Simulation of Diurnal Thermal Energy Storage Systems: Preliminary Results

**S. Katipamula
S. Somasundaram
H. R. Williams^(a)**

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**Pacific Northwest Laboratory
Richland, Washington 99352**

MASTER

^(a) Summer Intern, Dept. of Mechanical Engineering, University of Alaska Fairbanks.

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SUMMARY

This report describes the results of a simulation of thermal energy storage (TES) integrated with a simple-cycle gas turbine cogeneration system. Integrating TES with cogeneration can serve the electrical and thermal loads independently while firing all fuel in the gas turbine. The detailed engineering and economic feasibility of diurnal TES systems integrated with cogeneration systems has been described in two previous PNL reports. The objective of this study was to lay the ground work for optimization of the TES system designs using a simulation tool called TRNSYS (TRaNsient SYstem Simulation). TRNSYS is a transient simulation program with a sequential-modular structure developed at the Solar Energy Laboratory, University of Wisconsin-Madison. The two TES systems selected for the base-case simulations were: 1) a one-tank storage model to represent the oil/rock TES system, and 2) a two-tank storage model to represent the molten nitrate salt TES system.

Results of the study clearly indicate that an engineering optimization of the TES system using TRNSYS is possible. The one-tank stratified oil/rock storage model described here is a good starting point for parametric studies of a TES system. Further developments to the TRNSYS library of available models (economizer, evaporator, gas turbine, etc.) are recommended so that the phase-change processes is accurately treated.

CONTENTS

1	INTRODUCTION	1
2	TRNSYS (TRaNsient SYstems Simulation)	3
	2.1 COMPUTATIONAL SCHEME	3
	2.2 SIMULATION METHODOLOGY	4
3	CASE STUDY I: ONE-TANK OIL/ROCK TES SYSTEM	7
	3.1 CONCEPT	7
	3.2 IDENTIFICATION OF COMPONENTS REQUIRED TO SIMULATE ONE-TANK TES SYSTEM	8
	3.3 SELECTION OF INDIVIDUAL COMPONENTS PARAMETERS	8
	3.4 SIMULATION RESULTS OF ONE-TANK OIL/ROCK TES SYSTEM ..	11
	3.5 VARYING STEAM LOAD	15
4	CASE STUDY II: TWO-TANK TES MOLTEN SALT SYSTEM	19
	4.1 CONCEPT	19
	4.2 IDENTIFICATION OF COMPONENTS REQUIRED TO SIMULATE TWO-TANK TES SYSTEM	20
	4.3 SELECTION OF INDIVIDUAL COMPONENTS PARAMETERS	20
	4.4 SIMULATION OF TWO-TANK MOLTEN SALT TES SYSTEM	20
5	CONCLUSIONS AND RECOMMENDATIONS	25
6	REFERENCES	27

FIGURES

2.1 A Flow Diagram Showing an Example of all Interconnections Between Components	5
3.1 Oil/Rock TES Technology	7
3.2 Schematic of the One-Tank Oil/Rock TES System	9
3.3 Change in the Diurnal Range of the Temperature	13
3.4 Change in the Diurnal Range of Selected Temperatures as a Function of the Storage Tank Volume	13
3.5 Change in the Diurnal Range for Selected Temperatures with the Average Density of Oil/Rock Storage Media (With conditions specified in Table 3.4 and base-case density)	14
3.6 Temperature of the Storage Media (oil/rock) as a Function of Tank Depth and Hour of the Day. (Tank depth of 1 corresponds to the top of the tank)	15
3.7 Schematic of the One-Tank Oil/Rock TES System for Varying Steam Load	16
3.8 Variation of Steam Load, Steam Temperature, and Mean Storage Tank Temperature Over a Typical Week	17
4.1 Molten TES Technology	19
4.2 Schematic of Two-Tank Molten Salt TES System for Varying Steam Load	21
4.3 Variation of Steam Load and Steam Temperature Over a Typical Week	24

TABLES

3.1 Design Operating Conditions and Physical Properties of Exhaust Gas, Water, Oil, and Rock	10
3.2 Design Parameters Based on the Operating Conditions and Physical Properties Given in Table 3.1	11
3.3 Base Case for Selected Parameters	12
3.4 Selected Parameters for the Sensitivity Analysis	14
3.5 Selected Parameters for Varying Steam Load Case	18
4.1 Design Operating Conditions and Physical Properties of Exhaust Gas, Water, and Molten Salt	22
4.2 Design Parameters Based on the Operating Conditions and Physical Properties Given in Table 4.1	23
4.3 Base Case for Selected Parameters	23

1 INTRODUCTION

The Pacific Northwest Laboratory^(a) leads the U.S. Department of Energy's Thermal Energy Storage Program. The program focuses on developing thermal energy storage (TES) for daily cycling (diurnal storage), annual cycling (seasonal storage), and utility applications. Diurnal TES can decouple the generation of electricity from the production of thermal energy, thus allowing the cogeneration facility to supply dispatchable power. The excess thermal energy recovered from the exhaust of the prime mover (gas turbine) is stored to meet diurnal thermal loads.

In previous studies by Somasundaram et al. (1992, 1993), the use of diurnal thermal energy storage combined with cogeneration systems (TES/Cogen) was evaluated. Although the designs presented in the studies were practical and operable, they were not optimized from a system cost and performance perspective. This report lays the ground work for the optimization of the TES/Cogen system. In this study, optimization of the system design is done by use of a simulation tool called TRNSYS (TRaNsient SYstem Simulation). TRNSYS is a transient simulation program with a sequential-modular structure developed at the Solar Energy Laboratory (SEL), University of Wisconsin-Madison, Madison, Wisconsin (Klein et al. 1976, 1994).

The selection of a specific storage system depends on the quality and quantity of recoverable thermal energy and on the nature of the thermal load to be supplied from the storage system. The focus of this investigation is to evaluate the simulation tool to design and optimize diurnal TES systems; therefore, the TES systems selected for evaluation were based on previous studies by Drost et al. (1989, 1990) and Somasundaram et al. (1992, 1993). The two different TES systems selected for the base-case simulations using TRNSYS were: 1) one-tank oil/rock TES system and 2) the two-tank molten nitrate salt TES system.

This report contains six sections. In Section 2, an introduction to TRNSYS and its capabilities as related to the simulation of TES systems are briefly discussed. This is followed by the case-studies: one-tank oil/rock TES system (Section 3) and the two-tank molten salt TES system (Section 4). The conclusion and recommendations in Section 5 are followed by a list of references in Section 6.

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2 TRNSYS (TRaNsient SYstems Simulation)

Design of any system has to be optimized to minimize the operating cost (life-cycle cost) while providing the desired performance. Optimization of the system design by simulation is a common practice because it is inexpensive. There are several tools to simulate thermal system performance (TRNSYS, HVACsim, etc.). TRNSYS was selected for this study because of its flexibility and modularity. In this section, a brief introduction to TRNSYS and TES system simulation methodology are provided.

TRNSYS is a transient simulation program with a sequential-modular structure developed by the Solar Energy Laboratory (SEL), University of Wisconsin-Madison (Klein et al. 1976, 1994). Although it was primarily developed to model solar thermal transient systems, it is widely used for non-solar transient thermal systems analysis as well (Klein et al. 1976, Huges 1979, Hackner et al. 1984, Guinn 1988, Katipamula et al. 1988).

TRNSYS functions as a compiler for a high level computer language designed specifically to connect component models of transient systems, and solve the resulting algebraic and differential equations describing the system. The system component is described by an individual FORTRAN subroutine that is either taken from the TRNSYS library or is user specified. The component models can be analytical or empirical representations of component performance. The modular format and the ability for the user to provide his or her own component models provide TRNSYS with general simulation capability applicable to almost all transient thermal system problems. TRNSYS library has a large number of thermodynamic component modules such as pumps, thermal storage units, valves, controllers, flow diverters, and heat exchangers. In addition, it also has general routines to perform psychrometric analysis, process solar radiation, solve differential equations, etc.

2.1 Computational Scheme

TRNSYS simulation models include a main module, several utility modules, and component modules interconnected in a sequential and logical manner describing the system to be studied. The performance of the system is the combined dynamic performance of all the components interconnected. To convey the information to TRNSYS, a simple language with essentially seven keywords^(a) (SIMULATION, UNIT, TYPE, PARAMETERS, INPUTS, OUTPUTS, DERIVATIVES, and END) is used.

Three distinct types of information are associated with each component model: PARAMETERS, INPUTS, and OUTPUTS. Throughout the simulation, the values of the PARAMETERS (such as physical size and area of the component) remain constant. INPUTS provide information that may or may not change with time (such as temperature, mass flow, and energy flow). OUTPUTS of a component, as a function of time, are

^(a)There are several other keywords that are optional.

calculated from the PARAMETERS and the INPUTS. A flow diagram showing an example of all the interconnections between components is shown in Figure 2.1.

During each simulation time step, TRNSYS uses successive substitution to solve for the output values. The solution is obtained by iteratively solving the set of simultaneous equations in the component modules until all changes in the values of inputs are less than the allowable tolerance values. When all inputs converge, the simulation proceeds to the next time step. In case the simulation does not converge with the specified number of iterations, the program will terminate with an error message. The tolerance values specified by the user affect the degree of accuracy of the simulation, and the time required for convergence. The current version of TRNSYS (version 14) implements a new computational scheme known as equation blocking to improve convergence properties, and it handles discrete control decisions in a manner that promotes convergence in the iterative calculations (Fiksel et al., 1994).

Previous work with TRNSYS by Hackner et al. (1984, 1985), Guinn (1988) and Katipamula et al. (1988) indicates that the program is sufficient for simulating the process control dynamics of the building and HVAC systems. Nevertheless, two limitations were mentioned by Hackner et al. (1985). First, the program did not accurately model the components at a small time step (less than 1 minute). Control dynamics such as hysteresis were not modeled in TRNSYS. Second, the simulation with a time step greater than 1 hour did not accurately show the dynamics of components built into the models.

Despite the above limitations, TRNSYS has many advantages over other energy simulation programs because of its modular nature. Also, an individual user can develop new component models and add them to the existing standard TRNSYS library. This feature enables the users to create modules for different types of equipment and control functions. The time step limitations mentioned above in no way compromise the simulation results of the diurnal thermal energy storage system because we intend to use a time step greater than 1 minute and less than 1 hour.

2.2 Simulation Methodology

To simulate TES systems described in the previous section using TRNSYS, the following steps were taken:

- 1) First, all components needed to model both the one-tank and the two-tank TES system were identified.
- 2) Design parameters (such as heat exchanger sizes, and tank volume) and operating conditions (temperatures and flow conditions) for both the one-tank and the two-tank models were determined.
- 3) A one-tank model was developed by interconnecting the existing component modules from the TRNSYS library.

- 4) A two-tank model was developed by interconnecting the existing component modules from the TRNSYS library.
- 5) A base-case simulation with constant 24-hour steam demand was run for both the one-tank and the two-tank models. This was necessary to establish the numerical stability of the model.
- 6) Certain modifications were made to the base-case configuration to simulate varying steam demand.

FIGURE 2.1. A Flow Diagram Showing an Example of all the Interconnections Between Components

3 CASE STUDY I: ONE-TANK OIL/ROCK TES SYSTEM

In previous studies, the relative benefit of combining a TES system with an existing cogeneration system for generating peak and/or intermediate load power has been shown (Somasundaram et al. 1992, 1993). In both studies, the sizes of the components (heat exchanger and the thermal storage tank) were not optimized. In this section, the minimum^(a) tank size for a given diurnal input heat rate and steam load is estimated by simulation. First the concept of the one-tank oil/rock TES system is presented, followed by development of a TRNSYS simulation deck, and then the simulation results.

3.1 Concept

The concept of integrating an oil/rock TES system in a natural-gas-fired simple-cycle cogeneration facility is shown in Figure 3.1. The oil and rock are contained in one or several carbon steel tanks, depending on the size of the TES system. A substantial portion of the tank volume is filled with inexpensive rock; the remaining volume is filled with more costly oil. The oil, which is about one-quarter of the storage volume, stores about 20% of the thermal energy as sensible heat, while the rest of the thermal energy is stored in the rock. Hot oil is added or removed from the top of the tank, while cool oil is removed or added from the bottom of the tank. This arrangement maintains a density-driven segregation (thermocline) between the hot oil at the top of the tank and the cool, denser oil at the bottom of the tank. The thermal storage capacity of the tank is determined by the temperature range achievable in the heat transfer medium. The heat transfer oil used in such applications tends to degrade above 304 °C (580 °F); therefore, this type of TES system is only to be used for low-temperature storage (maximum temperature less than 300 °C). However, the typical range is between 288 °C (550 °F) at the high end to about 121 °C (250 °F) at the low end.

FIGURE 3.1. Oil/Rock TES Technology

^(a)minimum tank size for a diurnal change of ± 1 °C in the hot water temperature at the exit of the economizer, this is discussed in detailed later in this section.

3.2 Identification of Components Required to Simulate One-Tank TES System

The first step in developing a TRNSYS model is to identify the thermodynamic components required to simulate the thermal system. Then the individual component parameters are identified. The third step is to associate unit numbers with the components and interconnect the components logically to describe the thermal system. Finally, the control statements are selected.

To simulate a one-tank oil/rock TES system, three types of thermodynamic components are required: 1) heat exchangers, 2) pumps, and 3) an oil/rock storage tank. The TRNSYS library has a pump module, a heat exchanger module, and a stratified storage tank module. The stratified storage tank module from the TRNSYS library assumes a homogeneous thermal medium. However, the oil/rock TES system has oil and rock as storage media. To simulate the oil/rock media, the average properties (specific heat and density) of the oil and the rock are used. Also, for this study, the pumps are not simulated. An 8-hour TES tank charging period is used throughout the study.

3.3 Selection of Individual Component Parameters

To model a component in a thermal system, the user must be able to adequately describe the performance of the components mathematically and identify the following: 1) parameters, 2) inputs, 3) outputs, and 4) derivatives for time-dependent variables. Because the components needed to simulate the one-tank oil/rock TES system are already formulated (TRNSYS library), only the design parameters based on the design operating conditions have to be calculated.

Therefore, the next step is to size the heat exchangers for the design operating condition. As shown in Figure 3.2, three heat exchangers are needed: 1) to extract heat from the exhaust gas from the gas turbine, 2) to raise the temperature and pressure of the feed water (from now on this is referred to as the economizer), and 3) to evaporate the hot water from the economizer to produce saturated steam (from now on this is referred to as the evaporator). Table 3.1^(a) lists the design operating conditions and the physical properties of the media; Table 3.2 lists the design parameters of the heat exchanger, the economizer, and the evaporator, respectively. Because Table 3.2 is generated using a spreadsheet, design parameters for a different set of design conditions can be easily generated.

^(a)The design operating conditions for this analysis were based on a previous study by Somasundaram et al. (1992).

UA: Overall heat transfer coefficient of heat exchanger; C_p : Specific heat of oil/gas/water;
 Vol: Volume of the storage stratified storage tank; ρ : Density of oil; U_{loss} : Heat loss coefficient;
 H: Height of the stratified storage tank;

FIGURE 3.2. Schematic of the One-Tank Oil/Rock TES System. (Required parameters for each of the components are also shown)

The only other design parameter that is not established yet, for the given operating conditions (Table 3.1), is the storage tank size. The minimum size of the storage tank is a function of several parameters: 1) the specific heat and density of the TES media, 2) the temperature difference between the top and bottom of the tank, and 3) the amount of stratification. The minimum size of the storage tank is determined by a series of simulations.

TABLE 3.1. Design Operating Conditions and Physical Properties of Exhaust Gas, Water, Oil, and Rock

Design Conditions	SI	IP
Steam load; kg/h, lb/h	181,440	400,000
Feed water temperature; °C, °F	49	120
Steam temperature; °C, °F	164	328
Enthalpy of feed water; kJ/kg @49 °C; Btu/lb @ 120 °F	209	88
Enthalpy (hfg); kJ/kg @7bars, 164 °C; Btu/lb @ 100 psia, 328 °F	2,760	1,187
Enthalpy (hf); kJ/kg @7bars, 164 °C; Btu/lb @ 100 psia, 328 °F	700	298
Charge time over 24-hour period	8	
Begin time of charge (noon)	12	
Temperature of the exhaust; °C, °F	531	988
Temperature of the gas exiting heat exchanger; °C, °F	204	400
Maximum temperature of hot oil; °C, °F	288	550
Storage tank temperature at the bottom of storage tank; °C, °F	149	300
Hot side exit temperature evaporator; °C, °F	177	350
Hot side exit temperature economizer; °C, °F	149	250
U-value for economizer; kJ/h-m ² -°C, Btu/h-ft ² -°F	3,046	150
U-value for evaporator; kJ/h-m ² -°C, Btu/h-ft ² -°F	3,046	150
U-value for Oil/Gas heat exchanger; kJ/h-m ² -°C, Btu/h-ft ² -°F	540	27
Physical Properties		
Specific heat of oil; kJ/kg-°C, Btu/lb-°F	1.68	0.4
Specific heat of water; kJ/kg-°C, Btu/lb-°F	4.19	1
Specific heat of exhaust gas; kJ/kg-°C, Btu/lb-°F	1.09	0.26
Specific heat of rock; kJ/kg-°C, Btu/lb-°F	0.84	0.20
Density of oil; kg/m ³ , lbm/ft ³	849	53
Density of rock; kg/m ³ , lbm/ft ³	1,600	100

TABLE 3.2. Design Parameters Based on the Operating Conditions and Physical Properties Given in Table 3.1

	Heat Exchanger		Evaporator		Economizer	
	SI	IP	SI	IP	SI	IP
Surface area; m ² , ft ²	20,321	218,744	2,493	26,838	673	7,240
Energy transfer; kJ/h, Btu/h	1,388,560,320	1,316,170,919	373,766,400	354,280,948	87,364,267	82,809,732
UA; kJ/h-°C, Btu/h-°F	10,973,528	548,676	7,594,301	4,025,626	2,048,763	100,891
Fraction of temperature drop			79.86%	79.86%	20.14%	20.14%
Fraction of energy drop			81.05%	81.05%	18.95%	18.95%
Mass flow rate hot side; kg/h, lb/h	3,899,322	8,596,389	2,010,307	4,431,895	2,010,307	4,431,895
Mass flow rate cold side; kg/h, lb/h	5,963,966	13,148,073	181,440	400,000	181,440	400,000

3.4 Simulation Results of One-Tank Oil/Rock TES System

Once all components of the TES systems have been identified and the parameters of the components selected, the components have to be interconnected in a logical manner to simulate the one-tank oil/rock TES system. The logical order to simulate the oil TES system is shown in Figure 3.2. The heat exchanger that charges the cold oil from the TES tank is referred to as Unit 1, the TES tank is referred to as Unit 2, the evaporator and the economizer are referred as Units 3 and 4, respectively. The simulation begins with heating of the cold oil from the bottom of storage tank (Unit 2) in the heat exchanger by the exhaust gas from the gas turbine prime mover. The hot oil then enters the top of the tank to charge the TES tank. The hot oil is continuously withdrawn from the top of the storage tank and circulated through an evaporator/economizer pair (Unit 3 and Unit 4) to heat the feed water and generate process steam.

Whatever numerical modeling technique is used, it is important to select a proper time step and error tolerance for stable and accurate results. TRNSYS allows the user to select the time step, error tolerance for numerical integration, and error tolerance for algebraic equations. The error tolerance can be relative or absolute. Selection of the time step depends on type and order of the differential equations involved in the formulation of the component module. In this case (storage tank), only first order linear differential equations are involved in determining stratified tank temperatures; therefore, a time step of 0.25 (15 min.) and a relative error tolerance (integration) of 0.01 is selected.

TABLE 3.3. Base Case for Selected Parameters

Parameter	Base Case Value
Exhaust gas flow and temperature	Constant (see Table 3.1)
Steam load	Constant (see Table 3.1)
Tank volume	300,000 m ³
Charge time	Constant (see Table 3.1)
Relative integration error tolerance	0.01
Time step	0.25 h (15 min.)
Input time interval	1 hr (60 min.)

The choice of algebraic tolerance affects tank size; therefore, it was selected by performing parametric runs. While performing parametric runs, the following temperatures were used to characterize the performance of the one-tank oil/rock TES system: 1) the diurnal range of the mean oil temperature in the storage tank (i.e., the difference between the maximum and the minimum mean oil temperature during a 24-hour operation), 2) the diurnal range of the oil temperature at the top of the storage tank, 3) the diurnal range of the oil temperature at the bottom of the storage tank, and 4) the diurnal range of the hot water temperature at the exit of the economizer (Unit 4). To select the optimum algebraic error tolerance, a series of runs were made with varying absolute algebraic error tolerances. Tank size was intentionally made large for these runs to limit its (tanks) influence on the stratification (tank volume of 300,000 m³) (Table 3.3).

The diurnal range of the mean oil temperature in the storage tank, and the diurnal temperature range at the top and the bottom of the tank are insensitive to the absolute algebraic tolerance (Figure 3.3). However, the diurnal range for hot water temperature at the exit of the economizer changes from 2.3 °C with an error tolerance of 0.01 °C to 0.1 °C at 0.5 °C error tolerance. A diurnal change of ± 1 °C in the hot water temperature at the exit of the economizer is reasonable. It can be achieved with an absolute algebraic error tolerance of 0.5 °C.

Once the algebraic error tolerance is fixed, the next step is to optimize the tank size. Again, the same temperatures that were used to establish an optimum absolute algebraic error tolerance are used in the selection of the minimum tank size. A series of parametric runs with varying tank volumes were made (100,000 to 300,000 m³). The diurnal change in the selected temperatures is shown in Figure 3.4. There is a rapid decrease in the diurnal range of all four temperatures. By using the same criteria, that is, a diurnal change of ± 1 °C in the hot water temperature at the exit of the economizer, the minimum tank size is 150,000 m³.

- — diurnal range in the hot water temperature at the exit of the economizer
- △ diurnal range in the temperature of the oil at the bottom of the storage tank
- - - - diurnal range in the temperature of oil at the top of the storage tank
- ◇ - · - · diurnal range of the mean oil temperature in the storage tank

FIGURE 3.3. Change in the Diurnal Range of the Temperature

FIGURE 3.4. Change in the Diurnal Range for Selected Temperatures as a Function of the Storage Tank Volume

FIGURE 3.5 Change in the Diurnal Range for Selected Temperatures with the Average Density of Oil/Rock Storage Media (with conditions specified in Table 3.4 and base-case density)

TABLE 3.4. Selected Parameters for the Sensitivity Analysis

Parameter	Base Case Value
Exhaust gas flow and temperature	Constant (see Table 3.1)
Steam load	Constant (see Table 3.1)
Tank volume	150,000 m ³
Charge time	Constant (see Table 3.1)
Relative integration error tolerance	0.01
Time step	0.25 h (15 min.)
Absolute algebraic error tolerance	0.5 °C
Input time interval	1 h (60 min.)

Figure 3.5 shows the effect of the change in the average density of the oil/rock storage media. The diurnal change in all four temperatures decreases with an increase in the average density of the storage media.

FIGURE 3.6. Temperature of the Storage Media (oil/rock) as a Function of Tank Depth and Hour of the Day. (Tank depth of 1 corresponds to the top of the tank)

Figure 3.6 shows the variation of temperature in the storage tank as a function of the depth of the tank and the hour of the day. The charging of the TES system begins at 12 noon and ends at 8 p.m. The diurnal variation in the tank temperatures can be clearly seen; for example, the minimum temperature both at the top and the bottom of the tank occurs just before the charge begins (11 a.m.) and the maximum temperature occurs just after the charge ends (8 p.m.).

3.5 Varying Steam Load

In the previous section, all simulations were performed with constant exhaust gas flow and constant steam load. The model developed in the previous section is not adequate to model the diurnal variation of steam because only one evaporator/economizer pair was used. To simulate varying steam loads a new model is needed. The new configuration, which has four identical evaporator/economizer pairs, is shown in Figure 3.7. This

FIGURE 3.7. Schematic of the One-Tank Oil/Rock TES System for Varying Steam Load

configuration allows for better control of the steam conditions under varying steam loads. For example, to meet a steam load of 50% of the total rated steam demand, only two loops would be used; the other two would have no flow going through them. Using this new configuration, the performance of the one-tank TES system was simulated under varying steam loads and constant exhaust gas flow. The new steam load profile varied from 50% at night time to 100% during the day time for weekdays and it was constant at 50% during weekends (Figure 3.8). The base case for selected parameters for this new configuration is shown in Table 3.5. The results as characterized by the steam temperature and the mean temperature of the storage tank are shown in Figure 3.8. These results are similar to the results obtained for the constant steam load case.

FIGURE 3.8. Variation of Steam Load, Steam Temperature, and Mean Storage Tank Temperature Over a Typical Week

TABLE 3.5. Selected Parameters for Varying Steam Load Case

Parameter	Base Case Value
Exhaust gas flow and temperature	Constant (see Table 3.1)
Steam load	Varying (Figure 3.7)
Tank volume	150,000 m ³
Charge time	Constant (see Table 3.1)
Relative integration error tolerance	0.01
Time step	0.25 h (15 min.)
Input time interval	1 hr (60 min.)

4 CASE STUDY II: TWO-TANK TES MOLTEN SALT SYSTEM

In this section the concept, development of TRNSYS simulation deck, and the simulation results for the two-tank molten salt TES system are presented.

4.1 Concept

The density-driven segregation (thermocline) helps maintain the temperature difference between the top and the bottom of a one-tank TES system. The efficiency and the size of this system (one-tank) depends on the thermocline. Instead of relying on a thermocline to store sensible energy in a single tank, an alternate option is to use two tanks (Figure 4.1). In the two-tank system, the hot and cold streams are isolated. By separating the hot and the cold salt, the difficulties associated with maintaining the thermocline are avoided. Thermal energy extracted from the exhaust of the gas turbine is stored as sensible heat in the molten salt (hot tank). The molten salt is a mixture of sodium nitrate (60 wt%) and potassium nitrate (40 wt%). The salt mixture degrades at a temperature above 593 °C (1100 °F) and it freezes at a temperature near 240 °C (464 °F); therefore, the operating temperature range is between 510 °C (950 °F) and 288 °C (550 °F).

FIGURE 4.1. Molten Salt TES Technology

4.2 Identification of Components Required to Simulate Two-Tank TES System

To simulate a two-tank molten salt TES system, three types of thermodynamic components are required: 1) heat exchangers, 2) pumps, and 3) variable-volume storage tank. The TRNSYS library has all three of these modules. Unlike the stratified storage tank used with the one-tank TES system, the storage tank used for the two-tank model is fully mixed (i.e., the media temperature is constant). Again, as in the case of the one-tank system, the pumps are not simulated and an 8-hour TES tank charge period is used throughout the study. The schematic of the two-tank molten salt TES system is shown in Figure 4.2.

4.3 Selection of Individual Component Parameters

Because the components needed to simulate the performance of the two-tank molten salt TES system are already formulated (TRNSYS library), only the design parameters based on the design operating conditions have to be calculated. The design operating conditions for this analysis were also based on a previous study by Somasundaram et al. (1992). As shown in Figure 4.2, three heat exchangers are needed: 1) to extract heat from the exhaust gas of the gas turbine, 2) to raise the temperature and pressure of the feed water (from now on this is referred to as the economizer), and 3) to evaporate the hot water from the economizer to produce saturated steam (from now on this is referred to as the evaporator). Table 4.1 lists the design operating conditions and the physical properties of the media; Table 4.2 lists the design parameters of the heat exchanger, the economizer, and the evaporator, respectively. Because Table 4.2 is generated using a spreadsheet, design parameters for a different set of design conditions can be easily generated.

4.4 Simulation of Two-Tank Molten Salt TES System

The logical order to simulate the two-tank TES system is shown in Figure 4.2. The heat exchanger that charges the cold salt from the cold tank is referred to as Unit 2; the hot salt tank is referred to as Unit 3; the evaporator and the economizer pairs are referred as Units 33/43, Unit 34/44, Unit 35/35 and Unit 36/46, respectively; and the cold tank is referred to as Unit 6. The simulation begins with the heat exchanger (Unit 2) where salt from the cold tank (Unit 6) is heated by the exhaust gas from the gas turbine prime mover. The hot molten salt is then stored in the hot tank (Unit 3). The hot salt from the hot tank is continuously withdrawn and circulated through an evaporator/economizer pair (Units 33/43, 34/44, 35/45, 36/46) to heat the feed water and generate process steam.

Because the two-tank TES system does not depend on the density-driven difference for storing the sensible energy, the tank size (both hot and cold) is just a function of the steam load and properties of the storage salt media. No parametric runs are necessary because all the simulation parameters are known. The simulation parameters are tabulated in Table 4.3. The simulation with varying steam load was performed and the results, as characterized by the steam temperature, are shown in Figure 4.3.

FIGURE 4.2. Schematic of the Two-Tank Molten Salt TES System for Varying Steam Load

TABLE 4.1. Design Operating Conditions and Physical Properties of Exhaust Gas, Water, and Molten Salt

Design Conditions	SI	IP
Steam load; kg/h, lb/h	181,440	400,000
Feed water temperature; °C, °F	49	120
Steam temperature; °C, °F	164	328
Enthalpy of feed water; kJ/kg @49 °C; Btu/lb @ 120 °F	209	88
Enthalpy (hfg); kJ/kg @7bars, 164 °C; Btu/lb @ 100 psia, 328 °F	2,760	1,187
Enthalpy (hf); kJ/kg @7bars, 164 °C; Btu/lb @ 100 psia, 328 °F	700	298
Charge time over 24-hour period	8	
Begin time of charge (noon)	12	
Temperature of the exhaust; °C, °F	531	988
Temperature of the gas exiting heat exchanger; °C, °F	302	575
Temperature of hot tank; °C, °F	510	950
Temperature of cold tank; °C, °F	288	550
Hot side exit temperature evaporator; °C, °F	327	620
Hot side exit temperature economizer; °C, °F	288	550
U-value for economizer; kJ/h-m ² -°C, Btu/h-ft ² -°F	3,046	150
U-value for evaporator; kJ/h-m ² -°C, Btu/h-ft ² -°F	3,046	150
U-value for salt/gas heat exchanger; kJ/h-m ² -°C, Btu/h-ft ² -°F	540	27
Physical Properties		
Specific heat of salt; kJ/kg-°C, Btu/lb-°F	1.62	0.4
Specific heat of water; kJ/kg-°C, Btu/lb-°F	4.19	1
Specific heat of exhaust; gas kJ/kg-°C, Btu/lb-°F	1.09	0.26

TABLE 4.2. Design Parameters Based on the Operating Conditions and Physical Properties Given in Table 4.1

	Heat Exchanger		Evaporator		Economizer	
	SI	IP	SI	IP	SI	IP
Surface area; m ² /ft ²	149,078	1,604,716	506	5,448	145	1,566
Energy transfer; kJ/h, Btu/h	1,388,560,320	1,316,170,919	373,766,400	354,280,948	87,786,317	83,209,779
UA; kJ/h-°C, Btu/h-°F	80,502,169	4,025,108	1,541,657	817,209	443,166	21,824
Fraction of temperature drop			82.50%	82.50%	17.50%	20.14%
Fraction of energy drop			80.98%	80.98%	19.02%	18.95%
Mass flow rate hot side; kg/h, lb/h	5,557,242	12,251,416	1,261,588	2,781,278	1,261,588	2,781,278
Mass flow rate cold side; kg/h, lb/h	3,866,659	8,524,381	181,440	400,000	181,440	400,000

TABLE 4.3. Base Case for Selected Parameters

Parameter	Base Case Value
Exhaust gas flow and temperature	Constant (see Table 4.1)
Steam load	Varying (Figure 4.3)
Hot/cold tank volume	m ³
Charge time	Constant (see Table 4.1)
Relative integration error tolerance	0.01
Time step	0.25 h (15 min.)
Input time interval	1 hr (60 min.)

FIGURE 4.3. Variation of Steam Load and Steam Temperature Over a Typical Week

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main objective of this study was to lay the ground work for optimization of the TES/Cogen system with the use of TRNSYS. The results clearly indicate that such optimization is possible and TRNSYS can be used as an effective design tool for optimization of diurnal thermal energy storage applications with cogeneration. The one-tank stratified oil/rock storage model described here is a good starting point for parametric studies and further developments to the model.

5.2 Recommendations

Because the TRNSYS library has no evaporator or economizer modules, these components were modeled as simple heat exchangers. In the case of the evaporator, a very high UA (overall heat transfer coefficient of the heat exchanger) value was selected to minimize the change in temperature of the water, and therefore mimic the behavior of a true evaporator. Modeling the economizers as heat exchangers effectively ignores saturation temperature vapor fraction changes. Eventually, subroutines should be written that will allow more accurate treatment of the phase-change processes that occur in real evaporators and economizers.

The TRNSYS library also does not include a gas turbine module. This would be a useful subroutine for this system in particular, and may be of general interest to TRNSYS users. Having a gas turbine module would allow simulation of the entire TES/Cogen system. The standard TES tank module in the TRNSYS library can simulate only 15 stratified layers, and this may have to be modified depending on the height of the storage tank.

Once an industrial site is identified for a site-specific feasibility study, some consideration of the minimum tank size would be required. If optimization for a specific installation shows that the tank required is on the same order of magnitude as the one in this study, the model would need to be adapted to include multiple tanks to realistically model tanks that are available on the market and the safety issue (maximum allowable height). Also, with a specific site in mind, realistic ambient temperature data could be incorporated into the input data file to improve the accuracy of heat transfer losses to the environment. The pumps and the energy required for pumping should also be simulated in the future.

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APPENDIX

TRNSYS Input Deck Listing

Appendix

I. Listing of TRNSYS input deck for one-tank oil/rock TES system simulation.

ASSIGN \TRNSYS14\work\oiltes\MULTI3.LST 6
ASSIGN \TRNSYS14\work\oiltes\MULTI3.DAT 10

ASSIGN \TRNSYS14\work\oiltes\M170q41.OUT 12
ASSIGN \TRNSYS14\work\oiltes\M170q42.OUT 13
ASSIGN \TRNSYS14\work\oiltes\M170q43.OUT 14
ASSIGN \TRNSYS14\work\oiltes\M170q44.OUT 15

SIMULATION 1 840 0.25
TOLERANCES 0.01 -0.5
WIDTH 72

EQUATIONS 17

Steps = 840
Start = 1
Vol = 150000
CpMed = 1.007
DenMed = 1495
Load = 181440
Flow = 2021757
HXUA = 8230146
EvUA = 7594301
EcUA = 2048763
HfLd = 0.5 * Load
QtLd = 0.5 * HfLd
HfFl = 0.5 * Flow
QtFl = 0.5 * HfFl
QtEvUA = 0.25 * EvUA
QtEcUA = 0.25 * EcUA
HxFlow = 0.75*[9,3]

UNIT 9 TYPE 9 DATA READER

PARAMETERS 5

*mode,# inputs,data dt,logical unit,format type
2 8 1 10 -1

UNIT 1 TYPE 5 HEAT EXCHANGER

PARAMETERS 4

*MODE, UAHX, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE

2 HXUA 1.089 1.675

INPUTS 4

*Thi, m_h, Tci, m_c

0,0 HxFlow 2,1 9,4

531 0 288 0

UNIT 2 TYPE 4 OIL TES

PARAMETERS 20

*mode, Vf, c_poil, density_oil, u_loss, tank height

1 Vol CpMed DenMed 0.00204 -100 1 1 1 288 18 0 15 15 149 18 0 0 0 316

INPUTS 5

*Tht mt Tb mb To

1,3 1,4 59,1 0,0 9,2

288 0 149 Flow 27

DERIVATIVES 15

288 280 275 265 255 245 235 225 215 205 195 185 175 165 149

*TRACE 241 264

UNIT 50 TYPE 11 CONTROLLED FLOW DIVERTER

PARAMETERS 1

*mode

2

INPUTS 3

*T_i m_i gamma

2,3 2,4 0,0

288 Flow 0.5

UNIT 51 TYPE 11 CONTROLLED FLOW DIVERTER

PARAMETERS 1

*mode

2

INPUTS 3

*T_i m_i gamma

50,1 50,2 0,0

288 HiFi 0.5

UNIT 52 TYPE 11 CONTROLLED FLOW DIVERTER

PARAMETERS 1

*mode

2

INPUTS 3

*T_i m_i gamma

50,3 50,4 0,0

288 HiFi 0.5

UNIT 33 TYPE 5 EVAPORATOR

PARAMETERS 4

*MODE, UAHX, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE

2 QtEvUA 1.675 4969.6

INPUTS 4

* T_hi, m_h, T_ci, m_c

51,1 51,2 43,3 43,4

288 QtFi 164 QtLd

*TRACE Start Steps

UNIT 34 TYPE 5 EVAPORATOR

PARAMETERS 4

*MODE, UAHX, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE

2 QtEvUA 1.675 4969.6

INPUTS 4

* T_hi, m_h, T_ci, m_c

51,3 51,4 44,3 44,4

288 QtFi 164 QtLd

*TRACE 241 264

UNIT 35 TYPE 5 EVAPORATOR

PARAMETERS 4

*MODE, UAHX, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE

2 QtEvUA 1.675 4969.6

INPUTS 4

* T_hi, m_h, T_ci, m_c

*52,1 52,2 45,3 45,4

52,1 52,2 45,3 9,7

288 QtFI 164 QtLd

TRACE Start Steps

UNIT 36 TYPE 5 EVAPORATOR

PARAMETERS 4

*MODE, UAHX, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE

2 QtEvUA 1.675 4969.6

INPUTS 4

* T_hi, m_h, T_ci, m_c

*52,3 52,4 46,3 46,4

52,3 52,4 46,3 9,8

288 QtFI 164 QtLd

*TRACE 241 264

UNIT 43 TYPE 5 ECONOMIZER

PARAMETERS 4

*MODE, UAHX, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE

2 QtEcUA 1.675 4.187

INPUTS 4

* T_hi, m_h, T_ci, m_c

33,1 33,2 0,0 9,5

177 QtFI 49 QtLd

*TRACE Start Steps

UNIT 44 TYPE 5 ECONOMIZER

PARAMETERS 4

*MODE, UAHX, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE

2 QtEcUA 1.675 4.187

INPUTS 4

* T_hi, m_h, T_ci, m_c

34,1 34,2 0,0 9,6

177 QtFI 49 QtLd

UNIT 45 TYPE 5 ECONOMIZER

PARAMETERS 4

*MODE, UAHX, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE

2 QtEcUA 1.675 4.187

INPUTS 4

* T_hi, m_h, T_ci, m_c

35,1 35,2 0,0 9,7

177 QtFI 49 QtLd

TRACE Start Steps

UNIT 46 TYPE 5 ECONOMIZER

PARAMETERS 4

*MODE, UAHX, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE
2 QtEcUA 1.675 4.187
INPUTS 4
* T_hi, m_h, T_ci, m_c
36,1 36,2 0,0 9,8
177 QtFI 49 QtLD
*TRACE Start Steps

UNIT 57 TYPE 11 TEE PIECE
PARAMETERS 1
*mode
1
INPUTS 4
*T_1 m_1 T_2 m_2
43,1 43,2 44,1 44,2
149 QtFI 149 QtLD

UNIT 58 TYPE 11 TEE PIECE
PARAMETERS 1
*mode
1
INPUTS 4
*T_1 m_1 T_2 m_2
45,1 45,2 46,1 46,2
149 QtFI 149 QtLD

UNIT 59 TYPE 11 TEE PIECE
PARAMETERS 1
*mode
1
INPUTS 4
*T_1 m_1 T_2 m_2
57,1 57,2 58,1 58,2
149 HtFI 149 HtFI

UNIT 53 TYPE 11 TEE PIECE
PARAMETERS 1
*mode
1
INPUTS 4
*T_1 m_1 T_2 m_2
33,3 33,4 34,3 34,4
164 QtLD 164 QtLD
*TRACE Start End

UNIT 54 TYPE 11 TEE PIECE
PARAMETERS 1
*mode
1
INPUTS 4
*T_1 m_1 T_2 m_2
35,3 35,4 36,3 36,4
164 QtLD 164 QtLD
*TRACE Start End

UNIT 55 TYPE 11 TEE PIECE

PARAMETERS 1

*mode

1

INPUTS 4

*T_1 m_1 T_2 m_2

53,1 53,2 54,1 54,2

164 HfLd 164 HfLd

*TRACE Start End

*Print steam delivery temps from four evaporators and hot water

*temps at the exit of the economizer (cold side) and mean tank temp.

UNIT 10 TYPE 25 PRINTER

PARAMETERS 5

*STEP START STOP LOGICAL-UNIT UNITS

1 Start Steps 12 2

INPUTS 10

55,1 33,3 34,3 35,3 36,3 43,3 44,3 45,3 46,3 2,12

551 333 343 353 363 432 442 452 462 212

*Print outputs from unit 1 (heat exchanger) and unit 33 (evaporator)

UNIT 5 TYPE 25 PRINTER

PARAMETERS 5

*STEP START STOP LOGICAL-UNIT UNITS

1 Start Steps 13 2

INPUTS 10

1,1 1,2 1,3 1,4 1,5 1,6 33,1 33,2 33,3 33,4

11 12 13 14 15 16 331 332 333 334

*Print outputs from unit 2 (Stratified TES) partial

UNIT 7 TYPE 25 PRINTER

PARAMETERS 5

*STEP START STOP LOGICAL-UNIT UNITS

1 Start Steps 14 2

INPUTS 10

2,1 2,2 2,3 2,4 2,6 2,7 2,11 2,13 2,14 2,15

21 22 23 24 26 27 211 213 214 215

*Print outputs from unit 2 (Stratified TES) partial

UNIT 8 TYPE 25 PRINTER

PARAMETERS 5

*STEP START STOP LOGICAL-UNIT UNITS

1 Start Steps 15 2

INPUTS 10

2,16 2,17 2,18 2,19 2,20 2,21 2,22 2,23 2,24 2,25

216 217 218 219 220 221 222 223 224 225

END

II. Listing of TRNSYS input deck for two-tank molten salt TES system simulation.

```
ASSIGN \TRNSYS14\WORK\MSALT\multi.LST 6
ASSIGN \TRNSYS14\WORK\MSALT\multi.DAT 10

ASSIGN \TRNSYS14\WORK\MSALT\UNIT31.OUT 12
ASSIGN \TRNSYS14\WORK\MSALT\UNIT32.OUT 13
ASSIGN \TRNSYS14\WORK\MSALT\UNIT33.OUT 14
ASSIGN \TRNSYS14\WORK\MSALT\UNIT34.OUT 15

SIMULATION 1 672 0.25
TOLERANCES 0.01 -0.5
WIDTH 72

EQUATIONS 27
Load = 181440
LhFlow = 1261588
UaHx = 80502169
UaEv = 1541657
QtUaEv = 0.25*UaEv
UaEc = 443166
QtUaEc = 0.25*UaEc
CpSalt = 1.616
CpGas = 1.0885
CpWater = 4.187
GasT = 531
DenSalt = 1849
Start = 1
Steps = 672
FeedT = 49
PI = 22./7.
TVol = 18162
iHotTVol = 7224.769544
iColdTVol = TVol - iHotTVol
THEi = 37
TDia = 25
TCir = PI*TDIA
Txa = PI*TDIA*TDIA/4
HfLd = 0.5*Load
QtLd = 0.25*Load
HfFl = 0.5*LhFlow
QtFl = 0.25*LhFlow

UNIT 9 TYPE 9 DATA READER
PARAMETERS 11
*MODE, # INPUTS TO READ, LOGICAL UNIT FORMAT TYPE
*2 8 1 10 -1
* forcing nointerpolation on col 7 and 8
2 8 1 -7 1 0 -8 1 0 10 -1
UNIT 2 TYPE 5 HEAT EXCHANGER
PARAMETERS 4
*MODE, UAHX, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE
2 UaHx CpGas CpSalt
```

INPUTS 4

*Thi, m_h, Tci, m_c

0,0 9,3 6,1 9,4

GasT 0 288 0

*TRACE START Steps

UNIT 3 TYPE 39 SALT HOT TANK

PARAMETERS 12

*mode,Vf,vmin,vmax,Cx, Ax, U_w, U_d, C_psalt, density_salt, T_i, m_i

2 TVol 1 TVol TCir Txa 0.0001 0.0001 CpSalt DenSalt 510 iHotTVol

INPUTS 4

*Tht mt mb To

2,3 2,4 0,0 9,2

510 0 LhFlow 32.2

*TRACE START Steps

UNIT 50 TYPE 11 CONTROLLED FLOW DIVERTER

PARAMETERS 1

*mode

2

INPUTS 3

*T_i m_i gamma

3,1 3,2 0,0

510 LhFlow 0.5

UNIT 51 TYPE 11 CONTROLLED FLOW DIVERTER

PARAMETERS 1

*mode

2

INPUTS 3

*T_i m_i gamma

50,1 50,2 0,0

510 HiFi 0.5

UNIT 52 TYPE 11 CONTROLLED FLOW DIVERTER

PARAMETERS 1

*mode

2

INPUTS 3

*T_i m_i gamma

50,3 50,4 0,0

510 HiFi 0.5

UNIT 33 TYPE 5 EVAPORATOR

PARAMETERS 4

*MODE, UA EV, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE

2 QtUaEv CpSalt 2060

INPUTS 4

*T_hi, m_h, T_ci, m_c

51,1 51,2 43,3 9,5

510 QtFi 164 QtLd

*TRACE START 48

UNIT 34 TYPE 5 EVAPORATOR

PARAMETERS 4

*MODE, UAEV, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE
2 QtUaEv CpSalt 2060
INPUTS 4
*T_hi, m_h, T_ci, m_c
51,3 51,4 44,3 9,6
510 QtFI 164 QtLd
*TRACE START 48

UNIT 35 TYPE 5 EVAPORATOR

PARAMETERS 4

*MODE, UAEV, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE
2 QtUaEv CpSalt 2060
INPUTS 4
*T_hi, m_h, T_ci, m_c
52,1 52,2 45,3 9,7
510 QtFI 164 QtLd
*TRACE START 48

UNIT 36 TYPE 5 EVAPORATOR

PARAMETERS 4

*MODE, UAEV, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE
2 QtUaEv CpSalt 2060
INPUTS 4
*T_hi, m_h, T_ci, m_c
52,3 52,4 46,3 9,8
510 QtFI 164 QtLd
*TRACE START 48

UNIT 43 TYPE 5 ECONOMIZER

PARAMETERS 4

*MODE, UAEe, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE
2 QtUaEe CpSalt CpWater
INPUTS 4
*T_hi, m_h, T_ci, m_c
33,1 33,2 0,0 9,5
327 QtFI FeedT QtLd
*TRACE START 48

UNIT 44 TYPE 5 ECONOMIZER

PARAMETERS 4

*MODE, UAEe, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE
2 QtUaEe CpSalt CpWater
INPUTS 4
*T_hi, m_h, T_ci, m_c
34,1 34,2 0,0 9,6
327 QtFI FeedT QtLd
*TRACE START 48

UNIT 45 TYPE 5 ECONOMIZER

PARAMETERS 4

*MODE, UAEe, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE
2 QtUaEe CpSalt CpWater
INPUTS 4
*T_hi, m_h, T_ci, m_c

35,1 35,2 0,0 9,7
327 QtFI FeedT QtLd
*TRACE START 48

UNIT 46 TYPE 5 ECONOMIZER

PARAMETERS 4

*MODE, UA_{Ee}, SP. HEAT HOT SIDE, SP. HEAT COLD SIDE

2 QtUa_{Ee} CpSalt CpWater

INPUTS 4

*T_{hi}, m_h, T_{ci}, m_c

36,1 36,2 0,0 9,8

327 QtFI FeedT QtLd

*TRACE START 48

UNIT 57 TYPE 11 TEE PIECE

PARAMETERS 1

*mode

1

INPUTS 4

*T₁ m₁ T₂ m₂

43,1 43,2 44,1 44,2

288 QtFI 288 QtLd

UNIT 58 TYPE 11 TEE PIECE

PARAMETERS 1

*mode

1

INPUTS 4

*T₁ m₁ T₂ m₂

45,1 45,2 46,1 46,2

288 QtFI 288 QtLd

UNIT 59 TYPE 11 TEE PIECE

PARAMETERS 1

*mode

1

INPUTS 4

*T₁ m₁ T₂ m₂

57,1 57,2 58,1 58,2

288 HIFI 288 HIFI

UNIT 53 TYPE 11 TEE PIECE

PARAMETERS 1

*mode

1

INPUTS 4

*T₁ m₁ T₂ m₂

33,3 33,4 34,3 34,4

164 QtLd 164 QtLd

*TRACE Start Steps

UNIT 54 TYPE 11 TEE PIECE

PARAMETERS 1

*mode

```

1
INPUTS 4
*T_1 m_1 T_2 m_2
35,3 35,4 36,3 36,4
164 QtLd 164 QtLd
*TRACE Start Steps

UNIT 55 TYPE 11 TEE PIECE
PARAMETERS 1
*mode
1
INPUTS 4
*T_1 m_1 T_2 m_2
53,1 53,2 54,1 54,2
164 HfLd 164 HfLd
*TRACE Start Steps

UNIT 6 TYPE 39 SALT COLD TANK
PARAMETERS 12
*mode,Vf,vmin,vmax,Cx, Ax, U_w, U_d, C_psalt, density_salt, T_i, m_i
2 TVol 1 TVol TCir Txa 0.0001 0.0001 CpSalt DenSalt 288 iColdTVol
INPUTS 4
*Tht mt mb To
59,1 59,2 9,4 9,2
510 LhFlow 0 27
*TRACE START Steps

*Print outputs average steam temperature and steam/hot temperature at exit
* of evaporator/economizer
UNIT 7 TYPE 25 PRINTER
PARAMETERS 5
*STEP START STOP LOGICAL-UNIT UNITS
1 Start Steps 12 2
INPUTS 10
55,1 55,2 33,3 34,3 35,3 36,3 43,3 44,3 45,3 46,3
551 552 333 343 353 363 433 443 453 463

*Print outputs from unit 2 (heat exchanger) and unit 33 (evaporator)
UNIT 8 TYPE 25 PRINTER
PARAMETERS 5
*STEP START STOP LOGICAL-UNIT UNITS
1 Start Steps 13 2
INPUTS 10
2,1 2,2 2,3 2,4 2,5 2,6 33,1 33,2 33,3 33,4
21 22 23 24 25 26 331 332 333 334

*Print outputs from unit 3 (hot tank) and unit 6 (cold tank)
UNIT 10 TYPE 25 PRINTER
PARAMETERS 5
*STEP START STOP LOGICAL-UNIT UNITS
1 Start Steps 14 2
INPUTS 10
3,3 3,4 3,5 3,6 3,7 3,8 3,9 6,1 6,2 6,3
33 34 35 36 37 38 39 61 62 63

```

*Print outputs from unit 3 (hot tank) and unit 6 (cold tank) and steam
*delivery temperatures from four evaporators
UNIT 11 TYPE 25 PRINTER
PARAMETERS 5
*STEP START STOP LOGICAL-UNIT UNITS
1 Start Steps 15 2
INPUTS 6
6,4 6,5 6,6 6,7 6,8 6,9
64 65 66 67 68 69
END

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