric flow rate of the inlet steam, and the turbine blade design (impulse or reaction). Use of an incorrect calculation can result in errors on the order of 1 – 10 MW of electrical output.

4
MODEL CONFIGURATION

Before using a model, the baseline assumptions used to develop it must be determined and validated. Assumptions made in the development process may not be valid for the current study. For example, if a plant heat balance diagram is used as the baseline, the feedwater heaters are modeled to match the turbine vendor assumptions of performance. Since this usually does not reflect actual heater performance, using the model to study the effect of taking a heater out of service will not produce meaningful results for the downstream heaters.

4.1 Documentation

Model documentation is essential for the proper user of models. Utility engineers are frequently rotated into different jobs and new inexperienced personnel become the owners of models. Without documentation, the results of a model may be confusing and incorrect.

The new user could overlook the lack of documentation and not be aware of all the inputs or assumptions being carried forward. Conversely, the user could notice undocumented model features (which may be valid) and decide to remove them.

There are two ways to document a model:

- In-model documentation– by adding notes within the model file to describe the model geometry, data input, and the basis for assumed component performance. Documentation can be attached to individual components, entire data sets, or both.
- Outside model documentation is placed in an electronic format or hard copy format in a separate file from the model input data. Good practice dictates that his file would be stored in the same folder as the model(s) or in a separate folder clearly labeled for model documentation.

In-model documentation is easy to update as the model is changed. However, the modeling software's method for accessing the documentation may not be straightforward, especially if notes are tied to components in data sets previous to the active data set. It is important to understand exactly how the particular modeling software graphic user interface presents data and what is the basis for the data displayed. For instance; what set of data inputs for the various components is being displayed and altered as you make changes.

Outside documentation provides much more control over formatting and organization, but it can be harder to update if many untracked changes were made to the model. It is generally good practice to keep both the documentation and the model open at the same time to encourage recording changes as they occur.

4.2 Complexity

A user may choose to make a model more or less complex depending on the desired output. A model that represents multiple trains of equipment (i.e. feedwater heaters, steam turbines) as one train is useful when the user is focusing on electrical output. More complex models with multiple trains are better when more detail is needed (or available such as plant instrumentation) and the performance of individual pieces of equipment, such as input flow rate and output temperature, is of interest.

4.3 Multiple Models

Rather than having a single model with alternate model configurations in different data sets, a plant may have a number of different models which contain major differences in model configurations or expected operating conditions. The description of each of the model types listed below describes the purpose of the model. The configuration in each of the models will vary depending on the circumstances. For example, an as-built model will vary from the design heat balance model due to changes that occurred during installation of equipment or changes in plant configuration that differ from what was provided to the turbine vendor or architectural engineering firm.

- Design Heat Balance Model – Useful for studying the effects of plant changes on MWe output
- As-Built Model – Provides a baseline for actual plant performance.
- Current Cycle Model – This can be based on either the Design or As-Built model using current plant operating data. Provides expected results at different conditions
- Troubleshooting Models – These models may have more complex configurations to study specific components.

It should be noted that having multiple models means that the user must revise and maintain multiple models if a change is made to the cycle that effects all models. Therefore, the creation and saving of duplicate models should be done with caution. If a model is no longer valid, it should be marked, such as “superseded”.

4.4 Updating a Model

Models will need to be updated for the following reasons:

- Plant Uprate
- Replacement of Major Components
  - High Pressure (HP) Turbine
  - Intermediate Pressure (IP) Turbine
  - Low Pressure (LP) Turbines
  - Nuclear Reheaters
  - Steam Generators

  - Feedwater Heaters
  - Pumps
  - Permanent Change In Operating Configuration

Models tuned to plant operating data must be updated if an input instrument is determined to be faulty. This could mean applying a specific correction to account for instrument error or using a completely new data set to re-tune the model. The user’s judgement with the specific modeling scenario will be necessary to select an approach.

4.5 Performance Based Versus Design Based Components

Modeling software can have multiple calculation methods for components. These are generally divided into two methods: 1) a “performance” mode where the performance of a component is determined simply by an energy balance around a component converging on a user entered performance parameter such as a Terminal Temperature Difference (TTD) in a Feedwater Heater, or 2) a “design” mode where performance of a component is calculated (i.e. TTD) based on fundamental thermodynamic or heat transfer equations appropriate for that component. Each mode is useful in different situations as long as the user is aware of their limitations.

In a model a component is considered to be performance based when performance parameters are directly input into the component data. This is sometimes referred to as a “black box” approach. Heat balances around the component assume the component always operates at the particular performance level. A good description of this is the use of TTD and Drain Cooler Approach (DCA) values as inputs for feedwater heater components. Extraction steam flow is calculated by the feedwater heater component and demanded from the steam turbine train in order to transfer enough heat to achieve a tube-side outlet temperature relative to the shell saturation temperature.

Performance based components reduce a models complexity: they use fewer inputs and are usually simpler resulting in fewer software iterations to achieve convergence to completion.

A component is considered to be operated in design mode when the performance data for the component is calculated from basic design information such as heat transfer surface area or pump impeller diameters. A good example is the feedwater heater TTD and DCA performance characteristics are calculated from the number of tubes, tube diameter and wall thickness, effective length, flow obstructions and other parameters. Extraction steam flow is calculated using all of these parameters in an iterative heat balance around the heater. For a design mode component the performance parameters are calculated whereas for a performance mode the performance parameters are a direct input.

Design components are helpful in “what if studies.” In a “what if” study the user attempts to determine the performance impact of a particular change. For example, a unit is considering taking a low pressure feedwater heater out of service for emergent maintenance. Prior to the maintenance they want to determine the impact on MWe output and change in extraction steam flow of the upstream feedwater heater.

Table 4-1 is an example of such a study, although there may also be other changes due to power limitations with a feedwater heater out of service.

Table 4-1
Example of a "what if" study

690 MW BWR Unit - FWH Study		FWH #14A In Service	FWH #14A Out of Service	Change
Gross MWe	MWe	688.5	687.1	-1.4
Final FW Temp	degF	397.8	395.9	-1.9
Final FW Flow	lbm/hr	8,339,428	8,318,170	-21,258
HPT Exhaust Pressure	psia	261.7	255.9	-5.8
Extraction Flow to FWH 14B	lbm/hr	111,826	112,045	219
Extraction Flow to FWH 15A/B	lbm/hr	589,657	747,003	157,346
Extraction Flow to FWH 13A/B	lbm/hr	474,802	432,562	-42,240

Design components add complexity to the model but may improve results for "what if" studies, since they react to changes in upstream and downstream cycle conditions. In general, they require more iterations of the model solution to converge to completion.

4.6 Performance Versus Design Models

A thermal model is considered to be a performance model when most of the components are performance based and the focus of the model is to compare predicted performance of a thermal cycle with the actual performance of the cycle. It is considered to be a design model when many of the components are design based and the focus of the model is to predict cycle performance with new equipment or a new operating point.

Most models used to monitor thermal performance and troubleshoot thermal performance issues are predominately performance models. Some performance models may use a design based component or components. For example, a performance model may contain a design based condenser to allow condenser performance to vary with changing load conditions or changes in circulating water temperature and flow.

4.7 Vendor Performance Curves

Performance curves are provided by equipment vendors of some components. Important curves for modeling include turbine exhaust loss curves, pump efficiency curves, turbine stage moisture removal curves, and valve loss curves. Implementing these curves in the model allows component performance to change with load and more accurately represent plant performance.

Centrifugal pumps typically have a pump curve provided by the manufacturer. The curves predict the pump efficiency and output parameters based on the flow rate and fluid conditions entering the pump. Data from a pump curve can often be input into pump component data. The benefit of using a pump curve is that pump performance is allowed to vary within the model based on changing input data conditions.

4.8 Model Tuning

Tuning a model refers to changing model geometry or component performance parameters to better simulate an actual operating condition. Typically it means adjusting the model so that the electrical output or heat rate of a model matches what is occurring in the plant. It can also be done at the component level so that equipment such as a feedwater pump matches actual operation.

Care must always be used when tuning a model to ensure that the correct parameters are tuned. For example, it is possible to make a model match actual plant electrical generation by changing the turbine stage efficiencies. This is correct if the turbine efficiencies are the issue, but is incorrect if the difference between predicted output and actual output is due to a limitation in a feedwater heater or a cycle isolation issue. Future studies using the model with incorrect assumptions could result in misleading output or a failure to converge.

It is also important when tuning a model that the data used to tune the model is vetted and that the location in the cycle corresponds correctly to the model input location. For example if the model is being tuned based on throttle pressure and the plant measurement point is upstream of the throttle the consequent throttle valve position will be incorrect due to the differences in specific volume based on the plant pressure location and the location assumed in the model.

In addition to instrument locations, sometimes selecting the correct data points can be an issue. For instance, many plant computers have multiple instruments and indications for condenser shell pressure and these instruments may not always be in perfect agreement. If the user selects a condenser pressure value for input to the model that has some bias or error it can have a significant effect on the model. Figure 4-1 illustrates the potential generation impact of a condenser pressure error.

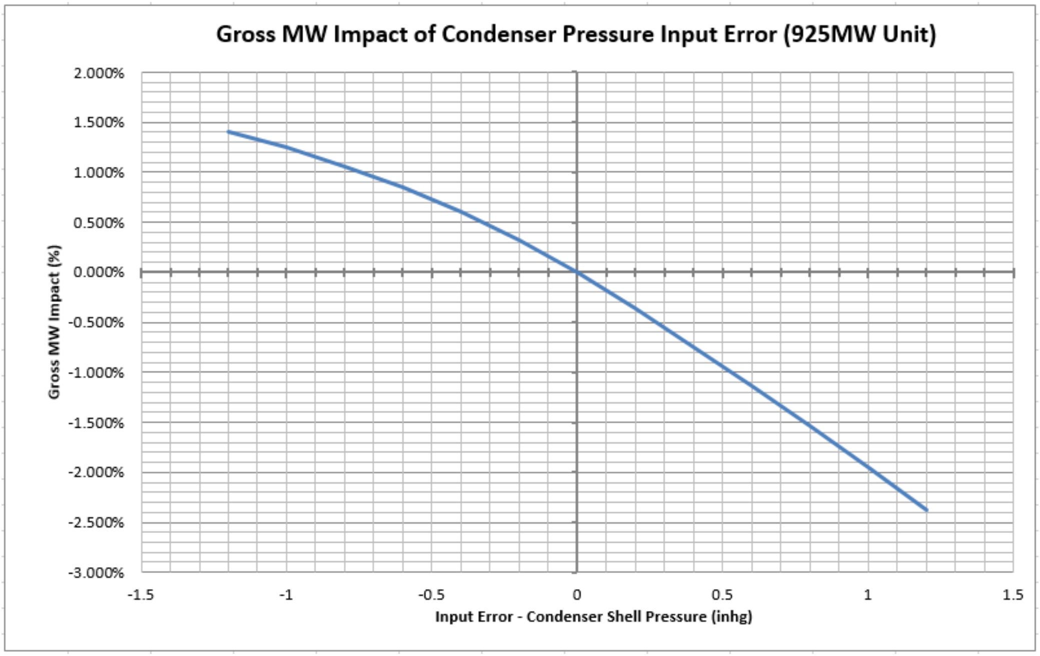

Figure 4-1
Example of potential generation impact of a condenser pressure error

4.9 Controls

Controls is a term used by some thermal performance software to describe user developed equations added to a model which will adjust the model to achieve a specific parameter value. An example would be varying the steam quality entering a model based on the amount of energy input into the model. Generically it is similar to using a solving function that manipulates an input to achieve a specific desired output, such as preloaded tools in spreadsheet programs.

4.10 Operations or User Developed Equations

Most thermal performance models have a methodology to integrate a user developed equation(s) into the model to either calculate a specific variable or to be used as a method to adjusting the model based on the desired equation.

4.11 Lower Load Models and Load Following

A thermal model is typically tuned to produce results for a given energy input or power level of the nuclear reactor. In a base loaded plant the power level is the maximum licensed core thermal power in a nuclear facility. With increased use of alternative energy sources some “base loaded” plants may eventually convert their mode of operation to “load following” which is modeled as the target lower required electrical output of the model. This means that the model must be able to float reliably at lower loads and a thermal cycle model may need to be validated at different power levels.

Care should be taken when modeling low loads as the software may not be stable below a certain threshold. Using a load-generalized model at 50% load when it was originally baselined for Valves Wide Open (VWO) or 100% load may not produce accurate results, especially if equipment is taken out of service at the lower load. Table 4-2 illustrates how a model can deviate at lower loads.

Table 4-2
Example of model deviation at lower loads

Reactor Power	Heat Balance Gross Gen:	Model Prediction (at Heat Balance Conditions)	Deviation
%	MWe	MWe	%
100	950.17	951.05	0.09%
75	729.24	726.24	-0.41%
50	480.42	475.03	-1.04%
25	220.97	211.10	-4.52%

5
MODEL USES

The following Section presents the various uses of thermal performance models. This includes using models for evaluating impacts of design changes, troubleshooting, sensitivity studies, and expectations for megawatt output.

5.1 Design Studies

A design study is the process of changing components in the model, or the performance parameters of a particular component (or set of components) to determine the electrical output or heat rate of a particular plant design. Design studies are used to produce information that can be used in the technical and economic evaluation process to decide on the best equipment to meet the objectives of the utility.

For example, a design study would be used to predict the performance gain from replacing the HP turbine of a unit. A design study could also be used to help make sense of vendor claims by modeling the proposed changes for an expanded view of how vendors' claims would impact the rest of the cycle.

5.2 Troubleshooting

Thermal performance software models are not designed to be used as a stand-alone troubleshooting tool. However, they can be used as a tool in conjunction with the implementation of a troubleshooting plan.

Thermal cycle problems can be effectively modeled when information is available about where in the thermal cycle the problem is suspected to be occurring. This information will come from the troubleshooting plan. Typical resources for a troubleshooting plan may include a unit trouble report, a MWe accounting program, or from the use of the EPRI Thermal Performance Engineer Handbooks [Ref EPRI[4] [5] [6]].

The troubleshooting model will be used to quantify the performance impact of equipment problems or validate that a particular problem exits. The impact of a problem is quantified by using degraded performance data from the equipment as input data to simulate the equipment problem. The results are compared to a baseline condition (design heat balance model or as-built

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[4] *Plant Engineering: Thermal Performance Engineering Handbook, Volume 1: Supersedes TR-107422-V1*. EPRI, Palo Alto, CA: 2013. 3002000560.

[5] *Plant Engineering: Thermal Performance Engineering Handbook, Volume 2*. EPRI, Palo Alto, CA: 2013. 3002000489.

[6] *Thermal Performance Engineering Handbook, Volume 3*. EPRI, Palo Alto, CA: 2015. 3002005346.

plant model) to determine the impact on electrical output or the performance impact on affected components.

A problem is validated by modeling equipment failure or equipment degradation and comparing the results of the model to actual plant data. If the model results match actual plant data the problem can be considered validated. Of course, all the usual precautions about coming to the wrong conclusion as listed in the EPRI Thermal Performance Handbook [Ref EPRI[7] [8] [9]] apply.

An example of quantifying a performance issue would be to input the number of plugged tubes of a heat exchanger into the model and using a “design mode” calculation to determine the impact of the plugged tubes on the TTD, DCA, heat transfer coefficient, or MWe output.

An example of validating a problem would be the failure of an extraction steam expansion joint bellows. If other plant indications point to a possible failure the software model can be modified to simulate the expansion joint failure. The results would be compared to actual plant data to verify the failure without shutting down the plant and opening a condenser for a physical inspection.

5.3 Sensitivity Studies

A sensitivity study is the method of determining the impact of a change of one input parameter on the model output results. Thermal performance software and models produce the theoretical expected sensitivity of a parameter; however, the accuracy of the predicted sensitivity depends on the accuracy of the model and the TP software internal calculations. Empirical data is useful in validating the sensitivity predicted by a model. Figure 5-1 shows a MWe vs Condenser Pressure curve predicted by a model along with actual plant data for comparison.

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[7] *Plant Engineering: Thermal Performance Engineering Handbook, Volume 1: Supersedes TR-107422-V1*. EPRI, Palo Alto, CA: 2013. 3002000560.

[8] *Plant Engineering: Thermal Performance Engineering Handbook, Volume 2*. EPRI, Palo Alto, CA: 2013. 3002000489.

[9] *Thermal Performance Engineering Handbook, Volume 3*. EPRI, Palo Alto, CA: 2015. 3002005346.

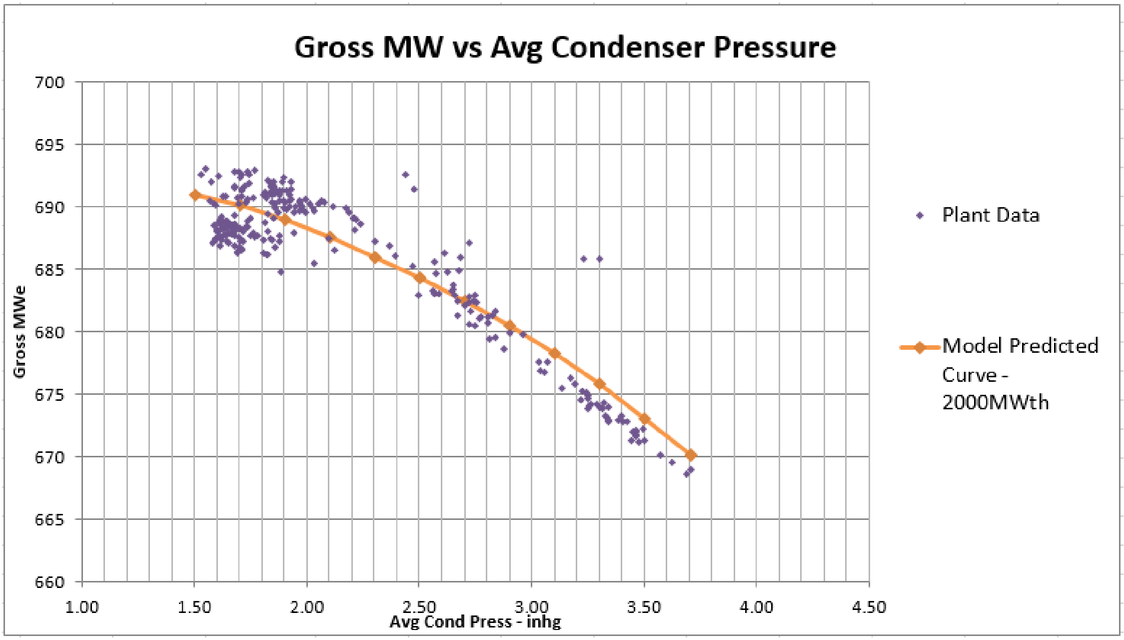

Figure 5-1
Megawatt versus Condenser Pressure Curve

Typically, a sensitivity study is used to determine the impact on electrical output by incrementally varying an input parameter of interest over a given range. For example, a user may be interested in determining the impact of final feedwater temperature on the electrical output. In this case the user would run a model multiple times, each time changing the final feedwater heater TTD by a fixed value such as 0.5 °F. This would produce a set of data at each final feedwater temperature which can be used to evaluate the effect on output or some other plant parameter such as heater shell pressure. In order to produce an accurate comparison the model must be set up to “float”. These studies can be performed by creating sets where the input parameter is changed incrementally or by using a built-in software option. When using the built-in option the user should be aware of the way the software handles the increments and other relevant inputs.

5.4 Daily Expected MW Output

A good model with the attributes listed in the previous section that is well tuned to a particular operating point and “floats” well can be used to predict daily performance given the ambient conditions, power level, and up-to-date plant conditions.

Operating Experience has demonstrated that a model must be revisited in order to ensure it is still correctly tuned to the changing operating conditions. Data collected automatically must be monitored daily to detect unexpected data problems. The following data problems are frequently encountered in automatic data.

- Missing data
- Data outside of expected operating conditions (due to maintenance, instrument failure, etc.)
- Changes in operating equipment line-ups

- Manually collected data such as reactor or steam generator outlet steam moisture content
- Data collected during short duration downpowers
- Changes in steam generator blowdown or reactor water clean-up

The model will have to be reviewed frequently to ensure it is modeling the actual operating condition. The frequency of the review will depend on several factors including frequency of use such as weekly or monthly and historical susceptibility to problems. A model used every day may need to be checked weekly but a model used once a month or less should be checked with every use. Once a deviation between the model's expected MWe output and actual plant MWe output is found, additional troubleshooting is required to determine where the loss is occurring.

Many plants use a spreadsheet based system to predict daily output rather than TP software models. Both methods are subject to producing misleading results. The misleading results may be due to input data errors, changes in the operating point, and the accuracy of sensitivity curves such as circulating water temperature versus MWe output.

5.5 Non-Standard Components

Most thermal cycle software contains standard components such as a pumps, feedwater heaters or turbine sections that can be grouped together to form a model. These standard (pre-made) components reduce the complexity of a model and simplify data input. A non-standard component in a thermal cycle model consists of several standard components being grouped together to simulate a component in the plant or the use of a standard component in a different way to simulate a plant component.

For example, in a nuclear power plant a software package may contain a standard component that represents a moisture removal component such as the moisture separator reheater (MSR). However, the moisture removal component can also be used to represent a heater drain tank that flashes off steam through one port and saturated liquid in a separate port. Sealing steam systems are often modeled as a series of mixing and splitting components bypassing the turbine components.

5.6 Sub-models

A sub-model is a small model of an individual component or group of components in a thermal cycle. Typically it would not include a turbine or electrical generator component. The ability to produce a sub-model will depend on the software used. The advantage of a sub-model is that it allows the user to focus on a specific component and specific set of inputs and assumptions. It simplifies the troubleshooting of particular component and reduces the output data which decreases the amount of time needed to interpret the results.

A good example of a sub-model would be the tuning of a design mode heat exchanger component, such as a feedwater heater or condenser, to match its design performance as shown on an equipment specification. Once the heat exchanger model is developed in the sub model, it can then be placed into the turbine cycle model.

6
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1. Steam Turbines and Their Cycles, J. Kenneth Salisbury, 1950
2. Steam Turbine Performance and Economics, Robert L. Bartlett, 1958
3. A Method for Predicting the Performance of Steam Turbine-Generators…16,500 KW and Larger, ASME Paper No. 62-WA-209, R. C. Spencer, K. C. Cotton and C. N. Cannon, 1962Please add references here
4. *Plant Engineering: Thermal Performance Engineering Handbook, Volume 1: Supersedes TR-107422-V1*. EPRI, Palo Alto, CA: 2013. 3002000560.
5. *Plant Engineering: Thermal Performance Engineering Handbook, Volume 2*. EPRI, Palo Alto, CA: 2013. 3002000489.
6. *Thermal Performance Engineering Handbook, Volume 3*. EPRI, Palo Alto, CA: 2015. 3002005346.

A
QUALIFICATIONS

A.1 Attributes

Users of Thermal Performance Software need a fundamental understanding of thermodynamics, the turbine cycle and a specialized skill set to accomplish the task effectively. These specialized skills are developed through software training and on the job experience. Appropriate training and experience combined with high frequency of use helps users to become proficient and get the most from their models.

A.2 Expertise

Expertise is gained through training and experience. The following expertise levels help the utility user and their manager to determine the appropriate training and experience necessary to use and maintain a plant model. NOTE: The following expertise levels refer to utility users, but may apply to a third party contractor.

- Novice Level
- Competent Level
- Expert Level

Table A-1
Novice User Level

Novice Level
A novice user will be capable of the following actions:
Identify the type of thermal performance software used at their plant and when it was last updated
Identify the location of the various models in the plant filing system
Identify the purpose of each of the models
Identify the requirements of the plant software control procedures
Identify the basic building blocks of a model, equipment nodes and connectors
Demonstrate an understanding of the minimum input data in a model and the location of the data
Be able to run an existing model and understand the basic output
Make changes to input data on the model
Use the model on an annual basis

Table A-2
Competent User Level

Competent Level
A competent user will be capable of the following actions:
Perform all of the actions of a Novice user
Make simple changes to model construction to simulate a problem in the plant such as leakage through a feedwater heater alternate drain to the condenser
Utilize advanced functions of the software to perform additional calculations and functions
Update a model to include retrofitted equipment
Use an external software interface (if software is capable) to aid in running multiples models or sets
Use the model at least 4 times per year

Table A-3
Expert User Level

Expert Level
An expert user will be capable of the following actions:
Perform all the actions of a competent user
Build a new model from vendor heat balance diagrams
Build a model of the as-built and as-operated plant
Use advanced features of the user's software (if available)
Use basic design details of a piece of equipment in a model in conjunction with software features (if available) to predict the equipment performance
Perform design studies to assist in developing specifications of new equipment
Develop an external software interface for running the model
Use the software at least one per month

A.3 Training

- For a Novice User completion of a commercially available initial training class on the use of the thermal performance software is recommended. Initial training classes generally help the user to become familiar with the specifics of building a simple model and learning how to run and troubleshoot the model.
- For a Competent User advanced training is recommended. Advanced training focuses on learning to build and run more complex models. It also covers the use of more advanced application of the software such as use of design models, performance of sensitivity studies, troubleshooting, and daily MW monitoring. Advanced training is often offered by the software vendor and 3rd party contractors.

- Work experience provides the practice necessary to become proficient in the use of thermal performance software and models. Tasks such as breaking a single line of feedwater heaters into two trains to represent actual plant configuration provide invaluable lessons and an established baseline to check work.

A.4 Training Resources

A.4.1 Thermal Performance Software Developer

The developer of the plant thermal performance software may periodically offer training classes for new and advanced users. Contact the software vendor for more information.

A.4.2 Consulting Party Support

Architecture/Engineering firms, independent contractors, and industry expert users may offer support and training for thermal performance modeling software. Contact industry peers for the names of firms or individuals currently offering training.

B
MODEL CONFIGURATION CONTROL

Configuration control of a model includes four elements, intent of the model, documentation of initial base values, documentation of initial model geometry (components and connections), and documentation of changes. Good documentation enables a user to find a model quickly, review revision history, and determine the status of the input data.

B.1 Documentation

B.1.1 Heat Balance Values

Data take directly from a vendor heat balance diagram or thermal kit should be documented in the model with comments. For example the source document of the HP turbine pitch diameter should be documented in the model if possible, or the input data file, or in a separate documentation file included in the file folder. Providing documentation in an input data file or separate documentation files may be easier to tract and review, but are also easier to lose as a software model changes owners.

B.1.2 Plant Data Values

The following data should be included in the input data file, if possible, or in a separate document included in the same folder as the input data file.

- Date and Time Of Data Collection
- Data Averaging Interval
- Plant Data instrument tagnames
- Plant operating conditions, such as power level, load, MW output, etc.

B.1.3 Model Configuration

The following information should be included in a documentation file (if available and applicable) or the source of the information should be noted in an appropriate location.

- Valves: stop, intercept and control valves: types, pressure drops and positions
- Turbine admission mode: Full arc, partial arc, etc.
- High pressure turbines: Stage efficiencies, governing stage pitch diameter (or calculation thereof), pressure/flow functions, number of ends, and type of turbine rotor
- MSRs: pressure drop, moisture separator efficiencies, reheater TTDs, hot reheat temperature, number of drain tanks, etc. or reheater design mode inputs

- IP turbines: Stage efficiencies, pressure/flow functions, internal HP-IP leakages, and number of ends
- Low pressure turbines: stage efficiencies, pressure flow functions, last stage blade length or annulus area, number of ends, type of turbine, number of moisture removal stages
- Generator: mechanical and electrical losses, power factor
- Condenser: Shell pressure, amount of subcooling or design mode inputs
- Condensate/Condensate Booster Pumps: number and pump curve (efficiency and head) information
- Feedwater Heaters: design TTD, DCA, and Temperature Rise or design mode inputs
- Main Feedwater Pump and Feedwater Pump Turbine (if used): Pump and turbine efficiencies, pressure rise, exhaust pressure (Feedwater Pump (FP) turbine), types and numbers

B.2 Organization of Model Files

The following figure is a sample of a generic file structure that can be used as the starting point for a user to organize and store TP models.

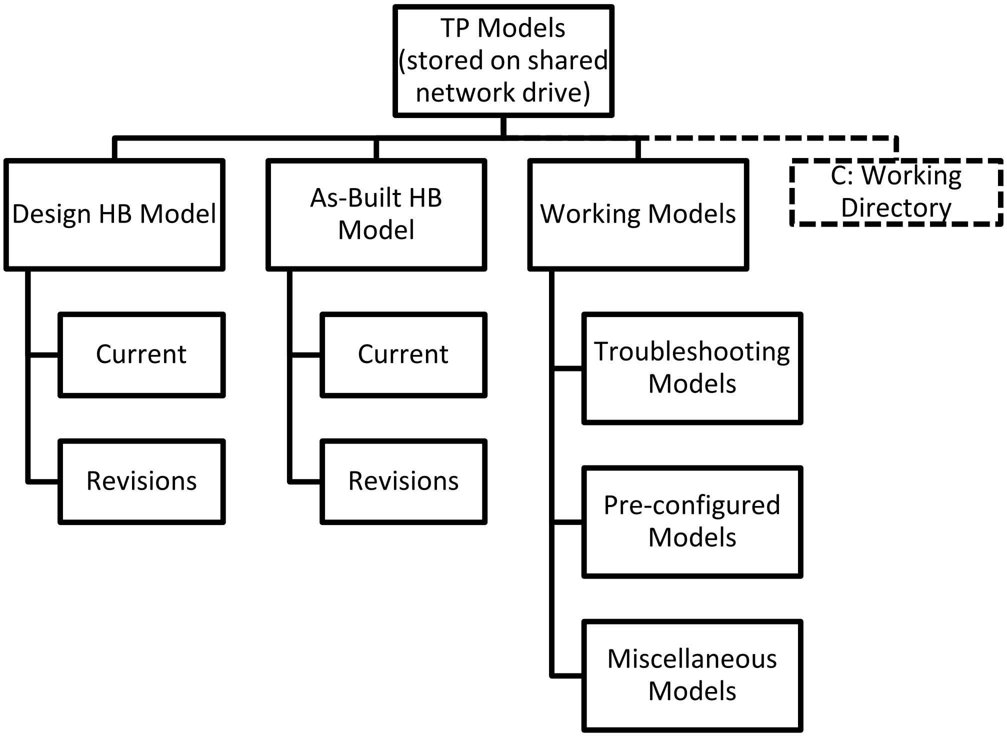

Figure B-1
TP Model File Structure

C

DEVELOP/MAINTAIN A MODEL OF THE DESIGN HEAT BALANCE

Every plant should have a thermal performance software model of the most recent design heat balance. When developed this model becomes the basis of the other TP software models. Developing and testing a model is a labor intensive activity of building a model from scratch and may be done by utility engineers or a 3rd party.

The goal of a Design Heat Balance model should be to match the most recent design heat balance. If the heat balance differs from the current operating or as-built condition of the plant, these changes should be applied after the Design Heat Balance model is completed and kept as a separate set of inputs or model (see Appendix D: Develop/Maintain a Model of the Baseline Data With As-Built Plant Design).

C.1 Qualification Required

An Expert Level of expertise or higher is required to build and tune a Design Heat Balance TP software model. (See Appendix A: Qualifications)

C.2 Model Development

1. Obtain The Turbine Vendor Design Thermal Kit
    a. The first step in developing a thermal performance software model is to obtain the most recent thermal kit for the unit. If plant changes have occurred that are not reflected in the thermal kit such as a change in HP or LP turbine rotors or other components, then the ability to develop a design model is made more difficult. If operational changes like a power uprate with no component modifications have occurred, then the original thermal kit can still be used to develop the initial model.
    b. Find the full load heat balance and a valves wide open (VWO) heat balance that represents the maximum steam inlet flow/energy into the thermal cycle.
    c. Find the guaranteed heat balance at the plant design thermal power.
    d. The first model built will be based on the VWO heat balance and once the configuration and parameters match the VWO heat balance, changes are incorporated to produce a guaranteed heat balance. If there is difficulty in matching both conditions the focus should be on matching the guaranteed heat balance over the VWO heat balance.

2. Build A Simple Flow Model

    a. Typically, a design heat balance from a turbine vendor or architect/engineering firm will be a simple flow model. (See Figure C-1)

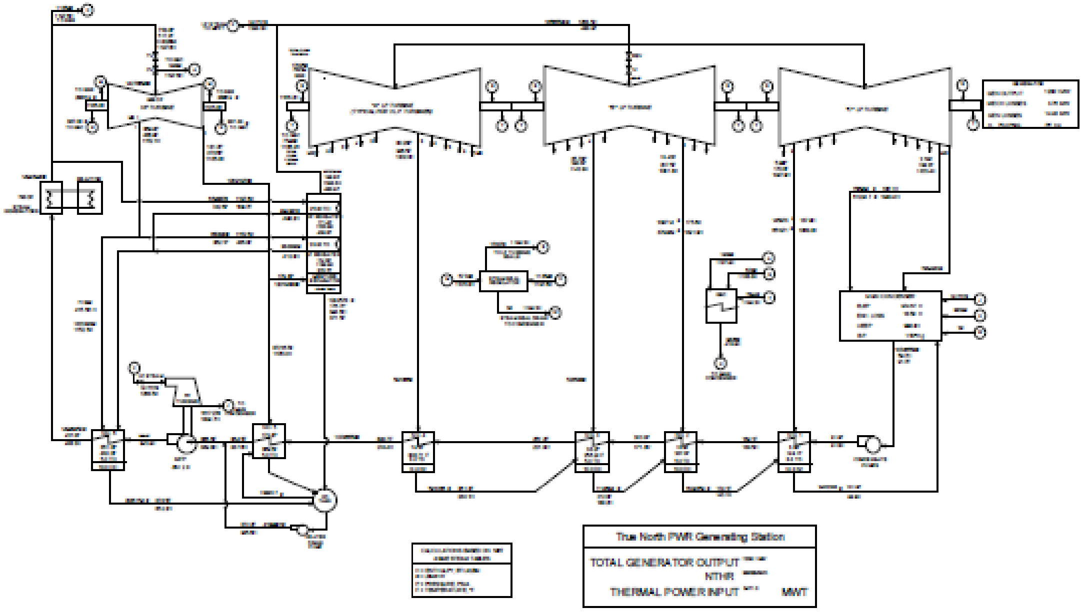

Figure C-1
Generic example of a simple flow model

    b. Using information from the software construct a single line flow diagram of the major components as shown on the heat balance diagram.

3. Add Heat Balance Design Data Into The Flow Model

    a. Use simplified/performance mode for major components.
    b. List of Heat Balance data that may be needed for the model:

        i. Main Steam – Boiler/Reactor/Steam Generator outlet conditions (flow, pressure, enthalpy/quality/temperature)
        ii. Feedwater Heater data – TTD and DCA values
        iii. Pump Data – outlet pressure, efficiency/enthalpy rise
        iv. Feed Pump Turbine – exhaust pressure, turbine efficiency
        v. Pressure Drop Data – Any steam line or component where pressure values are given: Main steam, reheat steam, extraction steam, MSR drain lines, etc.
        vi. Reheater Data – Hot reheat temperature or TTD value, tube/shell pressure drops
        vii. Moisture separator - efficiency, pressure drop
        viii. VWO or 100% power data if needed for initial guesses
        ix. Turbine inlet valve volumetric flow data at VWO
        x. Turbine data - HP turbine pitch diameter, LP turbine exhaust area, pressure/flow functions, stage efficiencies or conditions.
        xi. Generator Data: Mechanical and electrical losses, hydrogen pressure, power factor
        xii. Condenser - shell pressure

4. Add more detail to model turbine components
    a. Determine LP turbine exhaust losses
        i. Thermal Kit will often include an exhaust loss curve developed by turbine vendor
    b. Locate turbine moisture removal effectiveness curve
        i. Thermal Kit will often include this curve developed by turbine vendor
        ii. Heat balances at various loads can also be used to calculate moisture removal effectiveness at different loads/flow conditions
    c. Vendor stage group efficiency and expansion line shape
        i. Lower load heat balances can be used to determine how each stage efficiency changes with load
    d. Modeling turbine performance can be done in several different ways depending on the TP software being used.
        i. Use calculation for the particular vendor if available in the software.
        ii. Insert stage group efficiencies
5. Get Model Running
    a. Check all connections between equipment components are correct. The TP software may or may not produce alarms or error messages to help locate problems.
    b. The turbine stage groups may cause a problem and outlet conditions may have to be adjusted to get a model to converge.
    c. Throttling valve pressure drop may need adjustment to get the inlet conditions on the HP turbine in a range that the model can iterate to a solution.
    d. Initial estimates (or guesses) for extraction steam flow may need to be adjusted. Using the flow values on the Heat balance may help the model to iterate to a solution.
6. Tune Model To Match Heat Balance Output
    a. Check to ensure the TP model is using the same energy input into the cycle as the heat balance.
    b. Match condenser pressure through direct input into the model.
    c. Check feedwater heater TTDs and DCAs and nuclear reheater TTDs on the heat balance are calculated correctly and use those values in the TP model
    d. Some modeling products have tools to aid in the development of the correct inputs for the turbine stage sections. Sometimes using trial and error steps are necessary to match the flows, pressures, and enthalpies on the heat balance with the TP model.
    e. Check the generator portion of the model to ensure the same mechanical and electrical losses are being used as well as the power factor and hydrogen pressure assumed on the heat balance or thermal kit.

   f. A model will may never match a heat balance perfectly. The level of agreement depends on the amount of detail used in baselining the performance of each component. As mentioned above it is most important to match the 100% guaranteed load. Best practice values for a good model:

      i. Match HP Turbine pressures: +/- 0.5 psia
      ii. Match IP Turbine pressures: +/- 0.25 psia
      iii. Match LP Turbine pressures: +/- 0.1psia
      iv. Try to match enthalpies within 0.5 Btu/lbm
      v. Match extraction flows as close as possible
      vi. Match Gross MWe within +/-0.1%

7. Create “floating” or load generalized model

   a. Model low load heat balance diagrams in addition to VWO and 100% load. Loads as low as 25% are typically provided in thermal kits. It is often difficult to achieve a good match at the 25% load because of the difference in full power and lower performance characteristics of thermal cycle components. At low loads it is difficult to predict turbine efficiencies, pump efficiencies, and feedwater heater performance. Also, the vendor assumptions about equipment taken out of service at low loads may differ from plant practices.
   b. Build performance tables or curves for input variables that change between loads (for load generalization).
   c. Set the model components to interpolate input values from the performance curves based on modeled conditions instead of using static values. Typical curves include:

      vii. Turbine stage efficiencies
      viii. Turbine moisture removal stage moisture removal effectiveness based on extraction pressure
      ix. Turbine exhaust losses
      x. Generator electrical losses
      xi. Main turbine inlet valve throttling losses
      xii. Turbine leakoff flows

   d. Check that results at all modeled loads still match the heat balances.
   e. Add an input for the total power input to the cycle (Reactor thermal power, boiler heat duty) for each different load set. This sets the thermal power constant.
   f. Check that results at VWO, 100%, and low loads still match the heat balances with thermal power held constant.
   g. Check that results at one or two different loads between heat balance conditions make sense.

8. Save The Model

   a. The Design Heat Balance model should be saved in a location where it is protected from changes. Copies of the model that can be modified for monitoring or troubleshooting should be saved in a different set of folder. (Appendix B: Model Configuration Control).

C.3 Model Maintenance

Once the Design Heat Balance model is developed and tuned properly it should not require any maintenance. The model will need to be revised if a significant change is made to the thermal cycle and an updated heat balance is issued. Examples of significant changes would be a power uprate, a major change in the steam conditions, new turbine rotors with enhanced design, or a feedwater heater or reheater replacement.

D

DEVELOP/MAINTAIN A MODEL OF AS-BUILT PLANT DESIGN AND PERFORMANCE

Every plant should have a heat balance model of the baseline as-built plant. When developed this model becomes the basis of the other TP software models that can be used for monitoring and troubleshooting performance. Developing and testing this type of model is a labor intensive activity of building a model from scratch or modifying an existing Design-based model and may be done by utility engineers or a 3rd party.

An as-built model will be the baseline of other models for monitoring or troubleshooting; consequently, it should model all significant equipment drains and bypasses as well as all major equipment, including multiple trains. This addition of equipment and flow paths will increase the complexity of the model and also increasing the number of iterations before convergence. Special care will be required to split the design flows appropriately keeping in mind the impact on pressure drops. It is often a good practice to use plant P&IDs to verify plant configurations which are not detailed in turbine vendor heat balance diagrams.

The benefit of building a complex model is that it provides the ability to model the impact of a single piece of equipment. In actual operation, it is likely that one piece of equipment will experience degradation but the same piece of equipment in parallel trains will not degrade at the same time. A complex model will allow this exact situation to be modelled accurately.

D.1 Qualification Required

An Expert Level of expertise or higher is typically needed to build and tune an As-Built TP software model. (See Appendix A Qualifications)

D.2 Model Development

1. Begin With The Design Heat Balance Model
    a. The first step in developing an as-built TP software model is to locate and validate the latest design heat balance model.
    b. Changes should be made iteratively. Run the model after completing each major component change to ensure the model is working correctly and the results still make sense. This saves time trying to determine which change or combination of changes is producing errors.

2. Build A Complex Flow Model
    a. Split components to match the actual plant configuration.
        i. Common equipment to split includes steam turbines, feedwater heater trains, condensers, moisture separator reheaters (MSRs), and pumps.
        ii. Most thermal kits only show one combined train. Care should be taken with flow values when modifying the design input data.
        iii. Carefully consult plant P&IDs for actual flow paths through multiple trains of equipment. Some plants combine feedwater outlets between LP and HP heaters, or sometimes different LP heaters.
    b. Compare results from the modified model to the original Design Heat Balance model. They should be very close.
        i. The model solving process converges when mass flow and energy changes between iterations are below pre-defined thresholds. Because of this it is impossible to produce identical results between the Design Heat Balance model and the Complex Flow model.
        ii. As a best practice the changes in pressures, temperatures, enthalpies, and flows should not be more than about 0.01%.
    c. Additional components not typically modelled in heat balance models can be added but the increased model complexity may not be worth the trouble depending on the software's ability to accurately model the component and available design data. Typical additional components include:
        i. Nuclear steam generators
        ii. Blowdown heat exchangers
        iii. Cooling Towers (only beneficial to Design Mode condensers where the circulating water inlet temperature is determined by ambient conditions)
        iv. Auxiliary steam/water.
3. Make Changes To Match the As-Built Plant Performance
    a. An additional input data set after the design data set should be added for modifying component parameters.
    b. Components can be modified using a separate input referencing the component variable instead of duplicating the entire component.
4. Get Model Running
    a. Check all connections between equipment components are correct. The TP software may or may not produce error messages to help locate problems.
    b. The turbine stage groups may cause a problem and outlet conditions may have to be adjusted to get a model to converge.
    c. Throttling valve pressure drop may need adjustment to get the inlet conditions on the HP turbine in a range that the model can iterate to a solution.
    d. Initial guesses for extraction steam flow may need to be adjusted. Using the flow values on the design HP balance may help the model to iterate to a solution.

5. Tune Model With Test Data
    a. Filter all test data for faulty instruments and plant equipment problems. Data should not be a snapshot; but averaged data to reduce error. The As-Built model should model the plant as closely to test conditions as possible in order to establish baseline performance.
    b. Use test data to set model parameters in the As-Built set. Parameters to change include:
        i. Turbine stage efficiencies (if available) – sometimes iterated to achieve actual generator output
        ii. Turbine pressure/flow functions – sometimes iterated to get measured extraction pressures
        iii. MSR TTDs
        iv. FWH TTDs and DCAs
        v. Condenser pressures
        vi. Condenser subcooling
        vii. Cooling/Circulating Water inlet temperature and flow
        viii. Total heat input into the cycle (Reactor/SG thermal power)
        ix. Main Steam pressure, temperature, and quality
        x. Hot Reheat temperature (if applicable)
        xi. Pressure drops (valves and piping losses)
        xii. Generator power factor and hydrogen pressure
    c. The only forced pressures and temperatures should be at the heat source (reactor or Steam generator) and the heat sink (condenser or cooling tower). All other input parameters are relative performance indicators. The model will not float correctly if, for example, if turbine bowl/shell pressures are input directly.
    d. Turbine extraction line pressure drops to the feedwater heaters can be used to better match measured heater shell pressures. To ensure pressure drops will adjust correctly with absolute pressure changes the pressure drops should be based on a volumetric methodology which adjusts for the change in specific volume.
    e. Use trial and error to match the MWe output and measured pressures, temperatures, and flows from the test data. Check the generator portion of the model to ensure the same mechanical and electrical losses are being used as well as the power factor assumed on the heat balance. It may not be possible to accurately match the MWe output based on test data as there is typically some inherent error in the measurements.

6. Change Performance Mode components to Design Mode
    a. Making the switch to Design Mode should be performed after initial tuning to avoid hiding modeling errors Design Mode tuning variables.
    b. Design mode allows components to react to model changes instead of operating at an assumed performance level such as a FWH TTD or condenser pressure.
    c. Design information can be found in equipment specification sheets and design drawings.
    d. Some software packages offer a simplified design mode for some components to reduce the amount of input data required. The benefits of a full design mode are often outweighed by time and labor required to obtain the high number of inputs that may not be on the specification sheet and thus need to be measured manually.

   e. Typical components to use in design mode:
      i. Feedwater Heaters
      ii. Condensers
      iii. MSR’s
      iv. Pumps
      v. Other heat exchangers such as nuclear Steam Generators
   f. Design mode components make the model more complex to solve and thus more prone to errors or convergence problems. Some software packages allow design mode components to be modeled as performance mode components for a certain number of iterations to allow the other components to stabilize.
   g. Design mode components can be tuned to the measured performance levels from the test data, such as FWH TTDs. Heat transfer coefficients or tuning factors can be calculated by the software. These are entered into the component configuration and the tuning assistance disabled to complete tuning the component.
   h. Results should match those from the Performance Mode set once design tuning is complete. The ability to match is dependent on the quality of the plant data.

7. Save The Model
   a. The as-built model should be saved in a location where it is protected from changes. Copies of the model that can be modified for monitoring or troubleshooting saved in a different set of folders. (Appendix B: Model Configuration Control).

D.3 Model Maintenance

Once the model is developed and tuned properly it should not require any maintenance. The model will need to be revised if a significant change in performance of existing equipment is apparent or a modification is made to the thermal cycle.

E

INPUT DATA VALIDATION METHODS

Data validation is one of the most overlooked factors required to achieve valid results. The use of automated data collection greatly increases the amount of data available and provides better modeling opportunities. However, it also increases the chance of invalid data being used in the model leading to less accurate results.

E.1 Common Data Problems

- Incorrect engineering units
- Gage vs. absolute pressures
- Data out of range
- Data points are “frozen” or overwritten with a constant or “bogey” value
- Historical data collected from archive systems with exception processing filters (data not archived if within defined minimum/maximum boundaries)
- Data value is missing from data set
- Data value is incorrect due to instrument drift, degradation or failure
- One instrument used in a group average or flow calculation fails
- Data collected from more than one data acquisition source or manual entry with mismatched collection times
- Instanteous data “snapshots” or averaged data collected over a long duration (i.e. daily average)

Several methods are available to assist the user in finding invalid data in data set.

E.2 Familiarity with Data

As a user gains more experience in trending and monitoring plant data they become familiar with the valid ranges of the various parameters. This familiarity helps them to scan through data quickly finding in valid data. Knowledge of how data collection software works and where it comes from is important and helps detect the cause of suspicious data. Also, it’s very helpful to know what alternative sources of data might be available.

Often data point failures result in steam table values produce calculated performance values that are outside of the laws of physics. TP software can produce results outside of the laws of physics such as negative feedwater heater drain flows due to bad input data. TP software will sometimes produce error messages about calculated equipment conditions that are not possible. The values are often difficult to check because the actual error shows up in later calculations.

E.3 Data Filter

A data filter can be used to check if each data point falls within a valid range. These types of filters may be developed by the user, or an outside vendor.

E.4 Two Sigma Data Trending

Another method to validate data, if historical data is available, is called the two sigma data check. Two sigma represents 2 standard deviations and a 95% confidence interval. This method involves calculating the average data value and standard deviation of the data set of a particular point. The last collected data is checked for validity by checking to see if it falls outside of the two standard deviations of the average.

This method can also be used to detect flat line data due to “frozen” data or manual override of a particular data point. Many times these points are in an expected range and it is very difficult to detect a problem using other methodology.

Depending on instrument accuracy and location this may not be a reliable indicator due to excessive measurement noise. Additionally, care should be taken when selecting an averaging interval for certain measurements. Circulating water temperature varies with environmental conditions, and doing a two sigma analysis on 6 months of data would hide some outliers due to the normal change due to seasonal changes.

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