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AUXILIARY FEEDWATER REHEATING TO MITIGATE PRIMARY AND SECONDARY SIDE THERMAL STRESSORS

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ABSTRACT

A consequence of operating steam cycles under time varying loads, is the variability of the feedwater temperature entering the bottom of the steam generators. This variability is a direct result of changes in turbine impulse pressure and subsequently turbine tap pressures in response to the load changes, with a reduction in feed temperature during periods of low turbine demand. These fluctuations over time will increase thermal cycling and threaten the integrity of the tube bundle as well as other components in the feed system.

Sensible heat, TES systems have been shown to be an effective load management strategy allowing nuclear reactor systems to operate at effectively 100% full power while storing excess thermal energy for recovery later. A byproduct of the TES system is the availability of large amounts of low grade waste heat that can be used for ancillary applications, including auxiliary feed heating during periods of low turbine demand. The addition of an auxiliary feed heater at the end of the traditional feed train can minimize feed temperature variations during periods of low turbine demand, reducing the effects of thermal cycling and increasing overall thermodynamic efficiency.

This paper discusses the design, operation and control strategies for an auxiliary feed water system as an integral component of a coupled Thermal Energy Storage system and Integral Pressurized Water Reactor. The impact on system performance, particularly as it affects reactor dynamic response and reductions in thermal cycling will be addressed. In addition to the improved thermal efficiency, a benefit of this approach is the relocation of thermal stressors from the reactor coolant system to more easily managed Balance of Plant systems

Key Words: TES, SMRs, NR-HES, Sensible Heat Storage

1 INTRODUCTION

Thermal energy storage has been proposed as a load management strategy for Small Modular Reactors (SMRs) deployed on constrained grids and/or in hybrid energy systems [1]. Nuclear- Renewable Hybrid Energy Systems (NR-HES) can include process steam applications, and the presence of intermittent energy sources such as wind and solar. Under these conditions, the reactor can be subjected to significant time varying electric loads. Options for accommodating this load have included operating nuclear reactors in a load follow mode, or operating the reactor at or near steady state and bypassing steam directly to the condenser [2]. Both of these strategies result in lost energy potential. Load follow operation can also result in additional stresses on the fuel and other mechanical components. A more attractive approach is to operate the reactor at or near steady state and bypass excess steam to a thermal energy storage system. The thermal energy can then be recovered, either as a supplement to the power plant during peak demand times, or can be used for other ancillary applications [1]. Sensible heat thermal energy storage systems have been demonstrated in solar energy systems [3].

1.1 Design of Thermal Energy Storage System

The proposed Thermal Energy Storage (TES) System is shown in Figure 1. An outer loop interfaces with the reactor's Balance of Plant (BOP) directly through four parallel auxiliary turbine bypass valves connected at the pressure equalization header, each staged to open at a certain percent of the maximum auxiliary flow demand. Bypass steam is directed through an intermediate heat exchanger (IHX) and discharged to the main condenser. An inner loop containing a TES fluid consists of two large storage tanks along with several pumps to transport the TES fluid between the tanks, the IHX and a steam generator. Flow Bypass Valves are included in the discharge lines of both the Hot and Cold tanks to prevent deadheading the pumps when the Flow Control Valves are closed. Common TES fluid properties are given in Table I. Therminol-66 is chosen as the TES fluid in this work as it is readily available, can be pumped at low temperatures, and offers thermal stability over the range (-3˚C - 343˚C) which covers the anticipated operating range of the TES system (176˚C - 260˚C). Other benefits of using Therminol-66 include its Material Safety Data Sheet (MSDS) classification as a nonhazardous material [4]. In addition, as hydrocarbons do not readily exchange hydrogen atoms with other materials [5], tritium migration would be mitigated in the rare event of simultaneous leaks in the steam generator and an IHX tube allowed activated primary water to mix with the TES fluid. In this event, the TES tanks would act as holding tanks for the activated water.

Table I: Properties of Possible TES fluids at ~260 degrees Celsius (500 degrees Fahrenheit)

Heat Transfer Fluid	Boiling Point (˚C)	Heat Storage ($W*hr/m^3{\circ}C$)	Operating Range (˚C)
Therminol®-66 [6]	358 (678 F)	1039 (576.95 $W*hr/m^3{\circ}F$)	-2.7-343.3 (27 F-650 F)
Therminol®-68 [7]	307 (586 F)	1013 (563.03 $W*hr/m^3{\circ}F$)	-25.5 – 360 (-14 F-680 F)
Therminol®-75 [8]	342 (649 F)	992 (551.54 $W*hr/m^3{\circ}F$)	79.44 – 385 (175 F-725 F)

The TES system is designed to allow the reactor to run continuously at ~100% power over a wide range of operating conditions. System parameters for an mPower [9] size system are given in Table II. During periods of excess capacity, bypass steam is directed to the TES unit through the auxiliary bypass valves where it condenses on the shell side of the IHX. TES fluid is pumped from the Cold Tank to the Hot Tank through the tube side of the IHX at a rate sufficient to raise the temperature of the TES fluid to some set point. Condensate is collected in a hot well below the IHX and drains back to the main condenser. The TES fluid is then stored in the Hot Tank at constant temperature. The system is discharged during periods of peak demand, or when process steam is desired, by pumping the TES fluid from the Hot Tank through a boiler (steam generator) to the Cold Tank. This process steam can then be reintroduced into the power conversion cycle for electricity production [10] or directed to some other application. While the boiler in Figure 1 implies a Once Through Steam Generator (OTSG) design, a U-Tube design could just as easily be substituted. Although it is not indicated in Figure 1, pressure relief lines connect the shell side of the IHX with the condenser to prevent over pressurization of the heat exchanger during periods of low condensation rate. A nitrogen cover gas dictates the tank pressures during charging and discharging operation.

During charging, condensate is collected in a hotwell at the bottom of the IHX. This condensate is maintained at the saturation pressure of the IHX 4.83MPa (~700psia). While the condensate is no longer useful in terms of the thermal energy storage system, the condensate is a source of low grade waste heat that can be used for other ancillary applications [11], including feedwater heating. To utilize the condensate for feed water heating, a TES feedheater is added at the end of the conventional feed train. During periods of low electricity demand, the turbine impulse pressure and subsequently the feed water temperatures are at their minimum, while the charging rate of the TES system and production rate of condensate is at its highest providing a heat source to raise the feed water temperature prior to the steam generator inlet.

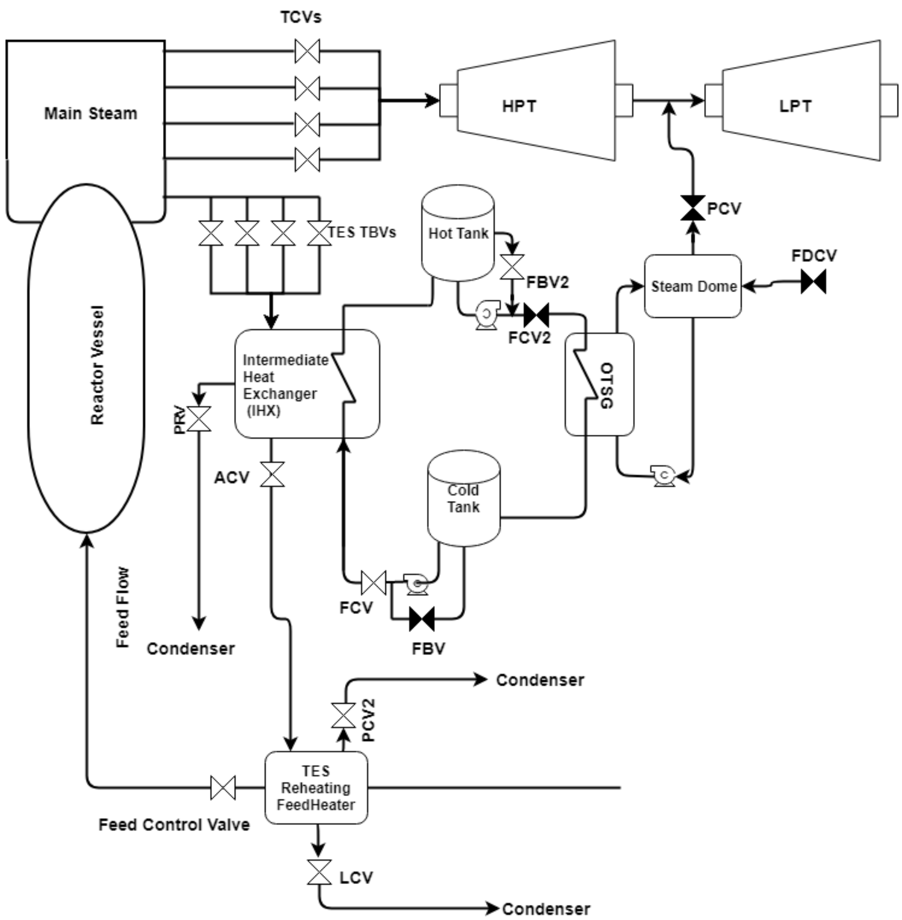

Figure 1: Schematic of an IPWR connected to a two-tank sensible heat thermal energy storage system, charging mode.

1.2 FeedHeater Equation Set

The time dependent behavior of the regenerative feedheater is obtained by solving mass, energy and simple momentum balances on the shell side of the feedheater.

Shell Side

Mass:

$$V_{FD}\frac{\partial \rho_{FD}^{t+\Delta t}}{\partial t}=\dot{m}_{IHX}^{t}-\dot{m}_{PCV2}^{t}-\dot{m}_{LCV}^{t} \tag{1}$$

Energy

$$V_{FD}\frac{\partial \rho u_{FD}^{t+\Delta t}}{\partial t}=\dot{m}_{IHX}^{t}h_{f,IHX}-\dot{m}_{PCV2}^{t}h_{g,FD}-\dot{m}_{LCV}^{t}h_{f,FD}-Q_{FD}^{t} \tag{2}$$

Momentum

$$P_{FD}^{t+\Delta t} = P_{cond}^{t} + \frac{\left(K_{PCV2}^{t} + K_{PCV2line}\right)\left(\dot{m}_{PCV2}^{t+\Delta t}\right)^2}{2\rho_g A_{PCV2}^2} \tag{3}$$

$$P_{FD}^{t+\Delta t} = P_{cond}^{t} + \frac{\left(K_{LCV}^{t} + K_{LCVline}\right)\left(\dot{m}_{LCV}^{t+\Delta t}\right)^2}{2\rho_f A_{LCV}^2} \tag{4}$$

State Equations:

$$\rho = \rho_f \alpha_f + \rho_g \alpha_g \tag{5}$$

$$\rho u = \rho_f u_f \alpha_f + \rho_g u_g \alpha_g \tag{6}$$

Heat Transfer

$$\dot{Q}_{FD} = (UA)_{FD}\left(T_{sat} - \bar{T}_{FD}\right) \tag{7}$$

where $\bar{T}_{FD}$ is the average fluid temperature within the feedheater. To obtain the average feedheater temperature we solve a simple energy balance on the fluid.

$$\dot{m}_{FD} c_p \frac{dT_{FD}}{dz} = (UP_w)_{FD}\left(T_{sat} - T_{FD}\right)$$

$$\frac{dT_{FD}}{dz} = \frac{(UP_w)_{FD}}{\dot{m}_{FD} c_p}\left(T_{sat} - T_{FD}\right) \Rightarrow \frac{dT_{FD}}{dz} = \frac{\beta}{L}\left(T_{sat} - T_{FD}\right)$$

where, $\beta = \frac{(UA)_{FD}}{\dot{m}_{FD} c_p}$

$$\frac{dT_{FD}}{dz} + \frac{\beta}{L} T_{FD} = \frac{\beta}{L} T_{sat}$$

$$T_{FD}(\mathrm{z})\,\mathrm{e}^{\frac{\beta z}{L}} = T_{inlet} + \int_0^z \frac{\beta}{L} T_{sat} e^{\frac{\beta z'}{L}} dz' \Rightarrow T_{FD}(\mathrm{z})\,\mathrm{e}^{\frac{\beta z}{L}} = T_{inlet} + T_{sat} e^{\frac{\beta z'}{L}}\Big|_0^z$$

$$T_{FD}(\mathrm{z}) = T_{inlet}\,\mathrm{e}^{-\frac{\beta z}{L}} + T_{sat}\left\{1 - \mathrm{e}^{-\frac{\beta z}{L}}\right\} \tag{8}$$

Now defining $\bar{T}_{FD}$ as

$$\bar{T}_{FD} = \frac{1}{L}\int_0^L T_{FD}(\mathrm{z})dz$$

where the TES fluid temperature is from equation

$$\bar{T}_{FD} = \frac{1}{L}\int_0^L T_{inlet}\,\mathrm{e}^{-\frac{\beta z}{L}}\,dz + T_{sat} - \frac{T_{sat}}{L}\int_0^L \mathrm{e}^{-\frac{\beta z}{L}}\,dz$$

$$\bar{T}_{FD} = T_{sat} + \frac{\left(T_{sat} - T_{inlet}\right)}{L}\int_0^L \mathrm{e}^{-\frac{\beta z}{L}}\,dz$$

$$\bar{T}_{FD} = T_{sat} + \frac{\left(T_{sat} - T_{inlet}\right)}{L}\left(\frac{L}{\beta}\right)e^{-\frac{\beta z}{L}}\Big|_0^L$$

Rearranging gives the final equation.

$$\bar{T}_{FD} = T_{sat} - \frac{\left(T_{sat} - T_{inlet}\right)}{\beta}\left\{1 - e^{-\beta}\right\} \tag{9}$$

Further, the determination of Q_{FD} requires the UA value

$$UA_{FD} = \frac{2\pi nL}{\frac{1}{h_i r_i} + \frac{1}{k}\ln\left(\frac{r_o}{r_i}\right) + \frac{1}{h_o r_o}} \tag{10}$$

where an average condensation heat transfer coefficient is assumed for the shell side of the form,

$$h_o = h_{cond}\left(T_w\right) = 0.725\left[\frac{\rho_f\left(\rho_f - \rho_g\right)g h_{fg}^{'} k_f^3}{\mu_f d\left(T_{sat} - T_w\right)}\right]^{\frac{1}{4}} \tag{11}$$

$$h_{fg}^{'} = h_{fg}\left[1 + \frac{0.68 c_{p_f}\left(T_{sat} - T_w\right)}{h_{fg}}\right]$$

and T_w satisfies

$$h_{cond}\left(T_w\right) r_o\left(T_{sat} - T_w\right) = \left\{\frac{1}{k}\ln\left(\frac{r_o}{r_i}\right) + \frac{1}{h_i r_i}\right\}^{-1}\left(T_w - T_{FD_{avg}}\right)$$

$$T_{FD_{avg}} = \frac{T_{inlet} + T_{exit}}{2}$$

$$h_i = \frac{k_{FD} Nu_i}{De_{FD}} \tag{12}$$

$$Nu_i = \max\left[0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}, 4.66\right] \tag{13}$$

1.3 FeedHeater Control

The feedheater has three valves directly affecting its operation, a pressure control valve, a level control valve, and the IHX auxiliary control valve. The level control valve maintains a liquid level at the bottom of the feedheater. The level control valve operates on a three-element controller where the first error signal is based on liquid level and the second error signal is based on trying to match the inlet flow with the outlet flow.

$$\mathrm{Signal}_{LCV} = G_1 E_1 + G_2 E_2 \tag{14}$$

$$E_1 = \frac{\text{Level-Level}_{\text{Ref}}}{\text{FeedHeater}_{\text{Height}}} \tag{15}$$

$$E_2 = \frac{\dot{m}_{IHX} - \dot{m}_{FD}}{\dot{m}_{IHX} + \dot{m}_{FD}} \tag{16}$$

G_1 and G_2 are gains used to create the proper control. Both error signals are normalized to be between 0 and 1. This is to ensure they can be properly implemented with instruments that take a 4-20mA signal.

The pressure control valve ensures the pressure inside the feedheater is maintained at the pressure required to maintain a saturation temperature of 212 ◦C (414◦F) (the nominal steam generator inlet temperature).

$$Signal_{PCV} = \frac{P_{\text{Feedheater}} - P_{\text{FeedHeater}_{\text{Setpoint}}}}{P_{\text{FeedHeater}_{\text{Setpoint}}}} \tag{17}$$

The auxiliary control valve (ACV) maintains the IHX hot well level. This valve operates on a three element controller based on the level of the IHX and the difference in mass flows into and out of the IHX as shown in equations 18 and 19 where G_1 and G_2 are error weighting gains. Gains were selected to allow for smooth operation of the ACV over the foreseeable operating bands.

$$Signal_{ACV} = G_1 E_1 + G_2 E_2 \tag{18}$$

$$E_1 = \frac{Level{-}Level_{Ref}}{Hotwell_{Height}} \tag{19}$$

$$E_2 = \frac{\dot{m}_{bypass} - \dot{m}_{ACV}}{\dot{m}_{bypass} + \dot{m}_{ACV}} \tag{20}$$

1.4 Results

These simulations focus only on the charging mode of the TES system. A 24-hour simulation was run with an electric load profile representative of a typical summer day in an area with mixed commercial and residential characteristics [12], [13]. The load profile has been scaled such that the minimum load is approximately 60% of nominal full power. Time zero corresponds to midnight. A 24 hour cycle was chosen because it is the minimum amount of time required to show a full daily cycle for a region during a season. The system is sized in accordance with Table II.

Table II: System Design Parameters.

Parameter	**Value**
Reactor Thermal Output	530 MWt
Electric Output	180 MWe
Primary System Pressure	14.134 MPa (2050 psia)
Core Inlet Temperature	296.67 °C (566 °F)
Core Exit Temperature	321.67 °C (611 °F)
Core Flow Rate	13.608×10^6 kg/hr (30 Mlbm/hr)
Steam Pressure	5.688MPa (825 psia)
Steam Temperature	299.44 °C (571 °F)
Nominal Feed Temperature	212.22 °C (414 °F)
Steam Flow Rate	9.53×10^5 kg/hr (2.1Mlbm/hr)
TES Fluid	Therminol-66
IHX Volume	101.94 m^3 (3600ft^3)
IHX Reference Exit Temperature	260 °C (500 °F))
FeedHeater Volume	1500 ft^3
Tube material	Inconel-690
Number of tubes	38,000
Tube inner diameter	0.013 m (0.044 ft)
Tube outer diameter	0.018 m (0.058 ft)
Condenser Pressure	0.00483 MPa (0.7 psia)
FeedHeater Pressure Setpoint	2MPa (290 psia)

1.4.1 Regenerative FeedHeater Inactive

As a baseline case the results are initially shown with only the standard feedheater train running. For this case the waste heat from the IHX is sent directly to the condenser.

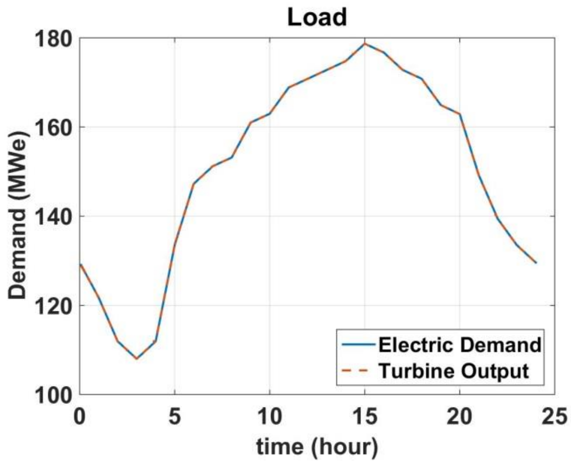

Figure 2: Turbine Output and Demand

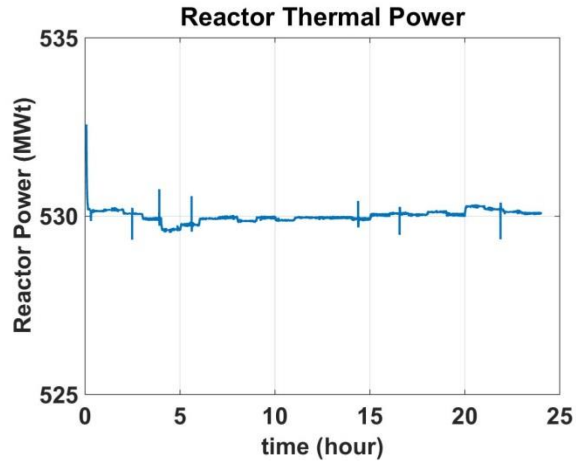

Figure 3: Reactor Power

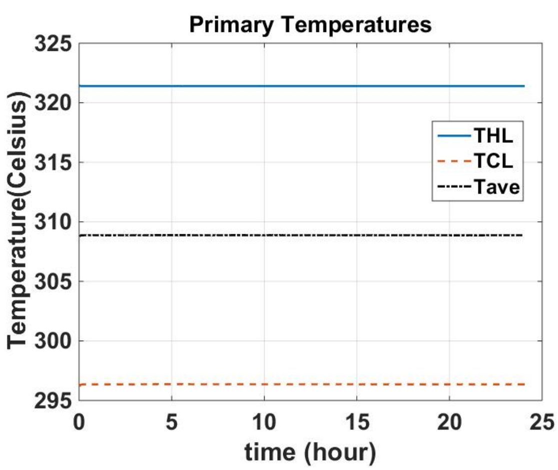

Figure 4: Primary Temperatures

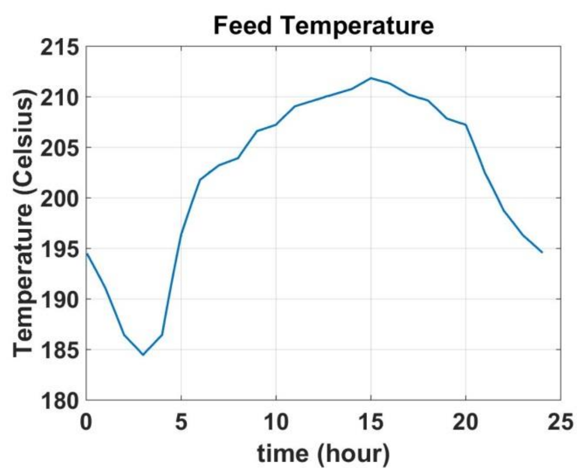

Figure 5: Feed Temperature

As illustrated in Figure 2 and Figure 3, the plant is able to maneuver such that the electric demand is satisfied while keeping reactor power effectively constant. Since reactor power and reactor coolant temperatures were essentially constant, this maneuver could be executed without control rod movement and thermal stresses associated with changes in temperatures and power distributions. However, as illustrated in Figure 5, the cycling of feed temperature remains and could add additional stresses to the steam generator tubes.

1.4.2 Regenerative FeedHeater Active

In this example the waste heat from the TES system is used to operate a regenerative feedheater at the end of the feed train prior to entering the steam generator.

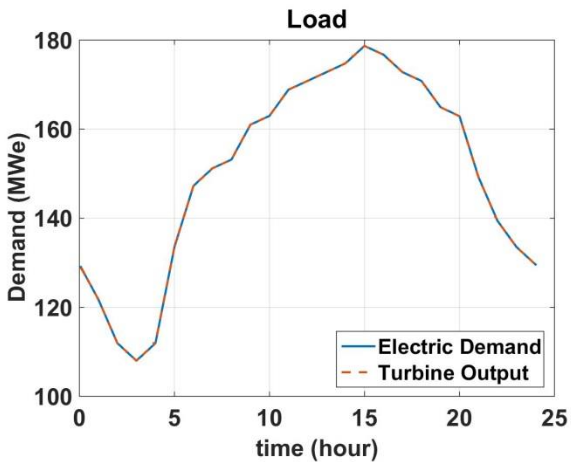

Figure 6: Turbine Output and Demand

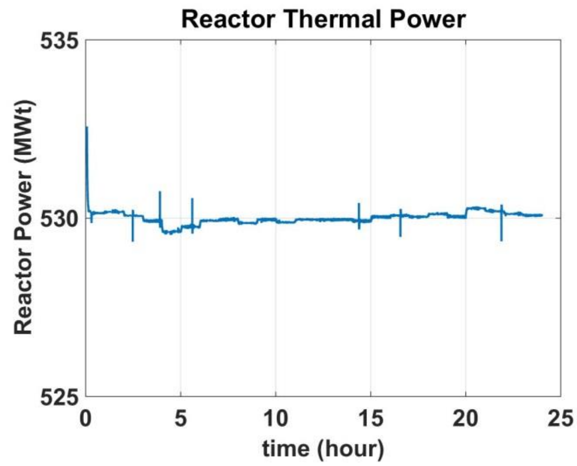

Figure 7: Reactor Power

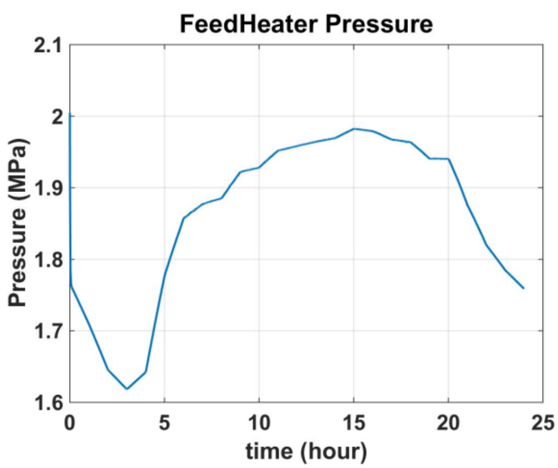

Figure 8: FeedHeater Shell Side Pressure

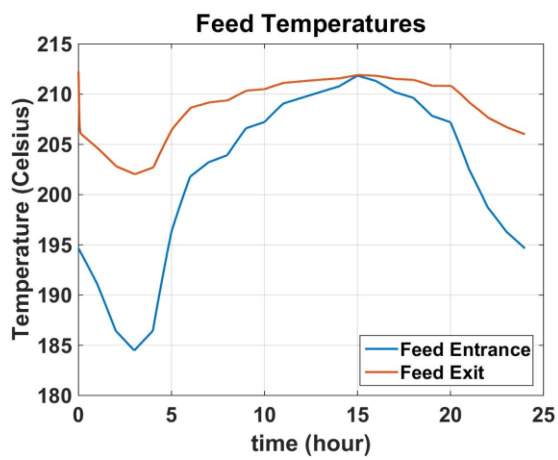

Figure 9: Feed Temperatures into and out of the regenerative feedheater

Similar to the previous case Figures 6 and 7 demonstrate load is able to be met while maintaining reactor power approximately constant and this maneuver could be executed without control rod movement. As a consequence of adding the regenerative feedheater, the feed temperature entering the bottom of the steam generator is dramatically increased as illustrated in Figure 9. Prior to the introduction of the TES feedheater, the temperature entering the steam generator varied approximately 27.7˚C (50˚F). With the inclusion of the feedheater, temperature variations are reduced to approximately 11.11˚C (20˚F). In addition to increases in the cycle thermal efficiency during periods of low electric demand, the increase in feed temperature should mitigate thermal cycling of pipes, valves, and other components prior to entering the steam generator, and potentially reduce the downtime associated with enhanced aging of these components.

2 CONCLUSIONS

The results presented demonstrate the feasibility of using TES systems coupled to Small Modular Reactors to minimize power swings during periods of variable electric load. During times of low electric demand, excess steam is bypassed into the TES system at a rate sufficient to maintain full reactor power thus taking stressors off the nuclear system and placing it onto the less expensive storage system. The thermal energy can be recovered later for either electric peaking or ancillary applications requiring steam such as multistage flash desalination. Further, it has been shown that the charging systems waste heat can be used to operate a regenerative feedheater placed at the end of the feedtrain. The feedheater is able to limit feed temperature oscillations, further isolating the nuclear system from load fluctuations. This reduction increases the system lifetime, efficiency, and ultimately the systems overall economic benefit.

3 NOMENCLATURE

α	void fraction
A	area
ACV	auxiliary control valve
BOP	balance of plant
c_p	specific heat
FBV	feed bypass valve
FD	feed
FDCV	feed control valve
FCV	flow control valve
H	height
HPT	high pressure turbine
IHX	intermediate heat exchanger
K	loss coefficient
LPT	low pressure turbine
$\dot{m}$	mass flow rate
MWe	megawatts electric
MWt	megawatts thermal
OTSG	once through steam generator
P	pressure
ρ	density
PCV	pressure control valve
PRV	pressure relief valve
$\dot{Q}$	heat transfer rate
Δt	change in time
t	time
TBV	turbine bypass valve
TES	thermal energy storage
u	internal energy
v	velocity
V	volume
$\dot{W}$	power

Subscripts

cond	condenser
f	saturated liquid
g	saturated vapor
Line	losses in lines
ref	reference
SG	steam generator

4 ACKNOWLEDGMENTS

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