SECTION 9 B

Using PEPSE® to Model Nuclear Steam Generators

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ABSTRACT

This paper discusses the capabilities in the latest version, 70, of the PEPSE program for design mode modeling of nuclear steam generators. As presented here, attention is devoted to U-tube applications in pressurized water reactor plants. The paper gives a structured presentation of the alternative modeling approaches that are available and of the inputs that are used to select these alternatives. Example PEPSE models are attached for a U-Tube steam generator to demonstrate the application of each modeling alternative.

Introduction

The steam generator (SG) component, Type 76, is intended for applications in modeling the steam supply system of a pressurized water reactor nuclear power plant for steady state performance evaluation. This component can be used flexibly in combination with other PEPSE components to represent parts or all of the power generation system.

Both performance and design mode applications are available for the SG component. Both "once-through" (OT) and "U-tube" (UT) arrangements are available. This paper focuses on the UT design mode application.

The design mode capability for analyzing nuclear steam generators has been included in PEPSE since the introduction of Version 61, that was released 9 years ago. This year's development work has included significant effort to investigate the behavior of the model and to improve it for U-tube steam generators. In the event that the user's group gives it a high priority, similar work will be performed for the once-through type of steam generator in Version 71.

You are advised to use a submodel for your initial attempt(s) at running the design mode for a steam generator component. In other words, keep it simple.

It is assumed here that one of the available modeling configurations can be used to represent your actual as-installed steam generator. Furthermore, it is assumed that you can successfully enter the necessary data inputs. The focus of this paper is to organize and describe the several alternative tuning and predictive uses that are available via the design mode. For additional descriptive information about the Type 76 Component for modeling steam generators, see Appendix A of this paper and Ref 1.

Parts of the text of this paper have been extracted verbatim from Chapter 12 of the Version 70 Volume 1 PEPSE User's Manual, Ref 1. Additional background and previous applications information can be found in Refs. 2 and 3.

It is hoped that presenting organized guidance on alternative uses of the design mode will stimulate PEPSE modelers to make use of the capability.

Modeling Alternatives Provided by the Design Mode Steam Generator Component

The design mode steam generator component provides programmed alternatives for its application. There are two alternatives for tuning, and there are two alternatives for predictive analyses. These alternatives are summarized in the tabulated matrix, Table 1 below. The program development effort in Version 70 to expand and clarify these alternatives has been concentrated on U-Tube steam generators. One or more of these options may have greater difficulty (or even fail) for some Once-Through steam generator models.

This section describes the combinations of specific input variables that are necessary in order to invoke any one of these options. The variables are discussed by name, as they appear in the PEPSE input manual and on the forms of the graphics program. Depending on the particular application, any one of these variables may be either fixed by your input specification, or they may be only initial guesses, or they may be target values for the PEPSE calculations. The text and tabulation of this paper indicate the differences.

Both tuning options and the predictive options hold the delivered main steam quality (XMSLSG) fixed at the specified input value, and both provide for specifications of blowdown (variables IBLDWN, WWBLDN, and HHBLDN). The blowdown enthalpy can be defaulted, to be determined by the calculations, or if a non-zero value is entered for HHBLDN, its value is fixed.

In the first tuning option (Case TA in Table 1), the heat transfer coefficient multiplier is calculated by PEPSE. The specified value of the multiplier (UIAMSG>0.) is used as a flag, and the value is used as an initial guess. In the calculation, its value is adjusted such that the model's heat transfer and thermodynamic results match specified target/known operating conditions - thermal power, steam generator secondary-side pressure, and main steam quality (PWRPSG, PREFSG, XMSLSG, respectively). In this option, energy balance requirements may also cause adjustment of the thermal power from the specified value. If adjustment occurs, a warning message is printed.

The second tuning option (Case TB in Table 1) differs from the first in that the specified input value of thermal power (PWRPSG) is held fixed, and the secondary side's operating pressure (PREFSG) is adjusted, if necessary, in order to satisfy energy balance requirements. This option calculates the needed heat transfer coefficient multiplier, whereas the specified value (UIAMSG>0.) is used as a flag and an initial guess.

In the predictive options, the tuned component is used to calculate the behavior that would be expected under varying operating conditions and under some variations of the component itself, e.g. tube plugging, fouling, etc. Both predictive options hold the delivered main steam quality fixed at the specified input value (XMSLSG), and both provide for specifications about blowdown.

The first predictive option (Case PC in Table 1) holds the thermal power fixed at the specified input value (PWRPSG) and allows the steam generator's secondary-side pressure to vary from the guessed input value (PREFSG). It is useful to realize that the combination of inputs for this predictive option automatically determines the secondary side's operating pressure as constrained by an energy balance. No heat transfer analysis is necessary, and none is performed. Therefore, no detailed heat transfer results are available in the steam generator table of the .out file. This includes heat transfer coefficient multiplier (UIAMSG), which cannot be determined for this case.

The second predictive option (Case PD in the table below) allows both the thermal power (PWRPSG) and the secondary side's operating pressure (PREFSG) to vary, subject to heat transfer consistency, given the incoming conditions, the blowdown conditions, and the description of the steam generator. Unlike the first predictive option, this option requires use of the heat transfer details in order to obtain a complete solution (including use of UIAMSG, where the negative sign is a flag used to hold the value fixed in the calculation).

If none of the options provided satisfies a specific analysis need, it may be possible to select one of the available options and to combine use of PEPSE control(s) to satisfy the need. For example, it may be possible to combine one of the predictive options with a control that adjusts the main steam quality in order to match a specific/required value of operating pressure (or thermal power). The x variable in the control would be the input variable, XMSLSG, for the steam generator component. The y variable in the control would be PP for the U-port stream for pressure, or it would be BKPRSG for the steam generator component for calculated thermal power. By this method, you could predict the actual main steam quality that would be expected under varying conditions. Other combinations with controls are possible.

The specific combinations of inputs needed to select the tuning and predictive options are noted in Table 1 below. The options are in the same order as described in the text above. The combination of values and prefix/signs are used to flag the specific options.

In all cases, it is understood that the steam generator's internal geometry and its inlet conditions are given. The inlet conditions are provided by the flows that arrive at the steam generator component from other upstream components.

See the appendices for examples of each one of the alternative modeling approaches.

Table 1 – Matrix of UT Design Mode Modeling Alternatives (note that secondary exit quality is fixed as specified)

Option/ case	PWRPSG input value	PRESFG input value	UIAMSG input value	Results Calculated	Comments
TA	> 0.	> 0.	> 0.	Power fixed (see notes below and text below) Pressure fixed UIAMSG adjusts	Tunes SG heat transfer to match known conditions. UIAMSG > 0.0 is the flag to run option A or B
TB	> 0.	< 0.	> 0.	Power fixed Pressure adjusts UIAMSG adjusts	Tunes SG heat transfer to match known conditions. UIAMSG > 0.0 is the flag to run option A or B
PC	> 0.	> 0.	0., or < 0.	Power fixed Pressure adjusts UIAMSG fixed	UIAMSG 0. means default, i.e., UA multiplier is 1. UIAMSG < 0. means abs value enhances or diminishes UA
PD	< 0.	> 0.	0., or < 0.	Power adjusts Pressure adjusts UIAMSG fixed	Same comment as option PC above.

IMPORTANT NOTES:

1. For all cases above, XMSLSG specified is positive (secondary outlet quality fixed). There is also an additional group where XMSLSG is negative. The interpretation of XMSLSG then is: absolute value is the “moisture removal effectiveness” of the dryer. In this instance, the main steam quality is no longer explicitly specified by the user. Instead, the quality is calculated by PEPSE based on the heating zone’s and the dryer’s performance.
2. In case TA, specified power and pressure might be inconsistent. A First Law evaluation is done, and power may be reset if found to be inconsistent.
3. Options PC and PD offer the opportunity to overlay PEPSE controls, e.g. on UIAMSG, or on XMSLSG, or potentially on others.

The text below gives additional descriptions and explanations about the inputs, the calculations, and the results of the available options.

Option TA – for tuning:

Power, Pressure, and Xmsl are specified. Pressure is to be held fixed, and thermal power may be adjusted for energy balance consistency. The heat transfer coefficient multiplier is calculated by PEPSE.

To run this case, specify input values:

PWRPSG > 0.0 (may adjust in the calculations)
PREFSG > 0.0 (fixed in the calculations)
XMSLSG > 0.0 (fixed)
UIAMSG > 0.0 (a flag and initial value; will adjust in the calculations)

With a successful termination of the run, the steam generator performance table includes the value of the UIAMSG tuning factor that was calculated in order to produce a self-consistent answer, i.e. to match the specified conditions.

The results of this case have the potential to give a thermal power value that differs from the one that is specified. This is a consequence of the fact that the inputs overspecify the solution, and thus the power may be inconsistent with the other inputs specified and the inflowing conditions. See the secondary-side energy balance discussion below. The present option will provide the desired result only when the inputs described below are consistent. If there is preference for retaining the value of thermal power, option TB should be used.

In the TA option, the main steam quality, the secondary (shell) side operating ("reference") pressure, and the NSSS thermal power are known and are to be specified to PEPSE. In addition, the blowdown flow rate and its enthalpy are known.

With all of the givens, it is possible that inconsistencies exist in the input data. In particular, given the value of pressure, along with the known shell-side inflows and enthalpies, the thermal power taken on by the secondary side is fixed by energy balance requirements. This is easy to see by reference to the first law of thermodynamics (energy balance) applied to the shell side:

$$Q = w_{ms}*h_{ms} + w_{bd}*h_{bd} - w_{fw}*h_{fw}$$

In this equation, Q is the thermal power to the shell side, that must equal the tube side's thermal power in a converged solution,

w_{ms} is the main steam flow rate,
h_{ms} is the main steam enthalpy,
w_{bd} is the blowdown flow rate,
h_{bd} is the blowdown enthalpy,

w_{fw} is the feedwater flow rate,
h_{fw} is the feedwater enthalpy value

In the above the main steam enthalpy is related to the quality as follows:

$$h_{ms} = h_f(p) + x*(h_g(p) - h_f(p))$$

where
h_f is enthalpy of saturated liquid
h_g is enthalpy of saturated vapor
p is pressure
x is quality

These equations show that, once x and p are known, hms is set. Therefore, with all terms on the right hand side given, the value of Q is set. To deal with this potentially inconsistent overspecification, PEPSE performs a check of consistency. If inconsistency is found, the user-specified value of Q (thermal power) is reset, and a warning is printed.

A subset of this case occurs where the enthalpy of blowdown is not known, i.e. defaulted. For this case, the user specifies a zero value, which is a switch to invoke a default calculation, using the enthalpy that enters the steam generator's heating section at the bottom. This enthalpy depends on the pressure. As such, the application of the formulation above becomes somewhat more complex. However, the fundamental concepts and conclusion remain the same.

In order to obtain a solution in the present option, with the given quantities, and the calculation of thermal power using the heat transfer equations, some parameter must be allowed to adjust. The UA product (heat transfer coefficient times area) is adjusted via variation of the multiplier UIAMSG. An internal algorithm exists for adjusting the value of UIAMSG in order to match the other known conditions.

A large number of internal steam generator iterations may be required in order to obtain convergence of this case. The maximum allowed number of iterates, input variable ITMXSG, may have to be in the hundreds.

The built-in algorithm to calculate UIAMSG, the UA multiplier, may not always converge. In the event that convergence is not obtained, use of other options may be required. One workable approach would be to change the input specifications of the steam generator component to use the predictive option, PD, and then to overlay a control on UIAMSG. You could specify:

- PWRPSG has a minus sign; the value will be used as first guess,
- PREFSG is positive; the value will be used as first guess,
- UIAMSG is negative, e.g. –1.0; the value will be used as first guess,
- Define a control with UIAMSG as the x variable (specify lower and upper limits, e.g. –1.5 and -.7, respectively), and PP of the main steam stream as the y variable. The target value should be the desired pressure.

Option TB – for tuning

Power, pressure, and main steam quality are specified. Power is to be held fixed, and pressure is to be adjusted for energy balance consistency. The heat transfer coefficient multiplier is calculated by PEPSE, given the initial guess in UIAMSG.

To run this case, specify input values:

PWRPSG > 0.0 (fixed in the calculations)
PREFSG < 0.0 (initial value only)
XMSLSG > 0.0 (fixed in the calculations)
UIAMSG > 0.0 (a flag and initial value; will adjust in the calculations)

For the case where the value of the thermal power is of paramount importance, the Case TA should not be used. The present case is required in order to obtain a solution. As always, the first law of thermodynamics, shown above, must still be satisfied. The specified input value of thermal power, along with inflows, with main steam quality, and with steam generator description determines the operating pressure, which will be adjusted by the calculations.

Option PC – for prediction

Power, pressure, and main steam quality are specified. Power is to be held fixed, and pressure is to be adjusted for energy balance consistency. The combination of inputs for this predictive option automatically determines the secondary-side operating pressure, as constrained by the energy balance of the equations above. Therefore, no heat transfer analysis is needed, and none is performed. The heat transfer coefficient multiplier has no effect; the required input may be either defaulted (zero value specified), or specified (including a minus sign as a flag).

To run this case, specify input values:

PWRPSG > 0.0 (fixed in the calculations)
PREFSG > 0.0 (initial value only, will adjust in the calculations)
XMSLSG > 0.0 (fixed in the calculations)
UIAMSG = 0.0 (default to internal fixed value of 1.0), or
UIAMSG < 0.0 (absolute value is used in calculations)

In the table above, option PC fixes the thermal power and the main steam quality and adjusts the pressure for consistency. The option is flagged by specification of the inputs as shown. In this case, the UA multiplier, UIAMSG may be the default (0.0), or a negative value may be specified, having no effect on the results.

Option PD – for prediction

Power, Pressure, and secondary-side outlet steam quality are specified. Power and pressure are to be adjusted for energy balance and heat transfer formulation consistency. The heat transfer coefficient multiplier may be either defaulted (zero value specified), or specified (including a minus sign as a flag).

To run this case, specify input values:

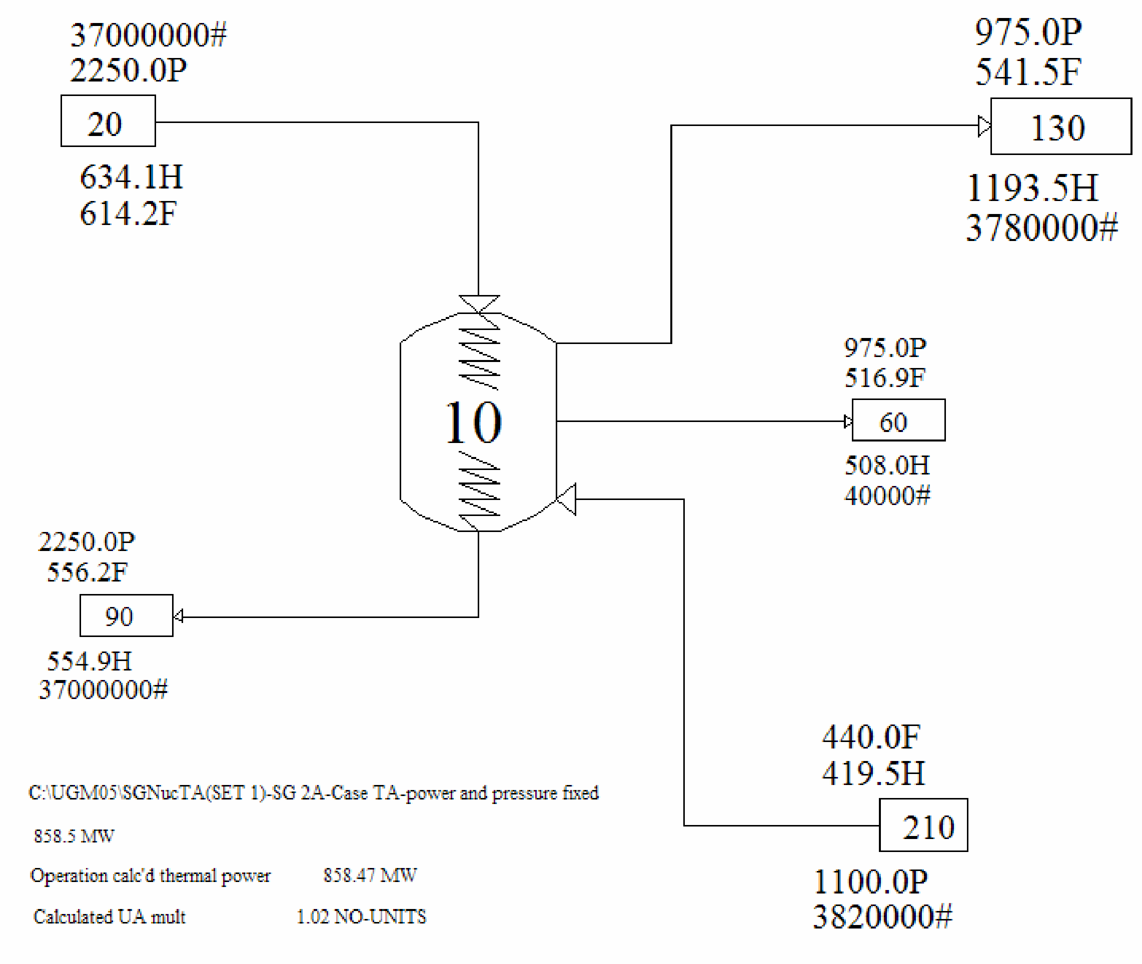
PWRPSG < 0.0 (initial value only, will adjust in the calculations)
PREFSG > 0.0 (initial value only, will adjust in the calculations)
XMSLSG > 0.0 (fixed in the calculations)
UIAMSG = 0.0 (default to internal fixed value of 1.0), or
UIAMSG < 0.0 (absolute value is used in calculations)

In the table above, option PD fixes the main steam quality and allows the thermal power and the pressure to adjust. The option is flagged by specification of the inputs as shown. In this case, the UA multiplier, UIAMSG may be the default (1.0), or a value may be specified to enhance or diminish the heat transfer that is calculated. The flag to accomplish this is a minus prefix when the value is specified.

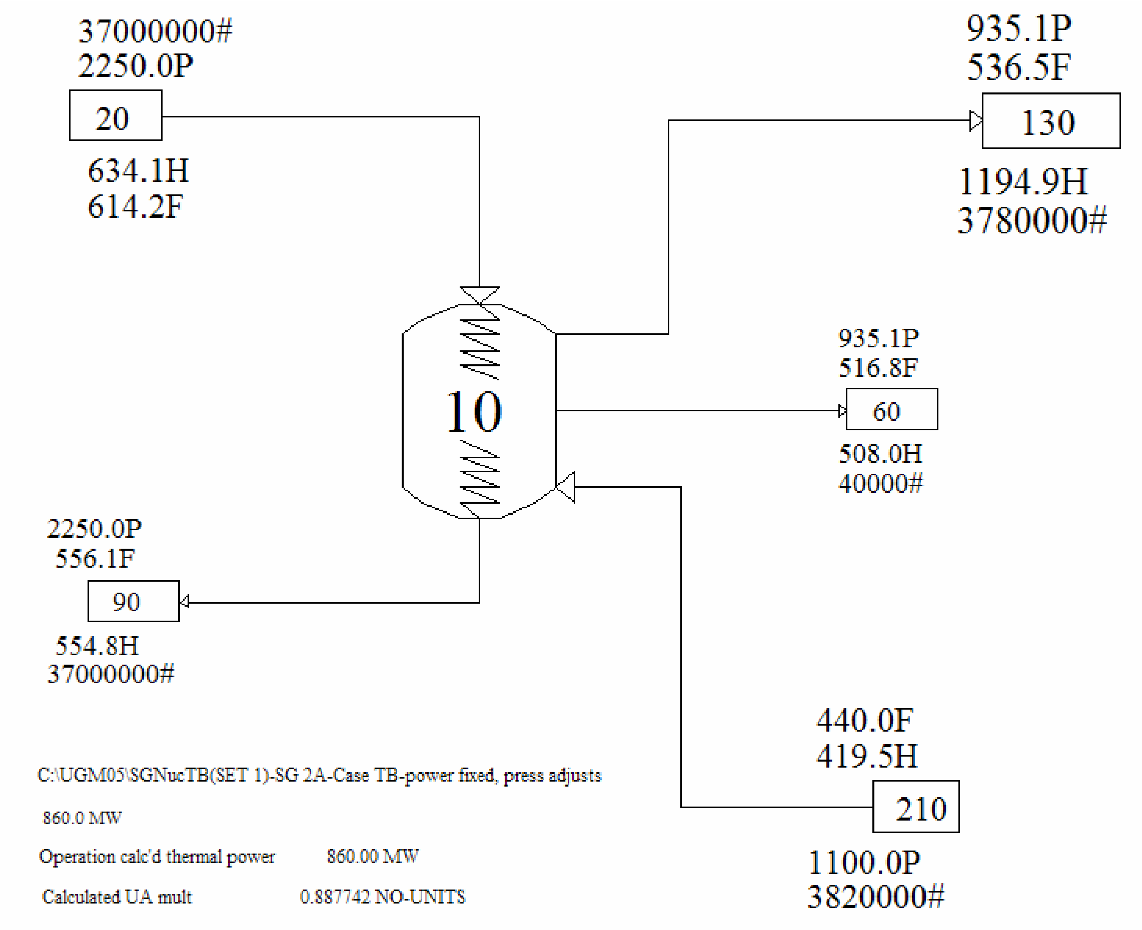
Results from Example Cases

Example models to demonstrate the four basic alternative cases have been created and run. The model used is a representative U-tube steam generator that is not necessarily exactly the same as any existing steam generator. The electronic files for these models are included with this paper. The figures below show results of calculations from these models.

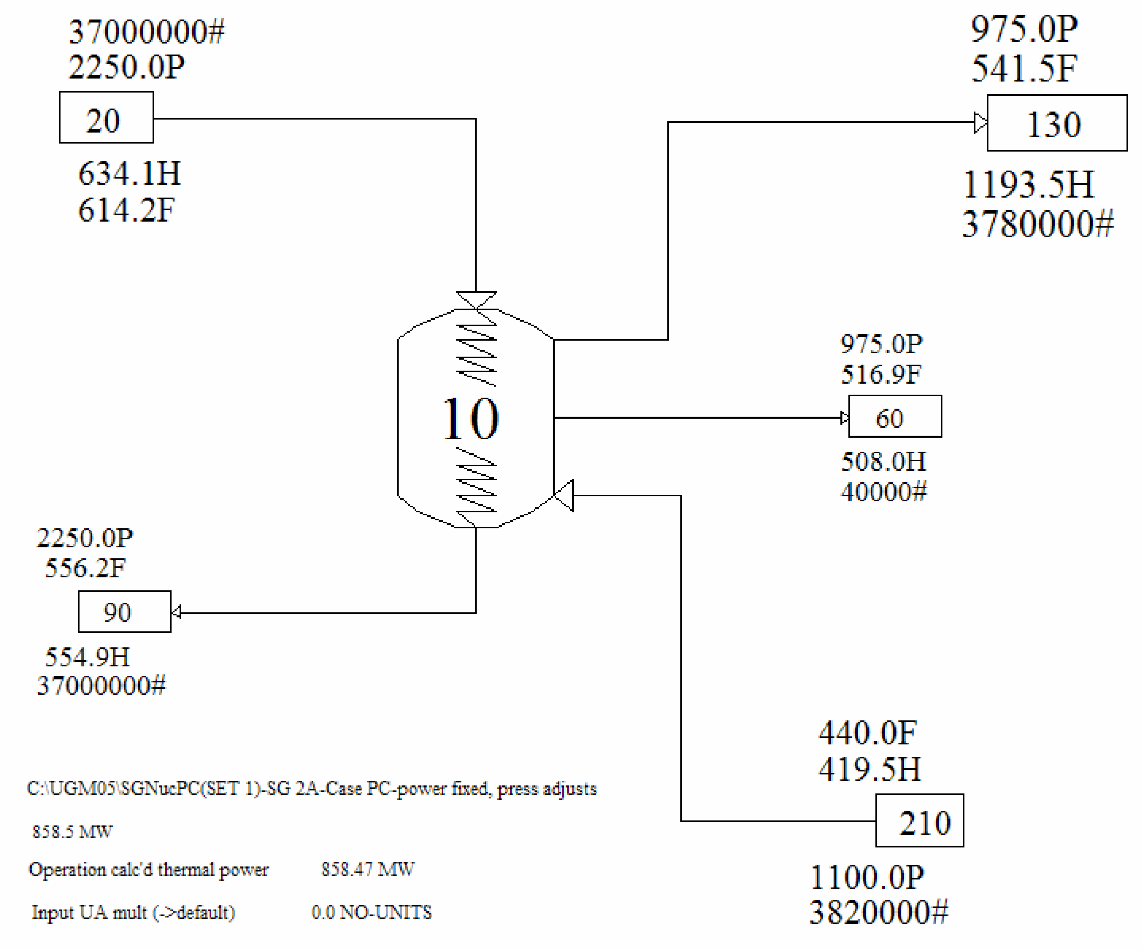
SGNucTA.MDL:


37000000#
2250.0P
20
634.1H
614.2F
975.0P
541.5F
130
1193.5H
3780000#
10
975.0P
516.9F
60
508.0H
40000#
2250.0P
556.2F
90
554.9H
37000000#
440.0F
419.5H
210
1100.0P
3820000#
C:\UGM05\SGNucTA(SET 1)-SG 2A-Case TA-power and pressure fixed
858.5 MW
Operation calc'd thermal power 858.47 MW
Calculated UA mult 1.02 NO-UNITS

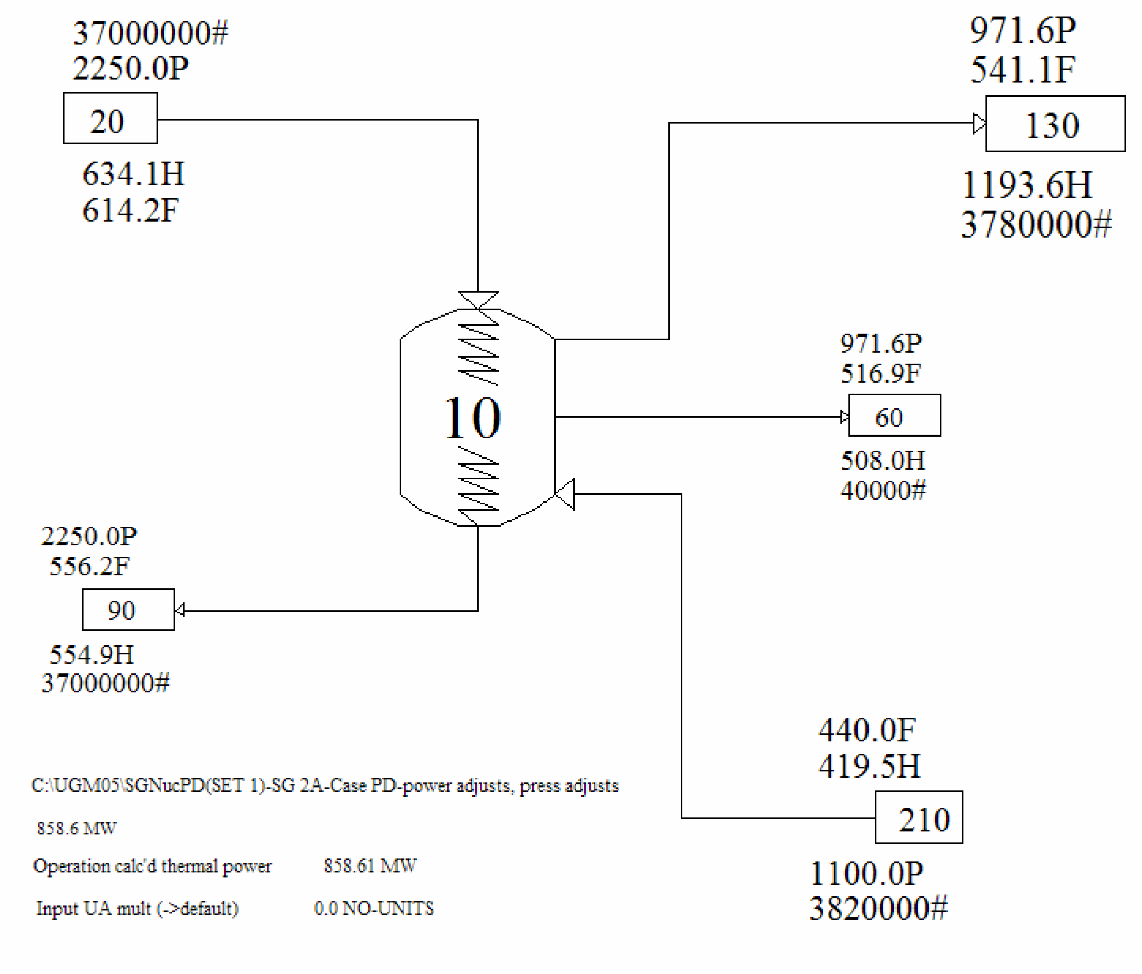
SGNucTB.MDL:


37000000#
2250.0P
20
634.1H
614.2F
935.1P
536.5F
130
1194.9H
3780000#
10
935.1P
516.8F
60
508.0H
40000#
2250.0P
556.1F
90
554.8H
37000000#
440.0F
419.5H
210
1100.0P
3820000#
C:\UGM05\SGNucTB(SET 1)-SG 2A-Case TB-power fixed, press adjusts
860.0 MW
Operation calc'd thermal power 860.00 MW
Calculated UA mult 0.887742 NO-UNITS

SGNucPC.MDL:


37000000#
2250.0P
20
634.1H
614.2F
975.0P
541.5F
130
1193.5H
3780000#
10
975.0P
516.9F
60
508.0H
40000#
2250.0P
556.2F
90
554.9H
37000000#
440.0F
419.5H
210
1100.0P
3820000#
C:\UGM05\SGNucPC(SET 1)-SG 2A-Case PC-power fixed, press adjusts
858.5 MW
Operation calc'd thermal power
858.47 MW
Input UA mult (->default)
0.0 NO-UNITS

SGNucPD.MDL:



Comparison of the results of the TA and TB cases shows that the UA multiplier and the shell-side pressure are quite sensitive to the specified value of thermal power. This demonstration suggests the importance of caution in validating and verifying results of models.

Summary

This paper has discussed the modeling of a U-Tube nuclear steam generator using the design mode component. Several analysis alternatives are possible. Two of these serve to tune factors to match known conditions (such as a vendor's performance claims or performance data), and two of these serve to predict the performance of a steam generator under varying operating conditions. Each of these alternatives has its specific combination of steam generator performance parameters that are fixed and those that vary, thus calculated by the model.

References

1. Minner, G.L., et al, “PEPSE Manual Volume 1, User Input Description”, Scientech, Inc, 2005.
2. Hughes, E.D. and Minner, G.L.,“Mathematical Models and Numerical Solution Methods for Nuclear Plant Steam Generators”, EPRI Nuclear Plant Performance Improvement Seminar, Asheville, NC, September 3-4, 1996.
3. Minner, G.L. and Hughes, E.D., “Application of PEPSE for Nuclear Steam Generator Analysis”, The 1996 Performance Software Users Group Meeting Proceedings, Charleston, S.C., June 11-14, 1996.

Appendix A

Steam Generator (Component Type 76)

The steam generator (SG) component, Type 76, is intended for applications in modeling the steam supply system of a pressurized water reactor nuclear power plant for steady state performance evaluation. This component can be used flexibly in combination with other PEPSE components to represent parts or all of the power generation system.

Both performance and design mode applications are available for the SG component.

Both "once-through" (OT) and "U-tube" (UT) arrangements are available. The boiling portion consists of vertical parallel tubes carrying the "primary" flow, immersed in the shell-side up-flowing "secondary" flow which is surrounded by a cylindrical shroud or "wrapper". Surrounding the shroud is a "downcomer", where recirculating (UT) or aspirated (OT) flow is occurring downward to re-enter the heating zone near the bottom of the vessel.

This paper focuses on the UT design mode application.

The performance mode analysis does an overall, macroscopic, heat balance calculation. Since it does not involve internal details, it applies equally well to the OT and UT configuration. This mode has several options available for user specification. In the normal hierarchy of data within PEPSE, whenever there is a redundancy or potential conflict of data inputs, the data appearing later in the list of inputs for the components overrides the earlier. The options include specification of secondary or primary side outlet fluid temperature or quality. Otherwise, it is possible to specify the primary-side thermal power. Once any one of these input parameters takes priority, PEPSE can calculate the others, by straightforward application of basic conservation principles, and integrate the impact of this component into the system analysis.

For design mode analysis, the UT SG model includes the option to describe a preheater, also called an economizer. In addition to the basic UT steam generator without a preheater, there are five types of preheater options in PEPSE modeling.

The design mode analysis by PEPSE does a detailed, mechanistic thermal/thermodynamic analysis of the heat transfer and energy transport processes in the steam generator. Ref 2 provides a comprehensive description of the details of this analysis. A complete description of the internal details of the steam generator must be provided by the user as inputs to PEPSE. The information needed includes tube diameters, lengths, thermal conductivities, and others.

In the design mode the method of calculation uses basic formulations of fluid mechanics and heat transfer, supplemented by friction factor and heat transfer coefficient correlations that are appropriate to the regime of flow and heat transfer.

Because of significantly varying heat transfer phenomena from one elevation to another, the design mode model breaks the steam generator’s heating zone into horizontal slices, called cells. Within any cell, the heat transfer regime is treated as uniform, and the primary fluid, tube wall, and secondary fluid temperatures are treated as uniform values. These cells communicate with each other through flow boundaries called links and through tube wall boundaries between primary and secondary-side cells. From a primary-side cell to a secondary-side cell, heat passes from the primary fluid through the tube wall boundary to the secondary fluid. The user chooses the number of horizontal slices that are used to represent the heating zone. The number of horizontal slices determines the numbers of primary-side and secondary-side cells. When a preheater section is present, it is also nodalized in this fashion, and the number of cells representing the preheater is also selected by the user. The size and count of cells at the corresponding elevations on the hot side (where there is no preheat section) is determined by the specifications for the preheater.

To provide versatility in methods, the heat transfer correlations used in the boiling section of the steam generator are an "old" set, called the Schrock-Grossman and the Dittus-Boelter correlations, and a "new" set, called the Winterton and the Petukhov correlations. See the bibliography of Ref 1 for additional details. We recommend that you select the “new” set.

The steam generator component has its own convergence criterion, input variable CNPWSG, that is used to monitor convergence of iterations within the component itself. The default value of this criterion is 1.e-5. It is a fractional tolerance used to monitor the difference between the primary side’s calculated thermal power and the secondary side’s calculated thermal power. When the fractional difference between these two power values falls below this criterion, the solution is converged. While you can override the default value, it is recommended that you do so judiciously. We have successfully used values as large as 1.e-3 and 1.e-4. However, it would be risky to use values that are larger than this. If you use larger values, the solution may be <u>called</u> converged, but the results will probably not be reliable.

U-Tube Steam Generator

The number of possible geometric arrangements of U-tube steam generators is large, depending on vendor and time-of-design and manufacture. Some of these devices are fairly simple, having a hot (primary-entering) side of the U-tube and a cold (primary-exiting) side of the U-tube. In this case, all of the feedwater generally enters high in the downcomer and mixes with the recirculating water flow. The split of downcomer water may not be equal from hot to cold side. PEPSE allows specification of this split via input.

Many other arrangements are possible, and several of these are provided for in the design mode, including up to 5 alternative descriptions of preheaters.

It is assumed here that one of the available modeling configurations can be used to represent your actual as-installed steam generator. Furthermore, it is assumed that you can understand and enter the necessary data inputs. The focus of this paper is to organize and describe the several alternative tuning and predictive uses that are available via the design mode.

Steam generator design mode models are computationally complex, and they are susceptible to difficulties that result in printing of warnings or failures. Some cases may fail or terminate abnormally with only a minimum of explanation/diagnostic information being provided. Potentially useful additional information about the causes of failure may be obtained by using the debug feature.

You are advised to use a submodel for your initial attempt(s) to run the design mode for a steam generator component. In other words, keep it simple.

Appendix B

See the PEPSE model, on this CD, called SGNucTA.MDL for an example of the tuning alternative, TA. Selection of this alternative has been made via inputs for the steam generator component in accordance with Table 1 in the main body of this paper.

See the PEPSE model, on this CD, called SGNucTB.MDL for an example of the tuning alternative, TB. Selection of this alternative has been made via inputs for the steam generator component in accordance with Table 1 in the main body of this paper.

See the PEPSE model, on this CD, called SGNucPC.MDL for an example of the predictive alternative, PC. Selection of this alternative has been made via inputs for the steam generator component in accordance with Table 1 in the main body of this paper.

See the PEPSE model, on this CD, called SGNucPD.MDL for an example of the predictive alternative, PD. Selection of this alternative has been made via inputs for the steam generator component in accordance with Table 1 table in the main body of this paper.