Power Uprate Studies for Nuclear Power Plants Using PEPSE - Lessons Learned
Update 2

William C. Kettenacker
SCIENTECH, Inc.
P.O. Box 292606
Lewisville, TX 75029

Power Urate Studies for Nuclear Power Plants Using PEPSE - Lessons Learned Update 2

by
William C. Kettenacker
SCIENTECH, Inc.

Abstract

In recent years many nuclear plants have investigated and implemented changes to their plants in order to obtain more electrical generation. In some cases the changes have included an uprate to their licensed reactor power levels, in other cases it has been a change in equipment in their secondary system (turbine cycle), and in many cases it has been a combination of both. In order to investigate these changes before they are implemented, many have used the PEPSE (Performance Evaluation of Power System Efficiencies)[1] energy balance software to simulate these changes and determine ahead of time the plant response to these changes. Key lessons have been learned in implementing model simulations, interpreting and using plant data, and applying the results.

Introduction to Update 2

This paper was originally published in 2002 and was based on the author's experiences in developing, modifying, and/or using PEPSE models of nuclear plants in their application for power uprate studies up to that time. Since then, more experience has been gained in developing PEPSE models for these studies. The first update to this paper, released in mid-2003, reported additional experiences gained in the year following its first release. Now a second update offers further experiences, applications, and knowledge gained in this area.

Where's My PEPSE Model?

Almost every plant has a PEPSE model. Sometimes it is a recently-constructed model using the latest version of PEPSE; sometimes it is an old "mainframe" model with the graphics hand-drawn on a piece of paper. Some models have been developed by the current performance engineer and reflect the latest heat balances or plant data. Others have been modified over the years by many people who have come and gone, and no one knows what's "in there" anymore. The best approach – if the model cannot be verified as "current" by the plant performance engineer who has a good working knowledge of PEPSE, then build a new model from scratch using the latest turbine vendor's heat balances.

Developing a Base Model

The first step is to secure or develop a base PEPSE model that can be verified against some standard performance. This standard performance is usually the original turbine vendor heat balance diagrams at several loads or the "new" turbine vendor heat balances produced by the new turbine vendor (if new turbines are to be part of the power uprate effort). It can also be the plant performance measured during a recent performance test, or simply data collected on a day-to-day basis. Tuning the model to actual data is sometimes called the "as-built" plant model. If the power uprate is to be done in several steps, i.e., power uprate first followed by the installation of new turbines later, then the first step in the development of the base model would be based on the original turbine vendor's heat balances (not the new turbine vendor turbine performance characteristics found on the new turbine vendor heat balance diagrams – that process is described later).

When developing the base PEPSE model, a "one-line" model (single string of turbines, single string of feedwater heaters) is acceptable, but a more rigorous model may be required if the model is to be tuned to actual plant data in the future, i.e., an as-built plant model. In addition, a one-line model will not adequately simulate the effects of different condenser pressures if the plant has a multi-zone condenser (or multiple condensers) with each zone or condenser at a different backpressure.

Modeling both "ends" of a double-flow HP (high pressure) turbine and each "end" of all the double-flow LP (low pressure) turbines ensures the greatest detail, but this is also the most complicated. In some cases this is not justified. Experience has shown a good compromise is to represent a double-flow HP as a single string of PEPSE turbine components and each double-flow LP as its own string. Ultimately the heater arrangement and the extraction arrangement will dictate the best approach. For example, if the HP extractions from each end of the HP turbine are connected in some type of header arrangement before splitting to the high pressure heaters, there is no need to separate the HP turbine ends. Their effects are "mixed" and separating them will tell you nothing unique. If, however, the extractions do not mix but instead go directly to separate heaters, then modeling separate ends of the HP may be of benefit. Figure 1 shows several ways to model the turbines.

If the model is to be tuned eventually to actual plant data, all feedwater heater strings should be included. This will allow for the differences in heater data and heater performance for each heater in the different strings.

The level of modeling complexity for the other components in the model is variable and should be evaluated based on their thermodynamic impact. One example would be pumps. Including all condensate pumps and all circulating water pumps does nothing to enhance (or hinder) the thermodynamic calculations. This may not be the case for main feed pumps, especially if they are turbine-driven, because the steam supply may vary based on individual pump and turbine performance. Another example is valve components, which are not needed to accurately represent the thermodynamics of the model. It is true that valve components can be used to simulate pressure drops and also

can be opened or closed to allow flow to pass or be cut off, but these same effects can be obtained using a stream. Using a stream for pressure drops or shutting off flow is simpler than using a valve. With all this said, the "political factor" should be considered when deciding to include components or not. Usually someone in management must be "sold" on the PEPSE results. A more detailed model rather than a simpler model may be a better way to do this.

Vendor Diagram
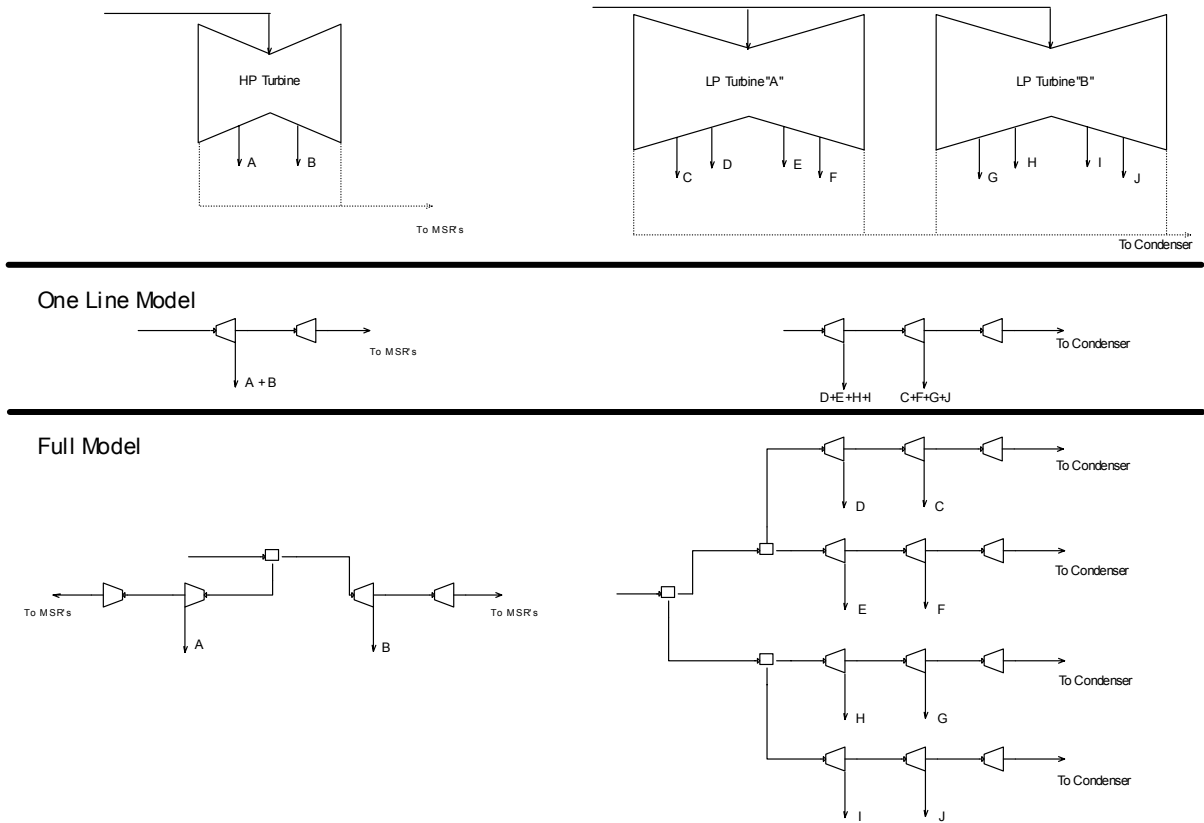
One Line Model

Full Model

Figure 1
Turbine Modeling Options

Where available in PEPSE, the components should be characterized using the design mode input option. By enabling these basic-principles formulations to calculate the performance for these components automatically, this option gives the model greater flexibility with changing load, changing operating conditions, or changing inlet boundary conditions. It is easier to do this using the design mode rather than using the performance mode input option. The design mode requires input data that describes hydraulics and heat transfer rather than just gross performance parameters. In most cases, after preparing a component's design mode input, the user must "tweak" or adjust the

calculations to match a specified performance because PEPSE does not have the component's specific operational calculations for each equipment manufacturer. PEPSE's design mode calculations are based on industry-standard first-principles calculations that adapt with variations in operating conditions but do not necessarily match a particular component vendor. The adaptation of the design mode calculations using adjustment factors allows PEPSE's performance to match that of the manufacturer.

Turbine types 1-3 automatically invoke the design mode for the turbines. As with all design mode components, PEPSE's turbine calculations for types 1-3 are based on a particular set of procedures and must be adjusted to match the performance of your turbines. These adjustment factors are called efficiency multiplying factors and expansion line shape factors. Type 8 (general) turbines may be used in lieu of types 1-3 and do not require adjustment; however, type 8 turbines (performance mode turbines) do not offer the load generality that types 1-3 offer.

PEPSE allows several options for the feedwater heaters in the design mode. It is recommended that the Simplified Design Mode be used. The inputs are easier than the other design mode options while offering the same calculational accuracy. There are many adjustment factors for the feedwater heaters in the design mode but the most common is a multiplying factor on the overall heat transfer coefficient.

Condensers should be modeled using the HEI[4] design mode option. This is discussed in more detail later.

At the time of the original writing of this paper, the use of the design mode for nuclear reheaters was not recommended. Its design mode calculation did not offer the flexibility needed to model the complex reheaters of today. However a later release of PEPSE, Version 67, released in the fall of 2002, remedied this and is discussed in more detail later in this paper.

Miscellaneous heat exchangers may also be modeled using the design mode input option. However, finding all the required input data may be difficult. Generally, modeling them in the performance mode does not diminish the flexibility or accuracy of the model.

Base Model Using Original Turbine Vendor Heat Balance Diagrams and Thermal Kit

Using the original turbine vendor's heat balance diagrams and thermal kit is the most common method of developing and tuning a base PEPSE model. This information is readily available and the model has usually been developed previously. This model should match the vendor's heat balances at several loads, most importantly VWO (valves wide open) and 100% power. Loads that match to within 500 kW and thermodynamic properties that match to within 0.25% are considered good.

Usually all of the data required by PEPSE for this type of model are found on the heat balances or in the thermal kit. Missing data can be obtained by contacting the turbine

manufacturer or by making educated guesses based on knowledge of the system and previous modeling experience.

If the base model is to be developed using the original turbine vendor heat balances and thermal kit only and will not be modified later to reflect new turbines or actual plant data, it may not be necessary to use the design mode input option for the feedwater heaters or reheaters. The heat balance values of terminal temperature difference and drain cooler approach temperature difference for feedwater heaters, and final temperature difference for reheaters, may be sufficient for bounding the results when going to a different power level.

Base Model Using New Turbine Vendor Heat Balance Diagrams with New Turbines

Sometimes a power uprate will include a simultaneous turbine upgrade, either to the HP or LP turbine. If heat balance diagrams are available with both the power uprate and new turbine performance included, the PEPSE model should be developed and tuned to these balances. The same procedure as outlined in the previous section should be followed.

Base Model Using Performance Test Data

The most accurate power uprate model is based on actual plant data – this model represents the plant as it is currently operating and not necessarily as it was originally designed. Data for this model may be from a recent performance test or from the daily data logs.

It is imperative for matching as-tested performance that as many components as possible be characterized using the design mode input option. The plant data are used to tune the calculations for these components to their current performance using the design mode option adjustment factors. Then, when the power uprate condition is applied to the model, the results for these components will float to their new condition, giving an accurate prediction of the power uprate.

It is best to start with the base model that was originally constructed from the turbine vendor's heat balances. Then, put all components as possible in the design mode. Following that, using PEPSE's control feature, control individual component adjustment factors to match the measured performance. When this is completed, take these adjustment factors and put them into the model, remove the controls, and run the model at the new power level. A systematic way of doing this is to develop a series of sets that step through this process and pass the required information from one set to the next automatically. One way to do this would be the example as follows:

> Set 1 – Base Model Using Turbine Vendor Heat Balance at 100% Load
> Set 2 – Plant Data at 100% Load - Tuning Using Controls
> Set 3 – Power Uprate Study Using Adjustment Results from Set 2 Tuning

In Set 2, use a series of controls to get the adjustment factors, but turn these controls off in Set 3. These factors will be automatically passed to Set 3. Set 2 must be characterized using the Run Separator = "Save Case". This is illustrated in Figure 2.
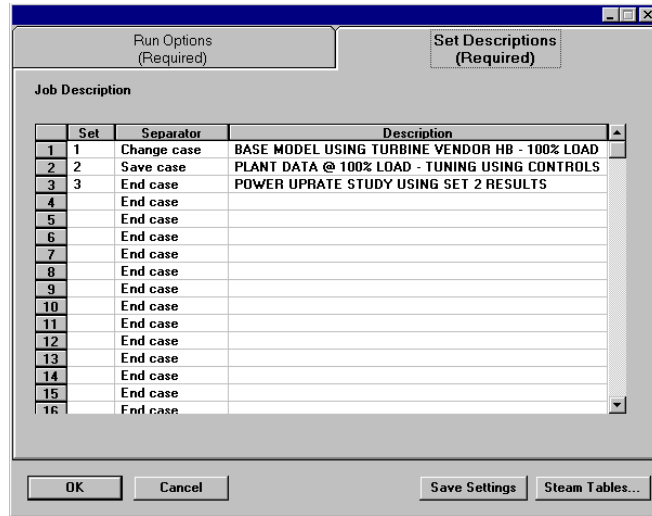

	Set	Separator	Description	
1	1	Change case	BASE MODEL USING TURBINE VENDOR HB - 100% LOAD	
2	2	Save case	PLANT DATA @ 100% LOAD - TUNING USING CONTROLS	
3	3	End case	POWER UPRATE STUDY USING SET 2 RESULTS	
4		End case		
5		End case		
6		End case		
7		End case		
8		End case		
9		End case		
10		End case		
11		End case		
12		End case		
13		End case		
14		End case		
15		End case		
16		End case		

Figure 2
Tuning to Actual Performance Data – Run Set Sequence

Base Model Using Performance Test Data and New Turbine Vendor Heat Balance Diagrams with New Turbines

If a new turbine (or turbines) will be part of the uprate project, it is best to first develop the model using actual plant data as described in the previous section and then later bring the description of the new turbine(s) into this model.

First, obtain the performance of the new turbine(s) from the turbine manufacturer. This is usually supplied in the form of new heat balance diagrams with the new turbine(s) included. Because the other plant components in these new heat balance diagrams are usually at assumed conditions, not your real plant conditions, you should not tune the turbine adjustment factors in the existing model. Instead, build a separate submodel that includes just the new turbine(s) and tune the adjustment factors using the data from the new heat balance diagrams, i.e. tweak the turbine(s) using the adjustment factors to match the specified performance on the new heat balance diagrams. An example of an HP turbine submodel is shown in Figure 3. Finally, take the new turbine data and adjustment factors from the submodel and put them in the model that has been tuned to actual plant data – put them in Set 3 (see discussion in previous section).
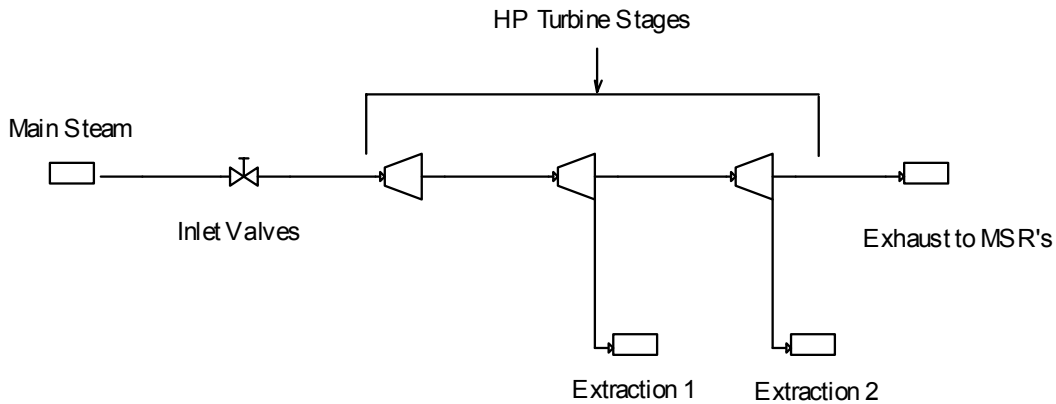
Figure 3
High Pressure Turbine Section Submodel Example

Setting the Input Thermal Power

Dialing in the thermal input power and having PEPSE determine the cycle behavior is the desired result of a power uprate study. There are several ways to set the thermal input power. But be careful! In some cases the thermal power is the net thermal power to the turbine cycle, in other cases it is the reactor thermal power. The user should study and understand which option is being used for each application.

Special Option 4

In its simplest application, Special Option 4 is a quick way to set the thermal input power to the turbine cycle. PEPSE looks at the final feedwater energy out from the turbine cycle model (at the output component type 32), the main steam inlet energy (at the input component type 33), and adjusts the flow to the turbine cycle model at the input component to match the target net thermal input power to the turbine cycle model. Only the input component flow is adjusted.

As a new option in Version 68 of PEPSE, released in the fall of 2003, the user may input the reactor thermal power plus any primary side heat additions (e.g. reactor coolant pump power) and losses (e.g. radiation, blowdown). PEPSE takes this information and converts it to a net thermal power to the turbine cycle and applies it as explained in the paragraph above. Reactor thermal power is a more common plant term, and therefore this new option allows its use in common plant language.

Steam Generator

A steam generator component (or components) can be used to simulate the steam generator(s) in a PWR plant or the reactor in a BWR plant. When using this component, the model becomes "closed"; there is a complete loop. The output flows from the final feedwater heaters go to the steam generator(s) and the output flows from the steam generator(s) go to the HP turbine. There is no open cycle as there is when the final feedwater flow terminates at the output component and the main steam flow originates at the input component.

One of the inputs on the steam generator component is thermal power, the amount of energy that passes from the primary to secondary side in the steam generator. i.e., the thermal power <u>to</u> the turbine cycle. When this is specified, PEPSE adjusts the outlet energy (enthalpy) of the steam that exits the steam generator(s). Unlike Special Option 4, the thermal power is not used to adjust the user-specified main steam flow at the input component.

Reactor Component

Beginning with Version 68 of PEPSE, an actual reactor component was made available. This reactor component is used along with other components that make up the primary side (pumps, steam generator for a PWR plant, pressurizer, and others).   This component is discussed in more detail in a later section of this paper. When using this component, the reactor thermal power may be input directly.

User Action

The user can employ a variety of methods to set the thermal input power in lieu of traditional methods. This may be to set the reactor thermal power directly or the thermal power <u>to</u> the turbine cycle. One way would be to write a series of operations that use the final feedwater conditions as the net energy out from the turbine cycle, and then adjust one of the input variables for the main steam inlet component (the input component energy in), such as flow, enthalpy, quality, or pressure, to match the desired turbine cycle thermal input power. The same matching could be done using PEPSE's control feature.

Another method would be to use one of PEPSE's general heat exchangers (type 20 or type 27) to simulate the steam generator(s) or reactor by specifying an energy input equal to the desired thermal input power.

Condenser Modeling

It is very common for a nuclear plant to have a multi-zone condenser with each zone at a different backpressure. Usually different backpressures result because the circulating water is in series, going from one zone to the next at a hotter and hotter temperature. In these plants where there is some kind of equalizing line (pipe or duct) intended to keep

the pressures equal in the various zones, the pressures are still often slightly different in the zones. Slightly different backpressures can also occur in multi-zone condensers where the circulating water is piped in parallel, i.e., all zones have the same circulating water inlet temperature. Whether intended or not, the pressures in the various zones are rarely equal. A difference of 0.1 " Hga can cause as much as a 1 MWe swing in electrical output. Because of this, it is recommend that all zones be included in the PEPSE model by using a separate condenser component to simulate each zone.

It is also common for each LP turbine section to exhaust to a different condenser zone. If so, the PEPSE model should have each LP section exhausting to the proper zone (condenser component) without mixing the LP section exhaust lines together. This must be strictly adhered to. The correction to the LP expansion line endpoint that is based on actual condenser pressure is made in the LP turbine itself. To properly account for this requires the correct condenser connections. This is illustrated in Figure 4.
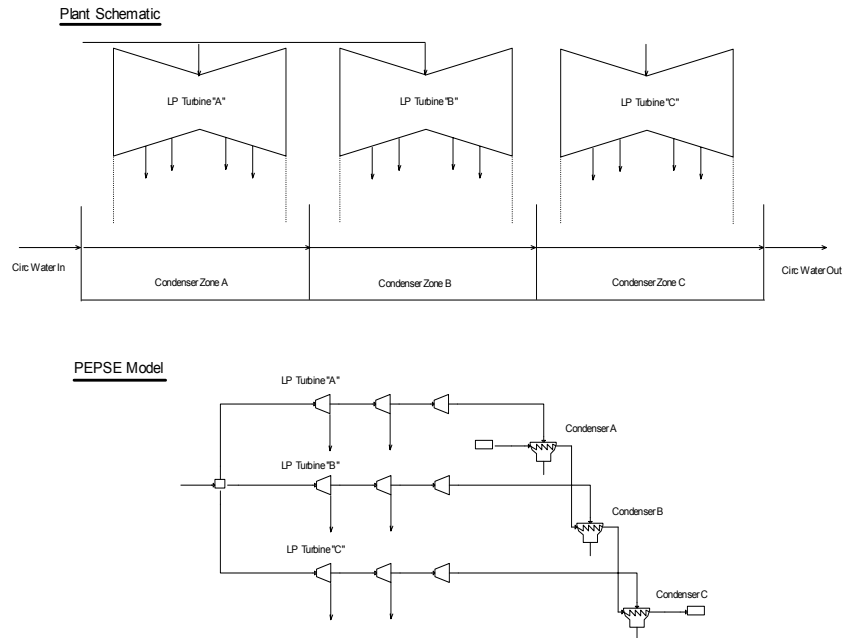

Figure 4
PEPSE Modeling for Multiple Condenser Zones

Modeling the plant condenser(s) using the design mode input option allows the condenser(s) performance to adjust automatically to changing circulating water inlet temperatures and changing condenser loads. A popular method for this is the HEI condenser calculations that are included in PEPSE. They offer good results with a minimum of input requirements.

Cleanliness Factor

One observation that has emerged in using the various condenser design mode calculational methods has been the variability of the cleanliness factor (inferred from

performance test data) at different circulating water inlet temperatures. When the cleanliness factor is adjusted to obtain a match between calculated and measured backpressure, the factor changes with changing circulating water inlet temperatures. This has been observed not only with the built-in PEPSE calculations, but also with other unrelated applications of cleanliness factor methodology at nuclear plants where a cleanliness factor calculation is included in their day-to-day plant reporting.

The literature addresses use of the cleanliness factor in this fashion. Quoting from ASME PTC 12.2[2], "The cleanliness factor is a unique value, since it applies to only one specific operating condition. To use it as a constant factor of new clean tube heat transfer or other conditions of operation introduces error. The amount of this error varies directly with the degree of heat transfer change from a value corresponding to the reference performance point to a value corresponding to some other performance point. Although it is common practice to use an established condenser cleanliness factor as a constant for any operating condition for a given condenser, the user of this Code is cautioned to estimate the error which may result in following this practice before accepting this procedure as a satisfactory means for establishing condenser performance at conditions other than the cleanliness factor determination reference point."

Typically, the cleanliness factor is applied as a multiplier (x) on the overall heat transfer in the equation below[3]:

$$q = xUA\Delta T \tag{1}$$

where: q = heat transferred
U = overall heat transfer coefficient
A = heat transfer area
ΔT = temperature difference or LMTD
x = cleanliness factor

But "cleanliness" is actually a fouling term, usually on the inside of the tubes. The accounting for fouling is more rigorously accounted for as an additive thermal resistive term, not a multiplicative term, in the "U" coefficient[3]:

$$U = \frac{1}{\dfrac{1}{h_o} + R_o + R_k + \dfrac{R_i A_o}{A_i} + \dfrac{A_o}{h_i A_i}} \tag{2}$$

where: U = overall heat transfer coefficient
h_o = tube outside film coefficient
h_i = tube inside film coefficient
R_o = tube outside fouling resistance
R_i = tube inside fouling (or "cleanliness factor") resistance
R_k = tubing wall resistance
A_o = tube outside area
A_i = tube inside area

Using the fouling as an additive term (Equation (2)) may be a better characterization, but it may not give better results. This term, if inferred from test data, may still vary over the load range or over a range of circulating water inlet temperatures, and, in fact, investigations using PEPSE show this to be true.

If cleanliness factor is the choice for tuning, a common method of addressing the variability of the cleanliness factor is to input this factor in a curve (schedule) as a function of circulating water inlet temperature. A better way is to input the cleanliness factor as a function of both the circulating water inlet temperature and heat duty on the condenser using a bivariate schedule.

When the tube side and shell side temperatures do not remain constant, the literature[3] suggests the variability of the so-called cleanliness factor "x" in Equation (1) as a correction factor (commonly called "F") that is a function of the tube-side in and out temperatures and the shell-side inlet temperature, commonly called "P" as given below:

$$P = \frac{(T_{to} - T_{ti})}{(T_{to} - T_{si})} \tag{3}$$

where: T = temperature
       ti = tube inlet
       to = tube outlet
       si = shell inlet

"F" is also a function of the mass flow rates and heat capacities of the tube-side and shell-side flows, commonly referred to as "Z", as given below:

$$Z = \frac{W_t Cp_t}{W_s Cp_s} = \frac{(T_{si} - T_{so})}{(T_{to} - T_{ti})} \tag{4}$$

where: W = mass flow
       Cp = specific heat
       t = tube side
       s = shell side
       so = shell outlet

Using Figure 5 to show these terms graphically, this factor "F" typically ranges from 0.5 to 1.0; the "P" factor ranges from 0.0 to 1.0; the "Z" factor can range from 0.1 to as high as 20.0. Therefore, the variation in the cleanliness factor is verified in the literature, but only if the condensing zone temperature is non-constant. This non-constant condensing zone temperature could be due to subcooling or other phenomena in the condenser heat transfer process.
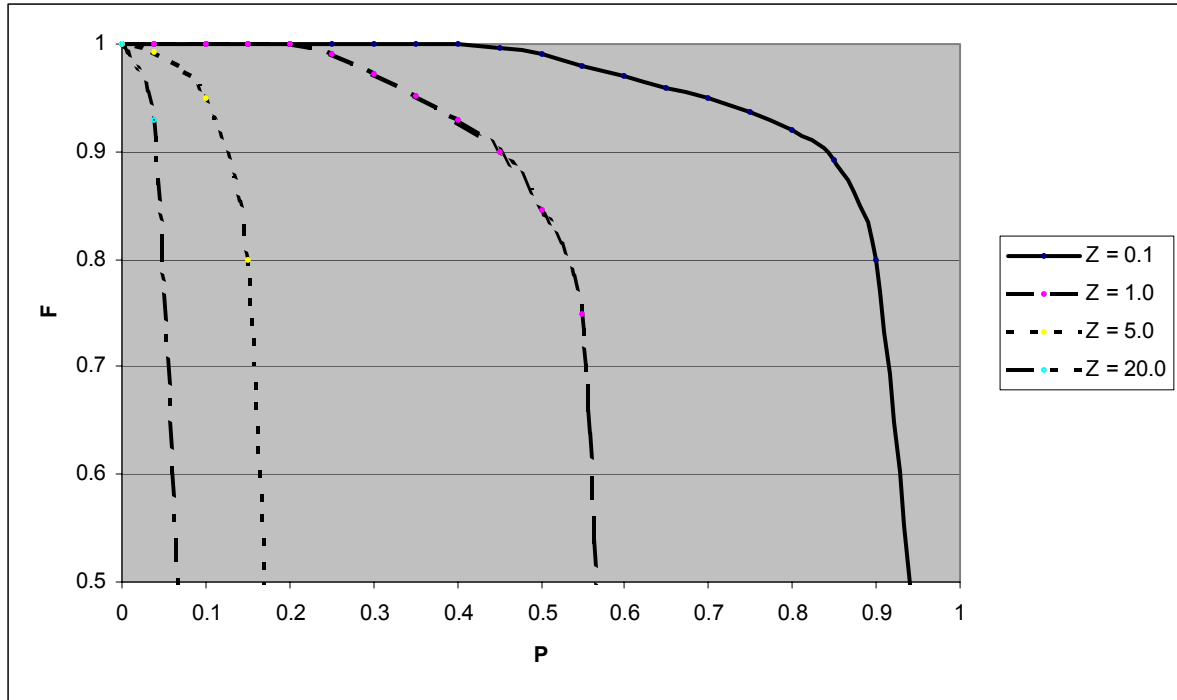
Figure 5
Sample "F" Curve

Retubing

In rare cases a condenser has been partially re-tubed, resulting in two different tube materials – the original and the new. This must be modeled using two separate PEPSE condenser components, one representing the original tube material, the other representing the new tube material. If the tubes have the same dimensions (very likely), then the circulating water flow split to the two condenser "halves" is proportional to the number of open tubes in each side.

Primary Side Components – Reactors and Steam Generators

It is not necessary to model the reactor for a PWR or BWR plant, or the steam generator(s) for a PWR plant. PEPSE's input component (type 33) and output component (type 32) can serve as the boundary conditions for these. Some plants include the primary side components for the sake of completeness while others believe their inclusion complicates the model. When modeled, these components close the cycle, or "close the loop", and it is no longer open-ended; the main flow makes a continuous loop.

If one chooses to model the reactor and/or steam generator(s), several recommendations are offered. An input component and an output component should still be used. First,

they are the components used by PEPSE to calculate the turbine cycle heat rate. If not present, the thermodynamic calculations will be unaffected, but a heat rate number will not be calculated or printed in the output. Secondly, they serve as anchor points in the cycle analysis. They allow the setting of thermodynamic properties at these points for a given number of iterations, stabilizing the model. Finally, they allow removal of the reactor and/or steam generator(s) without having to add additional components later. When using the input component and output component, connect their optional inlet connection and outlet connection, respectively, to the primary side components. For the input component, use the optional data input form to flag PEPSE that it is "double-ended" and flag the option that allows the pressure, temperature, and flow to be passed from inlet to outlet after a certain number of iterations (the pass-through flag), usually 15. For the output component, just flag the double-ended option. Figure 5 shows an example of a connection using double-ended input and output components.

When the loop is closed by including primary side components, the turbine cycle inlet conditions are NOT dictated by the input component specifications. They are set by either the steam generator(s) input parameters or by the reactor parameters. The input component temperature (or quality), pressure, flow, and optionally enthalpy, serve as a first guess only and are used up to an iteration number specified by the user. If the user fails to set this iteration number and the pass-through flag, there will very likely be an energy imbalance in the input component and the model will not converge.
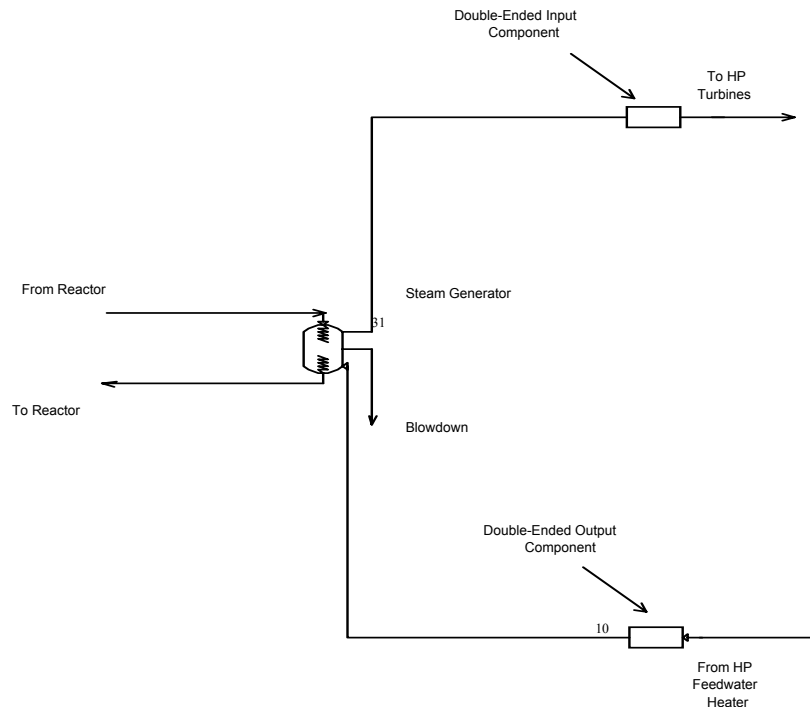

Double-Ended Input
Component

To HP
Turbines

From Reactor

Steam Generator

31

To Reactor

Blowdown

Double-Ended Output
Component

10

From HP
Feedwater
Heater

Figure 5
Use of a Double-Ended Input and Output Component

Pressurized Water Reactor Plant

The reactor and the steam generator(s) may be modeled, or just the steam generator(s) may be modeled. If only the steam generators are modeled, the flow from the reactor will come from an infinite source (type 31) and the flow back to the reactor will go to an infinite sink (type 30). If the reactor is modeled, use a type 27 for the reactor, or the new type 78 reactor component for Version 68 and later. Be sure to include the reactor coolant pumps in the primary loop, and optionally the pressurizer. Also, make sure to include an infinite source (type 31) in the primary loop, set the flow, initial conditions, double-ended flag, and the pressure/temperature/flow pass-through iteration number in this infinite source.

The reactor power will be an input in the type 27 heat exchanger component, specified in BTU/hr, or the new type 78 reactor component, specified in MWt. The steam generator input allows several options, the most important being the exit pressure, the exit temperature (or quality), blowdown, and optionally the thermal power supplied by the steam generator(s). If both the exit temperature (or quality) and the thermal power are input, the temperature (quality) will override the thermal power. As stated earlier, if the thermal power is input, its value will be used to set the steam generator(s) outlet thermodynamic conditions, not the specified flow rate to the turbine cycle. If the temperature (or quality) is input in the steam generator, the turbine cycle inlet temperature (or quality) specified for the input component (type 33) is only a first guess. Usually a pressure drop is modeled from the steam generator(s) outlet to the main turbine inlet valves. If so, the temperature (or quality) would be different because of the pressure drop.

Boiling Water Reactor Plant

Several options are offered to model a boiling water reactor - a type 27 heat exchanger component, the new type 78 reactor component, or a steam generator component (type 76). If a steam generator component is used, include an infinite source (type 31) to supply a "dummy" reactor side flow, and use an infinite sink to receive the primary-side outflow from the steam generator component.

Reheaters

A reheater is typically a multi-pass or multi-zone heat exchanger with different heat transfer regimes occurring in the different passes. Heating steam from throttle (or from the HP turbine) has a high quality and represents steam-to-tube heat transfer. This heating steam condenses inside of the tubes, approaching a saturated liquid condition. In some circumstances, subcooling of the liquid occurs inside of the tubes near the exit.. On the heated steam side, the steam is usually saturated, perhaps with slight liquid carryover from the moisture separator. The heating produces superheated cycle steam at the reheater outlet. Modeling these different regimes requires a model with multiple passes.

This may be accomplished with multiple reheater components (type 22) or one reheater component and one or more general heat exchanger components (type 20).

Figure 6 shows an example of a reheater with several passes and the PEPSE model used to simulate it. The water/steam separation between passes 2 and 3 is represented using a moisture separator (type 62) component. Normally this component is used to simulate the moisture removal phase at the inlet of the MSR's (moisture separator – reheater), but it may be used to simulate any water and steam separation process.

If multiple reheaters are installed in the plant, all should be included in the PEPSE model unless a one-line model is being built.
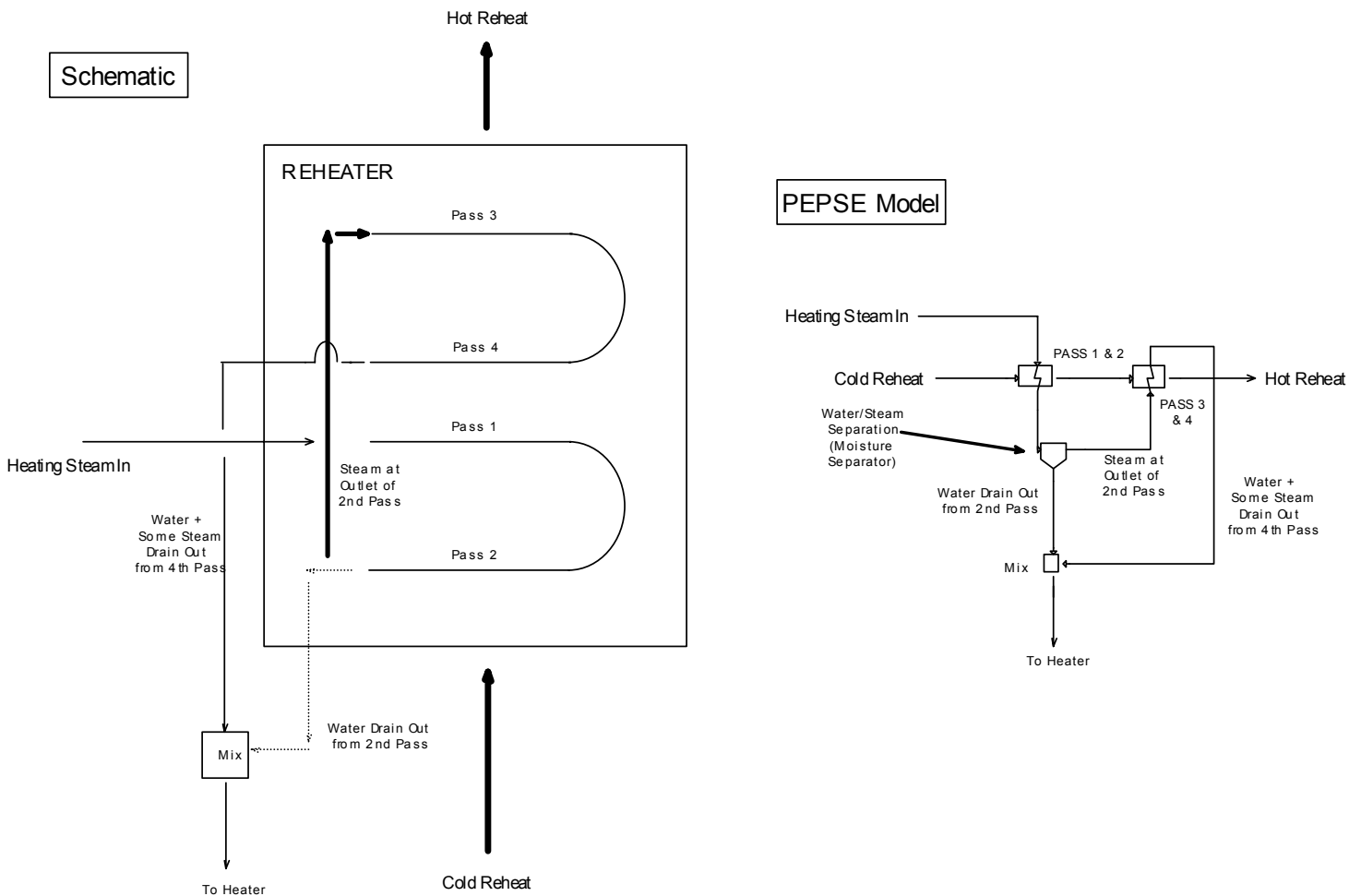
Figure 6
Multi-Pass Reheater Modeling Example

In the fall of 2002 with the release of PEPSE Version 67, a new design mode reheater component simulation was made available which automatically takes into account

various tube side bundle passes for one pass, two passes, or four passes. This eliminates the need for multiple components to handle multiple tube pass bundles, thus simplifying the modeling process.

Moisture Removal Stages

Nuclear turbines operate almost entirely in the wet steam region. The LP turbines can have especially high amounts of moisture. Because of this, special grooved moisture extracting buckets are built into the LP turbines, mostly in the latter stages where moisture is the highest. Turbine vendors often supply a curve of expected moisture removal effectiveness for each of these moisture removal stages – see Figure 7 as an example.
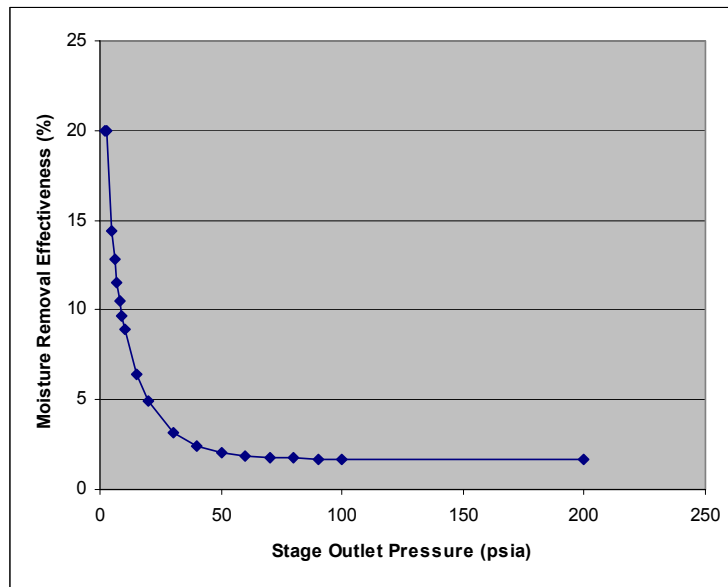

Figure 7
Moisture Removal Effectiveness Curve Example

PEPSE has several built-in moisture removal effectiveness curves. Experience has shown that for new turbines, these curves are rarely satisfactory. New advances in turbine design have produced different moisture removal characteristics in the turbines, requiring the user to secure and input a new curve (similar to Figure 7) using a schedule. Another example, shown in Figure 8, has the moisture removal effectiveness as a function of load. Load-dependent curves, although not widespread, are becoming more common in the industry.
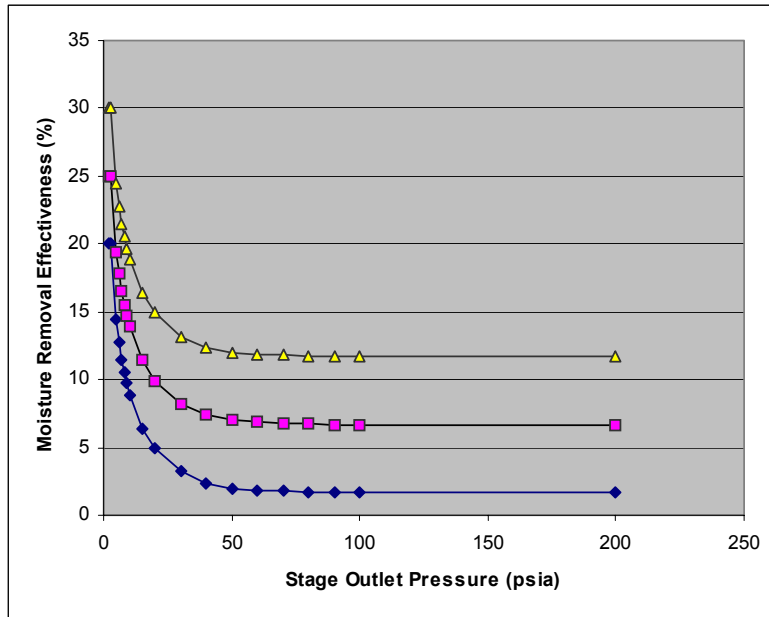
Figure 8
Moisture Removal Effectiveness Curves vs. Load
(Lines on Chart are for Different Loads)

Figure 9 also shows a moisture removal effectiveness curve as a function of load, but with a twist. At low pressures, the moisture removal effectiveness starts out low, increases up to a certain pressure, and then decreases. This type of behavior is rare but has been seen in a few cases.

In some cases, the turbine manufacturer has set a constant moisture removal effectiveness for each stage, independent of pressure. Each stage has a different value, but the value for that stage does not vary vs. pressure, load, or any other parameter.

If lucky, the user can secure the new curve from the turbine vendor. If not available, however, the best way to generate a new moisture removal effectiveness curve is to produce it from the results shown on the new turbine heat balance diagrams. This is most easily accomplished using PEPSE's control feature.

Having an accurate moisture removal effectiveness curve is extremely important in matching the turbine vendor heat balance diagrams and predicting plant performance at a different power level. Experience has shown that a curve that is off by 1% to 2% can cause swings in power generation of as much as 50 MWe.
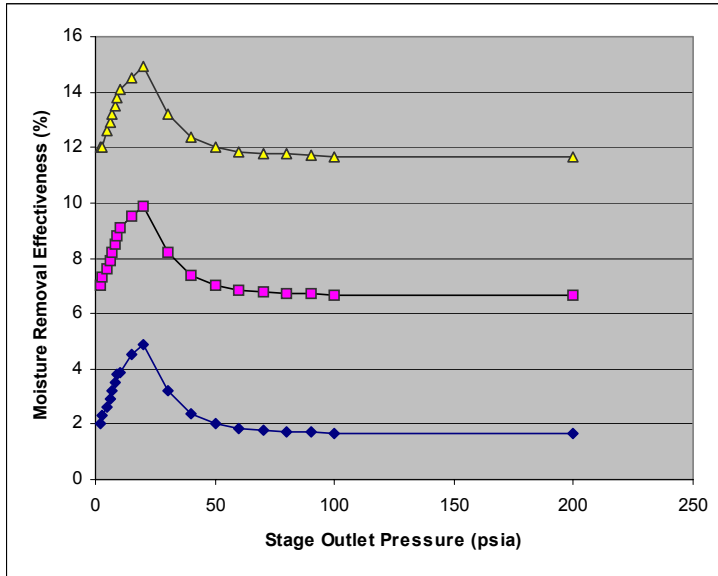
17

Figure 9
Moisture Removal Effectiveness Curves vs. Load
(Lines on Chart are for Different Loads)

Corrections for Wet Region Operation and Reheat Factor

Most turbine manufacturers use a correction curve to account for turbine exhaust stage operation in the wet steam region and for the reheat factor. This correction curve is usually referred to as the "Correction to Base Endpoint Pressure for Actual Condenser Pressure", but may also have a different name. Turbine manufacturers generally construct a "base" low pressure turbine (condensing turbine) expansion line endpoint to 1.5" Hga as an initial characterization of the condensing section. If the actual condenser pressure is different from 1.5 "Hga, they apply a correction to the calculated 1.5 "Hga endpoint rather than construct an expansion line to the actual condenser pressure. This correction is applied before the exhaust loss is applied.

PEPSE has a built-in curve for this correction representing the correction at zero percent moisture. The curve is automatically modified with a "moisture function" if the exhaust moisture at 1.5 "Hga is greater than 0.0. This moisture function is as follows:

$$\Delta ELEP = \Delta ELEP_{M=0}(0.87)(1-0.01M)(1.0-0.0065M) \tag{5}$$

where: ELEP = expansion line end point at actual condenser pressure
$ELEP_{M=0}$ = ELEP @ 0% moisture (from curve)
M = moisture (%) at 1.5"Hga

18

Most turbine manufacturers apply the moisture function to the curve, but some do not. In PEPSE for all Versions 67 and earlier, the moisture function is automatically applied to the built-in "Correction to Base Endpoint Pressure for Actual Condenser Pressure" curve or any curve input by the user via a schedule for this endpoint correction curve. The moisture function may be cancelled from a scheduled curve using operations, but only if the curve is input by the user (not if the built-in curve is used). In Version 68 and later, this moisture function can be cancelled from the built-in curve or from a scheduled curve merely by setting a flag in the low pressure turbine input.

Exhaust Loss Curve

A typical vendor-supplied LP turbine exhaust loss curve shows dry exhaust loss as a function of either exhaust annulus velocity or exhaust volumetric flow. This dry exhaust loss may or may not be corrected for actual moisture – a check of the exhaust loss curve directly determines if this correction is present.   Care should be exercised when inputting (via a schedule) a vendor-supplied LP turbine exhaust loss curve, especially the variety that has dry exhaust loss vs. exhaust volumetric flow. The volumetric flow on the vendor-supplied curve may be calculated either at the expansion line end point "ELEP" (before exhaust loss is applied) or at the turbine end point "TEP", also known as the used energy end point "UEEP" (after exhaust loss is applied – an iterative procedure). Sometimes it is not clear which point was used to calculate the volumetric flow. The best way to check this is to use it both ways in the PEPSE model to see which one gives the better result. This is an easy process, changing only the variable name for the "x" axis variable in the schedule. First try the ELEP volumetric flow, then the TEP/UEEP. This procedure works best if the LP turbine is "tuned" to the ELEP using PEPSE's expansion line modifying factor EFMULT rather than tuning to the TEP/UEEP.

When using a vendor-supplied LP turbine exhaust loss curve with the dry exhaust loss as a function of the exhaust annulus velocity, the velocity at the ELEP should be used. The built-in PEPSE exhaust loss curves use this method.

Flow to MSR's and LP Turbines

Plants with steam turbine-driven main feed pumps typically have the driving steam to these turbines supplied from the outlet of the moisture separator reheaters (MSR's) or the outlet of the moisture separators if reheaters are not present. If multiple MSR's (or moisture separators) are present, there is a strong possibility that this turbine steam supply originates at the outlet of only one or two MSR's (or moisture separators) but not all. With this configuration, how do you split the HP turbine exhaust flow to the MSR's (or moisture separators) and how do you split the flow to the LP turbines?

For a one-line model it doesn't matter - all the flow is going through one HP turbine, one MSR (or moisture separator), one LP turbine, etc. If multiple HP turbines, MSR's (or moisture separators), LP turbines, condensers, etc., are modeled, the answer can be more complex. It is common for the HP turbine to be double-flow, that is, it has main steam

entering and splitting to two ends of the turbine. Usually the HP turbine exhaust from each of the two ends goes directly to one, two, or three MSR's (or moisture separators) separately without mixing with the exhaust from the other end. It is from one (or two) MSR's (or moisture separators) outlets from "one end" of the HP turbine exhaust that the steam turbine-driven feed pump turbine gets its driving steam. The flow split to these MSR's (or moisture separators) may be the same as the others that are not supplying steam to the feed pump turbines, or it may be different. Well, what is it? Plant knowledge is essential here. The inlet flows to all MSR's (or moisture separators) may be the same, or the outlet flows to the LP turbines after steam is taken to the feed pump turbines may be the same. Whichever it is, the model flow splits must be adjusted accordingly.

Matching Several Loads

Experience has shown that tuning the as-built model to match at one load point does not guarantee a match at other loads. Usually the difference in load points is attributable to different condenser backpressures. Summer backpressures are generally higher than in winter and can represent a swing of 10-50 MWe. Tuning the model to one load (backpressure) and then inputting another backpressure may not give the measured plant output. How can this be? There may be something wrong with the input data or the assumptions used when setting up the model. Some of the discrepancies may be explained as follows:

     a.   The model was tuned using bad data, or the new load data are bad
     b.   There may be inconsistencies in how the data were taken at the two loads
     c.   There may be performance factor changes that are not known
     d.   There may be component performance changes between the two data sets
     e.   There may be real physical effects that are not accounted for in the model
     f.   Others

How do you get the PEPSE model to match the plant at all loads? A little experience helps here. Sometimes the exhaust loss curve is modified, but usually the last stage LP turbine adjustment factor (efficiency multiplying factor) is modified to match the measured output at the various loads. The last LP stage is influenced by the backpressure. It is logical (and accepted) to modify the last LP stage to make the model match the plant. These modifications can be set up in a curve (schedule) versus some parameter such as backpressure, circulating water temperature, electrical load, thermal power, or main steam flow.

Conclusions

Making a set of mathematical equations such as those in PEPSE match "mother nature" (the plant) requires experience, practice, and a little luck. These lessons learned are based on experience, a lot of practice, and a little luck. Passing them on to others will

make their modeling experience a little more user-friendly. As they say, "There's no teacher like experience – someone else's!".

References

1. G. L. Minner, W. C. Kettenacker, D. R. Fleming, G. C. Rice, *PEPSE – User Input Description*, SCIENTECH, Inc., Idaho Falls, Idaho, 2001.
2. *Code on Steam Condensing Apparatus*, ANSI/ASME PTC 12.2, The American Society of Mechanical Engineers, New York, New York, 1983.
3. Kreith, Frank, *Principles of Heat Transfer*, International Textbook Company, Scranton, Pennsylvania, 1965.
4. Standards for Steam Surface Condensers, 9th edition, Heat Exchange Institute, Inc., Cleveland, OH, 1995.